REPORT OF THE WORKING GROUP ON HIGH LUMINOSITIES AT LEP

Edited by
E. Blucher, J. Jowett, F. Merritt, G. Mikenberg,
J. Panman, F.M. Renard and D. Treille

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REPORT OF THE WORKING GROUP
ON HIGH LUMINOSITIES AT LEP

Edited by
E. Blucher, J. Jowett, F. Merritt, G. Mikenberg,
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ABSTRACT

The availability of an order-of-magnitude increase in the luminosity at LEP (CERN’s Large Electron–Positron Collider) can dramatically increase its physics output. With the help of a pretzel scheme, it should be possible to increase the peak luminosity beyond $10^{32}$ cm$^{-2}$ s$^{-1}$ at the Z energy and to significantly increase the luminosity around the W-pair threshold.

This report spells out the physics possibilities opened up by the availability of several $10^7$ Z events. The three domains of physics that benefit mostly from this abundance are very accurate measurements of Standard Model parameters, rare decays of the Z, and the physics of fermion–antifermion states such as B physics.

The possibilities and implications for the machine and the experiments are presented.

The physics possibilities are explored and compared with these at other accelerators.
SUMMARY

The availability of high luminosity at LEP (HLEP) can dramatically increase the output of physics from that machine and its detectors, at a moderate cost.

With the help of a pretzel scheme, it should be possible to push the peak luminosity beyond $10^{32}$ cm$^{-2}$ s$^{-1}$ at the Z. Significant increases in luminosity also appear possible at higher energies, up to around 95 GeV.

On the Z, high luminosity opens up three domains of physics, of which the first two will never be explored if LEP misses this opportunity.

The first domain is the one of very accurate measurements. HLEP will be the only machine able to provide precise measurements of the weak coupling constants of leptons and quarks, thus considerably improving the LEP 1 measurements. These measurements will lead to an accuracy in $\sin^2\theta_W$ comparable to the one that can be achieved with polarized beams, therefore allowing critical tests of the Standard Model.

For the electroweak sector, LEP could become an analogue of what the $g - 2$ was for QED. These measurements are needed in order to feel and identify new physics occurring at higher masses than those available at existing machines.

This information can in some cases also be obtained with a programme of longitudinal polarization in LEP, but with different methods and therefore different sources of uncertainty. However, a whole class of measurements that provide specific information depends on high luminosity being available, and does not require polarization.

The second domain concerns the rare decays of the Z. Many interesting modes could appear at the $10^{-6}$ level or below it. The visibility of several of them has been demonstrated. Exposures of several $10^7$ Z are needed.

The third domain is the physics of fermion–antifermion states. High-luminosity LEP can be regarded as a heavy-flavour factory, in particular a B-factory. All species of B’s are produced, including yet unobserved states such as $B_s, B_c$, as well as baryon states containing b and c quarks. The heavy quarks are produced with a large boost, enabling the identification of the decay products of each heavy-quark state separately, and allowing for the measurement of the secondary vertices. These features will allow experiments to measure $B_s - \bar{B}_s$ oscillations in the full allowed range, as well as to measure lifetimes of still unknown states containing b and c quarks.

Direct observation of CP violation in the $B^0$ system can only be seen at LEP with $10^8$ Z and if the parameters are at the most favourable edge of the range allowed by the Standard Model. Only an asymmetric and very luminous ($10^{34}$ cm$^{-2}$ s$^{-1}$) B-factory can have a good chance of reaching the required sensitivity.

An upgraded LEP can produce important results, in particular in B spectroscopy, B lifetimes, and especially B$_s$ mixing, which by giving access to the phase of the KM matrix provides another way of tackling the CP problem.

At LEP 200 it is vital to achieve, in a reasonable time, an integrated luminosity that is at least equal to the ‘Aachen quantum’ of 500 pb$^{-1}$; the quality of several crucial measurements and searches is indeed merely a matter of statistics. The availability of adequate power and accelerating voltage would permit us to obtain 190 GeV in the centre-of-mass system with reasonable luminosity, and an optimum $W^+W^-$ rate might be reached with $2 \times 8$ bunches. The interest of these two exposures has been emphasized at the ECFA Workshop on LEP 200 (Aachen, 1987) and re-expressed in the present study.
In order to upgrade the LEP machine to higher luminosities, a scheme with up to 36 bunches separated with a pretzel scheme appears feasible.

Electrostatic or RF-magnetic separators and upgrades to a number of other pieces of hardware will be needed. However there are no really drastic changes to the machine apart from the pretzel scheme itself. It should be easy to revert to, for instance, high-energy LEP operation with 4 bunches.

Operation of LEP with a pretzel scheme will be a lot more complicated and further detailed work remains to be done, particularly on the optics, beam-beam effects, RF system, separator development, etc., before final performance and cost estimates can be given. However, the first experiments on simulated pretzel orbits have given encouraging results, and further studies in the near future should advance our understanding considerably.

Although a number of problems remain to be solved before LEP can be operated with larger numbers of bunches, our perception of the feasibility of the pretzel scheme has steadily improved. The principal difficulty is the upgrading of the higher-order mode couplers on the superconducting cavities to cope with the higher power levels.

The implications for the experiments for running at LEP operating in a multibunch mode have been assessed. The conclusions from these studies have to be regarded as preliminary; work on studying high-luminosity problems and required upgrades is continuing in all four experiments.

All of the experiments could be ready for 8-bunch running by 1993, and perhaps by 1992. The total minimum cost is about 1.2 MSF.

Upgrades to 18 bunches are more difficult, but could probably be carried out by 1994 or 1995. Running with 36 bunches presents some substantial difficulties. More difficult upgrades than those discussed in this report (e.g. pipe-lining) might be required. In all cases, timing for the Level-1 trigger is critical and requires further study.

Total upgrades from 4 to 36 bunches for the four experiments are estimated to cost about 23 MSF. Additional upgrades required for on-line and off-line event processing could add 10–15 MSF to this figure.

For the machine an 8-bunch scheme appears to be possible at minimal cost using existing equipment, and is currently being implemented. Depending on which solutions are required the total cost for the machine varies between 18.4 and 33.9 MSF for a 36-bunch scheme.

It should be noted that the cost estimates for both the experiments and the machine are still provisional.
PREFACE

The High-Luminosity Working Group was set up following a request by the LEP Committee for a study of future possibilities for increasing the LEP luminosity by about an order of magnitude. The work was to cover the physics possibilities at higher luminosity, the requirements placed on the detectors to cope with higher rates, and the feasibility and probable time scales for implementation at LEP. The first meeting was held on 16 October 1989.

Although the main emphasis of the study has been placed on the feasibility of a 36-bunch scheme operating at the Z peak, the Working Group has also considered other possibilities such as operating LEP with smaller numbers of bunches, in particular with 8 bunches per beam at energies above the $W^+W^-$ pair production threshold, where added luminosity would be of great value.

This report has appeared earlier in preliminary form in order to have it available for a first discussion at the LEPC meeting on 5 and 6 June 1990 and for the special meeting of the LEPC at Cogne from 24 to 29 September 1990. Some additions have been incorporated into this final version in order to include the results of work done in recent months. These additions affect Part I, on machine design considerations, and Part IV, on the implications for the detectors of the possible high-luminosity options. Parts II and III on the physics case and on the comparison with other machines have not been changed in any significant way.

The report brings together the work of many people. Their efforts have been coordinated by members of the High-Luminosity Working Group who have been responsible for setting up different subgroups to study the different topics and who have themselves contributed substantially to the preparation of the corresponding sections of the report. The members of the working group are listed below and are included in the full list of authors on p. viii.

In concluding this preface, I should like, as chairman of the Working Group, to thank all who have been involved in the study for the excellent work they have done, and also the CERN Scientific Reports team for their invaluable help in the preparation of the manuscript.

J.J. Thresher

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Members of the High-Luminosity Working Group

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PART I

HIGH-LUMINOSITY OPTIONS FOR LEP

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HIGH LUMINOSITY OPTIONS FOR LEP

Abstract
By increasing the number of bunches beyond the original design value of 4, a substantial increase in the luminosity of LEP could be achieved throughout its range of operating energies. With respect to the “design” values, calculated for 4 bunches of 0.75 mA per beam, the increase in luminosity obtained by this means alone could be a factor 2 at 90 GeV (where it is limited by RF power) and a factor 9 at the Z^0-peak (where it is limited by other beam-dynamical effects). In the eventuality that the single-bunch current is limited below the design value, multi-bunch operation could provide larger gains at the higher energies. Of course, part of this gain may already be in hand if higher single-bunch currents can be collided at these energies.

To avoid parasitic beam-beam effects, the bunches must be separated at their unwanted encounters in the arcs of the machine. The amount of separation necessary and schemes for obtaining it are described. A preliminary survey of the necessary additions and modifications to LEP and its injectors shows that certain hardware modifications and extra equipment are required but these are largely compatible with, or included in, the plans to increase the beam energy. A very preliminary cost estimate for the so-called “pretzel” scheme is provided.

Note: this chapter of the report has been modified to take account of new developments since the Preliminary Draft in May 1990. To assist the reader in identifying the changes, those sections which are either completely new or significantly modified have been marked with the symbol ♠ in their headings and in the Table of Contents. Some of these sections also include a number of new figures. Minor corrections and improvements are not indicated.

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1 ♠ INTRODUCTION

LEP, the largest $\epsilon^+\epsilon^-$ storage ring ever built, is now operating successfully with a substantial fraction of its "design" luminosity. This design value was calculated assuming that the machine would run in a mode similar to most of the earlier generations of $\epsilon^+\epsilon^-$ colliders. Building on the experiences of its smaller predecessors, improved simulation capabilities and improved understanding of how beam-dynamics limit luminosity, the predictions of the luminosity for LEP were made rather realistically. At the same time, budget constraints and the need to keep the project well-defined for the large community of users, meant that more exotic, untried modes of operation were not considered as options for the first phase of running.

Now, as the physics motivations become clearer and our understanding of the machine steadily advances, the evaluation of options such as polarized beams or much higher luminosities becomes correspondingly more concrete.

In the following, we present a survey of the beam-dynamics, operational and engineering issues to be dealt with for a High-Luminosity LEP. We must stress that this is only an interim report, the outcome of a few months of far-from-full time work since the members of the machine physics subgroup of the Working Group on High-Luminosity LEP are also heavily committed to the immediate problems of improving the performance of LEP. Nevertheless we have tried to cover most of what is likely to matter or at least to indicate clearly where there are gaps in the coverage which remain to be filled.

By the nature of our field, discussions of future accelerator projects always contain an element which is unknown, something that has never been done before. Often, c.f., the prediction of polarization levels in rings like LEP and HERA or the prediction of dynamic apertures, the problem is essentially computational: although we may even be in possession of the "correct" theory, computation and simulation technique have to be pushed to their limits and their results may be inconclusive, remaining open to doubt and valid criticism. Often though, a relatively simple experiment—if it can only be done—may resolve some of the uncertainties.

In the case of High Luminosity LEP, we are in the happy situation of having the machine to hand. We had therefore hoped to be able to include the results of a systematic programme of machine experiments bearing on the high luminosity schemes in this report. Unfortunately, only a few hours of machine development were available for this in summer 1990. However these pilot experiments (see Section 3.6) were successful well beyond our expectations. We trust that more time will be available for further systematic studies in 1991 and later.

1.1 Increasing the luminosity of LEP

The luminosity of an $\epsilon^+\epsilon^-$ storage ring collider is often written in the form

$$L_0 = \frac{k_b f_0 N_s^2}{4\pi\sigma_x^* \sigma_y^*}$$

(1)

where $\sigma_x^* = \sqrt{\epsilon_{xc}^* \beta_x^*}$, $\sigma_y^* = \sqrt{\epsilon_{yc} \beta_y^*}$, and the emittances $\epsilon_{xc}$, $\epsilon_{yc}$ are determined by the intrinsic betatron coupling of the ring and the balance between radiation damping and quantum excitation according to well-known formulae.

---

1 Our notations are defined in Appendix A.
Introducing the unperturbed beam-beam strength parameters

\[ \xi_{yo} = \frac{(I_b/e f_0) r_e \beta_y^*}{2 \pi (E_0/m c^2)(\sigma_z^* + \sigma_y^*) \sigma_y^*}, \]

\[ \xi_{xo} = \frac{(I_b/e f_0) r_e \beta_z^*}{2 \pi (E_0/m c^2)(\sigma_z^* + \sigma_y^*) \sigma_z^*}, \]  

(2)

and the assumption of "optimal coupling"

\[ \kappa^2 \overset{\text{def}}{=} \frac{\epsilon_{yc}}{\epsilon_{xc}} = \frac{\beta_y^*}{\beta_z^*}, \]  

(3)

the formula (1) may be rewritten

\[ L_0 = \frac{k_b I_b (E/m c^2) \xi_{yo}}{2 e r_e \beta_y^*}. \]  

(4)

In fact (1) and (4) assume not only that the spatial distributions of particles within the bunches remain gaussian but that there is no blow-up due to the beam-beam interaction. In maximum luminosity conditions, near the beam-beam limit, these assumptions do not hold. To take account of the beam-beam effect, the luminosity of LEP is usually estimated \([1,2,3]\) as

\[ L = L_0 \frac{\xi(\xi_{yo}, \ldots)}{\xi_{yo}} = \frac{k_b I_b (E/m c^2) \xi}{2 e r_e \beta_y^*} \]  

at beam-beam limit

(5)

where the form of \(\xi(\xi_{yo}, \ldots)\) gives the effective value of the beam-beam strength parameter as a function of the unperturbed value and other machine parameters (such as the damping time). The detailed form of this function is abstracted from phenomenology and simulation results; here we need only recall that, at 45.5 GeV and in favourable conditions at the beam-beam limit, it reaches a saturation value \(\xi \simeq 0.035\) with an unperturbed value of \(\xi_{yo} \simeq 0.06\).

The other "nominal" parameters for operation at the \(Z^0\) peak are: \(E = 45.5\) GeV, \(I_b = 0.75\) mA, \(\beta_y^* = 7\) cm, and \(k_b = 4\). These yield the luminosity

\[ L = 1.7 \times 10^{31}\text{cm}^{-2}\text{sec}^{-1}. \]  

(6)

It is reasonable to hope to exceed this with little or no changes to the machine hardware. Luminosity improvements may come in the following ways:

**Increasing \(I_b\):** Although the design current has not yet been attained, there are arguments which suggest that we will eventually be able to exceed it, say, by a factor 2.

**Changing beam sizes:** When the beam-beam limit has not yet been reached, the luminosity can be improved by reducing emittance. For example, the LEP lattice with 90° phase advance per cell should give higher luminosity when \(I_b\) is low \([3]\). This optics is presently being tried out.

On the other hand, once \(I_b\) is sufficient to reach the beam-beam limit, it may be necessary to increase the emittance using damping partition number variation or the wigglers.
Lowering $\beta_y^*$: At present the low-$\beta$ section is being tuned to give $\beta_y^* = 4.3\,\text{cm}$ which should give a factor 1.6 in luminosity.

Higher $\xi$: An optimist can always hope that, once the right conditions are found, the beam-beam limit might be higher than expected, perhaps by a factor 1.5.

If all of these approaches were to succeed together—a very optimistic assumption—then we might achieve $L \simeq 7 \times 10^{31}\,\text{cm}^{-2}\text{sec}^{-1}$.

Once these means of increasing luminosity have reached their natural limits, the only way to increase it further is to increase the number of bunches stored in the ring. There is always the risk that, in doing this, some of the other gains are negated, i.e., that the luminosity achieved per crossing may be less when there are more bunches in the ring. The number of bunches cannot be increased without changing the mode of operation and, almost certainly, some hardware.

1.2 More bunches

With $k_b$ bunches per beam, spaced equidistantly around the circumference, there are $2k_b$ points where bunches encounter each other and will collide unless the $e^+$ and $e^-$ bunches are somehow separated. In the design version of LEP [4] (and in current operation), we have $k_b = 4$. Out of the 8 crossing points, 4 are occupied by the LEP experiments and therefore require head-on collisions. At the other 4 crossing points, the beams are separated vertically by local, closed, vertical orbit bumps generated by electrostatic separators.

If more bunches are added, collisions will take place in the arcs of the machine. There would be correspondingly more beam-beam interactions per radiation damping time and the distribution of particles in phase space would span a greater range of transverse oscillation frequencies ("tune spread"). The latter effect is quantified by the beam-beam tune-shift parameters (see Section 4.2 below) and would generally cause complete beam loss.

To reduce these parasitic beam-beam interactions to an acceptable level, some means of separating the beams at their unwanted encounters has to be found. Some machine designs do this by separating the beams near the Interaction Point (IP) into two independent vacuum chambers. Alternatively local electrostatic separation bumps can be inserted around the encounters. Figure 1 illustrates this.

Unless one is lucky enough to be able to locate them at special betatron phases, these schemes require 3 or 4 extra separator units per encounter in order to close the bump. This can obviously be continued to $k_b > 8$ but quickly becomes expensive and impractical.

A more versatile and economical solution is to start a separation bump but not close it until many betatron wavelengths later around the ring; see Figure 2. Encounters are

---

2These are the even-numbered points: P2, \ldots, P8.
3These are the odd-numbered points: P1, \ldots, P7.
4This mechanism for beam loss has already been observed in LEP by allowing beams of moderate intensity to collide at the Interaction Point (IP) at injection energy where beam-beam tune shifts are large: $\xi \propto E^{-3}$. Of course, this is precisely why there are separators for use during injection and ramping.
5In the sense of requiring fewer separators.
Figure 1: Schematic layout of local separation at an encounter in an arc of LEP. The diagram shows one octant of LEP, stretching from an even-numbered IP on the left to an odd point on the right. The existing vertical separation system at the odd point is also indicated. Because of the need to match the bump there may in reality be up to two separators for each one shown here unless it is possible to position them at positions of special betatron phase.

Figure 2: Schematic layout of a pretzel scheme in one octant of LEP. By arranging the right betatron phase advance between the separator and the odd point, there need be only one separator per octant. The $e^+$ and $e^-$ orbits are separated in many places but not near the nodes of the pretzel orbits. To continue the diagram into adjacent octants, we not only take the mirror image about the end point but also invert the direction of the orbits (see Section 3.2).
then permissible in many—but not all—places inside the bump. This is the basis of the so-called pretzel\textsuperscript{6} scheme to be described and analysed below.

A pretzel scheme in LEP would allow not only a larger number of bunches, but also a selection of intermediate numbers. We shall see later how a judicious choice could lead to the largest possible luminosity at all energies.

1.3 History

The idea of putting 8 bunches per beam in LEP goes back a long way. There were various proposals for separation schemes in the middle of the arcs [5,6,7] but these ideas were not adopted, mainly for budgetary reasons. Consideration stopped at $k_b = 8$ because this is the maximum value compatible with operation of the spherical storage cavities on top of the normal-conducting accelerating cavities.

The idea of LEP as a $Z^0$-factory with many more bunches, to exploit the additional RF power available from the superconducting system at the $Z^0$ energy, was initiated more recently [8] and this led to a feasibility study started in summer 1988. The results were presented in various talks and in [9].

Subsequently the Working Group on High-Luminosity LEP, consisting of experimental and accelerator physicists, was set up and a study on the LEP Luminosity Upgrade started in the accelerator divisions in January 1990. For the present report we have completely reworked the calculations of [9] (with updated optics, etc.) and found more favourable results. In addition, a good proportion of the uncertainties indicated in [9] have been satisfactorily resolved, thanks to further theoretical and hardware studies and to the first experiments on LEP itself. On the other hand, some new problems have emerged.

1.4 Other machines

LEP would be by no means the first machine to store two beams on separate orbits in the same vacuum chamber. However it should be remembered that hadron colliders are not directly comparable to $e^+e^-$ colliders.

CEA The Cambridge Electron Accelerator collided at a single IP with 120 bunches separated all around the rest of the ring [10].

CESR The highest luminosity ever achieved in an $e^+e^-$ storage ring is that of CESR at Cornell and is obtained with the help of a pretzel scheme [11,12] in the horizontal plane. The success of this scheme was a major inspiration of the present study.

Initially at least, the gain in luminosity of 7-bunch operation over single-bunch operation was rather less than 7, typically 4. The main reason for this appears to have been the necessity to reduce the beam size and the pretzel amplitude in order to keep the tails clear of the vacuum chamber walls. Implementation of the pretzel operation required a lot of machine study time.

\textsuperscript{6}In the interests of scholarship, and to deflect a recurring criticism of our spelling, we point out that this is the English word derived from the German \textit{brezel}; in fact the meaning seems to have changed to about the same degree as the spelling, a \textit{brezel} being a kind of bread and a pretzel a little salty cocktail biscuit baked in a similar shape.
**SppS** At CERN, the SppS collider made the transition from 3- to 6-bunch operation by implementing a scheme of separated orbits [13]. This is another horizontal separation scheme. The asymmetric positioning of the UA1 and UA2 experiments allowed the phase advance over one half of the ring to be chosen so that all bunch encounters in that half-ring would occur at the same maximum separation.

**Tevatron** It is also worth noting that plans to run the Tevatron [14] with 36 bunches are currently being implemented. In this case the proton and antiproton orbits are separated in both horizontal and vertical planes, resulting in two interlaced helical orbits. The operating experience which will be gathered at this machine in the near future will also be very relevant to LEP. In particular, the Tevatron will be ramped with separated orbits. The beam dynamics and control problems associated with this are not encountered in CESR which injects at top energy. In fact, ramping LEP is likely to be less difficult than ramping a superconducting ring like the Tevatron.

### 1.5 Other schemes for LEP

There has been some discussion of other ways of separating the beams in LEP at unwanted encounters with a view to a quicker implementation of more bunches.

#### 1.5.1 Local separation bumps

It is still possible to return to the idea of the local vertical bump in mid-arc (Figure 1) which was dropped in 1982. This scheme has the advantage of simplicity in the beam dynamics and would allow $k_s = 8$ at the price of installing $10^7$ separator units [5,6,7]. It would require the removal of some sextupoles and the replacement of some dipoles in the middle of the arcs to make room for the separators. Locations for the high-voltage supplies would have to be found or excavated. Despite a considerable amount of disruption to the machine layout in the middle of each arc, we consider that it would be fairly straightforward to implement. It might be taken as a low-risk option to gain a factor of 2 over whatever luminosity is available in 4-bunch operation.

#### 1.5.2 Separation by energy differences

Another proposal is to take advantage of the differential horizontal orbits due to the dispersion and "energy sawtoothing" around the circumference. This may not be enough at lower energies because the synchrotron radiation losses are $\propto E^4$ and the orbit separation $\propto E^3$. However one could exaggerate the effect by anti-phasing some RF stations so as to decelerate the beam. This may attempted in machine development time in summer 1990 but no conclusive results were obtained. Conceivably, such a scheme could be implemented within a year—if it worked and decisions were taken to devote time and effort to developing it.

#### 1.5.3 Use of existing separators

Another possibility would be just to use the existing vertical separators near the IP to generate vertical pretzel orbits everywhere except in the immediate vicinity of the IP.

---

7 Or perhaps 24, if asymmetric 3-separator bumps were found to be necessary.
This would fly in the face of a lot of conventional wisdom and the constraints for a clean pretzel scheme which are enumerated in Section 2.1 below. However it might just work if the problems due to synchro-betatron resonances and betatron coupling turned out to be manageable. Again, this is something which could be tried out fairly easily in machine development time in the short term.

2 A PRETZEL SCHEME IN LEP

2.1 Layout

The pretzel scheme is based on the installation of electrostatic separators which make a closed orbit distortion in each arc of opposite sign for each beam so that bunches miss each other except at the IPs. The following constraints have to be satisfied:

1. The beams must collide at the even-numbered IPs.

2. The beams are to be separated throughout as much of the machine as possible, especially in the arcs.

3. To avoid creating a driving mechanism for synchro-betatron resonances [15] there should be no closed-orbit deviation for either beam in the RF cavities.
   Even if we can compensate this effect with dispersion, it would not be possible to do so for both beams at the same time.
   With respect to the IPs, therefore, the pretzel separators must lie on the outboard side of the RF system (as already indicated in Figure 2) so that the $e^+$ and $e^-$ have common orbits in the RF sections.

4. Since the minimum bunch spacing is determined by the length of the part of the machine where the orbits are common, we should nevertheless try to minimise this.

5. Closure of the pretzel scheme requires a betatron phase advance of $n\pi$ in the plane between the separator and the odd IP in which the orbits are separated (see Section 3.2).

6. The possibility of reversion to 4-bunch operation on the central orbit should always be kept open. This requires, in particular, that we retain the independent vertical separation at the odd crossing points.

7. Clearly we should minimise the changes to the LEP200 layout.

8. We should try to ensure compatibility between the pretzel scheme and the plans for installing spin rotators.

Thus we are led to put the pretzel separators in the first available space beyond the RF cavities\(^8\). But there is no such space! The first lattice section beyond the RF section is the dispersion suppressor, followed by the regular FODO structure of the arcs. The trouble is that nearly all of the gaps between quadrupoles in both these sections are

\(^8\)We suppose that we are considering one of the interaction regions equipped with cavities since they all will be ultimately.
filled up with bending magnets. It is impossible to find a few clear metres to install the separators.

So we are forced to install the separators in the last RF half-cell\(^9\), close to the quadrupole QS11. Around P2 and P6 however, this space is presently occupied by copper RF cavities which would need to be removed (their accelerating voltage will soon be made up by superconducting (SC) RF). In practice it seems more likely that one whole RF station would be removed, so that its klystron could be put to work elsewhere, than that a few cavities would be replaced by a dummy load.

*The installation plan for the SC cavities must preserve the necessary free space for the pretzel separators.* It appears that, if the pretzel separators occupy half the space (22 m) between the quadrupoles QS10 and QS11, then there will still be enough space in the LEP200 straight section layout [16,17] for the installation of 192 cavities. It does not seem difficult to ensure compatibility of the pretzel scheme with the layout currently under discussion for installation of the SC RF provided the requirements are anticipated from the beginning and kept in mind.\(^10\)

It will be possible to run with \(k_b > 8\) and some of the normal-conducting RF system in operation provided the storage cavities are not used.

### 2.2 How many bunches?

With the separators located just before QS11, the minimum bunch separation possible is

\[
\min S_b \gtrsim 2 \times \text{distance from IP to DISS} = 490 \text{ m}
\]

which implies the inequality

\[
k_b = \frac{C}{S_b} < 54
\]

on the number of bunches.

Since the bunches must fit into RF buckets, \(k_b\) must divide the RF harmonic number (chosen with great foresight!)

\[
31320 = 2^3 \times 3^3 \times 5 \times 29
\]

and must also be even so that there are 4 crossing points. From this criterion alone, the only possibilities are

\[
k_b \in \{2, 4, 6, 8, 10, 12, 18, 20, 24, 30, 36, 40\}.
\]

We shall see in detail later how the optimum \(k_b\) depends on the maximum single-bunch current, \(I_b\), achievable, the RF power available and the beam dynamics in the pretzel scheme. *The optimum \(k_b\) will vary as a function of \(E\).*

Intermediate bunch numbers are possible by filling only some of, e.g., 36 evenly spaced buckets. However this does not help to avoid dangerous collision points where

---

\(^9\)In fact this arrangement, in which there is no dispersion at the separators, has advantages over installing the separators in the dispersion suppressor from the point of view of orbit isochrony (see Section 3.3).

\(^10\)This is being taken account of in the present planning.
the two pretzel orbits are not well separated. As far as we know, there is no valid reason for intentionally producing an uneven distribution of the bunches.

Some of the values in (10) are not divisible by 4, in which case there are no collisions in the odd points. The existing vertical separators can then be switched off there.

### 2.3 Horizontal vs. vertical separation

Vertical separation has the advantages that:

- The separation requirements are reduced if beams are flat (this is why it was chosen for the local separations at the usual 8 crossing points).

- The same design of vertical separators could be used, cutting the time required to implement a pretzel scheme considerably.\(^{11}\)

On the other hand, the disadvantages are:

- There is less vertical aperture.

- Pretzel orbits pass off-centre vertically in sextupoles where the Hamiltonian for transverse motion contains the term

\[
H_{\text{sext}} = \frac{K_2}{6} (x^3 - 3xy^2) = \frac{K_2}{6} \left( x^3 - 3x(\pm y_c + y_\beta)^2 \right) \\
= \frac{K_2}{6} (\ldots \pm 6y_c x y_\beta \ldots)
\]

where we have written the total vertical displacement as \( y = \pm y_c + y_\beta, \pm y_c \) being the pretzel closed orbits of electrons and positrons. The term exhibited in the second line of (11) is an effective skew-quadrupole of opposite sign for the two beams. This will generate extra betatron coupling and vertical dispersion. When photon emission occurs in the dipoles the vertical dispersion will give rise, in its turn, to vertical quantum excitation and an irreducible vertical emittance. The beams will then no longer be flat and much of the point of the vertical separation will be lost.

However, since a vertical pretzel could be implemented much more quickly, there is a strong impetus to find a means of compensating the coupling for both beams simultaneously. The obvious way would be to install many electrostatic skew quadrupoles but this would clearly be ruled out on grounds of cost, complication and development time. At present we can see no solution to this problem but some calculations of vertical pretzel schemes have been done (see Section 5.3).

Both CESR and SppS chose horizontal separation schemes rather than vertical and we shall focus mainly on a horizontal pretzel in LEP, pending a solution of the coupling problem for a vertical scheme.

\(^{11}\)It is also conceivable that such separators might first be used in a mid-arc separation scheme (see Figure 1 and Sections 1.3 and 1.5.1) and later re-installed for a vertical pretzel scheme.
3 BEAM OPTICS

3.1 Choice of optics

We have chosen to work mostly with the high tune version of the LEP lattice which has 90° of betatron phase advance per FODO cell in the arcs. The 60° lattice can only be used up to about 70 GeV and turns out to be less suitable for a pretzel scheme.

The 90° lattice has the advantage of a smaller natural emittance which allows it to be used at high energy. However it can also be used at Z° energy where ε can be increased with the wigglers if necessary. Higher luminosities are also available in the event that the single-bunch current is low [3]. We shall show that it provides a good basis for a pretzel scheme.

We have not yet investigated the utility of other phase advances, e.g., making μx ≠ μy. The values of 60° and 90° are usually favoured for reasons of chromaticity correction but it is quite possible that some other value would be optimal for a pretzel scheme or for operation at the highest energies.

At present the details of the straight section layouts for the energy upgrade are still being worked out, so definitive versions of the LEP200 optics are not yet available. Previously published work on the pretzel scheme [9] used an older 90° optics with the present hardware layout (the so-called B1T1H optics in the LEP database).

For the present report, the calculations have all been repeated using an optics (LEP290 MAD) [17], which still has the existing layout of the straight sections around the IPs but has new values for the tunes. Once the final layouts have been established, the optics of the straight sections (around even and odd points) will have to be adjusted. If it turns out that the optics lacks the necessary flexibility, it may be necessary to change the phase advances slightly in the arcs. In the meantime, the model pretzel orbits are not properly closed but this should not affect the conclusions significantly since we have treated a model octant of LEP as a beam-transport line starting from an IP.

3.2 Pretzel asymmetry and closure

We have insisted that the pretzel orbits have nodes at the odd-numbered crossing points in LEP. This leads to the conditions for an antisymmetric pretzel scheme, namely that the pretzel orbits satisfy

$$x_+(s) = -x_+(-s), \quad x_-(s) = -x_-(-s)$$

(12)

where s is azimuthal distance measured from any of the points P1, ..., P8. This also implies that the electric field in the separators alternates in sign from one octant to the next.

In this way any differences in optics between the two orbits, e.g., the slow accumulation of a differential phase advance, generated by edge effects in the bending magnets and amplified by the quadrupoles and sextupoles, will be cancelled between adjacent octants. Thus, for example, the global tune of the machine should remain the same for the two beams, except insofar as the effects of errors and imperfections do not cancel.

The phase advance from a separator to the following odd point must be nπ for some integer n (20 or 21 in fact). This has to be arranged by rematching the long straight section and/or adjusting the phase advance of the regular FODO structure in the arcs. In the latter case, care has to be taken that close encounters between the
bunches are not introduced. In operation of CESR [11], the analogous condition is trimmed operationally by adjusting quadrupole gradients so as to move quantities of horizontal betatron phase between the inside and outside of the pretzel, keeping the tune $Q_x$ constant. Globally, the $Q_x$ of LEP will first have to be set by variations of the focussing outside the pretzel region, specifically in the RF straight sections around the even IPs. Measurement of orbits using the wide-band pickups close to the even and odd points will provide a convenient null condition for these operations.

In the example pretzel orbits shown here we have not adjusted the orbit and optics to meet these conditions. In a first approximation it is not necessary in order to evaluate the parasitic beam-beam effects. New features in the beam optics program MAD [18] have just been implemented which will help us with the technicalities of simultaneous matching of orbit functions and off-centre orbits. Up till now, such calculations have been difficult to carry out.

Experience at the Sp$\bar{p}$S suggests that it may be also very useful to install some sextupoles in the long straight sections where the beams are separated. Since these would provide an effective quadrupole field with different values at the $e^+$ and $e^-$ orbits, they would allow phase advances to be adjusted independently for the two beams. Similarly there may be some scope for using quadrupoles to correct the two orbits independently.

With the removal of one of its former two interaction regions in order to double the number of bunches [12], CESR has in fact made the transition from an antisymmetric pretzel configuration to a symmetric one. The electrostatic separators near one IP were removed and a peak of the pretzel closed orbit was arranged to occur at the former IP. Thus, the differential optical effects are the same for each beam in each half of the ring but different from those of the other beam. Consequently, there is no global equalising of the effects for the two beams. It appears [19] that this has indeed led to some problems.

### 3.3 Orbit lengthening and isochrony

Looking at plots of pretzel orbits, one is inclined to think that they must make a significant change to the length of the closed orbit and the revolution frequency. It is somewhat surprising to realise that, for the case of the orbit shown in Figure 3, the orbit is lengthened by only 234 $\mu$m, i.e., only 1 part in $10^6$.

This value is small thanks to the long wavelength of betatron oscillations in LEP. In the case of a non-zero dispersion $\eta_S$ at the separator, the orbit-lengthening can be greater: $\Delta C = \eta_S \Delta x'$ where $\Delta x'$ is change in angle of the closed orbit due to the separator. Typically, $\Delta x' \approx 10^{-4}$ so even this contribution would be small for LEP.

In reality, of course, the exact orbit will be determined by the value of the RF frequency—the equilibrium momentum of the beam will change so that it can move onto an orbit whose length is an integer number of RF wavelengths.

### 3.4 ♠ Dynamic aperture

In most discussions of this topic, the term “dynamic aperture” is taken to mean the largest connected region of initial conditions of (preferably) 6-dimensional single-particle phase space for which the long-term motion of particles is “stable” according to some more-or-less precise criterion. This region includes the usual closed-orbit, passing close
to the centres of the magnets, as an elliptic fixed point of any suitably-constructed one-turn map.

In a pretzel scheme, on the other hand, we require simultaneous stability of trajectories of counter-rotating electrons and positrons with respect to their respective closed pretzel orbits, i.e., two different dynamical systems.

It is clear that stability around the pretzel orbits will be harder to achieve than stability about the usual central orbit. However we may hope to derive analytically some conditions on sextupole excitation strengths which will help to provide simultaneous stability. Furthermore, the condition of pretzel asymmetry about the odd IPs goes some way towards making the two dynamical systems equivalent again\textsuperscript{12} if one neglects the effects of imperfections and the discreteness of the distribution of the RF system.

So far there has not been sufficient time or manpower available to compute the dynamic aperture for a pretzel scheme. This would proceed mainly on the front of single-particle tracking in carefully prepared lattices but would require considerable human and computer resources. Since the parasitic beam-beam effects make significant changes to the closed-orbit and optics, a truly satisfactory tracking program will have to include these too, as well as modelling the usual non-linear elements and imperfections of the machine. Some work along these lines has been done for the Tevatron [20].

From a more pragmatic point of view, we can note that during the commissioning phase, low-intensity beams were stored in LEP with closed orbit deviations of $\gtrsim 20$ mm. This implies that, even without any special effort, there was a useful dynamic aperture about orbits which were larger and more irregular than those likely to be needed in a pretzel scheme.

First measurements of the dynamic aperture [21] of LEP at 20 GeV indicated that the maximum stable betatron amplitudes were only about 1/3 of the values expected from tracking studies made in the design phase. This might lead one to question the validity either of the tracking programs used, the modelling of the lattice, or the computational stability criterion. However later measurements, including first measurements of dynamic aperture for pretzel-type orbits (see Section 3.6) gave much better results.

The dynamic aperture is expected to improve at higher energy as the influence of unwanted magnetic fields such as those of the earth or the nickel layer on the vacuum chamber diminishes. So far there is no experimental information on the dynamic aperture of the $90^\circ$ lattice which we propose to use for the pretzel scheme.

3.5 ♠ Proposed machine experiments

Although we cannot properly simulate a pretzel scheme with two beams until the electrostatic separators are available, there is much that can be done with one beam at a time on an orbit of the pretzel type. Such closed orbits can easily be created using the orbit correction magnets.

Important topics for study include:

**Dynamic aperture:** Can beams be stable on pretzel orbits? Are particles executing large amplitude oscillations around these orbits lost too rapidly? (See Section 3.6.)

**Orbit correction:** correction to an ideal pretzel orbit instead of the usual central orbit.

\textsuperscript{12}Under a rotation of $\pi/2$ about the centre of LEP.
<table>
<thead>
<tr>
<th>Orbit used</th>
<th>Theoretical maximum in arc QF / mm</th>
<th>Dynamic acceptance $A_x$ / mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central</td>
<td>0</td>
<td>2500</td>
</tr>
<tr>
<td>Half pretzel</td>
<td>5.5</td>
<td>950</td>
</tr>
<tr>
<td>Full pretzel</td>
<td>11</td>
<td>450</td>
</tr>
</tbody>
</table>

Table 1: ♠ Dynamic acceptance measurements

**Phase advance:** imposing the appropriate phase advances on the lattice and fixing of a good global tune.

**Coupling:** check and try to compensate the effects of the anomalous sources of betatron coupling in LEP for both horizontal and vertical pretzel orbits.

**Simultaneous stability:** Can beams be stable on two different orbits when nothing in the machine is adjusted differently (except the correctors used to “separate” the orbits)? This would include chromaticity correction and dynamic aperture measurements.

**Accumulation:** test the possibility of injecting beams onto a pretzel orbit and how large the single-bunch current can be. (See Section 3.6.)

### 3.6 ♠ First experiments on LEP

Here we briefly summarise the results of measurements related to the pretzel scheme carried out during the summer of 1990. Only a fraction of the machine development time scheduled for these studies was actually obtained because of various breakdowns and urgent studies which took priority on some occasions.

These studies were done using the 60° production optics since the 90° optics, intended for LEP200 and the pretzel scheme, was still under development. Given this, it was considered that basing the pretzel studies on it would not be meaningful.

The action of the electrostatic separators in generating pretzel orbits was simulated by means of orbit correction magnets close to their intended positions at the ends of the arcs. Of course, this meant that only single-beam studies were possible. The experiments were done at a beam energy of 20 GeV.

#### 3.6.1 ♠ Dynamic aperture measurements

The aim of this experiment (about 5 hours of beam time) was to compare the dynamic acceptance around a simulated pretzel orbit with the dynamic acceptance around the central orbit.

The dynamic aperture around an orbit was measured by sweeping the frequency of the $Q$-meter kicker across the betatron tune, increasing the amplitude until losses were observed, and then scraping the beam with a collimator until further losses occurred.

A “full pretzel” orbit of ±11 mm and a half-pretzel orbit of ±5.5 mm were created, imposing antisymmetry conditions between adjacent octants as in real scheme.

The results of the measurements are given in Table 1. The following points are worth noting:
• Owing to lack of time, no effort was made to improve the dynamic aperture or correct orbit, chromaticity, etc., beyond a small tune change.

• Although the pretzel orbit was supposed to be closed (in a perfect machine) there was some residual orbit deviation in straight sections and some coupling of the pretzel orbit into the vertical plane.

• At 20 GeV the rôle of the nickel layer (unwanted coupling) is probably very significant, especially on the displaced orbits. This is expected to improve at higher energy.

• The dynamic aperture on central orbit turned out much larger than measured previously, probably thanks to new tune values. Previous measurements for the usual injection conditions gave values comparable with those measured on the full pretzel orbit. Although the dynamic aperture was reduced by more than a factor 2 (in radial position $\propto \sqrt{A_z}$) in the move from the central orbit to the full pretzel orbit, it remained adequate.

• When large beam currents (around 0.3 mA per bunch) were stored on the central orbit and then displaced to the pretzel orbits, they remained stable.

These results will be described in more detail elsewhere [22].

3.6.2 ♣ Injection onto pretzel orbits

The aim of this experiment (about 2.5 hours of beam time) was to investigate the possibility of injection onto the same simulated pretzel orbit used in the dynamic acceptance study. It was largely motivated by worries arising from the belief that good injection requires orbits with small RMS deviations.

When the pretzel orbit was generated, some tune shifts were enough in themselves to restore a modest injection rate.

After adjusting the injection bump to compensate the orbit interpolated at the septum ($\geq -2.5$ mm) a very good injection rate was obtained, similar to that obtained in normal injection conditions. It was possible to accumulate single bunch currents $I_b > 0.44$ mA from scratch.

With longitudinal feedback switched on, the injection rate improved still further.

All bunches finally saturated at $I_b = 0.415$ mA, comparable with what is normally achieved in these conditions. Although no time was available to investigate, it is reasonable to suppose that the currents and beam lifetime (around 30 min) were then limited by the usual phenomena of synchro-betatron resonances, vertical dispersion, etc.

The most plausible explanation of the rather unexpected success of this experiment is that large orbit deviations in the arcs (which are asl that the pretzel scheme requires) are acceptable but that deviations in the straight sections, particularly in the RF cavities, are indeed harmful.

These results will be described in more detail elsewhere [23].

3.6.3 ♣ Higher-order mode loss measurements

The higher-order mode losses in the SC cavities were measured and found to agree well with predictions. This topic is covered in more detail in Section 8.5.
4 BEAM-BEAM EFFECTS

4.1 Orbit separations

The closed orbit deviations ("pretzel orbits") of the $e^+$ and $e^-$ beams in the arcs are

$$x_+(s) \simeq -x_-(s). \quad (13)$$

This is not an exact equality because of accumulating edge-effects which are amplified as they propagate through the arcs by the quadrupoles and sextupoles. The positron orbit is given by

$$x_+(s) \simeq \frac{\Delta p_x}{p_0} \sqrt{\beta_x(s) \beta_x(s_0)} \sin (\mu_x(s) - \mu_x(s_0)) \quad (14)$$

where $\Delta p_x$ is the transverse momentum kick given to the $e^+$ beam from the separator at $s = s_0$.

Encounters between bunches of the two beams occur at azimuths $s_j = nC/2k_b, \ j = 0, \ldots, 2k_b - 1$ where the separations between the centres of the two charge distributions are

$$X(s_j) = x_+(s_j) - x_-(s_j) \simeq 2x_+(s_j). \quad (15)$$

In the following formulae and in our calculations and simulations, it is important to allow for a similar separation $Y(s)$ in the vertical plane (which might be generated by coupling, for example).

Consider, for example, a positron which has a displacement $(x, y)$ from the centre of charge of the gaussian distribution of its own bunch. At encounter $j$, this particle has a displacement $(x_+(s_j) + x, y_+(s_j) + y)$ from the centre line of the magnets or a total displacement

$$(X(s_j) + x, Y(s_j) + y) \quad (16)$$

from the centre of charge of the other beam.

4.2 Beam-beam strength parameters

The beam-beam force on this particle can be derived from a potential which can be expressed as [24]

$$\Phi(x, y) = N_b e \int_0^\infty 1 - \exp \left((- (X + x)^2/(2\sigma_x^2 + t) - (Y + y)^2/(2\sigma_y^2 + t))\right) \frac{dt}{\sqrt{(2\sigma_x^2 + t)(2\sigma_y^2 + t)}} \quad (17)$$

where by $(X + x, Y + y)$ we mean (16) and by $\sigma_x$ and $\sigma_y$ we mean the local beam sizes

$$\sigma_x(s_j) = \sqrt{\varepsilon_x \beta_x(s_j) + \eta_x(s_j)^2 \sigma_z^2}, \quad \sigma_y(s_j) = \sqrt{\varepsilon_y \beta_y(s_j)} \quad (18)$$

which, like the pretzel orbits vary all around the ring with the $\beta$-functions and the dispersion $\eta$. Thus, the beam-beam encounters can occur with different values of several relevant parameters.

In the horizontal plane, our test positron receives a kick given by

$$\Delta p_x^{(j)} = -\frac{e}{p_0 c} \frac{\partial \Phi(x, y)}{\partial x} \quad (19)$$
which is itself a nonlinear function of \( x \) and \( X \).

The customary beam-beam strength parameter at the centre of the positron bunch is the tune-shift produced by a quadrupole field component equivalent to its linearisation about \( x = 0 \):

\[
\xi^{(i)}_x = - \lim_{s, x \to 0} \frac{\beta_x(s_j)}{4 \pi p_0} \frac{\partial \Delta p^{(i)}_x}{\partial x}
= \frac{N_b \beta_x(s_j) r_x}{2 \pi (E/\text{meV})^2} \Xi_x(X, Y)
\]  

(20)

where we have defined the function

\[
\Xi_x(X, Y) \overset{\text{def}}{=} \frac{1}{2} \lim_{s, x \to 0} \frac{\partial^2}{\partial x^2} \int_0^\infty \exp \left\{ -\left( \frac{(X + x)^2}{(2\sigma_x^2 + t)} - \left( \frac{Y + y}{2\sigma_y^2 + t} \right)^2 \right\} \sqrt{(2\sigma_x^2 + t)(2\sigma_y^2 + t)} \right. 
\]

(21)

\[
\Xi_x(0, 0) = \frac{1}{\sigma_x(\sigma_x + \sigma_y)}, \quad \Xi_y(0, 0) = \frac{1}{\sigma_y(\sigma_x + \sigma_y)},
\]

(23)

and we see that the formula (20) reduces to (2).

4.3 Stability criteria

It is clear that we wish to avoid close encounters where

\[
\mu_x(s_j) - \mu_x(s_0) \sim n \pi
\]

(24)

and that the residual beam-beam tune-shifts are the result of a kind of beating among “waves” of \( \beta_x, \beta_y, \eta_x \) and \( x_\pm \) which are then sampled with the comb of encounter points \( \{ s_j \} \).

There are different possible criteria for the minimum tolerable separation.

We can look at the total tune spread in the beams, which, in the approximation that the contribution from the parasitic encounters is small, is given by

\[
\Delta Q_{x,y} \simeq \frac{4}{4 \text{ IPs}} \left( \sum_{j=1}^{2k-1} \xi_{x,y}^{(j)} + O(\xi_{x,y}^2) \right)
\]

(25)

where the prime on the sum means that it extends only over the parasitic crossings and not the IPs. The tune spread should not change too much from the 4-bunch case and should certainly stay small, \( \lesssim Q_s \simeq 0.1 \) during injection and ramping [25].

\footnote{Note that in [9], and in many other treatments, the second term in the first parenthesis of the final expression of (22) was omitted—this is why we consider it necessary to derive these formulae here. It turns out that this omission gave results which were generally more pessimistic than necessary.}
Alternatively, there is some evidence from operating machines[26,13] that stability is determined by conditions at the encounter with the smallest value of the absolute separation $(X(s_j))$ or the encounter with the smallest value of the separation expressed in units of the beam size $(X(s_j)/\sigma_x(s_j))$ which should not be less than $\approx 5$. Note that these are not necessarily the same encounter.

More refined criteria await a full-scale simulation of all effects.

Stability of pretzelled beams will be rather delicate and require very carefully prepared ramping files and heavy reliance on the closed loop control of the tunes.

4.4 Coherent beam-beam effects

Strictly speaking, the strength parameters (20) apply only to the incoherent beam-beam effects. To properly treat the coherent beam-beam interaction will require a simulation which self-consistently includes the effect of the beam-beam kicks (19) in the calculation of the closed orbit and allows coherent motion of the bunches of both beams in each other's fields.

Treating the parasitic interactions as a perturbation, it is clear that they will produce a splitting of the lines in the coherent mode spectrum of the 4 bunch case.

We hope to be able to treat this in more detail in the future.

4.5 Proposed machine experiments

The stability criteria depend on how much parasitic beam-beam interaction we can add to a situation where beams are already colliding at the beam-beam limit. We cannot over-emphasize the importance of studying this experimentally.

One experiment would be to collide beams at, say, 2 or 4 IPs with parameters chosen so that the luminosity is beam-beam limited and then study the effect of changing separation at other IPs.

This would give information on how much additional beam-beam tune-spread can be tolerated at parasitic encounters.

5 PERFORMANCE OF A PRETZEL SCHEME IN LEP

We have studied the potential performance of various pretzel schemes in LEP using the following methodology. A second approach has also been started, see Section 5.4.

In a first step, the program MAD [18] is used to generate the pretzel orbits and optics. The program WIGWAM [27] is interfaced to MAD via the RDTWISS package [28]; in this application, it evaluates the synchrotron radiation integrals, optimises the electron beam and RF parameters, computes the strength parameters $\xi_x^{(j)}$ (20) and $\xi_y^{(j)}$ at the parasitic crossings and provides graphical output in many forms, e.g. Figure 3.

Separators are taken to be installed in the last RF cell just before the dispersion suppressor; although $\langle \beta_x \rangle$ is kept deliberately small in the RF section, we still get a reasonable $\beta_x(s_0) \approx 80 \text{ m}$ at the separator.\textsuperscript{14}

\textsuperscript{14}This is larger than with the optics used in [9], to which reference is made in Section 6.1. The pretzel amplitude for a given field is therefore somewhat larger here.
5.1 Effect of varying bunch number $k_b$

In the following, the electric field and effective length are fixed at

$$E_x = 0.8 \text{ MV/m}, \quad L_{\text{SEP}} = 8 \text{ m}$$  \hspace{1cm} (26)

(or equivalent for RF magnetic separators), giving a pretzel orbit with amplitude $\hat{x}_\pm = 15 \text{ mm}$. The separators described in Section 6.1 should be able to go a factor 2 further in strength, i.e., they should be capable of the same separation at $W^+W^-$-energy or twice the separation at $Z^0$ energy.\footnote{Since the 8 m of effective separator length is given in practice by two 4 m units, we could also install half the system and use it at full field at the $Z^0$ energy; however this would not give adequate separation at high energy.}

Taking a bunch current $I_b = 0.75 \text{ mA}$ and assuming the same dynamic aperture\footnote{This may need to be revised when dynamic aperture results for the new lattice become available; moreover we should really use dynamic apertures computed around pretzel orbits as discussed in Section 3.4.} as in [3], the performance optimisation carried out by WIGWAM suggests that we set the damping partition number to $J_x = 0.5$ and excite the emittance wigglers with a field $B_{\text{EW}} = 0.435 \text{ T}$ giving an emittance $\epsilon_{x\epsilon} = 34.4 \text{ nm}$. Without the wigglers, it would be about 26 nm.

We can now study the stability criteria as functions of the number of bunches $k_b$.

We start by computing the parasitic beam-beam parameters for the maximum $k_b = 40$. The results are shown in Figure 3. In this case two very close encounters, almost head-on collisions, occur in the dispersion suppressor and near the beginning of the arc, giving rise to very large tune-shifts. The expressions

$$\sum_{j=1}^{2k_b-1} |\xi_x^{(j)}| \simeq 0.56 \quad \sum_{j=1}^{2k_b-1} |\xi_y^{(j)}| \simeq 9.1$$  \hspace{1cm} (27)

denote the sums of the absolute values of the beam-beam strength parameters over the parasitic crossings only (excluding the IPs) but include all 8 octants. With such an enormous vertical tune-shift, it is clear that $k_b = 40$ is unacceptable in this optics.

In Table 2, we have listed the results of similar calculations for all the allowed bunch numbers in (10). The table shows parameters related to the different stability criteria showing that, on the whole, application of one of the other criterion would lead to similar results as far as selecting good values of $k_b$ goes.

In Figure 4 we show the analogue of Figure 3 for $k_b = 36$ which, as can be seen from Table 2, is the most favourable among the larger bunch numbers. With this choice, it turns out that all encounters occur at a good separation ($X > 5\sigma_x$) and the contributions to the beam-beam tune-spread are small.

In fact, the only bunch numbers which look definitely bad in these conditions are $k_b \in \{20,30,40\}$. With $I_b = 0.75 \text{ mA}$, the tune-spread criterion delineates good values of $k_b$ very clearly from bad. However if $I_b$ were to be doubled, we would have $\sum_{j=1}^{2k_b-1} |\xi_x^{(j)}| \simeq 0.1$ which looks marginal.

5.2 How much separation is needed?

Let us now consider how much separation is really necessary, i.e., the minimum acceptable pretzel amplitude. This time we choose $k_b = 36$ and again use the same values for
Figure 3: The top frame of this plot (and similar plots later) shows the pretzel orbit of one beam in an octant of LEP; the IP is on the left. The "error bars" at the encounter points indicate the horizontal r.m.s. beam size (18). The second frame shows $\beta_x$ (full line) and the dispersion $\eta_x$ (dashed line) which is not properly matched here. The bottom frame shows the values of the parasitic beam-beam strength parameters (20) at each of the parasitic crossings. Since $\xi_x^{(i)}$ is negative for $x/\sigma_x \gtrsim 2$, we have plotted $-\xi_x^{(i)}$ on the log scale with $\xi_y^{(i)}$. Where $-\xi_x^{(i)}$ is off-scale it is always negative, which means that the encounter is unacceptably close. Where a value of $\xi_y^{(i)}$ is off-scale on these plots, it is usually because it is very small ($< 10^{-5}$) and therefore negligible.
Figure 4: Pretzel performance with \( k_b = 36 \); all other conditions the same as for Figure 3.

| \( k_b \) | \( \text{min } X/\text{mm} \) | \( \text{min } X/\sigma_x \) | \( \text{max } \xi_x^{(j)} \) | \( \text{max } \xi_y^{(j)} \) | \( \sum_{j=1}^{2k_b-1} |\xi_x^{(j)}| \) | \( \sum_{j=1}^{2k_b-1} |\xi_y^{(j)}| \) |
|----------|----------------|----------------|-----------------|----------------|-----------------|----------------|
| 2        | .              | .              | .               | .              | 0.              | 0.              |
| 4        | .              | .              | .               | .              | 0.              | 0.              |
| 6        | 12.6           | 5.18           | 0.0023          | 0.0003         | 0.0187          | 0.0024          |
| 8        | 3.05           | 13.5           | 0.0002          | 0.0000         | 0.0018          | 0.00007         |
| 10       | 1.21           | 10.0           | 0.0007          | 0.0005         | 0.0079          | 0.0044          |
| 12       | 1.21           | 5.18           | 0.0025          | 0.0003         | 0.0386          | 0.0046          |
| 18       | 1.26           | 5.18           | 0.0023          | 0.0004         | 0.0253          | 0.0057          |
| 20       | 0.88           | 0.71           | 0.0266          | 0.401          | 0.2221          | 3.21            |
| 24       | 1.21           | 5.18           | 0.0025          | 0.0003         | 0.0437          | 0.0049          |
| 30       | 2.15           | 1.90           | 0.0111          | 0.146          | 0.1278          | 1.1889          |
| 36       | 1.21           | 5.18           | 0.0025          | 0.0004         | 0.0571          | 0.0113          |
| 40       | 0.20           | 0.25           | 0.0399          | 0.730          | 0.5574          | 9.1             |

Table 2: Parasitic beam-beam effect as functions of the number of bunches, with \( I_b \) and other beam parameters kept constant. The table shows the minimum values of the total separation expressed in mm or the total separation in units of the beam size (the minima for these two quantities do not necessarily occur at the same crossing), the maximum values of the beam-beam strength parameters for individual encounters and, finally, the sums of the absolute values of these parameters over all the collisions (in 8 octants). The latter quantities contribute to the total tune-spread in the beams according to (25).
Figure 5: Example of insufficient separation; conditions are the same as in Figure 4 except that the separator field is reduced to half the value. Note the different scale on the frame showing the orbit.

The current per bunch and other beam parameters as in the previous section. We vary the amplitude of the pretzel orbit by changing the electric field in separators.

Figure 5 shows what happens when the separator field is reduced to \( E_x = 0.4 \text{ MV m}^{-1} \). The tune spread contributions are

\[
\sum_{j=1}^{2k_b-1} |\xi^{(j)}_x| \simeq 0.3 \quad \sum_{j=1}^{2k_b-1} |\xi^{(j)}_y| \simeq 0.2
\]

and there are encounters with \( X \simeq 2.5\sigma_x \). It is very unlikely that beams could be stored in these conditions.

In Figure 6, we have plotted the quantities \( \sum_{j=1}^{2k_b-1} |\xi^{(j)}_x| \) and \( \sum_{j=1}^{2k_b-1} |\xi^{(j)}_y| \) as functions of the separator field and the peak value of the pretzel closed orbit.

From these results, we can deduce that the minimum separation necessary for 36 bunches is obtained with \( E_x = 0.6 \text{ MV m}^{-1} \). In this case, the aperture requirements are met: beam size in QF is 2.3 mm where the peak orbit displacement is 11 mm

\[
x + 10\sigma_x = 11 + 10 \times 2.3 \simeq 34 \text{ mm}
\]

(c.f. the LEP horizontal aperture \( \pm 65 \text{ mm} \)).

According to the usual LEP luminosity model (see Section 1.1), some vertical beam-beam blow-up will occur to reduce \( \xi_y \) to 0.036, yielding a peak luminosity

\[
L \simeq 1.4 \times 10^{32} \text{ cm}^{-2}\text{sec}^{-1}
\]

with the nominal \( \beta^*_y = 7 \text{ cm} \).
LEP290 lattice, 45.5GeV $kb=36$ 0.75mA/bunch

Figure 6: Effect of variation of separator field on tune spreads. The quantities $\sum_{j=1}^{2kb-1} |\xi_j^{(j)}|$ and $\sum_{j=1}^{2kb-1} |\xi_y^{(j)}|$ are plotted as functions of the separator field. The upper axis shows the peak value of the pretzel orbit generated.

For $I_b = 0.75$ mA, it appears that we can separate enough to accommodate 36 bunches. If $I_b$ can be increased much beyond this, then it may be necessary to reduce the number of bunches or increase the pretzel amplitude. It follows that, if we are limited to a 1 cm pretzel, then it will be hard to get beyond a few $10^{32}$ cm$^{-2}$sec$^{-1}$ at the $Z^0$.

With a 1.5 cm pretzel the unwanted tune-shifts drop by a factor $\approx 2$. This would, in principle, permit a corresponding increase in single-bunch current ($I_b \approx 1.5$ mA) provided the optical problems associated with the larger orbit excursion are not significantly worse. Larger bunch currents than this are almost certainly excluded by the transverse mode-coupling instability but larger pretzel amplitudes are at least compatible with the physical aperture.

5.3 Vertical pretzel

In Section 2.3, we explained why a pretzel scheme using vertical separation is unlikely to work unless a solution to the coupling problem can be found. In Figure 7 this is illustrated by the large value of vertical dispersion which is generated on the pretzel orbits from the horizontal dispersion via the sextupoles. The beam-beam effects in this example are very severe.

5.4 Simulation results

The results presented in the preceding sections were obtained using the program WIGWAM [27]. They are based on the formulae given in Section 4.2 combined with optical
Figure 7: Example of a vertical pretzel scheme. The optics used corresponds to that used in [9]. Note that vertical quantities are plotted. The second frame shows the growth of the vertical dispersion in one octant.

data from MAD and WIGWAM’s evaluation of the electron beam parameters. They do not include the perturbations of the pretzel closed orbits by the beam-beam forces and no kind of particle tracking is performed.

Another program is under development [29] which tracks particles around the ring starting from the WIGWAM framework for the orbit and beam parameters. It is intended that this will eventually develop into a full many-particle simulation of the coherent and incoherent long- and short-range beam-beam effects.

Meanwhile tracking has been performed in a kind of weak-strong mode: a single-particle is tracked in the field of a strong beam whose orbit and charge distribution are fixed. The closed-orbit of the test particle includes the effect of the beam-beam forces. The tune-shifts of the particle can be found from an FFT of the tracking data. In unfavourable cases, the particle is found to be unstable.

These studies were done with the earlier version of the lattice described in [9]. The results given in Table 3 are consistent with those found with WIGWAM: the relative merits of different bunch numbers is about the same. However because of slightly different phase advances, the orbits are not so well separated in this optics.

6 SEPARATION SYSTEMS FOR PRETZEL SCHEME

6.1 Electrostatic separators

In the four even interaction points electrostatic separators would be installed in the last RF cell just before the dispersion suppressor, generating horizontal pretzel orbits of
\[
\begin{array}{|c|c|c|}
\hline
k_b & \text{min } X/\sigma_x & \text{Tune shifts} \\
\hline
6 & \approx 3.3 & < 0.01 \\
8 & \approx 6.7 & < 0.01 \\
10 & \approx 7.3 & < 0.01 \\
12 & \approx 3.3 \text{ (twice)} & 0.10-0.15, 0.02/\text{int in } x, 0.01/\text{int in } y \\
18 & \approx 3.3 & 0.10-0.15, \text{ as for } k_b = 12 \\
20 & \approx 1.4 & > 1.0, \text{ fast growth} \\
24 & \approx 3.3 \text{ (twice)} & 0.10-0.15, \text{ as for } k_b = 12 \\
30 & \approx 3.3 & > 0.1, > 0.50 \\
36 & \approx 3.3 \text{ (twice)} & 0.10-0.15, \text{ as for } k_b = 12 \\
40 & \approx 1.4 & > 1.0, \text{ fast growth} \\
\hline
\end{array}
\]

Table 3: Weak-strong simulation results for varying \(k_b\).

opposite amplitude for the \(e^+\) and \(e^-\) bunches (Figure 2). These pretzel orbits extend over two arcs and the inter-leaved straight section until the next pretzel separator set which brings them together again.

During accumulation and acceleration any collision in the eight interaction points of LEP is avoided with the help of the present separation system [30] which creates a fully compensated local deformation of the closed orbit in order to separate the \(e^+\) and \(e^-\) bunches in the vertical plane. At top energy, the bunches will be brought into collision in the even IPs whereas they will be kept separated elsewhere via the combined effect of the pretzel separators and the vertical separators installed around the odd points.

The electrostatic field required at \(Z^0\) energy for a pretzel orbit of \(11\,\text{mm}\) amplitude and a total electrode length of \(4\,\text{m}\) is \(1.6\,\text{MV}\,\text{m}^{-1}\) yielding a deflection of \(0.138\,\text{mrad}\).\(^{17}\)

For a pretzel scheme to be operated at \(W^+W^-\) energies a second separator unit must be installed in each of the last RF cells in order to maintain the same pretzel amplitudes.

Any High Voltage (HV) breakdown in one of the separators causes a noticeable reduction in luminosity or even a complete loss of the stored beams. This effect has been observed at CESR [31] operating with a horizontal pretzel separation scheme and at LEP [32] with the current separators providing a compensated local bump in the vertical plane. In the latter case, any HV breakdown at injection energy always causes complete loss for either a single stored particle beam or \(e^+e^-\) beams. To minimize the breakdown rate the electrostatic field will be limited to \(1.6\,\text{MV}\,\text{m}^{-1}\) and the vacuum in all separators will be kept at the low pressure of \(\leq 10^{-9}\,\text{Pa}\). Therefore, the separators must be baked at a temperature of \(300\,^\circ\text{C}\).

A separator unit (ZX) consists of a pair of hollow stainless steel electrodes, each \(4\,\text{m}\) long, mounted in an Ultra-High Vacuum (UHV) tank of about \(540\,\text{mm}\) inner diameter (Figure 8). Each electrode can be charged independently via its HV feedthrough.

Any synchrotron radiation incident on the HV electrodes could greatly increase the breakdown rate.\(^{18}\) Since the synchrotron radiation arriving from the main and weak dipoles is strongly concentrated in the horizontal plane, the electrodes will be built with

\(^{17}\)In Section 5, we assumed that two such separators were used with half the field strength so that the system could be used at twice the energy.

\(^{18}\)During LEP machine development experiments in April 1990, for example, we measured an increase by a factor of 10 of the spark rate in vertical separators at \(20\,\text{GeV}\) as compared to operation without beam. However this was with an electric field \(E_{\perp} \approx 5\,\text{MV}\,\text{m}^{-1}\) and cannot be directly compared with the case of pretzel separators.
Figure 8: Horizontal electrostatic separator for pretzel scheme.
<table>
<thead>
<tr>
<th>Energy (GeV)</th>
<th>46.5</th>
<th>93.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. deflection angle per unit (mrad)</td>
<td>0.138</td>
<td>0.069</td>
</tr>
<tr>
<td>Units per even interaction point</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Total number of units installed</td>
<td>8</td>
<td>16</td>
</tr>
<tr>
<td>Field length per unit (m)</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Min. gap width (mm)</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td>Max. operating field (MV m(^{-1}))</td>
<td>1.6</td>
<td>1.6</td>
</tr>
<tr>
<td>Max. operating voltage (kV)</td>
<td>±120</td>
<td>±120</td>
</tr>
<tr>
<td>Max. voltage for conditioning (kV)</td>
<td>±160</td>
<td>±160</td>
</tr>
<tr>
<td>Total number of HV circuits</td>
<td>16</td>
<td>16</td>
</tr>
</tbody>
</table>

Table 4: Main parameters of the pretzel separation system

A longitudinal slot\(^{19}\) so that most of the synchrotron radiation is not intercepted by the electrodes, but absorbed by horizontal collimators.

Since the electrostatic separators interrupt the continuity in the vacuum chamber cross-section, there will be higher order mode losses in these units. The energy lost by the beams is mainly deposited onto the separating electrodes. In the case of (a) \(I_b = 0.75\) mA, \(k_b = 36\) and a natural bunch length \(\sigma_z \approx 16\) mm, the power dissipated in both plates is estimated to be of the order of 1200 W. In case (b) of \(k_b = 8\) and the same bunch current, the total power dissipated in the electrodes is about 275 W. Finally, (c), doubling the bunch current to 1.5 mA would cause this figure to rise to about 1100 W which is comparable to the case (a). To prevent overheating and the resultant outgassing which might increase the breakdown rate, the electrodes and the feedthroughs of each separator will be equipped with a closed loop cooling system.

The HV circuit of the pretzel separation system in the even points requires two HV supplies of maximum 160 kV output—one of positive and one of negative polarity. They will be installed together with their control electronics in the underground caves (US), situated next to each even interaction point. This arrangement is preferred to an installation in a surface building since it halves the costs of the expensive HV cables and minimizes the electrical energy stored in them while still allowing access for interventions during LEP operation. During operation the HV supplies will run at a maximum of ±120 kV which corresponds to 1.6 MV m\(^{-1}\) in the gap. The maximum voltage of +160 kV is required since prior to operation the separators must be conditioned well beyond the operating field in order to minimize their breakdown rate.

The main parameters of the pretzel separators are given in Table 4.

Due to the significant increase in the total current for multi-bunch operation at the \(Z^0\) energy and to a smaller extent at 93 GeV, the 32 units (ZL) of the vertical separation system will be submitted to approximately the same higher order mode losses and must therefore be upgraded considerably. Because of budget restrictions, electrode cooling is presently implemented only in the even interaction points (16 ZL units) at a cooling capacity of about 1 kW per separator. Thus, the cooling capacity must be slightly increased and cooling of the feedthroughs should be added. The separators in the odd interaction points (16 ZL units) have to be equipped with hollow electrode supports to

\(^{19}\) In fact the longitudinal slot may not be necessary at all since it now appears that the separators will be adequately shielded from this radiation by collimators foreseen to protect the superconducting cavities; see Section 10.2.
allow for electrode cooling and the cooling of the feedthroughs should be added too. Any operation of LEP at higher energies will furthermore require eight additional ZL units in the even interaction points.

The horizontal separators ZX needed for the pretzel scheme require a completely new design in order to solve the problems of slotted electrodes, and efficient electrode and feedthrough cooling. Experience with HV devices such as separators has shown that a new design needs careful testing before series production is allowed to start. Therefore, a prototype unit should be built and thoroughly tested.

Furthermore, we need to carry out LEP machine development experiments in which beam-beam effects in pretzel-type orbits could be measured by using the current vertical separation system.

The construction of the new separators for the pretzel system and the upgrading of the vertical separators must proceed in parallel in order to arrive at the required minimum duration of the overall project. Provided that optimum conditions concerning both budget and personnel (staff and industrial support) could be obtained, the following time scale would be achieved:

- ZX prototype ............................................................. \( t_0 + 1.5\) y
- First batch of 8 ZX units needed for 46.5 GeV operation ................. \( t_0 + 3.0\) y
- Second batch of 8 ZX units needed for 93 GeV operation ............... \( t_0 + 3.5\) y
- This schedule is compatible with a pretzel scheme being fully operational for 93 GeV in early 1994 provided that authorization to start is obtained in summer 1990.
- If the project start is delayed beyond the end of 1990, a completion by early 1994 could only be achieved by taking the risk of launching the series production without prototype testing; this could reduce the relevant time scales by about a year.

A preliminary budget estimate for the new pretzel separators ZX and the upgrading of the current 32 vertical separators ZL is given in Table 5.

It should be stressed that the eight additional vertical separators ZL needed to achieve sufficient separation at 93 GeV (even with only 4 bunches) are (unlike earlier presentations of these estimates), not included in this budget since they will be financed from the LEP 200 programme.
6.2 RF-magnetic separators

In principle it is also possible to implement a pretzel scheme using RF magnetic separators, i.e., fast ferrite-loaded magnets which change their polarity between passages of \( e^+ \) and \( e^- \) bunches.

So far there has been no detailed hardware study to form the basis of a technical and economic comparison with electrostatic separators. This would require an engineering study of power consumption, the most appropriate ferrites, etc.

The main disadvantage of an RF-magnetic scheme is that the hardware would have to be built to run at a specific frequency which would be a multiple of the bunch frequency: \( f_{\text{RFS}} = n f_b = n k_b f_0 \). The value of the integer \( n \) depends on the relation of the distance between the separator and the IP to the bunch separation and can be determined following a line of argument given, e.g., in [33].

For the 36 bunch case with the positioning proposed for electrostatic separators, \( n = 1 \) appears possible. This would require a magnet frequency of \( f_{\text{RFS}} = f_b = 404.8 \text{ kHz} \) which appears reasonable but would limit the possible bunch numbers to \( k_b \in \{2, 4, 6, 12, 18, 36\} \), excluding the potentially useful value \( k_b = 8 \). The effective value of the field strength in the separating magnets would be about 0.8 of its peak value.

7 RF REQUIREMENTS AND HIGH ENERGY

A large part of the original motivation for the pretzel scheme was the idea of using the power available from the SC RF system at lower energies to accelerate higher beam currents [8].

The calculation of power requirements is much simpler for an SC system than for a system containing normal-conducting cavities since practically 100% of the power goes into the beam. For simplicity, therefore, we assume that the copper system is removed.

7.1 RF power at \( Z^0 \) energy

One RF half-cell contains 8 4-cell cavities, with a maximum accelerating field \( E_{\text{acc}} > 6 \text{ MV/m} \) over an effective length 13.6 m. Each 1 MW klystron powers either one or two such half-cells.

The power required for the parameters used in Section 5.1 is therefore

\[
P_{\text{beam}} = 2 k_b I_b U_0 \\
= 2 \times 36 \times [0.75 \text{ mA}] \times [123.5 \text{ MV}] \\
= 6.7 \text{ MW}
\]

which will be available at an early stage in the energy upgrading. So the time-scale for a pretzel scheme at the \( Z^0 \) will not be set by the installation of the SC RF.

It should be kept in mind that if \( I_b \) can be increased, then the power required will increase proportionally.

The main difficulty concerning the RF is that the original design of the higher-order mode couplers will have to be changed to cope with increased Higher Order Mode (HOM) power levels and also to damp higher modes between bunch passages. This is discussed in Section 8.5.
In addition, modifications to the input power couplers will be needed to allow operation with high power but relatively low peak voltage.

7.2 Global limits to performance by RF power

The synchrotron radiation loss per turn is given by

\[ U_0 = \frac{2 r_e E^4 I_2}{3 (mc^2)^3}, \quad I_2 \approx \frac{2\pi}{\rho}. \] (32)

The total beam current is limited either by the installed RF power or the maximum current per bunch max \( I_b \) and the maximum number of bunches \( k_b \):

\[ I_{\text{max}} = \min \left( \frac{P_{\text{RF}}}{2U_0}, k_b \text{max} I_b \right) \] (33)

Luminosity at the beam-beam limit is determined by the maximum current which can be stored according to

\[ L_{\text{max}} = \frac{I_{\text{max}}(E_0/mc^2)\xi}{2\varepsilon e \beta_y} \propto \frac{P_{\text{RF}}}{E^3} \] (34)

Another ultimate limitation is the heating by irradiation of vacuum chamber

\[ h_{\text{vac}} = \frac{P_{\text{RF}}}{2\pi\rho} \lesssim 4 \text{ kW m}^{-1} \] (35)

This implies that the total RF power should be \( P_{\text{RF}} \lesssim 64 \text{ MW} \) for LEP.

Figure 9 summarises the potential performance of LEP at all energies up to 100 GeV per beam with a pretzel scheme. There is no need to specify the optimum number of bunches at each energy—this depends on the single-bunch current \( I_b \) which can be achieved and the power available. However it is clear that at 90 GeV, for example, 32 MW of RF would allow perhaps 8 or 10 bunches to be stored with about the nominal current per bunch.

It is very important to note that, in the (unlikely but not impossible) eventuality that \( I_b \) remains limited below the design value, the pretzel scheme would provide an "insurance policy" permitting the luminosity to be increased towards the value given by the RF power limit.

8 ♠ COLLECTIVE INSTABILITIES AND FEEDBACK

The beam current which can be stored in LEP will eventually be limited by collective instabilities which are usually most severe at injection energy, and/or by the power dissipation in sensitive elements at any energy.

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Figure 9: Ultimate limits on the total beam-current and luminosity in LEP. The limits due to total RF power of 16 MW and 32 MW are shown as well as the limit due to a maximum current per beam of either $36 \times 0.75$ mA or $36 \times 1.5$ mA (this is an optimistic upper limit for $I_b$). The nominal current of $4 \times 0.75$ mA is also shown. The left luminosity axis is for the nominal $\beta_y^*$ and the right one is for $\beta_y^*$ reduced to 4 cm.
8.1 ♠ Impedance

Because of the much larger beam ports and the smoother shape of the SC cavities, their impedances are lower than those of the copper cavities. In particular, the transverse broad-band impedance, which is expected to limit the current per bunch to 3/4 mA in the present version of LEP, scales with the inverse third power of the beam port radius. At equal bunch lengths, the transverse loss factor of the SC cavities is found to be only about 1/8 of that of the copper cavities.

Nevertheless, the addition of SC cavities will increase the total impedance and thus reduce the maximum current which can be stored per bunch. Also the total current in all bunches will be reduced by coupled bunch instabilities due to the larger number of bunches and additional narrow band resonances in the SC cavities.

Only after a sufficient number of copper cavities is removed, will the transverse broad band impedance of LEP be reduced and the limiting threshold for the single bunch current will go up. The additional resonant modes must be damped by HOM couplers. Also the larger mechanical tolerances in the SC cavities (due to cooling to liquid Helium temperature inside inaccessible dewars) will increase the spreading of the mode frequencies of the individual cavities and effectively widen the resonances.

The pretzel scheme adds some other discontinuities to the vacuum chamber, the most significant of which are additional separators. The transverse broad band loss factor of the LEP separators and their tanks has been computed with the 3-dimensional computer code WELL [34] and gave values comparable to that of a single copper cavity cell. Since the number of separators is small compared to that of the cavity cells even for a mid-arc separator scheme, their contributions to the threshold current are expected to remain small.

8.2 ♠ Single-bunch instabilities

The transverse broad band impedance is expected to limit the current per bunch independently of the number of bunches in the machine. The estimate of the threshold current for transverse mode coupling in LEP is 0.75 mA at injection energy for standard synchrotron tunes $Q_*$ of 0.8 to 0.9, and a lengthened bunch with $\sigma_z = 3-4$ cm [35]. The small increase of the transverse broad-band impedance due to the SC cavities and separators is expected to reduce this limit only slightly. However, the replacement of 64 copper by SC cavities should increase the limit to over 1 mA (see Figure 10)

Higher currents per bunch should be possible with larger synchrotron tunes at injection (requiring crossing of synchro-betatron resonances during acceleration) or with longer bunches. Lengthening of the bunches can be achieved with wigglers: in addition to the present “damping” and “emittance” wigglers, more powerful “polarization” wigglers will be installed next year and should permit considerably longer bunches. However, wigglers change also the emittance and increase the energy spread, so this method may be limited at collision energies. Higher harmonic RF could be installed to increase the bunch length at constant energy spread, but the space foreseen for their installation will be used for SC cavities. However, when copper cavities are removed, they could be installed in their place.

Longitudinal single bunch instabilities are not considered dangerous in LEP, since they only lead to anomalous (“turbulent”) bunch lengthening and thus increase the threshold for transverse mode coupling. Also the energy deposited in the longitudinal...
impedances decreases strongly for longer bunches. Wiggler's are less useful at higher energies since they may not be strong enough to be effective or may generate excessive amounts of radiation. The "natural" bunch lengthening by turbulence will thus be very welcome.

8.3 Coupled-bunch instabilities

In a multi-bunch machine there may be little time for wake-fields to decay between the passages of successive bunches, in particular with very high-Q resonances of SC cavities which have a long decay time. Problems can then arise from coupled-bunch instabilities where sets of bunches execute coherent longitudinal or transverse oscillations with definite phase relationships from bunch to bunch. The most powerful method for countering these instabilities is to use feedback systems capable of acting upon each bunch independently. Their requirements are discussed in Section 8.4.

In addition, the growth-rate of the instabilities will be reduced if the wake-fields excited by one bunch in a cavity are damped sufficiently by the time the next bunch comes along. This is attempted by installing HOM couplers on each end of the SC cavities. Ideally, they should reduce the quality factors of all resonant modes sufficiently that the electro-magnetic fields decay between the passage of bunches. This is approximated when the damping times are small compared to the bunch spacing:

$$\tau_d = \frac{2Q_{\text{ext}}}{\omega} \lesssim \frac{T_0}{k_b}. \quad (36)$$

The problems of achieving this are discussed in Section 8.5.

Since the cavities are installed close to intersection points, electron and positron bunches will pass the cavities at short intervals. The instabilities which can be caused
Figure 11: Thresholds for coupled bunch modes (reduction factor 5).

by counter-rotating beams have been estimated for LEP [36],[37]. Fortunately, due to the large number of cavities the worst effects average out and the thresholds are about the same as for a single beam with twice the current.

Estimates of growth rates for coupled bunch modes of single beams with up to 36 bunches have been made. Assuming a reduction of the strongest narrow-band resonant impedances due to the spread in mode frequencies in individual cavities by a conservative factor of 5, we find a maximum growth rate of a little over 300/sec for transverse oscillations, and less than half of that for longitudinal ones (see Figure 11). Most likely, the reduction factor is even larger, since construction tolerances in the copper cavities of about $3.10^{-4}$ correspond to a maximum quality factor of some 3000, while individual modes have Q-values of 40–50,000 (i.e., a reduction by over 10). In the SC cavities all higher modes are damped by HOM couplers, and Q values below 2500 have been reached for the strongest modes. In addition, the mechanical and positioning tolerances for the SC cavities are quite large due to their fixation inside liquid Helium dewars with thin wires designed to limit the heat losses. The resulting widening of the bandwidth should also lead to lower effective Q values for a large number of cavities. Nevertheless, there is always the danger of trapped modes which are not reached by the HOM couplers—the quality factor of such modes could be several million and a single cavity could drive the beam unstable. It is therefore very important to verify that no trapped modes remain in the cavities.
8.4 Feedback systems

8.4.1 Longitudinal feedback for 36 bunches

Coupled dipole oscillations will be damped with a dedicated feedback system. The required voltage is determined by the maximum momentum spread $\Delta p/p$ and the feedback damping coefficient $a_{FB}$ which has to be greater than the maximum growth rate of an instability. For $\Delta p/p \simeq 10^{-3}$ and $a_{FB} = 400 \text{s}^{-1}$ the necessary voltage is [38]

$$ U_{FB} = 1.5 \text{ MV} \quad (37) $$

The system bandwidth is determined by the minimum time $t_{MIN}$ between bunch passages. The best feedback cavity location for operation with up to 36 bunches per beam is at 185 m from an even numbered intersection point. If the space occupied by the feedback cavities is 20 m, $t_{min} = 1.17 \mu s$. In this time interval at least 90% of the required cavity field should be reached. The cavity filling time is then 0.51 $\mu s$. From this the minimum cavity bandwidth is calculated to be 625 kHz.

At present the best location for feedback cavities is occupied by cavities no. 1–8 of the copper cavity unit nearest an intersection point. The simplest solution would therefore be a transformation of eight accelerating cavities to feedback cavities. The RF power generation system could be left essentially unchanged and the required bandwidth obtained by increasing the cavity input coupling coefficient.

With 1 MW of RF power applied to eight of the existing copper cavities at 352 MHz the feedback voltage is

$$ U_{FB} = 4.5 \text{ MV} \quad (38) $$

which should be sufficient to damp all modes of oscillation.

By taking into consideration that with more than two times eight bunches in LEP the copper cavity system can only be operated with one frequency this modification results in a loss in accelerating voltage of 18 MV.

The low power electronics used in the present feedback system can with some modifications be upgraded to 36 bunches.

8.4.2 Longitudinal feedback for 8 bunches

The dedicated longitudinal feedback system which is under study [39] can be used in the 8 bunch mode without modifications.

8.4.3 Transverse feedback

The requirements follow from Section 8.3 and it appears that the system will have to be rebuilt.

8.5 Higher-order mode coupling and extraction

The loss factor $k$ of the SC 4-cell LEP cavity has been calculated as a function of bunch-length. In using both URMEI which calculates the properties of cavity modes and TBCI which determines directly the beam-induced fields in the time domain, one can differentiate between a total loss-factor $k$ and a loss-factor $k_c$ for only those modes whose frequency is too low to allow their propagation into the beam tubes.
Figure 12: Higher order mode loss computed for SC cavity.

Figure 12, prepared from computed data, gives $k$ and $k_c$ as functions of bunch-length $\sigma_z$ and, in particular, values of $k_c = 0.22 \text{ V pC}^{-1}$ and $k \approx 3k_c$ for the present bunch length in LEP of $\sigma_z \approx 20 \text{ mm}$.

A bunch of charge $q$ passing through an empty cavity leaves fields with a stored energy $U = kq^2$ behind. If these fields decay sufficiently before the next bunch arrives then the energies of the bunches can be added and an average power calculated by multiplying $U$ by the bunch repetition frequency $f_b$.

The required minimum cavity damping which is proportional to the bunch spacing makes it necessary to mount special HOM couplers on SC cavities and to couple thus the non-propagating modes to external room-temperature damping resistors.

The system developed for LEP200 allows the extraction of 300 W of HOM power per cavity and provides adequate mode damping for $2 \times 4$ bunches in the machine.

Recent HOM measurements on one of the 4 Nb cavities installed in LEP confirmed the theory. With $k_c = 0.22 \text{ V pC}^{-1}$ one calculates for one circulating bunch of $q = 66 \text{ nC} (I_b \approx 0.75 \text{ mA})$ a HOM power of 10.9 W below cutoff; 12 W were measured. It was also found that for $2 \times 4$ bunches the powers of individual bunches simply add.

For $2 \times 36$ bunches, mode damping must be improved at least by a factor 9. In addition the power-handling capability of the couplers needs to be improved by the same factor: in fact a bunch charge of 100 nC would then result in 2.2 kW of HOM power per cavity below cutoff. For shorter bunch spacing, which occur at cavities near the interaction regions where electron and positron bunches cross after $2d/c$, the energies will no longer add linearly but—depending on the relative phases—up to quadratically. This means that the HOM couplers should be able to stand at least twice the power computed above.

In response to these requirements, a program to improve couplers and power-handling
systems was started at the beginning of this year.

So far, the geometry of a new HOM coupler which fits into the coupling chimney of the present version but provides 10 times better damping has been defined, a copper model built and its damping action measured.

The cryostat layout has been modified [40] to allow the use of medium power rigid coaxial lines for power extraction. Their detailed construction to obtain minimal heat flux into the He bath is under study. Construction of a Nb coupler prototype began in June 1990 and the system was tested in September. A schematic drawing of the coupler model is shown in Figure 13.

A problem of even greater concern remains the microwave power emitted into the high-frequency band beyond beam-tube cutoff. For $2 \times 36$ 100 nC bunches, 4.4 kW will be generated per cavity. The question of how to control this power by absorbing it safely into the beam-tubes to prevent any dissipation within cold parts of the cryostat has so far hardly been addressed.

### 8.5.1 Controlling HOM power loss

The HOM loss factors $k(\sigma_z)$ are strongly-dependent on the bunch length, decaying rapidly as the bunch length, $\sigma_z$, is increased. There is therefore some scope for reducing the power deposited in the SC cavities by lengthening the bunches. This can be done most simply by varying the damping partition numbers with the RF frequency. However, the constraints of luminosity maximisation usually require a certain emittance, which may not leave much freedom to do this [2,3] when in colliding beam mode, particularly at high energy. There is considerably more freedom at injection energy where long bunches are helpful against several instabilities.

In addition, the energy spread and consequently the bunch length can be increased by exciting wiggler magnets. The "damping" wigglers in LEP will reduce emittance slightly and increase bunch length while the "emittance" wigglers increase both. This allows some increase of bunch length while satisfying the emittance constraints. The main disadvantage of this, as pointed out in Section 9.2 is that special vacuum chamber cooling would be required to absorb the radiation power from a multi-bunch, high current beam at energies above 45 GeV.

In 1991, polarization wigglers will be installed [41]; these are like more powerful damping wigglers and can produce even longer bunches (see Figure 5 of [41]). Again, however, their usefulness for the pretzel scheme will be limited by synchrotron radiation proportional to the beam current.

### 8.5.2 The need for high-power HOM couplers

The pretzel scheme in LEP is not the only possible project which will require HOM couplers capable of extracting high power levels.

If single bunch currents much beyond 1 mA are achieved in 4-bunch operation, then improved couplers may be needed, particularly if the bunches are kept short, e.g., for compatibility with a low $\beta^*_y$. The so-called Type 5 coupler currently under development for LEP (a cheaper version of the coupler discussed above) would be capable of handling up to 12 bunches of 0.75 mA per beam. This would allow the full potential of the pretzel scheme to be realised at energies above the $W$-pair production threshold.
The plans to collide electrons in LEP with protons in the LHC [42,43] require large numbers of electron bunches of medium intensity, e.g., 540 bunches of \( I_b \approx 0.15 \, \text{mA} \) each. The HOM power losses per cavity are at best \( \propto k_i I_i^2 \), but could be proportional to the square of the number of bunches if these are close enough to each other that their fields add in phase \( \propto k_i^2 I_i^2 \). Comparing the HOM losses of the ep collision mode with those of 36 bunches with \( I_b \approx 0.75 \, \text{mA} \) each for the pretzel scheme, we see that they are comparable or even larger. High-power input couplers for SC cavities in the LHC itself require similar developments.

Future high-luminosity lower-energy \( e^+e^- \) factories like the \( \tau \)-charm Factory will be equipped with single-cell SC cavities which will require HOM couplers working at high power levels. \( B \)-factory designs in particular [44] will have to contend with HOM power loads which are more than an order of magnitude higher than those which will be generated even in a 36-bunch LEP. The development work required for LEP will most likely prove to be a useful step on the way to meeting these requirements.

9 VACUUM CONDITIONS

9.1 Beam lifetime due to gas scattering

The average vacuum pressure in LEP is dominated by the dynamic pressure which increases proportionally to the total circulating beam current. For one hour beam gas lifetime, the average pressure has to be about \( 2 \times 10^{-8} \, \text{Torr} \). The achieved performance
of the LEP vacuum system at 45 GeV operating energy, expressed in terms of the dynamic pressure rise in Torr/mA, is shown in Figure 14. It can be seen that from an initial value of above $10^{-7}\text{ Torr/mA}$, the specific pressure rise has decreased to about $2 \times 10^{-10}\text{ Torr/mA}$ after a total accumulated beam dose of 2 A hour. It has to be kept in mind that the evolution of the specific pressure rise shown in this figure reflects the combined effects of the cleaning of the vacuum chamber under photon bombardment on the one hand and of the gradual decrease of the pumping speed of the NEG ribbon due to the increasing amount of gas molecules pumped on the other. The full line in Figure 14 gives an extrapolation of those values of the specific pressure rise which were obtained immediately after reconditioning of the NEG pumps in LEP, hence for the known maximum achievable pumping speed of the system.

With 36 bunches and a total beam current (in two beams) of 54 mA, a vacuum beam lifetime of about 5 hours would require a specific pressure rise of $0.74 \times 10^{-10}\text{ Torr/mA}$. This figure is only a factor of 5 below the value now achieved. With the continuing operation of LEP, an improvement by a factor of 10 can be expected by the time the multi-bunch operation will start and hence the vacuum lifetime should not be a limiting factor for this mode of operation.

9.2 Synchrotron radiation power and cooling of vacuum chambers

The present level of synchrotron radiation power is sufficiently low that it was possible to save on the provisions for the cooling water supply and on the number of cooling water manifolds. However, in view of the synchrotron radiation power deposited on the vacuum chamber after the energy upgrading of LEP, the water cooling ducts in
the extruded vacuum chamber profiles have been dimensioned to evacuate an average power of up to 1500 W/m with a cooling water flow limited to less than 3 m/s to avoid any risk of erosion corrosion. This upgrading will require modifications of the water circuit giving an increase of the water flow per cooling water sector of 79 m length from the present value of about 1000 ℓ/hour to 5000 ℓ/hour [45]. Depending on the detailed scheduling of the energy upgrading and of the multi-bunch operation, the increased cooling capacity will have to be made available in time. For linear power deposition above 1.5 kW/m, it is necessary to reduce the length of the cooling circuits as shown in Figure 15.

More critical than the average power level in the arcs will be the local power deposition on the vacuum chamber. Areas which require increased cooling capacity and hence modifications of the cooling water circuits are the vacuum chambers near the wiggler magnets (if the wigglers are used with high beam current at high energy) and the special vacuum chambers near the injection equipment. According to the previous estimates made in [46], the peak power on some vacuum chambers downstream of the wiggler magnets reaches values of 400 W/mA m at 50 GeV, e.g., see Figure 16. This corresponds to a power of up to than 20 kW/m in the multi-bunch mode. It may be necessary to redesign some of the vacuum chamber in these critical locations.
Figure 16: Linear power density incident on the vacuum chamber near the LEP wigglers (from [46]).

10 PARTICLE BACKGROUNDs AND RADIATION

10.1 Particle Backgrounds at LEP Detectors

No major changes in the background rates per bunch crossing are expected for the multi-bunch mode when compared to rates at nominal LEP running.

Photon and electron background rates per bunch crossing from synchrotron radiation and beam-gas bremsstrahlung respectively, are proportional to the bunch currents and will therefore stay comparable to the nominal LEP case [47]. Integrated background rates, however, will increase in proportion to total beam currents.

The off-momentum electron background rate is proportional to the average vacuum pressure over the first 500 metres of beam line on either side of the experimental detectors. However, as explained in Section 9, it is expected, that by the time the multi-bunch operation starts, the increase of the dynamical vacuum pressure with beam current will be about a factor 10 below present values, so that, even with 36 bunches of nominal current, no major increase of the average pressure is expected.

10.2 ♠ Synchrotron Radiation onto SC Cavities and separators

At high beam energy the SC cavities and electrostatic separators in the last RF cell must be protected by special collimators from the very high flux of low energy photons radiated from the weak dipoles and first few metres of arc dipoles. These collimators are needed in any case for LEP200. At 100 GeV beam energy the critical energy of this radiation is about 713 KeV and an intolerable amount of radiation power (up to 6.5 W per mA beam current) would be incident per metre of cavity.
To stop these photons from hitting the inner surface of the SC cavities and cold transition pieces to the quadrupole chambers or electrostatic separator plates, two horizontal collimators must be located upstream from quadrupoles 10 and 11 (see Figure 17) and closed to below $\pm 20\sigma_x$.

The only remaining photon sources are then backscattered photons from the collimator jaws and photons radiated in nearby quadrupole magnetic fields. The amount of photons from these sources are smaller by at least a factor 100 and can be tolerated.

Detailed calculations of the amount of photons incident onto cavity and separator surfaces from quadrupole radiation and collimator back-scattering have not yet been carried out. They will be done once the final layout of quadrupoles, cavities and separators is known.

An important consequence of the present calculations is that it may not be necessary to build horizontal separators with slotted electrodes. This could make the design of the pretzel separators very similar to the existing vertical separators and do away with the long lead time required for electrode prototype development.

11 BEAM INSTRUMENTATION AND DIAGNOSTICS

The consequences of multi-bunch operation for the beam instrumentation have been investigated in order to specify and evaluate the modifications needed to ensure the performance of the different monitors under the new conditions.

The impact on the present system clearly depends on the final requirements, i.e., the number of bunches per beam and the mode of operation of the detectors. The following overview of the implications arising from multi-bunch operation is presented for the two cases of 8 or 36 bunches per beam.

11.1 Instrumentation for 8 bunches

11.1.1 Beam Synchronous Timing (BST) system

The simplest way of identifying eight bunches starting from the present BST message (4 independent bits, one per bunch) is to binary-code them since the injection of more than one bunch per LEP revolution is physically impossible. In this way, up to 16 possibilities would be available (15 different bunches and no bunch). The coding can be realized by reprogramming the Programmable Delay Module (PDM) of the BST-MASTER unit and slightly modifying its software. Some electronic printed cards of the bunch decoding system will have to be redone.

For the BST system itself, going from 4 to 8 bunches per beam does not imply major difficulties. More significant software modifications will be required at the Equipment Control Assembly (ECA) level for systems like the Beam Current Transformer (BCT), Beam Orbit Measurement (BOM), etc.

11.1.2 Collimators

No heating problems should appear at this level.
Protection of LEP200 Equipment in IP4 and IP8 from Dipole Synchrotron Radiation

\( E_{\text{beam}} = 100 \text{ GeV}, \quad \beta_y^* = 5 \text{ cm optics} \)
11.1.3 Beam Orbit Measurement (BOM) system

Wide Band (WB) System The 3\( \mu \)s conversion time of the Analogue-to-Digital Converter (ADC) is not affected by the reduced (from 22 to about 11\( \mu \)s) bunch-to-bunch time interval.

Narrow Band (NB) System The 600 ns acquisition time imposed by the analog processing time will prevent the use of four Beam Position Monitor (BPM)s around the middle of each Arc (PU.46.R, PU.48.R, PU.46.L, PU.48.L).

If these 32 BPMs are considered vital to provide orbit information around the new crossing points, Wide Band (WB) electronics must be provided at a cost of \( \sim 2 \) MSF.

11.1.4 Beam Current Transformers (BCT)

No problem should arise from the increase of the total DC current. Modifications are however required to the selection and acquisition procedure for the individual bunch measurement. A possible solution might be to specialize the eight electronic channels of each BCT to the \( e^+ \) and to the \( e^- \) beam separately.

11.1.5 Tune and chromaticity measurement

No substantial modifications are required for the hardware (shakers and power supplies). The software modifications mainly concern the bunch selection, requiring the programs at the ECA level and the application programs on the Apollo workstations to be adapted to the new situation.

11.1.6 Beam Profile Monitors

The problems are of different natures depending on the specific instrument.

Wire Scanners With the assumption that an increase of a factor of two in the deposited energy in the wires is still acceptable, only minor modifications in the acquisition are to be envisaged.

UV monitors The present design of the fast electronic shutters, specified for a bunch separation of \( \sim 22\mu s \) is not guaranteed to work for single bunch separation. If the 8-bunch operation is adopted, the improvement of the shutters may have to be envisaged.

X-Ray monitors, Autocorrelator, Streak-Camera All these instruments can select a maximum of four bunches at 22\( \mu \)s time interval. No particular problem from energy deposition is expected for the BEXE (hard X-ray monitor for vertical emittance measurements) and the autocorrelator up to 8 bunches per beam.

11.1.7 Bhabha Luminosity monitors

As for the other instruments a factor of two in the number of bunches requires minor modifications in the acquisition and in the software. The increased amount of synchrotron radiation from twice the beam currents should not cause more deterioration of the active parts of the detector than the energy upgrade.
11.2 Instrumentation for 36 bunches

11.2.1 Beam Synchronous Timing (BST) system

Three main modifications have to be considered:

1. The BST Message Assembler,
2. Interface and control software,
3. Re-allocation of BST message bits.

The first two can be done rather easily, while the third one is made difficult by the limitation in the available number of bits.

11.2.2 Collimators

The existing collimators used to limit the machine aperture cannot stand a beam current higher by an order of magnitude. They will be redesigned anyway for the LEP 200 programme and will therefore be adequate.

11.2.3 BOM system

Wide Band (WB) System The 2.4 μs time interval between consecutive bunches will cause the system to miss half of them, probably not in a coherent way from one ECA unit to the next. In addition to that, major changes are to be foreseen to the data acquisition and filtering software.

Narrow Band (NB) System Only 208 out of 448 Beam Position Monitor (BPM)s per octant will work. Even in this optics quite a number of modifications will be needed in the software as well in some parts of the hardware concerning the amplification stages ahead of the Fast Analogue-to-Digital Converter (ADC)s.

More extensive changes would be required to recuperate the 240 BPMs needed for complete integrity of the system and the implementation of Wide Band (WB) electronics is costly (c.f. Section 11.1.3).

11.2.4 Beam Current Transformers

The two monitors in LSS1 at ±163 m from IP1 as well as the two in the Arcs at ±956.8 m from IP1 will have serious cross-talk problems. If single bunch intensity measurements are required a ×9 multiplication in the electronic chains will need to be implemented.

11.2.5 Tune and chromaticity measurement

A new Analogue-to-Digital Converter (ADC) card is under development for the Q-meter, which besides improving resolution in the position measurements will also allow for gated measurements of a single bunch out of 2 × 36.

Concerning the beam excitation no hardware changes are to be foreseen besides those already needed to cope with the energy upgrade, at least for the “FFT” mode of operation of the device.
Some attention has nevertheless to be paid to investigate possible over-heating effects of the inner metallization of the ceramic vacuum chamber or the shaker magnet cores from higher average image currents.

11.2.6 Beam Profile monitors

Wire Scanners The use of a scintillator will be possible even if not for all the bunches in a single passage. The energy deposited in the wire and the consequent heating will almost surely limit the use of the instrument, unless a higher wire speed ($\sim 2 \text{ m/s}$) is adopted.

UV monitors No bunch selection will be possible with the present pulse generators of the shutters. New ones will have to be designed or bought.

Thermal deformations of the Be mirrors will have to be considered, which might cause the accuracy of the measurement to deteriorate.

X-Ray monitors, Autocorrelator, Streak-Camera Only four bunches will be selected via the PDM.

In addition, energy deposition problems will arise for the X-Ray monitors and for the Be synchrotron light extraction mirrors in LSS1 for the Streak-Camera and the other optical devices in the Optical Laboratory.

11.2.7 Bhabha Luminosity monitors

Although it is not clear at present how the monitors will be used during the LEP operation, modifications in the “integrate and hold” electronics will be needed to reduce the dead time, together with changes in the software.

The shielding of the detector against synchrotron radiation background will have to be improved; studies in the present situation will be performed to help designing a better radiation protection.

11.3 Summary of beam instrumentation

The operation of LEP with 8 bunches per beam does not require major modifications in the existing acquisition system and it is likely not to introduce serious environmental problems to the instrumentation itself, like overheating or radiation damage. However drastic modifications to the BOM system might be required.

For 36-bunch operation the present BOM system is inadequate and a large number of significant modifications, both on hardware and software, would be necessary.

Some delicate parts of the instrumentation like the Be mirrors for the UV monitors and for the extraction of the mini-wiggler synchrotron light to the Optical Laboratory and the X-Ray monitors will experiment high energy deposition doses which could not be withstood by the systems as currently designed.

For both 8-bunch and 36-bunch operation it may be possible to make do with the existing BOM system plus some ingenuity. For example one could devise strategies in which the main orbit measurement and correction procedures are carried out first with a smaller number of bunches in the machine. A limited amount of information would still be available in the multi-bunch operation and this, together with computations,
Table 6: Preliminary, rough estimates of costs of beam instrumentation upgrades; it should be kept in mind that it may not be necessary to fully upgrade the BOM system (see main text).

could suffice to correct the pretzel orbits. The feasibility of such a strategy requires detailed study and simulation, preferably including trials on the machine.

In Table 6, we give a very rough, preliminary estimate of the costs of all the upgrading of the beam instrumentation.

12 THE INJECTOR CHAIN

In this section we evaluate the performance of the LEP Injector Chain [48] working for the most demanding case of 36-bunch operation of LEP. The modifications to the injector chain and to the injection equipment in LEP itself which are needed to achieve the necessary performance are described and budgeted.

12.1 LEP filling time

The integrated luminosity is a function of the beam lifetime, limited mainly by beam-beam and beam-gas bremsstrahlung and of the dead time needed between dumping one fill and bringing a new one into collision.

Following [49] it can be shown that a maximum of the average to peak luminosity of 60% is obtained for a new filling of LEP every 3 to 4 hours with a dead time of 1 hour.

Assuming half of the dead time for all the other operations (beam dumping, field adjustment for a new injection, beam ramping and squeezing) leaves about 30 minutes for the injection of $1.5 \times 10^{13}$ particles in each beam. This corresponds to a filling rate of

$$8.3 \times 10^9 e^\pm/\text{sec},$$

(39)

a factor 3.6 above the present design figure.

12.2 Injector chain limitations

The performance of the injector chain is compared in Table 7 below with the LEP design values for both electrons and positrons.

The limiting factors come from:

- The LPI, for the particle production ($6.5 \times 10^{10} e^+/\text{sec}$ and $9.6 \times 10^{11} e^-/\text{sec}$). A proposal [50] has recently been made to increase the positron production rate by a factor of 3–7.

- The SPS, for the maximum number of particles per bunch ($1.0 \times 10^{10} e^\pm/\text{bunch}$) which is due to a transverse mode coupling instability during acceleration. During studies it has been shown that the threshold of this instability can be raised to $2.5 \times 10^{10} e^\pm/\text{bunch}$ by longitudinal blow-up and possibly by RF capture at injection in 100 MHz buckets.
<table>
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<th>Unit</th>
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<th>Electrons</th>
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Table 7: Present performance of the LEP Injector Chain

<table>
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<th>Unit</th>
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<th>Scheme 2</th>
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<td>LPI $e^-$ production rate</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>EPA particles/bunch</td>
<td>$N_{EPA}^-$</td>
<td>$10^{10}$ /b</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PS particles/bunch</td>
<td>$N_{PS}^-$</td>
<td>$10^{10}$ /b</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SPS particles/bunch</td>
<td>$N_{SPS}^-$</td>
<td>$10^{10}$ /b</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 8: Required performance of the LEP injector chain in the 3 operational schemes considered

12.3 Operation schemes

Assuming transfer efficiencies equivalent to the figures adopted during the LEP design:

\[
\begin{array}{c}
\text{LPI} \\ \rightarrow \begin{array}{c}
\text{PS} \\ \rightarrow \begin{array}{c}
\text{SPS} \\ \rightarrow \begin{array}{c}
\text{LEPinj} \\ \rightarrow \begin{array}{c}
\text{Collisions}
\end{array}
\end{array}
\end{array}
\end{array}
\end{array}
\]

and bunch cutting efficiency of 90% in EPA or PS, the variation of the LEP filling time and of the corresponding LPI particle production rate are plotted as a function as the number of particles per bunch in the SPS for different cases of possible supercycles.

The corresponding LEP filling time, LPI production rates and number of particles per bunch in the different machines are summarized in Table 8.

**Scheme 1: Nominal scheme (Figure 18)** This operation is based on a supercycle of 14.4 sec with 2 cycles of electrons and 2 cycles of positrons of 1.2 sec each as presently used in operation but with 8 bunches in each of the different machines. It imposes a positron bunch cutting in EPA as foreseen in the nominal scheme which has been installed and tested [51].

A filling time of 34 minutes is then possible, limited by both the positron production rate of LPI at the peak performance and the number of particles per bunch in the SPS.

**Scheme 2: SPS fast cycling (Figure 19)** A factor of two reduction of the filling time can be obtained by cycling the SPS at 1.7 Hz and introducing a bunch cutting in the PS for both kinds of particles. The feasibility of these modifications in the PS and SPS is discussed in the following sections.

The filling rate is then limited to 42 minutes by the positron production rate of LPI but can be reduced to 16 minutes if this production rate is increased by a factor 2.5.
Figure 18: Scheme 1: nominal supercycle (8 bunches) \( T_{\text{supercycle}} = 14.4 \text{ sec} \); \( n_{\text{cycle}}^+ = n_{\text{cycle}}^- = 2 \); \( T_{\text{cycle}} = 1.2 \text{ sec} \).
Figure 19: Scheme 2: LEP filling with SPS fast-cycling.
Figure 20: Scheme 3: Dedicated mode during filling. $T_{\text{supercycle}} = 2.4\text{ sec}$; $\eta^+_{\text{cycle}} = \eta^-_{\text{cycle}} = 1$; $T_{\text{cycle}} = 1.2\text{ sec}$. 
Scheme 3: Dedicated mode (Figure 20) A further slight reduction of the filling time to 11 minutes is obtained with a fully dedicated mode of the injectors during LEP filling but at the expense of an improvement of the LPI positron production rate by a factor 4.3.

12.4 PS modifications

As shown in Table 7, the PS has presently reached intensities of $5 \times 10^{10} e^+/\text{bunch}$ and $4 \times 10^{10} e^-/\text{bunch}$. Although the recorded peak performance in number of $e^+/\text{bunch}$ in the PS could be improved by a careful machine tuning when conditions are favourable (high intensity available together with machine study time), the maximum number of $e^-/\text{bunch}$ hits a harder limit. This limit comes from the fact that positive ions are trapped in the e- beam potential and induce vertical instabilities leading to hiccups and blow-up of extracted beam. It has been raised to $4 \times 10^{10} e^-/\text{bunch}$ but could possibly be further raised with further machine study time.

With these figures, the nominal scheme (case 1 presented above) does not need any modification in the PS. It only requires that the 8-bunch scheme be brought into an operational state. So far 8 bunches have been accelerated in the PS, 4 bunches have been extracted in 2 batches of 2 bunches and the required phase shift of the remaining bunches, after the first extraction, has been successfully tested. However the whole process, combining all steps, has not been tried. It only requires a common SPS/PS/LPI machine development.

The dedicated mode (case 3 presented above) leads to the same requirements as the nominal scheme.

Conversely, case 2 not only requires bringing the maximum number of $e^-/\text{bunch}$ to $5 \times 10^{10}$ but also requires major changes as compared to the nominal case. In this scheme the 8 lepton bunches are accelerated in the PS with a rate of rise of the magnetic field faster than the present one. These 8 bunches are split into halves by a slicing septum to be installed in the PS and 8 half bunches are extracted to the SPS. While the SPS accelerates and extracts these bunches to LEP, the remaining 8 halves are kept for 600 ms on the 3.5 GeV PS flat-top and extracted on the next SPS cycle (600 ms long).

The PS lepton cycle is kept to 1.2 sec but modified in order to present to the SPS extraction times regularly spaced by 600 ms. A possible PS supercycle matching the possible SPS lepton cycles is shown in Figure 21. Although this scheme looks feasible from the point of view of cycle and extraction times, it requires further studies:

- To determine where the slicing septum (or septa) should be installed in the PS.
- To evaluate the required optics changes to present the proper beam shape onto the slicing septum.
- To fire the extraction equipment twice in the same lepton cycle.
- To control the damping time constants in between the two extractions to keep the 2nd extracted beam to the same dimensions as the first one.
- To adapt the RF cavity short-circuit movement to the new supercycle.
- To make sure that $5 \times 10^{10} e^+$ or $e^-/\text{bunch}$ can be brought to 3.5 GeV with the proper beam dimensions on such a new cycle.
Figure 21: A possible PS supercycle which would match the lepton cycles proposed for the SPS.

12.5 SPS modifications

As in the PS, the 8 bunches/cycle injection scheme (case 1) is already foreseen with the existing hardware but has not yet been tested.

Going to twice the repetition rate, i.e., eight 0.6 sec cycles instead of four 1.2 sec lepton cycles (Scheme 2) should be possible hardware-wise. In the lepton cycles as they are now, there are fixed platforms before injection and after ejection in order to force the magnets to go through the same magnetic history. In this way the different cycles are magnetically decoupled so that trimming one of them does not perturb the others. These magnetisation platforms can be removed and a 20 GeV lepton cycle can fit into a 0.6 sec time interval.

However, this means the cycles are no longer magnetically independent, will increase the setting-up time substantially and may introduce magnetic instabilities. Moreover, the time between the down-ramp and the next injection will only be 60 msec, giving problems with eddy currents that will have to be corrected for. Doubling the number of lepton cycles will also involve software modifications on monitors and function generators.

Finally, it should be stressed that injection into LEP at 22 GeV (there is a proposal to raise the injection energy to this value) is not possible at intervals of 0.6 sec.

12.6 Summary for injector chain

A filling time of LEP at high luminosity within 34 minutes is feasible with the present LEP injector chain, working with the nominal injection scheme at the condition that the limitation of the number of particles per bunch is operationally increased to $2.5 \times 10^{10} e^\pm$. All necessary elements in the chain for 8-bunch operation have already been imple-
Table 9: Budget estimate for the LPI positron production improvement.

<table>
<thead>
<tr>
<th>Modifications for $N^+ = 20 \times 10^{10} e^+/sec$</th>
<th>MSF</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 new modulator and klystron station</td>
<td>1.10</td>
</tr>
<tr>
<td>3 new LIPS systems</td>
<td>0.28</td>
</tr>
<tr>
<td>High power HF network</td>
<td>0.12</td>
</tr>
<tr>
<td>HF low power (phasing, reference line)</td>
<td>0.10</td>
</tr>
<tr>
<td>Upgrade of converter target</td>
<td>0.10</td>
</tr>
<tr>
<td>LIL beam transport optics</td>
<td>0.20</td>
</tr>
<tr>
<td>Building and shielding modifications</td>
<td>0.30</td>
</tr>
<tr>
<td>Manpower</td>
<td>0.30</td>
</tr>
<tr>
<td>Total</td>
<td>2.50</td>
</tr>
</tbody>
</table>

mented and proven to work during machine studies. This scheme would make use of the full capability of the LPI positron production working at its peak performance.

A reduction of the filling time by a factor of two can be obtained but necessitates an improvement of the positron production rate of the LPI by a factor 2.5, the implementation of bunch cutting for both electrons and positrons in the PS and a doubling of the cycle rate of the SPS. All these improvements seem feasible but need to be carefully studied. A rough budget estimate for the LPI is annexed.

This scheme could be envisaged as an improvement programme and would make the best use of the single-bunch intensity limitations in the various machines.

Finally, the dedicated mode operation of the injector chain is not recommended as it brings only a slight reduction of the LEP filling time at the price of a major upgrading of the LPI positron production rate.

12.7 Injection into LEP

12.7.1 Present injection layout

The 2 injection insertions, one for $e^+$, the other for $e^-$, are located in the regular arcs about 500 m from either side of interaction point 1. The injection equipment [52] consists of 3 full aperture kicker magnets and 2 septum magnets in each of the 2 injection zones. The kickers are located at a distance of 79 m from each other near successive F-quadrupoles and create a fast local orbit bump in the horizontal plane.

LEP is filled by accumulating bunches over about 100 injection cycles with a minimum repetition time of 1.2 s. To achieve a high accumulation rate, up to 8 bunches can be injected per cycle. The minimum repetition time between the injection of successive bunches is $65 \mu s$.

The kicker magnets are presently powered by pulses with rise and fall times of $2.5 \mu s$ and $7 \mu s$. The flat top time, measured between the 99% amplitudes, is about $0.5 \mu s$. For synchronization reasons between bunches and kicks the pulses of successive kickers are delayed by about 250 ns. In the 4 bunch scheme, the pulses are sufficiently short to deflect only the forwards rotating stored bunch to which the injected bunch is to be added. Counter rotating bunches are not deflected.
12.7.2 Problems with shorter bunch spacing

In the 36 bunch scheme the distance between bunches of the same kind is 2.47 \( \mu s \), nearly 4 times less than the kicker pulse duration. Therefore several bunches will be deflected during the kicker pulse. As the pulse shapes of the 3 kickers are equal and the pulses synchronized with the bunches, the deflection of several forwards rotating bunches during one kicker pulse is acceptable.

Problems arise however with the counter rotating bunches. Due to the long flight time between the kickers the distance between forward and counter-rotating bunches is different at each kicker position, resulting in an uncompensated deflection of counter-rotating bunches. Figure 22 shows superimposed on the kicker pulse the positions of the correctly deflected forward bunch (cross at the top of the pulse) and of the 2 adjacent counter-rotating bunches at kicker 1 (squares) and kicker 3 (rhombus). The difference in kick strength of more than 40% between kickers 1 and 3 would cause unacceptably large betatron oscillations around the machine orbit.

12.7.3 A possible solution

The best remedy to the problem would be a decrease in pulse duration by about a factor 5 so that counter rotating bunches are no longer deflected. The rise and fall times required are 700 ns and 600 ns, with a flat top duration of some tens of nanoseconds to allow for jitter of timing pulses and power switches.

A 5-fold reduction in pulse duration corresponds to a 25-fold decrease of the pulse circuit elements, the pulser capacitance and the kicker magnet inductance. An 8-fold reduction of the inductance could be obtained by replacing the present 2-turn magnet coil by 2 half-turn coils connected anti-parallel in the two magnet halves and powered in parallel. The remaining factor 3.2 would be obtained by replacing the pulse capacitor by a pulse forming network (PFN) composed of 3 parallel coaxial high voltage cables of 70 m length each and a total characteristic impedance of 7.6 \( \Omega \).

The modified circuit diagram is given in Figure 24. The circuit consists of the following subsystems:

- A resonant charging power supply, housed in a surface building and providing the fast repetition rate. This subsystem does not need to be modified.

- An \( \approx 1000 \) m long coaxial pulse transmission cable between surface building and tunnel, remaining also unmodified.

- The new cable PFN and its thyatron discharge switch connected by short cables to
  - the ferrite kicker magnet, to be equipped with new coils.

The resulting magnet current pulse is shown in Figure 23.

The magnet is mounted around a metallized ceramic vacuum chamber. The titanium metallization of 2 \( \mu \)m thickness is optimized for the slow 9 \( \mu s \) pulse and would strongly attenuate the new short pulse. The metal film must therefore be removed. This is done with hot sulphuric acid in an existing installation. The chamber will then be re-metallized with a 0.4 \( \mu \)m thick layer, corresponding to a cut off frequency of 75 MHz, still low compared to the frequency spectrum of the bunches.
Figure 22: Present pulse shape of injection kickers and positions of correctly deflected forward bunch (cross) and adjacent counter-rotating bunches at kicker 1 (squares) and kicker 3 (rhombus).

Figure 23: Magnet current pulse for 36 bunch operation.

Figure 24: Circuit diagram of modified injection kicker.
The increased film resistance in combination with the higher beam current results in a power dissipation of about 300 W per chamber. A forced air cooling system must therefore be provided.

12.7.4 Cost estimate

The total cost of these modifications to the kickers would amount to about 400 kSF.

13 ♠ CONCLUSIONS AND COST SUMMARY

13.1 ♠ Feasibility of pretzel scheme

- With the help of a (36-bunch) pretzel scheme, it may be possible to push the peak luminosity of LEP beyond $10^{32} \text{cm}^{-2}\text{sec}^{-1}$ at the $Z^0$. Significant increases in luminosity (6, 8, 10, ... bunches) appear possible at higher energies up to and beyond the $W$-pair threshold, depending on the total RF power installed; see Figure 9 on page 35 for upper limits to luminosity.

- Electrostatic or RF-magnetic separators and upgrades to a number of other pieces of hardware will be needed. However there are no really drastic changes to the machine from the pretzel scheme itself. It would be easy to revert to, e.g., high energy LEP operation with 4 bunches.

- Operation of LEP with a pretzel scheme will be a lot more complicated and much detailed work remains to be done, particularly on the optics, beam-beam effects, RF system, separator development, etc., before solid performance and cost estimates can be given. Experiments on simulated pretzel orbits have already indicated that it is possible to preserve an adequate dynamic aperture, rapid injection rate and high single-bunch current on a pretzel orbit. Future machine studies, e.g., on parasitic beam-beam effects and with many bunches in a single beam still need to be carried out.

- The horizontal separation in the pretzel scheme does not rule out the possibility of obtaining polarized beams.

Although a number of problems remain to be solved before LEP can be operated with larger numbers of bunches, a number of potential obstacles to implementation of a pretzel scheme have been cleared away in recent months. The necessary upgrading of the higher-order mode couplers on the superconducting cavities to cope with power levels in a 36-bunch scheme appears feasible and a cheaper coupler design is available which would work for up to 12 bunches. There remain a certain number of unresolved questions concerning the beam dynamics.

The results of the present study must be understood as preliminary, as of September 1990. In the next few months it is hoped that further studies—mainly theoretical until LEP becomes available for machine studies again—will provide us with better information on some of the issues which require clarification.

The present report emerges in a period of active and sustained discussion of future particle accelerators such as linear colliders, superconducting hadron colliders or asymmetric-energy $e^+e^-$ factories with luminosities of $10^{33} \text{cm}^{-2}\text{sec}^{-1}$ and even greater.
In this context we feel bound to make some remarks to help set it in an appropriate perspective.

While there are serious technical problems to be solved and much detailed work to be done before a pretzel LEP can reach the projected luminosities, we emphasise that the scheme constitutes a *performance upgrade of an existing machine following an established path*. Present understanding suggests that these challenges are not of the same order as those presented by the types of machine mentioned above.

### 13.2 Schedule

The time schedule for implementation of a pretzel scheme depends on three critical items:

- Including 1.5 years for prototyping work, it would take 3.5 years to build and install the 16 horizontal separators units. This could well be less if (as now seems likely) slotted electrodes are not required or (as seems rather unlikely) a vertical pretzel scheme were found to be feasible.

- The superconducting RF cavities need to be equipped with HOM and input power couplers appropriate for the maximum number of bunches required. Work towards this goal is under way.

- Some of the normal-conducting RF system has to be removed to make space for the separators.

Unless the BOM system requires substantial upgrading, it appears that all the other modifications needed for the pretzel scheme could be made in parallel.

If the project were initiated now, with appropriate funding and resources, the installation work could be carried out in parallel with the energy upgrading so that a pretzel scheme could be ready to try out by the end of 1994. Its first rôle might therefore be to increase the number of bunches to 6, 8, 10, 12 or, perhaps, 18 and augment the luminosity at or above the $W^+W^-$ threshold.

### 13.3 Summary of costs

In Table 10, we summarise the budget estimates made in various sections of this report. We do not include items (e.g., the RF, HOM couplers, vacuum improvements, collimators, ...) which will in any case be included in the budget for the LEP energy upgrade. For some items, we specify a lower and an upper limit to the cost which reflects either present uncertainty or two possible levels of upgrading as discussed in the appropriate subsections of this report. For example, a pretzel scheme limited to 8 bunches requires considerably less hardware upgrading than a scheme with the full potential for 36 bunches.

This budget does not include any new feedback systems, additional magnets (e.g., a few sextupoles in the straight sections) or other contingencies. It would be wise to add, say, 5 MSF, to cover these.
<table>
<thead>
<tr>
<th>Item</th>
<th>Min. cost</th>
<th>Max. cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrostatic separators</td>
<td>12.3</td>
<td>17.3</td>
</tr>
<tr>
<td>BOM system</td>
<td>2.0</td>
<td>10.0</td>
</tr>
<tr>
<td>Other beam instrumentation</td>
<td>0.5</td>
<td>2.0</td>
</tr>
<tr>
<td>LPI $e^+$ production increase</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>LEP injection kickers</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>17.7</strong></td>
<td><strong>32.2</strong></td>
</tr>
</tbody>
</table>

Table 10: Budget summary for the pretzel scheme.

13.4 Alternatives to the pretzel scheme

Of the alternative schemes for increasing the number of bunches, the one which looks simplest from the point of view of beam dynamics is the local separation bump in mid-arc (see Section 1.5.1). This would involve installing 16 vertical separators (the same number as required in a full pretzel scheme) and replacing a number of magnets in the middle of each arc. The number of bunches could then be $k_5 = 8$, giving a potential factor 2 in luminosity over what can be achieved with 4 bunches.

Acknowledgements: We would like to thank numerous colleagues at CERN and Cornell, particularly D. Brandt, A.-M. Fauchet, G. Geschonke, E. Keil, R. Littauer, R. Schmidt, R. Siemann, M. Tigner, J. Welch and C. Wyss for information and helpful discussions.

References


[27] WIGWAM was written by J.M. Jowett, see [2,3,9] for further information.

[29] This program is under development by W. Herr and H. Moshammer.


[32] W. Kalbreier et al., LEP Performance Note, to be published.


[34] Y. Chin, LEP Theory Note 33 (1985)


[40] P. Bernard, private communication.


A List of symbols

\[ E_0 = m c^2 \gamma = \sqrt{p_0^2 c^2 + m^2 c^4} \]  beam energy
\[ C = 2 \pi R \]  circumference of machine
\[ f_0 = C/c \]  revolution frequency
\[ s \]  machine azimuth \((0 \leq s < C)\)
\[ e, m, r \]  electron charge, mass, classical radius
\[ k_b = f_b / f_0 = C / S_b \]  number of bunches per beam
\[ I_b = e N_b f_0 \]  current in a single bunch
\[ J = k_b I_b \]  total beam current
\[ x, y \]  radial, vertical displacements of particles
\[ \eta_x, \eta_y \]  pretzel orbits of e^+e^−
\[ X, Y \]  separation between centres of bunches at encounters
\[ K_2 \]  sextupole focussing strength
\[ \eta_x, \eta_y \]  radial, vertical dispersion function
\[ \beta_x, \beta_y \]  radial, vertical optical function
\[ J_x, J_y, J_z \]  radial, vertical, longitudinal damping partition numbers
\[ Q_x, Q_y, Q_z \]  betatron and synchrotron tunes
\[ \epsilon_x \]  total horizontal emittance (no coupling)
\[ \epsilon_x, \epsilon_y \]  radial, vertical emittances with coupling
\[ \sigma_e \]  r.m.s. fractional energy deviation
\[ \sigma_x, \sigma_y \]  r.m.s. radial, vertical beam size
\[ \sigma_z \equiv z_{rms} \]  r.m.s. bunch length
\[ U_0 \]  total radiation energy loss per turn
\[ V_{RF} \]  total peak RF voltage
\[ L_0, L \]  'unperturbed' and real luminosity
\[ \xi_0, \xi_{yc} \]  'unperturbed' beam-beam strength parameters
\[ \xi \]  effective beam-beam strength at saturation
\[ \Phi \]  beam-beam potential function
\[ \Xi, \Xi \]  auxiliary functions for beam-beam interactions
\[ E_x, E_y \]  electric fields in separators
\[ P_{beam} \]  total synchrotron radiation power
\[ \rho \]  bending radius in dipoles
\[ Q_{ext} \]  external Q-factor for SC cavity
\[ \omega \]  frequency of higher-mode in SC cavity
\[ a_{FB}, U_{FB} \]  feedback damping coefficient and voltage
\[ k, k_c \]  HOM loss parameters
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PART II

PHYSICS POSSIBILITIES

1 INTRODUCTION

F.M. Renard

Physics at LEP has been extensively discussed in the past, see e.g. the Proceedings of the Workshop on Z Physics at LEP 1 in 1989 and for LEP 2 the Proceedings of the Aachen Workshop in 1986. The boundary conditions for these studies were a normal phase with a design luminosity of $1.7 \times 10^{31}$ at the Z peak and $2 \times 10^{31}$ above the WW threshold.

At the time this report is prepared, LEP confirms its capability of reaching these expectations. Answers on several important issues in the verification of the Standard Model have already been obtained and the possible range for new physics effects is reduced. It is then reasonable to believe that the final goals which were given in the above mentioned workshops can be achieved in this normal LEP phase. More precisely, at the time being one can expect that, in 1993, about $5 \times 10^6$ Z will have been collected. However, in order to accumulate 500 pb$^{-1}$ at LEP 200, as required by the Aachen Workshop in order to allow a good analysis of the WW channel, about five years of running may be necessary.

The high-luminosity phase as presented in Part I (J. Jowett) should make it possible to gain a factor of 10 at the Z peak and a factor of 2 above the WW threshold. This leads us to expect that about $25 \times 10^6$ Z can be collected in a few years, and that, in the long run, $10^8$ Z could be reached. At LEP 200, the gain by a factor of 2 would be very helpful in accumulating the 500 pb$^{-1}$ in a shorter time (2–3 years, for example in 1994–1996).

Such an increase in the number of events should lead to two types of new issues:

i) an improvement in the precision tests of the electroweak interactions, i.e. in the determination of the parameters of the Standard Model that are still free and a high potentiality of discovering New Physics effects or very severely constraining their possible scales;

ii) the possibility of reaching phenomena (B physics aspects, rare Z decays, ...) which are beyond the range of accessibility of the LEP 1 phase.

In order to cover these aspects, four Sub-Subgroups were set-up, whose tasks were to study respectively:

SSG1 : Standard and non-standard physics from $b\bar{b}$ production (F.M. Renard, C. Verzegnassi et al.)
SSG2 : B decays (J. Donoghue et al.)
SSG3 : Rare Z decays, Higgs, New Physics, ... (B. Gavela, F. Zwirner et al.)
SSG4 : QCD and other standard processes (R. Stuart, T. Sjöstrand et al.).

In addition R. Kleiss devoted himself to the study of the improvements above the WW threshold.

The detailed presentation of the results of these studies is displayed in the following Sections :

2. Accurate measurements at the Z peak and implications for the Standard Model.
3. Higgs and New Physics,
4. Special features of $b\bar{b}$ production at the Z resonance,
5. B-fragmentation,
6. B decays,
7. QCD and related topics,

The highlights which came out are the following:

PRECISION TESTS: An accurate measurement of $F$–$B$ asymmetries, $Z$ partial widths and $\tau$ polarization will allow us to sensibly improve the tests of the Standard Model of electroweak interactions. At least a factor of 2 can be gained in accuracy on $\sin^2 \theta_w$ ($\pm 0.0004$) and the $\rho$ parameter would be measured to $\pm 0.002$. This means for example a constraint of $\pm 10$ GeV on the top mass around 150 GeV.

These numbers come very close to the ones which are expected from a measurement of the longitudinal polarization asymmetry $A_{LR}$ at $\pm 0.003$ and that are roughly a factor of 1.5 to 2 better.

These accuracies also mean that a higher potentiality of discovering New Physics would be available. For example $Z'$ effects could be seen if the $Z$–$Z'$ mixing angle is $0.01$ or even smaller, in some cases this implies $m_{Z'} > 1$ TeV. The disentangling of New Physics effects from standard radiative correction effects involving unknown parameters ($m_t, m_H$) is shown to be possible (a 3-step strategy) using the richness of LEP observables at the $Z$ peak (and especially the high accuracy which would come from the $bb$ channel) and the possible measurement of $m_W$ at $\pm 70$ MeV from the gain in luminosity expected just above the $WW$ threshold.

HIGGS BOSON: Limits on a directly produced Higgs boson either of a standard nature or expected in the minimal supersymmetric model are increased from about 45 GeV (in the normal phase) to about 70 GeV (in the High Luminosity phase). Although LEP 200 should give slightly higher limits, first it would be tempting to get these 70 GeV limits already during runs at the $Z$ peak and secondly, if by chance such a ‘low-mass’ Higgs would exist, the high-luminosity phase would allow a detailed study of its various production and decay modes, thus providing new tests of the scalar sector.

B PHYSIS: With about $3 \times 10^7$ $B$ mesons produced HLEP would already constitute a kind of $B$-factory (see Part III for a detailed comparison with other machines) with, from its $e^+e^-$ source, the special property of producing all varieties of $b$ hadrons on an equal footing. This means the possibility of discovering $B_c$ mesons, $\Lambda_b$ baryons, ..., studying rare $B$ decays (non-charmed modes, $B \rightarrow \tau + \nu, B \rightarrow K^* + \gamma, ...$), which offer new tests of the Standard Model in this heavy sector (origin of mass generation, $K$–$M$ structure,...) and different ways of looking for New Physics signals. In addition, the mean flight path of $B$ mesons produced at the $Z$ peak will open unique ways of studying the various $B$ lifetimes and observing $B_\pm \rightarrow B_\mp$ mixing up to very high values ($x_s > 15$) with an accuracy of $\pm 0.5$. Apart from a possible non-standard origin, this number of $B$ produced one should still miss observation of CP violation by roughly a factor of 10.

FURTHER NEW PHYSICS: A higher luminosity would also be beneficial for Supersymmetry searches, mainly in the neutralino sector, with the possible decay modes $Z \rightarrow XX$ (invisible width) and $Z \rightarrow XX'(X' \rightarrow X +$ visible, Zen events). Compositeness scales for radiative $Z$ modes, residual contact terms, ..., will be pushed a factor of 2 higher in the TeV range. Flavour Changing Neutral Couplings or CP-odd couplings will also be more severely constrained.
QCD DYNAMICS: A by-product of a larger number of events both at the Z peak and beyond (up to the WW threshold) is the possibility of obtaining a better description of hadronization processes, of the multijet production and of jet development, of extending the studies of photon-photon collision processes, and, with the availability of different initial energies with the same detectors, the possibility of getting an unbiased observation of the running of $\alpha$-strong.

On the whole, high luminosities at LEP appear to have very appealing and specific features. The physics issues often happen to be complementary to those which would be brought by LEP 200 and by longitudinal polarization, with little overlap. This makes the project worth while pursuing further. In Part III, a comparison with B-factories will be made and in Part IV the implications for experiments of such high luminosities will be discussed.
2 ACCURATE MEASUREMENTS


As emphasized in the theoretical part, one of the main goals of LEP physics is to provide accurate measurements of various observables in order to test the validity of the Standard Model. LEP could be, for the Standard Model, an analogue of what $g - 2$ was for QED.

The clarity of LEP physics has already been demonstrated: all measurements of the main Z resonance parameters have been obtained with an accuracy that is rather better than expected. The same is true for the number of neutrinos, using the invisible width method.

However, we are still far from obtaining any other measurement that could match in accuracy the determination of the Z mass. If we use $\sin^2 \theta_w$ as an index of quality, the present knowledge of the mass is equivalent to $\Delta \sin^2 \theta_w = 3.3 \times 10^{-4}$ and the expected one—once absolute calibration is determined by resonant depolarization—to $\Delta \sin^2 \theta_w = 1.3 \times 10^{-4}$.

At present, the only other independent measurement of $\sin^2 \theta_w$ quoted is obtained through neutral-current coupling of the leptons and gives $\Delta \sin^2 \theta_w (m_Z) = 0.008 [1]$.

The Workshop on Polarization at LEP [2] has clearly shown that an extremely promising observable is, in this respect, the spin asymmetry $A_{LR}$. The polarized charge asymmetries of the fermions $A_{ch}^{pol}$ give very interesting complementary measurements.

At the Workshop on Polarization, the conditions required to perform such a programme were neatly expressed (Table 2.1). From the experimental side, the requirement for the relative luminosity measurement looks totally realistic in view of the successful operation of all normalization devices, which gave better absolute numbers than were expected. The polarimetry programme is progressing, and a realistic scheme for the rotator is available.

The only 'unknown' is still the availability of polarization.

We discuss here what LEP at high luminosity can provide as accurate measurements in the absence of polarization.

2.1 Lepton charge asymmetry

We first recall that, for two-body final states, $A_{ch} \equiv A_{FB}$. The properties and limitations of this asymmetry have been reviewed in detail [3]. The measurement deals with simple, relatively abundant final states (3% of all Z decays per channel). The redundancy of trigger, reconstruction, and identification procedures allows all efficiencies to be measured, so that part of the instrumental systematic errors are in fact of statistical origin. The measurement is also normalization-free.

On the other hand, this observable is not very sensitive to $\sin^2 \theta_w$. Its steep variation across the Z makes it very dependent on initial-state radiative corrections—an aspect that can be gradually improved—and on the knowledge of the peak position. This last uncertainty may in the long run be the dominant and incompressible systematic error.
Table 2.2 gives an estimate of these errors. The statistical error is for 1000 \(\text{pb}^{-1}\). The systematic errors assume
- that the resonant-depolarization method of calibrating LEP energy is available (we assumed here an uncertainty of \(\pm 10\ \text{MeV/c}\), which could even be improved in the long run);
- that the radiative corrections are performed with a residual uncertainty of only 5\% of the correction itself;
- that the detectors and the analysis are properly used as indicated above. Owing to the quality of LEP detectors and to the absence of several background sources—still dangerous at PETRA and PEP—it should not be difficult to reach the quoted value.

With such systematic errors, the cross-over point (statistics = systematics) would be reached for \(\sim 10^7\) Z's.

### 2.2 Tau polarization

In the absence of polarization of the LEP beams, the most promising observable for accurate measurement of \(\sin^2 \theta_W\) is the polarization of final leptons. The potential information is the same as that from \(A_{\text{LR}}\).

However, this measurement is practical only for the \(\tau\) and is performed by studying specific spectra from \(\tau\) decay: on the whole, the efficiency is low and the statistics is poor.

The classical strategy is to measure the pion energy distribution from \(\tau \rightarrow \pi \nu\): the branching ratio is 10\%. In the full acceptance region, we get \(\sim 7000\) such \(\tau\) decays per \(10^6\) recorded Z's.

Assuming that there is e-\(\tau\) universality and pure \(V-A\) coupling of the \(\tau\) to the W\(^\pm\), we get \(\nu/\alpha = 1 - 4 \sin^2 \theta_W\) from a one-parameter fit; \(\nu/\alpha\) is deduced from \(A_{\text{pol}}\). The uninteresting range of \(\cos \theta < 0\), where the \(\tau\) has little polarization, is cut out. For \(\tau \rightarrow \pi \nu\), which is the most efficient mode, this procedure retains half of the events. From past studies [4] it appears that the systematic error on \(\sin^2 \theta_W\) can thus be brought down to \(\sim 0.0008\).

To get an equivalent statistical error, we have to record \(\sim 7 \times 10^6\) Z's. With 1000 \(\text{pb}^{-1}\) the overall error is \(\sim 0.001\) (Table 2.3). It is expected, as already shown by preliminary ALEPH data, that a substantial improvement can be obtained from the exploitation of other channels, such as \(\rho \nu\), \(\ell \nu \bar{\nu}\), etc.

Clearly the interest of accumulating very large samples will depend on the possibility of improving the systematic uncertainty. The most important contribution to this uncertainty comes from the misidentifications of the decay products: either mixing \(\pi \nu\) and \(\rho \nu\), or confusing \(\pi\) with leptons. Higher statistics can only improve the situation from the point of view of systematics since

i) we can afford to perform more severe cuts, for instance in the angular domain, in order to avoid dangerous kinematical regions;

ii) contaminations will not be estimated by Monte Carlo but rather measured by using redundant procedures, and therefore systematics and statistics are closely linked.

Precise extrapolations can only be done from real data, once a sufficiently large sample has been accumulated.
2.3 Quark charge asymmetries

In comparison with lepton asymmetries, quark asymmetries have several interesting features: greater sensitivity to $\sin^2 \theta_W$, and less dependence on electromagnetic radiative corrections and on the peak position. QCD corrections are well under control.

The major problem now is quark tagging, i.e. the identification of the quark flavour. Many studies relating to this subject have been performed [5]: however, it may be that the final answers will only be known a posteriori once the detectors are fully understood.

A priori the LEP detectors have the most favourable features: a vacuum chamber of relatively small radius ($\sim 5$ cm in the near future, it may be less later); high-performance microvertex detectors; lepton identification; $dE/dx$ information; RICH hadron identification for one of the experiments, high-quality measurements ($V^0$s, $\Delta p/p$, mass resolution). These features will be considered in more detail in the part on beauty physics.

For charge asymmetries, the flavour tagging must provide the charge of the quark. It must also be severe, so that the contamination by other flavours—or, worse, by the charge conjugate state—is small and well understood. The efficiency can therefore only be small, and high statistics are welcome if the systematic error is kept low enough.

Table 2.4a summarizes what we can a priori expect from LEP. The procedures leading to the quoted efficiencies are described in detail in Ref. [5]. They use both inclusive (identified leptons and hadrons) and semi-exclusive (explicitly reconstructed states such as $D^*$ for $b$ and $c$, $\phi$ for $s$, etc.) features of the events.

The quoted systematic errors are dominated by the tagging uncertainty as shown in Table 2.4b. Before data from LEP are exploited, the only procedure is to take existing Monte Carlos describing production and fragmentation, tuned on lower energy data, and to consider the residual dispersion between them as an estimate of the error. It has been shown [5] that the situation is already not so bad, and it will improve with the advent of abundant data from LEP, since these will allow the fragmentation models to be tuned, at the right energy, on global quantities such as the inclusive spectra of identified particles, correlations, etc. Note also that for tagging we use mostly the high-energy particles, and less frequently the more difficult soft fragmentation region.

Provided the detectors behave as expected, the systematic errors quoted in Table 2.4 should therefore be considered as conservative numbers.

For $bb$, the interesting complication due to mixing is considered in the next section. Previous studies have shown that the final accuracy on $A_{q\bar{q}}$ should not be worse in the presence of mixing, once the mixing parameters have been measured and the effect corrected for [6] (see Table 2.5).

For $cc$, besides the classical methods ($K^0\ell$ like-sign pairs with appropriate kinematics, high-$x$ $D^*$, etc.), there is the promising inclusive method of tagging on the $\pi$ from the $D^* \to \pi D$ [7], for which preliminary results already exist.

In the case of $u\bar{u}$, however, our present uncertainty in baryon production makes the prediction quite unreliable until more information becomes available.

With the efficiencies and systematic errors quoted in the tables the cross-over points are quite high:

$\sim 15 \times 10^6$ for $bb$, $\sim 15 \times 10^6$ for $cc$, $6-20 \times 10^6$ for $s\bar{s}$.

These numbers will be still higher if the systematic errors decrease with increasing statistics, as they should.
In fact with the availability of very high statistics one can then adopt a method different from the tagging schemes quoted above, which are essentially single-arm procedures. A severe double-arm tagging, in spite of its low efficiency, can be satisfactory from the point of view of both statistics and systematics.

Above 30 million Z's (i.e. 6 million b\overline{b}) a double-tag efficiency of \( \sim 2\% \) leaves more than 10,000 events, i.e. less than a per cent of statistical error. This efficiency is a pessimistic estimate of what can be achieved by a tag with opposite-sign leptons, one on each side, cut quite high in \( p_T \) (\( \geq 1.2 \) GeV/c).

The presence of \( B-\overline{B} \) mixing acts here at the second-order level (\( \sim 5\% \)), giving opposite-sign dileptons with the wrong configuration. This has to be corrected for, using the measurement of the first-order effect, giving like-sign dileptons within the same cuts, with abundant statistics.

The charm contamination (or any other) is at the 10\% level in each tag, and therefore at the 1% level overall. From the data themselves, a measurement of this charm contamination can be performed, using a severe and pure preliminary charm tag (\( \pi \)'s from \( D^* \)).

From Table 2.4b one sees that QCD is an important contribution to the systematics, but recent improvements in its treatment can decrease it a lot. Furthermore, it would disappear in a ratio of asymmetries.

Therefore, an overall error \( \Delta A_{b\overline{b}} \simeq 0.016/\sqrt{N_z(10^6)} \) can be envisaged. Probably other double-tag procedures (\( \pi \) of \( D^* \) for \( \overline{c}\overline{c} \) etc.) could be exploited as well. The uncertainty in \( \sin^2 \theta_w \), obtained by combining asymmetry measurements without polarization, is then quite competitive with the best of the other measurements, namely \( A_{LR} \) with polarized beams, when \( N_z \simeq 2.5 \times 10^7 \).

Very high luminosity can thus be considered as an alternative for accurate measurements, if polarization cannot be obtained. The systematic errors are totally different in the two cases and therefore the measurements are complementary.

But it should be emphasized that, compared with registering \( \sim 10^6 \) Z's with polarization and without requiring any final-state identification, the experimental burden would be much heavier.

However, such a large exposure will be the only way to perform other kinds of crucial measurements for testing the Standard Model.

### 2.4 The b\overline{b} asymmetry in the presence of mixing

The usual b tagging, which provides the quark charge, focuses mostly on single leptons from semileptonic b-decay [6]. Variants such as the Fischer discriminant methods use more variables, but single leptons and their \( p_T \) distribution still play the essential role, and arguments developed in this section are valid as well.

There is now evidence that mixing is present in the neutral B system. A small mixing in \( B^0_d \) and a near maximal mixing in \( B^0_s \) would be consistent with the present data.

The presence of mixing reduces the observed asymmetry; it must therefore be corrected for. Defining

\[
g_2 = \frac{b \rightarrow B^0_d}{b \rightarrow \text{all}}, \quad g_3 = \frac{b \rightarrow B^0_s}{b \rightarrow \text{all}},
\]
\[
\beta = \frac{B_d^0 \rightarrow \ell^- X}{(B_d^0 \rightarrow \ell^- X) + (B_d^0 \rightarrow \ell^+ X)}, \\
\gamma = \frac{B_s^0 \rightarrow \ell^- X}{(B_s^0 \rightarrow \ell^- X) + (B_s^0 \rightarrow \ell^+ X)}, \\
\chi = \beta g_2 + \gamma g_3,
\]

and the lepton asymmetry \( A_\ell \) by

\[
A_\ell = \frac{\sigma_F(\ell^-) - \sigma_F(\ell^+)}{\sigma_F(\ell^-) + \sigma_F(\ell^+)},
\]

we get the relation with the true \( b \bar{b} \) forward–backward asymmetry,

\[
A_{FB} = \frac{A_\ell}{1 - 2\chi}.
\]

To get \( \chi \), one measures the ratio of like-sign and total dileptons,

\[
R = \frac{N_{++} + N_{--}}{N_{++} + N_{--} + N_{+-} + N_{-+}} = 2\chi(1 - \chi).
\]

Then

\[
A_{FB} = \frac{A_\ell}{\sqrt{1 - 2R}}
\]

and [6]

\[
\sigma^2(A_{FB}) = \frac{1 - A_\ell^2}{N\ell(1 - 2R)} + \frac{R(1 - R)A_{FB}^2}{N\ell(1 - 2R)^2},
\]

where \( N\ell \) is the number of single-lepton tagged events and \( N\ell \) is the number of dilepton tagged events.

The principal background to the high-\( p_T \) lepton tagging procedure results from charm decays, either primary charm from the \( Z \) decay or secondary charm from the decay of the \( B \) states. Of these, secondary charm is expected to form the greater part of the background. Both of these effects reduce the observed asymmetry.

From secondary charm we get

\[
A_{FB} = A_\ell \frac{1 + \delta}{1 - 2\chi - \delta},
\]

\[
R = \frac{2(1 - \chi)(\chi + \delta)}{(1 + \delta)^2},
\]

where \( \delta (\sim 0.1) \) is a correction term depending on the branching ratio of \( b \rightarrow c \) and the relative efficiency of tagging the leptonic decay modes of \( b \) and secondary charm.

When both types of charm backgrounds are considered, and keeping only first-order terms, we get [6]

\[
A_{FB} \simeq A_\ell \left(1 + R + \frac{N_c}{N_b} \epsilon\right) + \frac{N_c}{N_b} A_{FB} \epsilon.
\]

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with $N_c/N_b (= 0.78)$ being the relative number of $c\bar{c}$ to $b\bar{b}$ events, $A_{FB}^{cb}$ the charm asymmetry (73% of $b\bar{b}$ asymmetry), and $\epsilon$ the tagging efficiency for primary charm relative to the $b$ tagging ($\epsilon \sim 0.1$).

The corresponding error on $A_{FB}$ is

$$\sigma^2(A_{FB}) = \left(1 + R + \frac{N_c}{N_b} \epsilon \right)^2 \frac{1 - A^2_1}{N_t} + 2 \frac{R(1 - R)}{N_H} + \frac{[N_c/N_b(A_\epsilon + A_{FB}^{cb})]^2}{\sigma^2(\delta)}$$

With $\chi = 0.12$, with a procedure for tagging 10% of $b\bar{b}$ events via the lepton from the $b$ ($b$) quark, 1% of $b\bar{b}$ events via the lepton from subsequent charm decay and 1% of $c\bar{c}$ events, and with a 20% error assumed in the corrections $\delta$ and $\epsilon$, we get the following errors:

<table>
<thead>
<tr>
<th>Luminosity</th>
<th>No. of $Z$</th>
<th>$\Delta A_{\text{stat}}$ a)</th>
<th>$\Delta A_{\text{syst}}$ b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 pb$^{-1}$</td>
<td>$6 \times 10^6$</td>
<td>$4 \times 10^{-3}$</td>
<td>$2.6 \times 10^{-3}$</td>
</tr>
<tr>
<td>2000 pb$^{-1}$</td>
<td>$60 \times 10^6$</td>
<td>$1.3 \times 10^{-3}$</td>
<td></td>
</tr>
</tbody>
</table>

(a) first two terms and (b) third term of above formula

This sketchy evaluation is quite representative of more elaborate Monte Carlos [8], [9].

The dependence on the lepton $p_T$ cut of $R$ and of the measured asymmetry can be found in Ref. [8]. Using a more elaborate tagging procedure than mere lepton identification, Ref. [9] gives the results of Table 2.5.

We can conclude that mixing does not prevent an excellent accuracy on $A_{FB}^{cb}$ from being reached: the cross-over point is for $\sim 15 \times 10^6 Z$'s.

If the exposure is abundant and if double tagging on opposite-sign leptons is used instead of single tagging, we have seen that mixing plays a role only as a second-order effect. The conclusion is identical, since the first-order effect of mixing can be measured (through like-sign dileptons, with the same cuts) with enough statistics, so that it is possible to correct for the contamination at second order.

### 2.5 Partial widths of the $Z$ into fermions

In the theoretical part we saw that these quantities and their ratios play an important role in the strategies foreseen for detecting and identifying the nature of departures from the Standard Model. The leptonic widths and their ratios to the hadronic width have already been obtained at LEP. They agree with universality at the 5% level. Assuming universality, we find the values shown in Table 2.6.

The arguments already put forward about redundant procedures tell us that from the experimental side the systematic errors are in fact governed by statistics. One million $Z$'s should allow us to decrease the global experimental error for $\mu\mu$ below the 1% level, including normalization, and for $\tau\tau$ the results should not be much worse.

For ee, the major problem is the treatment of the $t$-channel (and interference) contributions.

On the quark side the situation is different. The knowledge of the fragmentation properties will never be accurate enough to allow absolute measurement of widths or branching ratios on the basis of a single tagging or of the global properties of the events. One should use also double-tagging selection and extract the branching ratio $BR$ as
$$\text{BR} = \frac{(N_{b\rightarrow e})^2}{N_{b\rightarrow ee} N_Z} = \frac{[N_{b}^{(1)}]^2}{N_{b}^{(2)} N_Z}$$

a formula from which poorly known quantities disappear.

This has been illustrated for the very rewarding quantity $\Gamma_{bb}$ [10]. Single and double leptonic tagging are used. Backgrounds from charm and from misidentified hadrons are taken into account.

The statistical accuracy, using for electrons and muons the $b$-tagging efficiency already obtained in ALEPH for electrons, will be

$$\left. \frac{\Delta \text{BR}}{\text{BR}} \right|_{\text{stat}} = 0.45\% \sqrt{\frac{10^8}{N_Z}}.$$

The systematic error is due to the uncertainties in the background content (charm, misidentification). It can be expressed as

$$\left. \frac{\Delta \text{BR}}{\text{BR}} \right|_{\text{syst}} = \left\{ \left[ r_c^{(1)} \right]^2 \left[ \frac{2 N_c^{(1)}}{N_b^{(1)}} \right]^2 + \left[ r_{\text{miss}}^{(1)} \right]^2 \left[ \frac{2 N_{\text{miss}}^{(1)}}{N_b^{(1)}} \right]^2 \right. +$$

$$\left. \left[ r_c^{(2)} \right]^2 \left[ \frac{N_c^{(2)}}{N_b^{(2)}} \right]^2 + \left[ r_{\text{miss}}^{(2)} \right]^2 \left[ \frac{N_{\text{miss}}^{(2)}}{N_b^{(2)}} \right]^2 \right\}^{1/2},$$

where $r_c^{1,2}$ and $r_{\text{miss}}^{1,2}$ are the relative errors expected in the knowledge of these backgrounds for single and double tagging. With the numbers already obtained or foreseen for the amount of background, there will be a 1% systematic error in BR if a 2% relative accuracy for a single-tag background and 6% for a double-tag are achieved. With additional selection ($dE/dx$, etc.), the identification background should decrease to quite low values. The knowledge of the $c$ background at the level indicated is realistic since it can be determined by the data themselves, using a single-arm $c$-tagging procedure to measure on the opposite jet the effect of the leptonic tagging.

Another analysis based on a multidimensional procedure [11], in which high-$p_T$ leptons play the most important role, finds similar values for the tagging efficiency as well as for the background dominated by charm and by misidentified hadrons.

On this last point, half of the background rate from light quarks is due to misidentification: it is therefore important to determine the rate of false muons. In particular the punch through of hadrons can be obtained by using reconstructed $K_S^0 \rightarrow \pi^+ \pi^-$. To measure charm background, one can tag $c\bar{c}$ events by reconstructing $D$ and $D^*$ and apply the $b$ selection: this is complicated by the fact that some $b\bar{b}$ are selected as well.

The statistical error is found to be about the same as above:

$$\left. \frac{\Delta \text{BR}}{\text{BR}} \right|_{\text{stat}} \simeq 0.45\% \sqrt{\frac{10^8}{N_Z}}$$

(with single-tag efficiency $\varepsilon_s = 5\%$ per jet, background $b = 13\%$, and double-tag efficiency $\varepsilon_D = \varepsilon_s^2$).

To get a systematic error of 2% one should know the background with an accuracy of 8%, a goal that looks within reach with $25 \times 10^6$ $Z$. 

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The above examples illustrate quite well the interest of very high luminosity. The same
collection will be true each time severe double-arm tagging procedures are required, either
to eliminate insufficiently known quantities or to reach a very high level of purity.

2.6 Implications for the Standard Model

One important feature is the determination of the gain in sensitivity, with respect
to some relevant Standard Model parameters, which would be achieved by the high-
luminosity phase. To derive this in a quick way, rather than giving explicit separate
numerical tables, we follow a simplified procedure. First, we express all the $Z$ peak
asymmetries as functions of the quantity:

$$v \equiv 1 - 4s^2$$  \hspace{1cm} (2.1)

where $s^2$ can be, for our purposes, either the 'starred' quantity defined by Kennedy and
Lynn [12] or the 'barred' one used by Hollik [13]. To a certain approximation [neglecting
e.g. $O(v^2)$ terms] one can then write:

$$A_{FB}^{\mu \tau} \simeq 3v^2$$  \hspace{1cm} (2.2)

$$A_t \simeq 2v$$  \hspace{1cm} (2.3)

$$A_{FB}^{u,c} \simeq \frac{18}{20}v$$  \hspace{1cm} (2.4)

$$A_{FB}^{d,s,b} \simeq \frac{18}{13}v$$  \hspace{1cm} (2.5)

and, correspondingly (in absolute values):

$$\Delta A_{FB}^{\mu \tau} \simeq 6v\delta v = 24v\delta s^2$$  \hspace{1cm} (2.6)

$$\Delta A_t \simeq 2\delta v = 8\delta s^2$$  \hspace{1cm} (2.7)

$$\Delta A_{FB}^{u,c} \simeq \frac{9}{10}\delta v = 3.6\delta s^2$$  \hspace{1cm} (2.8)

$$\Delta A_{FB}^{d,s,b} \simeq \frac{18}{13}\delta v = 5.6\delta s^2$$  \hspace{1cm} (2.9)

showing the various sensitivities of the different asymmetries.

One sees that, for values of $s^2 \simeq 0.23$, $A_{FB}^{\mu \tau}$ is a factor of 2 less sensitive than $A_{FB}^{u,c}$,
a factor of 3 less sensitive than $A_{FB}^{d,s,b}$, and about four times less than $A_t$. In order to
transform the previous equations in more meaningful information, one can introduce the
one-loop correction to the $\rho$ parameter, $\Delta \rho$, exhaustively discussed elsewhere in this report
[14], and its scalar sector counterpart $\Delta Z$, remembering that, with the chosen definition
of $v$, one has to a very good approximation:

$$\delta v \simeq \frac{3}{2} \delta (\Delta \rho - \Delta Z).$$  \hspace{1cm} (2.10)

To a very good approximation one has for $m_t, m_H > m_Z$:

$$\Delta \rho^{(\text{top})} \simeq \frac{\alpha m^2_t}{\pi m^2_Z}, \quad \Delta \rho^{(\text{Higgs})} \simeq -\frac{\alpha}{4\pi} \ln \frac{m^2_H}{m^2_Z} = -\frac{9}{4} \Delta Z^{(\text{Higgs})}.$$  \hspace{1cm} (2.11)
Thus, for a fixed Higgs mass, we shall finally write

$$\Delta A_{\text{FB}}^{\mu,\tau} \simeq 9v\delta(\Delta \rho) \simeq 18v \frac{m_t \delta m_t}{\pi m_Z m_Z}$$  \hspace{1cm} (2.12)$$

$$\Delta A_{\tau} \simeq 3v\delta(\Delta \rho) \simeq 6 \frac{m_t \delta m_t}{\pi m_Z m_Z}$$  \hspace{1cm} (2.13)$$

$$\Delta A_{\text{FB}}^{u,c} \simeq \frac{27}{20} \delta(\Delta \rho) \simeq \frac{27}{10 \pi m_Z m_Z} \frac{m_t \delta m_t}{m_t}$$  \hspace{1cm} (2.14)$$

$$\Delta A_{\text{FB}}^{d,b} \simeq \frac{27}{13} \delta(\Delta \rho) \simeq \frac{54}{13 \pi m_Z m_Z} \frac{m_t \delta m_t}{m_t}$$  \hspace{1cm} (2.15)$$

Consider the b asymmetry. From Eq. (2.15), one can write:

$$\Delta A_{\text{FB}}^{d,b} \simeq (0.0002) \left( \frac{m_t}{150 \text{GeV}} \right) \left( \frac{\delta m_t}{1 \text{GeV}} \right).$$  \hspace{1cm} (2.16)$$

Adding the small uncertainty caused by a variation of $m_H$ from 100 to 1000 GeV, in a normal LEP phase, with a total error of $\pm 0.0055$ on $A_{\text{FB}}^b$, one obtains a sensitivity of $\pm 27$ (20) GeV on $m_t$, while in the high-luminosity phase an error of $\pm 0.003$ on $A_{\text{FB}}^b$ would lead to $\pm 15$ (11) GeV on $m_t$, for $m_t \simeq 150$ (200) GeV.

Conversely, if the top were found, one could consider the sensitivity with respect to $m_H$. From numerical estimates [15] and Table 2.7, or from Eqs. (2.11), one obtains

$$\Delta A_{\text{FB}}^{d,b} \simeq (0.00001) \left( \frac{300 \text{GeV}}{m_H} \right) \left( \frac{\delta m_H}{1 \text{GeV}} \right).$$

Assuming no error on $m_t$, $\pm 5$ GeV, and $\pm 10$ GeV error on $m_t$, with $\Delta A_{\text{FB}}^b = \pm 0.003$, one obtains $\delta m_H \simeq 300, 320,$ and 360 GeV, respectively.

It could thus be concluded that, with $\Delta A_{\text{FB}}^b \simeq 0.003$ one could at least check whether $m_H$ falls inside this range or if an extra (possibly non-standard [16]) contribution is required.

An analogous analysis can easily be performed for the other asymmetries. Taking into account either the smaller sensitivity of/and the worse experimental accuracy, it is easy to realize that the best quantity to be measured appears, by far, the b charge asymmetry. For example from $A_{\mu,\tau}$ with an error of $\pm 0.008$ one only reaches a sensitivity at least as large as 55 GeV on $m_t$ (for $m_t \geq m_Z$).

The previous analysis can easily be repeated for the partial Z widths. In general, these are less sensitive to $\Delta \rho$ than the considered asymmetries. Using the previous approximations, it is actually easy to see that:

$$\frac{\Delta \Gamma_{\mu,\tau}}{\Gamma_{\mu,\tau}} \simeq \delta(\Delta \rho)$$  \hspace{1cm} (2.17)$$

$$\frac{\Delta \Gamma_{u,c}}{\Gamma_{u,c}} \simeq \frac{8}{5} \delta(\Delta \rho)$$  \hspace{1cm} (2.18)$$
\[
\frac{\Delta \Gamma_{d,s}}{\Gamma_{d,s}} \simeq \frac{19}{13} \delta(\Delta \rho)
\]  

which shows that, even with a one per cent relative accuracy, they would be in this respect much less interesting than \( A_{FB}^b \). This (negative) statement only applies, though, within the Standard Model. When searches of direct and/or virtual effects of New Physics are considered, the situation becomes rather different and the potential information provided by the various widths and, in particular, by the ratio \( R' = \Gamma^{had}/\Gamma^\nu \) becomes much more interesting, as will be shown in the next sections. This positive remark applies in particular to the partial width of \( Z \) into \( b\bar{b} \), whose special virtues will also be examined in great detail in this report.

2.7 Neutrino counting by the radiative method

If it is felt that the counting of light neutrinos performed with the invisible width method should be checked or improved by the radiative method: high luminosity can bring much to such a measurement.

An abundant rate indeed allows us to choose the most favourable conditions to decrease the systematic errors.

One can sit at higher \( \sqrt{s} \) and select higher-energy photons at larger angles, therefore photons of higher \( p_T \). Above some \( p_T^{\min} \), the process becomes virtually background-free, since radiative Bhabhas cannot give such photons without getting visible in the forward luminometers.

The highest \( \gamma \) energy also allows a better quality of trigger and of measurement in the electromagnetic calorimeters.

Normalization through the small-angle tagger and the forward electromagnetic calorimeters should be obtained at the per cent level without problem.

From the theoretical side the knowledge of the expected cross-section seems to be safe within \( \sim 2\% \).

An exposure of 100 pb\(^{-1}\) (i.e. two weeks of pretzel LEP, at \( \sqrt{s} \sim 96-98 \) GeV) should give at least 2500 events (2\% statistical error). The measurement provides a peak in \( E_\gamma \) to be fitted. Photons being above 2–3 GeV, systematic errors (loss of \( \gamma \), non-linearities, ...) are likely to be kept below the statistical error. One can guess that \( \Delta N_\nu/N_\nu \) can be obtained with an overall error in the vicinity of \( \sim 3\% \).

The experimental implications are on the small-angle \( e^\pm \) tag and the quality of the \( \gamma \) detection. We assume that LEP experiments will at that time be equipped with a small-angle tagger covering the angular domain above \( \sim 25 \) mrad (as L3 is now). It is also likely that the barrel e.m. calorimeters will then be well understood, for instance through a systematic study of \( \pi^0/\eta \).
References


[9] P. Roudeau, as in Ref. [6].

[10] A. Roussarie, ALEPH Note contributed to this workshop.


[14] A. Djouadi et al., Section 4 of this part of the present report.

[15] We thank W. Hollik for providing us with this Table, see also Ref. [13].

[16] See e.g. G. Gounaris, F.M. Renard and D. Schildknecht, Bielefeld preprint (1989), and the various New Physics effects discussed in Sections 3 and 4 of this part of the present report.
Table 2.1

Typical conditions for obtaining $\Delta \sin^2 \theta = \pm 0.0003$ (experimental error) from $A_{\text{LR}}$ measurement. $L_{i,j}$ are luminosities registered with different spin configurations.

- Integrated luminosity: $\int L \, dt = 50 \, \text{pb}^{-1}$
- Polarization: $P \approx 50\%$
- Uncertainty on $P$: $\Delta P/P = 1\%$
- Rate of Bhabha events: $4 \times$ rate of $Z$ events
- Relative error on luminosity: $\Delta (L_i/L_j)_{\text{syst.}} = 1.5\%$

Table 2.2

Accuracy on $\sin^2 \theta_w$ from $A_{\text{ch}}^{\mu}$ (for 1000 pb$^{-1}$)

<table>
<thead>
<tr>
<th>Error</th>
<th>$\Delta A$ (%)</th>
<th>$\Delta \sin^2 \theta_w$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistical</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>Systematic:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta m_Z = \pm 10 , \text{MeV}/c^2$</td>
<td>0.08</td>
<td></td>
</tr>
<tr>
<td>Detection efficiency</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>QED radiative correction</td>
<td>0.12</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>0.21</td>
<td>0.0010</td>
</tr>
</tbody>
</table>

Table 2.3

Accuracy on $\sin^2 \theta_w$ from $P_{\tau}$ ($\tau \rightarrow \pi \nu$ channel only) (for 1000 pb$^{-1}$)

<table>
<thead>
<tr>
<th>Error</th>
<th>$\Delta P$ (%)</th>
<th>$\Delta \sin^2 \theta_w$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistical</td>
<td>0.4</td>
<td>0.0005</td>
</tr>
<tr>
<td>Systematic:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\rho \nu$ channel</td>
<td>0.65</td>
<td>0.0008</td>
</tr>
<tr>
<td>+ radiative corrections</td>
<td></td>
<td></td>
</tr>
<tr>
<td>+ ...</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>0.8</td>
<td>0.00095</td>
</tr>
</tbody>
</table>
Table 2.4a

Accuracy on $\sin^2 \theta_w$ from quark asymmetries $A_{ch}^{q\bar{q}}$ ($25 \times 10^6$ Z)

<table>
<thead>
<tr>
<th>Type of quark</th>
<th>b</th>
<th>c</th>
<th>c  (π of $D^*$)</th>
<th>s</th>
<th>u</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency of tagging</td>
<td>0.11</td>
<td>0.04</td>
<td>0.15</td>
<td>0.05</td>
<td>0.02</td>
</tr>
<tr>
<td>Stat. error on $A_{ch}$</td>
<td>0.0014</td>
<td>0.0026</td>
<td>0.0030</td>
<td>0.002</td>
<td>0.0036</td>
</tr>
<tr>
<td>Syst. error on $A_{ch}$</td>
<td>0.0028</td>
<td>0.0034</td>
<td>&gt; 0.0021</td>
<td>0.004</td>
<td>0.004</td>
</tr>
<tr>
<td>$\Delta \sin^2 \theta_w$</td>
<td>0.00065</td>
<td>0.0011</td>
<td>&gt; 0.00080</td>
<td>0.0008</td>
<td>0.0011</td>
</tr>
</tbody>
</table>

a) Signal/background = 1/5.
b) Without mixing.

Table 2.4b

Estimated error contribution to b and c charge asymmetry

<table>
<thead>
<tr>
<th>Source of error</th>
<th>b b</th>
<th>c c</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flavour tagging</td>
<td>0.0020</td>
<td>0.0030</td>
</tr>
<tr>
<td>Beam setting</td>
<td>0.0004</td>
<td>0.0006</td>
</tr>
<tr>
<td>Detector (DELPHI)</td>
<td>0.0002</td>
<td>0.0005</td>
</tr>
<tr>
<td>QED</td>
<td>0.0002</td>
<td>0.0002</td>
</tr>
<tr>
<td>QCD</td>
<td>0.0016</td>
<td>0.0013</td>
</tr>
<tr>
<td>Total systematic</td>
<td>0.0026</td>
<td>0.0034</td>
</tr>
<tr>
<td>Statistical error</td>
<td>0.0035</td>
<td>0.0070</td>
</tr>
</tbody>
</table>

Table 2.5

Errors on the b b asymmetry $A_{ch}^{bb}$ with mixing for two luminosities

<table>
<thead>
<tr>
<th>L (pb$^{-1}$)</th>
<th>200</th>
<th>2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Genuine systematic error</td>
<td>0.0028</td>
<td>0.0028 a)</td>
</tr>
<tr>
<td>Statistical error (including the effect of mixing)</td>
<td>0.0045</td>
<td>0.0014</td>
</tr>
<tr>
<td>Total</td>
<td>0.0053</td>
<td>0.0031</td>
</tr>
</tbody>
</table>

a) Should be smaller in principle, since harder cuts are possible with high L.
Table 2.6

Leptonic widths from the LEP experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>ALEPH</th>
<th>DELPHI</th>
<th>L3</th>
<th>OPAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma_{\text{lep}}$ (MeV)*</td>
<td>83.9 ± 2.2</td>
<td>83.6 ± 2.9</td>
<td>83.0 ± 2.1 ± 1.1</td>
<td>81.9 ± 2.0</td>
</tr>
</tbody>
</table>

*) Universality assumed.

Table 2.7

Values of $A_{FB}^b$ according to $m_t$ and $m_H$

<table>
<thead>
<tr>
<th>$m_t$</th>
<th>$m_H$</th>
<th>100</th>
<th>1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>0.0895</td>
<td>0.0825</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>0.0895</td>
<td>0.0850</td>
<td></td>
</tr>
<tr>
<td>150</td>
<td>0.0996</td>
<td>0.0929</td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>0.1094</td>
<td>0.1029</td>
<td></td>
</tr>
<tr>
<td>230</td>
<td>0.1163</td>
<td>0.1100</td>
<td></td>
</tr>
<tr>
<td>250</td>
<td>0.1212</td>
<td>0.1150</td>
<td></td>
</tr>
</tbody>
</table>
3 HIGGS AND NEW PHYSICS

F. Boudjema, R. Casalbuoni, P. Chiappetta, D. Cocolicchio, M. Dittmar, F. Feruglio, B. Gavela\textsuperscript{1}, R. Kleiss, S. Moubbarik, G. Ridolfi, J.W.F. Valle, F. Zwirner\textsuperscript{2}

3.1 Higgs

P. Chiappetta

The minimal version of the standard model is based on mass generation through the Higgs mechanism [1]. This mechanism of spontaneous symmetry breaking leads to the existence of a physical spin-0 particle, H, which has not yet been discovered and whose mass is unknown. Therefore standard Higgs search is one of the major prospects for LEP.

Low-energy supersymmetry is an attractive possibility to get rid of large radiative corrections to the Higgs potential which destabilize the Higgs mass, i.e. to solve the so-called hierarchy problem. In the minimal supersymmetric extension of the standard model, to be also considered below, one has a more complicated Higgs structure involving two SU(2) doublets. After symmetry breaking, one is left with five physical degrees of freedom: two of them (H\textsubscript{1} and H\textsubscript{2}) are neutral scalars, one (H\textsubscript{3}) is a neutral pseudoscalar, and the remaining two form a charged Higgs boson (H\pm). Since m\textsubscript{H\textsubscript{1}} > m\textsubscript{Z} and m\textsubscript{H\pm} > m\textsubscript{W}, we are interested here in H\textsubscript{2}, which must be lighter than the Z, and H\textsubscript{3}, which may be lighter than the Z. Further details can be found in Ref. [2].

3.1.1 Standard Higgs

The 1989 LEP run has already ruled out a standard model Higgs with mass less than about 25 GeV [3]. The present limit is 41.6 GeV. At the Z peak, assuming an integrated luminosity corresponding to 10\textsuperscript{7} Z events, the most far-reaching channel for the Higgs boson search is Z → H\ell\pm\ell\mp (\ell = e, \mu). Taking 10 H\mu\pm\mu\mp events per year as a plausible discovery limit, one can reach m\textsubscript{H} = 55 GeV [4]. Starting from 10\textsuperscript{8} Z events, 10 H\mu\pm\mu\mp events would correspond to m\textsubscript{H} ~ 65 GeV. The main background is Z decaying into q\ovline{q}μ\pmμ\mp. As can be inferred from [5], for m\textsubscript{H} = 60 GeV the Higgs signal from invariant distribution of muon pairs exceeds the background Z → b\ovline{b}μ\pmμ\mp but not Z → q\ovline{q}μ\pmμ\mp, where a summation over all possible quarks has been performed. Therefore one needs an efficient b-tagging to reach the limit of 60 GeV. As shown\textsuperscript{3} in Fig. 3.1, for m\textsubscript{H} > 60 GeV the decay rate for Z → H\gamma becomes larger than the one for Z → H\ell\pm\ell\mp. Therefore with 10\textsuperscript{8} Z bosons one should also consider the decay Z → H\gamma in order to get the most stringent limits reachable at the Z peak. Asking for 10 events per year, corresponding to Γ(Z → H\gamma)/Γ(Z → μ\pmμ\mp) = 3 × 10\textsuperscript{-6}, one could reach m\textsubscript{H} ~ 70 GeV. However, for this channel one has to deal with a severe background from quark final-state radiation. Recent measurements of the final-state radiation in hadronic Z decays [6] show good agreement between the data and the QED calculations. Extrapolating the results for photons of energy between 20 and 40 GeV, in a sample of 10\textsuperscript{8} Z decays one would expect about 10\textsuperscript{3} events/GeV. As an example, one can compare this number with the 30 Z → H\gamma

\textsuperscript{1}Convener
\textsuperscript{2}Convener
\textsuperscript{3}Our curves are not corrected for initial-state radiation, but can be easily rescaled as shown in [4].
events expected for $m_H = 60$ GeV, with H decaying mainly into $b\bar{b}$ jets and almost monochromatic photons. A resolution of 1–3 % for the photon energy would leave a signal of at most 30 events, to be compared with a background of about 1000. Even a very good identification of $b$-events would still leave a considerable background. We thus conclude that the observation of the Higgs in this channel would be very problematic.

If a spin-0 particle has previously been found, the high luminosity option will be helpful when measuring the Higgs decay rates into fermions and $H \to gg$. The branching ratios into tau pairs and charmed quarks, of roughly 10% [4], can be observable if $m_H < 50$ GeV, whereas a measurement of $H \to gg$ is reachable if $m_H < 40$ GeV.

We have now to compare with LEP 200 expectations. At $\sqrt{s} = 200$ GeV the Bjorken process $e^+e^- \to HZ$ is well suited for the Higgs search. Asking for an integrated luminosity of 500 pb$^{-1}$ one gets significant signals up to $m_H \sim 80$ GeV with the decays $H \to b\bar{b}$ and $Z \to \nu\bar{\nu}, e^+e^-, \mu^+\mu^-$ [7]. As far as Higgs masses between $m_W$ and $m_Z$ are concerned, without $b$-identification the LEP 200 luminosity would not be enough for discovery, even after taking advantage of the different lepton angular distributions for the signal and the $ZZ$ background [8]. However, an efficient tagging of the $b\bar{b}$ final state seems feasible with microvertex detectors. The study in Ref. [9] suggests that even for $m_H \sim m_Z$ it could be possible to obtain about 55 identified $b\bar{b}$ events with $\nu\bar{\nu}, e^+e^-, \mu^+\mu^-, \tau^+\tau^-$, with an approximately 1:1 signal-to-background ratio, but more detailed investigations are needed. In this case, of course, it would be crucial to reach the maximum LEP 200 energy ($\sqrt{s} \sim 200$ GeV) with the maximum possible luminosity. In any case, LEP 200 is more suitable for the standard Higgs search.

### 3.1.2 Supersymmetric Higgs

Only two parameters are needed to completely specify the Higgs sector of the minimal supersymmetric model: for example, the ratio $\tan \beta = v_2/v_1$ of the vacuum expectation values of the two Higgs doublets, and a Higgs mass $m_{H_2}$ or $m_{H_3}$. Since the top quark is much heavier than the bottom, one expects from the theory that $\tan \beta > 1$. In the search for supersymmetric Higgses, two production processes have to be considered: the Bjorken one ($e^+e^- \to H_2f\bar{f}$) and the associated one ($e^+e^- \to H_2H_3$). For $\tan \beta > 1$ and in the mass range of interest to us, the dominant decay channels are $H_2 \to b\bar{b}$ (>90%) and $H_3 \to b\bar{b}$ (>90%). For both $H_2$ and $H_3$, the branching ratio into $\tau^+\tau^-$ lies between 5% and 8% (we refer the reader to [4] for more details). The present limits from LEP are given in Ref. [10]: for $\tan \beta > 1$, $m_{H_1} > 20$ GeV and $m_{H_2} > 38$ GeV are already excluded at 95% CL. We now discuss the discovery limits on the Z peak, using as representative values $\tan \beta = 2, 5, 10, 20$. Assuming $10^7$ Z events ($10^8$ Z events), asking for 10 events per year one can probe cross-sections of $4 \times 10^{-2}$ pb ($4 \times 10^{-3}$ pb). The present limits from $Z \to H_2H_3$ are not going to improve significantly with more statistics, since in the region of parameter space where the Bjorken process is more strongly suppressed they are already very close to the kinematical limit. We will therefore focus on the Bjorken process. As shown in Fig. 3.2, for $\tan \beta = 2$ one can exclude $H_2$ in its full range from the clean $Z \to H_2\mu^+\mu^-$ channel, without need for high luminosity. As we will see, high luminosity becomes more important for higher $\tan \beta$ values. The best ones are obtained

---

4 We remind the reader that, for any given value of $\tan \beta$, $m_{H_2}$ is bounded by $m_{H_2} \leq |\cos 2\beta| m_Z$ without the radiative corrections due to heavy top.
for $Z \rightarrow H_2\nu\bar{\nu} \rightarrow b\bar{b}\nu\bar{\nu}$. For $\tan \beta = 5$ $H_2$ masses can be excluded up to 75 GeV instead of 60 GeV with normal luminosity (see Fig. 3.3). For $\tan \beta = 10$, as can be seen from inspection of Fig. 3.4, a scalar Higgs $H_2$ lighter than 70 GeV (instead of 45 GeV) can be ruled out.

We will now compare these limits with LEP 200 expectations. Asking for 10 events per year, a cross-section of $2 \times 10^{-2}$ pb can be reached assuming an integrated luminosity of 500 pb$^{-1}$ and $1.25 \times 10^{-2}$ pb for 800 pb$^{-1}$, as expected with the Pretzel scheme at $\sqrt{s} = 190$ GeV. However, in considering the two processes $e^+e^- \rightarrow H_2Z$ and $e^+e^- \rightarrow H_2H_3$ at $\sqrt{s} = 190$ GeV, one should take into account the backgrounds from QCD and from WW or ZZ production. For the process $e^+e^- \rightarrow H_2Z$, with $H_2 \rightarrow b\bar{b}$ and $Z \rightarrow \nu\bar{\nu}, e^+e^-, \mu^+\mu^-, \tau^+\tau^-$, with an excellent b-tagging, one expects to be able to be sensitive to cross-sections larger than 0.11 pb, corresponding to $m_{H_2} = 60$ GeV for $\tan \beta = 5$, whereas for $\tan \beta = 10$ the Bjorken process is too strongly suppressed to give a detectable signal. On the other hand, $e^+e^- \rightarrow H_2H_3$ with $H_2 \rightarrow b\bar{b}$, $H_3 \rightarrow b\bar{b}$ could be detected, again with excellent b-tagging, for cross-sections larger than $2.7 \times 10^{-2}$ pb, corresponding to $m_{H_2} = 65$ GeV for $\tan \beta = 5$ (see Fig. 3.5) and $m_{H_2} = 75$ GeV for $\tan \beta = 10$ (see Fig. 3.6). It could be more convenient to perform this search at $\sqrt{s} = 160$ GeV, just below the WW threshold. Here a detectable cross-section of 0.1 pb would correspond to $m_{H_2} = 55$ GeV for $\tan \beta = 5$, to $m_{H_2} = 60$ GeV for $\tan \beta = 10$.

It is clear from the previous considerations that large values of $\tan \beta$ are the most problematic for SUSY Higgs detection over the full allowed mass range at LEP. The phenomenology of SUSY Higgses at LEP has been recently studied in Ref. [11], with results similar to ours without considering background. It has also been suggested [12] that for $\tan \beta \gg 1$ an alternative mechanism for Higgs production at the Z peak ($Z$ decay into $b\bar{b}$ followed by $H_2$ or $H_3$ radiation from one of the $b$ legs) could be the dominant one. The lightest supersymmetric Higgs can be discovered in its full kinematical range (i.e. $m_{H_2} < m_Z$) also for large $\tan \beta$ values by considering the process $e^+e^- \rightarrow H_2Z$ with $H_2 \rightarrow b\bar{b}$ and $Z \rightarrow q\bar{q}$. With an excellent b-tagging and a good $Z$ mass reconstruction a luminosity of 500 pb$^{-1}$ is required at $\sqrt{s} = 190$ GeV. In fact this statement ignores possible large radiative-correction effects due to a heavy top on the mass of this lightest Higgs. Therefore it may turn out that a slightly higher energy will be required in order to obtain a complete exclusion.

### 3.1.3 Conclusions

Although high luminosity at the $Z$ peak would improve the mass limits from $Z \rightarrow HZ^*$, it cannot compete with LEP 200, which should be able to exclude a standard Higgs up to $m_H \sim m_W$ and might be able to reach $m_H \sim m_Z$. For supersymmetric Higgses, LEP 200 might be able to exclude the lightest supersymmetric Higgs in the full mass range allowed by theory, also for large values of $\tan \beta$.

### 3.2 Supersymmetry

*G. Ridolfi, F. Zwirner*

The idea of low-energy supersymmetry, motivated by the hierarchy problem, predicts a plethora of new particles with masses close to the electroweak scale. Its simplest
realization is the Minimal Supersymmetric Standard Model [13] (MSSM), with an exact multiplicatively conserved \( R \)-parity: \( R = 1 \) for quarks, leptons, gauge and Higgs bosons, \( R = -1 \) for their supersymmetric partners. In this section we discuss the impact on supersymmetry searches of an increased LEP luminosity at the \( Z \) peak. Supersymmetric Higgs bosons are discussed in section 3.1.2, thus we consider only strictly-supersymmetric particles \( (R = -1) \) and we divide them for convenience into three groups: 1) strongly interacting sparticles; 2) weakly interacting spin-0 sparticles; 3) weakly interacting spin-\( \frac{1}{2} \) sparticles. The signatures of supersymmetry depend crucially on the nature of the lightest supersymmetric particle (LSP): in the following we assume, unless otherwise stated, that the LSP is a neutral spin-\( \frac{1}{2} \) particle \( (\tilde{\chi}) \), as favoured by model calculations.

3.2.1 Strongly interacting sparticles

They include gluinos (\( \tilde{g} \)) and six flavours of 'left' and 'right' squarks \( (q \equiv \{\tilde{u}_L, \tilde{u}_R, \tilde{d}_L, \ldots\}) \). In general, these particles are better searched at hadron colliders. The present limits from the CERN \( p\bar{p} \) Collider and the Tevatron [14] confine squarks and gluinos to a mass region well beyond the reach of LEP, but they are derived assuming, among other things, five or six degenerate (left and right) squark flavours. One notable exception is the case of a light scalar partner of the top quark [15,16]. Whilst left–right mixing can be neglected for the first five squark flavours, which are expected to be approximately degenerate in mass, the stop mass matrix contains a potentially large off-diagonal term, proportional to the top-quark mass. It is quite possible that the lighter stop eigenstate,

\[
\tilde{t}_1 = \cos \theta_{t} \, \tilde{t}_L + \sin \theta_{t} \, \tilde{t}_R,
\]

is significantly lighter than the top quark and the remaining squarks. In this case, the \( p\bar{p} \) Collider limits of Ref. [14] do not apply to \( \tilde{t}_1 \). Low-energy \( e^+e^- \) data require \( m_{\tilde{t}_1} > 25 \text{ GeV} \), so \( Z \to \tilde{t}_1\tilde{t}_1 \) decays might be kinematically allowed. The corresponding partial width is, neglecting QCD corrections and defining \( \beta_{t_1} \equiv (1 - 4m_{\tilde{t}_1}^2/m_Z^2)^{1/2} \):

\[
\frac{\Gamma(Z \to \tilde{t}_1\tilde{t}_1)}{\Gamma(Z \to \nu\bar{\nu})} = 6 \left( \frac{\cos^2 \theta_{t}}{2} - \frac{2}{3} \sin^2 \theta_{W} \right)^2 \beta_{t_1}^3.
\]

Model calculations [16] show that the preferred values of \( \cos^2 \theta_{t} \) are between 0.4 and 0.5, so that \( \Gamma(Z \to \tilde{t}_1\tilde{t}_1) \leq 5-6 \text{ MeV} \cdot \beta_{t_1}^3 \), making this a relatively rare decay. The possible decay channels for such a light \( \tilde{t}_1 \) are the two-body mode \( \tilde{t}_1 \to c\tilde{\chi} \) and the four-body mode \( \tilde{t}_1 \to bff\tilde{\chi} \), with relative rates depending on the model parameters. The two-body mode would give rise to acoplanar jets plus missing \( p_T \), as for ordinary squarks. In the four-body mode, the \( ff \) pair has the quantum numbers of a \( W^+ \), and one would expect a \( \ell^+\nu \) pair of any given flavour roughly 10\% of the times. High statistics can certainly help in searching for a light \( \tilde{t}_1 \) in \( Z^0 \) decays. However, it would be more convenient to move away from the \( Z^0 \) peak, where the photon-exchange diagram considerably enhances the fraction of the total number of events corresponding to stop pair production.

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3.2.2 Weakly interacting spin-0 particles

They include sneutrinos ($\tilde{\nu} \equiv \{\tilde{\nu}_e, \tilde{\nu}_\mu, \tilde{\nu}_\tau\}$) and charged sleptons ($\tilde{\ell} \equiv \{\tilde{e}_L, \tilde{e}_R, \tilde{\mu}_L, \ldots\}$). All these particles have relatively large couplings to the Z. Neglecting $\ell_L-\ell_R$ mixing, as suggested by model calculations, and defining $\tilde{\ell} = \tilde{\nu}, \tilde{\ell}_L, \tilde{\ell}_R$, one has

$$\frac{\Gamma(Z \to \tilde{\ell}\tilde{\ell})}{\Gamma(Z \to \nu\bar{\nu})} = 2 \left( T_{3L}^\ell - Q^\ell \sin^2 \theta_W \right)^2 \beta_\ell^3.$$ (3.3)

In the presently allowed region of parameter space, sneutrinos are stable or decay invisibly most of the times [16], thus contributing to the invisible Z width if $m_{\tilde{\nu}} < m_Z/2$. From the model-independent fits to the Z line shape obtained from the 1989 LEP data [17] (corresponding to roughly $10^5$ Z decays), one deduces $(\Delta \Gamma_{\text{inv}}/\Gamma_{\nu\bar{\nu}}) < 0.2$ at 95% CL. This corresponds to $m_{\tilde{\nu}} > 39.2$ GeV in the case of three degenerate sneutrino species (suggested by model calculations), and to $m_{\tilde{\nu}} > 30.8$ GeV in the case of only one light s-neutrino species. A more precise measurement of the invisible Z width should be obtained by the ‘neutrino-counting’ experiment, performed a few GeV above the Z peak and looking for $e^+e^- \to \gamma + \text{invisible neutrals}$. It is clear that an increase in luminosity would be quite profitable for such an experiment [9]. For example, a sensitivity $(\Delta \Gamma_{\text{inv}}/\Gamma_{\nu\bar{\nu}}) < 0.1$ would correspond to $m_{\tilde{\nu}} > 41.7$ GeV and $m_{\tilde{\nu}} > 37.0$ GeV in the two cases considered before.

Charged sleptons have already been searched in the 1989 LEP data [18], considering the decay modes $\tilde{\ell}^\pm \to \ell^\pm \tilde{\chi}$ and looking for acoplanar lepton pairs with large missing $p_T$. The four LEP experiments are able to exclude regions of the $(m_{\tilde{\ell}_L,R}, m_{\tilde{\chi}})$ plane which are already very close to the kinematical limit for Z decays. Higher statistics would improve these limits only marginally. On the other hand, previous studies [19] indicate that at LEP 200 energies the experiments should be sensitive to charged slepton masses at least up to 75–80 GeV, provided that the LSP is sufficiently lighter than the charged slepton and that direct decays into the LSP are dominant.

3.2.3 Weakly interacting spin-$\frac{1}{2}$ particles

They include the charged ($\tilde{W}^\pm, \tilde{H}^\pm$) and neutral ($\tilde{\chi}, \tilde{Z}, \tilde{H}_0^0, \tilde{H}_0^0$) fermionic partners of the SU(2) × U(1) gauge bosons and of the Higgs bosons, usually called charginos and neutralinos. Their mixing is described by a $2 \times 2$ and by a $4 \times 4$ mass matrix, respectively, and the corresponding mass eigenstates are denoted by $(\tilde{\chi}_i^\pm, \tilde{\chi}_i^0)$ and by $(\tilde{\chi}_i^0, \tilde{\chi}_i', \tilde{\chi}_i'', \tilde{\chi}_i'''')$, in order of increasing mass. In the MSSM, all chargino and neutralino masses and couplings can be described in terms of only three parameters: the SU(2) gaugino mass $M_2$, the Higgs mixing parameter $\mu$, and the ratio of vacuum expectation values $v_2/v_1 \equiv \tan \beta$. The above parameters govern a variety of possible Z decays into spin-$\frac{1}{2}$ sparticles, the most important of which are $Z \to \tilde{\chi}_i^+ \tilde{\chi}_i^-$, $Z \to \tilde{\chi}_i^0 \tilde{\chi}_i^0$, and $Z \to \tilde{\chi}_i^0 \tilde{\chi}_i^0$. Z decays into chargino pairs, followed by $\tilde{\chi}_i^\pm \to \ell^{\pm} \nu \tilde{\chi}$ or $q\bar{q}^{\ell} \tilde{\chi}$, would give rise to acoplanar leptons and/or jets plus missing $p_T$. Since the couplings of charginos to the Z are always large, even with the 1989 data sample the LEP experiments are able to put bounds in the $(m_{\tilde{\chi}_i^\pm}, m_{\tilde{\chi}_i^0})$ plane which are very close to the kinematical limit [18]. On the other hand, Z decays into pairs of LSP could naturally have small branching ratios, and would contribute to the invisible Z width for a small fraction of a neutrino species. Also decays of the type $Z \to \tilde{\chi}' \tilde{\chi}'$ could naturally have small branching ratios: in this case, the subsequent decay $\tilde{\chi}' \to f\bar{f} \tilde{\chi}$ would give rise to spectacular one-sided events, sometimes called ‘zen’ events.
[20], with all the visible energy concentrated in one hemisphere. Unsuccessful searches for $Z \to \tilde{\chi} \tilde{\chi}'$ decays in the 1989 LEP data have already been reported [21]. It is then important to understand if the presently allowed region of parameter space leaves room for the decays $Z \to \tilde{\chi} \tilde{\chi}'$ and $Z \to \tilde{\chi} \tilde{\chi}'$, for which the high-luminosity option could help. Such an issue is conveniently discussed in the $(\mu, M_2)$ plane for given values of $v_2/v_1$. As representative values, suggested by model calculations, we choose $v_2/v_1 = \sqrt{2}, 2, 4$. Higher values of $v_2/v_1$ are also possible, but the qualitative features do not change with respect to the case $v_2/v_1 = 4$. Our conclusions are summarized in Fig. 3.7, which updates the results of Ref. [22]. The lower solid lines delimit the region of the $(\mu, M_2)$ plane already excluded by the present experimental data [2, 5, 7, 10]. The upper solid lines delimit the region which is kinematically accessible to $Z$ decays into spin-$\frac{1}{2}$ sparticles. Further chargino searches and more precise measurements of the total $Z$ width cannot extend significantly the excluded region [22]. On the other hand, a precise neutrino-counting experiment and further dedicated searches for one-sided events can still probe virgin land in parameter space. In Fig. 3.7, dotted lines correspond to $\Delta \Gamma_{\text{inv}}/\Gamma_{\text{tot}} = 0.1$ and dashed lines correspond to $\text{BR}(Z \to \tilde{\chi} \tilde{\chi}') = 10^{-5}$. To assess the significance of this result, it is useful to see which region of parameter space could be explored at LEP 200 energies. The most powerful tool will be given by chargino searches, which should easily exclude chargino masses up to 75–80 GeV. The dashed lines in Fig. 3.8 show contours of chargino masses in the $(\mu, M_2)$ plane, for the same values of $v_2/v_1$ as used in Fig. 3.7. To make the comparison easier, the solid lines of Fig. 3.7 corresponding to the kinematical limit $m_{\tilde{\chi}} = m_Z/2$ are repeated in Fig. 3.8: it is once again evident that high energy pays more than higher luminosity at the $Z$ peak.

### 3.2.4 Conclusions

Since the couplings of supersymmetric particles to the $Z$ are combinations of tree-level gauge couplings, supersymmetric $Z$ decays can usually have small branching ratios only for kinematical reasons. Therefore, higher luminosity at the $Z$ peak would not improve significantly the sensitivity attainable with the planned LEP luminosity. Possible exceptions are $Z$ decays into stop or neutralino pairs, but in both cases going to higher energies (with sufficient luminosity!) would be a more effective search strategy than running at the $Z$ peak with higher luminosity.

### 3.3 Compositeness

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The basic idea that quarks, leptons, Higgs, and massive vector bosons may be composite was introduced to solve the hierarchy problem and also the generation puzzle. Concerning the second problem, i.e. the understanding of number of generations and lepton and quark masses, the main difficulty is to reconcile the mass range of leptons and quarks with the compositeness scale in the TeV region. Since there is, as yet, no satisfactory model that reproduces the spectrum, we will perform a pure phenomenological analysis of possible manifestations at LEP and study the improvements [23] made possible by the high-luminosity option. We will consider an increase of luminosity of a factor of 10 at the $Z$ peak and of a factor of 2 at LEP 200 energy. This section will be divided into two
3.3.1 Non-standard decay modes at the Z peak

If nearby compositeness is present, i.e. at a scale $\Lambda$ of the order of the Fermi scale ($v \sim 250$ GeV), rare decay modes of the Z can be strongly enhanced. We will take as a guideline the Strongly Coupled Standard Model (hereafter denoted SCSM) [37]. The main idea of the SCSM is to build the Lagrangian of the Standard Model in a confining phase where SU(2) is not spontaneously broken. The confinement scale where the SU(2) gauge coupling constant becomes large is of the order of $v$. The most striking enhancement occurs for the decay $Z \rightarrow H\gamma$ since it is not due to a loop diagram as in the standard model. The decay reads:

$$\Gamma(Z \rightarrow H\gamma) = \frac{\alpha}{96} \left( k_1^2 + k_2^2 \right) \left( \frac{m_Z}{\Lambda} \right)^2 m_Z \left( 1 - \frac{m_H^2}{m_Z^2} \right)^3 .$$ (3.4)

The couplings $k_1$ and $k_2$ are chosen such that $k_1^2 + k_2^2 = 1$. We give in Fig. 3.9 the cross-section $\sigma(Z \rightarrow H\gamma)$ as a function of the Higgs mass for several values of $\Lambda/m_Z$. Asking for a signal twice larger than the standard model prediction and 10 events for LEP with the Pretzel scheme one can reach the scale $\Lambda = 50m_Z$ up to $m_H = 75$ GeV. For large Higgs masses one has to deal with a severe background from quark final-state radiation in ordinary hadronic decays, as discussed in section 3.1.1. Therefore a limit $\Lambda \sim 10m_Z$ looks more realistic. The process $Z \rightarrow \nu\bar{\nu}\gamma$, which is a priori enhanced since it does not occur via the one-loop diagram, is less interesting since the partial width is proportional to $\Lambda^{-4}$, therefore allowing only to reach the limit $\Lambda \sim 5m_Z$. The process $Z \rightarrow H\nu\bar{\nu}$ leads to cross-sections smaller than expected in the standard model. Let us stress that these results have been obtained from general effective Lagrangians and are therefore not specific of the SCSM.

Let us now consider the rare Z decay $Z \rightarrow \gamma\gamma\gamma$. Its observability will be limited by the QED background [38] due to two-photon production followed by initial bremsstrahlung. A careful study of the QED cross-section [39] leads to a possible detection of an anomalous contribution if the branching ratio is larger than $2 \times 10^{-6}$ instead of $1.1 \times 10^{-5}$ (95% CL) without the Pretzel scheme. Let us assume that the Z boson is a bound state of preons coupling to the photon through their electric charge $Q$, the $Z\gamma\gamma\gamma$ couplings being therefore allowed [40]. In this case the branching ratio:

$$\text{BR}(Z \rightarrow \gamma\gamma\gamma) \sim 2 \times 10^{-4} \langle Q^6 \rangle$$ (3.5)

(where $\langle Q \rangle$ is the average charge) is observable.

Another source of large decay into three photons could be an anomalous cascade $Z \rightarrow S\gamma$ ($S$ being a composite scalar particle) followed by the decay of $S$ into a photon pair. The partial width reads [41]:

$$\Gamma(Z \rightarrow S\gamma) = \frac{\alpha}{24\Lambda^2} \left( \frac{m_Z^2 - m_S^2}{m_S^2} \right)^3$$ (3.6)
Assuming a full $S \rightarrow \gamma \gamma$ decay one can reach large compositeness scales for scalar bosons $S$ lighter than the $Z$, as shown in Fig. 3.10. The high-luminosity option increases the bounds by roughly a factor of 2. Limits on a four-boson residual contact interaction are not significant: with the Pretzel scheme, $\Lambda = 50$ GeV could be reached, instead of 41 GeV with the present luminosity. This can be easily understood since the partial width reads [23]:

$$\Gamma(Z \rightarrow \gamma\gamma) = \frac{56\alpha^3}{144}m_Z \left( \frac{m_Z^8}{960\Lambda^8} \right)$$  \hspace{1cm} (3.7)$$

The existence of excited states of leptons and quarks, called excited fermions, is expected in composite models. At the $Z$ peak they are produced either in pairs or singly. We will assume they decay into $\ell + \gamma$ according to the general effective Lagrangian of magnetic type for the $\ell^*\ell\nu\nu$ interaction ($V \equiv \gamma, Z$) [42]:

$$\mathcal{L}_{\text{eff}} = \frac{e\lambda^V}{2\Lambda} \bar{\psi} \sigma^{\mu\nu}(c - d\gamma^5)\psi F_{\mu\nu} + \text{h.c.}$$  \hspace{1cm} (3.8)$$

CP invariance constrains $c$ and $d$ to be real and $g - 2$ measurements suggest $|c| = |d|$. The compositeness scale $\Lambda$ is sometimes fixed to the excited lepton mass $m_{\ell^*}$. The cross-section is given in Ref. [43]. Such a search has already been performed at LEP where ALEPH [32], assuming $\Lambda = m_{\ell^*}$ and $|c| = |d| = 1$, has excluded coupling strengths $\lambda^2/m_{\ell^*}$ larger than a few $10^{-3}$ GeV$^{-1}$ up to $m_{\ell^*} \approx 86$ GeV for $\ell^* = e^*, \mu^*$, and 72 GeV for $\tau^*$ since the background is more severe in the latter case. Following [23] we will study the restrictions asking for 10 events of type $\ell^+\ell^-\gamma$ without taking into account cuts, which have to be introduced in order to remove the QED background, and detectors efficiencies. We will focus on single $\ell^*$ production since phase space allows the limit $m_{\ell^*} = m_Z$ to be reached. As shown in Fig. 3.10, assuming $\Lambda = m_{\ell^*}$, the Pretzel scheme increases the bounds on $\lambda^2/m_{\ell^*}$ by roughly a factor of 3, compared with limits reachable for the luminosity of 100 pb$^{-1}$ normally expected. One reaches $\Lambda = m_{\ell^*} \sim 3 \times 10^{-5}$ GeV$^{-1}$ for $m_{\ell^*} = 86$ GeV. Let us now consider the more general case $\Lambda \neq m_{\ell^*}$. We give in Fig. 3.11 the allowed domains for $\Lambda/\lambda^2$ versus the excited electron mass. Inspection of this figure shows that the high-luminosity option will improve the bounds from 7 TeV to 20 TeV for $m_{\ell^*} \simeq m_Z$. For $\ell^* \neq e^*$ the bounds are slightly lower as shown in Fig. 3.12.

Let us now consider the radiative $Z$ decay: $Z \rightarrow \ell^+\ell^-\gamma$. We will focus on three anomalous contributions: excited electron, gauge-invariant contact term, and anomalous three-neutral-boson couplings $\ell$. The observability of an anomalous decay is limited by the bremsstrahlung effect on $e^+e^- \rightarrow \ell^+\ell^-$. We will study the sensitivity to an experimental accuracy of $5\%$ and $2\%$. It should be noticed that these accuracies are mainly determined by the detector, and the high-luminosity option will therefore not improve them. We have imposed the following cuts on photon variables: $\theta_\gamma > 5^\circ$ and $E_\gamma > 300$ MeV. We first study the limits on an excited electron. Following Ref. [44] we will consider the four chirality structures appearing in the Lagrangian (3.8): vector ($c = 1, d = 0$), axial ($c = 0, d = 1$), left ($c = d = 1/\sqrt{2}$), and right ($c = -d = 1/\sqrt{2}$). The value $\lambda^2 = (\sqrt{\sigma})^{-1}$ has been assumed. Limits in the plane ($\Lambda, m_{\ell^*}$) for $e^+e^- \rightarrow e^+e^-\gamma$ are given in Fig. 3.13. The most stringent bounds are obtained for vector and axial couplings. The relative deviations on the decay rate $Z \rightarrow e^+e^-\gamma$ for $\Lambda = m_{\ell^*}$ are plotted in Fig. 3.14. A $5\%$ experimental accuracy excludes $\Lambda = 260$ GeV for vector and axial couplings and $\Lambda = 200$ GeV for the
left case, which is the less sensitive one. If a 2% accuracy can be reached the bounds increase up to 300 GeV and 220 GeV respectively. A detailed analysis shows that the presence of an excited electron modifies the angular distribution in the central region since its contribution is more isotropic. As can be seen from Fig. 3.15, the sign of deviation can give also indications about the chiral structure of the coupling. Similar conclusions can be obtained by looking at the dependence on photon energy (see Fig. 3.16). Moreover higher bounds can be derived from these observables. Concerning gauge-invariant contact terms, if we restrict to chirality and CP-conserving amplitudes, the best sensitivity is obtained for the operator having the lowest dimension, i.e. the contact term called $R^2_{TT}$ in Ref. [44] (to which we refer for details) which is proportional to $\Lambda^{-4}$. As can be seen from Fig. 3.17, one can reach the limits $\Lambda = 150$ GeV (resp. 180 GeV asking for a 2% accuracy) for left and axial couplings and $\Lambda = 120$ GeV (resp. 130 GeV) for the less favourable case corresponding to a right coupling. The dependences on $\cos \theta$, and $E_r$ are affected in a similar way as for the excited electron exchange [45]. The sensitivity to a transverse-longitudinal term $R_{TL}$ [44] is around 100 GeV. The sensitivity to anomalous three-neutral-boson couplings is rather poor. We can only exclude large values of the $\xi$ parameters defined in [44] since we get $\xi_2, \xi_4 < 5$ when asking for 2% deviation. Much more stringent bounds will be obtained at $E = 190$ GeV from $e^+e^- \rightarrow \gamma \gamma$ since the limit $\xi_4 < 0.5$ is expected [44].

Let us finally discuss the indirect effects of an anomalous $ZWW$ coupling at the $Z$ peak. It is generally believed that LEP 200 is the ideal place to test the electromagnetic and self-couplings of the weak vector bosons, which are direct tests of the gauge non-Abelian nature of the standard model. Any deviation from their value in the standard model is an indication of new physics and in this particular case would derogate, from the $W$ bosons, the status of a gauge fundamental particle. A very detailed analysis of the effects of the most general anomalous $WWZ$ and $WW\gamma$ couplings has been given in Ref. [46]. However it had been realized (see Ref. [47]) that anomalous magnetic moment couplings could indirectly induce very large effects on the $\rho$ parameter (which we could precisely probe at LEP 1). However, if a global SU(2) custodial symmetry is imposed on the Lagrangian leading to such coupling, then this effect disappears. In fact such an approach should be highly advocated since we know that the $\rho$ parameter is to a very good approximation equal to one. Moreover in order to recover the universality of the weak coupling without invoking the principle of local invariance in a theory where the weak bosons are no longer genuine gauge bosons (source of anomalous couplings) one appeals, beside the global weak symmetry to the idea of vector-boson dominance. It can be shown [48] that the lowest-particle Lagrangian incorporating those two principles can be written:

$$\mathcal{L}_{WWZ/WW\gamma} = \mathcal{L}_{SM} + \frac{ie\lambda}{m_W^2} \left( F_{\mu\nu} + \cot \theta_w Z_{\mu\nu} \right) W_{\lambda\nu} W^{\mu\nu},$$

(3.9)

where $\mathcal{L}_{SM}$ is the standard model Lagrangian and the single additional parameter $\lambda$ contributes to the quadrupole moment of the $W$. The magnetic moment of the $W$ is as in the standard model. The low-energy limits one gets from this 'constrained' Lagrangian are very weak [such as $(g-2)_\mu, \ldots$] (see Ref. [49] for a recent analysis) as are the ones from a direct search at the $Z$ peak through $Z \rightarrow WW \rightarrow f_1 f_2 f_3 f_4$ due to phase space [50]. We can however [51] get a much better limit (in fact better than the one from LEP 200) by considering the virtual effects of such an anomalous coupling on the $Zff$ vertex. In fact
the additional coupling gives a contribution to only the left-handed part of the Z current, such that the amplitude for $Z(\mu) \to f(p_1) \bar{f}(p_2)$ is

$$\mathcal{M} = \frac{-g}{2 \cos \theta_w} \bar{u}(p_2) \gamma_\mu [c'_L(1 - \gamma_5) + c_R(1 + \gamma_5)] v(p_1),$$

(3.10)

with $c'_L = c_L + \delta$, $\delta$ representing the shift

$$\delta = \frac{\lambda \alpha}{8\pi \sin^2 \theta_w} \left( \cos^2 \theta_w \frac{m_Z^2}{m_W^2} \right) \log \left( \frac{\Lambda^2}{m_W^2} \right),$$

(3.11)

where $\Lambda$ acts as a regulator and represents the scale of ‘compositeness’. It is important to notice that since the dependence on this parameter is only logarithmic the limits on $\lambda$ do not sensibly depend on the scale and could be almost unambiguously compared with limits from direct searches at much higher energies; $c_L$ and $c_R$ are the usual standard model couplings, $c_L = T_3 - Q \sin^2 \theta_w$ and $c_R = -Q \sin^2 \theta_w$.

One can observe shifts in partial widths and asymmetries at the Z pole. To get an unambiguous limit independent of the radiative corrections within the standard model (top effects, ...) we have looked at the effect on a whole set of twiddled quantities [51, 52]. The best limit can be derived with ‘unpolarized’ LEP 1 variables formed from the combination of the ratio of the hadronic to muonic widths and the electron partial width [51]. In this special variable no $\Delta \rho$ dependence survives. Assuming that the overall (expected) precision of 1.25% can be attained, one can probe values of $\lambda$ as low as 0.34 taking the scale $\Lambda = 1$ TeV (we take this particular scale for comparison with previous limits on the same parameter).

### 3.3.2 Sensitivity to compositeness away from the Z peak

We first study the reaction $e^+e^- \to \gamma\gamma$ [44] and look for deviations from the standard model due to excited electron exchange and contact term $R_{TT}^2$ at $E = 100$ GeV and $E = 190$ GeV. We assume $\lambda = (\sqrt{\alpha})^{-1}$ and $g^2(c^2 + d^2) = 4\pi$. Asking for a 5% deviation (resp. 2% deviation) the most stringent limits can be reached by looking at the angular dependence in the central region ($\cos \theta = 0$). For vector and axial couplings one gets, for $m_{e*} = 1$ TeV, $\Lambda = 700$ GeV (resp. 950 GeV) and for $m_{e*} \sim 50$ GeV one obtains a sensitivity to scales $\Lambda = 4$ TeV (resp. 7 TeV). For left couplings the limits decrease by roughly 20%, and by a factor of 2 if one looks at integrated cross-sections. The comparison with LEP 200 is done in Fig. 3.18 assuming a 5% deviation. One reaches the limits $\Lambda = 2$ TeV for $m_{e*} = 1$ TeV and $\Lambda = 9$ TeV for $m_{e*} = 50$ GeV, showing therefore that the bounds are sizeably improved by increasing energy. Limits for the contact term $R_{TT}^2$ are given in Table 3.2 for integrated cross-sections and angular ones fixed to $\cos \theta = 0.5$ and $\cos \theta = 0$.

Let us consider now collective effects in Bhabha scattering and muon-pair production. A rather model-independent way to probe a substructure is based on the general Lagrangian for contact terms [53]:

$$\mathcal{L}_{\alpha\beta} = \frac{g^2}{2\Lambda_{WWW}^2} \sum_{i,j} \eta_{ij} \bar{\psi}_i^\alpha \gamma_\mu \psi_i^\alpha \bar{\psi}_j^\beta \gamma^\mu \psi_j^\beta.$$

(3.12)

We use the convention $g^2 = 4\pi$. For Bhabha scattering we are sensitive to $\Lambda_{WW}$ and for muon-pair production to $\Lambda_{e\mu}$; $\eta_{ij}$ sets the chirality. These new contact interactions can
be detected through interference with the standard model. The Z peak is not sensitive
to contact interactions since the standard model amplitude, which is imaginary, does not
interfere with real contact terms.

Nevertheless, as we will see, shifting off the Z peak by a few GeV leads to interesting
limits. Following Ref. [54] the bounds on $\Lambda$ are obtained by equating the relative deviation
on $d\sigma/d\cos\theta$ with the statistical error on the measurement:

$$\frac{d\sigma/d\cos\theta}{(d\sigma/d\cos\theta)_{SM}} = 1 \sim \frac{S}{\alpha\Lambda^2} \approx \frac{1}{\sqrt{N}}$$

leading to the scaling law:

$$\Lambda_{\alpha\beta} \sim \sqrt{\int \mathcal{L} dt \sqrt{S}}.$$  \hspace{1cm} (3.14)

Assuming an increase of luminosity by a factor of 10, one increases bounds on $\Lambda_{ee}$
from 1.5–4.8 TeV (according to the chiralities) to 2.6–8.5 TeV. Assuming an integrated
luminosity of 800 pb$^{-1}$, LEP 200 can reach the limits 3.6–11 TeV. For $\Lambda_{e\mu}$ one goes from
1.3–3.8 TeV to 2.3–6.75 TeV with the Pretzel scheme, to be compared with the LEP
200 limits of 3–9 TeV.

3.3.3 Production of leptoquarks

The production of scalar leptoquarks $D^0$ from the Z peak in the context of $E_6$ superstring
models has been considered in [55] leading to a signature of unlike-sign dileptons accompa-
nied by jets. Assuming a Yukawa $D^0\ell q$ coupling of electromagnetic strength, one can
exclude leptoquarks up to 80 GeV with the Pretzel scheme. This result is not specific of
$E_6$ models.

3.3.4 Conclusions

If nearby compositeness is present, the study of the decay mode $Z \to H\gamma$, a priori well
suited to put large bounds on compositeness scale, suffers from a severe background
due to quark final-state radiation, only allowing $\Lambda \approx 10m_Z$ to be excluded. Concerning
excited lepton production if $m_{e^*} < m_Z$ the most stringent limits are obtained at the Z
peak from single $\ell^*$ production with the Pretzel scheme. For heavier excited leptons,
since the highest energy available leads to the best bounds, LEP 200 is therefore more
appropriate to studying the reaction $e^+e^- \to \gamma\gamma$. Similar conclusions can be drawn for the
gauge-invariant contact terms. For collective effects in Bhabha scattering and muon-pair
production the most stringent bounds are obtained at the highest available energy, i.e. at
LEP 200. Indirect effects of an anomalous ZWW coupling at the Z peak are important.

3.4 Flavour-changing Z decays (leptonic)

*M. Dittmar, J. W. F. Valle*

3.4.1 Introduction

The search for rare Z decays at a high-luminosity Z factory such as LEP offers a unique
opportunity to test fundamental symmetries of the standard electroweak theory, such as
weak universality, flavour and CP conservation. This is specially interesting in the case of the lepton sector, because the novel effects associated with their violation would vanish exactly in the standard model, and thus their possible detection would signal the presence of new physics.

This new physics could arise from the existence of non-zero neutrino masses and the possible related existence of neutral singlet heavy leptons (NHLs) such as right-handed neutrinos. This provides an interesting window beyond the physics of the standard model, closely related to the properties of the neutrinos, such as their mass [56]. The NHLs occur in a very wide class of extensions of the standard electroweak theory, including string-inspired models [57,58]. In all these models the $Z$ may decay into a heavy singlet neutrino $N$ and an ordinary light neutrino [59,60]

$$ Z \to N + \nu . \quad (3.15) $$

This would lead to characteristic signatures consisting of very unbalanced events with a huge amount of missing transverse energy ('zen' events), originating from their subsequent decays

$$ N \to 3f , \quad (3.16) $$

where $f$ denotes an arbitrary quark or lepton. These decays were calculated in detail in Refs. [59,60].

Even if the NHLs are not light enough to be produced in $Z$ decays, their existence may still be revealed indirectly through the associated flavour and CP-violating processes that they would induce in the leptonic sector [61–64]. This could also lead to flavour and CP-violating decays of the $Z$ involving charged leptons, such as

$$ Z \to e_i + \bar{e}_j \quad (3.17) $$

as well as CP-violating asymmetries.

Here we examine the prospects for detecting these $Z$ decays. First we summarize the results of the studies made in Refs. [59,60], then we study the detectability prospects for lepton flavour and CP-violating decays of the $Z$.

### 3.4.2 $Z$ decays into heavy singlet neutral leptons

The process (3.15) results from the mixing of the light neutrinos with the NHLs in the electroweak currents, following the general pattern studied in Ref. [65]. There are limits on the magnitude of the gauge coupling strength of the NHLs in the electroweak currents. These are compiled in Fig. 3.20. They arise from various sources, including the universality observed in low-energy weak decays [66], beam-dump experiments [67], PEP [68] and Fermilab dimuon search experiments [69].

In most models the coupling of the NHLs to the gauge currents (and thus to the $Z$) is related to a finite mass of the associated neutrino. Since we know that the magnitude of neutrino masses (if neutrinos are stable) is severely restricted by cosmology [70], it follows that the NHL couplings to the $Z$ are correspondingly restricted to be too small to produce a detectable zen-event rate.

However, this can be circumvented in two ways. First, it is possible to have neutrino masses forbidden exactly by an exact lepton number symmetry. In this case the NHLs
are Dirac particles and can couple to the Z with a large strength, only restricted by the universality of the weak interaction. This, however, is still poorly determined in the case of the τ family. A detailed investigation of the attainable limits on the NHL couplings to the Z versus their mass, was given in Ref. [59]. The results are also shown in Fig. 3.20. With the large number of Z available at LEP these limits are rather impressive.

Alternatively, if NHLs are Majorana particles, and neutrino masses are therefore not required to vanish, they could have a large coupling to the Z, so their zen-event production rate is correspondingly sizeable, if the associated neutrino is sufficiently heavy. This need not cause any conflict with cosmology, since in any model where the violation of the total lepton number symmetry, responsible for the neutrino mass, is of the spontaneous type, there exists a massless Majoron that leads to new modes for neutrino decay and/or annihilation

\[ \nu' \rightarrow \nu + \text{Majoron} \]  
\[ \nu' + \nu' \rightarrow \text{Majoron} + \text{Majoron} \]  

(3.18)  
(3.19)

It is interesting to note that since the processes (3.18) and (3.19) do not generate entropy, they avoid all astrophysical bounds. Note also that the Majoron need not contribute to the invisible decay width of the Z if it is a singlet under SU(2) \( \otimes U(1) \), as we do assume here. This automatically avoids another restrictive constraint on non-singlet Majorons, that comes from stellar energy loss due to Majoron emission.

In the presence of such processes, neutrinos can disappear so fast that their relic density can be very small even if their mass lies in the forbidden range for stable neutrinos [71]. Therefore any value of the neutrino masses permitted by laboratory experiments is also cosmologically allowed. It is therefore interesting to evaluate the NHL zen-event production rate also in models with massive neutrinos. This investigation has been done in Ref. [60], incorporating the limits required by cosmology on the relic neutrino densities, paying attention to the fact that the zen-event rate may be diluted by the invisible NHL decay

\[ N \rightarrow \nu + \text{Majoron} \]  

(3.20)

Various models of this type were considered, where the signal is measurable despite the existence of the decay mode (3.20). A typical estimate of the allowed zen-event rate is presented in Fig. 3.21. It clearly demonstrates that in this case, too, the detectability of heavy singlet neutrino zen-events is well within LEP's capabilities.

### 3.4.3 Flavour- and CP-violating decays

Flavour- and/or CP-violating Z decays such as (3.17) vanish identically in the standard model. Their possible detection would thus signal new physics, closely related with the properties of the neutrinos and the leptonic weak interaction [58]. One may argue that such processes, if non-zero, ought to be very small. This is the typical situation when their existence is directly related to non-zero neutrino masses and suppressed by a GIM mechanism [72]. If NHLs exist in nature, however, they can mediate flavour-violating decays, such as (3.17), without being GIM-suppressed, so that one can expect a substantial enhancement in the expected flavour- and CP-violating Z decay rates.

There are two qualitatively different possibilities. If flavour-violating Z decays arise from the mixing of neutrinos with some heavy Majorana leptons, so that neutrinos acquire
a mass as a result of the mixing, even though there is no GIM mechanism, its violation is restricted by the smallness of neutrino masses. This happens in the simplest see-saw mechanism. As a result, flavour-violating Z decay rates are expected to be small in this model, because they are suppressed by the neutrino masses.

It is however possible to extend the standard SU(2) ⊗ U(1) electroweak theory so that leptonic flavour and CP violation arise even if the neutrinos are strictly massless [61–63]. As a result, the corresponding effects are potentially large and may be manifest either in the domain of low-energy processes, such as rare weak decays of the μ and the τ, or at the Z peak.

The simplest model of this type was described in Refs. [59,61–63]. In this model the NHLs are Dirac particles and neutrino masses are forbidden by lepton-number symmetry. The diagrams responsible for $Z \to e\tau$ have been calculated in Ref. [61]. The allowed value of flavour-violating branching ratios such as $Z \to e + \mu$ is restricted by the constraints from the corresponding effects at low energies, such as $\mu \to e + \gamma$ and $\mu \to 3e$. The non-observation of the low-energy processes implies severe constraints that make the expected effects at high energy unobservably small. This is why we are left with just two possibilities, i.e. violations in the $\tau-e$ and $\tau-\mu$ channels, since the corresponding constraints on flavour-violating processes are much weaker. In this case the only restrictions that apply are the universality constraints, although LEP may soon constrain the NHL gauge coupling strengths, if zen-events are not observed [59,60].

Combining all constraints related to the universality of the weak interaction\(^5\), we estimate the attainable flavour-violating branching ratio for $Z \to e + \tau$ as shown in Fig. 3.22.

The CP-violating Z decay asymmetries are defined as

$$\eta_{ij} = \frac{\Gamma(Z \to e_i + \bar{e}_j) - \Gamma(Z \to e_j + \bar{e}_i)}{\Gamma(Z \to e_i + \bar{e}_j) + \Gamma(Z \to e_j + \bar{e}_i)}$$  \hspace{1cm} (3.21)

for each value of the indices $i$ and $j$ which label the final-state charged leptons. In an $n$-generation model with extra isosinglet leptons these asymmetries involve $(n - 1)^2$ independent CP-violating quantities, the same number as the independent CP-violating phases that appear in the leptonic charged current [62,63]. For simplicity we consider the case of a two-family mixing model, as would happen in a scheme in which either the $\ell_\mu$ (for $Z \to e\tau$) or $\ell_e$ (for $Z \to \mu\tau$) lepton number is exactly conserved, in addition to the total lepton number. In this case there is a universal CP-violating quantity that determines all lepton CP-violating observables, such as our Z decay asymmetry, Eq. (3.21).

In order to generate non-zero CP asymmetries in flavour-violating Z decays, two conditions are required. The first is that the relevant CP-violating quantities be non-zero. The second condition is that some of the relevant graphs have an absorptive part, which is guaranteed in our case, even when the NHLs are heavier than the Z, by the fact that Z can always decay into the massless neutrinos.

In Ref. [63] it was shown that the CP-violating Z decays can be of the same order of magnitude as the corresponding flavour-violating process, i.e. the CP asymmetries defined as in Eq. (3.21) can be of order unity. It appears therefore that there is a chance that LEP, with upgraded luminosity, reaching $10^8$ or more Z's, may become sensitive to such small branching ratios.

\(^5\)We thank A. Santamaria for suggesting a clever way to combine the various universality constraints to obtain a more restrictive limit, used in Fig. 3.22.
3.4.4 The decay $Z \rightarrow e \tau$

We now analyse the experimental feasibility to detect the lepton-number-violating decay $Z \rightarrow e + \bar{\tau}$ (plus conjugate channel) at LEP, as well as the corresponding CP-violating asymmetries as a function of the number of produced $Z$'s.

The signature of such $Z$ decays would be events with an electron having the beam energy in one hemisphere and, opposite to this, the decay products of a tau having energy and momentum well below the beam energy. Realistic resolutions for tracks as well as for calorimeters limit the detectability of such events.

Possible background from $Z \rightarrow e e(\gamma)$ and $Z \rightarrow \mu \mu(\gamma)$ could be efficiently rejected by requiring the following criteria:

1. The event should be well contained inside the detector with the best possible resolution. All particles should be found within the barrel region and a $| \cos \theta | \leq 0.8$ with respect to the beam. For a real analysis, regions with dead detector elements should be excluded.

2. The electron candidate should have a measured momentum of more than 35 GeV and the energy in the calorimeter should exceed 40 GeV.

3. Opposite to the high-energy electron (the observed tracks should be collinear within less than $10^\circ$) should be 1 or 3 tracks consistent with $\tau$ decays and an energy deposited in the calorimeter of less than 30 GeV.

The only remaining background would be $\tau$-pair events with a $\tau$ decaying into an electron that gets almost the total energy of the $\tau$. Taking the branching ratio of $\tau$'s into electrons as 17.5% we obtain, for a total number of $10^7$ $Z$'s, around $3.3 \times 10^5$ $\tau$'s and about 50000 electrons (and 50000 positrons). Figure 3.23a shows the electron spectrum using the KORALZ program [73] for $\tau$ decays without detector resolutions. Experimental measurement errors for calorimeter scale with $5-20%/\sqrt{E}$ ($E$ in GeV) are envisaged for the different LEP experiments. In addition calibration uncertainties limit the resolution. A further uncertainty might be due to not fully contained electromagnetic showers for 45 GeV electrons. Details depend however on the specific calorimeters.

The calibration uncertainties should be relatively small, since a huge number of $e^+e^-$ pairs is available to check the calibration of the calorimeter. Accuracies of 1-3% for the calibration should be possible. In this context we want to mention that the OPAL Collaboration has already obtained an energy measurement with an accuracy of 3% at 45 GeV after a few months of operation [74].

The momentum resolution scales proportional to the momentum. Values of 2-10% at 45 GeV momentum are envisaged for the different LEP experiments. Again calibration effects should be monitored with good accuracy using $\mu$-pair events.

For most experiments the calorimeter resolution would give the most accurate measurement at these energies.

In Fig. 3.23b we have modified the electron spectrum of Fig. 3.23a to take into account the experimental resolution. The histogram indicates the signal for a $Z$ sample of $10^7$ and a resolution of $5%/\sqrt{E} + 1\%$ calibration error, added in quadrature. The points with error bars show the signal plus background for a $Z$ branching ratio of $10^{-5}$ for $Z \rightarrow \tau + e$, including acceptance cuts.
In Fig. 3.24 we show the number of expected background events as a function of the number of Z’s. The number of background and signal events was calculated from the number of electrons above an energy of 0.98 of the maximum energy. We estimate that the possible background would show up at about $10^6$ Z’s. This would lead to limits of about $10^{-5}$–$10^{-6}$ for a total number of Z’s of $10^7$ to $10^8$ depending strongly on the possible experimental resolution. Similar results could be obtained from the $Z \to \mu \tau$ decay with a more serious background of about an order of magnitude more events.

### 3.4.5 Conclusions

Given the present knowledge about the neutrino parameters and the structure of the leptonic weak interaction, we conclude that the observation of zen-event signals associated to NHLs are definitely within the capabilities of LEP, given its high luminosity. As for flavour- and CP-violating decays, engendered by NHL virtual exchange, we conclude that, with $10^8$ Z or more, there is some chance of detection in the $e-\tau$ channel, depending crucially on experimental resolution. The situation is worse for the $\mu-\tau$ channel.

### 3.5 Flavour-changing Z decays (hadronic)

D. Cococicchio, M. Dittmar

The original design luminosity of $1.4 \times 10^{31}$ cm$^{-2}$ s$^{-1}$ for the present LEP configuration might be increased by about an order of magnitude by a multibunch operation of LEP resulting in a rate of $10^8$ Z per experiment and year. With this abundant statistics, not only the systematic and the experimental errors could be reduced drastically, but also the sensitivity for rare decay modes of the Z would be strongly increased. In the following we want to discuss theoretically and experimentally the possibility to see hadronic flavour-changing decays of the neutral gauge boson.

### 3.5.1 Theoretical predictions

A decay like $Z \to Qq'$, where Q and q' are two quark flavours of identical charge (i.e. bs), occurs in the Standard Model through one-loop diagrams [75]. Such contributions are predicted in general to be extremely small (branching ratios $\sim 10^{-8}$). The existence of further new physics could lead to a sensible increase.

The almost general effective flavour-changing neutral $Z^0$ current can be evaluated by the general algorithm of two- and three-point functions developed by Passarino-Veltman [76] and Consoli [77] from the lowest-order diagrams. The most general form can be written as

$$J^Z_{\mu} = Q(p') \left[ \gamma^\mu A_{ij} + \eta_{\mu \nu} \frac{k_\nu}{m_Z} B_{ij} \right] q_j(p) + O(k_\mu)$$  \hspace{1cm} (3.22)

where $k$ is the four-momentum of the Z and

$$A_{ij} = F_L \ L + F_R \ R = -ig_1 a_{ij} \hspace{1cm} a_{ij} = a^{L}_{ij} \ L + a^{R}_{ij} \ R$$

$$B_{ij} = F^{TL}_L \ L + F^{TR}_R \ R = -ig_2 b_{ij} \hspace{1cm} b_{ij} = b^{L}_{ij} \ L + b^{R}_{ij} \ R$$
$L$ and $R$ are the left- and right-handed projectors $(1 \pm \gamma^5)/2$, and the $F$ are the
remaining terms can only arise from loop effects and can be
neglected if $k^2 \ll m^2_Z$, whilst the $A_{ij}$ can arise at tree and loop level.

In the minimal Standard Model, at tree level, the $Z$ couplings are diagonal and the
off-diagonal terms are already severely constrained by K and B physics [75].

In general, the partial width for a quark flavour $Q$ heavier than the other is given by

$$
\Gamma(Z \to Q\bar{q}') + Q\bar{q}' = \frac{m_Z}{16\pi} \left\{ \left( \frac{m_Q}{m_Z} \right)^2 \left[ \left[ \left( 2 + \frac{m_Q^2}{m_Z^2} \right) \left( |F_L|^2 + |F_R|^2 \right) \right] + \left( 1 + 2\frac{m_Q^2}{m_Z^2} \right) \left( |F^*_L|^2 + |F^*_R|^2 \right) + 6\frac{m_Q}{m_Z} \text{Re}(F^*_L F^*_R + F^*_R F^*_L) \right] \right\}.
$$

(3.23)

The existence of further new heavy quarks can lead to unconventional final states $Z
\to b\bar{b}$. The predicted branching ratios for the $Z$ flavour-changing decays can reach $10^{-6}$
[78]. For the $b\bar{b}$ the signature would depend on the decay mode of the $b'$. But since
the direct production of the $e^+e^- \to b'b'$ could easily be observed at LEP 200 we do not
consider this process further.

In the minimal Standard Model the above expression simplifies and, because of the
GIM mechanism, which cancels strangeness-changing neutral-current couplings, the decay
rate is unobservably small.

From the differential cross-section [79] it can be derived that the angular distribution
curves are rather similar to $e^+e^- \to \mu^+\mu^-$. The integrated cross-section $\sigma$ is peaked
around the $Z$ pole, and in the case of the decay mode $b\bar{s}$ it can reach $\sigma \sim 10^{-8}$ nb for
$m_t > 50$ GeV, several orders of magnitude smaller than $\sigma(e^+e^- \to \mu^+\mu^-) \sim 10^{-2}$ nb. A
fortiori, in the minimal Standard Model, the CP-violating asymmetry

$$
R_Z = \frac{\Gamma(Z \to b\bar{s}) - \Gamma(Z \to \bar{b} s)}{\Gamma(Z \to b\bar{s}) + \Gamma(Z \to \bar{b} s)}
$$

is unobservable.

The possible presence of quarks in exotic representations [80] could yield a sizeable
increase for the branching ratios for $Z \to b\bar{s}$. In the case of mirror quarks [81], the
branching ratio could be of the order of $10^{-9}$ for $b\bar{s}$ decays and as large as $10^{-3}$ for $b'b$
for the effects of new tree-level flavour-changing currents.

In the case of the singlet quarks accommodated in the left–right symmetric models the
enhancement for the $b\bar{s}$ branching ratio is not significant [82].

The vector singlets contributions in the $E_6$ model are expected to enhance the branching
ratio of the process $Z \to Q\bar{q}$ by some order of magnitude above that predicted in the
three-generation Standard Model by means not only of weak one-loop gluino diagrams
[83] but mainly via other induced graphs [84].

The charged Higgs-scalars emerging in extra doublet models have been thought of
as potential sources of the enhancement of hadronic rare $Z$ decays. In several recent
papers [85], it was reported, for example, that the branching ratio for $Z \to b\bar{s} + \bar{b}s$ could
receive a substantial enhancement from the charged Higgs boson contributions, leading
to a branching fraction up to $\sim 10^{-6}$, two orders of magnitude larger than the Standard
Model prediction.
In the case of left-right symmetric models, the current limits on the $W_L-W_R$ mixing [86] put a stringent bound on the effective vertex $Zbs$ [87] and the predictions are not too different from that of the Standard Model.

Within the framework of supergravity models, and taking into account the recent experimental limits on SUSY particles from the LEP experiments, the $Z \to b\bar{b} + b\bar{b}$ gluino-induced flavour violation turns out to be too small to be detected. The effects of charged Higgs scalars in a model with two Higgs doublets cannot be directly imposed over the supersymmetric theory because it would require correctly taking into account the rescaling conditions for symmetry breaking. Thus for these models it has been shown [88] that the $\text{BR}(Z \to b\bar{b})$ increases rather sharply with $m_t$ so that it can be as high as $O(10^{-8})$ for $m_H = 100$ GeV. This is significantly larger than the Standard Model expectation. Moreover, in this context, the charged Higgs contributions dominate over the gluino-induced ones for $m_H < 150$ GeV. In electroweak extensions with additional doublets but without supersymmetry, the charged Higgs contributions to $B_d^0 - \bar{B}_d^0$ mixing as well as to $\text{BR}(Z \to b\bar{b})$ are reduced for larger values of $m_H$, so that a compensatory increase in the ratio of the vacuum expectation values $\tan \beta = v_2/v_1$, to fit the ARGUS data on the observable of this mixing, results in a corresponding enhancement in $\text{BR}(Z \to b\bar{b})$. In the framework of supersymmetric models the value of the ratio $v_2/v_1$, for every value of $m_t$, is otherwise restricted to be in the range 1 to 4 by some stability constraints, then such compensation does not take place.

In these extensions, as we stressed, the magnitude for the hadronic rare $Z$ decays seem to be at most of the order of $10^{-5}$. In the rest of the paragraph we want to analyse if processes of such rates can be detected at LEP.

### 3.5.2 Experimental detection

In the following we describe the experimental signature and the feasibility to detect such direct quark-flavour-changing neutral currents in $Z$ decays and outline a possible strategy to detect the decay $Z \to b\bar{b}$.

1) Experimental signature (Fig. 3.25)

The lifetime of the b has been measured to be about 1 ps or a $c\tau$ of about 300 $\mu$m. A typical B-meson at the Z would get a momentum of about 30 GeV resulting in a mean decay length $\ell$ of about 2 mm ($\ell = \beta\gamma c\tau$). The b-decay particles would thus have a large impact parameter, which is of the order of 200 $\mu$m with respect to the interaction point. The particles emerging from the s-jet would on the other hand come directly from the interaction point. An observation of such an unbalanced lifetime per hemisphere would be a direct sign of such flavour-changing $Z$ decays. However, in practice such a measurement is diluted by several problems.

a) Measurement errors: The different LEP experiments are now operating vertex detectors which should have accuracies of about 30–50 $\mu$m for the impact parameter and about 300–500 $\mu$m for secondary vertices. Owing to the large radius of the current beam pipes, multiple scattering would dilute such an accuracy further, probably by a factor of 2. Several experiments are planning for smaller beam pipes with a radius of about 5 cm and high-precision silicon microvertex detectors. Resolutions of 10–20 $\mu$m for the impact parameter and about 150 $\mu$m for secondary vertices are envisaged.
b) The beam spread: The coordinates of the interaction point are known to about 20 \( \mu m \) in the vertical direction and this matches the experimental accuracy well. The horizontal beam spread, of about 200 \( \mu m \), requires in addition a good measurement of the main vertex on an event-by-event basis. In general this is not a big problem; however, in b-events such a measurement is limited by the uncertainty to determine which particle is prompt and which comes from a secondary vertex.

2) Tagging the b-jet

Besides the lifetime measurement, several methods have been developed during the last years to tag b-jets by using their semileptonic decays, and the relative large mass of b's, which results in high-\( p_T \) particles (more than 1 GeV) and the hard fragmentation of b's. Clean samples of b-events can be identified with efficiencies of 5–10\% (per b-jet) using leptons. Combining such a selection with the selection of separated vertices due to the lifetime and/or large impact parameters (above 100 \( \mu m \)) the efficiency can be increased, probably by factors of more than 2, with negligible background from light quarks (see Fig. 3.25).

3) Tagging the s-jet (non-b-jet)

Several methods have been proposed to tag light quarks using leading stable particles (or strange-meson resonances) kaons, \( K^\ast \) or \( \phi \)'s. Depending on the requirements for purity and efficiency, clean samples of light quarks could be obtained in Monte Carlo studies. Efficiencies of the order of 5\% per jet seem to be possible. At the same time a suppression of \( \geq 10^3 \) for b-jets is obtained. After more details of the fragmentation of s-jets will be known from the LEP data it might be possible to obtain a further b-rejection factor of 10 without losing more than a factor of 2 in the s-tagging efficiency. Combining such a method with the requirement that the particles within the s-jet are coming from the interaction point, a further suppression factor of about 10 for b-jets should be obtained. It should also be required that the s-jet has a well measured energy and a mass much lower than 5 GeV. In addition no lepton or charm candidate should be found in these jets.

4) Selection criteria

To identify the \( Z \) decay into s–b we have estimated the sensitivity by using the following combined criteria for b and s tagging. As can be seen, very high precision vertex chambers are essential for such a measurement.

a) b-tag: High-\( p_T \) leptons/hadrons with a large impact parameter of more than 100 \( \mu m \) [about 5\( \sigma \) (vertex resolution) away from the interaction point]. Efficiency of the order of 10–20\% might be possible if one does not require to know the charge of the b-jet. A limitation to higher efficiencies would be some possible background from charm events.

b) s-tag: A high-\( x \) particle or resonance with a mass of less than 1.2 GeV [e.g. \( \pi, K^\pm, p, K^0, \Lambda, \phi, K^\ast(892), \text{ etc.} \) with \( x = p/E_{beam} \) above 0.6 to 0.7 should be seen. Efficiencies of 5\% should be possible for a single s-jet. In addition one has to require that several tracks from the s-side come from the interaction point to guarantee the very small lifetime.

c) Main interaction point: To determine the event vertex it would also be necessary to have a few tracks from the b-jet which are prompt (from the fragmentation). In Table 3.3, we indicate how the different criteria select the signal events relatively to the background. We have started with a branching ratio of \( Z \to b\bar{b} \) of 10\(^{-4} \)
(with the charge conjugate). Being optimistic on the possible resolution for vertex detectors, about 10 background events would be expected from $b\bar{b}$ for $10^8$ $Z$ decays. A $5\sigma$ signal requires about 15 additional events, thus a branching ratio of a about $3 \times 10^{-5}$ could be observable. Going to the extremum of not seeing any deviation, about 4 events could be quoted as an upper limit or about a branching ratio of $10^{-5}$. In Fig. 3.26 we show the number of background events as a function of the number of $Z$'s.

However, some of the above assumptions are very ambitious and would require a big step in vertex detector technology. In addition, the data collection spread over at least a year, requires very stable and well-monitored running conditions for an experiment.

### 3.5.3 The radiative decays of the intermediate vector boson

The partial widths for two-body decays $Z \rightarrow \gamma + 2s+1L_J(q\bar{q})$ to a photon and a quarkonium state were predicted [89] and found to be substantially unobservable at LEP since for instance $\Gamma(Z \rightarrow \gamma + J/\psi) \sim 0.2$ keV.

On the other hand, the decay widths of an intermediate vector boson into a pseudoscalar meson and a photon were also calculated on the basis of the asymptotic behaviour of the meson form factor and found [90] to be too small to be observable at LEP:

\[
\begin{align*}
\Gamma(Z \rightarrow \pi^0\gamma) & \sim 0.03 \text{ eV} \\
\Gamma(W^\pm \rightarrow \pi^\pm\gamma)/\Gamma(W^\pm \rightarrow e^\pm\nu) & \sim 10^{-8}.
\end{align*}
\]

(3.24)

Recently, the pion dominance of the divergence of the axial vector current was proposed to increase the branching ratio up to $1.7 \times 10^{-3}$ for $Z \rightarrow \pi^0\gamma$ and 0.1 for $W^\pm \rightarrow \pi^\pm\gamma$ [91]. The $\pi\gamma$ decay rates instead of falling as $1/s$, are argued to follow the resonant $Z$ line shape with a controversial application of the chiral anomaly phenomenon in the electroweak sector in the case of the rather massive external particle. All this contradicts previous QCD-based estimates of the neutral-current pseudoscalar form factor that determines the partial widths [92], as well as recent approaches based on the SU(2) $\times$ SU(2) $\sigma$ model [93].

On the experimental side, the study of rare $Z$ decays should be possible at the LEP high-luminosity configuration in which a data sample of $10^7$-$10^8$ $Z$ events could be obtained in a year of running. Those branching fractions down to $10^{-5}$-$10^{-6}$, corresponding to partial widths of a few keV, might be measured.

The constraints from the $e^+e^- \rightarrow \pi^0\gamma$ reaction rate at TRISTAN [94] already put severe limits on the role of anomalies in the PCAC analysis at high energies.

The excess of radiative gauge-boson decays in the CERN pp Collider was already searched for [95]. Recently, using data taken with the UA1 detector during the 1983 to 1985 running period, a search of the decay signal $W^\pm \rightarrow \pi^\pm\gamma$ was performed, with the conclusion that this width is smaller than $5.8 \times 10^{-2}$ $\Gamma(W^\pm \rightarrow e^\pm\nu)$ [96]. A search for the decays of the $Z$ into $\pi^0\gamma$, $\eta\gamma$, and $\eta'(958)\gamma$ has recently been reported (Table 3.4) by the LEP experiments ALEPH [97] and OPAL [98].

Experimentally it is not possible to discriminate a 45 GeV photon from an equally energetic $\pi^0$ at LEP. Thus a limiting background to the process $Z \rightarrow \gamma\pi^0$ is thus the QED reaction $e^+e^- \rightarrow \gamma\gamma$, with a cross-section of approximately 20 pb for a $\cos \theta$ cut of 0.8 with respect to the beam direction for the detection of photons. This background
is however well known and can be subtracted from a possible signal. Since the decay $Z \rightarrow \gamma\gamma$ is strictly forbidden by Yang's theorem [99] and the contributions to the radiative corrections to $e^+e^- \rightarrow \gamma\gamma$ are negligible [38], any significant deviation from the QED expectation near the $Z$ mass must be due to non-standard decays of the $Z$ boson, such as $\pi^0\gamma$. The $\eta\gamma$ and the $\eta'\gamma$ modes, with charged final states, are more suitable with low background. An estimate of the possible sensitivity for events $\pi^0\gamma$ can easily be performed. The total expected number of such decays for $10^8$ $Z$ corresponds to a total luminosity of about $3000$ pb$^{-1}$, with an error of 1% that might be achieved, thus resulting in about $60000 \pm 250$(stat) $\pm 600$(syst). A 95% upper limit would therefore result in about 1000 events or a possible branching ratio of less then $1 \times 10^{-8}$. A signal with a 5$\sigma$ significance would need at least a branching ratio of $4 \times 10^{-8}$.

### 3.6 Heavy neutral gauge bosons

R. Casalbuoni, F. Feruglio

The aim of the present section is to study the bounds on the parameter space of various models describing heavier gauge vector bosons, derivable at LEP in the high-luminosity option. In particular we will focus on gauge extensions of the standard model as extra-U(1) models with gauge group $SU(2)_L \otimes U(1)_Y \otimes U(1)_Y \subset E_6$ [100] and left–right models with gauge group $SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$ [101]. We will also discuss a model with a breaking of the electroweak symmetry due to a strongly interacting sector (BESS) [102]. All these models have been fully discussed in the framework of the LEP 1 Workshop [103], and in more recent papers where an analytical discussion has been realized [104]. We refer to Refs. [103] and [104] for the description of the models and for the discussion of the formalism.

The observables that are likely to be relevant for LEP running with high luminosity are the asymmetries: the polarization asymmetry for the $\tau$ ($A_{pol}$), and the forward–backward asymmetries for muons, charm and bottom quarks ($A_{FB}^f; f = \mu, c, b$). The aimed for experimental errors on these quantities should go down by about a factor of 2 with respect to the values planned at LEP 1 [105]. More precisely:

<table>
<thead>
<tr>
<th>LEP 1</th>
<th>HLEP</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta_{exp}(A_{pol})$</td>
<td>0.016</td>
</tr>
<tr>
<td>$\delta_{exp}(A_{FB}^\mu)$</td>
<td>0.0035</td>
</tr>
<tr>
<td>$\delta_{exp}(A_{FB}^c)$</td>
<td>0.007/0.005</td>
</tr>
</tbody>
</table>

The high precision reachable with these measurements requires a comparable precision in evaluating the theoretical predictions. In particular, one should in principle take care of all the possible sources of small corrections such as radiative corrections in extended gauge models, finite-mass corrections (for the bottom quark) and so on. However we will be concerned only with the deviations of the previous observables from their standard model values, where most of the above-mentioned corrections act as a second-order effect. Therefore we think that the improved Born approximation [106] previously used [104] can be safely applied also in this context. Attention should be paid in the evaluation of the standard model values. Throughout this section we will use the value 100 GeV for the top-quark mass.
The deviations of the asymmetries can be evaluated analytically starting from the relations:

\[ A_{\text{pol}} = -A_{\mu} \]  
\[ A_{\text{FB}}^{(u, c, b)} = \frac{3}{4} A_{\mu} A_{(u, c, b)} \]  

(3.25)  
(3.26)

with:

\[ A_{l} = \frac{2a_{l} v_{l}}{a_{l}^{2} + v_{l}^{2}} \]  

(3.27)

where \( v_{l} \) and \( a_{l} \) are the vector and axial couplings of the fermions to the physical \( Z \). As discussed in Ref. [104], defining, for the generic observable \( X_{f}^{l} \) associated to the final state \( f \), the deviation from the standard model values as:

\[ \delta X_{f} = X_{\text{model}}^{f} - X_{\text{SM}}^{f} \]  

(3.28)

one finds, in the case of gauge extensions of the standard model:

\[ \delta A_{l} = K_{l}(D_{l} \Delta \rho_{M} + E_{l} \xi_{0}) \]  

(3.29)

where \( \xi_{0} \) is the mixing angle of \( Z' \) and \( Z \), \( \Delta \rho_{M} = \xi_{0}^{2}(m_{Z'}/m_{Z})^{2} \), and the coefficients \( K_{l} \), \( D_{l} \) and \( E_{l} \) are given in Ref. [104]. It is important to notice that \( K_{l} \), \( D_{l} \) are completely fixed in terms of standard model quantities, whereas \( E_{l} \) depends linearly on the couplings of \( Z' \) to the fermions [104]. It is reasonable to assume that for these models the mixing angle goes to zero for infinite \( m_{Z'} \), so that it is convenient to parametrize \( \xi_{0} \) and \( \Delta \rho_{M} \) as:

\[ \xi_{0} = c \left( \frac{m_{Z}}{m_{Z'}} \right)^{2}, \quad \Delta \rho_{M} = c^{2} \left( \frac{m_{Z}}{m_{Z'}} \right)^{2}. \]

(3.29)

For left-right models we will use the parameter space \((c, m_{Z'})\). In the case of the extra-U(1) models one need to specify a further angle \( \theta_{z} \) [107] in order to define the generator \( \tilde{Y} \) in terms of the two extra U(1) contained in \( E_{0} \). The parameter space is then \((c, m_{Z'}, \theta_{z})\).

We recall also that CDF results [108] set the bound \( m_{Z'} > 370 \) GeV for left–right models [109]. Analogous bounds for extra-U(1) models are also given in Ref. [109].

Assuming that no deviations from the standard model predictions are observed at the level of the experimental precision quoted before, we obtained corresponding physical regions in the parameter space. For the left–right models they are given by the following relation:

\[ c_{-} \leq c \leq c_{+} \]

where:

\[ |\delta A_{\text{pol}}| \leq 0.008 \rightarrow c_{\pm} = -0.050 \pm 0.18 \left( \frac{m_{Z'}}{300 \text{ GeV}} \right) \]

\[ |\delta A_{\text{FB}}^{u}| \leq 0.0025 \rightarrow c_{\pm} = -0.050 \pm 0.23 \left( \frac{m_{Z'}}{300 \text{ GeV}} \right) \]

\[ |\delta A_{\text{FB}}^{c}| \leq 0.003 \rightarrow c_{\pm} = -0.067 \pm 0.13 \left( \frac{m_{Z'}}{300 \text{ GeV}} \right) \]

\[ |\delta A_{\text{FB}}^{b}| \leq 0.003 \rightarrow c_{\pm} = -0.080 \pm 0.15 \left( \frac{m_{Z'}}{300 \text{ GeV}} \right) \]
For the extra-U(1) models we give in Figs. 3.27–3.30 the physical region in the plane 
\( e, \theta_2 \) for three values of \( m_{Z'} \) (\( m_{Z'} = 300, 600, 900 \text{ GeV} \)).

In the case of the BESS model, from [104] one gets:

\[
\delta A_{\text{pol}} = -3.48 \left( \frac{g}{g''} \right)^2 \rightarrow \left( \frac{g}{g''} \right) \leq 0.048
\]

\[
\delta A_{\text{FB}}^u = -0.66 \left( \frac{g}{g''} \right)^2 \rightarrow \left( \frac{g}{g''} \right) \leq 0.061
\]

\[
\delta A_{\text{FB}}^b = -2.46 \left( \frac{g}{g''} \right)^2 \rightarrow \left( \frac{g}{g''} \right) \leq 0.035
\]

\[
\delta A_{\text{FB}}^c = -1.87 \left( \frac{g}{g''} \right)^2 \rightarrow \left( \frac{g}{g''} \right) \leq 0.040
\]

In all these cases we can notice that \( A_{\text{FB}}^c \) is the most sensitive observable, followed in the order by \( A_{\text{FB}}^b \), \( A_{\text{pol}} \), and \( A_{\text{FB}}^u \). Moreover, as can be easily verified, the bounds on the ratio \( c/m_{Z'} \), and on \( g/g'' \) scale as \( [\delta_{\text{exp}}(X)]^{1/2} \). Finally, to compare the potential sensitivity of the measurements performed with the high-luminosity option to that reachable at LEP 200, we have considered as an example the deviations of \( A_{\text{FB}}^u \) at \( \sqrt{s} = 190 \text{ GeV} \) for BESS. Unless the heavy vector boson is lighter than 190 GeV, the bounds on \( g/g'' \) are very loose. For instance at \( m_{Z'} = 250 \text{ GeV} \) one gets \( g/g'' \leq 0.20 \) [for \( \delta_{\text{exp}}(A_{\text{FB}}^u) = 0.03 \)], whereas already at LEP 1 one would get from \( A_{\text{FB}}^u \) \( g/g'' \leq 0.073 \). On the other hand at LEP 200 observables such as \( d\sigma/d\cos\theta \) for \( e^+e^- \rightarrow W^+W^- \) could be considered. In the case of BESS almost no deviations are obtained at LEP 200 energies [110].

References


   M.Z. Akrawy et al. (OPAL Collab.), *Phys. Lett.* **244B** (1990) 135.
   B. Adeva et al. (L3 Collab.), *Phys. Lett.* **247B** (1990) 177.

[33] These limits have been set from considerations on the invisible width,


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[73] S. Jadach et al., in Z Physics at LEP 1, CERN /89-08.


[105] D. Treille, see Section 2 of this part of the present report.


### Table 3.1

Compositeness limits

<table>
<thead>
<tr>
<th></th>
<th>Pre-LEP</th>
<th>Present</th>
<th>Eventual [23]</th>
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<tr>
<td><strong>fermionic sector</strong></td>
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<td></td>
<td></td>
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<tr>
<td><strong>Excited fermions</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>$e^*$</td>
<td>$m_{e^*} &gt; 39.8$ GeV [24]</td>
<td>45.0 GeV [32]</td>
<td>45 GeV</td>
</tr>
<tr>
<td>$\mu^*$</td>
<td>$m_{\mu^*} &gt; 29.8$ GeV [24]</td>
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<td>45 GeV</td>
</tr>
<tr>
<td>$\tau^*$</td>
<td>$m_{\tau^*} &gt; 27.9$ GeV [24]</td>
<td>41.2 GeV [32]</td>
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</tr>
<tr>
<td>$\nu^*$</td>
<td>none</td>
<td>30 GeV [33]</td>
<td>45 GeV</td>
</tr>
<tr>
<td>$q^*$</td>
<td>$m_{q^*} &gt; 22.0$ GeV [25]</td>
<td>40 GeV(Λ* = 1 TeV) [33]</td>
<td>90 GeV(Λ* – dep)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Contact Interactions</strong></td>
<td></td>
<td>1.5-4.8 TeV</td>
<td></td>
</tr>
<tr>
<td>$e^4e^4$</td>
<td>Λ &gt; 0.7 - 2.9 TeV [26,27]</td>
<td>–</td>
<td>500 GeV</td>
</tr>
<tr>
<td>$e^3\mu$</td>
<td>Λ &gt; 0.9 - 4.5 TeV [26,27]</td>
<td>–</td>
<td>500 GeV</td>
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<tr>
<td>$e^3\gamma$</td>
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<td>–</td>
<td>500 GeV</td>
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<td>$e\gamma Z$</td>
<td>Λ &gt; 14 GeV [28]</td>
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<td>200 GeV</td>
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<tr>
<td></td>
<td></td>
<td>1,5-4.8 TeV</td>
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<td><strong>bosonic sector</strong></td>
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<td><strong>Scalars</strong></td>
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<td>Hyperpions</td>
<td>$m &gt; 20$ GeV [29]</td>
<td>35 GeV [34]</td>
<td>45 GeV</td>
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<td><strong>Vectors</strong></td>
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<td>424 (525) GeV [35]</td>
<td>500(700) GeV</td>
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<td>Isoscalar $Y$ ($Y_L$)</td>
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<td>500(700) GeV</td>
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<tr>
<td>3-neutral bosons</td>
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<td>–</td>
<td>500(700) GeV</td>
</tr>
<tr>
<td>2 fermions–2 bosons</td>
<td>–</td>
<td>–</td>
<td>Λ &gt; 130 GeV</td>
</tr>
<tr>
<td>4 bosons ($Z\gamma\gamma$)</td>
<td>–</td>
<td>23.52 GeV [36]</td>
<td>Λ &gt; 30 GeV</td>
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Table 3.2
\[ \text{e}^+\text{e}^- \rightarrow \gamma\gamma: \text{Contact term } R_{T T}^2 \]

<table>
<thead>
<tr>
<th>Energy GeV</th>
<th>Chirality</th>
<th>Deviation %</th>
<th>Integrated cross-section GeV</th>
<th>(d\sigma/d\cos\theta) for (\cos\theta = 0.5) GeV</th>
<th>(d\sigma/d\cos\theta) for (\cos\theta = 0.0) GeV</th>
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<tr>
<td>100</td>
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<td>600</td>
<td>640</td>
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<td>325</td>
<td>435</td>
<td>465</td>
</tr>
<tr>
<td></td>
<td>Left</td>
<td>2</td>
<td>415</td>
<td>545</td>
<td>590</td>
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<td>190</td>
<td>Left</td>
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<td>620</td>
<td>825</td>
<td>885</td>
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<tr>
<td></td>
<td>Left</td>
<td>2</td>
<td>790</td>
<td>1041</td>
<td>1117</td>
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</tbody>
</table>

Table 3.3

Some possible efficiencies.
The multiplicative numbers are per b-jet starting from a total sample of \(10^8\) \(Z\).

<table>
<thead>
<tr>
<th>Cuts</th>
<th>No. of hadronic events</th>
<th>No. of (b\bar{b} + b\bar{b}) events</th>
</tr>
</thead>
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<tr>
<td>Event selection</td>
<td>(7 \times 10^7)</td>
<td>(2 \times 10^4)</td>
</tr>
<tr>
<td>(p/E_{beam} &gt; 0.6) lepton/hadron impact parameter</td>
<td>(b)-tag</td>
<td>(3 \times 10^6)</td>
</tr>
<tr>
<td>(p/E_{beam}) s-tag</td>
<td>(3 \times 10^3)</td>
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</tr>
<tr>
<td>High (p/E_{beam}) additional cuts on K tracks</td>
<td>(s)-tag</td>
<td>300</td>
</tr>
<tr>
<td>Vertex detection small lifetimes</td>
<td>(s)-tag</td>
<td>30</td>
</tr>
<tr>
<td>Small mass</td>
<td>(s)-tag</td>
<td>10</td>
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</tbody>
</table>
Table 3.4
The branching ratios of the decays of the neutral intermediate vector boson Z into pseudoscalar mesons and a photon

<table>
<thead>
<tr>
<th>Experiments</th>
<th>BR($Z \rightarrow \pi^0\gamma$)</th>
<th>BR($Z \rightarrow \eta\gamma$)</th>
<th>BR($Z \rightarrow \eta'\gamma$)</th>
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<tr>
<td>ALEPH</td>
<td>$&lt; 4.9 \times 10^{-4}$</td>
<td>$&lt; 4.6 \times 10^{-4}$</td>
<td>$&lt; 2.2 \times 10^{-4}$</td>
</tr>
<tr>
<td>OPAL</td>
<td>$&lt; 3.9 \times 10^{-4}$</td>
<td>$&lt; 5.8 \times 10^{-4}$</td>
<td></td>
</tr>
</tbody>
</table>
Fig. 3.1: Branching ratios for $Z \rightarrow H\ell^+\ell^-$ (solid line) and $Z \rightarrow H\gamma$ (dashed line), relative to that for $Z \rightarrow \mu^+\mu^-$, as functions of the Higgs mass. Here $\ell = e, \mu, \tau$ but the solid line does not sum over families. Full curve: $H\ell^+\ell^-$. Dashed curve: $H\gamma$.

Fig. 3.2: Total cross-section for SUSY Higgs production as a function of $H_2$ mass at the $Z$ peak for $\tan\beta = 2$. Full curve: Associated production without decays. Dashed curve: Bjorken process with decay into $b\bar{b}\nu\bar{\nu}$. Small dashed curve: $H_2 \mu^+\mu^-$. 

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Fig. 3.3: The same as in Fig. 3.2 for tan β = 5.

Fig. 3.4: The same as in Fig. 3.2 for tan β = 10.
Fig. 3.5: The same as in Fig. 3.2 for $\tan \beta = 5$ at $\sqrt{s} = 190$ GeV.

Fig. 3.6: The same as in Fig. 3.2 for $\tan \beta = 10$ at $\sqrt{s} = 190$ GeV.
Fig. 3.7: The lower solid lines delimit the region excluded by present experimental data, the upper ones the region kinematically accessible to $Z$ decays into spin-$\frac{1}{2}$ particles. Dotted lines correspond to $\Gamma(Z \to \tilde{\chi}\tilde{\chi})/\Gamma(Z \to \nu_e\bar{\nu}_e) = 0.1$, dashed lines to $\text{BR}(Z \to \tilde{\chi}\tilde{\chi}) = 10^{-5}$. The three representative values $v_2/v_1 = \sqrt{2}$, 2, and 4 are considered in (a), (b), and (c), respectively.

Fig. 3.8: The dashed lines are contours of constant mass (in GeV) for the lighter chargino, the solid lines correspond to the kinematical limit $m_\tilde{\chi} = m_Z/2$. The values of $v_2/v_1$ are the same as in Fig. 3.7.
Fig. 3.9: Total cross-section for $H\gamma$ production. Full curve: Standard Model prediction. Dashed curves: SCSM for $\Lambda/m_Z = 1, 10, 50$.

Fig. 3.10: Limits on the compositeness scale for anomalous three-photon decay at the $Z$ peak from a scalar particle as a function of its mass.
Fig. 3.11: Limits on the coupling $\lambda/m_{e^+}$ as a function of excited electron mass from single excited electron production at the Z peak.

Fig. 3.12: Bounds in the $(\Lambda, m_{e^+})$ plane from single excited electron production at the Z peak. Full curve: present luminosity. Dashed curve: Pretzel scheme.
Fig. 3.13: The same as in Fig. 3.12 for an excited lepton.

Fig. 3.14: Limits on excited electron exchange from radiative Z decay into electron pairs in the \((\Lambda, m_{\nu'})\) plane for several chiralities \((V, A, L, R)\).
Fig. 3.15: Relative deviation on $\Gamma(Z \to e^+e^-\gamma)$ due to excited electron exchange as a function of the compositeness scale $\Lambda = m_{e^*}$ for several chiralities.

Fig. 3.16: Relative deviation on $d\sigma/d\cos\theta_{\gamma}$ for $Z \to e^+e^-\gamma$ as a function of $\cos\theta_{\gamma}$ due to excited electron exchange for $\Lambda = m_{e^*} = 300$ GeV.
Fig. 3.17: Relative deviation on $d\sigma/dE_\gamma$ for $Z \rightarrow e^+e^-\gamma$ as a function of photon energy $E_\gamma$ due to excited electron exchange for $\Lambda = m_{t'} = 300$ GeV.

Fig. 3.18: Relative deviation on $\Gamma(Z \rightarrow e^+e^-\gamma)$ due to a transverse-transverse contact term $R_{TT}^2$ as a function of the compositeness scale $\Lambda$ for several chiralities.
Fig. 3.19: Bounds in the \((\Lambda, m_\tau)\) plane from two-photon production at \(E = 190\text{ GeV}\) asking for a 5% deviation from the standard model. Full curve: limit from integrated cross-section. Dashed curve: limit from \(d\sigma/d\cos \theta\) for \(\cos \theta = 0.5\). Small-dashed curve: limit from \(d\sigma/d\cos \theta\) for \(\cos \theta = 0\).

Fig. 3.20: Constraints on NHL coupling strength parameters that arise from low-energy experiments: (1) beam-dump experiments at CERN and Fermilab, valid for \(N_e\) as well as \(N_\mu\) [67], (2) Fermilab dimuon search experiments, valid for \(N_\mu\) [69], (3) monojet searches at PEP, valid for \(N_e\) [68]. In all cases we have neglected family mixing. We have also displayed the limits on the NHL coupling strength parameters that can be reached for different number of \(Z\) plotted as a function of the NHL mass. This is evaluated for \(N_\tau\), neglecting generational mixing. LEP limits on \(N_e\) and \(N_\mu\) may also be obtained from the analysis presented in Ref. [59]. Here we have included only leptonic final states, including NHL decays into \(\tau\)'s with the corresponding detection efficiencies. The horizontal line shows the constraint implied by weak universality.
Fig. 3.21: Typical branching ratio for the combined process of NHL production in $Z$ decays and subsequent NHL decay into all visible channels, as a function of the NHL mass. These curves have been estimated in the model given in the second paper of Ref. [71] for different masses of the associated $\tau$ neutrino of 10 MeV, 1 MeV, and 100 keV (solid, dashed, and dotted curve, respectively). In all cases the cosmological constraint on the primordial abundances of light relic neutrinos is obeyed as a result of the existence of the invisible neutrino decay channel, $\nu' \rightarrow \nu + \text{Majoron}$. We have assumed the simplest two-family neutrino mixing scheme and a value for a mass of the daughter neutrino of 6 eV, consistent with all existing limits, including the non-observation of neutrinoless double-beta decay. For additional curves, see Ref. [60].
**Fig. 3.22:** Attainable branching ratio for the process $Z \rightarrow e\tau$. This estimate takes into account all the constraints on the parameters describing the leptonic weak interaction. Here we assumed a simplified two-family mixing scheme. The CP-violating asymmetry in this decay can be of order unity.

**Fig. 3.23:** (a) The electron energy spectrum as a function of $X = E_{e^\pm}/E_{\text{beam}}$, for $\tau$ decays without the detector resolution. (b) The histogram shows the electron energy spectrum from $\tau$ decays with $X \geq 0.9$, but now including detector effects. The points with error bars show the signal (for a branching ratio of $10^{-5}$) plus the background for a calorimeter resolution of $5\%/\sqrt{E} + 1\%$ and a total of $10^7 Z$ decays.
Fig. 3.24: The expected number of background events (rising curves) for calorimeter resolutions of $(5-20)/\sqrt{E} + 1\%$ requiring that the measured electron energy exceeds $98\%$ of the beam energy. The falling curves indicate the required branching ratio of $Z \rightarrow e\tau$ for a $5\sigma$ effect; it scales proportional to $1/\sqrt{N}$ ($N$ = the number of $Z$'s).

Fig. 3.25: Typical experimental signature for the decay $Z \rightarrow b\bar{s}$.

Fig. 3.26: The number of background events for the signal $Z \rightarrow b\bar{s}$ (or $s\bar{b}$) as a function of the number of $Z$'s produced at a high-luminosity LEP.
Fig. 3.27: Allowed region in the \((c, \theta_2)\) plane from a measurement of \(A_{\text{pol}}\) assuming 
\(\delta_{\exp}(A_{\text{pol}}) = 0.008\). Dashed, dotted and full lines correspond to \(m_{Z'} = 300, 600, 900\) GeV, respectively. Regions inside a closed line are excluded.

Fig. 3.28: Same as in Fig. 3.27 for \(A_{\text{FB}}^\mu\) assuming 
\(\delta_{\exp}(A_{\text{FB}}^\mu) = 0.0025\).
Fig. 3.29: Same as in Fig. 3.27 for $A_{FB}^b$ assuming $\delta_{\exp}(A_{FB}^b) = 0.003$.

Fig. 3.30: Same as in Fig. 3.27 for $A_{FB}^c$ assuming $\delta_{\exp}(A_{FB}^c) = 0.003$. 

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4 SPECIAL FEATURES OF b\bar{b} PRODUCTION ON THE Z RESONANCE

A. Djouadi, G. Girardi, W. Hollik, F.M. Renard\(^1\) and C. Verzegnassi\(^1\)

4.1 Introduction

The forthcoming high-precision measurements at e\(^+\)e\(^-\) colliders appear as a nearly unique tool to uncover new physics via indirect effects, i.e. through definite deviations of the experimental results from the theoretical predictions at one-loop of the Minimal Standard Model (MSM). In fact, thanks to a remarkable combined experimental–theoretical effort [1, 2], the latter predictions are now known to a sufficient accuracy, once the value of the Z mass is given, to allow for a search of discrepancies at the level of one per cent or less.

On the theoretical side, the uncertainties are related to still unknown parameters, and mostly come from the top quark (in the MSM), the Higgs boson contribution being generally still marginal in this scheme, as was shown in Section 2.6. Throughout this section, we will ignore the small differences induced, by the Higgs contribution to the vacuum polarization, in the partial widths, in the asymmetries, and in the W/Z mass ratio, which are of the order of ΔZ as given in Eq. (2.11). In the MSM, the top quark contributes in two quite different quantities that might have an effect on several observables. The first one is the oblique correction to the gauge boson propagators, usually called [3] Δρ(0)

\[
Δρ(0) = \frac{Π_{ZZ}(0)}{m_Z^2} - \frac{Π_{WW}(0)}{m_W^2}
\]

that represents, in fact, the one-loop correction to the ρ parameter [4] and, for sufficiently large \(m_t\), behaves like

\[
Δρ(0) \sim \frac{α m_t^2}{π m_Z^2}
\]

(a smaller, negative Higgs contribution is also present) becoming as large as 1% when \(m_t \simeq 2 m_Z, m_H \leq 1 \text{ TeV}\). The second effect appears as a one-loop correction to the Zb\bar{b} vertex, stemming from virtual t–W exchange [5]. Using \(α, G_μ\), and \(m_Z\) as input parameters and taking into account the running of the electric charge, the partial decay width of the Z into a b\bar{b} pair is [6]:

\[
Γ_b = Γ_b^{(0)} \left\{ 1 + \frac{19}{13} [Δρ(0) + Δ_b^{(0)}] \right\}
\]

where

\[
Γ_b^{0} = \frac{α(m_Z^2)}{16 \cdot s_0^2 c_0^2} \cdot \frac{β(3 - β^2)}{2} \left( \frac{4}{3} s_0^2 - 1 \right)^2 + β^3 \right) \times (1 + δ_{\text{QCD}})
\]

where \(β\) is the usual threshold factor given by \(β = \sqrt{1 - μ^2}\), \(μ = 2 m_b/m_Z\), the parameter \(s_0^2 = 1 - c_0^2\) is defined through

\[
s_0^2 = \frac{1}{2} \left[ 1 - \sqrt{1 - \frac{4πα(m_Z^2)}{\sqrt{2} m_Z^2 G_μ}} \right] = \frac{1}{2} \left[ 1 - \sqrt{1 - \frac{4(38.45 \text{ GeV})^2}{m_Z^2}} \right]
\]

\(^1\) Convener
and the QCD correction is, to a very good approximation, given by:

$$\delta_{QCD} = \frac{\alpha_s}{\pi} \left[ 1 + \frac{27}{13} \mu^2 \ln \left( \frac{4}{\mu^2} \right) \right].$$  (4.6)

For large $m_t$ the vertex correction behaves as:

$$\Delta_{bV}^{(t)} \simeq -\frac{20}{19} \frac{\alpha}{\pi} \left( \frac{m_t^2}{m_Z^2} + \frac{13}{6} \ln \frac{m_t^2}{m_b^2} \right)$$  (4.7)

A rather peculiar property of this vertex correction is that, owing to a cancellation between the vectorial and the axial parts of the $Zb\bar{b}$ coupling, it does not affect the related forward–backward asymmetry $A_{FB}^b$:

$$A_{FB}^b = \frac{2v_0}{1 + v_0^2} \frac{1 + v_0/2}{\beta^2 + \frac{2}{9}(3 - \beta^2)(1 + v_0/2)^2} \times (1 + \delta_{QCD}^{FB}) \simeq \frac{18}{13} v_0$$  (4.8)

with $v_0 = 1 - 4 \delta_0^2 \ll 1$ the (reduced) vectorial coupling of the electron to the $Z$ and where, to a very good approximation, the QCD correction is:

$$\delta_{QCD}^{FB} = -\frac{\alpha_s}{\pi} \left( 1 - \frac{4}{3} \frac{m_b}{m_Z} \right).$$  (4.9)

Note that, contrary to what happens in $\Delta \rho(0)$, the Higgs does not contribute to $\Delta_{bV}^{(t)}$.

From Eqs. (4.3) and (4.7) one realizes that the vertex correction $\Delta_{bV}^{(t)}$ is of opposite sign to $\Delta \rho(0)$ and, owing to the non-negligible logarithmic term, is of larger size than the oblique correction $\Delta \rho(0)$. In fact, for $m_t \simeq 2m_Z$, $|\Delta_{bV}^{(t)}|$ is almost equal to 2%, i.e. nearly twice as large as $\Delta \rho(0)$. This already suggests that isolating the full vertex component [Eq. (4.7)] would be an interesting alternative way in the MSM of searching for virtual top effects in measurable quantities, compared with the more ‘conventional’ way of isolating the $\Delta \rho(0)$ effect, as pointed out in previous papers [6, 7].

As soon as one considers extensions of the MSM, the differentiation between $\Delta \rho(0)$ and $\Delta_{bV}^{(t)}$ becomes deeper. Models with extra families, ‘non-canonical’ extra Higgses, extra vector boson(s), might all contribute (both at one-loop and at tree level) to a single ‘effective’ measurable quantity [8]:

$$\nabla \rho \equiv \Delta \rho(0) + \Delta \rho^{\text{New Physics}}.$$  (4.10)

In general, if one discards for instance the cases of extra Higgses or of charged $W'$, the new contributions to $\nabla \rho$ are positive [8, 9], i.e. they enhance the pure top contribution of the MSM. However, such additional terms are completely independent of $m_t$. Thus, a substantial value of $\nabla \rho$ does not necessarily imply a correspondingly large value of $m_t$, in models with New Physics. Conversely, if $m_t$ were known, one might try to derive, from a measurement of $\nabla \rho$, information on its possible New Physics content. The copiousness of possible contributing models would however make this task a not easy one, unless some extra, complementary information is added.

In the case of $\Delta_{bV}^{(t)}$, extra families, non-canonical neutral Higgses, extra $Z$ would not contribute whereas charged Higgses would be important [10]. This would be the case of a non-supersymmetric model with one extra doublet of Higgses characterized by two
independent vacuum expectation values $v_1$ and $v_2$ providing masses to up and down quarks respectively. In particular, the contribution to the vertex is roughly proportional to $m_t^2$, inversely proportional to $\tan^2 \beta$, where

$$\tan \beta = v_2/v_1, \quad (4.11)$$

and weakly dependent on the charged Higgs mass. This contribution has the same sign as that of the MSM top quark and thus enhances the sensitivity of the vertex to large $m_t$ values. Taking $\tan \beta \simeq 1$ and $m_{h^+} = 100$ GeV, one finds for instance an extra term that, for $m_t = 150$ GeV, is numerically equal to $\sim \frac{1}{3}$ of the MSM contribution of Eq. (4.2).

Models like SUSY, which naturally contain charged Higgses, might thus also modify the MSM expectations. If no other extensions of the MSM are considered, one can conclude that the possible effect of New Physics will be that of defining an effective observable quantity:

$$\nabla_{bV} = \Delta_{bV}^{(t)} + \Delta_{bV}^{(SUSY)}. \quad (4.12)$$

If the considered SUSY model is the so-called ‘minimal’ one $\equiv$ MSSM [11], the extra contributions have two interesting features [7]:

a) they are negative, i.e. they enhance the pure top contribution of the MSM, and

b) they are still dominantly proportional to $m_t^2$. In this sense, $\nabla_{bV}$ represents a more genuine ‘top indicator’ than $\Delta \varrho(0)$. Also, if $m_t$ were known, the possible New Physics content of $\nabla_{bV}$ would be much simpler to examine than for $\Delta \varrho(0)$, because of the aforementioned features.

The previous discussion indicates the reasons why we believe that a measurement of $\nabla_{bV}$ represents an interesting and unconventional way of obtaining information on electroweak physics, both within the MSM and within the MSSM. An obvious statement is that the proper quantity to achieve this goal is the partial width of $Z$ into $b\bar{b}$ quarks, or other quantities containing this width, provided that measurements of sufficient accuracy are achievable. This, however, does not represent a sufficient condition for the previous programme, unless it is possible at the same time to isolate the vertex correction from other contributions coming e.g. from other kinds of New Physics that confuse the $\nabla_{bV}$ effect. In particular, models with one extra $Z$ of either extended gauge origin [12–14], or composite $Z$ origin [15], might introduce a ‘mixing’ effect that would act in this sense and make the situation confuse.

Our aim here is to show that if a next phase of ‘high luminosity’, corresponding to $\sim 10^7$–$10^8$ produced $Z$, were available at LEP 1 [16], a full and self-consistent strategy might be developed, which would allow from a measurement of the $Zb\bar{b}$ width and forward–backward asymmetry, the $\nabla_{bV}$ effect to be unambiguously isolated from the mixing effect of a new $Z$ and to measure them both to a typical $\sim 1\%$ accuracy. Moreover, it would also be possible to obtain an independent measurement of the oblique block $\nabla_{\rho_1}$ to an accuracy of few per mille, comparable to that which can be provided by a determination of $m_W$ with a precision of $\sim 100$ MeV.

Thus, at the end of the game, a drastic picture would emerge, either in favour or against the MSM, that should orient future experimental searches.
4.2 Effects of supersymmetry on the Zb\bar{b} vertex

In the MSSM, the scalar Higgs sector has essentially the same features (with much less freedom for the parameters) as in the two-Higgs doublet model previously considered and thus its contribution to the Zb\bar{b} vertex will be formally identical. However, the contribution of the 'genuinely' supersymmetric particles will have to be computed, and added to the previous one. This implies an evaluation of both the neutralino and the chargino exchange diagrams. Actually, the first ones have already been computed in the literature [17]. Their effect seems completely negligible in the MSSM, and we shall accept this result. The explicit contribution from the chargino sector, corresponding to the diagrams represented in Fig. 4.1, is not available. We have therefore carried out its computation, to be completely self-contained, and we give here a discussion of the results.

The numerical outcome of our analysis depends on a number of parameters. The non-genuinely supersymmetric part, Fig. 4.1a, contains the top, the charged Higgs masses, and \tan \beta defined by Eq. (4.11). For the latter quantity, the model favours the range

\[ 1 \leq \tan \beta \leq 10. \]  

(4.13)

The genuine SUSY contribution Fig. 4.1b depends also on \tan \beta. Moreover, it contains the stop mass and the parameters \(m, \mu\) that enter the chargino mass matrix. The actual situation is, luckily, less complicated since several theoretical or experimental bounds can be used, that make our task relatively simpler.

To start with, we shall adopt the criterion of 'naturality' [18], which implies the limits:

\[ 0 \leq m \leq 200 \text{ GeV} \]  

(4.14)

\[ |\mu| \leq 250 \text{ GeV}. \]  

(4.15)

Within this reduced region, there are the existing experimental bounds provided by the absence of observation of supersymmetry at LEP 1 and at other machines. A very recent analysis [19] gives the limits shown in Fig. 4.2 for the typical value tan \beta = 4. Similar figures can be drawn for other values of tan \beta, like the ones that we shall consider\(^2\). Thus, for every value of tan \beta, we have considered in the (\(m, \mu\)) plane the area enclosed between the experimental boundaries of Ref. [19] and the extreme new boundaries given by Eqs. (4.14) and (4.15). All our numerical results, for simplicity, will be presented for two values of tan \beta = 1, 10, but the prescription to extrapolate to different tan \beta is very simple and will be indicated. We shall also give our predictions for a stop and a charged Higgs mass of 100 GeV, that would make these objects, in principle, visible at LEP 200. The results are rather smooth with the latter masses, and reasonable variations around 100 GeV would not affect our conclusions appreciably.

With the described limitations on the parameters, our analysis becomes relatively simpler. In particular, the following general features emerge:

1) In all the considered range, the contribution to the Zb\bar{b} vertex coming from the chargino sector is always of the same sign as that of the charged Higgs sector (this would not be true for values of (\(m, \mu\)) beyond the naturality bounds, Eqs.(4.14) and (4.15). Thus, the full MSSM contribution to the vertex adds coherently to that of the MSM top and enhances it. Note that the dominant part of the chargino contribution is proportional

\[^2\text{We thank G. Ridolfi and F. Zwirner for making such figures available to us}\]
to $m_t^2$; this is also true of the full charged Higgs contribution. In this more general sense, the Zbb vertex acts as a 'genuine' $m_t$ indicator: a large value of the $\nabla_{bV}$ vertex correction can never be obtained with a light top quark, contrary to the case of the oblique correction $\nabla_\rho$.

2) The maximum chargino contribution in the considered range is higher than the contribution of the charged Higgses. When these two terms are added to the MSM one, a maximum contribution to $\nabla_{bV}$ is obtained that is about three times larger than that of the MSM alone, for $\tan \beta \sim 1$.

In Table 4.1, we present separately the contributions to $\nabla_{bV}$ from the different sources for $m_t = 150 \text{GeV}$ [the SUSY contributions for others values of $m_t$ can be obtained by simply rescaling our results by a factor $(m_t/150)^2$]. Note that the charged Higgs contribution also scales as $(\cot \beta)^2$ and the chargino one as $1 + (\cot \beta)^2$, thus remaining practically constant as soon as $\tan \beta \geq 3$.

Although still qualitative, the previous discussion shows, we believe, the great interest of a determination of the Zbb vertex via a high-precision measurement of $\Gamma_b$ (or of $\Gamma_b/ \Gamma_t$). However, to achieve such a goal, one has to isolate the $\nabla_{bV}$ term from other possible competitor effects that generally enter the previous observables. One such quantity would be the $\nabla_\rho$ block, as Eq. (4.3) shows. Another, and in principle even more dangerous, effect would come from the class of models with one extra Z described in Refs. [12, 15] (that such models can give sizeable contributions to the various widths has already been discussed in previous references [20, 21]).

Three kinds (at least) of possible New Physics effects, of quite different origins, must thus be separated; this requires a well-defined and self-contained strategy. In the next subsection, we shall show how this strategy can actually be built and used in a high-luminosity programme like that of Ref. [16].

### 4.3 A strategy for disentangling the $Z'$ mixing effect

In order to work out a self-consistent scheme to isolate the effects of a certain type of New Physics, it is opportune to recall what are the possible manifestations of models with one extra Z. As has already been exhaustively discussed in the literature [8, 21], two kinds of effects may arise on top of the Z resonance. The first one simply redefines the $\rho$ parameter by adding a term

$$\delta_\rho^{(c)} = \sin^2 \theta_M \left[ \frac{1}{\epsilon} - 1 \right] \sim \frac{\theta_M^2}{\epsilon},$$

(4.16)

where $\epsilon = m_Z^2/m_{Z'}^2$, and $Z$, $Z'$ are the two physical mass eigenstates. The second one (≡ $\delta_M$) is a pure mixing effect, $\delta_M \approx \theta_M$. Analogous properties characterize the effect of a $Z'$ generated by a strongly interacting electroweak sector [14], or by a composite Z [15], as fully discussed in previous papers [22]. The mixing effect $\delta_M$ is a tree-level effect that modifies the Z couplings to fermions and cannot be reabsorbed into either $\nabla_\rho$ or $\nabla_{bV}$. As such, it is a 'genuine' $Z'$ manifestation on the Z resonance, which for certain models can be sizeable (say, up to a relative 10% [22]).

From this short preliminary discussion, a possible identification strategy has now become reasonably clear. It consists in generating special combinations of observables to isolate contributions that are specific of the various proposed MSM extensions, so that a minimum number of unknown parameters contribute, which may be reliably fixed or
severely constrained. More precisely, we shall first define observables that are both \(\nabla_\rho\) and \(\nabla_{bV}\) free, and are therefore ideal tools to measure the \(Z'\) mixing (\(\delta_M\)) effect. Once the latter will be either understood or under control, we shall consider observables that are either \(\nabla_\rho\)-free and \(\nabla_{bV}\)-dependent, or vice versa. In this way, at the end of a sequential chain of measurements, all performable on the \(Z\) resonance via a high-luminosity programme, one can get independent estimates of the three separate quantities, to a precision that will be specified in the following. This would lead to firm, unbiased conclusions on the investigated models, which we shall analyse in a systematic way.

To proceed with our programme, we first show how to isolate the mixing \(\equiv \delta_M\) effect. This can actually be done, in principle, in the first phase (\(\sim 10^6\) produced \(Z's\)) at LEP 1 by considering the following two \(\nabla_\rho\)- and \(\nabla_{bV}\)-free observables [23]:

\[
\gamma - \frac{1}{3} A_\tau \equiv \left[ \gamma - \frac{1}{3} A_\tau \right]^{\text{MSM}} + \zeta \tag{4.17}
\]

\[
\xi - \frac{1}{2} A_\tau \equiv \left[ \xi - \frac{1}{2} A_\tau \right]^{\text{MSM}} + w. \tag{4.18}
\]

Here \(\gamma = \frac{9}{\alpha(m_Z)} \left[ \Gamma(Z \to \mu\mu)/m_Z \right]\), \(A_\tau\) is the final \(\tau\) polarization [24] and the ratio

\[
\xi = \frac{m_W^2}{m_Z^2 c_\theta^2} \tag{4.19}
\]

is to be measured with high accuracy at \(p\bar{p}\) colliders and, later, at LEP 200.

In the MSM, the theoretical predictions for the two quantities in Eqs. (4.17) and (4.18), are the following (we allowed 90 GeV \(\leq m_t \leq 250\) GeV, to be rather conservative):

\[
\left[ \gamma - \frac{1}{3} A_\tau \right]^{\text{MSM}} = 1.018 \pm 0.003 \tag{4.20}
\]

\[
\left[ \xi - \frac{1}{2} A_\tau \right]^{\text{MSM}} = 0.939 \pm 0.004. \tag{4.21}
\]

The smallness of the theoretical uncertainty is related to the absence of the \(\nabla_\rho\) and \(\nabla_{bV}\) terms, which leaves an almost negligible residual \(m_t, m_H\) dependence, to be added to the uncertainty coming from the redefinition of the electric charge \(\alpha(m_Z)\) [25]. Thus, the only possibly sizeable source of error will be the experimental one, which in a conventional LEP 1 phase should be approximately \(\pm 0.020\) for Eq. (4.20) and \(0.015\) for Eq. (4.21), assuming \(\delta m_W \approx 300\) MeV.

The mixing effects on Eqs. (4.17) and (4.18) in the different models with one extra \(Z'\) have been thoroughly investigated in Ref. [23], and we do not insist on them here. In the plane of the \((\zeta, w)\) variables that represent deviations from the (known) MSM predictions, the 'genuine' \(Z'\) effects are shown in Fig. 4.3 together with the expected experimental error. Note that, indeed, effects induced by different types of models are rather well distinguished by the choice of variables. In particular, gauge models and models without Higgses [14, 15] are almost completely separated.

With a high-luminosity phase, it will become possible to also measure with high accuracy \(\Gamma_{Z\to b\bar{b}} \equiv \Gamma_b\) and \(A^b_{FB}\). We shall assume, in what follows, that these observables can be measured with the following accuracies:

\[
\frac{\delta(\Gamma_b/\Gamma_l)}{\Gamma_b/\Gamma_l} = \pm 0.01; \quad \delta A^b_{FB} = \pm 0.003. \tag{4.22}
\]
As an immediate first consequence of these assumptions, we can introduce \((\Gamma_4 \equiv \Gamma_{\text{had}} - \Gamma_b)\) a new \(\nabla_{p'} \nabla_{bV}\)-free variable:

\[
D \equiv \frac{6}{23} \left[ \frac{1}{4} \frac{\Gamma_4}{\Gamma_t} - \frac{26}{27} \frac{A^b_{FB}}{A_{FB}} \right] \equiv D^{\text{MSM}} + \delta D
\]  

(4.23)

for which

\[
D^{\text{MSM}} = 1.039 \pm 0.001.
\]

(4.24)

With a precision in the measurement of \(R' \equiv 3/59(\Gamma_{\text{had}}/\Gamma_t)\) of \(\pm 0.005\) [16], the experimental error on \(D\) would be:

\[
\delta D^{(\text{exp})} \simeq \pm 0.006,
\]

(4.25)

much larger than the theoretical uncertainty in the MSM.

Also, in a high-luminosity phase, it will be possible to use the variable \(w_b\), instead of \(w\) [Eq. (4.18)], by simply replacing \(A_r\) by the (theoretically equivalent) \(13/9A_{FB}^b\):

\[
\xi - \frac{13}{18} A_{FB}^b = \left[ \xi - \frac{13}{18} A_{FB}^b \right]^{\text{MSM}} + w_b.
\]

(4.26)

This would be meaningful since one of the final goals of the high-luminosity programme is to improve the accuracy, leading to a final \(\sim 70\) MeV error on the \(W\) mass determination at LEP 200 [16] and, consequently, to a precision \(\delta w_b \simeq 0.004\), comparable with the theoretical error.

In the \((w_b, \delta D)\) plane, the various models with one extra \(Z\) correspond to the regions depicted in Fig. 4.4. In addition to the property of largely separating the various models, the use of these two variables leads to a much better test of the predictions. This can be seen by comparing in each case the limits on the 'mixing' parameters (in the case of models without Higgs, these would actually be mass ratios) that can be derived from a negative search in the 'conventional' LEP 1 phase \((\xi, w)\) variables and in a 'high-luminosity' phase \((w_b, \delta D)\) variables.

As can be seen from Figs. 4.5 and 4.6, in the case of extra gauge models, the gain is impressive, leading to a severe final bound, \(|\theta_M| \leq 0.01\) in case of negative searches. Analogous improved results are obtainable for the models without Higgs, as Table 4.2 shows. In general, for all the models with one extra \(Z\), the bounds obtained in the high-luminosity phase would be at least a factor of 2 stricter with respect to the ones derived in the 'conventional' LEP 1 phase.

In the next section, we shall show that this is sufficient to carry on our subsequent programme of measuring \(\nabla_{bV}\) without introducing any appreciable theoretical uncertainty.

### 4.4 An unbiased measurement of the \(Zb\bar{b}\) vertex

With the \(Z'\) mixing effect under control, isolating the \(\nabla_{bV}\) term is relatively simple. One has to choose observables that are \(\nabla_p\)-free and \(\nabla_{bV}\)-dependent, and to impose on the residual \(\delta_M\) effect the constraints derived in the previous section and represented in Figs. 4.5 and 4.6 and in Table 4.2. The choice of the proper observable is mainly dictated by convenience. In Ref. [6] it was shown that the \(\nabla_p\)-free combination

\[
M = \frac{3}{13} \left[ \frac{\Gamma_b}{\Gamma_t} - \frac{26}{27} \frac{A^b_{FB}}{A_{FB}} \right]
\]

(4.27)
(the numerical coefficient $3/13$ is chosen such as to normalize $M$ to one) enjoys several interesting features that make it rather special. We briefly review here the main properties of Eq. (4.29), adding the presentation of the explicit calculation of the full supersymmetric vertex, which did not appear in Ref. [6].

Consider the mixing contribution from a $Z'$ of extended gauge origin first. In the most general case of an $E_6$ generated extra $U(1)$ [12], this can be written as:

$$\delta M^{(E_6)} \simeq \frac{8}{13} \theta_M \left( \frac{5}{\sqrt{6}} \cos \beta_{E_6} + \frac{\sqrt{5}}{3 \sqrt{2}} \sin \beta_{E_6} \right)$$  \hspace{1cm} (4.28)

where $\cos \beta_{E_6}$ parametrizes the symmetry-breaking pattern to the final $SU(2)_L \times U(1)_Y \times U(1)_Y$, situation.

This mixing contribution is severely bounded by the previous analysis summarized in Fig. 4.5, from which it is possible to set the rigorous bound (or uncertainty):

$$|\delta M^{(E_6)}| \leq 0.005 \cdot$$  \hspace{1cm} (4.29)

For a $Z'$ of left–right symmetry origin, an analogous estimate can be performed. The theoretical contribution is:

$$\delta M^{(LR)} \simeq \theta_M \frac{8}{13} \left[ \frac{1}{\alpha_{LR}} + \alpha_{LR} \right],$$  \hspace{1cm} (4.30)

where

$$\frac{2}{3} \leq \alpha_{LR} \leq \sqrt{2}.$$  \hspace{1cm} (4.31)

A glance at Fig. 4.6 shows that, within this range, the unpredictable shift of Eq. (4.30) remains always limited to

$$|\delta M^{LR}| \leq 0.01 \cdot$$  \hspace{1cm} (4.32)

The bound is saturated for values of $\alpha_{LR} \geq 1$, while for $\alpha_{LR}$ values at the edge, $\alpha_{LR} \simeq \sqrt{2}/3$, it decreases to about 0.005.

In conclusion, the residual theoretical uncertainty due to the possible existence of one extra $Z$ of the considered extended gauge origin would be, at most, of 1%, i.e. smaller than (or equal to) the realistically expected experimental error on $M$ that can be estimated from Eq. (4.22) to be:

$$\delta M^{(exp)} \simeq 0.01.$$  \hspace{1cm} (4.33)

Similar, even more optimistic, conclusions apply to the case of a $Z'$ either due to a strongly interacting electroweak sector [14], or to a composite $Z$ [15]. In fact, in most of these cases, the $Z'$ contribution vanishes exactly owing to the properties of the quantity $M$, that is $\nabla_\rho$-free and built out of ratios of observables, as already discussed in Ref. [6]. Thus, for our next purposes, we shall consider from now on the $Z'$ contribution to $M$ as known, with an uncertainty of at most 1%, and include it as a $\delta Z'$ correction in the theoretical expression of Eq. (4.27). With this convention, we shall consequently write:

$$M = M^0 \left[ 1 + \frac{19}{13} \nabla_{LV} \right],$$  \hspace{1cm} (4.34)

where

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\[ M^0 = 1.036 \pm 0.004 + O(\alpha_s) + \delta Z' \]  
\[ (4.35) \]

and the \( O(\alpha_s) \) term has been given previously in Eqs. (4.6) and (4.9).

From the discussion given in this section, it turns out that the determination of the \( Zb\bar{b} \) vertex given by Eqs. (4.34) and (4.35), is of a rather general nature. It is valid in a class of theoretical models that includes either non-canonical neutral Higgses or new families (besides \( Z' \), whose contribution can always be controlled). The only possible source of enhancement to the MSM effect Eq. (4.7) would therefore come from SUSY diagrams that we have estimated in Section 2 for the particularly appealing case of the MSSM. We now give a quantitative discussion of the possible size of such an effect, keeping in mind that the limit for observability is placed by Eq. (4.33) at the 1% 'threshold'.

Table 4.3 shows the effect of the MSM alone and the possible maximum effect of the MSSM on \( M \) for the representative value \( \tan \beta = 1 \) and for several \( m_t \) masses. From inspection of this table, one draws the following conclusions:

1) In the MSM, values of \( m_t \) beyond 150 GeV would produce visible effects. For \( m_t = 200 \) GeV the shift from \( M \) (\( m_t = 90 \) GeV) would be of 2%. Note that this effect would measure the top mass in the (not minimal) Standard Model independently of the value of the \( \rho \) parameter, owing to the property of the chosen observable \( M \). Therefore, the possibility of a top mass equal to (or even slightly larger than) \( \sim 200 \) GeV cannot be a priori discarded, as stressed in a recent analysis where the top mass effect and the \( \rho \) parameter were independently fitted [26]. If we accept the 'extreme' bound \( m_t \leq 230 \) GeV, which is probably a pessimistic one, we see that the SM top effect cannot be, anyway, larger than 3%.

2) For values of \( \tan \beta = v_2/v_1 \) not far from 1, the maximum allowed effect of the MSSM can be much larger than that of the SM alone. For instance, for a top mass of 150 GeV, the negative shift from \( M \) (\( m_t = 90 \) GeV) could be of 4% for \( \tan \beta \simeq 1 \), and for \( m_t = 200 \) GeV, the same shift would be of 8%, much beyond the tolerable values in the SM. This value becomes larger for smaller \( m_t \) values (for \( m_t = 50 \) GeV, \( m_t \) = 200 GeV, it would be of \( \sim 10\% \)). Thus, for conceivable values of the parameters, one would obtain an impressive, characteristic and, to our knowledge, unique virtual signal of minimal supersymmetry in a 'standard' \( e^+e^- \to qq \) reaction.

The previous example has been chosen to illustrate our strategy with a particularly simple observable. In principle, though, one could repeat the same procedure considering different \( \nabla_{V} \)-free and \( \nabla_{V_{bV}} \)-dependent quantities. We quote here a list of several possible candidates:

\[ q = R^2_{Z} - \frac{13}{54} A_{FB}^{b} \simeq q^0 \left( 1 + \frac{1}{3} \nabla_{bV} \right) \]  
\[ (4.36) \]

\[ S = 2 \left[ \frac{\Gamma_b}{\Gamma_{\tau}} - \frac{1}{4} \frac{\Gamma_4}{\Gamma_{\tau}} \right] \simeq S^0 \left( 1 + \frac{38}{3} \nabla_{bV} \right) \]  
\[ (4.37) \]

\[ V_{LR} = \frac{72}{31} \xi + \frac{118}{155} R^0_{Z} - \frac{65}{31} M - \frac{28}{15} A_{FB}^{b} = V^0_{LR} \left( 1 - \frac{95}{31} \nabla_{bV} \right) \]  
\[ (4.38) \]

\[ V_{Es} = \frac{13}{9} \left( M - \frac{4}{9} S \right) \simeq V^0_{Es} \left( 1 - \frac{95}{27} \nabla_{bV} \right) \]  
\[ (4.39) \]

where the \( q^0 \ldots \) are the analogues of \( M^0 \) [Eq. (4.34)] and are all normalized to \( \sim 1 \). Their QCD corrections can be easily computed using Eqs. (4.6) and (4.9) and are again completely under control. Next, Table 4.4 shows the precision on \( \nabla_{bV} \) (which would be

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\sim 0.007 using the variable M) that could be obtained by a measurement of these variables with a relative accuracy of 1\% for \Gamma_b/\Gamma_e and of 0.005 on \mathcal{R}'_z, together with some \delta Z' effects for a mixing angle \left|\theta_M\right| \leq 0.01. Note one special property of the variables \(V_{E_b}\) and \(V_{LR}\): while \(V_{E_b}\) is blind to LR models effects, \(V_{LR}\) is blind to \(E_6\) effects. This leads to the particularly impressive Fig. 4.7, showing that in the (\(\delta V_{LR}, \delta V_{E_b}\)) plane, i.e. in the plane of the deviations (\(V_{LR} - V_{LR}^0, V_{E_b} - V_{E_b}^0\)), the \(\nabla \delta V\) effect would belong to a direction totally separated from those of the extra \(Z'\) models. Note also that for all those variables that are \(\nabla \rho\)-free and are defined by ratios of observables, i.e. \(g, S\), and \(V_{E_b}\), the effect of the \(Y, Z^*,\) and \(Z_V\) (see Refs. [14, 15]) is identically zero, as already stressed in Ref. [8]. This leads to a great simplification of the analysis, and explains the motivations of the particular specific choice of the different combinations, which is allowed by the copiousness of the available variables.

The previous discussion has shown more quantitatively than in Section 1 the reasons why we believe that a high-luminosity programme at LEP as that illustrated in Ref. [16] would be interesting and efficient to uncover New Physics. To conclude our paper in a self-consistent way, we still have to examine two points. The first one is related to the fact that, rather than \(b\) quarks, one will see in general \(b\)-jets. A general discussion of how to extract from the realistic data the theoretical \(b\)-quantities has been already given and can be found in previous references [27], showing that the extra uncertainty introduced in this way is also completely under control, at the realistic experimental conditions of Ref. [16]. The second point is related to the fact that the high-luminosity programme would also provide an increase in luminosity of a factor of \(\sim 2\) at the WW production threshold at LEP 200 [16].

4.5 An accurate measurement of the oblique correction \(\nabla \rho\)

In principle, in a high-luminosity phase, and with the \(Z'\) mixing effect under control, a measurement of the full block \(\nabla \rho\) might be provided by the \(\nabla \delta V\)-free observable \(A_{FB}^{0}\), whose theoretical expression in the general class of models that we have considered reads:

\[
A_{FB}^{0} = [A_{FB}^{0}] + \frac{27}{13} \nabla \rho \tag{4.40}
\]

where

\[
[A_{FB}^{0}] = [0.084 \pm 0.002] + O(\alpha_s) + \delta Z' \tag{4.41}
\]

where \(\delta Z'\) is known to \(\sim 0.005\) [6], and the \(O(\alpha_s)\) correction is given in Eqs. (4.8) and (4.9).

As pointed out in Section 1, several models of New Physics can contribute to \(\nabla \rho\), with both signs. Thus, it is important to separate in what follows the topic of a precise determination of \(\nabla \rho\) from that of the consequent theoretical interpretation. One sees from Eq. (4.40) that \(A_{FB}^{(b)}\), with an overall uncertainty of \(\sim 0.006\), would lead to a determination in \(\nabla \rho\) with a precision:

\[
\delta(\nabla \rho) = \pm 0.003 \tag{4.42}
\]

In making this estimate, we have assumed an experimental error of 0.003 and we have combined it with the theoretical error from the renormalization of the electric charge [25] and from \(\delta Z'\).
This precision on $\nabla \rho$ should be compared with the corresponding value obtained from a measurement of the W mass. In fact, the theoretical expression of the $m_W/m_Z$ ratio can be written as:

$$\frac{\frac{3}{2}}{m_Z^2 c_0^2} = [0.998 \pm 0.003] + \frac{3}{2} \nabla \rho^{(W)}$$

(4.43)

where, if extra charged W are absent, $\nabla \rho^{(W)}$ is the same quantity as the one that appears in Eq. (4.40). Equation (4.43) implies an experimental error on $\nabla \rho^{(W)}$

$$\delta \nabla \rho^{(W)} \approx \frac{4 \delta m_W}{3 m_W}$$

(4.44)

Note that, in this case, no other source of theoretical error ($\delta Z', \alpha_s, \Delta \alpha, ...$) is present in the determination of $\nabla \rho$ via $\xi$.

To be better than $A^b_{FB}$ at $\pm 0.006\%$ (overall) $m_W$ should thus be measured to better than $\sim 150$ MeV accuracy. This would be achievable at LEP 200 with a high-luminosity phase that would reduce the experimental error on $m_W$ to a value of $\leq 70$ MeV [16], and thus would lead to a determination of $\nabla \rho$ close to $\pm 0.002$!

Therefore, within this program, two independent and extremely accurate determinations of $\nabla \rho$ will be available. A meaningful theoretical interpretation of these measurements requires a thorough investigation, to be given elsewhere. Here we shall only give a summary of the salient features of several models that would contribute to $\nabla \rho$, namely:

1) SUSY. The supersymmetric contribution to $\nabla \rho$ has been computed by several authors [17], not always with an explicit discussion of the complete $t, b$ doublet with physical (mixed) stop states. For the sake of completeness, we have computed this effect, and we give here the result in the MSSM. All the other possible contributions in this model are known to be negligible [17], and we shall omit them. Thus, we can write in practice:

$$\nabla \rho^{(MSSM)} \simeq \nabla \rho^{(t, b)}$$

(4.45)

Varying the parameters of the model within their allowed range and taking into account the existing experimental constraint [28]

$$m_\delta \gtrsim 100-150 \text{ GeV}$$

(4.46)

we were able to set a conservative limit:

$$0 \leq \nabla \rho^{(MSSM)} \leq 0.004$$

(4.47)

Thus, the (positive) MSSM contribution to $\nabla \rho$ would not produce spectacular effects in any case.

2) Models with one extra neutral gauge boson. In general [Eq. (4.16)], these models contribute positively to $\nabla \rho$ in a model-dependent way, since one can write:

$$\theta_M = P \epsilon ; \quad \epsilon = m_Z^2/m_Z^2,$$

(4.48)

so that

$$\nabla \rho^{(Z')} \simeq P^2 \epsilon$$

(4.49)

where $P$, which depends on the Higgs sector of the model, is of $O(1)$. 145
3) Models with \(Z'\) of alternative origin. These can contribute to \(\nabla \rho\) with both signs, the contribution still being of \(O(\epsilon)\).

4) Non-SUSY models with extra Higgses. These can contribute to \(\nabla \rho\) with both signs, either at tree level (non-'canonical' Higgses) or at one loop (extra doublets). They are not always simply or directly related to observable quantities, nor deeply motivated by theoretical arguments. Still, a negative shift in \(\nabla \rho\) might lead to a reconsideration of their role, particularly if independent analyses ruled out possible alternative \(Z'\).

5) As a final example, we consider the effect of one extra charged \(W\). This would only affect the \(\nabla \rho \wedge\) derived from the \(W\) mass, and not the \(\nabla \rho\) that appears in \(A_{\text{FB}}^b\). Thus, a sizeable difference between these two quantities might be an interesting alternative way to reveal such extra charged sector.

4.6 Concluding remarks

We have examined in this section some of the physics possibilities of a project of high luminosity at LEP 1, illustrated in Ref. [16].

Via a systematic procedure that isolates and constrains different effects in succession, we have been able to prove that experiments in this phase would not miss:

a) a top of at least 150 GeV,

b) an extra gauge \(Z'\) mixing angle of at least 0.01,

c) anomalous contributions to \(\nabla \rho\) of the order of a few per mille. From this point of view, it should be kept in mind that a determination of \(A_{\text{FB}}^b\) would give the same information as that provided by a measurement of the hadronic longitudinal polarization \(A_{\text{LR}}^{\text{had}}\), with the formal identification \(A_{\text{FB}}^b \equiv 9/13 A_{\text{LR}}^{\text{had}}\), as already discussed in this report. Thus, \(A_{\text{FB}}^b\) to \(\pm 0.006\) (overall) would be as good as \(A_{\text{LR}}^{\text{had}}\) to \(\pm 0.009\) (overall).

Finally, we have seen that the virtual effects of supersymmetry might be spectacular and have rather specific signature. We believe to have shown, therefore, that such a programme looks quite promising and, to some extent, unique for challenging the Minimal Standard Model and several of its candidate extensions.

References


[16] See the general discussion given in Section 1 of this part of the present report.


[18] This is discussed e.g. by R. Barbieri et al. in Ref. [2]


[22] R. Gatto et al., in Ref. [2].

[23] F. Boudjema and F.M. Renard, in Ref. [1].


[25] See e.g. Z. Wgs, in Ref. [1].


[27] For a general discussion of the existing bounds on $m_t$, see A. Blondel, preprint CERN-EP/90-10. This paper also provides the bound $m_t \leq 203$ GeV, which is valid in an extended 'not minimal' Standard Model.


Table 4.1

Contributions to \(-\nabla_{bV}\) from the Standard Model, charged Higgses and charginos sectors of the MSSM (for the charginos, the maximum allowed contribution \(\equiv M\) is given for \(m_t = 150\ \text{GeV}, m_{\tilde{t}} = m_{H^+} = 100\ \text{GeV}, m_x \geq 45\ \text{GeV}\)).

<table>
<thead>
<tr>
<th>(\tan\beta)</th>
<th>(-\nabla_{bV}^{\text{SM}})</th>
<th>(-\nabla_{bV}^{(H^+)})</th>
<th>(-\nabla_{bV}(M))</th>
<th>(-\nabla_{bV}^{\text{MSSM}}(M))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.012</td>
<td>0.005</td>
<td>0.015</td>
<td>0.032</td>
</tr>
<tr>
<td>10</td>
<td>0.012</td>
<td>(5 \times 10^{-5})</td>
<td>0.006</td>
<td>0.018</td>
</tr>
</tbody>
</table>

Table 4.2

Limits on the parameters of models with one \(Z'\) of alternative (composite \(Z\)) origin from 'standard' and high-luminosity LEP 1 experiments. The notations are those of Ref. [22].

<table>
<thead>
<tr>
<th></th>
<th>(Y)</th>
<th>(Y_L)</th>
<th>(Z^*)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEP 1</td>
<td>(m_Y &gt; 500\ \text{GeV})</td>
<td>(m_{Y_L} &gt; 700\ \text{GeV})</td>
<td>(m_{Z^*} &gt; 600\ \text{GeV})</td>
</tr>
<tr>
<td>HLEP 1</td>
<td>(m_Y &gt; 900\ \text{GeV})</td>
<td>(m_{Y_L} &gt; 900\ \text{GeV})</td>
<td>(m_{Z^*} &gt; 1500\ \text{GeV})</td>
</tr>
</tbody>
</table>

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Table 4.3

Effect of the variation of the top mass on $M$ in the Standard Model and maximum allowed effect in the MSSM. For simplicity we neglected the (constant) contributions from $\alpha_s, \theta_M$. The values of the MSSM parameters are fixed as in Table 4.1.

<table>
<thead>
<tr>
<th>$m_t$</th>
<th>$M^\text{SM}_{(\alpha_s=\theta_M=0)}$</th>
<th>$M^\text{MSSM}_{(\alpha_s=\theta_M=0)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>1.03</td>
<td>1.02</td>
</tr>
<tr>
<td>150</td>
<td>1.02</td>
<td>0.99</td>
</tr>
<tr>
<td>200</td>
<td>1.01</td>
<td>0.95</td>
</tr>
<tr>
<td>230</td>
<td>1.00</td>
<td>0.93</td>
</tr>
</tbody>
</table>

Table 4.4

Mixing contributions of the various models with one extra $Z$ to the four observables defined by Eqs. (4.36)–(4.39) and related bounds (in brackets) when $|\theta_M| \leq 0.01$ and $\epsilon \leq 10^{-2}$. The accuracy on $\nabla_{L^V}$ corresponds to the experimental error on $q, S, V_{Ee}, V_{LR}$ obtainable at HLEP.

<table>
<thead>
<tr>
<th></th>
<th>$E_0$</th>
<th>$L-R$</th>
<th>$Y_L$</th>
<th>$\delta \nabla_{L^V}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta q$</td>
<td>$\sim \theta_M (\cos \beta_{Ee} + \sin \beta_{Ee})$</td>
<td>$\sim \theta_M \frac{1 + \alpha^2_{LR}}{2\alpha_{LR}}$</td>
<td>$\sim \frac{5}{6} \epsilon$</td>
<td>$\pm 0.015$</td>
</tr>
<tr>
<td></td>
<td>$\sim (\pm 0.015)$</td>
<td>$\sim (\pm 0.010)$</td>
<td>$\sim (+8 \times 10^{-3})$</td>
<td>$\pm 0.015$</td>
</tr>
<tr>
<td>$\delta S$</td>
<td>$\sim \theta_M (2 \cos \beta_{Ee} - \frac{5}{2} \sin \beta_{Ee})$</td>
<td>$\sim \theta_M \frac{1 + \alpha^2_{LR}}{\alpha_{LR}}$</td>
<td>$\sim \frac{4}{3} \epsilon$</td>
<td>$\pm 0.008$</td>
</tr>
<tr>
<td></td>
<td>$\sim (\pm 0.030)$</td>
<td>$\sim (\pm 0.020)$</td>
<td>$\sim (+1.3 \times 10^{-2})$</td>
<td>$\pm 0.008$</td>
</tr>
<tr>
<td>$\delta V_{Ee}$</td>
<td>$\sim 3 \theta_M \sin \beta$</td>
<td>$\sim \frac{1}{3} \epsilon$</td>
<td>$\sim (+3 \times 10^{-3})$</td>
<td>$\pm 0.015$</td>
</tr>
<tr>
<td></td>
<td>$\sim (\pm 0.030)$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\delta V_{LR}$</td>
<td>$\sim \theta_M (-2\alpha_{LR} + \frac{4}{3\alpha_{LR}})$</td>
<td>$\sim (-1.6 \times 10^{-2})$</td>
<td>$\pm 0.007$</td>
<td>$\pm 0.007$</td>
</tr>
</tbody>
</table>
Fig. 4.1: The set of considered diagrams contributes to the Zb̄b vertex. The subset (a) gives the result of one extra doublet of charged Higgses, Ref. [10].

Fig. 4.2: Allowed region in the \((m, \mu)\) parameter space, taken from Ref. [19]. The dotted and point-dotted lines delimit the region already excluded by negative searches at LEP 1.
Fig. 4.3: Mixing effects on the \((w, \zeta)\) variables of several models with one extra \(Z\). Three different experimental errors on \(w\), corresponding to \(\delta m_w = \pm 600, 300, 100\) MeV are shown.

Fig. 4.4: Same as in Fig 4.3, in the plane of the \((w_b, \delta D)\) variables.
Fig. 4.5: Bounds on the mixing angle for a general $E_6$ model obtainable from a conventional (LEP 1) and a high-luminosity LEP phase, assuming three different determinations of $m_W$ as in Figs 4.3 and 4.4. The same full line in the left-hand corner corresponds both to (LEP 1, $\delta m_W = 100$ MeV) and to (HLEP, $\delta m_W = 300$ MeV).

Fig. 4.6: Same as in Fig. 4.5, for a general left–right symmetric model.
Fig. 4.7: Standard and non-standard contributions to the $\nabla \rho$-free combination of observables $V_{LR} = -\frac{65}{31} M + \frac{118}{155} \rho + \frac{72}{31} w$ and $V_{E_6} = -\frac{4}{9} S + \frac{13}{9} M$. We represent deviations $\delta V_{LR}$ and $\delta V_{E_6}$ due to i) new vector bosons of gauge ($E_6, R - L$) or alternative origin (only $Y_L$ contributes). The open domains are those allowed before LEP. ii) vertex corrections, $\nabla_{bW}$: Black domains correspond to the standard $t-W$ exchange ($90 \leq m_t \leq 230$ GeV) and the hatched domains to the maximum SUSY enhancement ($\tan \beta \approx 1$). The expected final accuracy at HLEP is also indicated in the figure by the cross in the right-hand lower corner.
5 THE HEAVY-QUARK
FRAGMENTATION FUNCTION

B. Mele and P. Nason

5.1 Introduction

The QCD production properties of b-flavoured hadrons at LEP have a considerable impact
on the possibility of studying b physics. In fact, the harder the fragmentation function,
the easier it will be to determine the b energy, so that also the study of lifetimes and
oscillations becomes easier.

While the study of the b fragmentation function at lower-energy e⁺e⁻ colliders has
been somewhat limited by the lack of statistics [1],[2],[3], at LEP there are already some
results [4],[5], and one certainly expects substantial improvements in the future.

From a theoretical point of view, it was realized very early that, according to the usual
QCD picture of hadronization, heavy-flavoured hadrons should retain a much larger part
of the momentum of their parent quark than light flavoured ones [6],[7],[8],[9]. In most
hadronization models, one ends up with a typical momentum fraction of the hadron with
respect to the quark of order

\[ z = \frac{(E + P_{||})_{\text{had}}}{(E + P)_{q}} \approx 1 - \frac{m_L}{m_Q} \tag{5.1} \]

where \( m_L \) is a typical light mass scale (of the order of the \( \rho \) mass) and \( m_Q \) is the mass of
the heavy quark. This is the case, for example in the Peterson [10] model, in the cluster
fragmentation model [11] and in some string fragmentation models [12],[13],[14].

It turns out that, also from a purely perturbative viewpoint, the fragmentation func-
tion of a heavy quark must be hard. In fact, the mass of a heavy quark provides a cut-off
to collinear gluon emission. Roughly speaking, the heavier the quark the harder it is to
share its momentum with a massless gluon. For this reason, the fragmentation function
of a heavy enough quark is calculable to an arbitrary order in the strong coupling con-
tant (evaluated at the scale of the heavy quark mass). The calculation at fixed order in
perturbation theory is, however, not adequate. Large logarithms of the ratio \( s/4m^2 \) must
also be resummed, so that one has an expansion of the form:

\[
\frac{d\sigma}{dx} = \sum_{j=0}^{\infty} a_j(x)[\alpha_s(m_Q)\log(s/4m_Q^2)]^j + \\
\sum_{j=0}^{\infty} \alpha_s(m_Q)b_j(x)[\alpha_s(m_Q)\log(s/4m_Q^2)]^j + ... , \tag{5.2}
\]

where \( x \) is the fraction of energy of the final quark. The first sum is usually referred to
as the leading contribution, and the second sum is the next-to-leading term. Neglected
subleading effects are of order $\alpha_s(m_Q)$ in the leading calculation, and $\alpha_s^2(m_Q)$ in the
next-to-leading one.

While the leading result has been known for a long time [15], the calculation of the
next-to-leading contribution has been completed only recently [16].

Of course, perturbative calculations neglect all effects which are suppressed by powers
of the ratio $\Lambda_{QCD}/m_Q$. For a heavy enough quark this is justified. For $b$ and especially
for $c$ quarks, however, one expects that these non-perturbative effects may be important
and, in order to give a realistic description of the data, they should be properly modelled.

5.2 Phenomenology of heavy-quark fragmentation

A number of $e^+e^-$ annihilation experiments report results on the fragmentation function
of heavy quarks. In Ref. [3] there is a quite complete discussion of the various methods
and variables that have been adopted by experimental groups.

Different definitions of the fragmentation variable are found in the literature. A commonly
used variable is the one defined in Eq. (5.1). Alternatively, one can use the more
physical definition

$$x_E = \frac{E_{\text{had}}}{E_{\text{beam}}}$$  \hspace{1cm} (5.3)

In lower-energy $e^+e^-$ experiments, there also exists the alternative of defining
an $x_{\gamma} = 2E_{\text{had}}/\sqrt{s_{\text{eff}}}$ corrected for initial-state radiation [3]. We find it more convenient to use the
definition:

$$x = 2E_{\text{had}}/E_{\text{cm}}$$  \hspace{1cm} (5.4)

where $E_{\text{had}}$ is the energy of the heavy-flavoured hadron in the hadronic centre-of-mass
system, and $E_{\text{cm}}$ is the total energy of the hadronic system. Since at LEP initial-state
radiation effects are usually small, there is probably very little difference between the
variables $x_E$ (used also by the L3 experiment [4]) and $x$. In the literature one often
finds results formulated in terms of the variable $z$, defined as the ratio of the hadron to
the parton momentum. Different variants of this definition are used, according to the
procedure adopted to define the parton momentum [3]. While the distribution in $x$ is
physical, i.e. it can in principle be measured with arbitrary precision, the distribution in
$z$ depends upon the specific Monte Carlo model used. It is therefore preferable to always
refer to the distributions in $x$.

A recent review of heavy-quark fragmentation models is given in Ref. [17]. There (on
p. 299) one can also find a comparison between HERWIG 3.2 and JETSET 7.1. In the
HERWIG model the fragmentation function for the $b$ turns out to be much softer than
in JETSET, while for the $c$ the difference is less pronounced. Both models incorporate
leading-order perturbative fragmentation effects. The difference between them could arise
from the non-perturbative hadronization part, which is much harder in the JETSET
model. The data favour a softer fragmentation function than in JETSET.

In Ref. [16] we have performed a first principle calculation of the heavy quark frag-
mentation function. Our aim was to include next-to-leading-order corrections, in order
to determine to which extent the leading-order prediction can be trusted, and to include
all perturbative effects, such as the emission of soft gluons, which can affect the fragmentation function at very large values of $x$. In the following section we describe our result.

5.3 Next-to-leading results for the fragmentation function

The next-to-leading calculation of Ref. [16] includes the following effects:

- Leading-order evolution, that is to say the sum of all terms of the form 
  $[\alpha_s \log(s/m_Q^2)]^n$ ($n = 1, 2, \ldots$) in the perturbative expansion.

- Next-to-leading order terms, i.e. all terms of the form $\alpha_s[a_n \log(s/m_Q^2)]^n$.

- Sudakov effects in the evolution. These are terms of the perturbative expansion which are enhanced by powers of $\log (1 - x)$, and are therefore important at large $x$. These effects also appear in the evolution of light hadron fragmentation functions [18]. They produce a softening of the fragmentation function at large $x$.

- An effective mass reduction effect. This is caused by terms of the form $\alpha_s \log (1 - x)$, not arising from evolution, important at large $x$. It is specific to heavy quark production [16]. Because of this effect, the heavy quark behaves as if it was lighter in the emission of soft gluons. These effects also soften the fragmentation function.

In Fig. 5.1 we plot the second, fifth, and tenth moments of the fragmentation function $D_b(x)$, at $E_{cm} = 91$ GeV for $\Lambda_{MS}^5 = 0.2$ GeV and $m_b = 5$ GeV, versus $\mu$, the scale of separation of low ($\approx m_Q$) and high momenta in the problem. The moments of $D_b(x)$ are defined as

$$D_b^N = \langle x^{N-1} \rangle = \int D_b(x)x^{N-1}dx.$$  \hspace{1cm} (5.5)

The fragmentation function $D_b(x)$ is defined as

$$D_b(x) = \frac{1}{\sigma_{b\ell}} \sum_{\ell} \frac{d\sigma_{b\ell}(x)}{dx},$$  \hspace{1cm} (5.6)

where the sum is over all the bottom-flavoured hadrons. We have used the approximation of neglecting all powers of $m_Q^2/s$. Therefore, our $x$ variable can be defined either as $x = 2E_{had}/E_{cm}$ or $x = 2P_{had}/E_{cm}$, and our results should be trusted only for $x > 2m_b/E_{cm}$.

If one had summed up all the orders of the perturbative expansion, the result would not depend upon $\mu$. At any finite order in perturbation theory, one has instead a residual $\mu$ dependence. It can be seen from Fig. 5.1 that the scale dependence is milder for the next-to-leading result than for the leading one. This indicates that the perturbative expansion is well behaved. Since $\mu$ must be taken of order $m_b$, one can see that choosing, for example, $\mu = m_b/2$, $m_b$, $2m_b$ the corresponding uncertainty in the result is considerably smaller for the next-to-leading curves than for the leading-order ones. We also notice that
the next-to-leading calculation does not drastically alter the leading-order one [16], thus confirming the validity of leading-order QCD models.

In Fig. 5.2 we show the pure QCD result for the $b$ fragmentation function. The three curves in the figure correspond to different choices of $\mu$. In Fig. 5.3 we give the fragmentation function for different values of $\Lambda$. As can be seen, the sensitivity to $\mu$ is larger. Varying the bottom mass between 4.5 and 5.5 GeV produces small changes, which can be ignored if compared to the $\mu$ sensitivity.

In Table 5.1 we show the average value of $x$ for different choices of $\mu$ and $\Lambda$, for $m_b = 5$ GeV and $E_{cm} = 91$ GeV, as obtained from the purely perturbative calculation. The values range from 0.7 to 0.83. The L3 collaboration [4] gives $\langle x \rangle = 0.69 \pm 0.04$ and ALEPH [5] gives $\langle x \rangle = 0.67(0.04, -0.03)$. The measured values are somewhat lower than the purely perturbative results. They are however not inconsistent with them.

One can notice that in all cases, the fragmentation function predicted by perturbative QCD peaks for very large values of $x$. The position of the peak depends strongly upon $\mu$ and $\Lambda$. In the range of parameters of Table 5.1, however, it is always above $x = 0.92$. The perturbative calculation therefore suggests that the peak of the fragmentation function is at a very large value of $x$, even if the average value of $x$ can be relatively moderate, as can be seen from Table 5.1. We cannot exclude however the presence of non-perturbative effects, which could shift the peak to lower values of $x$, by a factor of order $1 - m_L/m_Q$, where $m_L$ is few hundred MeV. We also studied the effect of the inclusion of a non-perturbative fragmentation term parametrized as

$$D_{\text{NP}}(x) = A(1 - x)^\alpha x^\beta, \quad \text{with} \quad \frac{1}{A} = \int (1 - x)^\alpha x^\beta dx,$$  \hspace{1cm} (5.7)

to be convoluted with the perturbative one. We find that for $\alpha = 1.3$ this parametrization is fairly close to the Peterson fragmentation function, if the $\epsilon$ parameter is tuned so that the position of the peaks is the same. The average value of $x$ arising from our non-perturbative component is given by

$$\langle x \rangle_{\text{NP}} = \frac{1 + \beta}{\alpha + \beta + 2}. \hspace{1cm} (5.8)$$

For illustration, we choose $\beta = 19.7$, so that $\langle x \rangle_{\text{NP}} = 0.9$. This is consistent with the assumption $\langle x \rangle_{\text{NP}} = 1 - m_L/m_Q$, and corresponds to $m_L = 0.5$ GeV. For $\Lambda = 0.2$ GeV and $\mu = m_b$, we get a full (perturbative and non-perturbative) mean value of $x$:

$$\langle x \rangle_{\text{full}} = \langle x \rangle_P \langle x \rangle_{\text{NP}} = 0.695. \hspace{1cm} (5.9)$$

In Fig. 5.4 we plot the convolution of the perturbative term with the non-perturbative one in Eq. (5.7), together with the purely perturbative result.

### 5.4 Conclusions

The study of $b$ meson oscillations and decay in a high-luminosity phase of LEP 1 is strongly dependent upon the hardness of the $b$ fragmentation function. We have completed a next-to-leading calculation of the heavy-quark fragmentation function, including
also all leading Sudakov effects. The result is reasonably stable under scale changes, thus suggesting that the perturbative expansion works well. Perturbation theory alone suggests a hard fragmentation function. Furthermore, the shape of the perturbative fragmentation function peaks at very large values of $x$, but has a substantial tail that gives a relatively moderate average value of $x$. We have also given some indications on how non-perturbative effects could alter our conclusion.

References

Table 5.1: $(x)$ for different choices of $\Lambda$ and $\mu$

<table>
<thead>
<tr>
<th>$\Lambda$</th>
<th>$\mu = m_b/2$</th>
<th>$\mu = m_b$</th>
<th>$\mu = 2m_b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1 GeV</td>
<td>0.782</td>
<td>0.806</td>
<td>0.828</td>
</tr>
<tr>
<td>0.2 GeV</td>
<td>0.736</td>
<td>0.772</td>
<td>0.801</td>
</tr>
<tr>
<td>0.3 GeV</td>
<td>0.699</td>
<td>0.746</td>
<td>0.781</td>
</tr>
</tbody>
</table>
Fig. 5.1: $\mu$ dependence of the second, fifth, and tenth moments of the fragmentation function, both for the leading-order and the complete (next-to-leading) result. The values of the parameters are: $E_{cm} = 91$ GeV, $\Lambda^{HS}_S = 0.2$ GeV and $m_b = 5$ GeV.

Fig. 5.2: The $b$ fragmentation function for three different choices of the scale $\mu$. 

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Fig. 5.3: The $b$ fragmentation function for three different choices of $\Lambda_{\text{MS}}^2$.

Fig. 5.4: Effect of the inclusion of a non-perturbative term. The dashed line is the next-to-leading pure QCD result. The solid line is obtained by convoluting a nonperturbative term of the form $(1-x)^\alpha x^\beta$ with the next-to-leading QCD result.
6 B DECAYS


6.1 General comments

This section concerns the physics possibilities for the study of B-meson decays at a high-luminosity extension of LEP (HLEP). There is widespread interest in the community regarding present and future studies of B decays, because of the rich variety of electroweak effects exhibited there. There is a strong likelihood that one or more B-factories will be built in the future in order to explore this physics in more depth. Would HLEP make a good B-factory?

The Z decays are rich in B mesons [1, 2]: $10^8 Z$'s would produce a sample of about $31 \times 10^6 B_{d,u}$ mesons, $4.5 \times 10^6 B_s$ mesons, and $2 \times 10^6$ b baryons. This is an order of magnitude more than has been produced at present machines [CESR (Cornell), DESY (Hamburg)]. The production in Z decays has some inherent advantages and disadvantages over production at threshold. Among the advantages are the production of all the varieties of b hadrons and the resolvable flight path (about 2 mm) of the high-energy B meson. Disadvantages include the loss of the beam energy constraint from threshold production, and the difficulty of full reconstruction with the LEP detectors. These issues are explored in more detail by the subgroup responsible for the comparison of different experimental facilities. However, it is clear that HLEP would be able to offer insight into a variety of problems that other machines could not study. Our task here is to outline what the B-decay physics programme at HLEP would include.

It is likely that a luminosity increase for LEP will have the biggest impact on the study of B physics. The study of important aspects of B decays remains luminosity-limited, and the proposed order of magnitude increase will allow qualitatively new types of physics to be explored: $10^8 Z$'s at LEP would be equivalent to a $L = 10^{33}$ cm$^{-2}$ s$^{-1}$ B-factory, with the added advantage of producing all the species of B hadrons. The time-scale for HLEP, the availability of proven and well-tested detectors, a small-diameter beam pipe, vertex detector, and the high energy, all ensure that HLEP will provide the first, and/or unique, information on many of these important issues.

6.2 Overview of B-physics goals

The physics menu for the b-quark and its decay is quite varied. It is perhaps best to break the goals into two broad categories: i) topics that bear directly on the underlying electroweak theory, most often with the possibility of confirming or refuting the Standard Model, ii) topics that bear on the dynamics of weak decays and on our ability to calculate these processes. The first category is, of course, the primary one, but the second is also important, as understanding the weak dynamics allows us to make a better connection with the electroweak theory in many applications.

In the first category there is a range of physics connected with the Kobayashi–Maskawa (KM) matrix: the $b \to c e \nu$ decay and the b lifetime are governed by $V_{bc}$; semileptonic
b → uνν decays reveal V_{ub} most directly; B_d−B̄_d mixing is driven by the element V_{td};
whilst B_s−B̄_s mixing is governed by V_{ts}. We need to study each of these in order to
constrain and check the KM weak mixing structure. The KM elements also predict large
CP violation in the B system. This is a crucial prediction to test. It could easily be false
if there is new physics, beyond the Standard Model, which is responsible for CP violation.
The Standard Model is also tested in rare decays that proceed through loop diagrams
such as B → K^*γ, B_s → φγ. Non-standard theories can predict enhancements in these
processes. Finally, the Standard Model predicts that b-quarks that come in Z → b̄b are
highly polarized. Observation of this polarization is likely to be difficult, but if possible
would be worth while.

In the study of heavy-quark dynamics, there are many decay processes that reveal
different aspects of b decay. For example, the observation of the process B → τν would
allow the extraction of f_B (once V_{ub} is known). This constant also plays a major role in
B–B̄ mixing, and its measurement would give better values of V_{td} and/or constraints on
m_t. Knowledge of exclusive semileptonic and non-leptonic rates restricts the models used
to predict branching ratios, and ultimately increases our ability to predict CP violation
asymmetries. Lifetime differences between the mesons have been predicted in various
models of weak decay. There are other radiative decays (B → D^*γ, B → J/ψ + γ), which
occur at tree level. In addition, the B_c remains to be discovered, and little is known about
b baryons.

It is not likely that any one B-facility will be able to accomplish all of these goals.
Threshold factories using the Φ(4S) will likely do well on measurements of B_{u,d} properties
but will not study lifetime differences, B_s, B_c, or baryons. Hadron machines or HLEP
produce all the particles, but will miss some decay modes because of detection problems.

6.3 b̄b tagging

To exploit the potentialities of b physics, it seems necessary that the separation of b̄b
events from other hadronic events be achieved with a high purity and good efficiency.
When the charge of the quark is needed—as in the case of asymmetry measurements or B^0
mixing—one has to use either leptons from semileptonic decay or the charge measurement
of reconstructed fragments carrying the quark quantum numbers: the tagging efficiencies
shown in Tables 2.4 and 6.1 [3] are generally at or below the 10% level, with typically
90% purity. More severe double-tagging procedures can also be used if needed (for Γ_{b̄b}
for instance).

However, if the quark charge is of no relevance, different methods with much higher
efficiencies can be implemented. The key role is then played by the microvertex detectors,
and a study is made of the track offsets that are present in the event. The latter is usually
complemented by the inspection of other features: leptons and identified hadrons with
appropriate p_T cuts, topological variables, etc. Normally, double tagging is performed by
the technique of multidimensional analysis. For a general study of b̄b final states, the
full event, i.e. jets on both sides, can be used. If, however, the aim is to search for rare
and peculiar b decays, we have to leave one side free and tag on the other side only.
A detailed discussion can be found in Ref. [4]. Based on a simplified but nevertheless
realistic simulation of the detector measurements, this study has shown that quite high
purities and efficiencies can be expected for $b\bar{b}$ tagging. Two different treatments give, for instance

i) 85% efficiency, 85% purity (Table 6.2);

ii) up to 99% purity, with only 70% efficiency.

These numbers refer to $b\bar{b}$ events which fall within the acceptance of the microvertex detector ($\sim 75\%$).

In the results of Table 6.2 the role of the microvertex detector is a major one: the simplified simulation quoted here treats the relevant measurement errors correctly, with $r_{\text{min}} = 9$ cm, but ignores the problems of pattern recognition, which should not be important when three layers are used. Tagging on one side only will reduce the performances slightly. The numbers quoted above are indicative, and only data will provide a firm answer. However it is legitimate to expect that a very efficient isolation of $b\bar{b}$ states will be possible in the LEP detectors, equipped with second-generation microvertex detectors.

### 6.4 $B_s$ mixing

In the Standard Model, $B_s$–$ar{B}_s$ mixing must be large, given the known values of $B_d$–$ar{B}_d$ mixing and the fact that the KM elements satisfy $V_{ts} > V_{td}$. The prediction is

$$\frac{x_s}{x_d} = \frac{|V_{ts}|^2}{|V_{td}|^2} \frac{F_{B_s}^2}{F_{B_d}^2} = \frac{1}{\lambda^2 |1 - \rho e^{i\delta}|^2} \frac{F_{B_s}^2}{F_{B_d}^2},$$

where

$$x \equiv \Delta m / \Gamma,$$

$$x_d = 0.70 \pm 0.13,$$

$$\lambda = 0.22.$$

With present estimates of $|\rho| \approx 1/2$ (from the apparent observation of $b \rightarrow u\nu\nu$) and $F_{B_s}/F_{B_d} \approx 1.2 \pm 0.1$, this requires $x_s > 9$. There are two levels that we need in order to test this prediction. The most important is to verify that $x_s$ is in fact large, so as to test whether it is the Standard Model that is responsible for $B$–$ar{B}$ mixing. If $x_s$ were to be small, then we would have evidence for non-standard physics. At the next level, once the Standard Model is presumed to be verified by the large $x_s$, we are interested in its precise value in order to obtain more constraints on the KM elements.

The first of these goals, i.e. verifying that $x_s$ is large, should already be accomplished at LEP 1 [1, 2]. There the integrated dilepton signal $N(\ell^+\ell^+) + N(\ell^-\ell^-)$ will measure the combined effect of $B_d$ and $B_s$ mixing. Previous studies have indicated that this will allow the extraction of the mixing fraction

$$r = \frac{x^2}{2 + x^2}$$

for $B_s$, with an error of about 25%. This is enough to verify that $x_s$ is large, but is extremely insensitive to its precise value.

In order to actually observe $x_s$, we need to observe the oscillations as a function of time. This involves the following steps: i) The initial flavour of $B_s$ versus $\bar{B}_s$ must be identified
by tagging on the $B_{u,d,s}$ meson on the opposite side of the event, using semileptonic $b$ decay. ii) The $B_s$ must be identified through full or partial reconstruction (see below). iii) The proper time of the $B_s$ must be known to sufficient accuracy. Previous studies have shown that more than 500 observed $B_s$'s are needed in order to reconstruct an oscillation pattern. The proper-time resolution is

$$\frac{\Delta t}{\tau} = \sqrt{\left(\frac{\Delta \ell}{L_0}\right)^2 + \left(\frac{t}{\tau}\right)^2 \left(\frac{\Delta E}{E}\right)^2},$$

where $L_0$ is the mean decay length of the $B$ and $\Delta \ell$ and $\Delta E$ are the uncertainties in the distance and energy of the $B_s$. This parameter needs to be less than $\Delta t/\tau \approx 1/5(2\pi/x_s)$ in order that the oscillation be observed. In $Z$ decays for $x_s \approx 15$ this corresponds to vertex resolutions of about 200 $\mu$m, which should be possible.

There are two options for the reconstruction. i) Full reconstruction may be required in any flavour-sensitive channel. For example, modes such as $B^0_s \rightarrow D^+_s\pi^-$ will tag the flavour of the decaying meson, whilst $B^0_s \rightarrow D^+_sD^-_s$ will not. This option has previously been studied [5] for the LEP environment, and the conclusion reached was that the number of events needed would have to be an order of magnitude more than what is expected even at a high-luminosity version of LEP. ii) The second possibility is to tag the flavour of the $B_s$ by a partial reconstruction of the semileptonic decay $B_s \rightarrow D^*_s\ell\nu$. The presence of $D^*_s$ distinguishes between $B_s$ and $B_d$, whilst the sign of the lepton identifies $B_s$ versus $B_d$. What is lost here is a direct measurement of the energy of the $B_s$, because of the missing neutrino. It is proposed to deal with this by using the hard fragmentation function of the $B$: that is, for a heavy quark, the final meson is expected to carry a large fraction of the energy of the original heavy quark, with the fragmentation function peaking near $z = 1$ for very heavy quarks. A preliminary report of a detailed QCD analysis [this volume] confirms this expectation, and we will soon have an experimental test of the result from LEP 1. Owing to this peaking and to constraints present in $B$ decay, we should know the $\gamma$ factor of the $B_s$ to better than $\pm 10\%$. With the radius foreseen for the LEP vacuum chamber ($\sim 5$ cm), and with the microvertex detectors under development (based on existing prototypes), the resolution on primary and secondary vertices is quite sufficient, i.e. less than one tenth of the mean $B_s$ flight length. This allows accurate measurement of $x_s$ up to large values, and has been demonstrated in simulations based on existing detectors.

Three detailed studies of $B_s$ oscillation have been performed [6, 7]. The first one is described in detail in Ref. [6]. The mode

$$B^0_s \rightarrow D^-_s + X$$

$$\downarrow \phi \pi$$

is considered and a Fourier transformation of the measured time distribution is performed. It peaks approximately at the oscillation frequency $\Delta m/\Gamma$. The number of events necessary to obtain a significant signal is deduced.
The crucial parameters which determine the ability to observe $B_s$ oscillations are

- the quality of the flavour tagging, and
- the accuracy of the measurement of the proper time.

The latter determines the range of accessible $x_s$. As shown in detail in Refs. [6, 7], LEP is in a much better position than a B-factory in this respect.

On the other hand, good evidence for oscillations (say $\sigma_{x}/x = 0.2$) can be obtained, with a few $10^6$ $Z$, up to $x_s \approx 10$, and up to $x_s \approx 18$–20 with $25 \times 10^6$ $Z$.

The results of all three studies are in good agreement and can be summarized as follows. Table 6.3 [7] gives the number of $Z$ required to observe $B_s$ oscillations up to the corresponding $x_s$ value. An accuracy of $\sigma_{x}/x = 0.1$ is assumed. With $10 \times 10^6$ $Z$'s one can measure oscillations up to $x_s \approx 10$. With $\sim 50 \times 10^6$ $Z$'s one can reach $x_s \approx 15$.

To get a very accurate measurement of $x_s$, larger statistics are needed. For instance to get $\sigma_{x_s} = 0.5$ at $x_s = 10$ one needs about four times more events than indicated in Table 6.3, namely $\sim 50 \times 10^6$ $Z$'s.

### 6.5 Lifetime differences

The various $B$ hadrons are expected to have about the same lifetime, governed by the decay of the $b$-quark about independent of the spectator quark(s). However, models of the decay process do predict lifetime differences in the 10–20% range. These are due to interactions with the spectator quark and to the presence of non-spectator decay mechanisms. The theoretical issues are reviewed in detail in the LEP 1 Study [1, 2]. The experimental resolution of the lifetime differences would allow theorists to refine the models of weak decay. This process would lead to more accurate predictions for other reactions that are of interest.

The inclusive mean $B$ lifetime, averaging the results from the PEP and PETRA experiments, is measured to be $\tau_B = 13.1^{+1.4}_{-1.3} \times 10^{13}$ s. What are the prospects at LEP for improving this measurement? Can we go beyond and measure individual $B_0^0, B^+_s, B^0_s,$ and $\Lambda^0_b$ lifetimes? As said above, the theoretical expectation for the $B^0, B^+$ lifetime difference is at most 10–20%. Can we go below the interesting level of 10% precision on individual lifetimes?

#### 6.5.1 Inclusive $B$ lifetime measurement

The method of measuring the impact parameter of a lepton coming from semileptonic decays presents several advantages. The mean impact parameter does not depend, in a first approximation, on the energy of the $B$ meson and hence on the precise knowledge of the fragmentation function. The residual dependence of the mean impact parameter on the $B$-meson energy, is smaller at LEP than it was at PEP and PETRA energies. Selecting leptons with high momentum, and with high transverse momentum with respect to the jet axis, allows the tagging of $B$ mesons with typical efficiencies of 10% (where efficiency is defined as the number of tagged $B\bar{B}$ events over the total number of $B\bar{B}$ events) and purities of 70–80%. The background consists of cascade $b \rightarrow c \rightarrow \ell$ decays, primary $c \rightarrow \ell$ decays, and $u, d, s \rightarrow \ell$ decays or misidentified hadrons. As the lepton spectrum is rather well known, these backgrounds can be estimated with a good accuracy.
The mean impact parameter for a B lifetime of $13 \times 10^{-13}$ s is 350 $\mu$m in space or 230 $\mu$m projected in the plane perpendicular to the beam axis. The resolution on the impact parameter expected in the LEP experiments, with their foreseen vertex detectors and the recently adopted design of the beam pipe ($r \approx 5$ cm), will be typically 15 $\mu$m at momenta above 10 GeV/c, while the multiple scattering in the beam pipe and in the detector itself leads to a resolution of 20 (40) $\mu$m at 5 (2) GeV/c. The knowledge of the primary vertex is determined first by the beam-crossing profile. At LEP one expects $\sigma_{x} \approx 15$ $\mu$m and $\sigma_{y} \approx 350$ $\mu$m in the plane perpendicular to the beam direction. Reconstruction of the primary vertex on the event-by-event basis can further constrain $\sigma_{y}$ about 30–50 $\mu$m. Hence we will know the primary vertex with an average precision of about 50 $\mu$m, to be combined with the 20–40 $\mu$m precision on the impact parameter (i.p.) of the lepton in the momentum range considered. The precision on the lifetime measurement will be

$$\frac{\sigma_{\tau}}{\tau} \approx \frac{\sqrt{1 + (\sigma_{\text{i.p.}}/\text{i.p.})^2}}{\sqrt{N_{\tau}}} \approx \frac{1}{\sqrt{N_{\tau}}}.$$ 

For $10^{6}$ Z's, i.e. 300,000 B mesons, we expect about 30,000 selected leptons and a negligible statistical error on the lifetime. At PEP and PETRA, systematic errors were estimated to be of the order of 20%, with contributions from the background subtraction, knowledge of the fragmentation function, and understanding of the detector resolution. Given the high statistics available at LEP, the background will be reduced by a more restrictive selection of the leptons and a corresponding reduction of their contribution to the systematic error. As already mentioned, the residual dependence of the mean impact parameter on the fragmentation function is smaller at LEP. So altogether, a smaller systematic error is expected.

6.5.2 Exclusive B lifetime measurement

Fully reconstructed hadronic decays are natural candidates for identifying the B mesons. Table 6.4 summarizes the branching fractions for low-multiplicity exclusive decays and the expected number of events per $10^{7}$ Z's before selection criteria are applied, assuming the LUND 6.3 or Webber Monte Carlo 'prediction' of $B_{s}^{0}: B_{d}^{0}: B_{u}^{+} \approx 1 : 3.6 : 3.6$, and 9% baryon production.

The number of events in exclusive hadronic decay modes are not large. One has to consider that the numbers presented in Table 6.4 are further reduced by the acceptance of the vertex detectors and reconstruction efficiency, i.e. a factor of 2–3. Decays to $J/\psi$ are expected to give a clean sample, whilst decays to D mesons + hadrons have some combinatorial background. The precision on the reconstructed decay vertex is of the order of 200 $\mu$m along the flight path, to be compared with an average decay length of 2.2 mm. In fully reconstructed decays, the momentum of the B meson is measured; so we have $\delta t/\tau \lesssim 10\%$ and hence $\delta \tau/\tau \approx 1/\sqrt{N_{B}}$. The systematic error will come mainly from effects in reconstructing the flight path. For $3 \times 10^{7}$ Z's, with the present knowledge of the branching fractions, it will be possible to gather enough statistics to reach a few per cent statistical error in the individual lifetime.
To find decay modes with higher branching fractions, we have to turn to semileptonic decay channels: \( \text{BR}(B \to e + \nu + \text{hadrons}) = 12.3 \pm 0.8\% \) and \( \text{BR}(B \to \mu + \nu + \text{hadrons}) = 11.0 \pm 0.8\% \). Decays \( \text{BR}(B \to \ell + D + \nu) \) and \( \text{BR}(B \to \ell + D^* + \nu) \) are expected to be dominant and in the ratio \( D^*/D \approx 3 \).

The following pattern is obtained:

\[
\begin{align*}
B^+_u & \to \ell^+ \bar{D}_0^0, \\
D^{*0} & \to \bar{D}^0 + (\pi^0, \gamma) & 100\% & , \\
B^0_d & \to \ell^+ \bar{D}^-, \\
D^{*-} & \to \bar{D}^0 + \pi^- & 50\% & , \\
D^- & (\pi^0, \gamma) & 50\% & , \\
B^0_s & \to \ell^+ D_s^-, \\
\bar{D}_s^{*-} & \to D_s^- + \gamma & 100\% & .
\end{align*}
\]

Pairs \( \ell^+ D^- \), \( \ell^+ D^{*-} \), and \( \ell^+ D_s^- \) are unambiguous signatures for \( B^0_d \) and \( B^0_s \), respectively, whilst \( \ell^+ \bar{D}^0 \) pairs come 60% from \( B^+_u \) and 40% from \( B^0_d \) if the cascade \( D^{*-} \to \bar{D}^0 + \pi^- \) is not identified in the event. Clean samples are expected for \( B^0_d \to \ell^+ D^{*-} \) and \( B^0_s \to \ell^+ D_s^- \) thanks to the small combinatorial background for the \( D^{*-} \to \bar{D}^0 \pi^- \) cascade and the \( D_s^- \to \phi \pi^- \) decay. The expected number of events for \( 10^7 \) Z's before selection criteria are applied is \( 4100 \ B^0_d \) and \( 1600 \ B^0_s \), an order of magnitude more than for the hadronic decay modes. The precision on the position of the decay vertex is again of the order of 200 \( \mu \text{m} \).

The momentum of the B is not known; but the \( D_s \) momentum is measured and one has simply to get the missing neutrino. This method results in a precision of about 7% on \( p_B \).

Hence we obtain \( \sigma_s/\tau \approx 10\% \). With 10 million Z's, the error on lifetimes of individual B mesons is at the 3–4% level.

The situation in each jet is in fact quite comparable to what occurred in fixed-target experiments (such as E691 or NA14/2) measuring charm lifetimes.

### 6.6 Spectroscopy of B particles at HLEP

At LEP energies, B mesons are fast-moving particles produced in hadronic jets. Such a situation is quite different from the one at CESR or DORIS, where the B's are generated at rest. The B-mass peaks will be broader because the beam energy constraint is lost, but the combinatorial background is less severe.

#### 6.6.1 A few requirements for the detectors

In order to identify narrow states, a good accuracy on charged-track reconstruction is needed. LEP experiments satisfy this condition, with typically

\[
\sigma_p/p = 1\% \text{ for } p = 10 \text{ GeV/c, } \sigma_\phi \approx 1 \text{ mrad}.
\]

Thus for D and B mesons decaying into charged particles, the expected mass accuracies are \( \sigma_D = 15–20 \text{ MeV} \) and \( \sigma_B = 50–70 \text{ MeV} \). The mean number of charged particles produced in a B decay is about five; a similar number of photons are also emitted. To have access to
channels involving $\pi^0$'s or $\eta$'s, a finely segmented electromagnetic calorimeter is needed. This calorimeter has also to provide good rejection against hadrons in order to help in the electron identification.

Kaons from B decays have a momentum higher than 1.5 GeV/c. The bulk of the energy spectrum is between 2 and 12 GeV, with a maximum at around 5 GeV. Particle identification in such a momentum range is required. It gives typically a factor of 10 reduction in the combinatorial background for the channels that we consider below.

As we are searching for particles with a short lifetime, the microvertex detector will help in the background reduction and will also improve the mass resolution of the spectrometer. A large contribution to the combinatorial background comes from charm jets. Thus it is not sufficient to detect tracks that do not issue from the interaction point—the detector must also allow for the reconstruction of multiple secondary vertices.

6.6.2 The combinatorial background

At LEP energies, events with three or more jets are more abundant than genuine two-jet events. This abundance depends on the energy cut-off imposed on the additional jet, which usually has a low energy. Using a jet algorithm (LUCLUS) one requires that a jet energy be higher than 30 GeV in order to eliminate hadrons from gluon jets. The B-decay products belong to a well-defined jet; the corresponding geometrical acceptance of the apparatus is proportional to $\Delta \Omega$ ($\Delta \Omega =$ equipped solid angle), whereas it varies as $\Delta \Omega^N$ for an $N$-body decay channel when the B is produced at rest.

One can also take advantage of the peaked fragmentation function of heavy quarks, considering only mass combinations that have a large fraction ($z$) of the jet energy. Typical cuts are $z > 0.4$ for charm, $z > 0.6$ for beauty.

6.6.3 D, F, and $\Lambda_c$ reconstruction

Since B cascades usually into charm states, a few predictions for charm reconstruction at LEP are given. A detailed study can be found elsewhere [8]. From 10 million $Z$'s after a cut on $z$ ($> 0.3$) and without a microvertex detector, 50,000 decays of the $D^0$ into $K^-\pi^+$ are reconstructed. The ratio of signal-to-background ($S/B$), which is $\sim 1/3$, can be improved by using microvertex detector information but at the expense of a small reduction in the signal: 30,000 events with $S/B \approx 1$. The F meson can be measured, for instance, in the channel $K^+K^-\pi^\pm$. If we assume a branching ratio of 3% one expects 5000 events over a similar background (without microvertex detector information and with a cut $z > 0.4$). The $\Lambda_c^+$ decaying into $pK^-\pi^+$ can be observed in a similar way, if one can identify protons in the same energy range (RICH counters of DELPHI).

6.6.4 Beauty reconstruction [9]

'Normal' B decays into a charmed particle and a pion ($D^0\pi^-, \ D^+\pi^-, \ldots$) give rise to clear signals. With a $z$ cut at 0.6, identification of hadrons and use of the microvertex, one gets typically, for $10^7$ $Z$'s, 100–200 events of signal with background/signal between 2 and 5.

More specific B decays can be isolated with much better $S/B$ ratio. Such examples of B reconstruction are:
i) $B^+ \rightarrow J/\psi + K^+$ (ALEPH): for $10^7$ Z's, $\sim 52$ events are expected over a background of 6 to 8. The mass resolution ($\sigma$) is $\sim 65$ MeV. Assuming the same BR for $J/\psi + K_S^0$, the key channel for CP violation, and requiring the detection and measurement of $K_S^0 \rightarrow \pi^+\pi^-$, one obtains $\sim 10$ events.

ii) $B^0 \rightarrow \pi^- D^{**}$ (OPAL)

\[ \rightarrow \pi^+ D^0 \]
\[ \rightarrow K^- \pi^+ \]

Radiative corrections and detector simulation have been treated correctly. The $K^-$ is identified by $dE/dx$. One requires a combination of $\pi^+ K^-$ with mass consistent with a $D^0$: then the difference $m(\pi^+ D^0) - m(D^0)$ should be less than 150 MeV. Against charm, one requires: $E_{D^*} < 25$ GeV. Due to the hard fragmentation of $b$, one requires finally $E_B > 30$ GeV. The resulting efficiency is 18%. The signal obtained is background-free. One expects of the order of 150 events for $10^8$ Z's.

iii) $B_s \rightarrow J/\psi + \phi$ (OPAL). The assumed BR is $\sim 10^{-3}$. One looks at the $J/\psi \rightarrow e\bar{e}$, $\mu\mu$ modes and $\phi \rightarrow K^+K^-$; $K$'s are identified by $dE/dx$. The efficiency is $\sim 15\%$. A background-free signal is obtained, with $\sigma \sim 70$ MeV, and 100 events for $10^8$ multihadronic decays of the $Z$.

iv) ALEPH looked at the semi-reconstructed channel $B_s \rightarrow \ell \phi\pi$, 300 to 400 events of the type $\ell_{tag}\ell\phi\pi$ (where the $\phi$ and $\pi$ are from a $D_s$) are expected, at least 90% being $B_s$.

6.6.5 The discovery of the $B_c$

The $B_c^+ = (\bar{b}c)$ is a bound state of two heavy quarks of different flavours. It is therefore an interesting object for QCD studies, whilst its rich decay channels make it interesting for the weak interactions.

It is not clear how many $B_c$ mesons will be produced at HLEP. The $b$-quark would generally be produced in $Z$ decays, whilst the $c$ would come from a perturbative QCD $c\bar{c}$ pair production, with the $\bar{b}$ and $c$ binding to form the $B_c$. This reaction has not been included in many of the Monte Carlo event generators. However, with one of these (JETSET version 7.1) it was estimated that 14,000 $B_c$ or $B_c^*$ would be produced with $10^8$ $Z$'s. We will adopt this number provisionally for our estimates, but the main conclusion is that a sizeable number of $B_c$ mesons should be produced at HLEP. Can we discover this particle and learn anything about its properties?

First let us consider the expectations for the decay channels of a $B_c$ meson. In the spectator model the decay rate would be the sum of the rates for the $\bar{b}$ decay and the $c$ decay. These rates should in turn be those of the $B$ and $D$ mesons, respectively. For the $B$ mesons the result is clear, as it is expected that $B_u$, $B_d$, and $B_s$ should all have about the same lifetime. Therefore, $\tau(b) \approx \tau(B) = 10^{-12}$ s. However, for $D$ mesons the choice is not as clear, since $\tau(D^+) = (1.07 \pm 0.03) \times 10^{-12}$ s, whilst $\tau(D^0) = (0.43 \pm 0.01) \times 10^{-12}$ s. Since the semileptonic branching ratio of the $D^+$ corresponds more nearly to the spectator-model predictions, whilst that of $D^0$ is suppressed, we will take this to mean that the hadronic modes of the $D^0$ are enhanced. This implies that the $D^+$ lifetime is a more accurate
indicator of the spectator-model decay of a c-quark. The final states of \(B_c\) decay should not exhibit any unusual final-state enhancements. The expectation, then, for \(B_c\) decay is a 50\%–50\% split into \(B\) decay and \(c\) decay, with a lifetime of about \(\tau(B_c) \approx 0.5 \times 10^{-12}\) s.

When the charmed quark decays (c \(\to\) sud or c \(\to\) sev, s\(\mu\)\(\nu\)), the final states will be so difficult to observe that we may consider them as lost decays. The final states will consist of a \(B\) or \(B_s\) plus extra hadrons. The most observable of these modes might be the \(B_c \to B_s^* e\(\nu\)\) semileptonic decay, which would have a branching ratio of about 3\%. However, \(B_s^*\) is not easy to reconstruct so that the overall efficiency of this path is negligible.

It is preferable to use the channels where the \(b\) quark decays, \(b \to c\(\bar{u}\), ccs, c\(\bar{e}\)\(\nu\), c\(\bar{\mu}\)\(\nu\). Combined with the spectator c-quark, this produces a final state with two or three charmed quarks in it. Estimates of the branching fractions for some of this class of decays are shown in Table 6.5. These have been obtained as follows. We have used the BSW model results for \(B\) decays from the LEP 1 Study report. The spectator quark has been changed from a \(u\), \(d\), or \(s\) to a c-quark, with the resulting change of final-state particles. We have not modified the wave-function overlaps when making this substitution, although some difference is to be expected. However, within the expected level of accuracy of the estimates, this should not be a large effect. We have included a factor of 0.5 to account for the fact that only half of the \(B_c\)'s are expected to decay via the \(b\)-quark. The explicit numbers have been quoted for \(a_1^2 \approx 2\) and \(a_2^2 = 1/16\), which is what is required if the model is to fit presently known \(B\) branching ratios (in particular, \(B^+ \to D^0D_s^-\), \(B^0 \to D^+D_s^-\), \(B^- \to J/\psi K^-\), \(B^0 \to J/\psi K^0\)).

From these estimates we see a favourable circumstance: namely, final states containing \(J/\psi\) are sizeable. Thus a general search strategy for \(B_c\) would be to look for \(B_c \to J/\psi + X\), where \(X = \pi, \rho, \mu\(\nu\), e\(\nu\), D_\(s\), D_s^*, \) etc. We observe the \(J/\psi\) in either its \(e^+e^-\) or \(\mu^+\mu^-\) decay, which has an efficiency of 0.14, yielding an estimated number of events in the various channels, as given in Table 6.6. The numbers are not large, but they would be sufficient if backgrounds are not important. The two sources of backgrounds are expected to be \(B_u, B_d\), and \(B_s\) decays and direct \(J/\psi\) production. The latter is expected to produce 1000–4000 \(J/\psi\)'s for \(10^8\) \(Z\)'s (the range is a function of the event generator used). Probably more important, though, are the \(J/\psi\)'s produced in \(B\) decays. With a 1\% branching ratio of \(B \to J/\psi + X\), this yields \(3 \times 10^5\) \(J/\psi\) events. Of course, most of these will not end up in the kinematic mass range of the \(B_c\). However, a full Monte Carlo simulation is needed in order to address this question of backgrounds.

### 6.7 Decay modes of \(B\)-mesons

At present, only a few hundred \(B_{ud}\) events have been fully reconstructed. This will, of course, improve if CLEO II fulfils its potential. However, the measurement of branching ratios for \(B_s\) requires a machine such as HLEP where copious amounts of \(B_s\) are produced. A sample of \(\sim 4 \times 10^6\) \(B_s\) mesons from \(10^8\) \(Z\)'s, combined with the use of a vertex detector to identify the flight path, would lead to important progress towards obtaining these branching ratios. Many two-body decay modes of \(B_{ud,s}\) occur with branching ratios at the per cent level, although others are more suppressed. A thorough survey has been provided in the LEP 1 report [1, 2]. Monte Carlo studies of the observability of various modes have been undertaken.
One study [10] used the characteristics of the ALEPH detector. Two categories of events were considered: i) hadronic decays with large missing energy, and ii) non-charm two-body decays. The first includes $B \to \tau \nu$ in addition to $B \to M_{uq} \tau \nu$. The second category was split into $(\pi^+ \pi^-, K^\pm \pi^\mp, K^+ K^-)$ and $p \bar{p}$. In each case, a series of energy and topology cuts were introduced in order to remove non-B backgrounds. Both the signal and the background were studied by Monte Carlo simulation. At $5 \times 10^6 Z$'s, $3\sigma$ observability was found down to branching ratios of $2 \times 10^{-4}$ for the first class, to $6 \times 10^{-5}$ for $(\pi^+ \pi^-, K^\pm \pi^\mp, K^+ K^-)$, and $5 \times 10^{-5}$ for $p \bar{p}$. At HLEP, the factor of 20 increase in the number of $Z$'s would push down the observability limit yet further. The goal of separating $B \to \tau \nu$ from the general missing-energy sample has not yet been reached.

A more detailed study of the first class of events is under investigation [11]. Preliminary results have been obtained using an updated Monte Carlo generator (LUND–7.2 PS) and a LEP detector simulation with the feasibilities of a RICH and a $\mu$-vertex detector for a better determination of the impact parameters, the missing energy, the geometrical reconstruction and the charge asymmetry. The backgrounds of $Z \to q\bar{q}, \tau^+ \tau^-$ and $D_s \to \tau \nu$, are taken into account. Under these conditions, a branching ratio of the order of $10^{-4}$ can be reached with $10^7 Z$'s.

For decays involving a $J/\psi$, the experimental signal would involve the identification of the $J/\psi$ through its $e^+e^-$ and $\mu^+\mu^-$ final state (total BR = 14%). Interesting modes include $B_s \to J/\psi + \phi, J/\psi + \eta, J/\psi + K_S, B_d \to J/\psi + K_S$, and $B^- \to J/\psi + K^-$. For the $B^0 \to J/\psi + K_S$ mode, studies have indicated that the main obstacle is the number of events. With a branching ratio of about $3 \times 10^{-4}$ and seeing the $K_S$ in its $\pi^+ \pi^-$ final state, we would expect 500 $J/\psi + K_S = (\ell^+ \ell^- + \pi^+ \pi^-)$ events per $10^8 Z$'s. Estimates of efficiencies for the detection of this channel predict a final sample of about 300 events [10]. With similar efficiencies, the decay $B_s \to J/\psi + \phi \to (\ell^+ \ell^- + K^+ K^-)$ should also be easily seen.

6.8 Rare B decays

There is considerable interest in observing the rare decays of $B$ mesons. The most accessible decays in this category are generated by $b \to s\gamma$, such as $B \to K^* \gamma, B_s \to \phi \gamma$. These transitions are forbidden at tree level and are generated only through loops involving heavy quarks. There is extensive literature on the calculation of these rates within the Standard Model and beyond. For large $m_t$, the dependence on the mass of the $t$-quark is weak, and a branching ratio of $10^{-4}$ for $B \to K^* \gamma$ and for $B_s \to \phi \gamma$ is predicted. Enhancements are possible if new physics exists.

The observability of $B^0 \to K^* \gamma$ at LEP has been studied by a full Monte Carlo simulation using detector properties similar to present LEP versions [12]. The $\pi/K$ separation was achieved using ring-imaging Cherenkov (RICH) detectors. A set of cuts were implemented on the energy of $K^*$ and $\gamma$ and on their relative angles, with an efficiency of $(37 \pm 2)\%$. Backgrounds were simulated using the LUND Monte Carlo. The $3\sigma$ observability of a $10^{-4}$ signal was found for $2 \times 10^6 Z$'s, and for $10^8 Z$'s a level of $\sim 10^{-5}$ could be reached, leading to easy observability of the Standard Model signal. With similar efficiencies, the $B_s \to \phi \gamma$ mode should also be observable at HLEP.
Among the possible sources of background for the decay $B^0 \to K^{*0}\gamma$, particular attention should be paid to

$$B^0 \to \bar{D}^{*0}\gamma$$
$$\quad \quad \quad \quad \quad \quad \downarrow \bar{D}^{0}\pi^0$$
$$\quad \quad \quad \quad \quad \quad \downarrow K^{*0}\pi^0$$

$$B^0 \to \bar{D}^{*0}\gamma$$
$$\quad \quad \quad \quad \quad \quad \downarrow \bar{D}^{0}\gamma$$
$$\quad \quad \quad \quad \quad \quad \downarrow K^{*0}\pi^0$$

$$B^0 \to \bar{D}^{*0}\pi^0$$
$$\quad \quad \quad \quad \quad \quad \downarrow K^{*0}\pi^0$$

(1)

(2)

(3)

As a matter of fact, in these decay channels the final state differs from $(K^{*0}\gamma)$ for 2$\pi^0$, 1$\pi^0$ and 1$\gamma$, or it contains 2$\pi^0$ instead of one photon. Since the neutral particles could be confused with products of the fragmentation process, the decays (1) to (3) could produce significant backgrounds to $B^0 \to K^{*0}\gamma$. In order to estimate the branching ratios, a prediction for $B^0 \to \bar{D}^{*0}\gamma$ and $B^0 \to \bar{D}^{0}\pi^0$ is needed.

In Ref. [13] the following results have been obtained:

$$\text{BR}(B^0 \to \bar{D}^{*0}\gamma) \leq 10^{-6},$$

$$\text{BR}(B^0 \to \bar{D}^{0}\pi^0) = (10^{-4} - 10^{-3}).$$

(4)

(5)

The result (4) is obtained by considering three different contributions

i) vector meson dominance terms

$$B^0 \to \bar{D}^{*0}\omega, \rho;$$
$$\downarrow \gamma$$

ii) annihilation diagrams, where the B mixes with an off-shell $\bar{D}^{0}$ meson through the vacuum state, and the photon couples to $\bar{D}^{0}$ and $\bar{D}^{*0}$;

iii) W-exchange diagrams, where the B mixes with an off-shell $\bar{D}^{0}$ meson through intermediate charmed states.

These three contributions are of the same order, but their relative phase is unknown, so that only an upper limit can be reliably computed.

As for the result (5), this is obtained by considering factorizable contributions [14] and W-exchange contributions, where the B meson mixes with an off-shell $\bar{D}^{*0}$ meson through intermediate charmed states, and $\pi^0$ is emitted from the charmed-meson leg. The results (4) and (5) show that whereas the backgrounds (1) and (2) are negligible, the branching ratio for the decay channel (3) can reach the value $10^{-5}$, which is relatively high compared with the expectations for $B^0 \to K^{*0}\gamma$; therefore, in order to exclude it, a careful experimental analysis of the final state should be performed.
6.9 CP violation

Let us try to summarize briefly the Standard Model predictions for CP violation [15], so that we will know what we need to test. The Wolfenstein expansion of the KM matrix

\[
V_{\text{KM}} = \begin{pmatrix}
1 - 1/2\lambda^2 & \frac{\lambda}{1 - 1/2\lambda^2 - i\eta A^2\lambda^4} & A\lambda^2[\rho - i\eta(1 - 1/2\lambda^2)] \\
\frac{-\lambda}{A\lambda^2(1 - \rho - i\eta)} & 1/2\lambda^2 - i\eta A^2\lambda^4 & A\lambda^2(1 + i\eta\lambda^2) \\
\frac{-\lambda}{A\lambda^2(1 - \rho - i\eta)} & -A\lambda^2 & 1
\end{pmatrix}
\]

is best for our purpose. We can see that, to lowest order, the CP-violating phase can be put into the \(V_{ud}\) and \(V_{ub}\) elements. Thus in this basis, \(B_d - \bar{B}_d\) mixing has a phase, whilst \(B_s - \bar{B}_s\) does not. Similarly, the KM-favoured \(b \to c\) transitions have no leading phase, whilst suppressed decays using \(b \to u\) do. In this parametrization, \(\lambda \approx 0.22\), \(A \approx 1\) (from \(b \approx c\)), and \(\rho^2 + \eta^2 \approx 1/2\) (from \(b \to u\nu\)).

The three standard types of CP asymmetries that are most often discussed are:

1) semileptonic decay asymmetry,
2) partial rate differences that utilize mixing,
3) partial rate differences with an interference between two decay channels.

Each tests something different. The semileptonic asymmetry

\[a_{\text{SL}} = \frac{\Gamma(\bar{B} \to \ell^+X) - \Gamma(B \to \ell^-X)}{\Gamma(\bar{B} \to \ell^+X) + \Gamma(B \to \ell^+X)}\]

tests the inequality of the \(B \to \bar{B}\) versus \(B \to B\) mixing rates, which is due to a form of mass-matrix CP violation,

\[a_{\text{SL}} \approx \frac{\Delta \Gamma}{\Delta m} \sin \phi(\Delta B = 2),\]

where \(\Delta \Gamma\) is the width difference between the \(B\) eigenstates and \(\sin \phi(\Delta B = 2)\) is the measure of mass-matrix CP violation.

The second category tests asymmetries, such as those to CP eigenstates:

\[a_I = \frac{\Gamma(B \to f) - \Gamma(\bar{B} \to f)}{\Gamma(B \to f) + \Gamma(\bar{B} \to f)} .\]

Here the interference is between \(B \to f\) directly and \(B \to \bar{B} \to f\), and thus tests the phase difference between the direct transition and the mass matrix.

The third category is best illustrated without hadronic CP eigenstates, such as

\[a_{\text{II}} = \frac{\Gamma(B \to f) - \Gamma(\bar{B} \to f)}{\Gamma(B \to f) + \Gamma(\bar{B} \to f)} ,\]

for example in the charged \(B\)'s. Here the interference is between two possible ways of making the transition to the final state, involving different KM factors and different final-state interaction phases.
Given these features, the rough predictions are clear. In category 1, $a_{SL}$ will always be small for $B_d$ because $\Delta F_{B_d}$ is small. For $B_s$, $\Delta F/\Delta m$ may reach several per cent. However, $B_s$ mixing has little phase, so that again $a_{SL}$ is small. We note, however, that alternative models of CP could produce a phase in $B_s$ mixing, and hence it is more useful to study $a_{SL}$ for $B_s$ than for $B_d$.

In category 2, if the decay is KM-favoured, only $B_d$ will have a reasonable magnitude, as only it has a phase in the mass matrix. In KM-suppressed modes using $V_{ub}$, both $B_d$ and $B_s$ have sizeable phases. However, the rapid $B_s$ oscillations wash out much of the signal.

The third category always requires at least one KM-suppressed channel, as the KM-favoured mode cannot interface with itself. We note also that there is a major difference in the theoretical reliability of the different types of decay. Predictions for most class-2 modes, such as $B \to J/\psi + K_S$, are extremely clean and free from uncertainties in hadronic matrix elements. In contrast, class 3 involves severe uncertainties from matrix elements and final-state phases.

The universal primary choice for hadronic CP asymmetries is the mode $B_d \to J/\psi + K_S$. It is in the KM-favoured class, the prediction is very clean, and the experimental signature is optimal. Its branching ratio is somewhat smallish for a KM-favoured mode, $\text{BR}(B_d \to J/\psi + K_S) = (3.3 \pm 0.8) \times 10^{-4}$. [To obtain this, we have combined data on $B^0 \to J/\psi + K_S$ and its isospin partner $B^- \to J/\psi + K^-$.] Note that there are some KM-suppressed modes that are nevertheless expected to have larger branching ratios $\text{BR}(B \to D^+D^-) \approx 10^{-3}$ is expected if we scale from the indications of $B \to D^+D^-$. However, the experimental clarity of the $J/\psi + K_S$ final state is such that it will be easier to study. If we include $\text{BR}(J/\psi \to e^+e^- + \mu^+\mu^-) = 0.14$ and $\text{BR}(K_S \to \pi^+\pi^-) = 0.69$, we can hope to see 10% of these decays. The efficiency in the observation of this decay has been evaluated to be 30% [16], after performing a calculation using a full detector simulation (GEANT) and a reconstruction based on now available track-reconstruction and lepton-finding algorithms, in an existing detector. To form the CP asymmetry one has to tag the $B$ or $\bar{B}$ produced in the opposite hemisphere. This can be done using leptons (10% efficiency), or using charged $K$ with a momentum larger than 2 GeV/c. This is possible since the $J/\psi + K_S$ final state is almost free of non-(b-\bar{b}) quark contamination. Using $K$, with the requirement that there be no additional charged $K$ in the same hemisphere, leads to a $B-\bar{B}$ tagging efficiency of 30% (13% for $B_s$) and a wrong tagging in 3% of the events (40% for $B_s$). Combining kaons and leptons, an overall tagging efficiency of 35% can be achieved. Using this procedure, and taking into account $B^0_{ds} - B^0_{dS}$ mixing, a reduction of the observable CP asymmetry of ~70% could be reached. With these values, CP violation could be observed near the maximum allowed value of $A_0$. This performance is comparable to what could be achieved in a threshold B-factory with a luminosity of $10^{33}$ cm$^{-2}$ s$^{-1}$.

In the case of the $B_s$, the study of hadronic CP asymmetries will be impossible because of the more limited statistics and of the large $B_s-\bar{B}_s$ mixing that will wash out the CP-odd effects. However, there is an important null test for the Standard Model, which can be best performed using $B_s$. The semileptonic asymmetry described above is predicted in the
Standard Model to be of the order of $10^{-3}$. However, superweak-style models in which the CP violation occurs uniquely in the mass matrix can produce the larger values of $a_{\ell\ell}$,

$$a_{\ell\ell} = \frac{N(\ell^+\ell^+) - N(\ell^-\ell^-)}{N(\ell^+\ell^+) + N(\ell^-\ell^-)},$$

which could range up to several per cent for $B_s$. This asymmetry was studied at the LEP 1 Workshop, where it was concluded that a level $a_{\ell\ell} \lesssim 0.03$ could be reached. This limit is primarily statistical, so that $a_{\ell\ell} \lesssim 0.01$ could be expected at HLEP. Dileptons include a mixture of $B_s$ and $B_d$ events, with $B_d$ being more important. The asymmetry, however, is due entirely to the $B_s$ component, for the reasons explained above. A non-zero signal in $a_{\ell\ell}$ is not impossible in non-standard theories, and any non-zero measurement would be a clear indication of physics beyond the Standard Model.

6.10 The B physics programme at HLEP

The two major studies of B physics at HLEP are i) the determination of the $Z \to b\bar{b}$ couplings in order to provide precise tests of the Standard Model and possibly discover new physics influencing the radiative corrections; and ii) the study of the decays of the B hadrons produced in Z decays, which reveals the weak interactions properties of heavy quarks. The first of these is at the heart of LEP 1 physics, and the HLEP Study Subgroup 1 has described how the high-luminosity option enhances the prospects of finding new physics. The second aspect has been described in detail in the preceding section. The work of Study Group IV has shown that many of these features are unique or especially timely when compared with prospects for future B-factories (see Table 6.7).

With the radius foreseen for the LEP vacuum chamber and the microvertex detectors under development (based on existing prototypes), the observability of $B_s$ mixing is very good using the semileptonic decay path. The Standard Model values in the range $x_s \approx 10$–20 should be measured. Using the same class of events, lifetime differences of the various B hadrons will be measurable. Decay branching ratios of $B_{u,d}$ and of $B_s$ will be obtained for several channels. Rare decays such as $B^0 \to K^*\gamma$, $B^0 \to \phi\gamma$, and $B \to D^*\gamma$ will be found if the Standard Model predictions are correct. Because all flavours of B hadrons can be produced in Z decay, there is the possibility to discover the $B_c$ using its decay modes into $J/\psi$. For CP-violation studies, HLEP is equivalent to an asymmetric B-factory with a $10^{33}$ cm$^{-2}$ s$^{-1}$ luminosity, reaching the limit of observability of CP asymmetries in the $J/\psi + K_S$ mode.
REFERENCES

    C. Defoix, Collège de France preprint, contributed to this workshop.
[9] G. Mikenberg, OPAL Note contributed to this workshop.
    P. Roudeau as in Ref. [8].
       (1989).
[12] D. Cocoricchio and A. DeAngelis, The suppressed and rare B decay at \( \text{Le}^+\text{e}^-\text{P} \),
[15] A good general reference is I.I. Bigi, V.A. Khoze, N.G. Uraltsev and A.I. Sanda,
[16] J. Pinfold, OPAL Note contributed to this workshop.
    High Energy Physics in the 1990's, Snowmass, Colo. (USA), 1989 (World
Table 6.1

Tagging of beauty on one arm.

$\epsilon$ is the efficiency, $A$ the percentage of the asymmetry effectively observable; $G (= A\sqrt{\epsilon})$ is the figure of merit (Ref. [3])

<table>
<thead>
<tr>
<th>Process</th>
<th>$\epsilon$ (%)</th>
<th>$A$ (%)</th>
<th>$G$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Semileptonic decays</td>
<td>7</td>
<td>67</td>
<td>18</td>
</tr>
<tr>
<td>Exclusive D signals</td>
<td>3.5</td>
<td>84</td>
<td>16</td>
</tr>
<tr>
<td>Charge of the B</td>
<td>11</td>
<td>80</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>64</td>
<td>35</td>
</tr>
<tr>
<td>Beam polarization</td>
<td>63</td>
<td>45</td>
<td>36</td>
</tr>
<tr>
<td>($P = 45%$)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6.2

The percentage of well-classified events is $80.3 \pm 0.9\%$. Example of a classification of 2000 $Z \rightarrow q\bar{q}$ events between four classes: L ($q = u, d, s$); C ($q = c$); B ($q = b$); T ($q = t$). Events are classified according to a ‘class likelihood’ derived from 15 variables, seven of which use the measurement of impact parameters given in the barrel region by the microvertex detector. (Ref. [4].)

<table>
<thead>
<tr>
<th>Classified</th>
<th>Purity (%)</th>
<th>L</th>
<th>C</th>
<th>B</th>
<th>T</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>90.8</td>
<td>1012</td>
<td>87</td>
<td>14</td>
<td>2</td>
</tr>
<tr>
<td>C</td>
<td>47.0</td>
<td>173</td>
<td>187</td>
<td>38</td>
<td>0</td>
</tr>
<tr>
<td>B</td>
<td>87.4</td>
<td>9</td>
<td>41</td>
<td>348</td>
<td>0</td>
</tr>
<tr>
<td>T</td>
<td>66.3</td>
<td>14</td>
<td>4</td>
<td>12</td>
<td>59</td>
</tr>
<tr>
<td>Loss (%)</td>
<td>16.2</td>
<td>41.4</td>
<td>15.5</td>
<td>3.3</td>
<td></td>
</tr>
</tbody>
</table>
Table 6.3
Number of $Z$'s to observe $B_s$ mixing

<table>
<thead>
<tr>
<th>$x_s$</th>
<th>5</th>
<th>10</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_Z$</td>
<td>5</td>
<td>13</td>
<td>55</td>
</tr>
<tr>
<td>$10^6$ events</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6.4

The expected number of $B$ mesons per $10^7$ $Z$'s is calculated with the theoretical values of the $B$ branching fractions [12]. No acceptance or efficiency factors are included. For $D$-meson and light-meson branching fractions, the Particle Data Group values are assumed, except for $\text{BR}(D_s \rightarrow \phi \pi)$ where 4% is used. [Branching fractions in %.]

<table>
<thead>
<tr>
<th>Decay channel</th>
<th>ARGUS</th>
<th>CLEO</th>
<th>THEORY</th>
<th>No. $B/10^7$ Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0_d \rightarrow D^{*-} \pi^+$</td>
<td>$0.35 \pm 0.18 \pm 0.13$</td>
<td>$0.16 \pm 0.12 \pm 0.10$</td>
<td>0.15</td>
<td>100</td>
</tr>
<tr>
<td>$D^{*-} \rightarrow \overline{D}^0 \pi^+$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\overline{D}^0 \rightarrow K^+ \pi^-$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B^0_d \rightarrow D^+ \pi^-$</td>
<td>$0.31 \pm 0.13 \pm 0.10$</td>
<td>$0.16_{-0.26}^{+0.32}+0.15$</td>
<td>0.58</td>
<td>550</td>
</tr>
<tr>
<td>$D^- \rightarrow K^+ \pi^- \pi^-$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B^+_{u} \rightarrow \overline{D}^0 \pi^+$</td>
<td>$0.19 \pm 0.10 \pm 0.06$</td>
<td>$0.51_{-0.15}^{+0.17}+0.11$</td>
<td>0.37</td>
<td>170</td>
</tr>
<tr>
<td>$B^0_{s} \rightarrow D^- \pi^+$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$D^+_s \rightarrow \phi \pi^-$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\phi \rightarrow K^+ K^-$</td>
<td>0.5</td>
<td>30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B^0_d \rightarrow J/\psi + K^{*0}$</td>
<td>$0.33 \pm 0.18$</td>
<td>$0.06 \pm 0.03$</td>
<td>0.39</td>
<td>430</td>
</tr>
<tr>
<td>$J/\psi \rightarrow \ell^+ \ell^-$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$K^{*0} \rightarrow K^+ \pi^-$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B^+_{u} \rightarrow J/\psi + K^+$</td>
<td>$0.07 \pm 0.04$</td>
<td>$0.05 \pm 0.02$</td>
<td>0.09</td>
<td>150</td>
</tr>
<tr>
<td>$J/\psi \rightarrow \ell^+ \ell^-$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B^0_{s} \rightarrow J/\psi + \phi$</td>
<td></td>
<td></td>
<td>0.3</td>
<td>70</td>
</tr>
<tr>
<td>$J/\psi \rightarrow \ell^+ \ell^-$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\phi \rightarrow K^+ K^-$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 6.5
Branching ratio estimates (in %)
for some selected decays of $B_c$

<table>
<thead>
<tr>
<th>Decay</th>
<th>Branching ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_c \rightarrow (J/\psi)\pi^+$</td>
<td>0.16 ($a_1^2$) → 0.3</td>
</tr>
<tr>
<td>$(J/\psi)\rho^+$</td>
<td>0.6 ($a_1^2$) → 1.1</td>
</tr>
<tr>
<td>$\eta_c\pi^+$</td>
<td>0.2 ($a_1^2$) → 0.4</td>
</tr>
<tr>
<td>$(J/\psi)D_s^+$</td>
<td>0.15 ($a_1^2$) → 0.3</td>
</tr>
<tr>
<td>$(J/\psi)D_{s^{*+}}$</td>
<td>0.9 ($a_1^2$) → 1.8</td>
</tr>
<tr>
<td>$D^0\bar{D}^0$</td>
<td>0.1 ($a_2^2$) → 0.01</td>
</tr>
<tr>
<td>$D^{*0}\bar{D}^{*0}$</td>
<td>0.3 ($a_2^2$) → 0.02</td>
</tr>
<tr>
<td>$(J/\psi)e\nu$</td>
<td>4</td>
</tr>
<tr>
<td>$(J/\psi)\mu\nu$</td>
<td>4</td>
</tr>
<tr>
<td>$\eta_c e\nu$</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 6.6
Estimated number of events in the specific two-body branching ratio with a $J/\psi$ observed through its $\mu^+\mu^-$ and $e^+e^-$ decays

<table>
<thead>
<tr>
<th>$B_c \rightarrow J/\psi + X$</th>
<th>$e^+ e^- + \mu^+\mu^-$</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X = \pi^+$</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>$X = \rho^+$</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>$X = D_s^+$</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>$X = D_{s^{*+}}$</td>
<td>35</td>
<td></td>
</tr>
<tr>
<td>$X = e^+\nu$</td>
<td>80</td>
<td></td>
</tr>
<tr>
<td>$X = \mu^+\nu$</td>
<td>80</td>
<td></td>
</tr>
</tbody>
</table>
## Table 6.7
Comparison of b-factory techniques

<table>
<thead>
<tr>
<th>Factor</th>
<th>Asym. Y(4S)</th>
<th>Sym. Y(4S)</th>
<th>$\sqrt{s} =$ 16 GeV</th>
<th>Z P = 0</th>
<th>Z P = 0.9 (P = 0.45)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b\bar{b}$ cross-section, $\sigma$ (nb)</td>
<td>1.2</td>
<td>0.3</td>
<td>0.11</td>
<td>6.3</td>
<td>6.3</td>
</tr>
<tr>
<td>Fraction of $B^0_1$, $f_0$</td>
<td>0.43</td>
<td>0.34</td>
<td>0.35</td>
<td>0.35</td>
<td>0.35</td>
</tr>
<tr>
<td>$J/\psi K_S$ reconstruction efficiency, $\varepsilon_t$</td>
<td>0.61</td>
<td>0.61</td>
<td>0.61</td>
<td>0.46</td>
<td>0.46</td>
</tr>
<tr>
<td>Tagging efficiency, $\varepsilon_t$ (&amp; method)</td>
<td>0.48 ((\ell, K))</td>
<td>0.48 ((\ell, K))</td>
<td>0.30</td>
<td>0.18</td>
<td>0.61 ((A_{FB}))</td>
</tr>
<tr>
<td>Wrong tag fraction, w</td>
<td>0.08</td>
<td>0.08</td>
<td>0.08</td>
<td>0.08</td>
<td>0.125</td>
</tr>
<tr>
<td>Asymmetry dilution, d</td>
<td>0.71</td>
<td>0.63</td>
<td>0.52</td>
<td>0.52</td>
<td>0.71</td>
</tr>
<tr>
<td>$\int L , dt$ needed for $3\sigma$ effect ($10^{40}$ cm$^{-2}$ ster$^{-1}$)</td>
<td>0.3–12</td>
<td>2.2–78</td>
<td>14–490</td>
<td>0.5–19</td>
<td>0.1–3.6 (0.3–9.6)</td>
</tr>
<tr>
<td>Relative $\int L , dt$ needed</td>
<td>1.0</td>
<td>6.4</td>
<td>40</td>
<td>1.5</td>
<td>0.3 (0.8)</td>
</tr>
</tbody>
</table>

a) The peak luminosity needed in units of $10^{33}$ cm$^{-2}$ s$^{-1}$ for $10^7$ s of fully efficient running at peak luminosity [17].
7 QCD, $\gamma \gamma$, and charm

L. Bergström, I. Bigi, M. Drees, T. Sjöstrand

This section describes standard model physics, not covered elsewhere in the report, that could potentially be studied with the high-luminosity option of LEP (HLEP) operating near the $Z$ resonance. We have tried to be fairly comprehensive and therefore examine a number of quantities that do not obviously benefit from the addition of high luminosity. In this way it is hoped to give a realistic picture both of the limitations and benefits to be obtained.

7.1 QCD physics

Standard QCD phenomena are expected to vary smoothly with energy. The $Z$ peak therefore stands out only by virtue of providing a high event rate, not by any unique physics aspects of that particular energy. Although most QCD studies could be done with $10^8$ $Z$'s or less, there exists topics where larger event samples are required.

Many QCD studies would profit from using the highest possible energy, and from having data samples at different energies. For these studies, the limit will therefore not be the number of $Z$ events, but the number that can be produced at higher energies. The high-luminosity LEP option is therefore particularly interesting in this connection.

For the study of the foundations of QCD, such as the presence and form of three- and four-gluon vertices, one is hampered by the fact that there exists no viable alternative to QCD. It is therefore difficult to quantify what statistics is needed if one wants to 'prove' QCD by excluding 'the alternatives'. In the following we will mention the Abelian toy model as an alternative but, quite apart from internal consistency problems, this model is already excluded by the observed running of $\alpha_s$ with c.m. energy [1].

As a final, general comment, one must remember that the exploration of QCD is an iterative procedure, to a much larger extent than that of the electroweak theory. We will therefore be in a much better position to assess the usefulness of $10^8$ $Z$'s once the first batches of data have been analysed, and interesting discrepancies between models and data begin to show up.

7.1.1 QCD at the $Z$ peak — Ordinary processes

QCD phenomena are, as a rule, not rare ones. The natural expansion parameter in QCD studies is $\alpha_s$. If jets are required to be well separated, one finds three-jet fractions of order $\alpha_s \approx 0.1$, four-jet fractions of order $\alpha_s^2 \approx 0.01$, etc. If less restrictive jet resolution parameters are used, the multijet (i.e. not two-jet) fraction is dominant. In fact, in QCD parton shower based models the data support the use of a cut-off in the 1–2 GeV scale, i.e. with an average parton multiplicity of around 8–10.

The perturbative phase is followed by a non-perturbative one, in which the partons fragment into hadrons, which in their turn may decay further. Since non-perturbative QCD remains unsolved, one here has to rely on (tuned) phenomenological models for fragmentation and decays. For calorimetrically defined quantities, the influence of the non-perturbative aspect should decrease as the c.m. energy is increased, but fragmentation effects are still non-negligible even at the highest LEP energies.
For the study of global event measures, such as thrust or sphericity, every event gives a non-vanishing contribution. The same holds true for simple one-particle distributions, such as longitudinal and transverse momentum spectra, and also for a number of inclusive correlation measures, such as the energy–energy correlation and its asymmetry. The limiting factor is then likely to be the systematic errors, and not the statistical ones. The experimental systematic errors reflect the loss of particles down the beam pipes or in cracks, track reconstruction efficiencies, energy/momentum reconstruction errors, etc. If one wants to correct for these errors, it is necessary instead to put faith in the Monte Carlo programs used to generate physics events, and in the programs used to simulate the subsequent detector response.

The feeling in the LEP groups seems to be that, for inclusive measures like the ones listed above, current statistics, i.e. of the order of some $10^4$ events, already give statistical errors about as small as the systematic ones. To improve on this, it is necessary to achieve both a better modelling of perturbative and non-perturbative QCD theory aspects, and a better understanding of the detectors. Ultimately, the break-even point might be at a few $10^5$ events.

For the exploration of rare corners of phase space, one may profit from higher statistics. One example is the shape of the fragmentation function close to the kinematic limit, and the relative composition of $\pi/K/p$ among charged particles in this region. Another example is correlations among pairs or triplets of particles, such as $pp$, $p\Lambda$, $\Lambda\bar{\Lambda}$, $\Lambda p\bar{K}$, $\Xi\bar{\Lambda}K$, or $\Xi K\bar{K}$, which will provide information on the nature of the fragmentation mechanism. Finally, one might mention the detailed exploration of production properties of rarely produced particles, such as $\Omega^-$ and (anti)deuterons.

In many QCD studies, it would be of great interest to have ‘tagged’ three- or four-jet events, i.e. events in which it is known which are the quark/antiquark jets and which the gluon jet(s). For three-jet events, the main applications are to be found in the study of various coherence phenomena, see e.g. Refs. [2,3]. For four-jet events, a detailed study of the three-gluon coupling is on top of the list, using various angular distributions [4]. The most obvious tag method is prompt lepton ($\mu/e$) production in semileptonic decays of charm and bottom hadrons.

In Table 7.1 are presented results of a Monte Carlo study of event rates, using the JETSET 7.2 program [5]. Out of the 25000 events generated, the second line shows how many events were found with the right number of jets [using the JETSET cluster algorithm to construct the requested number of jets, but then requiring each jet to have a minimum energy of 10 (8) GeV and all jet–jet opening angles to be above 60° (50°) for three (four) jets]. The third gives the number of events that contain a lepton above 3 GeV, once $e^+e^-$ and $\mu^+\mu^-$ pairs with an invariant mass below 0.5 GeV have been removed, and the fourth those where these leptons are found only inside 20° cones around the jet axes. These latter events are then divided into four classes, depending on whether one or two jets contain leptons, and on whether these jets then are the two that contain the initial $q$ or $\bar{q}$ (correct) or not (false). Contamination from false assignments appears to be small, contrary to the case for conventional methods based on assuming the lowest-energy jets to be the gluon ones.

If a 50% experimental efficiency for lepton identification is added, the end result is thus a fraction $10^{-3}$ ($10^{-4}$) of doubly tagged three-(four-)jet events. Even with normal luminosity one may thus expect roughly 5000 (500) events, which should be enough to
reach the limit of systematic errors, although having more tagged four-jet events could prove useful.

One interesting topic might be to tag five-jet events in a corresponding manner. It seems highly doubtful that the presence of the four-gluon coupling could be established at all at LEP, given that its contribution to the total five-jet rate is very small, but at least one might want to establish that five-jet events have the expected angular distributions. Since this would probably mean another order of magnitude reduction of rate compared with the four-jet figure, a high-luminosity LEP option would here be essential.

The non-Abelian nature of QCD might also be tested by a study of the flavour composition of four-jet events, which is dramatically different in an Abelian toy model: the ratio $N(q\bar{q}'q')/N(4\text{jets})$ is increased by about a factor of 10 compared with standard QCD, from roughly 4% to 40%, using suitable cuts for well-separated jets. The main reason is that the group factor $T_R$ is increased from $n_f/2$ in QCD to $3n_f$ in the toy model; in addition the rate of $q\bar{q}gg$ events is reduced by the absence of the three-gluon vertex ($N_C = 0$ rather than 3) and the smaller rate of double gluon bremsstrahlung ($C_F = 1$ rather than 4/3).

One method to study the rate of $(qq'q')$ is to consider the production of heavy flavours, like $b\bar{b}b\bar{b}$ events, as suggested by Z. Fodor. With four-jet cuts that retain roughly 3% of the total number of hadronic events, the fraction of four-jet events where one jet is a $b$ one is increased from 21.1% in QCD to 31.4% in the non-Abelian model; for events with two $b$ quarks the rate is increased from 0.17% to 2.24% [6]. Note that, to study the latter number, it is important to be able to distinguish $b$ from $b$: obviously the rate of $bb$ pairs, as opposed to $bb$ ones, is equal to the single $b$ rate (to be precise, a tiny bit larger, by combinatorics in $b\bar{b}b\bar{b}$ events).

The size of the observable $b\bar{b}b\bar{b}$ signal thus depends strongly on the probability to tag $b$ jets, also against the $c$ background (from $cc\bar{c}$ and $b\bar{c}c$ events, and from $b \to c$ decays), and on the probability to distinguish $b$ from $b$. As an example, to use the lepton-flavour tagging scheme of Table 7.1, with the additional requirement that two jets contain a same-sign lepton pair, does not give a significant separation between QCD and the Abelian model. If one optimistically assumes that vertex tagging techniques could give a 10% $b$ quark tagging efficiency (including the $b/b$ separation), then $10^7$ hadronic $Z$ events corresponds to $10$ doubly-tagged $bb$ or $b\bar{b}$ events for QCD and $135$ in the Abelian model, i.e. just enough to provide a reasonable test. The advantages of having $10^8$ $Z$ events are here obvious.

7.1.2 QCD at the $Z$ peak—Rare processes

Observation of one or more exclusive $Z$ decays to quarkonia would provide useful information on bound-state dynamics. Most calculations to date have been performed within the framework of non-relativistic potential models. The applicability of such models at the large momentum transfers involved in $Z$ decays has, however, not yet been demonstrated. Moreover, there are final states containing light mesons where the quarkonium picture is not applicable at all. Alternative methods of calculation involve e.g. QCD sum rules or effective Lagrangians. A high-luminosity LEP option should enable at least a couple of these rare decays to be detected, and would therefore shed light on the nature of quark–antiquark bound states.
As an example, we first discuss $Z \to V + \gamma$, where $V$ is $J/\psi$ or $\Upsilon$. These processes were first calculated in the non-relativistic potential model by Guberina et al. [7]. They obtained branching ratios of around $5 \times 10^{-8}$ and $3 \times 10^{-8}$ for the two decays, respectively. Using instead an effective Lagrangian with a point-like vector VQQ coupling determined by the V leptonic widths, the decays are governed by the anomalous triangle diagram, and we find $1.2 \times 10^{-7}$ and $3 \times 10^{-8}$, respectively. Taking into account also the higher excitations in the $J/\psi$ and $\Upsilon$ systems, these numbers should be multiplied by factors of around 1.05 and 1.5, respectively.

If one has to rely on the $V \to \ell^+\ell^-$ decay modes these rates are obviously too small to be detected. It therefore becomes necessary to turn to hadronic decay modes, where the non-resonant background may be non-negligible: to a first approximation, the signal/background ratio for a given mass of the hadronic system is the same as for the contributions to $R = \sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$ at the corresponding c.m. energy (this statement should hold for the hadronic states with $J^{PC} = 1^{-+}$, with some modification when other partial waves are included as well). Thus a good mass measurement of the hadronic system is necessary if the peak is to stand out. Note that the recoiling photon energy is so close to the beam energy anyway, at least for the $J/\psi$, that a photon energy measurement cannot be used to derive the mass of the recoiling hadronic system. In conclusion, a measurement seems less than trivial, even with the maximum luminosity.

We may use the effective Lagrangian approach to calculate also the decays into light mesons, $Z \to \omega + \gamma$, $Z \to \rho + \gamma$. Since the decays go by the axial $Z$ couplings (by C invariance), there is a cancellation of the $u$ and $d$ quark contributions in the $\rho$ case, but a constructive interference in the $\omega$ case. We obtain a branching ratio of around $6 \times 10^{-8}$ for $Z \to \omega + \gamma$. Since the $\omega$ decays almost exclusively into $\pi^+\pi^0\pi^-$, one would get a 45 GeV $\gamma$ recoiling against a narrowly collimated three-pion system. As in the case of the $J/\psi$, finding the signal against the background may be difficult, however.

We note that the corresponding decays $Z \to P + \gamma$ (where $P$ is a pseudoscalar) are likely to be smaller in rate, as indicated by the non-relativistic calculations [7,8]. Here the effective Lagrangian approach is likely to fail since there is a constant (anomaly) contribution, which would make the rates unrealistically high. In reality, the amplitude should be cut-off like $(\Lambda_{\text{QCD}}/m_Z)^2$, since the compositeness scale of the light mesons is governed by $\Lambda_{\text{QCD}}$. This indeed renders the rates essentially unobservable, $10^{-10}$ or smaller. (See, however, Ref. [9].)

Another interesting rare decay is $Z \to ggV$ [10]. This process is related by crossing to $gg \to Vg$ and $gg \to V\gamma$, which are important processes for measuring the gluon structure function at high-energy hadron colliders. A measurement of this type of process in the cleaner environment of an $e^+e^-$ collider would give confidence to this gluon calibration scheme. In particular, one could get a handle on the relevant momentum scale in quarkonium production. There are indications [11] that a constant $\alpha_s(m_V^2)$ may fit the measured large $p_T$ $J/\psi$ production better than the running $\alpha_s(m_V^2 + p_T^2)$ naively expected. In addition, there is a possibility of a 'K factor' around two also in the $Z$ decays. Taking all these factors into account, the branching ratio $Z \to gg + \Upsilon$ (including excited $\Upsilon$ states) may be as large as $1.6 \times 10^{-6}$, or as small as $2 \times 10^{-7}$. In the former case, there is a fair chance of measurement (using the muon or electron decay channels of the $\Upsilon$), whereas the latter
rate is on the margin. Decays into $J/\psi$ should be of the same order of magnitude, but here the problem of background from B decays into $J/\psi$ is probably prohibitive.

Some other $Z$ decays involving quarkonia have recently been discussed in the literature [12]. These are of the type $Z \to Q\bar{Q} + (Q\bar{Q})_{\text{bound}}$. The widths were found to be $\Gamma(Z \to c\bar{c} + J/\psi) = 47$ keV, $\Gamma(Z \to c\bar{c} + \eta_c) = 145$ keV, $\Gamma(Z \to b\bar{b} + \Upsilon) = 6.4$ keV, and $\Gamma(Z \to b\bar{b} + \eta_b) = 6.5$ keV. The final states containing pseudoscalars unfortunately lack a distinctive signature, and $J/\psi$ production is dominated by B decays, but $Z \to b\bar{b} + \Upsilon$ may possibly be detectable if microvertex detectors are operational for reconstructing B decays.

The even rarer decay modes $Z \to VV$ and $Z \to PV$ have recently been calculated for the charmonium and bottomonium systems [13]. (The decay $Z \to PP$ is strictly forbidden by Lorentz invariance and Bose symmetry.) As expected, the branching ratios turn out to be very small, around $10^{-12}$ for charmonium and $10^{-10}$ for bottomonium. A theoretically interesting feature is the fact that the longitudinal parts of the $V$ polarizations contribute, meaning that the rate does not manifestly go to zero as $m_V \to 0$, as would be expected by analogy with Yang's theorem for $Z \to \gamma\gamma$. This means that the higher-order decays $Z \to PV\gamma$ and $Z \to VV\gamma$ (and $Z \to PP\gamma$, which is now allowed) are probably of the same magnitude as the non-radiative decays. Anyway, this type of decays seems to be way beyond observability even at a high-luminosity LEP.

Another type of exclusive decays involving quarkonia in the final state is $Z \to V\ell^+\ell^-$ ($\ell = e$ or $\mu$) [14]. This has a very clean signature and could in principle interfere with the search for weakly coupled (non-standard) Higgs particles. Of all possible diagrams contributing to order $\alpha^2$ to this process, only those where the $V$ meson is produced from a virtual photon radiated by the leptons are important. This means that the rate can be calculated essentially without ambiguities since the radiative part is given by QED and the $\gamma^* \to V$ transition strengths are measured in the decays $V \to \ell^+\ell^-$. Inserting the experimental values for the $V \to \ell^+\ell^-$ decay widths, the following predictions are found [14] for the branching ratios $BR_V = \Gamma(Z \to V\mu^+\mu^-)/\Gamma(Z \to \mu^+\mu^-)$: $BR_{\rho} = (2.8 \pm 0.1) \times 10^{-4}$, $BR_{\omega} = (2.3 \pm 0.1) \times 10^{-5}$, $BR_{\phi} = (3.6 \pm 0.1) \times 10^{-5}$, $BR_{J/\psi} = (2.0 \pm 0.2) \times 10^{-5}$, $BR_{\Upsilon} = (6.3 \pm 0.2) \times 10^{-7}$, where the estimated errors come from the uncertainties in the measured values of the V leptonic decay rate.

The production mechanism of the vector mesons through the $\gamma^*$ mixing means that the differential distribution of the $\ell^+\ell^-$ pair will be similar to that of ordinary QED radiation processes. In particular, the differential distribution in invariant mass will tend to peak at the highest values kinematically possible. Since the final state typically is a lepton pair plus a low-multiplicity hadronic system, this type of process is a potential background to the Higgs search, as also Higgs radiation tends to give a lepton pair at high invariant mass. To discriminate between the processes one has to use the fact that the hadronic invariant mass here of course fits one of the known vector meson masses, or the fact that this background is non-existent in the $Z \to H\nu\bar{\nu}$ channels.

### 7.1.3 QCD above the $Z$ peak

As we noted above, there is no a priori reason, within the framework of QCD, to prefer the $Z$ energy. Rather, many of the most interesting aspects are related to the energy variation of event properties, i.e. scaling violations. The running of $\alpha_s$ with c.m. energy has already been demonstrated experimentally up to LEP 1 energies [15]. It would here
be useful to have two further c.m. energies available, say at 120 and 150 GeV, each with at least $10^4$ multihadronic events, to match the error of the OPAL point of Fig. 7.1. In fact, since a number of detector uncertainties would divide out in a comparison between results at 90, 120, and 150 GeV, an even higher statistical sample would still be of use.

The presence of reasonably high-statistics measurements at a few (evenly spaced) energy points will also be useful for an extrapolation (directly or via tuning of Monte Carlo) into the region around and above the $W^+W^-$ threshold: one might choose to rely only on the total event rate for a determination of the $W^+W^-$ cross-section as a function of energy, but smaller errors should be achievable if hadronic events could be separated into $\gamma/Z$ and $W^+W^-$ ones. And, of course, this separation ability becomes crucial for any study that would involve the angular orientation of jets from $W^+W^-$ decays.

The number of jets that may be resolved increases with c.m. energy. There are therefore a number of multijet studies that require high statistics at the highest possible c.m. energy (either below the $W^+W^-$ threshold or, if above, with the $W^+W^-$ contribution removed) to be practicable. One example is the study of angular ordering in the shower evolution, as arising from QCD coherence effects [16,3]. While some aspects of QCD coherence may be studied at the $Z$ peak, the direct observation of angular ordering is not feasible, since systematic errors will be too large.

An explicit example of a possible analysis method is given in Ref. [17], to which we refer for details. Basically, a clustering algorithm is used to find the number of jets in an event, with the clustering scale set so low that also a possible 'subjet' structure is resolved. Thereafter, the two clusters with smallest invariant mass are successively joined into a new cluster, until only two clusters remain. The ordering in which this clustering procedure happens gives a 'mass-ordered' parton shower event history. It is now possible to study whether successive branchings in this history description also correspond to angular ordered emissions or not. Specifically, for two consecutive branchings $1 \rightarrow 2 + 3$, with opening angle $\theta_1$, and $3 \rightarrow 4 + 5$, with opening angle $\theta_3$, the ratio $r = \theta_3/\theta_1$ is studied. In an ideal world, $r$ should always be less than unity in the angular ordering scenario, with no such constraint if coherence effects are not taken into account. Spurious cluster reconstruction and recombination will introduce contaminations. The ratio $R = n(1.4 < r < 2)/n(0 < r < 0.6)$ gives a measure of the fraction of non-ordered branchings, disregarding the uncertain regions of $r$ close to unity or very large. This ratio is shown plotted in Fig. 7.2, as a function of $m^* = m_3$, for models with and without angular ordering imposed on branchings. The region of large $m^*$ values provides a control region, while the range $8 < m^* < 16$ GeV gives the best separation between the alternatives. The size of the error bars indicates the need for statistics of the order of $10^4$ events at 150 GeV.

7.2 $\gamma\gamma$ physics

Two-photon physics differs from the physics of $e^+e^-$ annihilation at LEP in two important respects:

- The existence of the $Z$ pole is a handicap rather than an opportunity; it increases potential backgrounds (which are totally negligible away from the peak) without increasing the signal.
- All cross-sections rise with the c.m. energy with at least some power of a logarithm. This is due to the logarithmic increase of the photon flux with the beam energy. Furthermore, in processes where at least one of the two photons is resolved into quarks and gluons ('resolved processes') the cross-section is proportional to the quark or gluon density inside the electron, which rises even faster with energy.

The question is then whether increasing the luminosity by a factor of 10 at the Z peak can compensate for the loss of cross-section (compared to running at the highest possible energy) and the drastic increase of the annihilation background.

Clearly an annihilation event can only be a background if a large part of the energy is lost, mainly due to incomplete detector coverage around the beam pipes. In other words, the background is given by events with at least one energetic jet going in the forward or backward direction. Presumably the outer fringes of this jet will still be detected, which allows for the possibility to discard all events of this type. However, a characteristic feature of all 'resolved' two-photon events is the occurrence of forward/backward 'spectator' jets; this large and interesting class of processes could therefore not be studied if a veto against small-angle jets is used. Nevertheless, it seems possible to isolate the 'resolved' production of two high-\( p_T \) jets by requiring the \( p_T \) of the two jets to balance. More exclusive two-photon processes have usually even less annihilation backgrounds. We will therefore assume in the following that these backgrounds will not be an unsurmountable obstacle for doing \( \gamma \gamma \)-physics at the Z pole, although they will undoubtedly make life somewhat more difficult.

In order to decide whether the signal benefits more from an increase of the c.m. energy to 200 GeV or from an increase of the luminosity by an order of magnitude, we have computed the cross-sections of some relevant two-photon processes, focusing on reactions when both photons are (nearly) on-shell ('no-tag' situation). In Fig. 7.3 we compare the differential cross-sections for the production of two high-\( p_T \) jets as a function of the dijet invariant mass at the two energies. The cut \( p_T > 2 \) GeV has been implemented to assure the applicability (\textit{cum grano salis}) of perturbative QCD, while the rapidity cut \( |y| < 1.7 \) ensures that both jets can be well reconstructed (in the ALEPH detector). The long-dashed, long-short-dashed, and short-dashed curves represent the contributions where none, one, or both photons are resolved into quarks and gluons. The latter two classes of contributions are interesting because they depend on the hadronic structure of the photon, about which very little is known experimentally at present. The direct contribution corresponds to the simple \( \gamma \gamma \rightarrow q\bar{q} \) process; while the production is well understood in this case, this process might offer a new opportunity to test fragmentation models in a reaction that is as clean as \( e^+e^- \rightarrow q\bar{q} \) annihilation.

We see that for all three classes of contributions the 'low'-energy, high-luminosity option allows a larger range of \( m_{\gamma} \) values to be probed. Assuming somewhat arbitrarily that with standard luminosity a cross-section of 0.5 pb/GeV is necessary for a good measurement, we find that the high-luminosity option could investigate the direct process up to \( m_{\gamma} \approx 35 \) GeV, whereas the high-energy option would only reach 22 GeV. This difference is smaller for the resolved processes, whose cross-sections grow more rapidly with energy; it should also be noted that annihilation backgrounds close to the Z peak will become more severe at higher \( m_{\gamma} \).

A similar picture emerges for the two-photon production of \( b\bar{b} \) pairs, see Fig. 7.4. While the low-energy high-luminosity option would produce about 3 times more \( b\bar{b} \) pairs
in total, the number produced via resolved processes is almost the same for both options. This latter contribution is interesting, because it is proportional to the gluon content $G^\gamma$ of the photon, about which almost nothing is known experimentally. (The Drees-Godbole, or DG parametrization of the quark and gluon content of the photon [18], which was used throughout, assumes $G^\gamma$ to be rather small; the resolved cross-sections shown in these figures can thus be considered as conservative estimates.)

Another process which directly probes $G^\gamma$ is the two-photon production of $J/\psi$, see Fig. 7.5, for which no direct process exists in leading order. Here the low-energy high-luminosity option is clearly favoured, giving roughly three times more events before cuts. Note, furthermore, that at higher energies a larger fraction of $J/\psi$'s will have such a large rapidity that at least one of the two leptons originating from its decay will be lost. Note that the cross-section of Fig. 7.5 has not been multiplied with the BR($J/\psi \to e^+e^-, \mu^+\mu^-$) $\approx 1/7$. The signal rate will thus be marginal at the 'ordinary' LEP 1 (unless $G^\gamma$ is much larger than anticipated), but should be easily detectable given 10 times more statistics.

### 7.3 Charm (and $\tau$) decays

For the study of $\tau$ and charm decays, a dedicated $\tau$-charm factory offers significant advantages. It is doubtful whether LEP could be competitive, except in lifetime measurements and in precision electroweak tests in $Z$ decays. Many of the aspects involved are discussed in the section on comparisons with $\tau$-charm factories. We only give here a few comments on charm decays, which indicate that, although a number of interesting studies could be envisaged, few (if any) have a realistic chance of success at HLEP.

The study of weak charm decays has reached an advanced level, certainly on the experimental side and almost on the theoretical side. Ongoing experiments (at FNAL, CERN, CLEO, ARGUS, Mark III, and the Beijing machine) should, over the next 3–4 years, almost complete the following chapters on standard model physics in charm decays:

- map out $D_s$ decays and determine absolute branching ratios;
- study once- and twice-Cabibbo-suppressed $D$ decays in more detail than before; and
- map out the spectroscopy of the weakly decaying charmed baryons, their lifetimes and major decay modes.

As far as standard model physics is concerned, only two items will be left out:

- charm decays with multineutrals in the final state; and
- the decays $D^+, D_s \to \mu^+\nu_\mu$ and $D_s \to \tau^+\nu_\tau$.

It seems that these processes can be studied in a sensitive way only at $e^+e^-$ threshold machines.

However, there are three topics that are accessible to present machines and deserve further study:
1. rare D decays like doubly-Cabibbo-suppressed ones and like $D \to \rho \gamma$;

2. $D^0-\bar{D}^0$ mixing; and

3. CP violation in charm decays.

Typical examples of doubly-Cabibbo-suppressed D decays are $D^+ \to K^+\pi^+\pi^-$ or $D^0 \to K^+\pi^-$. They are interesting since they can teach us a lot about the mechanisms underlying non-leptonic D decays, and in addition they form an important background to searches for $D^0-\bar{D}^0$ mixing. Typical branching ratios are $\text{BR}(D^0 \to K^+\pi^-) = 0.0002$, $\text{BR}(D^0 \to K^+\rho^-) = 0.0001$, $\text{BR}(D^+ \to K^+\pi^0) = 0.0002$, and $\text{BR}(D^+ \to K^+\pi^+\pi^-) = 0.0002$. To distinguish a doubly-Cabibbo-suppressed decay from a Cabibbo-allowed decay, one generally needs flavour tagging. For LEP, the most promising possibility is likely to use D mesons coming from semileptonic decays of B mesons, with the sign of the lepton as tag.

For rare decays, there is a benchmark figure for branching ratios that has to be reached before searches become interesting. Its actual size depends of course on the kind of new physics envisioned. For non-minimal SUSY for example [19], it is $\text{BR}(D \to \rho \gamma) \simeq 10^{-6}$, where constraints have been used as imposed by the experimental bounds on $D^0-\bar{D}^0$ mixing. Thus a sample of about $10^7$ D mesons is required to make such searches meaningful, i.e. more than any existing experiments are likely to accumulate. Information on the decay vertex is in principle not essential, but in practice quite useful. Unfortunately, searches for signals of this kind may well drown in the general multihadronic background at LEP. Other rare decays, like $D^0 \to \mu^+\mu^-$, are expected to have unobservably small rates, except in very special models.

The present E691 bound on $D\bar{D}$ mixing is $r(D) < 3.3 \times 10^{-3}$, which translates into $x = \Delta m / \Gamma$ or $y = \Delta \Gamma / 2 \Gamma < 0.1$. Standard model predictions are not very refined yet, but they suggest $r(D) < 10^{-3}$, and presumably $r(D) \approx 10^{-4}$. New physics could easily boost $r(D)$ up to a few times $10^{-3}$ [20]. Experimental bounds will go down to $r(D) \simeq 10^{-3}$ in the next few years. It is desirable to push sensitivity levels down to $r(D) \simeq 10^{-4}$. A good way to look for $D^0-\bar{D}^0$ mixing is to study the decay-rate evolution in proper time: if it is not purely exponential, then there is mixing. Decay-vertex information is clearly essential in such an analysis.

Finally, present experimental bounds on CP violation in D are given by 100%—not too impressive. Standard model predictions are again very rough only: the typical scale is $10^{-4}$ and could perhaps be as ‘high’ as $10^{-3}$. With new physics, such as non-minimal SUSY or an extended Higgs sector, it could however reach above the 1% level. The best-suited two-body decay modes are $D^0$ or $\bar{D}^0 \to K^+K^-$ or $\pi^+\pi^-$ [20]. Flavour tagging is required, i.e. it is necessary to know if the $K^+K^-$ or $\pi^+\pi^-$ comes from a meson that was born as a D or as a $\bar{D}$. A direct CP violation would express itself as a difference, between the $D^0 \to K^+K^-$ and the $D^0 \to K^-K^+$ decay rates, which is independent of the proper time of decay. A CP violation involving mixing, on the other hand, would express itself as a difference between the decay rates of the two CP conjugate states. This would give a dependence on proper time behaving like $\exp(-\Gamma t) \sin((\Delta m)t)$. In three- or four-body decay modes such as $D^0 \to K_S\pi^+\pi^-$ or $K_SK^+K^-$, or $D \to K3\pi$, or the Cabibbo-suppressed modes of the analogous type, CP asymmetries can be searched for in the Dalitz plot or in kinematically non-trivial triple correlations among momenta in the final state.
In summary, if any variant of new physics exists in D decays, it is not guaranteed that the signal could be dug out at HLEP. However, one should not disregard the possibility to do useful physics with a high statistics sample.

References


### Table 7.1

Number of events that survive quark-jet tagging criteria.
For further details, see text.

<table>
<thead>
<tr>
<th></th>
<th>3 jets</th>
<th>4 jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of events generated</td>
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<td>25000</td>
</tr>
<tr>
<td>... with acceptable jets</td>
<td>5382</td>
<td>1040</td>
</tr>
<tr>
<td>... with lepton(s) in event</td>
<td>679</td>
<td>124</td>
</tr>
<tr>
<td>... with lepton(s) in jets</td>
<td>629</td>
<td>112</td>
</tr>
<tr>
<td>1 jet with lepton(s), correct</td>
<td>550</td>
<td>100</td>
</tr>
<tr>
<td>1 jet with lepton(s), false</td>
<td>15</td>
<td>3</td>
</tr>
<tr>
<td>2 jets with leptons, correct</td>
<td>63</td>
<td>9</td>
</tr>
<tr>
<td>2 jets with leptons, false</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>
Fig. 7.1: The three-jet fraction as a function of c.m. energy, with two different scenarios for the energy variation of $\alpha_s$, and experimental data points. Some of the error bars shown are statistical only, while others include systematic errors as well. For normalization, note that the OPAL point is based on $10^4$ events [15], and that the inclusion of systematic errors has increased the error bar by roughly a factor 1.7 compared with the purely statistical error.

Fig. 7.2: The fraction of $R_\tau$ of non-ordered to ordered branchings as a function of the mass $m^*$ of the branching partons, using the algorithm described in the text. Full crosses give results with angular ordering and dashed ones without it. Results are for 10000 events at 150 GeV (without initial-state radiation); vertical bars indicate the size of statistical errors.
Fig. 7.3: Dijet invariant-mass distribution at a) 91 GeV and b) 200 GeV, with cuts as described in the text. The curves show: long-dashed the direct (no-resolved) contribution, long-short-dashed the once-resolved, short-dashed the twice-resolved, and full the sum.

Fig. 7.4: Total cross-section as function of c.m. energy for the production of $b\bar{b}$ pairs. Curves are labelled as in Fig. 7.3.

Fig. 7.5: Total cross-section as function of c.m. energy for the production of $J/\psi$. 
8 HIGH-LUMINOSITY PHYSICS AT LEP 200

R. Kleiss and D. Treille

In this section we shall review some possible implications of an increased luminosity at LEP 200.

Let us briefly summarize the conclusions of the 1986 Aachen Workshop [1]. To perform the interesting physics in a manageable way, quanta of 500 pb$^{-1}$ per experiment were required. Two energies, at least, were considered to be mandatory: the maximum energy ($\sqrt{s} \geq 190$ GeV) for most of the W-pair physics, searches, etc., and the region of W-pair threshold giving, for instance, the W mass through the cross-section excitation curve.

It should be emphasized that such requirements are not easily met. With the assumed nominal luminosity at top energy ($\sim 5 \times 10^{31}$ cm$^{-2}$ s$^{-1}$ peak), the Aachen quantum of 500 pb$^{-1}$ requires two good years of LEP operation.

As discussed in Ref. [2], it is unlikely that we can gain much in luminosity at the maximum energy. The quoted luminosity implies a current of $\sim 6$ mA per beam; for $\sqrt{s} = 195$ GeV, this in turn requires an RF power of 32 MW—a severe but realistic requirement.

When $\sqrt{s}$ decreases, we can, for a given RF power, increase the current per beam, such that $L \sim 1/E_0^2$. We will therefore assume that near the W-pair threshold an increase of L by a factor of 2 is feasible. The total increase in luminosity that can be foreseen is thus a factor of between 1 and 2 over the 500 pb$^{-1}$ assumed in the Aachen report, depending on which energies are decided upon. Although this increase is smaller than what can be anticipated at Z energies, it is potentially interesting because, at the currently foreseeable LEP 200 luminosities, statistical errors still play a major role.

In what follows, we have based ourselves on the extensive studies of LEP 200 physics presented in Ref. [1] (all references to page numbers in the present section are to this report). It is relatively straightforward to re-evaluate the most salient outcomes of this report in the light of a possible increase in luminosity: we shall discuss its impact on the measurement of the W mass $m_W$, the dynamics of the production process $e^+e^- \rightarrow W^+W^-$, the study of the properties of W decays, the search for new quarks and leptons and for SUSY particles, and the search for the Standard Model Higgs boson.

8.1 Measurement of the W mass

Roudeau et al. (pp. 49–84) considered three main approaches to extracting the W mass: threshold behaviour, mass reconstruction, and lepton spectrum end-points.

Assuming a five-point scan with 100 pb$^{-1}$ of luminosity at each point, between 160 and 172 GeV, the $W^+W^-$ excitation curve allows us to determine $m_W$ with a statistical error of between 100 and 130 MeV. The systematic errors depend mainly on the assumed energy behaviour of the background, and are characterized by a systematic shift in the observed value of $m_W$: however, this can be controlled to about 50 MeV using detailed Monte Carlo programs. In the high-luminosity case (assuming a gain of a factor of 2), the statistical error would decrease to about 80 MeV, making this an attractive option.

In the reconstruction of the invariant mass from the decay products in the $W \rightarrow$ hadrons channel, the statistical error is expected to be about 60 MeV, which
would hence become about 40 MeV with twice more luminosity. An important aspect of the control of systematic errors is the possibility to 'calibrate' the detectors on $e e \rightarrow \gamma Z$ (both visible): as $m_Z$ is perfectly known, the power of this method rests also on statistics, and a potential gain is to be expected as well.

However, the actual improvement could turn out to be limited, since the bulk of the $W$ events would come from the region of large cross-section around 190 GeV, where not much luminosity increase is expected.

Under similar reservations, the projected error of 90–120 MeV from the decays $W \rightarrow e\nu_e, \mu\nu_\mu$ might decrease to about 60–80 MeV.

The mass determination from the lepton spectrum end-point is not very promising: depending mainly on the calibration of the lepton energy measurement, an error of 300–500 MeV is expected, which would then improve to a possible 220–350 MeV.

### 8.2 The dynamics of W-pair production

The production of $W^+W^-$ pairs has long been recognized as a very attractive testing ground for the Standard Model, since it contains the three-boson couplings $W^+W^-Z$ and $W^+W^-\gamma$ already at the tree level, and considerable cancellations between the contributing Feynman diagrams occur, especially at large energies. In these couplings, most deviations from the strength and form predicted by the Minimal Standard Model result in a total cross-section—or at least a differential cross-section in the $W$ production angles—which is quite different from the Standard Model predictions. Davier et al. (pp. 120–157) have studied the prospects of LEP 200 for providing information on these couplings. Their result is that a c.m. energy of at least 190 GeV is an essential requirement (p. 132). For our purposes therefore, it appears that higher luminosity at lower energies cannot improve these tests of the Standard Model appreciably. On the other hand, the availability of polarized beams would certainly be helpful, even without increased luminosity.

### 8.3 Properties of W decays

Some properties of these decays were considered by Longo et al. (pp. 85–119). Their numerically most explicit results concern the tests of charged-current lepton universality, which can be conveniently measured since the decays into electrons, muons, and taus all occur in the same reaction and in an environment that is considerably cleaner than in hadron collisions. Denoting the couplings of $e\nu_e, \mu\nu_\mu$, and $\tau\nu_\tau$ to the $W$ by $g_e, g_\mu,$ and $g_\tau$, respectively, the following statistical errors on their ratios appear to be feasible: $\delta(g_\mu/g_e) \approx 0.020$ (which could become about 0.014 in the high-luminosity scenario), and $\delta(g_\tau/g_e) \approx 0.023$ (which could become about 0.016). Note, however, that already in the standard luminosity scenario the systematic errors in these measurements are at least as large as the statistical ones. Moreover, again the majority of the $W$ decay events would have to be generated at high energies, around 190 GeV, where the luminosity cannot be much increased.

### 8.4 Sequential new fermions; SUSY particles

These were studied by Igo-Kemenes et al. (pp. 251–311). As usual in $e^+e^-$ colliders, the limits that can be obtained on the masses of these particles are given essentially by
kinematics and not by the smallness of the cross-section. Therefore, even in the standard-luminosity scenario, the limits on new quarks and leptons will be the best possible. (In the increasingly improbable case that the top quark can still be produced at LEP 200, \( m_t < 100 \text{ GeV} \), it will already have been long detected in hadron–hadron collisions before LEP 200 is commissioned.)

Dionisi et al. (pp. 380–413) have studied the prospects of finding supersymmetric particles at LEP 200. Their conclusion is that the best place to perform searches is at the highest possible energies, so that again no improvement appears possible. One exception is the production of Zinos together with photinos, \( e^+e^- \rightarrow \bar{\tilde{\gamma}}\gamma \), for which the region just below the \( W^+W^- \) threshold seems to be the most appropriate: but in this case it is likely that we will not need 500 pb\(^{-1} \) in order to obtain the best possible limits.

We conclude that not much is to be gained by high luminosity for these classical searches: this situation can be compared with that at LEP 1, where at this moment, with a rather modest integrated luminosity, several limits close to the kinematical one have already been obtained.

This is, however, not true for all kinds of searches, direct or indirect.

For instance, the problem of the SUSY Higgses, to be fully explored [3], is very demanding in luminosity (see Section 8.5).

Charge asymmetries of the fermions and other quantities are basic ingredients of indirect searches (for heavier bosons, compositeness, etc.). These are completely dominated by statistics at LEP 200 and benefit fully from any possible increase in luminosity.

### 8.5 The Higgs boson

Wu et al. (pp. 312–379) have studied the searches for the Minimal Standard Model Higgs boson \( H^0 \) at LEP 200. The process chosen is \( e^+e^- \rightarrow Z^0H^0 \). Their conclusions are that with the standard luminosity of 500 pb\(^{-1} \), a limit of 70 GeV on the Higgs mass is possible. Note, however, that such a limit could also be obtained at LEP 1 using the related process \( e^+e^- \rightarrow H^0\bar{\tau}\bar{\tau} \), especially in the high-luminosity scenario, although it may be experimentally more difficult and demanding.

For higher Higgs masses, the Aachen report contains rather more pessimistic conclusions: Higgs bosons with masses comparable to \( m_W \) or \( m_Z \) could possibly be hard to distinguish from actually produced W's or Z's, so that in that case the problem is one of background rather than insufficient signal. However, it has been claimed since then that the good efficiency foreseen for tagging on b quarks [4] (which would be the dominant decay channel for a Higgs boson of such masses) could significantly improve the signal-to-background ratio up to Higgs masses of around \( m_Z \), so that such masses could be accessible with at least 500 pb\(^{-1} \). While \( M = m_Z \) has nothing magic for a standard Higgs, it is well-known that this mass region is an accumulation point for the neutral Higgses of minimal SUSY. One at least of these objects must be there, within a few GeV of \( m_Z \) (subject to a computation of radiative effects not yet available). The production rate of one or the other of the two scalars is at least equal to the production rate of the standard Higgs of \( m_H = m_Z \), provided no kinematical suppression occurs (i.e. \( \sqrt{s} = 190 \text{ GeV} \)). The visibility is then guaranteed with \( \int L \, dt \geq 500 \text{ pb}^{-1} \). This is discussed in detail elsewhere in this report [3]. It is an important issue, which has very clear consequences on the maximum \( \sqrt{s} \) needed and certainly deserves further studies.
8.6 Conclusions

Under the assumption that LEP 200 luminosity may be improved by about a factor of 2 in the $W^+W^-$ threshold region, but not by a significant amount near the maximum $\sqrt{s}$, the following conclusions appear justified:

- In the W-mass measurement from a study of the excitation threshold, the statistical error can be reduced from about 100–130 MeV to about 70–80 MeV. Other methods for the mass determination do not appear to be able to profit appreciably from a luminosity increase, since they rather rely on high statistics at the peak cross-section, which is at the very end of the LEP 200 energy reach.

- The tests of charged-current lepton universality may profit marginally from increased luminosity, since systematic errors seem to become rapidly dominant.

- Searches for classical sequential or supersymmetric new particles will already be sensitive enough with 500 pb$^{-1}$, with the possible exception of $\tilde{Z}$: however, as usual, this depends strongly on various choices of unknown mass values of supersymmetric particles such as $\tilde{\tau}$ or $\tilde{e}$.

- Higgs searches, for heavy Higgs masses, can certainly benefit from a luminosity increase. Although high L at LEP 1 could allow the mass limit to be pushed up to 60–70 GeV, LEP 200 is the right place to explore the highest masses. With a good b-quark tagging and 500 pb$^{-1}$ at least, one can even hope to reach $\sim 90$ GeV, provided that the maximum available energy is close to 100 GeV.

For SUSY Higgses a fortiori, a luminosity increase would be very beneficial.

In conclusion, let us state again that the physics at LEP 200, to be performed in a satisfactory way, needs large exposures ($\geq 500$ pb$^{-1}$). Given the very limited possibilities of improving the luminosity that we have assumed (none at top energy, a factor of 2 at the WW threshold), we could not expect dramatic improvements in the physics. The most obvious ones will be in the W mass determination and in the accuracy of asymmetries measurement. Another very important piece of physics where high luminosities (and large $\sqrt{s}$) are crucial is the systematic exploration of the heavy Higgs sector.

REFERENCES


[3] See Section 3 of this part in the present report.

[4] See Section 6 of this part in the present report.

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PART III

COMPARISON OF HIGH-LUMINOSITY LEP WITH OTHER MACHINES

E. Blucher, J.J. Gomez Cadenas, G. Coignet, J.F. Donoghue, J. Kirkby,
G. Mikenberg (convener), J. Panman
1 INTRODUCTION

The possibility of operating LEP in a multibunch mode to increase its luminosity brings within reach a broad physics potential in the near future. The luminosity would be raised by an order of magnitude at the $Z$ peak, and could lead to a factor of two increase at the $W^+W^-$ pair threshold. This increase would both accelerate and also enrich the high-energy programmes of LEP, in which the uncertainties on fundamental measurements such as the $W$ mass and triple gauge couplings are dominated by the statistical errors.

Before making a comparison between the high-luminosity LEP project (HLEP) and other machines, one should point out that there are several important physics experiments that are unique to HLEP. Of particular importance is the measurement of the weak coupling constants of the leptons and quarks, where the large statistics at HLEP will reduce the systematic errors by almost an order of magnitude (see Table 1.1). The precisions are comparable with those attainable with polarized beams, thus providing a critical test of the standard model. Other experiments that are unique to HLEP are the searches for rare decay modes of the $Z$, in particular $\gamma\gamma\gamma$, $\pi^0\gamma$, $\eta\gamma$, which are predicted to be large in some models. Flavour-changing neutral current decays such as $Z \rightarrow \tau e$ and $s\bar{b}$ (tagging $s$ quarks with $\phi$ mesons and $b$ with leptons) can be measured down to branching ratios below $10^{-5}$, complementing measurements that can be performed in $\tau$ decays.

The physics topics where HLEP will overlap with other machines is the study of the properties of $B$ and $D$ mesons, including lifetime measurements, $B_s-B_s$ oscillations and the possibility of detecting CP violation in $B_d$ decays. A direct comparison with hadron machines (both fixed-target and colliders) is very hard, because of the difficulties in detecting $B$ mesons within a large background of multihadron production; therefore a short resume is given in Section 2 on the possible expectations for fixed-target results in the coming years. In the case of $e^+e^-$ colliders, the experiments are similar in nature and therefore a proper comparison can be made.

The reason for the competitiveness of HLEP with $e^+e^-$ machines running at the bottom and to a lesser extent at the $\tau$-charm thresholds is the large $Z$ cross-section. Figure 1.1a shows the production cross-section for $b\bar{b}$ quarks ($\sigma_{bb}$); the highest cross-section occurs at the $Z$ peak. Figure 1.1b shows the ratio $\sigma_{bb}/\sigma_{tot}$ (hadr.) as a function of $E_{cm}$, for which the best values are obtained at the $Z$ and $\Upsilon_{4s}$ peaks. Figures 1.2a, b show the same distributions for $c\bar{c}$ production. It can be seen that a machine near threshold benefits from a larger $c$-quark cross-section as well as lower background.

As summarized in Table 1.2, the number of events at HLEP is comparable with that given by a $B$ factory (for $b\bar{b}$ events) and a factor of 5-10 below a $\tau c$ factory (for $\tau c$ events), assuming a factory luminosity of $10^{33}$ cm$^{-2}$ s$^{-1}$. In the case of $B$ studies HLEP has the advantage of a much larger $B_s$ cross-section than at the $\Upsilon_{4s}$. This combined with the strong boost allows, for example, excellent measurements of the $B_s-B_s$ oscillations [1] which cover all the allowed range of the $X_s$ ($X_s = \Delta m_s/\Gamma$) parameter, almost doubling the range that could be covered in an asymmetric $B$ factory.

The remainder of this Part III is organized as follows: first a review is given of the prospects for $B$ physics in fixed-target experiments; this is followed by a description of the existing and planned $B$ and $\tau c$ factories, including a physics comparison with HLEP; finally an overall comparison of the main points is made including the corresponding time scales.
Table 1.1

Errors obtained in the measurement of $\sin^2 \theta_w$

<table>
<thead>
<tr>
<th>Charged asymmetry</th>
<th>LEP 1</th>
<th>HLEP</th>
<th>Polarization with $\int L , dt = 40 , \text{pb}^{-1}$</th>
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</thead>
<tbody>
<tr>
<td>$\delta A_{FB}^\mu$</td>
<td>0.0017</td>
<td>0.0012</td>
<td></td>
</tr>
<tr>
<td>$\delta A_{FB}^\tau$</td>
<td>0.002</td>
<td>0.001</td>
<td>0.0003</td>
</tr>
<tr>
<td>$\delta A_{FB}^\tau$</td>
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<td>0.0009</td>
<td></td>
</tr>
<tr>
<td>$\delta A_{FB}^\tau$</td>
<td>0.0009</td>
<td>0.0003</td>
<td></td>
</tr>
</tbody>
</table>

Table 1.2

Number of $\bar{f}f$ pairs per $10^7$ s for B and $\tau c$ factories with $L = 10^{33} \, \text{cm}^{-2} \, \text{s}^{-1}$ and for HLEP with $L = 1.5 \times 10^{32} \, \text{cm}^{-2} \, \text{s}^{-1}$

<table>
<thead>
<tr>
<th>Events</th>
<th>HLEP</th>
<th>B fact</th>
<th>$\Upsilon_{4s}$</th>
<th>$\tau c$ factory</th>
<th>$E_{cm} = 3.67 , \text{GeV}$</th>
<th>$E_{cm} = 3.77 , \text{GeV}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b\bar{b}$</td>
<td>$10^7$</td>
<td>$10^7$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$c\bar{c}$</td>
<td>$8 \times 10^6$</td>
<td>$10^7$</td>
<td>-</td>
<td>-</td>
<td>$5 \times 10^7$</td>
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<td>$8 \times 10^6$</td>
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<td>$2 \times 10^7$</td>
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</tr>
</tbody>
</table>
Fig. 1.1: a) $\sigma_{bb}$ as a function of $E_{cm}$, 
b) $\sigma_{bb}/\sigma_{had}$ as a function of $E_{cm}$

Fig. 1.2: a) $\sigma_{cc}$ as a function of $E_{cm}$, 
b) $\sigma_{cc}/\sigma_{had}$ as a function of $E_{cm}$
2 B-PHYSICS WITH FIXED-TARGET EXPERIMENTS AND HADRON COLLIDERS

The study of B physics in fixed-target and hadron-collider experiments is a difficult task, mainly because of the low cross-section of beauty production with respect to the total cross-section. An additional difficulty is the small value of the branching ratios into modes with all charged particles. However, the large rate (up to $\sim 10^8$ $b\bar{b}$/year) indicates an important potential in future fixed-target and hadron-collider experiments.

Up to now, production cross-sections were inferred from multimuon production [2], and one event was fully reconstructed [3]. Physics objectives that can be addressed (in order of increasing difficulty) are: production cross-sections, lifetimes, $B^0 - \bar{B}^0$ mixing, and eventually CP violation. In proton-hadron interactions the unequal production rates of $B^0$ and $\bar{B}^0$ necessitates an auxiliary measurement if CP violation is to be tested. This is done by calibrating the $B^0/\bar{B}^0$ ratio with a decay mode that is not CP-violating [4] or by other means depending on the channel of interest. It was also pointed out that the difference of the two asymmetries in the modes $B^0/\bar{B}^0 \rightarrow J/\psi K_S^0$ and $B^0/\bar{B}^0 \rightarrow J/\psi K_L^0$ is sensitive to CP violation [5].

Various experiments are being prepared with the aim of reconstructing $10^2$ to $10^3$ $b\bar{b}$ events. Two different strategies are being developed. One method uses an inclusive trigger on $b\bar{b}$ pairs with a relatively high efficiency ($\sim 50\%$) and low interaction rate ($\sim 10^5$ int./s). Another method consists of selecting specific decay modes at the trigger level, such as $B \rightarrow J/\psi + X$, with a low efficiency (due to the low overall branching ratio) but a high interaction rate ($\sim 10^6$ or $10^7$ int./s). Even higher interaction rates are envisaged for experiments with restricted kinematic coverage. At CERN, WA82 used a silicon microstrip vertex detector with an impact parameter trigger [6]. They hope to isolate a few tens of events in their present data. About $10^3$ reconstructed $B\bar{B}$ events are planned, in an open-geometry experiment, WA92 [7], for 1991–1992 in a 360 GeV $\pi^-$ beam. The trigger looks for secondary decay vertices of the $b \rightarrow c$ decay chain.

An example of the second approach is E771 at FNAL [8]. They aim at obtaining a few $10^3$ to $10^4$ events of the type $B \rightarrow J/\psi + X$, triggering on dimuons forming a $J/\psi$. This experiment is expected to start operation in 1990–1991 and will run initially with $10^6$ interactions per second.

All these experiments make use of microvertex detectors to detect secondary vertices. Another method has been proposed by Kekelidze [9], to achieve higher statistics in a specific channel that is sensitive to CP-violation effects. The method consists of measuring the difference in the asymmetry of the decays $B^0(\bar{B}^0) \rightarrow J/\psi K_S^0$ and $B^0(\bar{B}^0) \rightarrow J/\psi K_L^0$, which is insensitive to the production ratio of $B^0\bar{B}^0$ [4]. A high rate is achieved by removing the need for a microvertex detector, and by using a dump which allows the $K^0$ to pass through a slot and favours the signal-to-background ratio. Charged particles are deflected by a sweeping magnet and absorbed. All $B\bar{B}$ events are accumulated in a single channel. The trigger is formed by the requirement of three muons, two forming a $J/\psi$, and one to tag the other B decay. This experiment is proposed for the 3 TeV UNK accelerator [9], and studies are being made to investigate its feasibility at the SPS [10].

Finally it should be mentioned that the fixed-target approach is very competitive for the measurement of lifetimes. In particular, WA92 aims at a measurement of the $B^+$ and $B^0$ lifetime ratio to within 5%.
Unlike experiments at HLEP, the success of the B physics programme at the Tevatron will largely be dependent on the success of the trigger systems. At Tevatron energies, the $b\bar{b}$ cross-section is very large, roughly 20 $\mu$b for centrally produced $b\bar{b}$ events. Roughly 1 event in 1000 is a $b\bar{b}$ event. In the 1988 CDF run, over $10^8$ $b\bar{b}$ events were produced. In contrast, CDF only wrote $6 \times 10^6$ events to tape.

In the 1988 CDF run, two triggers provided a fairly clean sample of B events. The first was the inclusive electron and muon triggers. Here the electron and muon candidates were required to be have a $p_T$ of 12 GeV and 9 GeV, respectively. The accompanying charm observed in these events implies that the sample is dominated by semileptonic B decays. The second trigger was the dimuon trigger in which both muons are required to have $p_T > 3$ GeV. This trigger provided a sample of 1700 $J/\psi \rightarrow \mu\mu$ events on a small background. Indications are that a non-negligible fraction of all $J/\psi$ observed at Tevatron energies are from B decay.

CDF has identified a sample of over 30 fully reconstructed B mesons in the decay channel $B \rightarrow J/\psi KK^*$. The signal-to-background ratio is greater than 1 to 1. It should be noted that both the inclusive lepton samples and the dimuon sample were collected with triggers that are only efficient at the high end of the B $p_T$ spectrum. This implies that large gains can be made in the B sample sizes by lowering the trigger thresholds. To this end, better background rejection in the trigger and a more powerful data acquisition system are required.

The b physics capabilities of CDF will be enhanced in 1991 with the use of its new silicon vertex detector and added muon coverage. CDF also plans to improve its triggering capabilities for leptons and dimuons.

Improvement by a factor of 10 or more in the observed $J/\psi$ cross-section is possible. This should yield of the order of 100,000 $J/\psi$ from B decay written to tape. Measurements of various B masses and lifetimes, for exclusive states such as $B^0$, $B^+$, and $B_s$, will be possible.

CDF and D0 also plan to collect of the order of $10^6$ semileptonic B decays from exclusive lepton triggers.

The B physics programme at the Tevatron is evolutionary. It is not clear what fraction of the large increases (factors of over 100) in luminosity planned for the Tevatron in the 1990's can be translated into correspondingly large increases in B-sample sizes and b physics capabilities. The 1991 run for D0 and CDF should be a good indication of future prospects.
3 B-MESON FACTORIES AND COMPARISON WITH HLEP

The simplest way to study the physics of the B mesons is at the $\Upsilon_{4s}$ (10.6 GeV) resonance which decays into $B_{ud}B_{ud}$ pairs. The $\Upsilon_{4s}$ has a large $bb$ cross-section and large relative rate (see Fig. 1.1). Since the $B$'s are produced near threshold, in a two-body final state with an accurate centre-of-mass energy, the mass uncertainty in kinematic reconstruction is only 2 to 3 MeV.

In addition to $b$ physics studies, a machine running at the $\Upsilon_{4s}$ also produces $\tau\tau$ events ($\sigma = 0.8$ nb, compared with 1.3 nb at $Z$) and $c\bar{c}$ events ($\sigma = 1$ nb, compared with 5.3 nb at $Z$).

Presently two experiments are running at symmetric-energy machines in the $\Upsilon_{4s}$ regions:

- ARGUS at DORIS II (DESY) with a peak luminosity $L = 3 \times 10^{31}$ cm$^{-2}$ s$^{-1}$,
- CLEO II at CESR (CORNELL) with a peak luminosity $L = 1 \times 10^{32}$ cm$^{-2}$ s$^{-1}$.

Although almost one million B decays have been recorded by CLEO and ARGUS, less than 500 of these decays have been fully reconstructed with low background. This low figure results from several factors. The average charged multiplicity of a B decay is about 6, leading to a large combinatorial background. Since the B mesons in $\Upsilon_{4s} \rightarrow BB$ decay are produced almost at rest, it is impossible to separate the tracks from the two B mesons topologically. The high background implies that excellent mass resolution is necessary to observe a clean signal. For both CLEO and ARGUS, this requirement has necessitated using only charged particles (although ARGUS sometimes considered decay modes with a single $\pi^0$). Finally, the exclusive branching ratios are very low; they are about a factor of ten less than the corresponding decays of charmed mesons. The additional charm branching fraction reduces the detection efficiency still further.

These problems suggest two requirements for further progress in B physics at the $\Upsilon_{4s}$: increased luminosity and improved detection efficiency for B decays. The CLEO and CESR programs at Cornell began such an upgrade plan several years ago.

The luminosity of CESR has increased steadily since the start of operation in 1979. Improvements during the last several years, including operation with seven bunches per beam and microbeta optics using permanent quadrupole magnets ($\beta^* = 1.5$ cm), led to a record peak luminosity of $10^{32}$ cm$^{-2}$ s$^{-1}$ while running at the $\Upsilon_{4s}$ resonance. The best month of running produced 90 pb$^{-1}$, corresponding to a potential of $10^6 \Upsilon_{4s} \rightarrow BB$ events per year.

CESR will be upgraded during the next two years to allow a further increase of a factor of five in peak luminosity (CESR+). The major increases in luminosity come from reducing the number of interaction regions from two to one (the CUSB experiment will be removed in 1990), doubling the number of bunches from seven to fourteen, and increasing the current per bunch by almost a factor of 2. By 1993, they expect to achieve a peak luminosity of $5 \times 10^{32}$ cm$^{-2}$ s$^{-1}$ on the $\Upsilon_{4s}$ resonance and an integrated luminosity of 25 pb$^{-1}$ per day [11].

The CLEO II detector has been operating at CESR since the fall of 1988. This detector features excellent resolution for both charged and neutral particles, and will allow efficient reconstruction of B mesons that decay to both charged and neutral particles. Estimates from design studies indicate that the new detector should allow at least a factor of
ten increase compared with the previous CLEO detector, in the fraction of B decays that can be fully reconstructed. These studies estimate an efficiency of 7000 $B^\pm/1000$ pb$^{-1}$ and 3000 $B^0(B^0)/1000$ pb$^{-1}$ [12].

3.1 Physics prospects by the end of 1993

Depending on the success of the CESR+ upgrade, CLEO II should have a sample of $3-10 \times 10^6 \ U_{4s} \rightarrow B\Bbar$ events, which corresponds to a sample of 27,000 to 90,000 fully reconstructed B mesons [13,12]. Even more B mesons will be partially reconstructed through their semileptonic decay and through decays like $B \rightarrow D^{\ast+}\pi^-$, where the $D^0$ from the $D^{\ast+}$ decay is not detected. This large data sample will allow detailed studies of several topics [14].

1. Rare decays. All two-body decays with branching fractions greater than $10^{-5}$ should be measured. For example, if predictions are correct, decays resulting from 'penguin' graphs (e.g. $B^- \rightarrow \Kbar^0\pi^-$) should be observed [15].

2. $V_{ub}/V_{cb}$. Measurement of exclusive charmless B decays and more precise measurements of the end-point of the lepton momentum spectrum will give better measurements of $V_{ub}/V_{cb}$.

3. Detailed study of semileptonic B decay. Assuming an average lepton identification efficiency of 0.7 [14], the above sample of fully reconstructed B decays implies between 4000 and 12500 semileptonic decays for which the recoiling B meson is fully reconstructed. Since the momentum of both B mesons is known in this case, the missing-mass distribution for the semileptonic B decay is very narrow, and is determined solely by the detector resolution. The tagged sample will allow a precise measurement of the ratio of neutral and charged B semileptonic branching fractions. If the leptonic widths of the neutral and charged B mesons are equal, this ratio gives the lifetime ratio of neutral to charged B mesons.

4. Accurate measurements of the branching ratios to important CP eigenstates such as $D\bar{D}$ and $\psi K_S$.

3.2 Asymmetric machines

The disadvantage when running with $e^+e^-$ beams of equal energy is that the two mesons are produced nearly at rest and their decay particles are topologically mixed, resulting in a low reconstruction efficiency (< 1%) and no reconstruction of the $B(\bar{B})$ vertex. In addition, the $B-\bar{B}$ are produced in a $C= P = -1$ state, and this precludes the observation of a possible CP violation in the decay to the CP eigenstate $B(\bar{B}) \rightarrow J/\psi K_S^0$, since the time difference between the two B mesons cannot be measured.

In order to avoid these disadvantages new B-factories are being considered with unequal beam energies to produce the $U_{4s}$ moving in the laboratory. This would result in B's boosted along the beam axis, and a measurable distance between the B and $\bar{B}$ (100-300 $\mu$m for large enough beam asymmetry).

An experiment with $0.5-1 \times 10^8 B\bar{B}$ produced, and with a microvertex detector placed at a small radial distance (~ 2 cm or so) from the interaction point, has a good chance of detecting CP violation in the $B(\bar{B})$ system [16]. $B_s-\bar{B}_s$ mixing could also be measured for $X_s$.
up to 7 or 12 depending on the beam asymmetry (see paragraph 3.3.2 below). Rare decays with branching ratios in the few $10^{-7}$ range would be detectable.

New circular colliders based on double rings are being actively investigated, in order to achieve a peak luminosity $L = 1-3 \times 10^{33}$ cm$^{-2}$ s$^{-1}$ (5–15 fb$^{-1}$/year), to be increased later to $L = 0.5-1 \times 10^{34}$ cm$^{-2}$ s$^{-1}$. They all plan to use high beam currents (multibunch), high tune-shift values and low $\beta^*$ values. Usually two interaction regions are foreseen.

The various plans are:

a) VEPP5 project at Novosibirsk [17]. Originally based on equal-energy beams, this has evolved into a 7 GeV $\times$ 4 GeV B-factory at $L = 10^{33}$ cm$^{-2}$ s$^{-1}$. Special emphasis has been put on obtaining a very small centre-of-mass energy spread (1 MeV). The project has been approved in 1989 but the time schedule is still uncertain. Construction of a multipurpose detector, KEDR, has already started.

b) BFI studies at CERN [18]. The feasibility study of a B-factory located in the ISR tunnel, which makes use of the CERN injection chain, has been completed. It involves an asymmetric $8(e^-) \times 3.5(e^+)$ GeV collider with

\[
L = 1 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1} \quad \text{('the reference machine')} \quad \text{and}
L = 1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \quad \text{('the ultimate machine')} \text{ after several years of R$\&$D}
\]

It would be possible to convert it to a 5.3 GeV $\times$ 5.3 GeV machine with a reduced luminosity: $L_{\text{sym}} = 0.6L_{\text{satym}}$.

c) B factory studies at KEK [19]. An asymmetric B factory has also been studied at KEK over the last year. The present scheme is based on two new rings, $8(e^+) \times 3.5(e^-)$ GeV, installed in a new tunnel (1.2 km circumference) making use of the linac injector and an upgraded TRISTAN Accumulating Ring. An initial peak luminosity $L = 2 \times 10^{33}$ cm$^{-2}$ s$^{-1}$ is planned, leading to $L = 1 \times 10^{34}$ cm$^{-2}$ s$^{-1}$ at a later stage. Only one interaction region is considered at present. An option to go to 2.46 $\times$ 12 GeV, with slightly reduced luminosity, has also been investigated. The construction of the machine and the detector, including R$\&$D, would take 5 years, i.e. the data taking could start in 1996 if a decision is taken in 1990.

d) CESR-B studies at CORNELL [20]. A new separated machine ($L = 10^{34}$ cm$^{-2}$ s$^{-1}$) is under study. It should make use of the existing injection chain and of the existing tunnel. One of the options involves flat beams, and another round beams. It could be run with slightly asymmetric beam energies. Tests and simulations are being performed. A proposal is expected to be ready by the end of this year.

e) PEP-B studies at SLAC [21]. A double-ring machine $[9(e^-) \times 3(e^+)$ GeV] is being designed in the PEP tunnel aiming at $L = 1$ to $3 \times 10^{33}$ cm$^{-2}$ s$^{-1}$. R$\&$D tests are planned for PEP and a proposal is expected in early 1991. A detector will also be designed. Optimistically the machine could start operating at the beginning of 1996 and quickly reach $L = 30$ fb$^{-1}$/year.

f) PETRA-B studies at DESY [22]. Studies have also been performed to add a small ring tangential to the PETRA tunnel. The expected performance of this 12 GeV $\times$ 2.3 GeV
collider is \( L = 10^{33} \text{ cm}^{-2} \text{ s}^{-1} \). An option with two rings in the PETRA tunnel is also being considered.

The optimization of the interaction region is a major challenge to all the asymmetric machines. Novel ideas have been proposed, such as ‘crab crossing’, and ‘tilted detectors’. They all need additional studies, mainly on background estimates.

New colliders based on linacs have also been investigated recently:

\( g \) Linear–linear colliders [23]. They offer many advantages, especially at the interaction region. Their main problems are positron production and large energy spread which limits the luminosity to \( L = 10^{33} \text{ cm}^{-2} \text{ s}^{-1} \) at the \( \Upsilon_{4s} \).

\( h \) Linear–circular colliders [24]. In this scheme intense positron bunches are stored in a ring where they collide with less intense high-frequency electron bunches from a linac. Linacs based on superconducting cavities have to be used and parameter lists have been computed for two designs: \( 2.8 \text{ GeV} e^- (\bar{e}^+) \times 10 \text{ GeV} e^+ (e^-) \). Recently a detailed study of \( 3 \text{ GeV} (e^-) \times 9 \text{ GeV} (e^+) \) has been performed [25]. This study tends to indicate that \( L = 10^{33} \text{ cm}^{-2} \text{ s}^{-1} \) would be attainable and that \( L = 10^{35} \text{ cm}^{-2} \text{ s}^{-1} \) should be within reach, after a vigorous R&D program.

A B factory detector has to satisfy the following design requirements:

- Microvertex detector surrounding a low-\( Z \) beam pipe with a 1.5 to 2 cm radius, able to reconstruct the \( B(\bar{B}) \) vertices with a resolution \( \sigma_z = 10-40 \mu \text{m} \) along the beam (silicon detector);
- Low-mass drift chamber to provide excellent momentum resolution and high efficiency for charged particles down to 20 MeV/c.
- Crystal electromagnetic calorimeter for the detection of photons and electrons with excellent energy and spatial resolution down to 30–50 MeV (CsI, BGO),
- \( dE/dx \), time-of-flight and Ring Imaging Cherenkov counters for particle identification up to 3 GeV,
- Superconducting solenoid coil to produce a high field (1–1.5 T),
- Muon identification and tracking in muon detectors embedded in the return flux yoke.

### 3.3 Physics prospects for asymmetric B-factories

#### 3.3.1 CP violation

The main motivation to build such a machine is the study of CP violation in the b-quark system. For events in which a \( B^0 \) or \( \bar{B}^0 \) is tagged at time \( t_1 \) and the other one decays at time \( t_2 \) into a CP eigenstate, for instance \( J/\psi K_S^0 \), the measurement of the time difference \( t = t_2 - t_1 \) yields a measurement of CP violation.

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The observable asymmetry is

\[ A_{\text{obs}} = \frac{N(J/\psi K^0_S, \bar{B}_{tak}) - N(J/\psi K^0_S, B_{tak})}{N(J/\psi K^0_S, \bar{B}_{tak}) + N(J/\psi K^0_S, B_{tak})} = A_0 \sin[\Delta m(t_2 - t_1)] \]

where

\[ A_0 = \sin 2\beta = 0.12 \rightarrow 0.48. \]

Integrated over time, \( A_{\text{obs}} = 0 \) on \( \Upsilon_{4s} \), but for boosted \( \Upsilon_{4s} \) with large enough \( \beta \gamma \) (= 0.4, 0.6) the time difference \( \Delta t = (t_1 - t_2)/\beta \gamma \) becomes measurable with a microvertex detector.

The various studies agree that a 3\( \sigma \) effect would be observed for an integrated luminosity of 10 to 200 fb\(^{-1} \) (10\(^7 \) to 2 \times 10\(^8 \) bb) depending upon the actual \( A_0 \) value, i.e. 0.48 to 0.12. In comparison HLEP could provide, after three years of running, 1 to 2\( \sigma \) hints of CP violation, provided that \( A_0 \) is in the range 0.48 to 0.3.

Once CP violation is seen in \( B \rightarrow J/\psi K^0_S \) decays, a wide research program on CP violation will open up, including other channels such as \( B \rightarrow \pi^+\pi^- \) and \( B \rightarrow K^\pm\pi^\mp \). Other parameters of the KM matrix will be determined with high precision.

3.3.2 \( B_s \bar{B_s} \) mixing

About one third of the \( \Upsilon_{4s} \) mesons are expected to decay into \( B_s \) mesons and the decomposition into \( B_s \bar{B}_s, B_s^* \bar{B}_s + B_s \bar{B}_s^*, B_s \bar{B}_s \) is unknown. Since \( B_s^* \) decays into \( B_s \gamma \) the decomposition can be determined by measuring the fraction of identified \( B_s \) accompanied by 0, 1, or 2 photons.

A first measurement of \( B_s \bar{B}_s \) oscillation would be possible from the integrated oscillation parameter

\[ X_s = \frac{N_s(\ell^+\ell^+)}{N_s(\ell^+\ell^-) + N_s(\ell^-\ell^-) + N_s(\ell^+\ell^+)} \]

It is estimated that \( X_s \) would be determined with \( L = 10 \) fb\(^{-1} \) if \( X_s < 3 \).

For larger \( X_s \) values, expected theoretically, a study of the time dependence of both \( B_s \) is required. For a given \( \Delta t = t_2 - t_1 \), integrated over \( t_1 + t_2 \) the rates of \( B_s \bar{B}_s, B_s B_s, \) and \( B_s \bar{B}_s \) are known functions of \( \Delta t, \Delta m \), and \( X \) which could then be determined.

The maximal \( X_s \) value which could be determined with this procedure increases with the energy asymmetry and is inversely proportional to the vertex resolution. The studies conclude that for \( L = 10 \) fb\(^{-1} \), \( X_s = 6.5 \) would be measured working at 8.4 \times 3.5 GeV, alternatively \( X_s = 12 \) at 11.75 \times 2.5 GeV.

In comparison, HLEP will be able to cover a range \( X_s \) of up to 20, which totally covers the presently allowed range, and will therefore permit a determination of the CP phase \( \delta \) in the Standard Model.
3.3.3 B decays

1) \( b \to c \). Large samples of fully reconstructed B decays

\[
\begin{align*}
B^0 \to D^+\pi^-, D^{*+}\pi^- & \quad 1000/30 \text{ fb}^{-1} \\
B^0 \to D^+\pi^0, \pi^0 & \quad 2000/30 \text{ fb}^{-1} \\
B^0 \to D^0\pi^-\pi^0 & \quad 2000/30 \text{ fb}^{-1} \\
B^0 \to D^+D^-, D^{*+}D^- & \quad 250/30 \text{ fb}^{-1}
\end{align*}
\]

would bring the experimental precision on the hadronic decays to a level allowing a detailed understanding of the hadronic–hadronic current interaction in the heaviest experimentally accessible quark system. In addition with partially reconstructed semileptonic decays, typically \( 10^6 b(b) \) would be tagged for \( L = 300 \text{ fb}^{-1} \), allowing to study rare decays at the \( 10^{-5} \) level. As has been shown before, the reconstruction efficiency for all charged decay modes of the B’s are comparable at HLEP; therefore one would expect samples of 50% of the above for the charged decay modes.

2) \( b \to u \). Better determination of the CKM matrix elements would be achieved from exclusive semileptonic decays like

\[ B \to \pi\ell\nu, \rho\ell\nu, D\ell\nu, D^*\ell\nu \]

With \( L = 20 \text{ fb}^{-1} \) a relative error of 20% on the decay fraction is expected for a branching fraction \( = 2 \times 10^{-5} \). In the absence of theoretical error (which could be as large as 50%) this would allow us to determine \( V_{ub} \) with an error of 10% for \( V_{ub} \) as small as 0.001. For the present value \( V_{ub} = 0.005 \), determined as by ARGUS and CLEO, a statistical error of 2% would be achieved; however the theoretical uncertainty in extracting \( V_{ub}/V_{cb} \) will still be the dominant factor.

Exclusive processes such as \( B \to \pi^+\pi^-, \omega^0\pi^0 \) would be detected for BF = \( 5 \times 10^{-5} \) with \( L = 20 \text{ fb}^{-1} \). Similar determinations could probably be achieved by the HLEP experiments on the \( \pi^+\pi^- \) mode, however one would expect CESR+ to provide an answer before those two projects are operational.

3) \( b \to s \gamma \). It seems that rather simple kinematic cuts could be used to isolate the channel \( B \to K^*\gamma \). Assuming BF = \( 2 \times 10^{-4} \), roughly 500 events could be reconstructed for \( L = 10 \text{ fb}^{-1} \). As it has been shown before, branching ratios of \( 10^{-5} \) could be measured in the HLEP option for \( 10^8 Z \). As mentioned before, CESR+ or a competitive LEP program could provide earlier answers.

3.3.4 B lifetime

This could be studied at an \( 8 \times 3.5 \text{ GeV} \) (12 \( \times 2.3 \)) machine with a boost \( \beta\gamma = 0.42 \) and a B decay length of the order of 150 \( \mu m \) (330). The distribution of the decay-time difference between the two B mesons from the \( \Upsilon_4s \) is identical to the decay-time distribution. In order to distinguish between a neutral and a charged B, one B must be fully reconstructed. Using known branching ratios and assuming a reconstruction efficiency of 0.5, a measurement of the lifetime difference at the level of a few per cent would be possible with a few 10 \( \text{ fb}^{-1} \). This result, as it has been shown in the previous section, is perfectly comparable with the precision that will be attainable at LEP and later at HLEP for \( B_u, B_d, \) and \( B_s \).
4 TAU-CHARM FACTORIES

4.1 The interest in \( \tau \) and charm physics

The \( \tau \) lepton and the charmed quark were discovered fifteen years ago and so it is natural to ask whether they still hold in store any experimental surprises. In fact, recent high-energy measurements have strengthened the interest in studying these particles with high precision. With the measurement of exactly three types of neutrino in the decays of \( Z \), it appears, within the Standard Model, that the \( \tau \) is the last lepton. We are therefore left with a limited number of constituents that hold the clues toward further progress.

The dearth of new particle discoveries at recent high-energy machines underscores the importance of a complementary approach to carry out precision studies of the known elementary particles. Meanwhile, such studies have become technically feasible thanks to advances in both machines and detectors since the initial round of experiments.

The reason for the existence of families and flavours is not understood. The best way to shed light on this puzzle is to search carefully for differences between the families. In this respect, the \( \tau \) lepton is particularly interesting since it is both a lepton and a member of the third family. Being a lepton implies that many decays are precisely calculable, resulting in a broad range of precise experimental tests of the Standard Model. Indeed, this feature has led to the exposure of the so-called ‘one-prong problem’, which is at present among the most significant signs of an experimental discrepancy with the Standard Model. Furthermore, as a member of the third family—which is the least well-known experimentally—the \( \tau \) lepton may provide some clues to explain the surprising features of this family, such as the relatively massive members.

In the Standard Model with three families, charm is the only up-like quark that can be studied in a variety of ways (since top is so massive that it will probably decay via \( t \rightarrow W_\text{real}b \)). Charm studies are likely to prove vital in investigating whether there is any difference between up-like flavours (u, c, t) and down-like flavours (d, s, b). Finally, it is sometimes said that charm is relatively uninteresting since its decays are tightly constrained by theory: \( V_{cs} \) and \( V_{cd} \) are determined by the Cabibbo angle, \( D^0\bar{D}^0 \) mixing is tiny, etc. In fact, this is an asset since charm decays thereby present an excellent laboratory to confront the Standard Model with precise experimental tests.

4.2 Overview of the \( \tau \)-charm factory

The \( \tau \)-charm factory (\( \tau \)cF)[26],[27] is a dedicated experiment that proposes to carry out precise studies of the third-generation leptons, \( \tau \) and \( \nu_\tau \); the second-generation quark family, through the decays of \( D^\pm \), \( D^0 \), and \( D_s^\pm \); and the spectrum of gluonic and other new light particles in the decays of \( J/\psi \) and \( \psi' \). The experiment involves a high-resolution detector integrated with an intense \( e^+e^- \) collider [28]–[31] operating in the energy range \( 3.0 \leq E_{cm} \leq 5 \text{ GeV} \) with a maximum luminosity of \( 10^{33} \text{ cm}^{-2} \text{ s}^{-1} \). The \( \tau \)-charm factory represents a substantial increase in the experimental sensitivity at these energies, owing to sharp improvements both in the machine luminosity and in the detector performance.

The physics and design of the \( \tau \)-charm factory is under study at several centres, including Dubna, ITEP (Moscow), Orsay, SLAC, and in Spain. Physicists from these and other centres
participated in the *Tau-Charm Factory Workshop* at SLAC, 23–27 May 1989. The outcome of the Workshop [32] was a broad recognition of the importance of a renewed, high-precision study of τ-charm physics and also of the suitability and feasibility of an intense e+e− collider operating near threshold for such studies. Following the Workshop, a formal τcF proposal [33] was considered at SLAC. However, the decision was made in November 1989 not to proceed with construction of a τ-charm factory at SLAC but instead to establish the laboratory as the centre for a US Collaboration at a European τ-charm factory, contributing to the detector design and construction, and to the data analysis. The most likely site in Europe is Sevilla, Spain. Initial discussions and planning towards the construction of a τ-charm factory in Andalusia, near Sevilla, are well advanced [34]. This project would involve integral collaboration with CERN. Assuming positive developments, the commissioning of the machine and its first physics results are expected during 1996.

The expected development during the next decade of the integrated luminosity in e+e− annihilation near the τ-charm threshold is shown in Fig. 4.1. Although there are inevitable uncertainties associated with such projections, the τ-charm factory could have collected \(\sim 10^8 \tau^+\tau^-\) events and \(\sim 10^8\) D\(\bar{D}\) events shortly after 1998, the date foreseen at present for LEP to begin its high-luminosity phase (HLEP) at the Z. With this timescale, HLEP could not compete with the τ-charm factory on τ or charm statistics, and therefore would probably focus on certain τ-charm physics topics for which it is especially suited.

### 4.3 Experimental aspects

In order to make significant progress in τ-charm physics, future data samples must have:

\[
\begin{array}{ll}
\text{Present expts.} & \rightarrow \tau cF \\
1. Reduced backgrounds & 5–10\% \quad \lesssim 0.1\% \\
2. Reduced systematic errors & 2–10\% \quad \approx 0.1\% \\
3. Increased statistics & \text{few } \times 10^5 \quad \approx 10^8 \\
\end{array}
\]

We have indicated here the anticipated improvements at the τ-charm factory; these are described in more detail below.

The τ-charm threshold region has several unique operating points which have backgrounds that are both exceptionally low and internally calibrated by small shifts in \(\vec{E}_{cm}\). The energies for τ studies are as follows:

**3.56 GeV.** This energy, which is just below the \(\tau^+\tau^-\) threshold, provides a direct calibration of all non-τ backgrounds: hadronic (uû, dd, and ss), two-photon, QED [ee(\(\gamma\)), \(\mu\bar{\mu}(\gamma)\), etc.] and beam gas/wall.

**3.57 GeV.** The \(\tau^+\tau^-\) cross-section has a finite value (0.22 nb) precisely at threshold, owing to a Coulomb interaction between the \(\tau^+\) and \(\tau^-\) [35]. When the beam energy is set to \(m_\tau + \sigma\) (the beam energy spread, which is 1.0 MeV at this energy) the \(\tau^+\tau^-\) cross-section is 0.47 nb, and \(\vec{\beta}_\tau = 0.024\). At this energy, the two-body τ decays, such as \(\pi^-\nu_\tau\) and \(K^-\nu_\tau\), give rise to monochromatic secondaries. The consequences are clean signatures for event selection, as well as kinematic separation of the different decay modes.

**3.67 GeV.** This energy provides the highest \(\tau^+\tau^-\) cross-section below the \(\psi'(3.69)\) and D\(\bar{D}\) threshold (3.73 GeV), a region where τ decay is the *only* source of prompt single leptons.
4.25 GeV. At this energy the $\tau$ continuum rate has its maximum value, coinciding with a minimum in the charm cross-section. The advantages here are the high rate and appreciable $\beta_t$ (0.54), which results in large polarization correlations in $\tau^+\tau^-$ decays. The presence of charm backgrounds, however, limits the range of experiments that are feasible.

A comparison of the production cross-sections of $\tau^+\tau^-$ and heavy-quark backgrounds at LEP and the $\tau$-charm factory is given in Table 4.1.

The energies for charm and charmonium studies are as follows:

- $J/\psi(3.10)$ and $\psi'(3.69)$.
- $\psi''(3.77)$. This energy provides pure $D^0\bar{D}^0$ and $D^+_sD^-_s$ final states, without contamination from other charmed particles or from jet fragments, thereby allowing studies of tagged $D^0$ and tagged $D^\pm$ decays.

4.03 GeV. This energy provides the highest charm cross-section in $e^+e^-$ annihilation [$\sigma(c\bar{c}) \approx 10$ nb] and is suitable for tagged $D^\pm_s$ studies, via $D^+_sD^-_s$ events.

4.14 GeV. This is a second identified energy for $D^\pm_s$ studies, via $D^+_sD^{*+}_s$ events.

An important experimental asset of the $\tau$-charm threshold region is the ability to tag the particle under study, whose decays can then be measured with minimum bias, with low backgrounds and with absolute flux normalization. This technique has been used extensively at $\psi''(3.77)$ for $D^0$ and $D^\pm$ studies. In the case of $D^\pm_s$, however, the present statistics are too poor even to allow absolute measurements of the branching ratios; not a single example exists of a double-tagged $D^+_sD^-_s$ event. At LEP, the only charmed hadron that can be tagged is $D^0$, via the soft $\pi^+$ in $D^{*+} \rightarrow D^0\pi^+$. However, even with secondary vertex cuts, the $D^0\pi^+$ tag has a larger background than the $D^0D^0$ tag at the $\psi''(3.77)$.

For the first time at any machine, it should also be possible to single-tag $\tau^+\tau^-$ events at the $\tau$-charm factory. All previous measurements have employed global event selection criteria that have imposed restrictions on both $\tau$ decays in each event. Single-tagging requires a signature from a single $\tau$ decay that is very clean. With the unique capability of the $\tau$-charm factory to produce $\tau^+\tau^-$ events near threshold and without contamination from heavy-flavoured particles, several signatures fulfill this requirement: $e + E_{\text{miss}}, \mu + E_{\text{miss}},$ and $\pi$(monochromatic) + $E_{\text{miss}}$ (at 3.57 GeV). The 'missing' energy in each event, $E_{\text{miss}}$, is measured in the hermetic $\tau$-charm factory detector. Hermeticity is provided by a combination of precise magnetic analysis of charged particles, a crystal electromagnetic calorimeter and a fine-grained hadron calorimeter, whose primary function is to detect the presence of $K_L^0/n$.

The relative hadronic and $\tau\tau$ production cross-sections are:

- $3.57$ GeV: $\sigma(q\bar{q})/\sigma(\tau\tau) = 15.7$ nb/0.47 nb = 33.4,
- $3.67$ GeV: $= 14.8$ nb/2.4 nb = 6.2.

Despite their large cross-sections, hadronic backgrounds can be very effectively eliminated below charm threshold by the single-tag signatures. Monte Carlo studies indicate that the combined $e + E_{\text{miss}}$ tag (with the requirements $E_e \geq 0.4$ GeV and $E_{\text{miss}} \geq 0.8$ GeV) results in final background/signal ratios of $1.2 \times 10^{-3}$ at 3.57 GeV, and $0.2 \times 10^{-3}$ at 3.67 GeV. The $\tau^+\tau^-$ detection efficiency with this tag alone is 0.24; when combined with other single-tags, there is a good overall efficiency of $\approx 0.5$.

In addition to high-precision measurements of charged particles, there are particular advantages for photon detection and particle identification near $\tau$-charm threshold. Since particles are essentially produced isotropically, the detection inefficiency caused by charged and neutral pile-up is minimized. This is especially important in the measurements of $\tau$ decays.
involving several neutral particles, which may hold the key to the ‘one-prong problem’. Pile-up will make these measurements difficult at LEP. A further advantage is that the kinematic limit of particles from $\tau$ and D decays is $\simeq 1 \text{ GeV/c}$ and so the identification of $\pi$, K, and p is relatively easy using a combination of time-of-flight and $dE/dx$. In this case, a RICH is not required for particle identification and the $\gamma$ detection is not compromised by the resultant inert material (20% of a radiation length). At LEP, hadron ($\pi K$) separation extends up to $\simeq 20 \text{ GeV/c}$, whereas the kinematic limit of the decay particles is close to the beam energy (45 GeV/c).

In addition to providing exceptionally clean data samples, the threshold region will provide higher statistics than HLEP (Table 4.2). In certain experiments that are not limited by systematic errors, the effective HLEP statistics can be increased up to a factor of 4 by adding the data from all detectors.

4.4 The complementarity of HLEP and the $\tau$-charm factory

High-luminosity LEP and the $\tau$-charm factory both produce large quantities of $\tau^+\tau^-$ and $c\bar{c}$ events, but under conditions that are kinematically and physically separate: LEP produces energetic particles from Z decays; the $\tau$-charm factory produces almost stationary, tagged particles under especially-low background conditions. This gives rise to $\tau$ and charm physics prospects at the two machines that are largely complementary, as can be seen from the following summary.

4.4.1 Experiments for HLEP only

Precision electroweak tests in Z decay. The decay $Z \rightarrow \tau^+\tau^-$ offers the unique experimental possibility at LEP of measuring the polarization of the final-state fermions. Decays such as $\tau^- \rightarrow \pi^-\nu_{\tau}$ provide a polarization analyser which will allow measurement of the $\tau$ polarization asymmetry $A_{\text{pol}}$ and of the polarized $\tau$ forward–backward asymmetry $A_{\text{FB}}^{\text{pol}}$. Measurements of these quantities have significant experimental and physical advantages [36]—in particular they have the same sensitivity to $\sin^2 \theta_W$ as does the left–right asymmetry ($A_{\text{LR}}$) with polarized beams, which is generally considered to be the pre-eminent experiment. In addition to these measurements, important electroweak tests are provided by measurements of the $c\bar{c}$ asymmetry and of the $Z \rightarrow c\bar{c}$ and $Z \rightarrow \tau^+\tau^-$ partial widths.

Lifetime measurements of $\tau^\pm$, $D^0$, $D^\pm$, $D^*_\pm$, and $\Lambda^\pm$. Precise measurements of these particle lifetimes are important in order to derive absolute rates from branching-ratio measurements, which may then be compared with the theoretical predictions. HLEP can measure each of these lifetimes with $\simeq 1\%$ accuracy, limited by systematic errors (statistical errors will be 0.2–0.5%). This should be compared with the present accuracies of 3% ($\tau^\pm$, $D^0$, $D^\pm$) and 10% ($D^\pm$, $\Lambda^\pm$) which, in the case of charm lifetimes, will probably be reduced by a factor of 3 in fixed-target experiments before HLEP startup.

4.4.2 Experiments for both HLEP and the $\tau$-charm factory

Rare decays: lepton-flavour-violating decays and flavour-changing neutral currents. Examples of these decays are $Z \rightarrow \mu^+\tau^-, Z \rightarrow c\bar{u}, Z \rightarrow b\bar{s}\tau^- \rightarrow 3\mu^\pm, D^+ \rightarrow \pi^+\mu^+\pi^-, D^+ \rightarrow \pi^+\mu^+\mu^-$ and $D^0 \rightarrow \mu^+\mu^-$. The decays $Z \rightarrow \ell^\pm\tau^\mp (\ell = e, \mu)$ and $\tau^- \rightarrow 3\ell^\pm$.
would be generated by the existence of a lepton-flavour-violating coupling of the Z. The experimental limit at HLEP (10^8 Z) is expected to be BR(Z \rightarrow \ell^+\ell^-) < 7 \times 10^{-7}, which is equivalent to BR(\tau^- \rightarrow 3\ell^\pm) < 10^{-7} [37]. The sensitivity of HLEP is therefore comparable with that of the τcF, which should reach BR(\tau^- \rightarrow 3\ell^\pm) < 2 \times 10^{-8}, for 10^8 τ^+τ^-. In the case of rare D decays, the τcF has significant advantages over HLEP beyond simply statistics. These include tagged events and precise, beam-constrained, mass measurements (\simeq 2 \text{ MeV}/c^2 compared with 30–50 MeV/c^2 at LEP) which will result in more favourable background conditions. Finally, we comment that a useful measurement of Z\rightarrow c\bar{u} seems impossible since there is no clean tag of a primary u quark and because of the inefficiencies of c detection, i.e., the inability to measure precisely the absence of an opposite \bar{c}. This can be compensated at HLEP by measuring BR(Z \rightarrow b\bar{s}) down to values below 10^{-5}.

τ decay parameters: \rho, \eta, \xi, \eta_{1,2}, and \delta, \ell = e, \mu. This is an important test of the universality of the weak interaction. These parameters are sensitive to non-Standard Model physics such as a charged Higgs or a right-handed boson. (Indeed, the corresponding measurements in \mu decay provide the best current limits on the presence of right-handed currents.) The Michel parameter \rho and the low-energy spectrum parameter \eta are determined from the e,\mu spectral distributions. The asymmetry parameters \xi and \eta are determined from energy and angular correlations (at finite \beta) between, for example, \tau^- \rightarrow e^-\bar{\nu}_e\nu_e and \tau^+ \rightarrow \pi^+\nu_\tau. In these studies, both HLEP and the τcF have the advantage of small corrections from initial-state radiation which, at other energies, is a major source of systematic error. The estimated precisions at HLEP are approximately 1% for \rho and 3% for \xi and \eta. (At present only \rho has been experimentally measured, to 8% accuracy.) An important systematic limitation at HLEP will be particle confusion, which will lead to contamination from misidentified τ decay modes. The situation is better at the τcF, since the kinematic limit of the secondaries is \simeq 1 \text{ GeV}/c and since certain parameters can be measured right at the τ^+τ^- threshold, where the various decay modes are separated kinematically. The τcF is also uniquely able to measure the low-energy spectrum parameter \eta and, with a \mu polarimeter, to measure the polarization parameter \xi_{\mu}. The expected accuracies at the τcF are 0.3% for \rho; 1% for \eta, \xi and \eta_{1,2}; and 10% for \xi_{\mu}.

CP violation in the lepton sector. This is expected to be unobservably small in the Standard Model, and therefore any CP-violating effects involving leptons would signal a new interaction. Finite electric dipole moments of leptons are one possible signature of CP violation (since they would signal a breakdown of T-reversal invariance and hence, via CPT conservation, also of CP invariance). The process e^+e^- \rightarrow τ^+τ^- allows a study of the electric dipole form factor \hat{d}_e(s)[ττ\gamma vertex] and weak dipole form factor \hat{d}_w(s)[ττZ vertex] [38]. [The τ electric dipole moment is \hat{d}_e(s = 0).] The measured cross-section for e^+e^- \rightarrow τ^+τ^- indicates |d_\tau| < 10^{-16} e cm. However this involves certain assumptions, and a better method—which is completely unambiguous—is to search for the sign of a CP-odd observable in final states such as e^+e^- \rightarrow τ^+τ^- \rightarrow π^+ν_τ,π^-ν_τ. After including other decay channels, the expected statistical precisions at both HLEP and the τcF are of the order of 10^{-17} e cm for d_\tau and, in the case of \hat{d}_e at HLEP, about 10^{-18} e cm. In certain extensions of the Standard Model, CP violation occurs quite naturally in the lepton sector. For example, in Higgs models of CP violation \hat{d}_e, \hat{d}_\mu \sim m_\tau^2. Therefore a d_\tau limit of 10^{-17} e cm would be equivalent to d_e < 10^{-28} e cm and d_\mu < 10^{-21} e cm. These go well beyond the present direct experimental measurements: d_e = (-2.6 \pm 0.2) \times 10^{-28} e cm and d_\mu = (3.7 \pm 3.4) \times 10^{-19} e cm.
4.4.3 Experiments for the $\tau$-charm factory only

$\nu_\tau$ and $\tau$ masses. The $\nu_\tau$ mass is investigated by measuring the end-point of the $5\pi^\pm$ mass spectrum in $\pi^\pm \to 5\pi^\pm \nu_\tau$, and the end-point of the $K^-K^+\pi^\pm$ mass spectrum in $\tau^\pm \to K^-K^+\pi^\pm \nu_\tau$. Combining both decays gives an upper limit (95% CL) of 3 MeV/c$^2$ at the $\tau$CF, which is an order of magnitude below the present limit. This will first require an improved measurement of the $\tau$ mass, which involves a precise determination of the threshold for the process $e^+e^- \to \tau^+\tau^-$. The expected $\tau$ mass error at the $\tau$CF is 0.2 MeV/c$^2$. The $\nu_\tau$ mass experimental limit scales as $\sigma_m(5\pi/KK\pi)/\sqrt{N}$. Consequently HLEP cannot compete, owing to both the relatively poor resolution ($\simeq 30$ MeV/c$^2$, against 2 MeV/c$^2$ at the $\tau$CF) and the statistical disadvantage. Finally, we mention that it is widely expected that massive $\nu$'s would follow the same mass hierarchy as the charged leptons and, in certain models such as the 'see-saw' model, $m_{\nu_\tau} \propto m_\tilde{\tau}^2$. In this case a sensitivity of 3 MeV/c$^2$ for $m_{\nu_\tau}$ would be equivalent to 0.3 eV/c$^2$ for $m_{\nu_\tau}$, which is below the present direct limit $m_{\nu_\tau} < 11$ eV/c$^2$ (95% CL).

Precise $\tau$ branching ratios. The decay rates of several $\tau$ decay modes can be rigorously calculated, and so precise measurements of the branching ratios provide sensitive tests of the Standard Model. Of special interest are the decays $e^-\bar{\nu}_e\nu_\tau$, $\mu^-\bar{\nu}_\mu\nu_\tau$, $\pi^-\nu_\tau$, and $K^-\nu_\tau$, which are theoretically understood at the level of the electroweak radiative corrections (1%). New physics could affect these branching ratios as perhaps a non-standard Cabibbo angle in the $\tau$ sector or a Higgs field. Of particular importance is the discrepancy between the inclusive $\tau \to 1 ~\text{prong}$ branching ratio (0.861 ± 0.003) and the sum of the exclusive 1 prong decays ($\leq 0.802\pm0.014$)—the so-called 'one-prong problem'—which remains an open question for the Standard Model. It is likely that the resolution of this discrepancy—be it experimental errors or new physics—will require an experiment with excellent control of systematic errors and with good sensitivity to all $\tau$ decays. Future measurements of these branching ratio measurements are likely to be dominated by systematic and background uncertainties, rather than by statistics. The optimum energy for these studies is 3.57 GeV, where the individual $\tau$ decays are separated kinematically and the backgrounds are both extremely low (< 0.1%) and internally calibrated. Moreover, near threshold, the overlap probabilities are greatly reduced (see, for example, Fig. 4.2 [39]) and so there are high detection efficiencies and correspondingly small corrections and small systematic uncertainties. The expected precisions at the $\tau$CF on the 1 prong branching ratios are 0.1% (e, $\mu$, $\pi$) and 0.5% (K).

D$^0\bar{D}^0$ mixing. Mixing may occur in the Standard Model by 'box diagrams' which, because of GIM cancellations, are expected to be small ($r_D \lesssim 10^{-6}$). [The mixing parameter is $r_D = B(D^0 \to \bar{D}^0 \to \bar{f})/B(D^0 \to f/\bar{f})$, where $f$ is a final state.] Long-range contributions, which are also second-order weak interactions, are expected to be larger, giving $r_D \approx 10^{-5}$–$10^{-4}$. The small D$^0\bar{D}^0$ mixing expected in the Standard Model makes this a promising channel to search for new physics, and sets the desired experimental sensitivity at $r_D \approx 10^{-5}$. HLEP can tag D$^0$ via the soft $\pi^+$ in D$^{+} \to D^0\pi^+$. However, even with secondary vertex cuts, the D$^0\pi^+$ tag is probably incapable of reaching the required purity; for example, at BF energies, the D$^0\pi^+$ tag results in a raw fake mixing rate of $\approx 10^{-3}$, after all cuts. In contrast, the fake rate from the D$^0\bar{D}^0$ tag at the $\psi''(3.77)$ is well below $10^{-5}$. Here the experimental signatures for mixing are either like-sign dilepton events from dual semileptonic decays ($e^+e^-X$, $\mu^+\mu^-X$, $e^+\mu^\pm X$) or two identical hadronic decays, such as $(K^-\pi^-)(K^+\pi^+)\nu$ or $(K^-\pi^+)(K^+\pi^-)$. (The latter must be carefully distinguished from doubly-Cabibbo-suppressed decays, which is possible at the $\tau$CF with quantum statistics.) A 1-year experiment at the
\( \tau cF \) is sensitive to \( \tau_D \approx 2 \times 10^{-5} \), at which level a mixing signal is expected to be seen in the Standard Model.

**KM matrix elements** \( V_{cs} \) and \( V_{cd} \). These important parameters of the Standard Model are poorly measured (\( \pm 10\% \)) at present, whereas they are constrained in the Standard Model to theoretical uncertainties of 0.1\% (\( V_{cs} \)) and 1\% (\( V_{cd} \)). The semileptonic decays of D mesons provide almost direct measurements of \( V_{cs} \) and \( V_{cd} \). There are a large number of semileptonic decays to study including, for example,

\[
\text{BR}(D \to K\nu_e) \propto \tau_D \left| f^K_+(t^2) \right|^2, \left| V_{cs} \right|^2
\]

\[
\text{BR}(D \to \pi\nu_e) \propto \tau_D \left| f^\pi_+(t^2) \right|^2, \left| V_{cd} \right|^2
\]

where \( f^\pi_+(t^2) \) are form factors and \( \tau_D \) is the appropriate D lifetime. The ability to tag cleanly the D is vital in these studies owing to the presence of the missing \( \nu \) and the low branching ratios (for the Cabibbo-suppressed decays). At the \( \tau cF \), the semileptonic decays of \( D^0, D^\pm \), and \( D^*_8 \) can be identified in fully constrained events with a single missing \( \nu \). At HLEP, however, only the \( D^0\pi^+ \) tag is available. The semileptonic branching ratios should be measured to better than 1\% precision at the \( \tau cF \), to be compared with the present errors of 12\% for \( D \to K\nu_e \) and 50\% for \( D \to \pi\nu_e \). The present theoretical uncertainties in the form factors can largely be avoided by taking the ratio of semileptonic branching ratios. In this way, \( V_{cd}/V_{cs} \) may be determined to 0.3\% precision at the \( \tau cF \)—similar to the present precision of \( \theta_C \).

**Pure leptonic D decays; measurement of \( f_D \).** The decays of interest are summarized in Table 4.3 where, in the final case, \( \tau^+ \to e^+\nu_e\bar{\nu}_\tau \) or \( \mu^+\nu_\mu\bar{\nu}_\tau \). The weak decay constant \( f_D(a) \) measures the overlap of the c and d(s) quarks in the \( D^\pm(a) \) meson. The decay constants appear in many second-order weak processes, including mixing and CP violation, and are therefore important quantities to be experimentally determined. Measurement of \( f_D \) is needed, for example, to improve the estimate of \( f_B \)—which is experimentally inaccessible in the foreseeable future—for calculations of mixing and CP violation in the B system. Furthermore, the relative value of the pure leptonic branching ratios will provide a good measurement of \( |V_{cs}/V_{cd}| \), since the uncertainty in \( f_D/a_f \) should be small. These decays are measured cleanly in the \( \tau cF \) with precision \( \approx 0.5\% \) in a 1-year data sample. At HLEP, once again, the absence of tags for \( D^\pm \) and for \( D^*_8 \) preclude these studies.
Table 4.1

Production cross-sections of $\tau^+\tau^-$ events and heavy-flavour backgrounds at LEP and the $\tau$-charm factory

<table>
<thead>
<tr>
<th></th>
<th>$\sigma(\tau\bar{\tau})$ (nb)</th>
<th>$\sigma(\text{cc})$ (nb)</th>
<th>$\sigma(\text{bb})$ (nb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEP</td>
<td>1.5 ($Z$)</td>
<td>5.3</td>
<td>6.7</td>
</tr>
<tr>
<td>$\tau$F</td>
<td>0.5 (3.57 GeV)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>2.4 (3.67 GeV)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>3.5 (4.25 GeV)</td>
<td>5.0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 4.2

A comparison of the direct $\tau$charm data samples at HLEP and at the $\tau$-charm factory. These samples correspond to:
i) HLEP, 2 fb$^{-1}$ [6 $\times$ 10$^7$ $Z$, equivalent to 1 year (@200 days) at 2 $\times$ 10$^{32}$ cm$^{-2}$s$^{-1}$], and
ii) $\tau$F, 10 fb$^{-1}$ [equivalent to 1 year (@200 days) at 10$^{33}$ cm$^{-2}$ s$^{-1}$].

<table>
<thead>
<tr>
<th>Particle</th>
<th>HLEP (Z)</th>
<th>$\tau$F</th>
</tr>
</thead>
<tbody>
<tr>
<td>D$^0$ (single)</td>
<td>$1.2 \times 10^7$</td>
<td>$5.8 \times 10^7$ ($\psi''$)</td>
</tr>
<tr>
<td>D$^+$ ($\pi^0$)</td>
<td>$0.5 \times 10^7$</td>
<td>$4.2 \times 10^7$ ($\psi''$)</td>
</tr>
<tr>
<td>D$^+_s$ ($\pi^0$)</td>
<td>$0.3 \times 10^7$</td>
<td>$1.8 \times 10^7$ (4.14 GeV)</td>
</tr>
<tr>
<td>$\tau^+\tau^-$ (pairs)</td>
<td>$0.3 \times 10^7$</td>
<td>$0.5 \times 10^7$ (3.57 GeV)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>J/$\psi$</td>
<td>$-\ $</td>
<td>$1.7 \times 10^{10}$</td>
</tr>
<tr>
<td>$\psi'$</td>
<td>$-\ $</td>
<td>$0.4 \times 10^{10}$</td>
</tr>
</tbody>
</table>

Table 4.3

Pure leptonic D decays and their expected branching ratios (assuming $f_D \simeq 200$ MeV)

<table>
<thead>
<tr>
<th>Process</th>
<th>$\text{BR} \propto$</th>
<th>Expected BR</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^+ \rightarrow \mu^+\nu_\mu$</td>
<td>$\tau_{D^+} f_D^2</td>
<td>V_{ud}</td>
</tr>
<tr>
<td>$D^+<em>s \rightarrow \mu^+\nu</em>\mu$</td>
<td>$\tau_{D^+<em>s} f</em>{D^+_s}^2</td>
<td>V_{us}</td>
</tr>
<tr>
<td>$D^+<em>s \rightarrow \tau^+\nu</em>\tau$</td>
<td>$\tau_{D^+<em>s} f</em>{D^+_s}^2</td>
<td>V_{us}</td>
</tr>
</tbody>
</table>
Fig. 4.1: The expected development during the 1990's of the integrated luminosity in $e^+e^-$ annihilation near the $\tau$-charm threshold. We indicate the integrated luminosities at $\psi''(3.77)$ that correspond to $10^8$ DD and $10^8 \tau^+\tau^-$ events.

Fig. 4.2: The minimum angular separation between any two particles (photons + charged tracks) in $e^+e^- \rightarrow \tau^+\tau^-$, where $\tau^+ \rightarrow e^+\nu_e\bar{\nu}_e$ and $\tau^- \rightarrow \pi^- 3\pi^0 \nu_\tau$. For comparison, an excellent $2\gamma$ resolution is $\approx 1^\circ$ (ALEPH).
5 SUMMARY

HLEP will be the only machine able to provide precise measurements of the weak coupling constants of leptons and quarks, thus considerably improving the LEP measurements. These measurements will lead to an accuracy in $\sin^2 \theta_W$ comparable to the one that can be achieved with polarized beams, therefore allowing critical tests of the Standard Model. HLEP stands furthermore in its own right as the only machine that can perform meaningful searches for rare decays of the $Z$, including competitive searches for flavour-changing neutral currents.

Another important aspect of HLEP is its capability as a heavy-flavour factory, and in particular a B factory. As such, LEP and HLEP provide various features that are competitive as well as some that are highly advantageous. In the first category one can include the large cross-section for production of b quark pairs, which will be discussed later in this chapter. The advantage of LEP with respect to B and C factories is that B and D mesons are produced with a large boost. Furthermore the Z also has a relatively high decay rate into yet unobserved states such as $B_s$, $B_c$ as well as baryon states containing the b and c quarks. Those two elements will allow the HLEP project to measure $B_s - B_s$ oscillations in the full allowed range as well as to measure accurately the lifetimes of still unknown states containing c and b quarks. In all these measurements, however, the high statistics attainable at HLEP are crucial and will be possible only with the accumulated luminosity achieved in three years of HLEP running.

LEP and HLEP are in competition with B factories in measuring decay modes of $B_s$ and $B_d$ mesons and their properties. Here the advantage of B factories lies in the fact that the B's are pair-produced at rest, and therefore one can use the beam energy constraint to obtain superb mass resolutions as well as make use of having one fully reconstructed B meson to investigate the properties of the accompanying $\bar{B}$. At LEP those two elements are not present; however, since the B's are strongly boosted, and therefore well separated, one substantially reduces the combinatorial problem. This fact, combined with the hard fragmentation properties of the b quark, leads to a reconstruction efficiency for totally charged decay modes of a B meson comparable to those achievable in a B factory. Such efficiencies have been evaluated in the previous section for various $B_d$ and $B_s$ decay modes. Since the reconstruction efficiencies are similar for fully charged decay modes, then one expects the physics output is expected to be comparable with the number of accumulated b events. Figure 5.1 shows a comparison of the accumulated number of $b \bar{b}$ events in CESR+ and LEP 1 as a function of time. Also shown in the plot is the assumed peak luminosity as a function of time. The number of accumulated $b \bar{b}$ events has been estimated by assuming an effective running time of $10^7$ s at the peak luminosity and $\frac{1}{2}$ of that time for LEP during 1990. It can be seen that the rates are comparable; however, in order to be able to keep a competitive situation until the end of 1993, LEP should move into an 8 + 8 bunch operation before 1993.

Figure 5.2 shows a similar comparison between HLEP and a generic B factory. It can be seen that, provided that the two run for similar periods of time per year and start to operate simultaneously, then with the assumed luminosities similar number of $b \bar{b}$ events would be accumulated during the first two years of operation, leading to comparable results in terms of reconstructed fully-charged decay modes of $B_s$ and $B_d$. This also implies that if the CP-violation effect is large in $B^0$ decays, then similar results would be obtained in both machines.
after two years of operation. After this initial period, the B factory will be superior to realize this kind of physics. Finally, to summarize, Table 5.1 gives a direct comparison of HLEP and the B, τc factories, for the points where they are competitive. It can be seen that the HLEP operation will add important elements to the testing of the electroweak theory as well as the understanding of the CP-violation phenomena.

**Table 5.1**

Comparison of performance between HLEP, a B factory, and a τcF after three years of operation, assuming $10^7$ s/y

<table>
<thead>
<tr>
<th>Subject</th>
<th>HLEP</th>
<th>B factory</th>
<th>τcF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precision measurements of weak couplings</td>
<td>$\delta (\sin^2 \theta_W) \sim 0.0003$, i.e. comparable to polarization. Precise measurements of the Zbb coupling (see Part II, Section 4), sensitive to extra Z' and SUSY phenomena</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Rare Z decays</td>
<td>For example: $\text{BR} (Z \rightarrow \tau\tau) &lt; 10^{-6}$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Flavour-changing neutral currents</td>
<td>$\text{BR} (Z \rightarrow \tau e) &lt; 10^{-5}$</td>
<td>$\text{BR} (\tau \rightarrow 3\ell) &lt; 10^{-7}$</td>
<td>$\text{BR} (\tau \rightarrow 3\ell) &lt; 2 \times 10^{-8}$</td>
</tr>
<tr>
<td>Spectroscopy:</td>
<td>$B_c$ $10^3$ reconstructed events</td>
<td>$10^3$ reconstructed events</td>
<td>$&lt; 10^3$ reconstructed events</td>
</tr>
<tr>
<td></td>
<td>$B_s$ $10^3$ reconstructed events</td>
<td>$&lt; 10^3$ reconstructed events</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>$\Delta r/\tau \sim 5%$ for each state ($B_s, B_d, B_s$)</td>
<td>$\Delta r/\tau \sim 5%$ for $B_s, B_d$</td>
<td>-</td>
</tr>
<tr>
<td>C$_P$ violation:</td>
<td>$B^0 \rightarrow J/\psi K^0$</td>
<td>$A_0 &gt; 0.44$ at 2σ level</td>
<td>$A_0 &gt; 0.3$ at 3σ level</td>
</tr>
<tr>
<td></td>
<td>$B_s-B_d$ mixing</td>
<td>$X_s(\text{max}) = 20$</td>
<td>$X_s(\text{max}) = 8-12$</td>
</tr>
</tbody>
</table>
Fig. 5.1: Number of accumulated $b\bar{b}$ events at LEP1 and the upgraded CESR with and without the assumptions that LEP will run on 8+8 bunches in 1993. The solid line describes the expected LEP peak luminosity.

Fig. 5.2: Number of accumulated $b\bar{b}$ events at LEP1+HLEP and in a B factory as a function of time. The assumed peak luminosities are described by the solid lines.
References


[22] H. Nesemann et al., The use of PETRA as a B-factory, same Proc. as Ref. [17], vol. 1, p. 439.


[34] J.A. Rubio, in Ref. [32], and private communication.


[38] W. Bernreuther and O. Nachtmann, in Ref. [32], p. 545.

PART IV

MODIFICATIONS REQUIRED IN THE LEP DETECTORS FOR HIGH-LUMINOSITY RUNNING

F. Merritt, E. Blucher, T. Camporesi, M. Fukushima
1 INTRODUCTION

1.1 Scope and limitations of the present studies

When the LEP experiments were designed, multibunch running was not envisioned. The 22 µs time between beam crossings was considered to be a fixed parameter of the machine, and the data-acquisition systems as well as detector elements were designed accordingly. In many cases, the 22 µs time was exploited to allow less expensive solutions to experimental problems such as providing a trigger or resetting the front-end electronics. Reducing the time between crossings to 2.5 µs (36 on 36 bunches) requires that such systems be redesigned and rebuilt. In the words of one of the LEP experimenters, ‘this experiment was not over-designed by a factor of 10!’.

This study took place during the 1989 and 1990 runs. Detailed designs of high-luminosity upgrades necessarily had a lower priority than making the present detector systems work and producing physics results from the current data. Therefore, the reports given below by each of the four LEP experiments should be regarded as status reports, particularly with regard to running with 18 or more bunches. During future runs and studies, the experimenters will continue to gain a better understanding of detector and processing limitations, of cost estimates, and of possible new solutions.

1.2 Overview of the kinds of upgrades required

Expected rates

The design luminosity for LEP is 1.6×10^{31} cm^{-2}s^{-1}, giving an interaction rate at the Z peak of about 0.3 Z’s per second. Increasing the number of bunches to 36 on 36 reduces the beam crossing time to 2.46 µs and increases the interaction rate to 2–6 Z’s per second at the peak.

We assume a constant bunch intensity, so that the luminosity in general scales with the number of bunches. Since the number of beam crossings increases linearly with the number of bunches, the backgrounds from cosmic rays and from beam–gas interactions should remain at least a constant fraction of the number of interactions. In fact, beam–gas interactions may increase because of poorer vacuum.

Characteristics required of a DAQ system for high luminosity

We can identify several specific elements required for high-luminosity running by the data-acquisition systems of all four LEP experiments:

- Level-1 trigger (L1): This must be fast (≤ 1.0 µs) so that if there is no trigger the detector can be reset before the next beam crossing at 2.5 µs (36 bunches). The trigger rate R_1 should be ≤ 3000 Hz.

- Reset: Most front-end systems require a reset pulse before each beam crossing. For 36-bunch running, the reset time must be minimized.

- Level-2 trigger (L2): Initiated only when L1 is satisfied. This should have a dead-time D_2 ≤ 20 µs and an output rate R_2 ≤ 20 Hz.

- Readout: This means transferring the processed data to local buffers. After readout is completed, the detector is ready for the next event.
• Processing time: The data stored in local buffers generally require processing and reduction before they are transferred to a final event record.

• Level-3 trigger (L3): This can use all information from the detector to perform a preliminary reconstruction, and should reject obvious backgrounds from cosmic ray or beam-gas interactions.

• Full pass-1 event analysis and writing to tape. This is discussed for all experiments in subsection 5.6.3.

**Expected problems which require modifications**

There are several specific sources of difficulty:

1. In order for a detector to reset before each beam crossing, the sum of the L1 decision time and the reset time, including all signal propagation times, must be less than the 2.46 \( \mu s \) between beam crossings. This is a severe requirement: signal propagation times are of the order of 500 ns, resets require at least 1 \( \mu s \), and therefore there is only 1 \( \mu s \) left for the trigger. L1 timing is probably the most difficult problem for all of the LEP experiments, and in many cases triggering systems must be completely redesigned. Only fast devices (e.g. scintillators) can be used in L1.

2. A positive L1 initiates the L2 decision process. Since the relative dead-time from this is the L1 rate times the L2 decision time \( D_2 \) per event, the product of these two numbers must be kept small. If \( D_2 = 15 \mu s \) and \( R_1 = 3000 \text{ Hz} \), the dead-time for 36-bunch running is about 4.5%. In general, this dead-time is not expected to be a major difficulty for the LEP experiments.

3. A positive L2 decision initiates readout, which means the process of storing the data in local buffers. The readout dead-time is therefore the product of the L2 rate times the readout time \( D_R \). If \( D_R = 3 \text{ ms} \) and \( R_2 = 15 \text{ Hz} \), the dead-time is 4.5%. In some cases significant improvements in front-end electronics are required to minimize \( D_R \).

4. For 36-bunch running, the reset time must be of the order of \( \leq 1 \mu s \). Several experiments extensively use a multiplexer which requires 6 \( \mu s \) for reset, and all systems using this multiplexer must be redesigned to run with more than 8 bunches; this can be an expensive and lengthy upgrade.

5. Data-flow and data-processing time limitations. This is a problem caused not by the reduced time between crossings, but by the higher event rate. Bottlenecks can occur both in the DAQ system and in the on-line analysis systems, both of which may require significant processing upgrades for multiple-bunch running. This will be a difficulty for running on the Z peak, but not at LEP 200 energies.
2 MODIFICATIONS REQUIRED FOR ALEPH

2.1 Introduction

In the beginning of 1990, the ALEPH Collaboration formed a working group to investigate the performance of the ALEPH detector at LEP operating with higher luminosities. We considered the long-term possibility of 36 bunches with \( L = 1.4 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1} \), or the more medium term case with 8 bunches and \( L = 3 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1} \), which is also possible for LEP 200. The study covered the limitations and possible solutions for the individual subdetectors under these conditions, and the performance and necessary modifications for detector-wide functions, such as trigger, data acquisition and data processing. The influence of enhanced radiation backgrounds is also considered. The full results of the study are available as an ALEPH Note [1].

In the following, we summarize the most important modifications required for each subdetector to run with an increased number of bunches in LEP.

2.2 Detector performance and required upgrades

Minivertex Detector

The Minivertex detector (VDET) will work unchanged in 8-bunch operation. For a 36-bunch mode a new timing chip must be developed to generate the necessary signals within 1 ms. The cost for this change is about 100'000 SF.

With the extended trigger rate some additional on-line computer power will be needed.

The radiation exposure of the detector under present running conditions is very low (few rads/year) and the expected tolerance is 10 krad. If this situation changes drastically the detector has to be rebuilt using radiation-hard electronics. A rough estimate of the cost for making the detector radiation-hard is 1 MSF; the work would take approximately one year.

Inner Tracking Chamber

The existing hardware of the Inner Tracking Chamber (ITC) would function without difficulty in all respects for the 8-bunch mode, since there is no need to change the Level-1 trigger timing. For more than 8 bunches, the Z readout would require substantial modifications and will not be useful for a Level-1 trigger decision. Necessary modifications to the \( r-\phi \) processor would cost around 125'000 SF.

Time Projection Chamber

For the Time Projection Chamber (TPC), new protocols for switching the gating potentials are being considered. For 8-bunch operation, the presently used synchronous mode, where the gate is opened before each bunch crossing, will continue to work. However, the quality of the coordinate measurements very near the end-plates will be degraded somewhat by gate switching noise. An alternative static mode, where the gate remains open to electrons permanently, looks promising but requires some modifications in reconstruction algorithms to recover the original in Z-resolution. For 36-bunch operation, the synchronous mode is not available. Instead, a choice must be made between the static or asynchronous modes where the latter requires a positive Level-1 trigger for the gate to be opened. This implies a significant loss of track information near the end-plates. For
the static mode, ageing of the end-plate wire chambers may become a critical issue if the background conditions are significantly worse than the present ones. None of these gating modifications imply a major investment.

The Time Projection Processors (TPPs) currently in use are able to handle the expected trigger rate even at the highest luminosity now under consideration. An upgrade of their program memories will add some flexibility in event buffering, and allow for future reductions in data size.

For the readout of the TPPs, an upgrade in the number and CPU power of the event builders is necessary. The cost estimate for the upgrades ranges from 100 kSF for 8-bunch operation, requiring only two more event builders, to 320 kSF for up to 36 bunches where four more event builders and the TPP memory extensions are needed.

Electromagnetic calorimeter

The Electromagnetic CALorimeter (ECAL) and Luminosity CALorimeter (LCAL) use the same front-end electronics. For an 8-bunch operation mode of LEP, the multiplexer switching protocol in the ECAL and LCAL front-end electronics must be changed to reduce the resetting time required after the Level-1 trigger decision. A satisfactory protocol has been found which requires no hardware modifications. However, the consequence is the permanent suppression of a trigger based on pad signals, which might otherwise be used to confirm the triggers formed from the wire signals alone. At present, only LCAL employs both pads and wires for triggering.

For a beam crossing interval below 5 μs the wire trigger formation interval must be reduced to about 1 μs. This can be achieved by integrating a smaller fraction (~ 30%) of the total charge. The loss of threshold precision is regarded as acceptable if the present levels of background are maintained. The pad readout cannot be tuned to operate at such small intervals between beam crossings. Good performance can only be achieved by rebuilding the pad front-end electronics with a reset time of the integrators of 0.5 μs and the elimination of induced oscillations in the detector.

A fall-back solution would be to reset the integrators at a fixed frequency, typically every 100 μs. This mode induces a dead-time loss of about 10% and would require much more complex DAQ software to handle pedestal shifts. It is not a preferred solution.

The foreseen resources required to change the front-end wire and pad electronics are:

- for the ECAL a total cost of 2 MSF, and 15 man-years over 3 years,
- for the LCAL about 60 kSF.

Hadronic calorimeter

For the Hadronic CALorimeter (HCAL) and Muon Chambers there are no changes required to the front-end electronics or the sequence used for controlling the readout when LEP doubles the number of bunches. A faster readout of the ADCs by the HCAL Processor (HCP) will be needed for a Level-2 trigger rate higher than 7 Hz, and can be achieved by increasing the number of HCPs or by implementing a faster readout mode (DMA block transfer).

For the 36-bunch mode of LEP, the sequencers must be replaced, which will cost about 50'000 SF. It will also be necessary to increase the readout speed further, ideally
by replacing the ADCs to allow a zero-suppressed mode of operation. This option will cost 350'000 SF if bought commercially.

**Solid-state luminosity calorimeter**

As a new detector in ALEPH, the Solid-state luminosity calorimeter (SiCAL) is designed to operate with more than 18 bunches in LEP. Extrapolating from our current knowledge of radiation levels, no degradation in performance is expected even at the highest LEP luminosity foreseen.

**Trigger**

The TRIGGER system will remain unchanged for the 8-bunch operation. However, a major reconfiguration is required. An efficient Level-1 trigger can be derived in less than 1.5 µs, using selected components of the ECAL, HCAL and ITC. This trigger is followed by a more sophisticated Level 2, which can confirm track candidates in space using the ITC and TPC. The cost of this upgrade is estimated to be about 80 kSF. The trigger rates expected at the Z for luminosities up to $1.4 \times 10^{32} \text{cm}^{-2}\text{s}^{-1}$ have been calculated assuming existing backgrounds. There is enough flexibility provided to adjust the trigger rate to the needs of the physics.

**Data acquisition**

The Data Acquisition system (DAQ) can accommodate 8-bunch operation with only minor modifications. These are already foreseen in planned upgrades over the next year. For higher bunch-crossing frequencies and data-taking rates, major improvements are required, which include significant changes in readout protocols and the upgrading of CPU power and memories in the readout processors. The design of a new FASTBUS event builder based on RISC technology has begun and a detailed simulation of the expected behaviour of the whole system is under way. A cost estimate for a minimal upgrade is about 700 kSF, which would need to be increased to 1.7 MSF if detailed studies show that all readout processors need to be replaced.

**Event reconstruction**

The local quasi-on-line reconstruction system (FALCON) again requires no significant changes to operate with 8 bunches. However, the proposal to increase the original design luminosity by a factor of about 10 in the Z region with 36 bunches necessitates a major upgrade to FALCON. A conceptual design study indicates that the present parallel-processor system will require ~ 20 times the existing CPU power and a corresponding improvement in I/O capability. We are confident that the appropriate data handling and processing power will be available at a reasonable cost. Including substantially larger dual-ported disks, the cost is estimated to be about 725 kSF.

### 2.3 Conclusions

ALEPH can be made to operate well with up to 36 bunches. Operation with 8 bunches requires only a minor upgrade to the TPC readout processors. Operation with 18 or 36 bunches will require substantial changes. In particular, the front-end electronics for ECAL must be replaced, the Level-1 trigger system reconfigured, and the data-acquisition system upgraded; the trigger reconfiguration might not be necessary for 18-bunch operation. A
summary of the required costs for 8- and 36-bunch operation is given in Table 2.1. The full cost of the upgrade for 36 bunches is estimated to be between 4.5 and 6.5 MSF.

Reference


Table 2.1

<table>
<thead>
<tr>
<th>Subdetector</th>
<th>8 bunches kSF</th>
<th>36 bunches kSF</th>
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</thead>
<tbody>
<tr>
<td>Mini-vertex detector</td>
<td>-</td>
<td>100</td>
<td>(+1'000) in case radiation hardness necessary</td>
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<td>Inner Tracking Chamber</td>
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<td>125</td>
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</tr>
<tr>
<td>Time Projection Chamber</td>
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<td>320</td>
<td></td>
</tr>
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<td>2'000</td>
<td></td>
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<tr>
<td>Luminosity Calorimeter</td>
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<td></td>
</tr>
<tr>
<td>Hadronic Calorimeter</td>
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<td>400</td>
<td></td>
</tr>
<tr>
<td>Trigger</td>
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<td>80</td>
<td></td>
</tr>
<tr>
<td>Data Acquisition</td>
<td>-</td>
<td>700</td>
<td>(+1000) to replace all read-out processors</td>
</tr>
<tr>
<td>FALCON</td>
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<td>725</td>
<td></td>
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<tr>
<td>Total (New Equipment)</td>
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<td>(+2000)</td>
</tr>
</tbody>
</table>
3 MODIFICATIONS REQUIRED FOR DELPHI

DELPHI is formed by several sub-detectors called partitions: Microvertex, Inner Detector, TPC0, TPC1, Barrel Rich, Outer Detector, HPC0, HPC1, TOF, Hadronic Calorimeter, Barrel Muon Chambers, Forward Chamber A, Forward Electromagnetic Calorimeter, Forward Rich, Forward Chamber B, Forward Scintillator Hodoscope, Forward Muon Chambers, Small Angle Tagger (calorimeter and tracker), Very Small Angle Tagger.

In the following we shall call dead time the percent of beam crossings lost during the readout of the detector.

3.1 Intrinsic detector limitation

The only possible intrinsic limitation are in the long drift detectors due to field distortion caused by ion feedback into the drift volume. In DELPHI there are three such detectors: TPC, HPC, RICH.

For TPC and RICH the standard solution is gating the ionisation only during the time between BCO and trigger decision. This solution could still be viable if the number of bunches is increased to 8 but cannot hold for any of the pretzel schemes. A possible solution is a continuous "diode" like gating scheme: in a 1.2 Tesla magnetic field and an Ar/CH₄ 80/20 atmosphere the electrons follow essentially the magnetic field lines while the ions follow the electric field lines, so creating a moderate transverse field at the gating grid one should prevent most ions from drifting back into the drift volume while not disturbing significantly the electron collection. Some preliminary tests have been made on a prototype chamber and further testing shall be carried out in DELPHI soon.

For the RICH detector a viable solution (at the expenses of losing a small portion of the available drift space) is to open the gate only after receiving a valid pretrigger from the outer detector. For the HPC we do not need gating as proven from test beam measurements where the occupancy was much worse than anything which can be expected at LEP.

3.2 Analog front end electronics limitation

Relevant parameter in this field is the minimum time needed by the front end to be ready to accept a new event after a reset. Most partitions in DELPHI need less than 1000 ns. warning time before a BCO. The only exceptions are:

1. Hadron Calorimeter: in the current readout scheme the minimum time needed between BCO is 6 μs due the time needed to refresh the Front End. There is no problem to run with 8 bunches. To run with 18 or more bunches one might envisage not to refresh every BCO. This needs partial modification of the front end electronics (cost ≤ 50000 SF).

2. The Outer Detector needs 1.5 μs before BCO to reset their front ends: this added to the trigger decision time might make the inter BCO time critical for the 36 bunches option.

3. Time Of Flight needs 2 μs to reset their front end: it can run with 18 bunches, but it needs modification/replacement to be able to run with 36 bunches.
4. Forward Chambers need at the moment 2 \( \mu s \) before BCO to reset their front end trigger memories. Upgrade of this part of the front end electronics is already planned: it has to be verified whether one can run with 36 bunches, while 18 should be ok.

5. Microvertex: fast reset rates of 200 kHz (18 bunches) have been already used during test beam operation of the detectors. Rates of 400 kHz (36 bunches) should be possible and the effect of possible deterioration of signal/noise should be studied in detail.

### 3.3 Trigger

Currently in DELPHI we have four levels of triggers:

- the first two levels are synchronous with BCO:
  - T1 decision time \( \leq 3.5 \mu s \)
  - T2 decision time \( \leq 35 \mu s \)

- the third level is based on a CHI (processor M68030) which processes information provided by the partition at higher granularity than that used by the first two levels and decides on the events after building correlations between different detectors. This level of trigger is not yet used to reject events, but it will be tested during the current running period. The decision of this trigger applies to the events waiting in the Local Event Supervisors pipelines (see below). The typical time for a decision is 20 ms.

- the fourth level of trigger is based on a set of 3081 emulators. The emulators have access to the whole event data and their purpose in the current scheme is mainly to be used for tagging: they are not yet included in the standard data flow and we foresee that they should be brought online before the end of this year run.

The current trigger parameters are fine to run with 8 bunches. More optimization is needed to go to 18 bunches:

- the first level trigger decision time must be shortened to \( 2.5 \mu s \) to be able to deliver it in less than 3 \( \mu s \). To achieve this we will need a new subtrigger for the track triggers (cost \( \leq 50000 \) SF).

- to improve the speed and the redundancy in the forward direction we might need to add an additional plane of scintillators in the end-caps (cost \( \leq 500000 \) SF). This option has to be studied more in details.

To be able to run with 36 bunches one needs a much improved trigger performance (see discussion on TPC digitizers below) as the first level trigger must be delivered to the detectors within 1 \( \mu s \). This implies:

- that the first level trigger can only be done without any of the available drift detectors
that while in the barrel we might be able to implement such fast trigger based on TOF and HPC scintillators in the forward region one must install new plane(s) of scintillators (cost \( \leq 500000 \) SF). We might also improve the timing of the FEMC trigger (currently 1.5 \( \mu s \) cable length) but for that one needs the replacement of all the shapers and trigger front-end with a rough cost estimate of around \( \geq 600000 \) SF.

### 3.4 Data acquisition limitation

Currently the first level trigger of DELPHI is running at \( \leq 5 \) Hz. In the following to be conservative we shall use 1 kHz T1 rate.

**Overview of current system.**

The main characteristics of the DELPHI readout are the following

- DELPHI is using only FASTBUS devices for acquisition: most of them developed especially for DELPHI

- Each partition (only exception Microvertex, see below) front end has 4 event deep buffers (Front End Buffer, FEB). A FEB is filled only after a positive 2nd level trigger decision

- some partition have an intermediate level of buffering (Board Event Buffer, BEB) which is used typically for zero skipping

- The FEB is readout by a Crate Processor which is based on the same Fastbus Master for all partitions: the FIP developed in Saclay. The imbedded code is also standard for every partition allowing a very high level of optimization. The Crate Processor houses the Crate Event Buffer, CEB which is \( \leq 256 \) events deep (256 kbytes) depending on the size of the event. The number of CPs varies from partition to partition from a max of 21 for TPC to 1 for detectors like TOF. The integrated CEB buffer space in DELPHI is ca. 15 Mbytes and even for partitions with large amount of data is able to store on average more than 20 events.

- All the CEBs for one partition are readout by the Local Event Supervisors in the Multi Event Buffer (which can contain up to 256 events). The LES are based on FIPs and the imbedded code is standard for all partitions. The MEB is acting as a pipeline as events can be discarded from it by the 3rd level trigger decision.

- The MEBs are read by the Event Supervisor (based on a FIP) into a memory module (DSM) via a Block Mover. At this level in the near future the data will be transferred into 3081 emulators.

- The data is transferred into the acquisition computer (a VAX 8700) by a CHI via an fiber optic link and eventually written out on cassette.

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3.5 Critical parameters for acquisition rates (see Table 3.1)

The rate of the first level trigger: as it is now a positive T1 decision causes the loss of 35 $\mu$s to wait for the T2 decision: for the 18 bunch option this amount to a loss of 8 BCOs for each T1 and this is less than 1% contribution to the dead time even if the T1 rate is 1 kHz.

Front End Freeing time: i.e. the time needed to have the synchronous buffers (FEB) filled. With present electronics this time is $\leq 1000$ $\mu$s for most partitions. The only exception is the Microvertex where only two level of buffering are implemented in the front-end and we must wait 30 ms from the first trigger before accepting a third one (noise reduction processing time). This implies a dead time of

- $\leq 2\%$ if T2 rate $\leq 10$ Hz
- $\leq 10\%$ if T2 rate $\leq 15$ Hz

This is our dominant limitation at this level: anyway it does not depend directly on the number of BCOs but on the Level 2 trigger rate.

The asynchronous processing happening during the transfer FEB-BEB-CEB for TPC (the same happens for other partition, but the problem is less severe as they have less data) is not completely independent from the BCO rate as between the BCO and T1 decision the FEB memory is being written by the FADC and as this memory is not dual port the 0-skipping process happening during the transfer to the BEB is interrupted and resumed after the negative T1 decision. For TPC the bare 0-skipping time is 2.1 ms. Depending on BCO rate it becomes:

$$T_{\text{osk}} = \frac{2.1\text{ms}}{1 - \frac{T_{\text{T1}}}{t_{\text{bco}}} - t_{\text{T2}} \cdot \text{Rate}_{\text{T1}}}$$

If $T_{\text{bco}} = 5$ $\mu$s, $T_{\text{T1}} = 3.5$ $\mu$s (as it is now), $T_{\text{T2}} = 35$ $\mu$s and $\text{Rate}_{\text{T1}} = 1000$ Hz then $T_{\text{osk}} = 8.5$ ms and given that we have 4 event deep buffers this will contribute less than 2% to the dead time if the T2 trigger rate is less than 40 Hz. So this will not be a limitation for running at with 18 bunches. It clearly will not work with 36 bunches unless the T1 decision time is shortened to be less than 1 $\mu$s. For HPC we are presently collecting a pedestal presample of 8 digitizations before BCO which are not 0-suppressed: we then process the data for each channel using the microprocessor onboard the digitizer (which comprises 32 channels) to discard the channels which have only the presample. We have to test whether we will be able to use the present scheme with 18 bunches. For the 36 bunches option we will need to modify the hardware 0-skipping logic (cost $\leq 50000$ SF). We can afford disposing of the presampling because our pedestals are very stable, less than a least count variation over weeks and we do not need event by event pedestal subtraction.

The fastbus readout time is on average 25 ms for an average $Z^0$ event (100 Kbytes): this implies that the 3rd level trigger rate must not exceed 10 Hz to keep dead time contributions below 2%. Note that this is a conservative estimate as the $Z^0$ events will be $\leq 3$ per second.

Last but most important is the data size: there is no bandwidth problem at the single partition level as the Fastbus bandwidth is more than adequate to cope with the max amount of data that a single partition will provide: the largest portions are from TPC and they are below 50 Kbytes for an average $Z^0$. The size of an average $Z^0$ event
is 150 kbytes while background triggers have an average of 25 kbytes. The optical link has no problem as it has a measured bandwidth of 4 Mbaud. The VAX 8700 BI bus has a bandwidth of 13 Mbaud and even if we have to share it with many peripherals it should be ok. The critical items are the DISK and MAGTAPE units bandwidth where the \( \leq 1 \text{ Mbaud} \) are becoming tight. In principle there should be no problem provided that we keep the logging rate below 10 Hz : as one expects at most 3 \( Z^0 \) per second and the background event size is 25 kBytes the data flow should be maintained below 600 Kbytes per second. Concerning this point several improvements should be made to run with 36 bunches and also if one wants to be safe for running with 18 bunches:

1. push pipelining concept by upgrading all FIPs to provide order of megabyte memory buffers and distribute 3rd level trigger decision to the CPs instead of LES: with this extended buffer the CP could hold \( \leq 100 \) events even for partition with large amount of data. (cost \( \leq 500000 \) SF)

2. if 1) then one might imagine to have more time to do additional processing of the data at CP level to do data compaction: clusters instead of strings of charge, track stubs instead of individual hits etc. Also, having this in mind, we might consider increasing the amount of distributed intelligence by using additional FIPs and/or CHIs (priced at 15 kSF each)

3. increase number of Emulators (to get to UA1 type of configuration) to 10 and use them as an additional buffering stage.

3.6 Conclusions

We do not see any acquisition or detector limitation for DELPHI to run with 8 bunches in LEP. To run at LEP with 18 bunches it will be necessary to carefully tune all the internal timings but apart from marginal problems with the HAD CAL we should be able to run. An investement of the order of 1 Msfr would allow us to have some safety margin (new fast forward trigger, additional front end memory and processing power). To run with 36 bunches there seem to be no severe intrinsic limitation but we need to study in much greater details the major issue which is to be able to deliver a trigger to the detector in less than 1 \( \mu \text{s} \). We will also need replacement of part of the front end electronics for certain partitions like OD and TOF. Extensive tests should be performed on the digitization chains for HPC and TPC to verify that they able to perform correctly with a 2.5 \( \mu \text{s} \) BCO time as it seems possible in principle. One must envisage upgrades of the data chain as described in the text . It is hard to make quantitative estimates on the cost to run with 36 bunches, but a reasonable estimate should be around 2 MSF.
Table 3.1

Current parameters of DELPHI acquisition

<table>
<thead>
<tr>
<th>Partition</th>
<th>Wng Time (ns)</th>
<th>FEF time (μs)</th>
<th>$Z^0$</th>
<th>Bckgnd</th>
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<tr>
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<td>1000</td>
<td>500-30000</td>
<td>8</td>
<td>3.2</td>
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<td>ID</td>
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<td>500</td>
<td>≤50</td>
<td>3</td>
</tr>
<tr>
<td>TPC</td>
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<td>≤500</td>
<td>80</td>
<td>≤4</td>
</tr>
<tr>
<td>Brich</td>
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<td>≤500</td>
<td></td>
<td></td>
</tr>
<tr>
<td>OD</td>
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<td>800</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>HPC</td>
<td>700</td>
<td>480</td>
<td>≤50</td>
<td>≤4</td>
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<td>1</td>
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<td>≤2</td>
</tr>
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<td>F.Chambers</td>
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<td>≤10</td>
<td>≤2</td>
</tr>
<tr>
<td>FEMC</td>
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<td>≤2</td>
<td>≤2</td>
</tr>
<tr>
<td>Forward $\mu$</td>
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<td>≤2</td>
<td>≤2</td>
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<tr>
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<tr>
<td>VSAT</td>
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<td>500</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>
4 MODIFICATIONS REQUIRED FOR L3

4.1 Overview

L3 is composed of the precision muon chamber, uranium proportional chamber hadron calorimeter, BGO electromagnetic calorimeter, time expansion chamber (TEC) and the small angle BGO luminosity monitor. The present detector has no intrinsic limitation for the shorter beam crossing time, and no major change of the detector, including its preamplifiers, is necessary up to the 36 bunch operation. On the other hand, the trigger and the data acquisition system (DAQ) is significantly affected by the shorter beam crossing time and several modifications will be required depending on the number of bunches in LEP.

L3's trigger and DAQ is composed of 3 levels of triggers embedded in FASTBUS. The level-1 trigger is composed of 4 sub-triggers, the energy trigger, the muon trigger, the TEC (vertex chamber) trigger and the scintillator trigger, and reaches a decision for each beam crossing. The one microsecond period before the next beam crossing is reserved for a fast clear of the data digitizers. On a positive decision of the level-1 trigger, the data are digitized within 500 $\mu$s and buffered in front-end memories. Four independent sub-triggers make the system highly redundant and a high trigger efficiency is obtained by combining several sub-triggers.

The system dead time is defined by the product of buffering time (500 $\mu$s) and the level-1 trigger rate because the subsequent event builder and the level-2 and level-3 triggers are capable of removing the event from the front end memories faster than the level-1 rate. At the time of this report, we are running with a maximum level-1 trigger rate of 7 Hz. The buffering time is less than 500 $\mu$s for all sub-detectors, except for 5 ms of the BGO which determines the dead time of 3-4 %. The longer buffering time of BGO takes advantage of the low level-1 trigger rate and minimizes the BGO noise level for the data digitization and the trigger analog sum.

The level-2 and level-3 triggers are an array of 3 XOP processors and 4 3081/E emulators respectively. Presently the level-2 trigger is in flagging mode to develop an effective filtering algorithm. The level-3 trigger is executing a conservative filtering analysis which rejects approximately 1/3 of the level-1 triggers with an average processing time of 200 ms. The throughput of the FASTBUS event builder is 40 Hz and easily supports the level-1 trigger rate of 7 Hz. By the end of 1990, we plan to reduce the BGO buffering time to the design value of 500 $\mu$s and to increase the FASTBUS throughput to 200Hz.

The impact to L3's trigger and DAQ system of more than 4 bunches is mainly felt by the level-1 triggers and the BGO readout. The modification and redesigning of these electronics becomes more and more difficult with increasing number of bunches owing to the constraints that the lowest level trigger must make a decision before the next beam crossing, and that an additional 1 $\mu$s is necessary for the fast clear of the digitizers. We could conceive, in principle, to build a pipelined trigger and data digitizers which could easily cope with 36 bunches if we were prepared to rebuild most of the trigger and DAQ electronics of the experiment. However, because of the obvious financial, temporal and human resource problems, we proceed under the assumption that our current trigger and DAQ architecture will be retained. In the following report, we assume the rate of the beam gas background per bunch will stay at the same level as the current 4 bunch operation.
and the total level-1 trigger rate will not exceed 100 Hz even for the 36 bunches. Times between beam crossings are assumed to be 11.1, 4.9 and 2.5 \( \mu s \) for 8, 18 and 36 bunch operation respectively.

### 4.2 8 Bunch Operation

**Level-1 Energy Trigger**

The digitization time of the current trigger ADCs (LRS4300) is 8.5 \( \mu s \) for 11 bits resolution. This trigger also uses the full 20 \( \mu s \) currently available to implement the fairly complicated trigger logic of, for example, cluster and single photon identification. For 8 bunch operation, we plan to replace the LRS4300's with an 8-bit flash ADC with logarithmic conversion to provide 11 bits of dynamic range with enough resolution. Pedestal subtraction, gain adjustment and coherent noise suppression will be implemented in the same module. This unit may have a few prompt trigger outputs to be used for 18 and 36 bunch operation, which are produced by applying a threshold on the measured energy in each analog sum.

A prototype of such an ADC is under development at INFN/Rome. By using the existing level-1 trigger logic, this newer and faster trigger ADC will allow us to make a decision within beam crossings on the basis of the total energy and the 'number of bits' in the calorimeter (level-0 trigger). When the decision of the level-0 is positive, we continue to make more refined decisions, such as single photon identification, using the current level-1 trigger logic.

**Level-1 Muon Trigger**

Presently the muon trigger searches for tracks in a total of 1300 'roads' in both the bending and non-bending plane muon chambers. This takes 18 \( \mu s \), or, including the maximum drift time of 2.1 \( \mu s \), the full 20 \( \mu s \). For 8 bunch operation, we will generate a level-0 muon trigger by combining several muon roads, thus reducing the number of searches to about 250. On a positive decision, we will repeat the search with the current level-1 roads. The inclusion of the level-0 trigger can be made by adding several CAMAC modules to the existing system and by upgrading the microcode of the trigger.

**Level-1 TEC Trigger**

The current TEC trigger decision time of 15.5 \( \mu s \) is composed of 8 \( \mu s \) of TEC drift time plus 0.5 \( \mu s \) for track finding plus 7 \( \mu s \) for track processing. The track finding is done in parallel for each sector. The 7 \( \mu s \) of track processing, which includes searches for clusters of tracks and acoplanar pairs of tracks, is performed serially in one FASTBUS module. By rebuilding this module to process the tracks in parallel, this step can be made much faster (less than 1 \( \mu s \)). A decision would then be available in under 9.5 \( \mu s \), which would be sufficient for 8 bunch operation. The new module may have a somewhat restricted capability compared to the present module but the important features, such as recognition of acoplanar pairs, can easily be implemented. The bulk of the electronics, most of them being the parallel track finders, do not need modification for this change.
Miscellaneous Changes

The level-1 scintillator trigger and the higher level triggers will stay unchanged for the 8 bunch operation. A minor modification will be necessary for the overall control logic of the trigger and DAQ to incorporate the level-0 trigger decision. The details of the timing requirements including cable delays and the necessary fast clear time are yet to be worked out. As the digitization and buffering is only initiated by the level-1 decision, most of the existing ADC’s and TDC’s do not see the change from 4 to 8 bunch operation.

Summary

It seems fairly straightforward to upgrade L3’s trigger for the 8 bunch operation without compromising the quality of the current system. This can be achieved by modifying the existing level-1 energy and muon triggers to provide another layer of trigger (level-0) and by speeding up the TEC trigger track processing. The additional dead time from level-0 will be only 1% even for a conceivable extreme case of 500 Hz. The change of the trigger conditions from the current level-1 trigger is minimal and an increase of the level-1 trigger rate should not exceed much more than a factor of 2 due to the increase in the gating frequency. This additional rate of level-1 triggers can easily be removed at the level-2 trigger.

The major task is the design and construction of the new trigger ADC. It may cost approximately 500 kSF and would require 2 years of lead time. We will also need at least a 3 month shutdown to perform the necessary changes, reintegrate the system and bring it into operation.

4.3 18 and 36 Bunch Operation

The BGO Digitizer

In the present system, the preamplified BGO signal is fed to a resettable gated integrator, followed by a sample hold circuit and a successive approximation ADC. This system was designed for 8 bunch operation, with a 5 µs integration time to minimize the BGO noise level. This low noise level is critical for the detection and measurement of low energy signals in the BGO. Note that any changes in the BGO ADC system will most likely result in an increase in the BGO noise level.

For 18 and 36 bunch operation, the BGO ADC must be replaced. A very preliminary study indicates that it is feasible to build a new ADC, similar to the current one, but with the integration time reduced to 2-3 µs. The shorter integration time will result in an increase in the BGO noise, however the dynamic range will be the approximately 20 bit range of the current ADC. This should be adequate for 18 bunch operation. For 36 bunch operation the resettable integrator may be marginal because of the very short shaping times required, and an entirely new approach may be necessary. This is currently being studied.

For the current system, analog sum signals are generated in the ADC unit by summing 30 neighboring crystals and transported to the level-1 energy trigger over 40 m of cables. For the new ADC unit, we are considering to integrate the first level of trigger (level-0) on the ADC board. This will avoid the problems of transporting the analog signals to the distant trigger electronics and allow programmable trigger thresholds for each crystal. These prompt (about 1 µs after the beam crossing) digital signals can then be combined as we now combine the analog signals, producing a trigger 'hit' pattern for several different
energy thresholds. This will substantially reduce the effect of correlated noise on the trigger rate. This also is being studied.

**Level-1 Energy Trigger**

For 18 bunch operation, we could form a level-0 decision by simple processing, such as hit counting, on the prompt trigger outputs from the new trigger ADC's. For 36 bunch operation, it is probably obligatory to use a prompt trigger output of the BGO ADC unit. Prompt outputs must also be generated for the hadron calorimeter. This will necessitate rebuilding the 400 FASTBUS auxiliary cards which generate the hadron calorimeter analog sum. So far as the level-0 trigger rate is maintained at a reasonable level of 2 kHz, the existing level-1 trigger can be used as is to reduce the accepted rate.

**Level-1 Muon Trigger**

For 18 bunch operation, we will have to rebuild the muon trigger data readout and encoders (22 FASTBUS cards in total) to generate a prompt output by simply counting the number of hits in a certain region of the muon chambers. We will also need a level-0 trigger logic to combine prompt outputs and form a rough muon road. For the 36 bunch operation, the prompt output will be generated on the trigger data latch (260 FASTBUS auxiliary cards in total). This will be limited only to a bending plane muon chamber due to a long drift time of the non-bending plane chambers. If, as expected, the dominant background in the muon chamber remains cosmic rays, it should be possible to limit the level-0 rate to a reasonable level. The current level-1 trigger electronics will stay intact for the changes to 18 or 36 bunches. We are also studying a possibility to use the hadron calorimeter for triggering the muon for 36 bunches.

**Level-1 TEC Trigger**

Due to its 8 µs drift time, the TEC chamber can not be used in a level-0 trigger for 18 and 36 bunch operation. To retain a charged particle trigger, we may use 2 layers of existing proportional wires just outside of the TEC and several layers of straw tube chambers to be installed in between the TEC and the beam pipe. The quality of the level-0 trigger derived from such devices will probably limit us to use it only as a backup or monitor trigger. To keep a highly efficient and low rate charged particle trigger, it would be necessary to build a completely new vertex chamber which incorporates enough numbers of trigger wires with sufficiently short response time. The necessity and feasibility of such a vertex chamber is yet to be thought through in the collaboration.

**Online Processing Power**

To cope with the increased luminosity and higher background rate, the processing power of the level-3 will have to be significantly expanded. The selection algorithm will have to be more refined and tightened to limit the tape writing only to a well selected event. Considering the construction technology, to increase the number of 3081/E's of the current system will be impractical by the start of high luminosity LEP. We will retain the current environment of FASTBUS and try to replace the emulators by an array of fast processors. One possible solution is a network of transputers and another possibility is a farm of RISC processors with an intelligent scheduler. These systems are expandable, use commercial modules and a lot of support software will be commercially available.
In the TEC chamber readout, a microprocessor is attached for every 2 wires and the digitized data are immediately processed for the track finding and the precise position determination by the center of gravity method. The throughput of this system is 50 Hz and the processing is presently performed for all the events triggered by the level-1. We should be able to keep the same system for 36 bunch operation by limiting the processing only for the level-2 accepted event. The current 8 event deep buffer memory should be sufficient for this operation.

Summary

18 and 36 bunch operation in LEP requires significant changes in the trigger and DAQ system of L3. As described above, it is conceivable to build a new system by adding another layer of trigger (level-0), rebuilding the analog circuits and ADCs of the BGO and adding additional processing power at the level-3 trigger while keeping the rest of the 4 bunch system intact. The modifications for 18 or 36 bunches involve different technologies so that the decision on the number of bunches will have to be considered in the early stage of the project.

For the case of 36 bunches, a big effort will be necessary to cut down the cable length and minimize the fast clear time to give sufficient time for the level-0 trigger. Some relocation of the electronics, which are currently distributed in 5 separated counting rooms, will probably be unavoidable. A crude guess of the cost for the 36 bunch operation is 7.5 MSF and 3-4 years of lead time will be necessary.

In return for the gain in luminosity, a degradation of some aspects of the performance of the experiment may occur, at 18 and 36 bunch operation. If the noise level of the BGO is increased, the low energy resolution will deteriorate. Triggering on single photons or charged particles will be more difficult (thresholds may be higher), due to the necessary simplicity of the level-0 trigger. For the same reason, trigger acceptance may be reduced for certain classes of events. The impact of these problems on the physics at high luminosity is not understood at this time. A detailed study is necessary to answer these questions in a reliable way, and to find ways to allow the detector to operate with its maximum performance during the high luminosity operation of the LEP.

Reference

5 MODIFICATIONS REQUIRED FOR OPAL

5.1 Overview of the OPAL data-acquisition system

A detailed description of the OPAL detector, data acquisition, and triggering systems can be found in Refs. [1–3]. Only a brief overview, relevant to understanding the upgrades required for multibunch operation, will be given here.

The OPAL data-acquisition system is based on the VME standard. A tree-structure organization is used to allow parallel data processing and readout from 17 independent subsystems (15 subdetectors, the trigger, and the track trigger). Each subdetector branch has one or two Local Systems Crates (LSC) which control the readout for that subdetector. Each LSC runs the OS9 operating system and is equipped with its own local microprocessor.

The 15 subdetectors are:

- FD: Forward Detector and Luminosity Monitor;
- SI: Silicon microvertex detector (under construction);
- CD: Central Detector, comprising three chamber arrays: CV (Vertex chamber), CJ (Jet chamber), and CZ (Zed chambers);
- TB: Time-of-flight counters (barrel region only);
- PB and PE: Barrel and end-cap electromagnetic presamplers;
- EB and EE: Barrel and end-cap electromagnetic calorimeter (lead glass);
- HT, HS, and HP: Hadron calorimeter (Towers, Strips, and Pole-tip Calorimeter);
- MB and ME: Barrel and Endcap muon chambers.

Trigger information from the subdetectors is sent to a General Trigger Unit (GTU), which produces an OR of several independent trigger conditions from various subdetectors. In addition, the GTU uses a \( \theta - \phi \) matrix incorporating information from several subdetectors to form additional triggers. Most physics reactions satisfy several independent trigger conditions; this redundancy gives a high trigger efficiency even for low-multiplicity events and non-standard decay modes, and allows a precise monitoring of the efficiencies of the different trigger components.

The GTU completes the trigger decision 16 \( \mu s \) after the beam crossing. If there is no trigger, all subsystems are reset in time for the next beam crossing. If the trigger conditions are satisfied, each subdetector completes necessary processing and stores its subevent data in local buffers in the LSC. When all subevent data have been stored, the detector is ready for a new trigger. The dead-time due to buffering and necessary processing in the LSCs (frequently referred to as readout dead-time) was about 50 ms or more in 1989, and will be reduced to 20 ms during the 1990 run.

Transfer of data from the LSCs is synchronized by the Event Builder; this is a VME system which initiates DMA transfers of subevent data, formats all of the data into a complete event structure, and makes them accessible to the Event Filter processors.
The Event Filter performs a fast analysis of each event, and events which are flagged as background can be optionally rejected at this stage. Events which pass the filter requirements are transferred through an optical link to the Top Crate, which resides on the surface. On-line reconstruction is carried out there through several Apollo DN10000 processors running in parallel, and both raw and reconstructed event records are written to tape.

High-luminosity running requires enhancements in four areas of the OPAL data-acquisition system:

- The increased event rate requires improvements in processing power for some subdetector systems, and also for the Event Builder, the Event Filter, and the on-line reconstruction systems. These upgrades are driven by the high rate rather than by the reduced time between crossings. Off-line processing and data storage also must be substantially improved to handle the much larger quantity of data.

- A new Level-1 trigger must be introduced when the time between bunch crossings is reduced below 22 µs.

- Significant modifications are required in several subdetectors in order to provide sufficiently fast signals for the new Level-1 trigger.

- The resetting of each of the subdetectors must be made in a much shorter time; this requires significant modifications to FD, PB, PE, and ME.

5.2 Upgrades required for VME system and data flow

A Level-2 trigger rate of 20 Hz requires that the readout time of the detector be reduced to less than 4 ms in order to keep total dead-time at an acceptable level. The present design readout time is 10 ms, but additional upgrades are still required before this is attained. A more important constraint at high luminosity will be the processing time in the LSCs, Event Builder, and Event Filter. These must be upgraded to maintain adequate data flow even for the 4-bunch design luminosity. Several upgrades all already planned, and will be carried out before the 1991 run. Only upgrades which are required solely because of high-luminosity running are included in the cost estimates presented here.

The subdetector LSCs will be upgraded in several ways. The existing 68020 processors can be replaced with 68040's to significantly improve the processing power. The VIP communications modules will be replaced with commercially available VICs to improve functionality and performance. Local memory in the LSC will be expanded in some instances to improve processing. The 14-slot VME crates can be replaced by new 15- or 20-slot crates when more space is needed. All of these changes can be made as required for those subdetectors which limit the total data flow rate, and all are compatible with the existing system. The most serious problems with data flow will be caused by CJ and CZ, since these have the largest data sizes. Significant improvements are already planned for the CJ system on a short time-scale.

The Event Builder will require similar upgrades. Some improvements to extend the degree of parallel data transfer will be made at the end of this running cycle. A complete redesign is likely to be necessary for the highest event rates. The Event Filter processing is currently done by four 68030 modules, and must be expanded even for full 4-bunch
design luminosity. A significant upgrade is required to handle high data rates. This might be accomplished by a farm of RISC processors; alternatively, a DN10000 might be used for both the Event Filter and the Event Builder. To develop this, will require study and manpower; such an upgrade for both the Event Filter and the Event Builder could probably be completed by 1993, at a cost in the neighbourhood of 200 kSF.

The ability to perform full event reconstruction in quasi-real time is essential for multibunch running. Apollo DN10000's are currently used for this, and fully analysed data records are written to tape. For the very high luminosities expected from 36-bunch running, a significant upgrade is needed. OPAL will almost certainly convert to a system that writes only DSTs and very compressed data records to disk or tape, probably using commercial RISC-based machines. Possible candidates are the Apollo DN10000/20000 or the new IBM R6000 series. This system will have to be evolved over the next few years. Costs are not included here, but are discussed in Section 6 below.

5.3 The new Level-1 trigger and timing considerations

New Level-1 trigger processor

At the present time, OPAL uses a single-level trigger which gives high efficiency and redundancy. About 16 μs are required to form the trigger, and for some subdetectors 6 μs or more are required for a reset. It is not possible to reduce the trigger time of all components by a factor of 3 (required for 8-bunch running). For running with more than 4 bunches, a new Level-1 trigger processor will be created, which will issue a fast reset if the trigger conditions are not satisfied. Such a processor can be built within a year, at a cost of about 50 kSF. The present trigger will continue to be used, but as a Level-2 trigger.

Since a trigger rate of 2000 Hz is acceptable for a Level-1 trigger, this trigger does not need to be very restrictive; rather, it will be designed to retain the high efficiency of the present trigger and sufficient redundancy for component trigger efficiencies to be measured reliably.

Timing constraints and possible Level-1 trigger inputs

The time between beam crossings (see Table 5.1 and sketch) must be greater than the sum of the times required to (a) prepare trigger information at the LSCs, (b) make a central Level-1 trigger decision, and (c) reset all of the LSCs. The times allotted for three stages of running scenarios are summarized in Table 5.1. If the Level-1 processor is located in a central position, minimum signal propagation times between the Level-1 processor and the LSCs are estimated to be 350 ns each way, with an additional 200 ns required for a trigger decision at the processor; this gives a total time B in Table 5.1 of 900 ns.

For 8-bunch running (11.1 μs between crossings), the required reset time of 6.0 μs means that subdetectors must send trigger information within 4 μs after the beam crossing. For 18-bunch running (4.93 μs between crossings), the long reset times required for the ALEPH multiplexer must be eliminated (as described in the following subsection), so that resets can be completed within 1.0 μs; in that case the Level-1 (L1) trigger signals must be sent at 3.0 μs after beam crossing.

For 36-bunch running (2.46 μs between crossings) the Level-1 trigger information must be sent from the LSCs at ~700 ns after beam crossing (see sketch), and the resets must
be completed within $\sim 0.85 \, \mu s$. These timing constraints are very tight for both the trigger and resets, and there is no safety margin in the allotted times. The trigger and reset times for 36-bunch running will require careful study during 1990–91.

There are two convenient trigger signals which can be used in the fast Level-1 trigger for 8-bunch running. These are the TB trigger from the barrel time-of-flight counters, and a CD trigger from fast hit-counts in azimuthal sectors of the central detector CD (specifically, from the CV and CJ chambers). If only CV and the inner regions of CJ are used, the maximum drift time is 2.5 $\mu s$ and the trigger information could be sent from the LSCs at 3.0 $\mu s$ after beam crossing. The precise requirements of each of these triggers needs more study and modifications to existing electronics, but each should give good efficiency with a rate of a few hundred hertz under present running conditions.

The combination of the TB and CD Level-1 triggers should give fairly good coverage of the barrel region for charged final states, and could be ready on a short time-scale (1991) for testing the Level-1 trigger system and for studying rates and efficiencies. However, in the end-cap region they would give less complete coverage than the present trigger, and no redundancy, and would be insensitive to some classes of events (e.g. $e^+e^- \rightarrow \gamma\gamma$). They will also be more sensitive to beam conditions and to beam-related backgrounds than the present calorimeter triggers. Physics data-taking will also require fast Level-1 calorimeter triggers from EE and EB.

The timing of the EB and EE triggers has been extensively studied over the last six months in an effort to find how to provide a fast calorimetric trigger. This has been a very successful study; we are now confident that a fast Level-1 trigger can be produced within 3.0 $\mu s$ for EB and within 3.5 $\mu s$ for EE, at a relatively low cost, as described in the following subsection. These times are easily sufficient for 8-bunch running, as shown in the second line of Table 5.1. It is likely that all the ECAL triggers can be produced within less than 3.0 $\mu s$.

In order to run with 18 bunches, the reset times of all subsystems must be reduced to $\leq 1 \, \mu s$. Major upgrades are required to achieve this, particularly in the ME front-end electronics, and these require extensive design work and a shutdown period of about four months. The ME system would also be redesigned to provide a fast Level-1 trigger which would be incorporated when the reset time is reduced. These changes could be completed in time for the 1994 (or possibly 1993) run, given sufficient support and an early commitment. In addition, a Level-1 trigger time of 3.0 $\mu s$ is required. The TB and CD triggers will already satisfy this. Additional modifications in EB and EE may be required which are still under study. The combination of these triggers would give, for 18-bunch running, the same high efficiency and redundancy over both the barrel and end-cap regions as the present OPAL trigger.

For 36-bunch running, the trigger signals must be provided within about 700 ns. The TB and ME triggers will be sufficiently fast for this. The EB trigger will require very extensive modifications as described below. The CD and EE Level-1 triggers will probably have to be abandoned. The remaining triggers should be adequate for most of the physics studies anticipated. Another possible trigger signal could be provided by a new scintillating-fibre subdetector surrounding the vertex chamber. This possibility is being considered.

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5.4 Modifications required in subdetector systems for multibunch running

The modifications and costs required for running with 8 bunches are summarized in Table 5.2. Improvements are required in the front-end electronics for CV, CZ, HS, and HT, costing approximately 200 kSF. Additional changes required to produce a fast trigger can be made for FD, CV, CJ, and TB for a cost of approximately 140 kSF.

Relatively minor modifications to the EB and EE triggers will be required to reduce these trigger times to 4.0 μs. The calorimeter triggers use analogue energy sums produced by the CIA (ADC) modules; signals from the near and far sides of the calorimeters are combined to make the present triggers. To combine these signals before making the trigger requires long cable lengths, which introduce propagation delay as well as some pulse slewing, which necessitates a long integration time. The new Level-1 trigger will use separate triggers for the two sides of the system, and will use a new fast output from the CIAs. In addition, some relatively simple modifications to the system can be made which will further reduce trigger time, and it may be possible to produce a trigger within 3.0 μs. The total cost of these upgrades is expected to be less than 100 kSF, although design work and studies are still under way.

Upgrading for 18 bunches (see Table 5.3) requires modifications to the front-end electronics for FD, CZ, PB, PE, ME, and TT. Most of these upgrades are associated with the reset time, which must be reduced from 6.0 μs to less than 1 μs. The total cost is estimated to be in the range 2.2–3.0 MSF. The largest item comes from redesigning the ME front-end system both to reduce the reset time and to provide the fast Level-1 trigger required for 36-bunch running; this is estimated to cost a total of 1.4 MSF (contributing 700 kSF to each of items 1 and 2 in Table 5.3).

For 36-bunch running, extensive modifications are required for the Level-1 ECAL triggers. Both EE and EB will require fast precision splitters for each phototube signal, which will be used to make a fast Level-1 trigger. The work for EE is estimated to require 1.5 years lead time and to cost about 300–500 kSF. Providing a Level-1 ECAL trigger within the 700 ns required for 36-bunch running is estimated to require 2.5 years lead time and to cost in the range 1.5–2.0 MSF. Other upgrades are relatively minor. TB and HT require front-end upgrades totalling 350 kSF. Additional improvements costing up to 800 kSF may be required to improve chamber readout time, depending on rate; we hope that these will be unnecessary, and they are therefore not included in our estimates.

5.5 Summary of required changes for each multibunch running mode

8-bunch scenario

A new Level-1 trigger processor must be installed with new Level-1 trigger inputs. A minimal system using TB and CD triggers could be set up for testing before the 1991 run, with the L1 trigger setting a flag rather than giving a trigger. This would allow tests of the system and measurements of timing, rates, and efficiency of the TB and CD triggers, to be carried out during 1991; both of these triggers could be optimized before the 1992 run. Fast triggers must also be provided from FD, EE, and EB. These triggers could be ready for a physics run in 1993, and possibly as early as 1992. Additional modifications
are required in the VME system and in the front-end electronics of several subdetectors. The total cost of upgrades for 8-bunch running is estimated to be 620 kSF (Table 5.4).

18-bunch scenario (4.93 μs between bunches)

The upgrade to 18 bunches requires that reset times be substantially reduced in FD, ME, PB, PE, and TT. The CJ and CZ chambers must be run in common-stop mode, requiring some modifications. Several subdetectors will require increased processing power to handle the higher rate.

The front-end system of ME must be redesigned, both to reduce the reset time (so that ME can be used as a detector), and also to provide a fast Level-1 trigger from ME (which will be needed for 36-bunch running). This is estimated to cost 1.4 MSF and to require 2.5 years lead time.

The total cost of all upgrades is estimated to be about 2.9 MSF (Table 5.4).

36-bunch scenario (2.46 μs between bunches)

When we go to 36 bunches, the Level-1 trigger timing becomes very tight. We will lose CJ, CV, and EE from the L1 trigger; only TB, EB, and ME will remain. EB and ME can only be used if the upgrades described above have been carried out. TB will require new upgrades to provide a signal in the 700 ns allowed (150 kSF). Processing will need to be improved at the Event Builder and Event Filter (200 kSF) to maintain adequate data flow.

Other modifications might be required, but need more study. EE might provide a Level-1 trigger with additional modifications (perhaps 500 kSF), and the CZ multiplexing system may need to be rebuilt (800 kSF) to reduce readout dead-time, depending on the event rate.

5.6 Conclusions

OPAL can set up a Level-1 trigger in a test mode using TB and CD before the 1991 run. Rates and efficiencies will be studied, and we expect to optimize these triggers during the 1991 run. New Level-1 ECAL triggers will be ready before the beginning of the 1992 run. We expect to be able to take 8-bunch data with a good Level-1 trigger during the 1992 run, at a cost of about 500 kSF.

The total cost of upgrading from 4 to 36 bunches is estimated to be about 6.3 MSF and to require at least three years lead time. Other possible modifications, mentioned in the text but perhaps not required, could add 1 MSF to this. Off-line upgrades, not included in this study, are likely to add another 1.5-2.0 MSF.

The total costs of upgrading to each of the three multibunch scenarios are summarized in Table 5.4. These are all preliminary estimates. Additional studies are required before we can be completely confident of being able to handle the timing constraints of the 36-bunch mode.
References


Table 5.1

OPAL times (μs) available for A: LSCs for send trigger signals; B: transit time from LSC to L1 trigger, plus L1 decision time, plus transit time for reset from L1 to LSCs; C: reset time of the LSC system.

![Diagram of time delays](image)

<table>
<thead>
<tr>
<th>Mode</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>BX (≥ A + B + C)</th>
<th>In L1 trig</th>
<th>Year ready</th>
</tr>
</thead>
<tbody>
<tr>
<td>8-b (test)</td>
<td>4.0</td>
<td>0.90</td>
<td>6.0</td>
<td>11.1</td>
<td>TB,CJ,CV</td>
<td>~1991</td>
</tr>
<tr>
<td>8-b</td>
<td>4.0</td>
<td>0.90</td>
<td>6.0</td>
<td>11.1</td>
<td>TB,CJ,CV,FD,EE,EB</td>
<td>~1992-3</td>
</tr>
<tr>
<td>18-b</td>
<td>3.0</td>
<td>0.90</td>
<td>1.0</td>
<td>4.93</td>
<td>TB,CJ,CV,EB,EE,FD,ME</td>
<td>~1994</td>
</tr>
<tr>
<td>36-b</td>
<td>0.70</td>
<td>0.90</td>
<td>0.85</td>
<td>2.46</td>
<td>TB,EB,ME (EE?)</td>
<td>≥1994</td>
</tr>
</tbody>
</table>

Table 5.2

The upgrades listed are required for OPAL to run with a Level-1 trigger in 8-bunch mode. The exact requirements of the Level-1 trigger will have to be studied during the 1990-91 running periods. More expensive upgrades may be required to produce the EE and EB Level-1 triggers (item 3 of Table 5.3).

<table>
<thead>
<tr>
<th>Required upgrade (8-bunch mode)</th>
<th>cost (kSF)</th>
<th>time required</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 L1 trigger processor</td>
<td>50</td>
<td>1 year</td>
</tr>
<tr>
<td>2 L1 and L2 trig inputs (FD,TB,CD)</td>
<td>140</td>
<td>1-2 years</td>
</tr>
<tr>
<td>3 FE electronics (CV,CZ,HT)</td>
<td>200</td>
<td>1-2 years</td>
</tr>
<tr>
<td>4 L1 trig for EE and EB</td>
<td>100</td>
<td>1-2 years</td>
</tr>
<tr>
<td>5 Data processing systems (VME)</td>
<td>130</td>
<td>1.5 years</td>
</tr>
<tr>
<td>Total</td>
<td>620</td>
<td>1-2 years</td>
</tr>
</tbody>
</table>

253
Table 5.3

The modifications in subdetector systems required to upgrade from 8 to 18 bunches

<table>
<thead>
<tr>
<th></th>
<th>Required upgrade (18-bunch mode)</th>
<th>cost (kSF)</th>
<th>time required</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Reduce reset time to μs (FD, TT, PE, ME)</td>
<td>1,350</td>
<td>1.2 years</td>
</tr>
<tr>
<td>2</td>
<td>Trigger upgrades (FD, ME)</td>
<td>790</td>
<td>2 years</td>
</tr>
<tr>
<td>3</td>
<td>Data processing systems (VME)</td>
<td>400</td>
<td>1.5 years</td>
</tr>
<tr>
<td>4</td>
<td>Other FE upgrades(FD, CJ, CV, HT)</td>
<td>330</td>
<td>1.2 years</td>
</tr>
<tr>
<td></td>
<td><strong>Total</strong></td>
<td><strong>2870 Msf</strong></td>
<td><strong>1993-4</strong></td>
</tr>
</tbody>
</table>

Table 5.4

Summary of OPAL upgrades required for each multibunch running mode. Costs are incremental for each level of luminosity, but times are cumulative

<table>
<thead>
<tr>
<th></th>
<th>8-bunch mode</th>
<th>18-bunch mode</th>
<th>36-bunch mode</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>cost(kSF)</td>
<td>years</td>
<td>cost(kSF)</td>
</tr>
<tr>
<td>Readout/reset</td>
<td>200</td>
<td>1.5</td>
<td>1680.</td>
</tr>
<tr>
<td>L1 Triggers</td>
<td>290</td>
<td>2.0</td>
<td>790.</td>
</tr>
<tr>
<td>VME, processing</td>
<td>130</td>
<td>1.5</td>
<td>400.</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>620</strong></td>
<td><strong>2.5</strong></td>
<td><strong>2870.</strong></td>
</tr>
</tbody>
</table>
6 PASS-1 EVENT PROCESSING

Assessments of computing facilities required for a first-pass event reconstruction in high-luminosity running have been made by each of the LEP experiments. Since there is general agreement and a common viewpoint between these, and since the uncertainties in estimates are common to all experiments, only a synopsis of these will be given here.

To cope with the high data rates expected, processing of events must be done in quasi-real time by each experiment, using a facility that has both the required CPU power and data transmission rates. From current experience, the full reconstruction of a Z event takes 30–45 s of CPU time in CERN units (= 4 Mips). Assuming a Z production rate of 4 events per second with 36 bunches, with an additional 30% from backgrounds, this requires in the neighbourhood of 200 CERN units of CPU in order to reconstruct all events in quasi-real time. A typical Z event record is 100–200 kbytes, so data flows of about 1.0–1.5 Mbytes/s should be expected.

A cost-effective way of providing both the CPU power and the needed data flow is with a farm of workstations. At present, the DEC DS3100 workstation has a CPU power of 3–4 CERN units, and an Apollo DN10000 has about 6 CERN units. Within a few years (1994) one can expect improved versions with 8–12 CERN units. A farm containing 16–20 CPUs of 10 CERN units each would be sufficient.

Clusters of 12 work stations are used currently by ALEPH and DELPHI. Since the data transmission within such an Ethernet-based cluster is currently limited to about 250 kbytes/s, one would need four such clusters, each with its own mainframe, peripherals, and I/O system, to provide the required data flow of 1 Mbyte/s. It is likely, however, that FDDI-based clusters will be available by 1994, providing the 1 Mbyte/s I/O bandwidth in a single cluster.

OPAL uses a farm of Apollo DN10000 processors for the Pass-1 event reconstruction. Events are transmitted directly from the DAQ system to the Apollos (or can be buffered to tape for later processing).

The total cost of each such farm is estimated to be in the range 1.0–1.5 MSF in 1994. The exact configuration of the farm will depend on the technology available and the preferences of the collaboration, but a solution of this general type seems to be favoured by all of the LEP experiments.

A more serious problem could be data-handling and access to the processed data. It is estimated that a single experiment could produce over 100,000 3840-cassette equivalents in a year of running at the highest luminosity. Even allowing for a significant increase in tape density (perhaps a factor of 5?) over the next few years, this is a large number of tapes.

There are two ways in which this quantity of data could be made more tractable. First, videotape technology, which will hold up to 100 Gbytes (a factor of 500 over 3840 cassettes), is becoming available. Over the next few years, one can expect this technology to develop and costs to become reasonable. Such tapes could be used for the mass storage of data.

Secondly, the experiments can write tapes consisting of DSTs only, or highly compressed data records, for general analysis use. Also, events will undoubtedly be classified and divided into different streams for different types of analysis. This might reduce the number of physics tapes used for most analysis work by a factor of a hundred or more.
In any case, there should be a significant upgrade in the CERN central computing facilities to efficiently handle new high-density tapes, to provide greatly increased disk storage, and to enhance central computing power. There will also need to be improvements in networking for the large number of workstations doing analysis, and high-speed links will need to be set up between the experiments and the central facility. These improvements in the CERN computing facility could cost the equivalent of 1.5–2.5 MSF per LEP experiment.

In summary, costs of Pass-1 analysis facilities are estimated to be in the range of 1.0–1.5 MSF per experiment. Additional costs to the CERN computing facilities (or perhaps alternatively to the individual experiments), which have not been studied in any depth for this report, are estimated to be an additional 2 MSF per experiment.
7 CONCLUSIONS

These conclusions represent the best estimates available from the LEP experiments at this time. Some questions still need to be answered with regard to running at the highest luminosities, and work on studying high-luminosity problems and required upgrades is continuing.

Running LEP with 8 bunches

- ALEPH needs to modify their ECAL reset procedure; a satisfactory solution which requires no hardware modification has been found.
- DELPHI foresees no significant problems in running with 8 bunches, and should be able to do so with minimal changes.
- L3 must modify the Level-1 trigger. The trigger ADC modifications require an estimated 500 kSF and a 3-month shutdown after 2 years lead time.
- OPAL must introduce a Level-1 trigger with new fast trigger inputs. A system suitable for tests of 8-bunch running can be ready in 1991-2, and physics data taking in this mode could begin in 1993. The total cost of all upgrades will be about 600 kSF.

Running with 18 bunches

- ALEPH will probably need to rebuild the front-end electronics for ECAL, requiring 2 MSF and 3 years. Significant improvements in the DAQ system also will be needed.
- DELPHI will need to modify their HCAL FE electronics (50 kSF). Upgrades to the trigger and processing (1 MSF) are advisable for 18 and essential for 36 bunches.
- L3 must redesign the BGO digitizer. Effects of higher noise and non-linearity must be studied. Muon trigger readout and encoders must be rebuilt. The TEC trigger will be lost; possible ways of building a fast charged-particle trigger are being considered.
- OPAL must fix reset problems and improve data flow. These changes require 2.5 years lead time and about 3 MSF. Additional ECAL trigger modifications may possibly be required.

Running with 36 bunches

- In addition to the modifications listed for 18 bunches, ALEPH will need to re-configure its Level-1 trigger. The total cost of the upgrade from 4 to 36 bunches would be between 4.5 and 6.5 MSF.
• DELPHI sees no intrinsic limitation, but needs to study trigger timing in much greater detail; this is considered to be the critical issue. Some FE electronics would have to be rebuilt, processing power will need to be upgraded, and more stringent timing tests must be performed for triggers and resets. Upgrades from 18 to 36 bunches are estimated in the neighbourhood of 2 MSF, bringing the total cost of upgrades to about 3 MSF.

• L3 will have to rebuild much of the trigger electronics. A big effort will be required to minimize the cable length and reset time. Timing considerations require more study. The concrete design of the BGO digitizer for 36 bunches is yet to be worked out. The trigger acceptance for certain classes of events may be reduced. It is estimated to cost 7.5 MSF and 3–4 years to upgrade from 8 to 36 bunches.

• OPAL will require major modifications to the EB and EE front-end electronics and to the EB trigger. The additional upgrades will cost 2.5 MSF and require 2 years lead time. The only Level-1 triggers will be TB, EB, and ME. Trigger timing must be studied more carefully. All of these bring the cost to upgrade from 4 to 36 bunches to a total of about 6.4 MSF.
APPENDICES

A: Measurement of $B_s^0 \rightarrow B_s^0$ oscillations using semileptonic decays, P. Roudeau

B: Measurement of $\Gamma_{b\bar{b}}$ and $A_{FB}$ with the DELPHI detector at pretzel LEP, E. Lieb, K. Mönig and S. Überschär

C: Conditions of observation of the $B_s^0$ oscillations in DELPHI and with higher luminosity at LEP, C. Defoix
APPENDIX A

MEASUREMENT OF $B_s^0$-$\bar{B}_s^0$ OSCILLATIONS USING SEMI-LEPTONIC DECAYS

P. Roudeau

Abstract

We show that LEP experiments have the capabilities to measure the particle-anti particle oscillations of $B_s^0$ mesons if a sufficient number of hadronic $Z^0$ decays are registered. The interest of this measurement, in the framework of the Standard Model, constitutes a large motivation to ask for a High Luminosity Collider operating at the $Z^0$ pole.

INTRODUCTION

We study in some details the measurement of $B_s^0$-$\bar{B}_s^0$ oscillations at LEP. More precisely we consider the evaluation of the $B$ energy, in case of semi-leptonic decays, the $B$ decay vertex reconstruction and the tagging of the particle-antiparticle nature of the $B$ meson. This work continues what has been already presented in [1] at Moriond in 1989. Studies on the same subject can be found also in [2-7].

WHAT GOVERNS THE OBSERVABILITY OF $B_s^0$-$\bar{B}_s^0$ OSCILLATIONS?

The mixing parameter $X_s = \frac{\Delta M}{1}$ is expected to be large for $B_s^0$ mesons ($X_s \sim \frac{X_d}{\sin^2 \theta_w}$) and the actual range of values favoured by the measurements is between 5 and 15 as can be seen in Fig. 1. In this domain, the measurement of the rate of same-sign dilepton production, which was efficient to measure $X_d$, is very insensitive to the exact value of $X_s$ and cannot be used to provide a meaningful value for this quantity. We have to use the proper time distributions of $B^0$ and $\bar{B}^0$ decays.

If we can prepare a pure $B_s^0$ state at $t=0$, this state will then evolve in time according to the following expression:

$$B_s^0(t) = e^{-t/r} \cos^2 \left( \frac{X_s t}{2r} \right)$$
where \( \tau \) is the \( B_s^0 \) lifetime

and a \( B_s^0 \) signal also appears which oscillates with an opposite phase:

\[
\overline{B_s^0}(t) = e^{-t/\tau} \sin^2\left(\frac{X_s t}{2\tau}\right)
\]

The oscillation period of the two signals is:

\[
T = \frac{2\pi}{X_s \tau}
\]

The amplitude of the oscillations is reduced because of the finite accuracy of the measurements and because of imperfections in the tagging method which consists in preparing a \( B \) or a \( \overline{B} \) state at \( t=0 \).

The first point defines the accessible \( X_s \) range. The decay proper time, \( t \), is measured with a given accuracy \( \sigma_t \) and the observed time evolution is a convolution of \( B_s^0(t) \) with a Gaussian distribution. It can be shown, analytically [1], that the main effect of this smearing is to decrease the amplitude of the oscillations by an amount \( \rho \) equal to:

\[
\rho = e^{-\frac{X_s^2}{4\sigma_t^2}} (\frac{\sigma_t}{\tau})^2 \tag{1}
\]

(The oscillation period is also modified, mainly for very short decay times, by a calculable amount:

\[
\frac{1}{T} = \frac{1}{T_0}(1 - \frac{\sigma_t^2}{\tau^2})
\]

We will not consider this effect because it does not really affect the observability of the oscillations.)

We see immediately from (1) that the amplitude of the oscillations is reduced to 10% of its initial value when:

\[
X_s \frac{\sigma_t}{\tau} \geq 2.1
\]

The accessible \( X_s \) domain is thus fixed by \( \frac{\sigma_t}{\tau} \) — and not by \( \frac{\sigma_t}{\tau} \) as said frequently — and, due to the Gaussian dependence of \( \rho \) on this quantity, the frontier of the domain is precisely defined.

The proper \( B_s^0 \) decay time is obtained from the knowledge of the distance \( L \) between the positions of the production and decay vertices and from the evaluation of the \( B_s^0 \) momentum, \( P \).

\[
ct = \frac{L}{P/M}
\]

Because of differences in production characteristics and also in experimental setups, these quantities are measured with different accuracies when working at an asymmetric \( B \) factory or at LEP. Thus, when doing the comparison of the possibilities of the two machines, these differences have to be taken into account.

**INTEREST OF SEMI-LEPTONIC DECAYS OF B MESONS**

Before going into the details of the measurements we would like to stress again the importance of using semi-leptonic decays of \( B \) particles to do these measurements.
The sign of the lepton electric charge gives the sign of the b quark.

The hadronic part of the final state is dominated by $D$ and $D^*$ mesons and this provides a nearly direct correspondance between the flavour of the decaying $B$ particle and the flavour of the produced charmed meson. In this respect, the identification of a $D_s^+$, ensures that we are dealing with $B_s^0$ decays [8].

The semi-leptonic branching ratio is large, when compared to other $B$ decay modes, of the order of 20%.

The final state is sufficiently simple so that, reconstructing only partially the $D_s^+$ meson, and using kinematical constraints we can measure the $B_s^0$ energy with enough accuracy for our purpose.

RECONSTRUCTION OF THE $B_s^0$ DECAY VERTEX

To reconstruct heavy flavour secondary vertices at LEP, the use of a microvertex detector is mandatory. In this study we have considered a Silicon vertex detector made of two concentric cylinders of 6.5 and 11 cm radius respectively. The extension of these detectors along the beam direction is such that tracks emitted with an angle greater than 45°, relative to the beam axis, are accepted. We assume that each cylindar provides the measurement of two coordinates on the track, with similar accuracies of the order of 5μ. The intrinsic accuracy of the detector is not really exploited, here, because most of the tracks having a momentum lower than 5 Gev, the effects of the multiple scattering, inside the material of the vacuum chamber and inside the Silicon, dominates the uncertainty on the track position in the vicinity of the $e^+e^-$ interaction point.

To be sure that the bulk of the $B$ decay products are situated in the acceptance of the vertex detector, we require that the event axis, defined, in this study, by the jet of highest energy makes an angle relative to the beam axis such that:

$$|\cos \theta_J| < .55$$

We also require that the two most energetic jets in the event make an angle which satisfies $\cos \theta_{JJ} \leq - .5$.

After these cuts we are left with about 30% of the initially produced hadronic events.

Reconstruction of the main vertex

We use only charged tracks situated inside the acceptance of the vertex detector. We keep only tracks with a momentum larger than 300 Mev. We do not use tracks which are rather energetic ($> 4$ Gev), if they belong to the two most energetic jets in the event. This is to eliminate, at the start, tracks which can come from the decay of heavy flavour particles. As we are mainly interested in semi-leptonic decays, identified leptons are not used in the primary vertex search. The knowledge of the beam spot size and position is used in this search. An iterative procedure, which consists in eliminating successively each track having the largest contribution to the vertex chisquare, is used until a reasonable value is obtained. In $\bar{b}b$ events a mean number of 7.5 tracks remain attached to this vertex.

The typical accuracies on the main vertex position are:

$$\sigma_L = 50\mu$$ in the direction of the jets
\[ \sigma_T = 30\mu \text{ in a direction perpendicular to the jets} \]
\[ \sigma_Z = 70\mu \text{ along the beam direction} \]

As we will see, these values are small when compared to the uncertainties affecting the measurement of the position of the \( B \) decay vertex.

**Reconstruction of the charm decay vertex:**

We consider charged particles with a momentum larger than 1 Gev, not attached to the main vertex, and emitted in the same hemisphere as the lepton candidate. Excluding the lepton track, we try to form a secondary vertex.

In Fig. 2 we show the \( D_s^+ \) decay length distributions when no additional track has been put at the vertex and the same distribution when a track from the primary vertex has been added. In view of these distributions, and to reduce the fraction of wrong associations, we have required a minimum \( D_s^+ \) decay length of 1.5 mm.

We have also studied the distribution of the number of tracks correctly attached to the reconstructed vertex. Some tracks, coming from the \( D_s^+ \), are lost because of the momentum cut (600 Mev) and also, in some cases, because the lepton track we are considering is not a direct lepton from the \( B \) decay but a false lepton or a lepton from a charm decay. If we keep only secondary vertices made with at least 3 charged tracks, this retains about 70\% of the events which have a \( B_s^0 \) and 40\% of the others. Consequently this cut has not been applied in the following.

If we identify \( K \) particles and if we keep only events with 0 or 2 charged kaons we can decrease by two the background coming from non-strange \( B \) decays with an efficiency of 89\% on the signal.

**Evaluation of the \( D_s^+ \) momentum:**

The \( D_s^+ \) energy is obtained in the following way.

We keep all the measured neutral energy which is situated inside a cone of half opening angle equal to 150 mrad, with axis given by the vectorial sum of the charged tracks attached already to the secondary vertex. This four-vector is added to the one corresponding to the charged tracks and their sum is rescaled by the ratio of the reconstructed and of the "mean" \( D_s^+ \) masses. The "mean" \( D_s^+ \) mass corresponds to a ponderated mean value of the \( D_s^+ \) and \( D_{s^*}^+ \) masses according to their relative production rates.

This procedure gives a resolution of 13\% on the \( D_s^+ \) energy if we keep only events having a reconstructed mass larger than 1 Gev before the rescaling.

The use of inclusive decay modes, instead of only the \( K K \pi \) final state allows us to gain about a factor 5 in statistics.

And now the \( B_s^0 \) decay vertex.

The \( B_s^0 \) decay vertex should be situated on the lepton track. We keep, as an estimate of the decay vertex position, the point on this track, which is at the closest distance from the reconstructed \( D_s^+ \) trajectory.

Fig. 3 gives the distribution of the difference between the real and the estimated vertex positions. The accuracy, determined from this distribution is 130\( \mu \) along the jet direction.
MEASUREMENT OF THE $B_s^0$ ENERGY

As the neutrino is escaping detection, to obtain a zero constraint kinematics, we still have to measure the $B_s^0$ direction and to assume that the $B_s^0$ mass is known.

The $B_s^0$ direction can be deduced from the secondary and primary vertex positions but this is not enough accurate when the decay occurs in the vicinity of the $e^+e^-$ interaction point. An other estimate consists simply in using the jet direction. Fig. 4 shows that we can achieve an accuracy better than 50 mrad on this quantity.

We obtain generally two solutions for the $B_s^0$ energy. In some cases one of the solutions is not physical, being much larger than the beam energy. An algorithm has to be defined which gives the best estimate of the $B_s^0$ energy, even when there is ambiguity, and we leave the freedom to the reader to invent his own. In Fig. 5 we show that an accuracy of about 10% on the $B_s^0$ energy can be achieved if we retain only events having a visible $B_s^0$ mass larger than 4 GeV.

This result depends on the peaking of the b-quark fragmentation function near the kinematical limit. In our simulation we have used a Peterson-like distribution with a parameter $\alpha_s = 0.008$. This value is presently favoured by the recent measurements at LEP [9] and corresponds to a mean value of 0.71 for the fraction of the beam energy taken by the $B$ particle. If we use, instead, the standard LUND fragmentation distribution our results will be improved.

EFFICIENCY BUDGET OF THE $B_s^0$ ENERGY RECONSTRUCTION

<table>
<thead>
<tr>
<th></th>
<th>cumulated efficiency (%)</th>
<th>efficiency for each step (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 jets relatively back to back</td>
<td>68</td>
<td>68</td>
</tr>
<tr>
<td>Vertex detector acceptance</td>
<td>32</td>
<td>47</td>
</tr>
<tr>
<td>Reconstruction of the main vertex</td>
<td>31</td>
<td>97</td>
</tr>
<tr>
<td>Lepton identified</td>
<td>25</td>
<td>80</td>
</tr>
<tr>
<td>Secondary vertex reconstructed including selection cuts</td>
<td>5</td>
<td>20</td>
</tr>
<tr>
<td>Energy reconstruction of the $B_s^0$</td>
<td>2.3</td>
<td>46</td>
</tr>
<tr>
<td>Efficiency for one produced $B_s^0$</td>
<td>0.43</td>
<td>20</td>
</tr>
<tr>
<td>Efficiency for one $b\bar{b}$ event</td>
<td>0.1</td>
<td>24</td>
</tr>
<tr>
<td>Efficiency for one hadronic $Z^0$ decay</td>
<td>0.022</td>
<td>22</td>
</tr>
</tbody>
</table>
If we apply the same selection to all the hadronic events produced at the $Z^0$ we keep essentially the events from the $b - \bar{b}$ component and with a similar efficiency. Thus, after this selection we have no enrichment in events containing a $B_s^0$.

**B Tagging and Enrichment in $B_s^0$**

Most of the tagging methods, proposed at LEP [1-6], consist in using the particles emitted in the opposite jet: leptons produced at large $P_t$, inclusive charm signals, electric charge measurement of the $B$.

A few years ago, A. Ali and F. Barreiro [10], have proposed to look for lepton-K-KK combinations (with appropriate selection on electric charges) in order to measure the rate of $B_s^0$ oscillations. This technique cannot provide an accurate measurement of $X_s$, if this parameter is larger than a few units for the reasons mentioned previously, but it can provide an enrichment in $B_s^0$ of the studied sample of events.

We have only searched for the charged Kaon, emitted at the primary vertex, which is the companion of the $B_s^0$. The sign of the electric charge of this Kaon determines the particle-antiparticle nature of the produced beauty meson.

A similar study has been done by the SLD group in ref. [11].

The basic idea is to identify the charged kaon which is the companion of the $B_s^0$ as shown in Fig. 6. Charged K can accompany also $B_d^0$ or $B^-$ particles (Fig. 7) but their presence is reduced by an amount which is proportional to the probability to produce a strange quark, instead of a u or a d quark, during the hadronization of the final state.

We thus expect, from this selection, an enrichment in $B_s^0$ mesons.

Furthermore the kinematical properties of the charged Kaons are different in the two situations (Fig. 8 and 9). The companion Kaon of the $B_s^0$ — call it the "Kmora" by analogy with the pilot fish attached to a shark — is produced by first generation of quark-antiquark strings and thus it has a tendency to be emitted in the same direction as the $B$ and with a not too low energy (Fig. 8). In the contrary the "Kmoras" of $B_d^0$ and $B^-$ have the opposite electric charge and, being produced more deeply inside the hadronization chain (Fig. 9), they are rather isotropic and of lower energy.

If we select only kaons with a momentum larger than 2 Gev, attached to the main vertex we obtain the following results:

<table>
<thead>
<tr>
<th></th>
<th>good sign K (%)</th>
<th>wrong sign K (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_s^0$</td>
<td>20</td>
<td>3</td>
</tr>
<tr>
<td>Background</td>
<td>5.4</td>
<td>9.4</td>
</tr>
</tbody>
</table>

This selection has two advantages:
- it is well competitive (and complementary) in terms of efficiency and purity when compared to the other proposed techniques.

- it provides an enrichment by a factor 2 to 4 in $B_s^0$, depending on the type of the $B - K$ particle-antiparticle correlation. The purity in $B_s^0$, $P$, is expected to be of the order of 20% and 14% for the $l^\pm K^{\mp}$ and for the $l^\pm K^\mp$ final states respectively. (These numbers have been obtained assuming that the mixing is complete for strange $B$ mesons.)

The precise angular and energy distributions of these Kaons depend on the hypothesis used for the fragmentation function.

VISIBILITY OF $B_s^0 - \bar{B}_s^0$ OSCILLATIONS

Using the previous results we can study the observability of $B_s^0 - \bar{B}_s^0$ oscillations at LEP, taking into account:

- the reduction of the oscillation amplitude coming from wrong flavour tagging and from the experimental resolution on the decay proper time.

- the expected ratio for the oscillating signal over the non oscillating background.

Reduction of the oscillation amplitude

As the $B_s^0(t)$ and $\bar{B}_s^0(t)$ signals oscillate with opposite phases, if we misidentify the particle-antiparticle nature of the $B$ meson at $t=0$, we do not only lose because of the efficiency of the tagging but we also kill an equal amount of the oscillating signal. The amplitude of the oscillations becomes:

$$A = A^0 \frac{N_{\text{good tag}} - N_{\text{bad tag}}}{N_{\text{good tag}} + N_{\text{bad tag}}}$$

$A = .74$ for the K tagging

The experimental resolution on the proper decay time introduces the additional reduction factor $\rho$ mentioned previously which depends on:

$$\left(\frac{\sigma_t}{\tau}\right)^2 = \left(\frac{\sigma_L}{L_0}\right)^2 + \left(\frac{\sigma_E}{E}\right)^2$$

The first term in this expression is fixed by the measurement accuracy on the $B_s^0$ decay vertex position.

The second term is related to the uncertainty on the $B_s^0$ energy reconstruction.

With the values for these parameters, obtained in this study, we get:

$$\left(\frac{\sigma_t}{\tau}\right)^2 = 4.4 \times 10^{-3} + 1.2 \times 10^{-2} \left(\frac{t}{\tau}\right)^2$$

At an asymmetric $B - \bar{B}$ factory, the $B$ energy is rather precisely known and, because of the smaller decay length of the $B$ particles the first term dominates [6]:

$$\frac{\sigma_t}{\tau} = \frac{\sigma_L}{L_0} \sim .20 - .40$$

(The range of these values is determined by the amplitude of the boost given to the $B$ particles.)
In Fig. 10 we have plotted the damping factor $\rho$ for various choices of the $X_s$ parameter.

Contrary to $B$ factories which, by construction, are limited, LEP has the potentialities to access a domain of large $X_s$ values if we are able to measure the oscillations at small decay proper times:

$$\frac{t}{\tau} < 1.5 - 2$$

The strategy, we have developed, to reconstruct the $B$ decay vertex and to tag the $B$ flavour has been designed to provide a good efficiency for small decay lengths. This is illustrated on Fig. 11.

Determination of the accessible domain in $X_s$ for different registered statistics of $Z^0$ decays.

For a detailed determination of the oscillation period of $B$ signals, using a Fourier analysis of the time distributions we refer the reader to reference [2].

In the following we consider a very simple model which allows us to determine easily the influence of the various parameters entering into that game. We consider first that the oscillations can be seen within a time interval inside which $\rho$ does not decrease by more than one half of its starting value. Because of the exponential dependence of the decay time distribution this reduces the total number of events which can be used to do this measurement. We consider also that one period of oscillation behaves like a Gaussian distribution having $\sigma = \frac{T}{4}$.

The oscillating signal, containing $N_s$ events, is situated above a smooth background and we have in total $N_T$ events. The accuracy with which we measure the oscillation period is of the order of:

$$\sigma_T \approx \frac{T}{2\sqrt{2}} \frac{\sqrt{N_T}}{N_S}$$

The total number of $B_s^0$ is $N_S^0$, among which only $N_S$ oscillate:

$$N_S = N_S^0 A \rho$$

If we call $P$ the purity of the sample in $B_s^0$ mesons:

$$N_T = N_S^0/P$$

and we obtain:

$$N_S^0 = \left(\frac{X_s}{\sigma_{X_s}}\right)^2 \frac{1}{8 P \rho^2 A^2}$$

To verify that this relation is meaningful we have used the conditions expected for $P$, $\rho$ and $A$ in ref. [2] and deduced the accuracy $\sigma_{X_s}$ with which we should observe the oscillations. The results are shown in Fig. 12 and the agreement appears to be satisfactory. This simple model cannot, of course, reproduce the non-Gaussian tails which are observed when we use the complete fitting procedure.

If we call $\epsilon$ the efficiency to reconstruct and to tag a $B_s^0$ candidate we can evaluate the total number of hadronic $Z^0$ decays $N_{Z^0} = \frac{N_S^0}{\epsilon}$ needed to observe the $B_s^0$ oscillations with a given accuracy.
Using the parameters determined in this study we obtain for $\frac{\sigma_{X^*}}{X^*} = .1$:

<table>
<thead>
<tr>
<th>$X_s$</th>
<th>5</th>
<th>10</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_Z$ ($10^6$ evts)</td>
<td>5</td>
<td>13</td>
<td>55</td>
</tr>
</tbody>
</table>

With 10 million of $Z^0$ decays we can measure with a reasonable accuracy the $B^0_s$ oscillations up to $X_s$ values of about 10. If we want to do a very accurate measurement of this quantity and for instance if we take the conditions of ref [1] – $\sigma_{X_s} = 0.25$ for $X_s = 10$ we need 16 times more statistics and we find a similar number of $Z^0$ as the one quoted in [1].

We should note also that, to be sensitive to the presence of $B^0_s$ oscillations ($\frac{\sigma_{X^*}}{X^*} \sim .2$) a few million of hadronic $Z^0$ decays can be sufficient.

CONCLUSIONS

With 10 million of hadronic $Z^0$ decays, at LEP, we can explore the domain of $B^0_s$ oscillations up to $X_s = \frac{\Delta M}{1}$ values of the order of 15 and do a measurement with a 10% accuracy up to $X_s \sim 10$.

With a statistics 10 times larger, a frontier situated around $X_s = 20$ can be reached or, of course, a precise measurement can be done if $X_s$ has been found to be lower.

The crucial parameters which determined the ability of a given experiment to observe these oscillations are:

- the quality of the particle-antiparticle tagging
- the experimental measurement accuracy of the proper decay time

This last parameter determines really the accessible $X_s$ range. Its effects cannot be compensated by an increase of the registered statistics, because of the very steep dependence of the smoothing of the oscillations on this quantity, for $X_s$ values above a threshold which is entirely determined by the experimental accuracy on the proper time measurement.

In this respect LEP is in a much better situation than an asymmetric $B - \overline{B}$ factory for $X_s$ values greater than 5.
AKNOWLEDGEMENTS
I thank C. Defoix, D. Treille and G. Wormser for helpful and stimulating
discussions.

REFERENCES
[8] E. Golowich et al., *LPTHE Orsay, 89/36*
[9] *Measurement of Z0 → b – b̅ decay properties, L3 Preprint #6*

FIGURE CAPTIONS

Fig. 1. Allowed domain for $X_s$ and $\delta$ in the Standard Model. The limits are given by:
- the recent measurement of $|V_{ts}|$ (full curves)
- the measurement of $X_d$ and its interpretation by considering different hypotheses for the top quark mass (dashed curves). These curves have been extracted from [12].
Values of $\cos \delta$ very close to $\pm 1$ are also excluded by the measurement of $\epsilon_K$. 270
Fig. 2. \( D_s \) decay lengths distributions.
- Full line: at least one charged track from the primary vertex is attached to the secondary decay vertex.
- Dashed line: no track from the primary vertex is attached to the secondary vertex.

Fig. 3. Distribution of the differences between the real and the reconstructed positions of the \( B^0_s \) decay vertex along the \( B^0_s \) direction.

Fig. 4. Distribution of the differences between the real \( B^0_s \) direction and the jet direction.

Fig. 5. Distribution of the differences between the real \( B^0_s \) energy and the reconstructed energy, normalized to the real energy.

Fig. 6. Correlations between the \( B^0_s \) meson and the spectator Kaons.

Fig. 7. Correlations between the \( B^- \) and the \( B^0_d \) with spectator Kaons.

Fig. 8. Correlations between the momentum and the direction of the charged Kaons produced, at the primary vertex, in association with a \( B^0_s \). The direction is measured relative to the jet axis. The histograms are the projections of the scatter plots. The discontinuity which appears at 4 GeV/c comes from the algorithm used to search for the main vertex of the event:
(a) \( B^0_s K^- \) and \( B^0_s K^+ \) events
(b) \( B^0_s K^+ \) and \( B^0_s K^- \) events

Fig. 9. Same distributions as in Fig. 8. for hadronic \( Z^0 \) decays compatible with a \( B \) semi-leptonic decay and excluding events containing a \( B^0_s \):
(a) \( \bar{B}K^- \) and \( BK^+ \) events
(b) \( \bar{B}K^+ \) and \( BK^- \) events

Fig. 10. Damping factor of the \( B^0_s \) oscillations due to the experimental resolution on the decay proper time.

Fig. 11. Influence of the cuts imposed to reconstruct the \( B^0_s \) energy and the decay vertex position on the acceptance at small decay proper times.
(a) after main vertex reconstruction.
(b) after secondary vertex reconstruction and lepton identification
(c) after Kaon tagging.
(d) is (c) divided by (a).

Fig. 12. Comparison between the results obtained by Fourier analysis (Ref. [2]) and our simple model.
Fig. 4

Fig. 5

$\mathcal{G} = .11$
The "Kmora" is a $K^-$
The second generation Kaon is a $K^+$

An exception, the "Kmora"
can be a $K^+$ in this case.

Fig. 6

The "Kmora" is a $K^+$
The second generation Kaon is a $K^-$

Fig. 7
Fig. 12
APPENDIX B

Measurement of $\Gamma_{b\bar{b}}$ and $A_{FB}^{b}$ with the DELPHI detector at Pretzel-LEP

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Fachbereich 8 Naturwissenschaften I

September 10, 1990

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4. Conclusions 9

1. Introduction

The Pretzel sheme has been proposed [1] to provide a high luminosity measurement at LEP. In this environment one will be able to produce of the order $10^{9}$ $Z^{0}$'s and maybe more. According to this number a very precise determination of several quantities will be possible. It allows us to use technics which are at our present situation out of reach.

On the heavy flavor sector a great promise is the measurement of the partial width of b-quarks $\Gamma_{b\bar{b}}$. This quantity is particular interesting due to sizeable vertex corrections from the top-quark [2]. Despite from this the determination of the forward-backward asymmetry of b-quarks gives also a precision test at Pretzel LEP, although it is mainly a measure of the initial state coupling. A detailed qualitative analysis of expected effects can be found in reference [3]. It will be shown that the evaluation of double tagged events is the most insensitive method to systematical errors and thus gives reliable results. To get an estimation of the expected statistical and systematical errors for the partial width and the forward-backward asymmetry, we have done some studies with the DELPHI fast simulation program and compared the obtained results with the expectation from pure event generation of the LUND Montecarlo.
2. Tagging of b-quark events with the DELPHI detector

A very high integrated luminosity will allow to apply in addition to single arm tagging also double arm tagging. This means that we divide an event into two hemispheres according to the plane perpendicular to the thrust axis and try to tag a b- (or \( \bar{b} \)-) quark separate in each hemisphere. The number of single tagged jets and double tagged events depending on the single tag efficiency \( \varepsilon_{1T} \) is obtained as follows:

\[
\begin{align*}
N_{1T} &= 2 \cdot \varepsilon_{1T} N_{b\bar{b}} \\
N_{2T} &= \varepsilon_{2T} N_{b\bar{b}}
\end{align*}
\]

with
\( \varepsilon_{1T} \) – single tag efficiency for one jet
\( \varepsilon_{2T} \) – double tag efficiency for one event (\( = \varepsilon_{1T}^2 \))
\( N_{b\bar{b}} \) – total number of b – quark events

The partial width can be expressed through the ratio of these two values:

\[
\Gamma_{b\bar{b}} = \frac{N_{1T}^2 \cdot \Gamma_{had}}{4 \cdot N_{2T} \cdot N_{had}}
\]

with \( N_{had} \) – total number of hadronic \( Z^0 \)'s

Note that the result does not depend on the b-quark tagging efficiency.

The measurement of \( \Gamma_{b\bar{b}} \) makes it necessary to separate b-quarks from light-quarks (u, d, s and c) with relativ high efficiency to allow double tag selection. For this purpose we use a multidimensional procedure, so called 'Fisher discriminant analysis' [5], to discriminate between the two groups of quarks. Only variables which are related to one hemisphere of the event are suited for double tag selection method. The variables we make use of are:

- \( p_{lT} \) - transverse lepton momentum with respect to the thrust axis
- \( p_{l,K} \) - \( \sqrt{p(l^+) \cdot p(K^\pm)} \) geometric mean momentum of same sign lepton-kaon pairs
- \( \theta_{l,K} \) - angle between lepton and kaon
- \( E_{lep} \) - leptonic energy
- \( E_{cha} \) - charged energy
- \( E_{had} \) - hadronic energy
- \( E_{str} \) - energy of identified \( K^\pm, K^0_L, K^0_S \)
- \( M_{inv} \) - invariant jet mass
- \( \sum p_\perp \) - sum over \( p_\perp \) for all particles
- \( \sum p_{\perp \text{had}} \) - sum over \( p_\perp \) for hadrons
- \( \langle Q \rangle \) - weighted mean jet charge
Table 1:  
Single arm efficiency and background including detector simulation for different cutvalues of the Fisher function

<table>
<thead>
<tr>
<th>$F_C$</th>
<th>$\epsilon_{12}^{\text{def}}$ [%]</th>
<th>background [%]</th>
<th>absolut</th>
<th>relativ</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>all</td>
<td>u</td>
</tr>
<tr>
<td>-0.5</td>
<td>13.5</td>
<td></td>
<td>23.3</td>
<td>9.</td>
</tr>
<tr>
<td>0.0</td>
<td>7.2</td>
<td></td>
<td>15.2</td>
<td>8.</td>
</tr>
<tr>
<td>0.3</td>
<td>4.3</td>
<td></td>
<td>11.9</td>
<td>8.</td>
</tr>
<tr>
<td>0.5</td>
<td>3.1</td>
<td></td>
<td>10.9</td>
<td>9.</td>
</tr>
<tr>
<td>1.0</td>
<td>1.3</td>
<td></td>
<td>9.7</td>
<td>8.</td>
</tr>
</tbody>
</table>

More information about the variables and the used method can be found in references [6], [7] and [8].

For the first part of this study 200,000 Monte Carlo events with the DELPHI FAST SIMulation program [4] and the LUND 6.3 parton shower model are generated. To optimize the weights in the Fisher analysis we have pre-selected events with $E_{\text{lept}} > 0.5 \text{GeV/c}$. This ensures us to obtain two classes with approximately the same number of events. Afterwards we chose a subsample of 3 variables out of the total sample of 12 variables in such a way that we minimize the distance between the two classes. Using all 12 variables gives only a slightly better result, because some of the variables are strongly correlated. However with all variables the statistical fluctuations for the coefficients are larger. As a result of our analysis we found that the following linear combination gives the best discrimination between the two groups of quarks:

$$F_D = -0.80 + 0.38 \cdot p_{\perp l} + 0.13 \cdot p_{t,K} - 0.06 \cdot E_{\text{had}}$$

The distribution of the Fisher variable for signal and background is shown in figure 1. The constant factor has been introduced to centre the total distribution around zero. The distributions of the selected variables can be found in figure 3. Having a look at the chosen variables, it is obvious that high energetic leptons play the most important role in this analysis. On the other hand identification of kaons with the RICH gives an improvement on the result by using the quantity $p_{t,K}$.

Depending on the cutvalue $F_C$ in the Fisher distribution we will achieve the results for single tag efficiency and background values shown in table 1.

Variables linked with the DELPHI micro vertex detector are not yet considered, but with the additional information from the VD the detection of secondary vertices from B and D mesons is possible. This reduces the dominant background from c-quarks and can therefore also improve the efficiency.

It is important to study the influences of the detector (e.g. $\mu$'s from secondary $\pi/K$ decays, hadronic punch through in the muon chambers, misidentified kaons) on the result. For this purpose the same kind of analysis has been done without detector simulation with 480,000 events generated with the LUND 6.3 parton shower model. In this case the resulting Fisher function is:

$$F_D = -1.6 + 0.43 \cdot p_{\perp l} + 0.14 \cdot p_{t,K} - 0.06 \cdot E_{\text{had}}$$

281
Table 2: Single arm efficiency and background without detector simulation for different cut values of the Fisher function

The variables which give the best discrimination are the same as in the case with detector simulation, only their weights are slightly different. The corresponding distributions for the Fisher variable and the selected event variables are shown in figures 2, 4. The results on efficiency and background are summarized in table 2.

3. Analysis of expected statistical and systematical errors

3.1 Partial width $\Gamma_{bb}$

The branching ratio can be determined from

$$\frac{\Gamma_{bb}}{\Gamma_{had}} = \frac{N_{bb}}{N_{had}} \quad \text{with} \quad N_{bb} \approx \frac{N_{1T}^2}{4 \cdot N_{2T}} \cdot \left( 1 - 2b_{1T} \right) \left( 1 - b_{2T} \right)$$

$N_{1T}$ is the number of single tagged jets

$N_{2T}$ double tagged events

$b_{1T}$ is the background value for single tagged jets

$b_{2T}$ double tagged events

with $b_{2T} \sim \mathcal{O}(b_{1T}^2)$

The above formula for the branching ratio has the advantage that two poorly known quantities, the semileptonic branching ratio in $bb$ events and the efficiency of the used tagging method, actually do not appear.

Assuming $10^8 Z's$ the statistical error turns out to be:

$$\frac{\Delta \Gamma_{bb}}{\Gamma_{bb}} \approx 0.43\% \cdot \sqrt{\frac{10^8}{N_Z}} \quad \varepsilon_{1T} = 5\%$$

" $\approx 0.71\% \cdot \sqrt{\frac{10^8}{N_Z}} \quad \varepsilon_{1T} = 3\%$

" $\approx 2.13\% \cdot \sqrt{\frac{10^8}{N_Z}} \quad \varepsilon_{1T} = 1\%$

The statistical error is mostly dominated by the error of the double tag selection.

The systematical error of the branching ratio depends on the accuracy of the background determination.

$$\frac{\Delta \Gamma_{bb}}{\Gamma_{bb}} \approx \left( \frac{4}{(1 - 2b_{1T})^2} \Delta^2 b_{1T} + \frac{1}{(1 - b_{2T})^2} \Delta^2 b_{2T} \right)^{1/2}$$
The relativ contributions of the errors of single and double tagging background can be seen in figure 5. The single tag background is much more important than the double tag background error. For the calculation of the systematical error we take values of $\varepsilon_{1T} = 5\%$ and $b_{1T} = 13\%$ for efficiency and background. Then we can achieve a value of $\frac{\Delta \Gamma_{bb}}{\Gamma_{bb}} \simeq 1\%$, under the assumption that the relativ errors are known at the order of $2\%$ for $\Delta b_{1T}/b_{1T}$ and $10\%$ for $\Delta b_{2T}/b_{2T}$. Comparing the results without and with detector simulation one sees that the relative background rate from light quarks increases from around $17\%$ up to around $35\%$. So it is important to determine the punch through of hadrons exactly. This can be done by reconstructing the neutral decay vertex $K^0_S \rightarrow \pi^+ \pi^-$ and analysing the decay particles. The momentum spectrum of pions originating from $K^0_S$ is very similar to the spectrum for all $\pi$'s, because $\pi$-mesons are normally produced at a late state in the $q \bar{q}$ fragmentation into hadrons or from decays of short living resonances. With FAST SIMulation the expected number of punch through particles from this decay mode, which are identified as a muon, is found to be:

$$N_P \simeq 60 000 \cdot \frac{N_Z}{10^8}$$

This leads to a statistical error for this measurement of:

$$\frac{\Delta N_P}{N_P} \simeq 0.41\% \cdot \sqrt{\frac{10^8}{N_Z}}$$

The experimental determination of charm background through the reconstruction of $D$- and $D^*$-mesons using the micro vertex detector seems to be possible but needs further investigation, because in this kind of analysis the most important background is due to $b$-quarks.

### 3.2 Forward-backward asymmetry $A_{FB}^b$

Providing high statistics a precise value of the forward-backward asymmetry $A_{FB}^{SM}$ for bottom quarks can be obtained in two different ways, using either single or double tag method.

As the composition of the background is dominated by anti-charm quark events, the measured quantity in the single tag case can be written as follows:

$$A_{FB}^{meas} = (1 - b_{1T}) (1 - 2 \chi_{eff}) A_{FB}^{b,SM} - b_{1T} A_{FB}^{c,SM}$$

The effective mixing parameter $\chi_{eff}$ can be obtained by measuring the ratio $R$ of like-sign to unlike-sign double tagged events:

$$\chi_{eff} = \frac{1}{2} (1 - \sqrt{1 - 2R}) \quad \text{and} \quad R = \frac{N^{++} + N^{--}}{N_{total}}$$

The reduction due to the factor $\chi_{eff}$ is based on two different causes; the mixing in
the $B_s^0$ and $B_s^-$ system and on the other hand the contribution from the decay $b \rightarrow c \rightarrow l$, which also increases the ratio $R$.

The numbers given in table 3 lead to a single tag efficiency of $\varepsilon_{1T} = 5.6\%$, primary charm background of $b_{1T} \approx 7\%$ and b-cascade contribution of $p_{casc}^b \approx 5\%$. Using double tag and assuming

$$\chi_{eff} = \chi_{ds} + p_{casc}^b = 0.14 + 0.05 = 0.19$$

one obtains a statistical error of the effective mixing parameter of less than 1\% (for $10^8 Z^0$'s), which translates to $\Delta A_{FB}^{b,SM} \approx 0.0012$. This results in a total uncertainty of

$$\Delta A_{FB}^{b,SM} \approx 0.002$$

As this value is dominated by statistics and mixing, the error of the background needs only to be understood to $\Delta b_{1T}/b_{1T} \approx 5\%$. Recent calculations of QCD corrections to $A_{FB}^{b,SM}$ [9] give effects of the order of $\delta A_{FB}^{QCD} \approx 0.3 \cdot \frac{g^2}{s} A_{FB}^{b,SM}$, where the error should be negligible compared to the other ones.

In case of double tagging the above written formula becomes slightly different:

$$A_{FB}^{meas} = (1 - b_{2T}^c)(1 - 2\chi_{eff}) A_{FB}^{b,SM} - b_{2T} c A_{FB}^{c,SM}$$

The influence of the effective mixing and the charm background $(b_{2T}^c \leq (b_{1T})^2)$ is now negligible. The absolute value for the statistical error of the forward-backward asymmetry, which is totally dominant, turns out to be:

$$\Delta A_{FB}^{b,SM} \approx 0.004 \cdot \frac{10^8}{N_Z}$$

including a double tag efficiency of $\varepsilon_{2T} = \varepsilon_{1T}^2 = (5.6\%)^2$. For more the $10^8 Z^0$'s this error will decrease steadily, whereas the error of the single tag method has it’s limit in the value quoted above.

### 4. Conclusions

The measurement of $\Gamma_{bg}$ at Pretzel LEP with double tagging will improve the result from LEP I, which will be of the order of 10\%. With a single tag efficiency of $\varepsilon_{1T} = 5\%$ the statistical error is below 0.5\%. A systematical error of 1\% seems to
reachable with a minimum of $10^8 Z^0$'s, but requires a precise background analysis and a well known detector.

For the error of the asymmetry for bottom quarks a value of $\Delta A_{FB}^{b,SM} \approx 0.002$ can be achieved with single tagged events, provided that systematics are kept under control. Again using double tagging a total error of $\Delta A_{FB}^{b,SM} \approx 0.004$ can be achieved without major uncertainties in the background and in mixing effects. Similar results results have been obtained in a study of the OPAL collaboration [10].

References

[1] C.Rubbia: *The future in high energy physics*
CERN-EP/88-130

$\Delta r$, or the relation between the electroweak couplings
and the weak vector boson masses
CERN 89-08 Vol.1 page 55

[3] W.F.L.Hollik:
*Radiative corrections in the standard model ...*
DESY 88-188

*FAST SIMulation for DELPHI*
DELPHI 87-27 Prog 72 Rev., User manual DELPHI 87-26 Prog 71

[5] P.A.Lachenbruch:
*Discriminant analysis*
Hafner Press 1975
W.W.Cooley, P.R.Lohnes:
*Multivariate data analysis*
John Wiley& Sons, Inc. 1971

[6] D.Delikaris, P.Lutz:
*Fisher discriminant analysis for heavy quark production, a contribution
to the "New Quarks and Leptons" LEP 200 working group*
DELPHI 87-3 Phys-15

*Forward-Backward Asymmetries*
CERN 88-06 Vol.1 page 317

[8] S.Überschär:
*Studien zur Quark Identifikation mit dem DELPHI Detektor*
Diploma thesis WU B 89-4

*Heavy flavors at LEP*
MPI-PAE/PTh 49/89
Figure 1: Fisher function (analysis including detector FAST SIMulation)

Figure 2: Fisher function (analysis with LUND P.S.)
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APPENDIX C

Conditions of observation of $B_s^0$ oscillations in DELPHI
and with higher luminosity at LEP\textsuperscript{1}

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Abstract: The possibility of observing the time evolution of $B_s^0 - \bar{B}_s^0$ oscillations and of measuring their characteristics at LEP, in the context of DELPHI, is studied. We show that high luminosity allows us to achieve such a challenge in a range of $\Delta m/\Gamma$ values reaching 18. Both hadronic and semileptonic decays of the $B_s^0$ are taken into account.

Résumé: Nous analysons la possibilité d'observer les oscillations $B_s^0 - \bar{B}_s^0$, développées en temps, et de mesurer leurs caractéristiques dans le contexte de DELPHI, à LEP. Il est montré que ceci est possible pour des luminosités élevées du collisionneur, jusqu'à des valeurs de $\Delta m/\Gamma$ atteignant 18. Les désintégrations hadroniques et semi-leptoniques du $B_s^0$ sont toutes deux prises en compte.

Keywords: Beauty particles, oscillations, colliding beams, electron, luminosity.

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1 Introduction:

Direct evidence for $B_s^0$ oscillations, together with determination of their characteristics is a real challenge. Knowledge of an important piece of the Cabibbo-Kobayashi-Maskawa sector and a test of the Standard Model (S.M.) with three families of quarks are inferred from a successful analysis of this topic.

As is well known, the results of Argus, CLEO, MARK II, UA1 ... concerning $B_d^0$ oscillation features when added to the unitarity of the C.K.M. matrix in the S.M. context with three families, lead us to expect the frequency parameter of $B_s^0$ oscillations:

$$x_s = \frac{2\pi \tau_s}{T_s},$$

in the range:

$$x_s \geq 3,$$

that is:

$$T_s \leq 3 \text{ picoseconds}$$

where $T_s$ is the corresponding period of oscillation in the $B_s$ referential.

Therefore, we have to foresee the observation of sinusoidal oscillations having a period of some $10^{-13}$ second. This observation needs:

- an experimental resolution on the $B_s^0$ decay proper time, $t$, of $\sim 0.1$ to $0.15$ picosecond.
- a sufficient number per bin of $\sim 0.15$ picosecond width, of $B_s^0$ in a well defined state of oscillation.

In the framework of LEP, and particularly of DELPHI, these conditions require:

α) a performant microvertex detector.
β) and a good performance of the off-line analysis of the $B\bar{B}$ system.
γ) and a high luminosity.

The first requirement is to provide sufficiently accurate data, in order to reconstruct the successive vertices observed in $B_s^0$ production and decay, and to minimize the wrong track-vertex assignments at the event reconstruction stage. Consequently, the proportion of successful determinations of $B_d^0$ and $\bar{B}_s^0$ states, as well as the accuracy on the $B$ decay length, $d$, are increased.

Beyond the pattern recognition ability and the precision on $t$, the second requirement leads us to optimize, for each event, the determination of the $B$ momentum, from which $t$ is defined according to the relationship:

$$t = \frac{M_B d}{c \rho_B} \quad (1) \quad \text{(where } M_B \text{ is the } B \text{ mass}).$$
Among the means we have, classically, to estimate \( p_B \), the \( B \) fragmentation function can be considered as model dependent and/or leading to too large uncertainties: the Lund generator used to simulate the DELPHI events gives a precision (Fig. 1): 

\[
\frac{\sigma_{PB}}{p_B} \simeq^{+25\%}_{-16\%}
\]

In other respects, the usual kinematical fit method provides the needed accuracy (a few percent) but only the constrained events are concerned: the final number of useful events remains too small, as already concluded in many reports (ref. [1]).

The present paper aims to show that, on the basis of the upgraded microvertex detector foreseen for DELPHI and of an efficient \( p_B \) (or \( t \)) estimator, specially developed for the \( B \) analysis, a higher luminosity of LEP should allow the observation of \( B^0 \) time oscillations. Then, the corresponding explored values of \( z \), go from 1 to \( \sim 20 \).

In the following paragraph, conditions are briefly described that allow us to obtain the necessary accuracy on \( t \): the layout and the basic expected performances of the so-called version 1.5 of the future microvertex detector and the \( B \) momentum determination method.

Paragraph 3 presents the way to select \( B^0_s \) and \( \bar{B}^0_s \) mesons, and two different methods used to tag their oscillation states.

The various causes of event loss, plus the way to account for wrong taggings and the background due to the \( B_u \) and \( B_d \) mesons are discussed in paragraph 4.

The results and their luminosity dependence are discussed in paragraph 5, and we conclude in paragraph 6.

2 B decay proper time estimation:

According to formula (1), the global error on the proper time estimation can be considered as resulting from the quadratic addition of two components:

\[
\left( \frac{\sigma_t}{t} \right)^2 = \left( \frac{\sigma_d}{d} \right)^2 + \left( \frac{\sigma_{PB}}{p_B} \right)^2 \quad (1')
\]

\( \frac{\sigma_d}{d} \) depends on the performances of the central detector and critically of the microvertex detector. \( \frac{\sigma_{PB}}{p_B} \) depends also on the method used to estimate \( p_B \), for each event.

2.1 The upgraded version of the microvertex detector:

Two cylindrical devices are set up respectively at \( R_1 = 6.5 \text{ cm} \) and \( R_2 = 11 \text{ cm} \) from the beam pipe axis. Each device is composed of two layers of crossed silicon strips (so that the \( Z \) coordinate is detected) and is equivalent to \( \sim 0.5\% \) of a radiation length. 1 \% of R.L. is assumed for the beam tube at \( R_0 = 6 \text{ cm} \). The microvertex detector resolution in the X Y plane, orthogonal to the beam axis, is \( 10\mu m \). The precision on the \( Z \) measure decreases from \( 15 \mu m \) at \( \theta = 90^\circ \) (i.e. in the directions parallel with the X Y plane) to \( 45 \mu m \) at \( \theta = 45^\circ \) (angular limits of this detector).
From these features, one expects a mean precision of 70 \( \mu m \) for the B production vertex (or main vertex, M.V.) position and of 160 \( \mu m \) for the vertex longitudinal position of the B decaying at least into three charged particles, successfully reconstructed in the central detector. Thus, a precision of \( \sim 180 \mu m \) is deduced for the B decay length, the average value of which is \( \sim 2.5 \) mm. The mean accuracy on the D vertex is similar (three charged particles also required), and the one on the BD distance reaches 230 \( \mu m \).

2.2 The \( p_B \) or \( t \) estimation:

As already said, it is not possible to obtain a large number of events using the usual kinematical fit method. Constrained and unconstrained hypotheses are treated according to the same process and are no longer dissociated for the same event. The method used in the present work is developed and explained in detail in Ref. [2]. In short, it tries to use the maximum information contained in the tracking results and the particle identification, and it relies on (Fig. 2):

- the vertex position measurement.
- the total values of the measured energy-momentum quadrivectors \( \vec{q}_{Bm} \) and \( \vec{q}_{Dm} \), respectively at the B and D vertices. Presently, only charged particles are considered. For the moment the decay \( K^0_s \rightarrow \pi^+\pi^- \) is ignored, as is the energy released in the calorimeters by the neutrals.
- the identification of the charged particles in question with the help of the RICH, TPC, e.m. and hadronic calorimeters and the muon chambers.

For a given event, the probability of observing \( q_{Bm}^i \) and \( q_{Dm}^i \) given \( p_B \), is calculated for each hypothesis \( i \) compatible with the physical region that the \( \vec{q}_{Bm} \) and \( \vec{q}_{Dm} \) values allow. This probability is built from the product of the branching ratio \( \gamma_i \) by the \( p_B \) dependent phase space weight corresponding to final state \( i \), both factors having to be correctly normalized. Then the principle of probability inversion is applied to deduce the probability distribution of \( p_B \), given the measured values of \( \vec{q}_B \) and \( \vec{q}_D \). That is:

\[
f_i(p_B) = \text{Prob} \left( p_B / (\vec{q}_{Bm}, \vec{q}_{Dm}) \right)
\]

The relative normalisation is included in the \( f_i \) functions so that the total distribution of \( p_B \) results from the sum over all the possible hypotheses:

\[
F(p_B) = \sum_i f_i(p_B)
\]

2.2.1 Case of the hadronic modes: \( B_s^0 \rightarrow \text{hadrons} + D_s \) (or \( D_s^* \)):

The probability distribution of \( t \) is directly deduced from (2):

\[
G(t) = \int F(p_B) \delta \left( t - \frac{M_B d}{c p_B} \right) dp_B
\]
The final states with 3 to 7 charged and 0 to 6 neutral particles can be taken into account at each vertex. In the simulation, the input data are smeared according to the multiple scattering in matter and the accuracies provided by the various detectors.

The "true" value of \( t \), some typical normalized distributions of \( \frac{t - \bar{t}}{t} \), for different \( B_s^0 \) hadronic decays, are shown in Fig. 3. The goodness of the \( t \) estimation can rely on the variance \( \sigma_t^2 \) of these \( t \) distributions: clearly, the event corresponding to the distribution of the figure 3c involves a large error on \( t \) and has to be eliminated in the context of \( B_s \) oscillation study.

Fig. 4 shows the total distribution of the mean value of \( \frac{t - \bar{t}}{t} \) (taken for each event), obtained from a sample of \( 10^4 Z^0 \rightarrow B \bar{B}(B = B_s, B_d \text{ and } B_s) \) simulated in DELPHI. Only the events with \( \sigma_t < 0.13 \) are kept, which correspond to 55% of the whole sample of the 3-prong \( B_s^- \) and \( D_s^- \) events entering the process. The bias is compatible with 0. The mean statistical error on \( t \) is \( \sim 7\% \). The statistical error for the constrained events (see Fig. 3a) is similar to the one given by the usual kinematical fit (between 1 and 2%) but the total number of good hadronic decays, useful to form a possible signal of oscillation, is increased by a large order of magnitude. The smooth curves include the uncertainty on the distance \( d \): a mean error of \( \sim 8\% \) is taken into account according to the relationship (1').

The other properties of the \( t \) estimation, which consists of taking the mean value \( \langle t \rangle \) of the \( t \) distribution for each event, are discussed in [2].

2.2.2 Case of the semi-leptonic decays: \( B_s^0 \rightarrow l^\pm \nu_l + D_s(D^*_s) \):

In this case, the formula (2) has to include the fact that the \( B \) vertex position is unknown. We may only suppose that its position is on the charged lepton trajectory (Fig. 2). Assuming the a priori probability of the abscissa \( z \) of this vertex along the \( l^\pm \) trajectory is flat, the following distribution of two variables, \( p_B \) and \( z \), has to be considered (Ref. [2]):

\[
f_t(p_B, z) = \text{Prob} \{ p_B, z | (\bar{q}_{B_m}, \bar{q}_{D_m}) \} \, dp_Bdz\]

where \( \bar{q}_{B_m} \equiv \bar{q}_{l_m} \). Then, one deduces:

\[
G(t) = \int \int f(p_B, z) \delta(t - \frac{M_B \cdot \sqrt{\frac{z^2 + \delta^2}{c^2 p_B}}}{c p_B}) \, dp_Bdz\tag{3}
\]

Three typical distributions \( G(t) \) are shown in Fig. 5. Frequent occurrence of two sets of solution is ascertained, for a given event, leading to a composite distribution: besides a main distribution, a second one takes often the aspect of a separated low probability signal or of a tail, the elimination of which is presently under study. Rough results are presented here for the semi-leptonic cases. After eliminating all the events with \( \sigma > 0.13 \), the distribution of \( \frac{t - \bar{t}}{t} \) resulting from the \( Z^0 \rightarrow B \bar{B} \) sample cited above is shown in Fig. 6. About 50% of the events involving a 3-prong \( D_s^0 \) decay are selected. The bias is negligible and the mean statistical error on \( t \) is \( \sim 14\% \). Note that the dominant part of the error
on the $B$ vertex position (and therefore on the distance $d$) is implicitly included, contrary to the hadronic case where $\frac{\alpha d}{l}$ has to be quadratically added.

Thus, for the main two modes of $B$ decay, the total uncertainty on $t$ remains within the limits required to see $B_s^0$ oscillations, inside a window defined by:

$$0.35 \, \tau_s \leq t \leq 1.5 \, \tau_s$$

The next problem consists of assuring a sufficient number of events to observe the emergence of a significant signal of oscillation inside the window in question.

3 $B_s^0/\bar{B}_s^0$ identification and tagging:

The event selection for oscillation develops in two steps:

- the identification of a $B_s^0$ in a defined C-eigenstate.
- the further tagging of the oscillation state which indicates whether the $B_s^0$ has oscillated or not.

To get a clear separation between vertices, minimum distances (for the hadronic modes) or impact parameters (for the semi-leptonic) equal to five times the error are required between the M.V. and $B$ ($d_{min} \simeq 1$ mm), then the $B$ and $D$ ($d_{min} \simeq 1.2$ mm) vertices. The $B_s^0$ is identified by the presence of no $K$ or of a $K\bar{K}$ pair, which can be detected, that is:

$$K^+K^-$$

$$K^\pm K_s^0 \rightarrow \pi^+\pi^-$$

$$K^\pm K_L^0$$

with $K_L^0$ seen in the e.m. and/or hadronic calorimeters inside a limited cone having the $D$ direction as axis and with $E_{KL}^0 > 4$ GeV, and $P_K^\pm \leq 1$ GeV/c in all cases.

Moreover, the determination of the C-eigenstate of the $B_s^0$ requires:

a) for the hadronic modes:

- the presence of at least three charged particles, at the $B$ vertex;
- a defined sign of the $D_s^\pm$ which can also rely on a charged lepton produced by its decay;
- the coherence between the total charges observed at the $B$ and $D$ vertices (i.e. opposite charges);

The cases of ambiguity are discussed later.
(β) for the semi-leptonic modes:

- a charged lepton, clearly separated from the main and D vertices, in the \( d_{\text{lim}} \) conditions cited above.
- a \( D_s \) compatible sign.

3.1 Tagging the oscillation states:

Two methods are used, providing two different tagged samples. In the reasonable hypothesis that the period of oscillation of the \( B^0_s \) is very large compared with the \( B^0_s \) (the Standard Model predicts \( \tau_{B_s} < 4.5 \)), the two samples may be added. A subset of common events, tagged by both methods, allows a mutual check of quality.

3.1.1 Tagging by the C-eigenstate of the \( B_u \) or \( B_d \) opposite:

In the opposite hemisphere, \( B_u \) and \( B_d \) mesons are dominant with respect to the occurrence of a second \( B^0 \). Then three main possibilities are used to define the C-eigenstate of this \( B \). However, to minimize the wrong tagging possibility, a clear \( D_{u,d} \) vertex involving at least two charged particles, is first required. Then one demands:

- either a charged lepton clearly separated simultaneously from the main and D vertices;
- or one (and only one) charged \( K \) or lepton in the D decay;
- or a well defined sign of the D (three constraint final state for example).

In the last two cases, the observation of a clear \( B \) vertex is not needed. The presence of a second D vertex, in the same hemisphere, leads to the elimination of the event to suppress ambiguous \( B \rightarrow D\bar{D} \) decays.

3.1.2 Tagging by a \( K^\pm \) meson produced with the \( B^0_s \):

This method is described in Ref. [3] and already applied in the work presented in Ref. [4]. It relies on the fact that a \( K^+ \) (resp. \( K^- \)) can be produced at the main vertex, in association with a \( \bar{B}^0_s \) (resp. \( B^0_s \)). In the framework of the Lund generator, the possibilities of such a tagging can be summarized by the scatter-diagram \( [p^K_\perp, \alpha^K_\parallel] \) shown in Fig. 7, where \( p^K_\perp \) and \( \alpha^K_\parallel \) are the \( K^\pm \) momentum and angle with the \( B \) jet axis. The events involving a number of \( K^\pm \) higher than 1 in the region \( \alpha^K_\parallel < 2 \) are eliminated. The full (open) circles are for right (wrong) taggings. The crosses are for the \( K^\pm \) which cannot be dissociated from the \( B_s \) or \( D_s \) vertices. A cut with \( p^K_\perp > 1 \text{ GeV/c} \) and \( \alpha^K_\parallel < 1.4 \text{ radians} \) allows to tag successfully \( (18.5 \pm 3.) \% \) of the \( B^0_s, (4.5 \pm 1.5) \% \) being wrongly tagged. The performance of the first method is similar.
4 Final signal over background ratio:

4.1 Causes of loss:

The multiple causes of loss which are taken into account in the present simulation are the following:

α) Acceptance
The main limitation of acceptance for events of sufficient accuracy comes from the microvertex detector. The total acceptance for the events tagged according to both methods described in paragraph 3 is \( \sim 0.5 \).

β) Pattern recognition and \( \pi/K \) separation
A provisional efficiency per track of 0.95 is assumed for the pattern recognition in the central detector and the microvertex detector, as for the \( \pi/K \) separation. For instance, the total efficiency obtained for the hadronic events involving only 3 charged particles, both at the \( B \) and \( D \) vertices, is \( \sim 0.7 \). The muons (\( e^\pm \)) with a momentum less than 3 GeV/c (2.5 GeV/c) are supposed to be unidentified.

γ) Vertex proximity
The rate of \( B_s^{0,\pm} \) s (resp. \( B_s' \)s or \( B_s'' \)s used to tag the \( B_s^0 \) oscillation states) kept after applying the criteria of clear separation between the successive vertices (paragraph 3) is \( \sim 0.28 \) (resp. \( \sim 0.43 \)).

δ) Mixing of tracks between vertices and wrong tagging

Event reconstruction relying only on the pattern recognition leaves an important percentage of tracks which stay compatible both with two or three vertices. This problem is particularly crucial for the hadronic decay modes. To minimize the ambiguities, the information contained in the particle momenta are introduced.

The distributions of the charged particle momenta, for each kind of vertex, are shown in Fig.8. The histogram 8a is for the charged particles, produced at the main vertex, and also compatible with the \( B_s^0 \) and/or the \( D_s^{\pm} \) vertices within a confidence interval of 99% (the uncertainties on the vertex positions being also taken into account). The singly shaded histogram in Fig. 8b (8c) is for particles produced at the \( B \) (\( D \)) vertex and compatible, within the same confidence interval, with the \( D \) (\( B \)) vertex. The doubly shaded histograms are for particles produced at the \( B \) or \( D \) vertices and also compatible with the main vertex.

This pattern of ambiguity induces the track-vertex association strategy which follows:

(a) Ambiguity between main and \( B \) or \( D \) vertices:
- a particle with \( p < 0.5 \) GeV/c and compatible with the \( B \) (or \( D \)) vertex is associated with this vertex only in case of incompatibility with the main vertex; in other words the main vertex has priority.
- conversely, for particles with \( p > 0.5 \) GeV/c, the \( B \) and \( D \) vertices have priority.
(b) Ambiguity between $B$ and $D$ vertices:
- for $p > 1.4$ GeV/c, the $D$ vertex has priority.
- for $p < 1.4$ GeV/c, the ambiguity is kept at this stage.

The ambiguities are solved in this manner, except if initial coherent charge states between the $B$ and $D$ vertices have to be left for incoherent states. More generally, all unique solution going in the sense of coherent charge states are kept. All events with an incoherent or ambiguous charge state for the $D_s$ are eliminated.

The wrong determination either of the C-eigenstate of the $B_s^0$ at its decay, or of the opposite $B_{u,d}$ in the first oscillation tagging method (section 3.2.1.) or the taking account of the irrelevant $K^\pm$ in association with the $B_s^0$, lead to a wrongly tagged event sample. The corresponding signal of oscillation has opposite phase to the right signal and it has to be subtracted from the latter.

Taking account of all the previous causes of loss and wrong tagging, the size of the emerging oscillation signals, for $10^8$ $Z^0$ produced in DELPHI and for each kind of decay mode and tagging, is reported in Table 1.

For the semileptonic modes tagged by a $K^\pm$ produced in association with the $B_s^0$, the order of magnitude of the emerging signal: $(3370 \pm 1070)$ events, is quite in agreement with the results of the ref. [4].

Finally, the total size of the signal reaches:

$$(11,800 \pm 2,000) \text{ events} / 10^8 Z^0$$

4.2 Background:

Given the method we choose to select the $B_s$, the $B_u$ and $B_d$ mesons can easily simulate a $B_s^0$ decay. The principal causes of contamination are:

$\alpha$) a $K^\pm$ coming from the main or B vertices and added to the products of a $D_u$ or $D_d$ decay into $K^\mp + n\pi$.

$\beta$) an unseen $K$, nevertheless present in a $D_u$ or $D_d$ decay: $K_s^0 \rightarrow \pi^0\pi^0, K_{LL}^0$ with $E < 4$ GeV in the hadronic calorimeter, $K^\pm$ lost in the tracking or at the $\pi/k$ separation stage ...

$\gamma$) the Cabibbo supressed modes of the $D_{u,d}$:

$$D \rightarrow K\bar{K}n\pi \text{ and } D \rightarrow n\pi \text{ etc...}$$

Obviously, a part of this background oscillates (the $B_s^0$ component), but given its relatively large period of oscillation, this phenomenon is not a real problem.

A preliminary estimate of its size by Monte Carlo using the Lund generator leads to:

$$\sim 33,600 \pm 6,500 \text{ events,}$$

so that the final signal to background ratio becomes:
\[ S/B = 0.35 \pm 0.09 \]

The respective mixing proportions for the three categories of \( B \) in the global sample are:

\[ \rho_u = 0.425 \; ; \; \rho_d = 0.315 \; ; \; \rho_s = 0.26. \]

5 \( B^0_s \) oscillations and LEP luminosity:

In the hypothesis of a large difference between \( x_s \) and \( x_d \), one assumes that:

\( \alpha \) the tagged event \( B^0_s.K^+ \) and \( \bar{B}^0_s.K^- \) (resp. \( \bar{B}^0_s.K^+ \) and \( B^0_s.K^- \)) are equivalent to the \( B_{u,d}.B^0_s \) and \( \bar{B}_{u,d}.\bar{B}^0_s \) (resp. \( B_{u,d}.\bar{B}^0_s \) and \( \bar{B}_{u,d}.B^0_s \)).

\( \beta \) for want of choice, the three kinds of \( B \) have the same mean lifetime, \( \tau \).

Then the time dependence of the ratio:

\[ R(t) = \frac{N(t)}{D(t)} = \frac{N_{B_{u,d}.B^0_s(t)} + N_{\bar{B}_{u,d}.\bar{B}^0_s(t)}}{N_{B_{u,d}.B^0_s(t)} + N_{\bar{B}_{u,d}.\bar{B}^0_s(t)} + N_{B_{u,d}.\bar{B}^0_s(t)} + N_{\bar{B}_{u,d}.B^0_s(t)}} \]

takes the form:

\[ R(t) = \frac{1}{2} \left( 1 - (1 - \chi_0). (\rho_u + \rho_d \cos \frac{x_d}{\tau} t + \rho_s \cos \frac{x_s}{\tau} t) \right) \]

where \( \chi_0 = \frac{1}{2}(\rho_d \cdot \frac{x_d^2}{1 + x_d^2} + \rho_s \cdot \frac{x_s^2}{1 + x_s^2}) \) \; ; \; (\chi_0 \leq 1/2).

The behaviour of \( R(t) \) for \( x_d = 0.7 \) and three different values of \( x_s \) \((3, 8, 18)\) are shown by dashed lines in Fig. 9. The full lines show what is observed when only the effect of the total error on \( t \) is taken into account. The expected error bars, for bins of 0.15 ps width and statistics of \( 10^8 Z^0 \), are superimposed.

Clearly, for \( x_s \sim 18 \) a limit is reached which is due to the error on the \( t \) estimate: the successive sinusoid arcs tend to overlap.

For the lower \( x_s \) values the integral method using the ratio:

\[ R = \frac{\int_0^\infty N(t)dt}{\int_0^\infty D(t)dt} \]

tends to become preferable.

The dependence on the number of \( Z^0 \) produced in LEP, and hence the LEP luminosity, is summarized by the graph of Fig. 10 which shows the number of tagged \( B^0_s \) events versus the maximum value of \( x_s \), we can achieve for 99 \% C.L. and 26 \% of purity. The full curves result from the method explained in Ref. [5] and correspond to different experimental resolutions \( \Delta \tau \).

The points corresponding to \( 10^7 \) \( Z^0 \), and \( 10^8 \) \( Z^0 \) observed in DELPHI, are shown. The figurative point for \( 10^6 \) \( Z^0 \) is outside the graph bounds: no oscillations developed in time can be observed, whatever the \( x_s \) value is.

The deductions coming from the two kinds of graphs, presented respectively in Fig. 9 and Fig. 10 agree. Interesting values of \( x_s \) are achieved for higher
luminosities of LEP. From some $10^6 Z^0$, oscillations can be observed for $z_s$ values between 3 and 8. $z_s = 18$ is reached from some $10^7 Z^0$.

6 Conclusion:

Observation and determination of the features of $B_s^0$ oscillations need both a good accuracy on the $B$ decay proper time estimate and relatively large event statistics, well identified and tagged. This is particularly the case in the context of the Standard Model with three families of quarks which predicts $z_s \geq 3$ and requires the observation of the oscillations developed in time.

A method specially developed to measure the $B$ proper time allows us both to add constrained and unconstrained, hadronic and semileptonic $B_s$ decays while remaining within the limits of sufficient accuracy for the $B$ proper time estimation. Added to the performances of the upgraded microvertex detector foreseen in DELPHI, this fact leads to good basis for the $B_s^0$ oscillation observation.

Clearly, a higher luminosity at LEP completes these possibilities by allowing a data taking of some $10^7 Z^0$. No precise analysis of error on $z_s$ and $z_d$ has yet been included in this work, but it seems that from this $Z^0$ number, accurate estimations of $z_d$ and $z_s$ would bring more precise and essential constraints on the knowledge of the Kobayashi-Maskawa sector.

References

  Prospects for the measurement of $B_s^0 - \bar{B}_s^0$ Mixing. P.Krawczyk et al. Desy 88-163 . Nov.88.
   Heavy flavours at LEP. J.M. Kühn, P.M. Zumas, M. Bosman et al. MPJ/PAE/PTh. 49/89 - August 89.
   etc ..

DELPHI NOTE 90-26/PHYS 63. (submitted to NIM).

Selected topics and $B$ Physics at LEP. P. Roudeau. LAL 89-21. May 89. 
Possibilities for the future of LEP Physics. D. Treille. Lectures given at the 
Ecole d'Eté de Physique Nucléaire et de Physique des Particules. Annecy. 
Sept.89. CERN EP/90-30. March 90, 
and this yellow Report : Measurement of $B^0_s - \bar{B}^0_s$ oscillations using semi-
Preprint LAL 90-47.

The possibility to measure the time dependence of $B^0_s - \bar{B}^0_s$ oscillations using 

<table>
<thead>
<tr>
<th>Hadronic Modes</th>
<th>Semileptonic Modes</th>
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<tbody>
<tr>
<td>$K^{\pm}/B^0_s$ tagging</td>
<td>0.04</td>
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<tr>
<td>$B_{u,d}/B^0_s$ tagging</td>
<td>0.042</td>
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<tr>
<td><strong>Total</strong></td>
<td>0.082</td>
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<td><strong>Grand total</strong></td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Efficiency of right $B^0_s$ identification and tagging [referred to the total 
number of $B^0_s \rightarrow$ at least 3 charged particles + $D_s(\rightarrow$ at least 3 charged 
particles) and $\rightarrow l^\pm \nu_l + D_s(\rightarrow$ at least 3 charged particles).] and 
final oscillation signal emerging from a sample of $10^8$ $Z^0$ in DELPHI.

**Figure Captions**

**Fig. 1:** Fragmentation function of the $B$ in the framework of the Lund generator used to simulate the DELPHI events.

**Fig. 2:** Information used to estimate the $B$ momentum or proper time for each event:

a) case of the hadronic decay modes;

b) case of the semileptonic decay modes.
**Fig. 3:** Proper time estimation of the hadronic decay events: typical three distributions of the variable $\frac{t - t_0}{\tau}$ for different chains of decay and numbers of unseen particles at the $B$ and $D$ vertices:

a) no and one unseen particle, respectively at the $B$ and $D$ vertices;

b) two and no unseen particles, respectively at the $B$ and $D$ vertices;

c) five and two unseen particles, respectively at the $B$ and $D$ vertices;

**Fig. 4:** Distribution of the mean values of $\frac{t - t_0}{\tau}$ for all the events having a goodness $\sigma < 0.13$ (hadronic decay modes).

**Fig. 5:** Proper time estimation of the semileptonic decay events: typical distributions of $\frac{t - t_0}{\tau}$.

**Fig. 6:** Distribution of the mean values of $\frac{t - t_0}{\tau}$ for the events with goodness $\sigma < 0.13$ (semileptonic decay modes).

**Fig. 7:** Tagging by the $K^\pm$ mesons produced in association with the $B_s^0$: scatter-diagram of $p_{K^\pm}$ versus $\alpha_{K^\pm}$ (explanation in text).

**Fig. 8:** Ambiguities of assignment between tracks and vertices versus the particle momentum: example of the hadronic decay modes.

**Fig. 9:** Three cases of $B_s^0$ oscillations developed in time (see explanations in text).

**Fig. 10:** Number of $Z^0$ produced in DELPHI, or well identified and tagged $B_s^0$ versus the $z_s$ achieved values (explanations in text).
a) Hadronic Modes.

\[ \vec{q}_{B_m} = \left( \vec{p}_B, \sqrt{p_B^2 + m_B^2} \right) \]

\[ \vec{q}_{D_m} = \left( \vec{p}_D, \sqrt{p_D^2 + m_D^2} \right) \]

M.V. (e^+e^-)

b) Semileptonic Modes.

\[ \vec{q}_{B_m} = \left( \vec{p}_B, \sqrt{p_B^2 + m_B^2} \right) \]

\[ \vec{q}_{D_m} = \left( \vec{p}_D, \sqrt{p_D^2 + m_D^2} \right) \]

\[ \vec{l} \]

\[ \vec{V}_l \]

Fig. 2

\[ \text{a}: B_s^0 \rightarrow \pi^+ \pi^- \pi^- + D_s^+ \]

\[ \text{b}: B_s^0 \rightarrow \pi^+ \pi^- \pi^- \pi^- + (\pi^0) \]

\[ \left\langle \frac{t - \bar{t}}{t} \right\rangle = 0.007 \]

\[ \sigma = 0.014 \]

\[ \text{c}: B_s^0 \rightarrow \pi^+ \pi^+ \pi^- \pi^- + (5 \pi^0) + D_s^- \]

\[ \left\langle \frac{t - \bar{t}}{t} \right\rangle = 0.27 \]

\[ \sigma = 0.24 \]

Fig. 3

303
Number of events /0.02

\[ \frac{t-\bar{t}}{t} = -0.0046 \]
\[ \sigma = 0.0716 \]

From \( 10^6 \) \( Z^0 \rightarrow B \bar{B} \)

Fig. 4

\( B_s^+ \rightarrow e^+ \nu e + D_{s}^- \)
\[ \frac{t-\bar{t}}{t} = -0.014 \]
\[ \sigma = 0.009 \]

\( B_s^+ \rightarrow \mu^- \nu \mu + D_s^0 \)
\[ \frac{t-\bar{t}}{t} = 0.06 \]
\[ \sigma = 0.068 \]

\( B_s^+ \rightarrow \mu^- \nu \mu + D_s^0 \rightarrow \pi^- + K^0 \pi^+ + (\pi^+) \)

Fig. 5

\( \frac{t-\bar{t}}{t} = 0.051 \)
\[ \sigma = 0.107 \]
Number of well identified and tagged $B^0$s.

$\frac{\alpha t}{\tau} = 30\%$, $20\%$

$\frac{\alpha t}{\tau} = 10\%$

$\frac{\alpha t}{\tau} = 5\%$

Integral Method

Fig. 10