New Results on $B_s^0$ Mixing from LEP

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1 Introduction

A prime goal of contemporary heavy flavour physics is the observation of $B_s^0$-$\bar{B}_s^0$ oscillations and determination of the mass difference $\Delta m_s$ to which the oscillation frequency is proportional. With the already well-measured quantity $\Delta m_d$ from studies of $B_d^0$-$\bar{B}_d^0$ oscillations [1], this would permit the extraction of the ratio of the CKM $V_{ts}$ and $V_{td}$ matrix elements

$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_s}}{m_{B_d}} \frac{|V_{ts}|^2}{|V_{td}|^2} \xi^2,$$

(1)

The theoretical uncertainties of roughly 10% are embedded in the $\xi^2$ parameter, the ratio of the decay constants and bag parameters of the $B_s^0$ and $B_d^0$ mesons. The phenomenological implication of $B_s^0$-$\bar{B}_s^0$ oscillations is a proper time-dependent asymmetry in the probability to observe a mixed decay (i.e., $B_s^0 \rightarrow \bar{B}_s^0 \rightarrow X$) compared to an unmixed decay (i.e., $B_s^0 \rightarrow B_s^0 \rightarrow X'$). These probabilities are given as

$$P_{\text{mixed}}(t) = \Gamma_s \frac{e^{-\Gamma_s t}}{2} [1 - \cos(\Delta m_s t)], \quad P_{\text{unmixed}}(t) = \Gamma_s \frac{e^{-\Gamma_s t}}{2} [1 + \cos(\Delta m_s t)],$$

(2)

assuming CP conservation and small lifetime differences. The challenge to experiments in measuring a value for $\Delta m_s$ is to determine if the $B_s^0$ meson decay is a mixed or unmixed one, and to measure the proper time associated to it.

The LEP experiments ALEPH [2], DELPHI [3, 4], and OPAL [5] have investigated $B_s^0$-$\bar{B}_s^0$ oscillations as have SLD [6] and CDF [7]. This paper focuses on new (i.e., released in early 2002) results from ALEPH [2] which motivate new LEP results on $B_s^0$-$\bar{B}_s^0$ oscillations and briefly reviews the results from DELPHI and OPAL.
2 Experimental Strategy

At LEP, $B_s^0$ mesons are produced from hadronic decays of the $Z$ boson ($e^+e^- \rightarrow Z \rightarrow b\bar{b}$). The boosted $b$ hadrons result in a characteristic displaced vertex topology relative to the interaction point, forming the basis of most heavy flavour physics analyses. The experimental strategy common to all analyses studying $B_s^0\bar{B}_s^0$ oscillations can be grouped into four categories discussed below. Figure 1 illustrates components of this strategy.

![Figure 1: A diagram illustrating components of the experimental strategy. The event is divided into two hemispheres with respect to the thrust axis; the hemisphere containing the $B_s^0$ candidate is referred to as the Same Side while the other is the Opposite Side.](image)

- **$B_s^0$ Selection and Event Purity Determination**
  Candidate $B_s^0$ events are selected from LEP data collected between 1991 and 1995 (roughly 4 million hadronic $Z$ decays per experiment).\(^1\) Table 1 summarizes different selections used by the LEP experiments. Figures 2 and 3 show invariant mass distributions obtained from the ALEPH fully exclusive and semi-exclusive analyses. A selection-dependent event-by-event purity improves the statistical power of the event sample \(^2\). A probability for each candidate to originate from signal and background components is used in the oscillation fit described below.

\(^1\)In one case, the ALEPH fully exclusive $B_s^0$ selection, $Z$ peak calibration data from LEP2 are included boosting the sample by about 400000 hadronic events.

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\(^2\)
Figure 2: Invariant mass distributions for the reconstructed $B_s^0$ candidates in the ALEPH fully-exclusive selection [2]. Data (dots with error bars) and the simulation (histograms) are shown: a) the $D_s^- \pi^+(\pi^0,\gamma)$ channel (a total of 44 events); b) the $D_s^- a_1^+(\pi^0,\gamma)$ channel (a total of 36 events); and c) the sum of the two. The lightly and darkly shaded vertical bands show the satellite regions and the main peak area defining the mass selection windows.

- Tagging the Initial and Final States
  A determination of the anti-particle/particle state of the $B_s^0$ candidate at its production (initial) and decay (final) is the key component of the analyses. The Final State tagging depends upon the selection. For fully exclusive decays, no ambiguity exists as all decay products are known. For the inclusive analyses with semileptonic $B_s^0$ decays, the charge of the lepton is used accounting for the non-zero mistag associated with cascade decays $b \rightarrow c \rightarrow \ell$. Initial State tagging is more complicated: information from both the Same and Opposite Sides may be used as the flavour of the b hadron in the Opposite Side is anti-correlated with that of the $B_s^0$ at production. In each case, a variety of discriminants are used. The Opposite Side tag may rely upon jet charges, primary and secondary vertex charges, and lepton and kaon particle identification techniques. The Same Side information must necessarily exclude $B_s^0$ decay products, attempting to build discriminants based upon fragmentation tracks; identified kaons from fragmentation (produced in conjunction with the $B_s^0$) provide powerful tagging information. Again, a variety of kinematic and particle-identification-based discriminants are used. The Same and Opposite
Side tags are then combined to yield an overall Initial State tag. The new ALEPH analyses [2] use series of neural networks (NN) to combine information, the final NN output is shown in Figure 4.

- **Measurement of Proper Time of the $B^0_s$ Decay**

  Proper time $t$ is given as $t = lm/p$ where $m$ is the $B^0_s$ mass; the $B^0_s$ momentum $p$ and the measured decay length $l$ must be measured. For the fully exclusive mode, the $B^0_s$ momentum is determined with excellent precision from knowledge of the momenta of all of the decay products. In more inclusive selections with semileptonic $B^0_s$ decays, a correction is done to account for missing neutrino momentum based upon event energy-momentum conservation; uncertainties associated with this correction procedure dominate the momentum resolution. The decay length is determined by the distance between the primary vertex and the $B^0_s$ decay vertex. At LEP, the primary vertex may be determined on an event-by-event basis. The secondary vertex determination is again selection-dependent, and the best precision (e.g., 180 µm for the ALEPH fully exclusive selection [2]) is obtained from the fully exclusive modes. More inclusive measurements suffer from a less precise knowledge of the $B^0_s$ flight direction (e.g., missing neutrinos from semileptonic B decay) onto which the primary-secondary vertex distance is projected.

- **Determination of $\Delta m_s$**

  A signal likelihood function can be constructed from the probability density function for mixed and unmixed events given in Equation 2. A procedure referred to as the Amplitude Method [10] replaces $\Delta m_s$ in the probabilities by a hypothesized oscillation frequency $\omega$ and an amplitude $A$ in front of the oscillation term. This per-
<table>
<thead>
<tr>
<th>Selection</th>
<th>Decay Modes</th>
<th>Sample (events)</th>
<th>Purity %</th>
<th>LEP Experiment</th>
<th>( \Delta m_s ) Limit obs. (exp.) ps(^{-1} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fully Exclusive</td>
<td>( B^0_s \rightarrow D^- s (\pi^+ \text{ or } a_1^+) ) &lt;br&gt;( B^0_s \rightarrow D^0_s K^- (\pi^+ \text{ or } a_1^+) )</td>
<td>50 – 80</td>
<td>50 – 80</td>
<td>ALEPH [2]</td>
<td>2.5 (0.4) &lt;br&gt;DDELPHI [4]</td>
</tr>
<tr>
<td>Semi-Exclusive</td>
<td>( B^0_s \rightarrow D_s(s^<em>)^{-\ell+\nu_\ell} ) &lt;br&gt;( B^0_s \rightarrow D_s(s^</em>)^{-h^+} )</td>
<td>10^2 – 10^3</td>
<td>40 – 60</td>
<td>ALEPH [2]</td>
<td>7.2 (7.5) &lt;br&gt;DDELPHI [3, 4]</td>
</tr>
<tr>
<td>Semi-Inclusive</td>
<td>( B^0_s \rightarrow \ell^+\nu_\ell + X )</td>
<td>10^4 – 10^5</td>
<td>10 – 20</td>
<td>ALEPH [2]</td>
<td>11.4 (14.0) &lt;br&gt;DDELPHI [8]</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>OPAL [9]</td>
</tr>
<tr>
<td>Fully Inclusive</td>
<td>( B^0_s \rightarrow X )</td>
<td>5 \times 10^5</td>
<td>10</td>
<td>DELPHI [8]</td>
<td>1.2 (4.9)</td>
</tr>
</tbody>
</table>

Table 1: A summary of the LEP experiments’ \( B^0_s \)-\( \bar{B}^0_s \) oscillation selections, their characteristics, and the resulting 95% C.L. lower limit on \( \Delta m_s \). DELPHI combine their Fully Exclusive and Semi-Exclusive \( D_s^{-} h^+ \) results providing only a combined exclusive result, denoted by the †.

mits combination of analyses including the systematic uncertainties. The likelihood is maximized with respect to the amplitude for each \( \omega \). An amplitude consistent with zero is expected for values of \( \omega \) far below the true value of \( \Delta m_s \); an amplitude consistent with unity is expected for values of \( \omega \) very close to the true value of \( \Delta m_s \). A range of \( \omega \) may be excluded at 95% C.L. if \( A + 1.645\sigma_A < 1 \).

### 3 Results

Results of all LEP studies of \( B^0_s \)-\( \bar{B}^0_s \) oscillations are summarized in Table 1. Results in terms of amplitude versus hypothesized \( \Delta m_s \) are shown in Figure 5 for the semi-exclusive analyses of DELPHI [3] and OPAL [5]. The corresponding plots for each of the new ALEPH analyses [2] are shown in Figure 6.

The combination of LEP results with those of CDF and SLD is shown in Figure 7 [11]. For this world combination, an observed 95% C.L. lower limit on \( \Delta m_s \) of 14.9 ps\(^{-1} \) is obtained with an expectation of 19.3 ps\(^{-1} \). There is an apparent difference between the expected and observed limits which suggests that a signal may lie in this region. Furthermore, there is an enticing deviation away from consistency with a zero amplitude hypothesis between 16 and 18 ps\(^{-1} \) which may hint at a signal; however the statistical significance of this deviation is below 2\( \sigma \).

### 4 Conclusions

To date, no experiment has been able to resolve oscillations. It is presumed that the oscillation frequency lies beyond the current experimental sensitivity to discover it at the
level of $5\sigma$; however, there may be a hint of signal in the $\Delta m_s$ region between 16 and 18 $\text{ps}^{-1}$. Further data from Run II of the Tevatron and results of future CDF and D0 studies may soon be available with the hope of discovering evidence for $B^0_s$-$\bar{B}^0_s$ oscillations.

**Acknowledgements**

This presentation summarizes the work of the ALEPH, DELPHI, and OPAL collaborations as well as the LEP B Oscillations Working Group. As a member of the ALEPH collaboration, I wish to thank my colleagues in the CERN accelerator divisions for the successful operation of LEP. I am grateful to Dr. Duccio Abbaneo for his help in preparing this presentation as well as members of the ALEPH Heavy Flavour Group and the LEP B Oscillations Working Group. Dr. Markus Elsing also provided valuable input and suggestions.

**References**


Figure 5: Plots showing Amplitude versus hypothesized $\Delta m_s$ for a) the DELPHI semi-exclusive analysis [3], and b) the OPAL semi-exclusive analysis [5]. In the case of the a) DELPHI analysis, an observed (expected) 95% C.L. lower limit of 7.4 ps$^{-1}$ (8.1 ps$^{-1}$) is obtained; b) OPAL analysis yields 1.0 ps$^{-1}$ (4.1 ps$^{-1}$).


Figure 6: The new ALEPH results [2] shown here in terms of Amplitude versus hypothesized $\Delta m_s$ ($\omega$)
for a) the fully exclusive analysis, b) the semi-exclusive $D_s\ell$ analysis, c) the semi-inclusive lepton analysis,
and d) the combination of the three. In each case an observed (expected) 95% C.L. lower limit is set on $\Delta m_s$: 
a) $2.4\text{ ps}^{-1}$ ($0.3\text{ ps}^{-1}$), b) $7.2\text{ ps}^{-1}$ ($7.4\text{ ps}^{-1}$), c) $11.4\text{ ps}^{-1}$ ($14.0\text{ ps}^{-1}$), and d) $10.9\text{ ps}^{-1}$ ($15.7\text{ ps}^{-1}$).
Figure 7: The combined $B^0$ oscillation results from ALEPH, CDF, DELPHI, OPAL, and SLD shown as amplitude versus hypothesized $\Delta m_s$ [11]. The dots with error bars show the fitted amplitude values and uncertainties. An observed (expected) 95% C.L. lower limit on $\Delta m_s$ of 14.9 ps$^{-1}$ (19.3 ps$^{-1}$) is obtained.