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ECFA EUROPEAN COMMITTEE FOR FUTURE ACCELERATORS

REPORT OF THE WORKING GROUP ON THE FUTURE OF ACCELERATOR-BASED PARTICLE PHYSICS IN EUROPE[1]

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[1] Address http://www.web.cern.ch/Committees/ECFA/ (Working Group)

REPORT OF THE WORKING GROUP ON THE FUTURE OF ACCELERATOR-BASED PARTICLE PHYSICS IN EUROPE

EXECUTIVE SUMMARY

The ECFA Working Group on the future of accelerator-based particle physics in Europe has considered the possible options and time-scales for the next major accelerator project, the implications for the current particle physics programme and the strategy that ought to be pursued in the long-term future. Although charged with considering the future for Europe, it has also considered the international context since particle physics is intrinsically international. The Working Group makes the following recommendations:

In the immediate future:

1) the allocation of all necessary resources to fully exploit the unique and pioneering LHC facility;

2) continued support for ongoing experiments, since they promise significant scientific results, provide an optimal physics return on previous investment, and are vital for the education of young physicists;

3) the realisation, in as timely a fashion as possible, of a world-wide collaboration to construct a high-luminosity e^+e^- linear collider with an energy range up to at least 400 GeV as the next accelerator project in particle physics; decisions concerning the chosen technology and the construction site for such a machine should be made soon;

4) an improved educational programme in the field of accelerator physics and increased support for accelerator R&D activity in European universities, national facilities and CERN.

For the long-term:

5) a co-ordinated collaborative R&D effort to determine the feasibility and practical design of a neutrino factory based on a high-intensity muon storage ring**;**

6) a co-ordinated world-wide R&D effort to assess the feasibility and estimate the cost of a 3-5 TeV e^+e^- linear collider (CLIC), a very large hadron collider (VLHC) and a muon collider; in particular, R&D for CLIC is well advanced and should be vigorously pursued.

The central role of CERN in Europe must continue and will be essential as the fulcrum of the long-term future of particle physics. The Working Group considers it essential that, through CERN, Europe should be able to play a key role in the exploration of the multi-TeV horizon that will open in the post-LHC era.

The implementation of these recommendations would ensure a vibrant and exciting programme of investigations into the fundamental structure of matter and maintain Europe's leading role in this pioneering adventure in science.

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REPORT OF THE WORKING GROUP ON THE FUTURE OF ACCELERATOR-BASED PARTICLE PHYSICS IN EUROPE

PREFACE

The year 2001 is the first year following the closure of LEP, and it is also the mid-point in the construction of the next large European project, the LHC, which received final approval in 1996 and will start operation in 2006.

It is therefore natural that the European Committee for Future Accelerators (ECFA) should attempt to construct a scenario for the future of accelerator-based particle physics. This is also timely because this year the Technical Design Report (TDR) for the TESLA project was presented and DESY asked ECFA to consider the impact of such a project on the future of particle physics.

To accomplish these tasks, ECFA has created a working group of 11 European physicists. Their mandate is to collect the opinion of national physics communities on desirable future initiatives in Europe in the framework of world-wide developments in the field, and to make recommendations on the optimum scenario.

The Working Group members and the countries they represent are listed in Appendix 1.

The Working Group listened at its initial meetings to detailed presentations of the options for future accelerators at the high-energy frontier. It discussed future scenarios with representatives of the United States, Japan and Russia. The detailed list of the meetings and of the presentations is given in Appendix 2.

1. INTRODUCTION

Particle physics has made striking advances in the last fifty years in describing the intimate structure of matter and the forces that determine the architecture of the universe. Our current view of the universe is based on a small number of matter particles acted on by four forces in a four-dimensional space-time continuum.

Matter consists of spin-1/2 constituents called quarks and leptons, organised in three families, each one containing a charged lepton, a neutrino and two quarks of charge +2/3e and -1/3e respectively, as shown in Figure 1.

<table>
<tr><th colspan="3">3 particle matter families
(fermions of spin $\frac{1}{2}$)</th><th colspan="4">Carriers of Forces (bosons)</th></tr>
<tr><td>e
electron
0.5 10^6 ev</td><td>μ
muon
1.06 10^8 eV</td><td>τ
tau
1.8 10^9 eV</td><td colspan="4">Spin 1 Gauge bosons :</td></tr>
<tr><td>ν_e
e-neutrino
< 3 eV</td><td>ν_μ
μ-neutrino
< 1.9 10^5 eV</td><td>ν_τ
τ-neutrino
< 1.8 10^7 eV</td><td>γ
photon
< 2 10^{-16} eV</td><td>W
W-boson
80.4 10^9 eV</td><td>Z
Z-boson
91.2 10^9 eV</td><td>g
gluon
~ 0</td></tr>
<tr><td>d
down-quark
1-5 10^6 eV</td><td>s
strange-quark
75-170 10^6 eV</td><td>b
beauty-quark
4.0-4.4 10^9 eV</td><td colspan="4">Unobserved Bosons:</td></tr>
<tr><td>u
up-quark
1-5 10^6 eV</td><td>c
charm-quark
1.15-1.35 10^9 eV</td><td>t
top-quark
174.3 10^9 eV</td><td colspan="2">h (spin 0) ?
Higgs boson
114 - 220 10^9 eV</td><td colspan="2">G (spin 2) ?
Graviton
Expected to be 0</td></tr>
</table>

Figure 1. Quarks and leptons arranged as three families, together with the force carriers of the electromagnetic (photon,γ), strong (gluon, g) and weak (W, Z) interactions. Also shown are the approximate measured or inferred quark, lepton and gauge boson masses. The allowed Higgs mass is quoted in the context of the Standard Model.

The forces which act among the matter particles are: the electromagnetic force, which explains atomic structure; the weak force, which describes radioactive decays and, in general, the transitions from one family to another; and the strong force, which glues together the quarks in protons and neutrons. The fourth force, gravity, is too weak to be of relevance in the microscopic world for accelerator experiments, but its inclusion in the quantum world has long been a challenge that is now being studied intensively.

All forces except gravity are transmitted via the exchange of bosons of spin 1, namely the photon for the electromagnetic interactions, the W and Z bosons for the weak interactions, and the gluon for the strong force. This simple structure forms the theoretical framework, called the "Standard Model", which has been able to predict with very good accuracy the value of many quantities that have been measured by experiments at modern accelerators, in particular the spectacularly successful prediction of the mass of the top quark.

However, this theory is still incomplete because the mechanism for electroweak symmetry breaking, leading to the striking asymmetry between the massless photon and the massive W and Z bosons, is not yet unravelled.

A major step towards answering this question would come from the discovery of the Higgs boson(s), possibly at the Fermilab Tevatron if it is light, and otherwise by experiments at the CERN LHC for masses up to 1 TeV. Such a spinless particle is responsible in the Standard Model for electroweak symmetry breaking. Its discovery would be a fundamental confirmation of the Standard Model, and the precise measurements of its characteristics would open the way towards a more global theory.

One possible example of an extension of the Standard Model is "supersymmetry". It predicts that more than one Higgs boson will ultimately be found, at least one of which is light. It also predicts that each constituent of matter has a partner with spin zero and that each force carrier has partners of spin 1/2, creating a complete symmetry between forces and matter. Searches for these "super-particles" at existing machines have so far been negative. However, the mass range at which supersymmetry, if it exists, should be revealed is between about 100 GeV and a few TeV, i.e. the region covered by LHC.

If no Higgs boson is discovered in the 100 GeV to 1 TeV mass range, the Standard Model will need serious revision, and totally different scenarios may be opened up, for example new strong interactions between W bosons.

The LHC has the potential to answer these questions, and thus to make major discoveries. There is little doubt however that a machine capable of more precise measurements, such as a linear e^+e^- collider, will be needed to understand the detailed nature of these discoveries. There is also little doubt that investigations beyond this energy range will eventually be necessary, prompting the need for higher energy colliders.

Another reason to believe the theory is incomplete is that it requires as input a large number of parameters such as the masses of all constituents and the coupling constants of all forces. Physicists today are convinced that the Standard Model is the low-energy approximation of a more global theory that might unify the various forces including gravity, explain the origin of the three flavour families, and describe the origin of particle masses. The hope is eventually to understand such unexplained facts as the difference by many orders of magnitude between the masses of neutrinos and those of the heavier quarks. Most of the scenarios for global theories invoke energy scales that are far beyond the reach of conceivable accelerators, but could leave observable traces at accessible energies. Experiments relevant to this quest are thus not restricted to the high-energy frontier. Two additional lines of research at low-energy scales are potentially quite promising.

The first field that might yield important results is neutrino physics. The fact that neutrinos have mass is now established. Following earlier observations on solar neutrinos, the studies performed at Super-Kamiokande in Japan and more recently at SNO in Canada have clearly demonstrated the phenomenon of neutrino oscillations, possible only if the masses of the neutrinos of the three families are different.

An important world-wide programme of neutrino experiments will explore this field over the next ten years. More powerful neutrino sources will be necessary beyond that time, to clarify the mixing of the various neutrino species and possibly to discover a difference between matter and antimatter particles, known as "CP violation" for leptons. Several possibilities are being studied, the most promising, the Neutrino Factory, based on a muon storage ring.

The second field is the study of CP violation in particles containing heavy quarks. This symmetry-breaking, discovered decades ago in the K° system, is now being extended to the B system with dedicated experiments at new b-factories, BABAR at PEPII in the US and BELLE at KEKB in Japan. The measurement of all quantities characterising the violation of CP in this new system will reveal whether the Standard Model consistently describes their values or whether a new window will be opened up on the unknown. Such a programme will be continued with much larger statistics by BTeV at FNAL and by LHCb at LHC, starting in 2006. This wide range of activity guarantees a rich future for this field of research, which will therefore not be discussed in this report.

The great potential of heavy-ion physics to test the theory of strong interactions under extreme temperature and pressure conditions will not be discussed here. The present generation of experiments at RHIC at Brookhaven in the US and the forthcoming ALICE experiment at LHC, will define the future of this field.

The structure of this document is as follows:

- Chapter 2: the present and future of hadron colliders, from the Tevatron and LHC, to possible LHC upgrades and ideas on VLHC;
- Chapter 3: electron-positron colliders, starting from the heritage of LEP, through the projects for sub-TeV linear colliders, and future possibilities in the multi-TeV region;

- Chapter 4: new possibilities of neutrino physics offered by neutrino factories based in particular on a muon storage ring;
- Chapter 5: the potential of a muon collider for high precision measurements and for high energy frontier searches;
- Chapter 6: the current situation in lepton-hadron physics and the future prospects in this field;
- Finally, Chapter 7 summarises the conclusions of the working group and presents its recommendations.

2. HADRON COLLIDERS

The hadron collider is the particle physicist's accelerator of choice to probe the high-energy frontier, in the search for new elementary particles and phenomena. The last two major discoveries have been made at hadron colliders. In 1983, the mediators of the electroweak interaction, the W and Z bosons, were discovered at the CERN $\mathrm{Sp\bar{p}S}$ Collider with a $\mathrm{\bar{p}p}$ collision energy of 540 GeV, and in 1995 the top quark was discovered at the Fermilab Tevatron Collider with a $\mathrm{\bar{p}p}$ collision energy of 1.8 TeV.

For the next five years the Tevatron Collider will be the frontier machine. Then, from 2006, experiments at the CERN LHC will allow the exploration of a new multi-TeV energy domain. The Higgs particle will be conclusively established if it exists with a mass below 1 TeV; most theoretical extensions of the Standard Model either predict the existence of new particles or measurable deviations from the Standard Model in this energy range. The direction of future particle physics activities will be profoundly influenced by results from the LHC.

2.1 The CERN Large Hadron Collider (LHC) and upgrades to the LHC

The CERN LHC [1], first proposed in 1984, is being constructed and is expected to operate from 2006. Four large experiments [2] are scheduled to collect data at the LHC, two general-purpose detectors, a third dedicated for b-quark studies and a fourth for the study of heavy ion collisions.

The main research goals for the two general-purpose experiments ATLAS and CMS, are:

- the exploration of the electroweak symmetry breaking mechanism, and in particular the discovery of the Higgs particle;
- the search for physics beyond the Standard Model and in particular supersymmetry.

Expectations from both the Standard Model and supersymmetry require the mass of a Higgs boson to be less than 1 TeV. The result will therefore be conclusive and by 2010 electroweak symmetry breaking via the Higgs mechanism will either be firmly established or our theoretical ideas will require a major revision. If the Higgs boson is discovered, its mass will be determined with high precision; it will be seen in most cases in more than one decay mode, allowing first tests of its other properties.

Similarly, the discovery or rejection of supersymmetry should be possible within the first two years of LHC operation, concluding decades of speculation. If supersymmetry exists, many new particles are expected to be produced leading to potentially spectacular signals. The partners of quarks and gluons will be easily detected at LHC and will be discovered up to masses of the order of 2 TeV. The partners of the leptons will mostly be seen in cascade decays and will be difficult to identify above 300 GeV. In general, the parameters of the supersymmetric model should be measurable with a precision of 1 to 10%.

A natural evolution of the LHC programme is an upgrade of the luminosity that will push detectors to the limit. A significant upgrade in energy of the accelerator will be technologically difficult. The upgrade path will be defined by results from the initial years of LHC operation.

2.2 The Very Large Hadron Collider (VLHC)

Among the accelerators that are being discussed for the post LHC era, the VLHC [3], working in an energy range up to 200 TeV, is the project that provides the largest discovery potential for heavy particles up to masses of the order of 30 TeV.

The need for such a machine will be determined by results from the LHC. Possible scenarios that would dictate exploration at such high energies include:

- if only a few supersymmetric particles are discovered and the pattern shows that other partners are as heavy as a few tens of TeV;
- if the existence of a new strong WW interaction is established;
- if traces of quark compositeness are observed with a scale of a few tens of TeV;
- if indications are found for large extra spatial dimensions confined to distances of the order of femtometres, a scale that can be probed only with collision energies larger than 100 TeV.

As important as performing tests of existing theories is the search for the unknown. A VLHC will open a completely new energy regime, which can then be probed for new physics.

Several possible designs are being developed and studied, mostly at Fermilab, for a system of accelerators built in a single tunnel of about 200 km circumference. These include a 40 TeV machine with low magnetic field (2 Tesla) that will act as the injector to a larger machine of up to a 200 TeV based on 12 Tesla magnets. A key issue for a realistic project is cost; several new magnet prototypes of very innovative design are being constructed with the aim of demonstrating an important reduction of the magnet cost per unit length.

2.3 Assessments and Comments of the Working Group

The first years of data taking at the CERN LHC will establish the existence of one or more Higgs particles, if such particles exist with mass below 1 TeV. The data will also provide the first indications of what lies beyond the Standard Model, for example supersymmetry. It will provide the essential guidance for the direction of future research in particle physics.

A natural evolution of the LHC programme is an upgrade of the luminosity, and possibly of energy. R&D towards such upgrades should be pursued.

The preparation for a machine such as the VLHC requires a large and well-organized international R&D programme, to bring the total cost to an affordable level. Any decision must obviously await results from that R&D programme, and, more importantly, results from the LHC.

3. ELECTRON-POSITRON COLLIDERS

Electron-positron (e^+e^-) collisions, due to their point-like nature and the well-defined energy and quantum numbers of the initial annihilation process, provide the means for making precision measurements which complement the results from other processes such as hadron collisions or lepton-nucleon scattering in an ideal and indispensable way. Therefore, in the past, e^+e^- colliders were successfully operated in a complementary way to hadron colliders which reach, in general, higher collision energies at a given state of technology.

At the highest energy frontier, the LEP Collider at CERN reached collision energies of 209 GeV. LEP closed at the end of 2000 after more than 11 years of successful operation. Of particular relevance for this report is the constraint on the Higgs mass, within the Standard Model, of between an experimental lower limit of 114 GeV and an indirect upper limit of about 220 GeV. The study of e^+e^- collisions substantially beyond the LEP energy range requires changing from circular to linear colliders. A proof-of-principle for the linear collider was provided by the pioneering Stanford Linear Collider (SLC). Further studies are currently being pursued in Europe, Japan, and the U.S.

3.1 Sub-TeV Linear Electron-Positron Colliders

The physics motivation for a next-generation e^+e^- collider has been studied in a large number of national and international workshops in Europe, the USA and Japan during the past 10 years [4]. The following main physics areas have motivated an intense international R&D program to develop a future e^+e^- linear collider at energies significantly beyond the reach of LEP:

1) The currently proposed linear colliders should provide over a hundred times more luminosity than LEP, resulting in much improved measurements of Standard Model parameters. Precision measurements at the Z pole and above, combined with a precise measurement of the top-quark mass, will, assuming a corresponding progress in theoretical calculations and other low energy measurements, provide tenfold improvements in consistency tests of the theory. Any deviation from these predictions will point to new physics beyond the Standard Model, even at energy scales that are far beyond the direct reach of the machine. This especially applies to possible scenarios for which no Higgs boson would be found at the LHC. In such a case, precision measurements will serve as a vital probe of physics at high-energy scales. These factors require an e^+e^- collider to span the collision energy range from 90 to at least 400 GeV.

2) Consistency of the Standard Model with present data requires a Higgs boson with a mass of less than 220 GeV, which, if it exists, will be discovered at the Tevatron or LHC. A high luminosity e^+e^- linear collider as specified above will be able to produce such a Higgs boson in large quantities and in a very clean environment. Such a collider will have the unique capability of precisely measuring its specific properties, for example its mass, its coupling to the gauge bosons, and if the mass is less than 160 GeV, its coupling to the quarks and leptons. The Higgs self-coupling is at the core of electroweak symmetry breaking; it can only be studied at the clean environment of a lepton, e.g. an e^+e^- collider.

3) The most exciting scenario for an e^+e^- linear collider will be if new particles exist within its energy range. For example, in most supersymmetry scenarios, some but not all of the predicted particles will have a visible signal at the LHC. However, a precise and unambiguous study of their properties will only be possible at an e^+e^- collider. In order to fully complement the physics potential of the LHC, e^+e^- collision energies of up to 1 TeV may turn out to be desirable.

The Technical Design Report (TDR) [5] for a superconducting e^+e^- linear collider, TESLA, reaching centre of mass energies of 500 to 800 GeV at luminosities exceeding 10^{34} cm^{-2} s^{-1} was presented by the DESY laboratory in March 2001. Other projects in a similar energy range pursued in the U.S. (the NLC) [6] and in Japan (the JLC) [7], which are based on normal-conducting acceleration structures, are expected to follow.

3.2 Multi-TeV Electron-Positron Colliders

Most of the arguments and motivations for a sub-TeV e^+e^- collider also apply to multi-TeV accelerators of that type. The mass range accessible to search for Higgs bosons or other new particles will be much larger, according to the energy of the accelerator. The potential for discoveries and precision studies at very high energies, comprising novel aspects such as the production of new gauge bosons, of new quarks and leptons and composite Higgs bosons, is therefore much enhanced and extends in many cases beyond that of the LHC.

While a multi-TeV e^+e^- collider offers a greater physics potential, many years of intense R&D are still needed for such a machine. The CLIC design [8], developed and studied at CERN for more than 10 years, offers a promising way to build such a machine in the 3 to 5 TeV range. It is based on a two-beam scheme where intense low-energy electron beams provide the rf power to accelerate the high energy electron and positron beams. It is designed to reach very high accelerating gradients, allowing a much shorter total linac length than other schemes. A test facility (CTF3), currently planned at CERN, is intended to demonstrate the conceptual feasibility of this technique within the next five years.

3.3 Assessments and Comments of the Working Group

The Working Group sees a strong physics motivation for the construction of an e^+e^- linear collider, reaching at least 400 GeV collision energy and exceeding luminosities of 10^{34} cm^{-2} s^{-1}. The motivation is based on current knowledge and experience from past or existing experiments. Because of the rich programme of study of currently known phenomena, the results of an initial LHC run are not needed to justify construction of such a collider. Flexibility to increase the energy range to significantly higher energies will enhance its capability to study new processes and physics beyond the Standard Model. Justification of an extended energy range will greatly benefit from results obtained at the LHC.

These conclusions in practice match the current status of R&D for future e^+e^- colliders. The recent presentation of the TDR of the TESLA project developed at DESY demonstrates the feasibility of a linear collider in the sub-TeV energy range.

The Working Group recommends the realisation of an e^+e^- linear collider in the collision energy range from 90 up to at least 400 GeV, with possible extension to higher energies. It is convinced that the decision to construct such a machine should be taken soon, because:

- its physics case has been established, its technical readiness has been demonstrated, and an international community of physicists is committed to its realisation;
- an overlap in time of the operation of the LHC and that of the Linear Collider would be extremely fruitful, given the complementarity of the two experimental approaches in the study of the same physics. The results from one community would stimulate the other and would clarify unexpected aspects of the other's results as happened for the LEP and Tevatron experiments.

Promising techniques for a multi-TeV e^+e^- linear collider like CLIC are being developed at CERN but still need significant R&D work before the technical feasibility can be demonstrated. The Working Group recommends the continuation of R&D to show the feasibility of an e^+e^- linear collider in the multi-TeV collision energy range, such as CLIC.

4. HIGH INTENSITY PROTON SOURCE AND NEUTRINO FACTORY

4.1 Neutrino Physics

After a thirty year period of observations, it has recently been established that neutrinos have mass. Following earlier experiments observing a deficit in the detected rate of electron neutrinos produced in the sun, the SuperKamiokande collaboration in Japan established in 1998 the disappearance of muon neutrinos produced in atmospheric air showers. The pattern of observations is accounted for by mixing and oscillations between the three known neutrino species. This was recently supported by the first results from the SNO collaboration. The intensive programme of experiments presently underway in Japan, United States, Europe and Canada will start the exploration of the nature of the observed phenomena.

A new programme of measurements should now be foreseen to determine the four parameters of the neutrino mixing matrix, and the two independent mass differences. Only two of these parameters are known, both with large errors. New phenomena are predicted that have so far not been observed and are unlikely to have been observed when the present programme is completed. In particular the observation of CP violation with leptons would constitute a major discovery. It is often invoked as one of the likely ingredients for the generation of the asymmetry between matter and anti-matter in the Universe.

The ultimate tool in this endeavour is a Neutrino Factory. The concept was proposed in 1998, based on previous studies of muon colliders. An intense beam of high-energy muons circulating in a storage ring would provide an intense and well-calibrated flux of high-energy neutrinos from muon decay. Subsequent studies [9] in USA, Japan and Europe have shown that long baseline experiments at a Neutrino Factory would allow precise determination of the oscillation parameters relevant to atmospheric neutrinos and provide high sensitivity to the transition between electron neutrinos and muon neutrinos. It would also allow the determination of the mass hierarchy of neutrinos and enable discovery of CP violation. In the immediate vicinity of the muon storage ring, neutrino fluxes of unprecedented intensity would allow high-precision neutrino experiments on nucleon and polarised nucleon structure, charm production, nuclear effects, and electroweak physics.

4.2 The Neutrino Factory

The Neutrino Factory [10] is a novel and complex accelerator. It comprises:

- a proton source with a beam power of nominally 4 MW, significantly larger than existing facilities;
- a target that can withstand at least 4 MW beam power, followed by a collection system to catch the largest number of pions and decay muons;
- an increase in the muon beam density by such techniques as ionisation cooling;
- a fast acceleration system to bring muons to the highest energy, implying very high total voltage and peak power;
- a muon storage ring in which long straight sections can point at experimental locations at differing distances, from several hundred to several thousand kilometres.

Although the studies undertaken at Fermilab, Brookhaven and CERN have shown the conceptual feasibility of a neutrino factory, a substantial R&D programme is required to establish the component and subsystem performance of the critical items, to reduce the cost and to elaborate a practical design.

4.3 Physics with a High-Intensity Proton Source

High-intensity proton drivers have been studied world-wide for neutron spallation sources, transmutation and incineration, and accelerator-driven energy amplification. A proton driver constitutes the basic starting point for neutrino factories and muon colliders. It also offers important physics opportunities in its own right.

If such a source were to be realised at CERN [11], for example, the increased proton intensities would greatly benefit the fixed target programme, including the CERN-Gran Sasso neutrino beam, as well as improving the operation of the LHC.

In addition, several specific programmes would open up. A high-intensity muon source would allow improvements in the reach for rare muon decay searches and other studies of muon properties. The observation of lepton flavour violation in muon decays, which is expected in many scenarios of physics beyond the Standard Model, would constitute a major discovery. The simultaneous presence on the CERN site of upgraded radioactive nuclear beams (ISOLDE), an antiproton source and an intense muon source would allow unique studies of antiprotonic and muonic atoms. Finally, a high-intensity, low-energy conventional neutrino beam could provide sensitivity to new types of neutrino oscillations and some early sensitivity to CP violation with leptons.

4.4 Assessment and Comments of the Working Group

A neutrino factory complex, beginning with its proton driver, allows a number of unique experiments in a fundamental domain: neutrino masses and mixing, CP violation, and lepton number violation. The realisation of this important programme requires a substantial international programme of R&D.

5. MUON COLLIDERS

An intense source of muons, as considered for a neutrino factory, can provide beams for high-energy muon ($\mu^+\mu^-$) colliders. Compared to the e^+e^- collider, the $\mu^+\mu^-$ collider offers several advantages: much reduced beam energy spread, excellent calibration of the muon beam energy and polarisation by measuring the muon decay asymmetry. Moreover the dimensions of a muon accelerator and storage ring are sufficiently compact for it to be housed in existing high-energy physics laboratories.

The physics motivations outlined in Section 3 for e^+e^- colliders apply equally well to a $\mu^+\mu^-$ collider. In addition the well-controlled muon beam energy and the fact that the muon is much heavier than the electron allows the operation of the $\mu^+\mu^-$ collider as a Higgs factory.

Much work has been done in recent years to study the concept of a muon accelerator complex and to fix some preliminary design parameters [12,13].

The luminosity for a physics programme at a high-energy $\mu^+\mu^-$ collider imposes more stringent requirements than for a neutrino factory. Conceptual studies are still needed to understand how to obtain, with realistic devices, the small beam-sizes and small momentum spread required for a $\mu^+\mu^-$ collider. Nevertheless, most of the elements for fast acceleration of intense muon beams are similar to those envisaged for a neutrino factory and should greatly benefit from the R&D

devoted to such a programme. A large R&D effort will be needed to demonstrate the feasibility of a $\mu^+\mu^-$ collider facility.

Since $\mu^+\mu^-$ colliders are intended for high precision measurements, the working parameters should be accurately tuned to optimise the performance for specific physics objectives. These can be clearly identified following the results of the LHC when the physics case for a high precision muon collider can be better elucidated. Two options are considered here: a Higgs factory and a multi-TeV $\mu^+\mu^-$ collider.

5.1 A Higgs Factory

The coupling of the Higgs field to fermions is proportional to the fermion mass. Therefore a $\mu^+\mu^-$ collider provides a possibility to study direct $\mu^+\mu^- \rightarrow$ Higgs production. This would allow a measurement of the mass and width from the line shape of the resonance to the sub-MeV level. Moreover, the cross-section measurements would provide precise information on the Higgs-boson branching ratios.

The Higgs mass, width and branching ratios are sensitive to possible extensions of the Standard Model. As an example, in the supersymmetric model there are Higgs bosons in different eigenstates of CP. A unique feature of a muon collider is the possibility to resolve resonances that are close in mass and to study CP symmetry in the Higgs sector.

5.2 A Multi-TeV Muon Collider

At very high energy, a $\mu^+\mu^-$ collider could in principle become rather competitive in luminosity compared to e^+e^- colliders. A 3 TeV $\mu^+\mu^-$ collider has access to the whole mass range explored at the LHC and can measure the mass of resonances and energy thresholds for production of new particles with unrivalled precision. This is of great interest if supersymmetry were to manifest itself in this energy range.

5.3 Assessments and Comments of the Working Group

There are formidable problems to be solved before a $\mu^+\mu^-$ collider can be seriously considered. From the machine point of view, these include the ionisation cooling of the muons and the hostile background radiation. From the point of view of the experiments, the huge muon and electron background could complicate the operating environment.

Despite these difficulties, $\mu^+\mu^-$ colliders offer the best properties for very precise measurements at high energy, and the physics goals are unlikely to lose their interest after the exploratory phase of the LHC. The construction of a $\mu^+\mu^-$ collider can be considered as the ultimate step of a long-term programme that includes the construction of an intense hadron source for low-energy secondary beams, the development of a neutrino factory and specific R&D.

6. LEPTON-HADRON PHYSICS

The scattering of leptons on nucleons has historically been one of the most productive techniques in particle physics, leading to the formulation of the quark-parton model and forming one of the foundations of the theory of the strong interaction. Experiments have used electrons, muons and neutrinos as probes. This research continues today, using both fixed-target and collider experiments. The advent of HERA, the electron-proton colliding beam facility at DESY, has ensured that the centre for lepton-proton scattering physics is firmly in Europe.

6.1 Existing Experimental Programmes

The HERA accelerator combines a superconducting proton ring which can accelerate protons up to 1 TeV and a normal-conducting electron ring accelerating electrons and positrons up to 27.5 GeV. HERA was a completely new type of accelerator and posed novel problems in accelerator physics. The physics programme at HERA greatly improved our understanding of the structure of the proton in the context of the theory of strong interactions. As well as its intrinsic interest, this has important implications for the understanding of new physics signatures at the LHC. The HERA upgrade, which is about to be completed, will increase the luminosity by a factor of five and provide longitudinally polarised electrons and positrons. The detectors are also undergoing major upgrades. The new physics programme opened up by these upgrades is expected to take at least four years to complete. A lepton-deuteron run, as well as a dedicated run with varying beam energies, are attractive extensions.

6.2 Future possibilities

Several possible extensions to the HERA programme can address specific areas. One extension would be the acceleration of heavy ions rather than protons. The provision of polarised protons would extend our knowledge of the angular momentum structure of the proton to a completely unexplored region. However, both of these options, in particular the polarisation of protons, would require considerable investment in both infrastructure and machine-physics development, the possibility of which is highly dependent on the future research strategy at DESY. Facilities for both polarised proton and polarised electron-nucleus interactions are under consideration for RHIC at Brookhaven in the US, although the collision energy would be a factor of three below that of HERA.

There are several possibilities for future lepton-proton facilities at collision energies well beyond that of HERA. One is to re-insert an electron or positron ring into the LHC tunnel to produce electron-proton or electron-nucleus collisions at a collision energy of up to 1.7 TeV. Another option, called THERA, which has recently been studied, is to collide electrons from the proposed TESLA linear collider with protons in the HERA ring, thus producing a collision energy of about 1 TeV. The physics potential of such a machine is considerable but limited by the attainable luminosity. Because of its much more symmetric beam energies, as well as the considerable increase in energy, THERA would increase the HERA kinematic range by a factor of ten.

Lepton-proton physics can also be carried out at a neutrino factory. The neutrino flux, which would be approximately 10^4 times higher than at conventional accelerators, would allow qualitatively new investigations on both polarised and un-polarised nucleons.

6.3 Assessments and Comments of the Working Group

Lepton-hadron scattering has played a major role in the understanding of the nucleon structure and of the theory of strong interactions. Depending on what discoveries will be made at the LHC and a linear collider, the case for a new dedicated lepton-hadron facility may again become strong.

7. SUMMARY AND RECOMMENDATIONS

7.1 Approved projects: LHC

The LHC project and its experiments at CERN are now in an advanced state of construction. They will start operation in 2006 and are expected to continue for at least 15 years. The experimental data will open the exploration of a new energy domain and will revolutionise our understanding of particle physics. **The Working Group recommends the allocation of all necessary resources to fully exploit this unique and pioneering facility .**

7.2 Support of running experiments

Despite the necessary concentration of resources to build the LHC, a limited number of excellent experiments are continuing operation in the period prior to commissioning of the LHC. **The Working Group recommends continued support for ongoing experiments. They promise significant scientific results, provide an optimal physics return on previous investment, and are vital for the education of young physicists.**

7.3 The case for the next project

On the basis of the physics discussions presented in this report, the Working Group is convinced that there is a strong physics case for precision measurements in the mass range extending from the Z boson to beyond the top-quark pair-production threshold (90 to at least 400 GeV). This can be best achieved using a high-luminosity e^+e^- linear collider.

Such a machine would allow a detailed study of the properties of a low-mass Higgs boson ($m_{Higgs} < 250$ GeV). Due to its high luminosity and to the clean experimental environment, this machine would clarify in a very effective way the findings of the LHC and would provide unique complementary measurements of the Higgs boson properties, similar to the way LEP elucidated the Z-boson sector. Even if no Higgs boson were found in this mass range, this machine would give vital clues to understand why the present precision measurements conspire to predict its existence below 200 GeV. If new particles exist in this energy range, as predicted by supersymmetry, this machine would provide an exciting programme of definitive measurements of their properties.

The international community has devoted a large R&D activity to the design of this machine and has demonstrated its feasibility, as shown by the recent TDR produced for the TESLA project. Therefore, **the Working Group recommends the realisation, in as timely a fashion as possible, of a world-wide collaboration to construct a high-luminosity e^+e^- linear collider with an energy range up to at least 400 GeV as the next accelerator project in particle physics. The Working Group urges the appropriate bodies to make decisions concerning the chosen technology**

and the construction site for such a machine soon. An upgrade of the collider energy may become desirable in the light of the results obtained during the first years of LHC operation and should therefore be anticipated.

7.4 Accelerator R&D

The size and complexity of high-energy particle accelerators results in the need for long and intensive R&D programmes. Typically 20 years are necessary to proceed from the first concrete ideas to the completion of such accelerator projects. The realisation of any future accelerator depends on R&D that is undertaken today. The working group noted, however, that this discipline is presently largely absent from most European universities, with the result that PhD students and post-doctoral physicists, who are the best candidates to inject new and fresh ideas, are in limited supply. The Working Group also noted that resources available at CERN for R&D on future accelerators are very scarce. **The Working Group recommends an improved educational programme in the field of accelerator physics and increased support for accelerator R&D activity in European universities, national facilities and CERN.**

7.5 Neutrino factories

Recent results on the properties of neutrinos, indicating the existence of flavour oscillations, motivate the development of more powerful and selective neutrino sources. Conceptual studies of possible muon storage rings which could achieve these goals have been recently performed taking advantage of previous international R&D activities towards muon colliders.

The Working Group recommends a coordinated collaborative R&D effort to determine the feasibility and practical design of a neutrino factory based on a high-intensity muon storage ring.

A basic tool for this activity is the availability of a powerful proton drive beam. The Working Group was pleased to see the advanced stage of design studies for such an accelerator, the SPL, at CERN in collaboration with several European laboratories. The working group notes that all CERN activities (LHC, ISOLDE, AD, neutron-TOF beam and CNGS) would substantially benefit from this machine.

7.6 The High-Energy Frontier

It is impossible to predict what the LHC will discover. Perhaps supersymmetry will become a reality, with the discovery of some of the super-partners of ordinary particles. Alternatively, a completely different mechanism may give indications of strong WW interactions or of extra spatial dimensions.

The LHC will surely reveal the answers to many of these fundamental questions, but many will remain and other questions will arise. This makes the eventual exploration of the multi-TeV region mandatory.

Several options are being studied: specifically a proton-proton collider in the 100 TeV energy region (VLHC), and lepton colliders of several TeV.

a) The VLHC

Given its extraordinarily large size (more than 200 km in circumference) and the strong magnetic field required, extensive R&D will be necessary to reduce the cost per unit length to a realistic level. If important break-throughs show the feasibility of this collider and of experiments able to operate at this energy and at the required high luminosity, such an option might become the natural step beyond LHC to explore the high-energy frontier.

b) Multi-TeV Lepton Colliders

At the same time, studies aiming at a multi-TeV lepton collider should be pursued, either as an alternative option to the VLHC or as a complement to it.

Currently two development options are being followed.

1) The R&D activity devoted at CERN to the study of the CLIC multi-TeV e^+e^- linear collider has demonstrated the feasibility of power transfer from a low- energy, high-intensity drive beam to the main beam at high frequency. Important R&D is still needed to show with a system test that a much longer structure behaves as expected, and to understand the final focus. If these fundamental steps can be successfully achieved within this decade, CLIC has the potential of being an excellent candidate for a lepton collider in the multi-TeV energy range.

2) A muon collider would have unique characteristics at low energy as a Higgs boson factory and at high energy for the detailed study of the physics beyond the Standard Model. However, the design of this accelerator is based on new and unproven technologies, in particular very efficient ionisation cooling. A large and comprehensive R&D activity is required. The first fundamental answers to these questions should be provided by R&D towards a neutrino factory.

   It is too early to assess the feasibility, cost and time-scale of this project. The R&D that is necessary to give clear answers to these questions will take longer than for the competitive projects described above. However, the potential interest of this collider justifies a methodical experimental study of its various steps.

On the basis of the discussion outlined above, **the Working Group recommends a coordinated world-wide R&D effort to assess the feasibility and estimate the cost of a CLIC, a VLHC, and a muon collider. In particular, R&D for CLIC is well advanced and should be vigorously pursued.** In 10 years from now the amount of experimental information collected in this work and the scenario of particle physics resulting from studies at the LHC should allow a choice on the next world-wide project to pursue the exploration of the multi-TeV mass range.

7.7 Final word

In conclusion, the Working Group believes that these recommendations would ensure a vibrant and exciting programme of investigations into the fundamental structure of the universe. They should be realised on a world-wide basis.

For the immediate future, the LHC is likely to revolutionise our present understanding of particle physics. The next step involves a linear e^+e^- collider built as an international effort. Europe has already played a leading role in this area with the publication of the TESLA TDR.

The central role of CERN in Europe must continue and will be essential as the fulcrum of the long-term future of particle physics. The Working Group considers it essential that, through CERN, Europe should be able to play a key role in the exploration of the multi-TeV horizon that will open in the post-LHC era.

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APPENDIX 1. MEMBERSHIP OF THE WORKING GROUP

Chairman:	L. Foà		
Members:	R. Aleksan	representing	France
	F. Barreiro		Bulgaria, Greece, Portugal, Spain
	S. Bethke		Germany
	A. Blondel		Switzerland
	F. Ceradini		Italy
	B. Foster		United Kingdom
	J.R. Hansen		Denmark, Finland , Norway, Sweden
	D. Kuhn		Austria, Czech Republic, Hungary, Poland, and the Slovak Republic
	F. Linde		Belgium, Netherlands and Israel
Secretary:	A. Clark		

APPENDIX 2. MEETINGS OF THE WORKING GROUP AND PRESENTATIONS TO THE WORKING GROUP

The Working Group met ten times in the period 29 August 2000 to 5 July 2001. The meetings are listed below. Presentations by representatives of major ongoing or future physics programmes to the Working Group are also listed below. Transparencies of those presentations are accessible at the Web address:

http://committees.web.cern.ch/Committees/ECFA/wghep/wgmeetings.html.

Meeting 1 29 August 2000, CERN.

This meeting was restricted to internal discussions

Meeting 2 29 November 2000, DESY.

This meeting was dedicated to presentations of the existing and planned DESY Physics programme, and to the physics motivation for future lepton-hadron or lepton-lepton Colliders. The following presentations were made:

a) R. Klanner, DESY	“Future Perspectives for $e^{\pm}$-p Physics”
b) D. Miller, London	“Physics Potential and Concrete Perspectives for <1 TeV Linear Colliders”
c) A. Wagner, DESY	“Views on the Future of DESY”
d) P. Zerwas, DESY	“Multi-TeV Lepton Colliders: the Physics Potential”

Meeting 3 29 –30 January, CERN.

This meeting was dedicated to presentations of the existing and planned CERN Physics programme, and to the physics motivation and development status for multi-TeV lepton-lepton or hadron-hadron Colliders. The physics potential and development status of muon storage rings to create intense neutrino beams was also discussed. The following presentations were made:

a) L. Maiani, CERN	“CERN: Views for the Future”
b) J-P Delahaye, CERN	“CLIC, a Two Beam Multi-TeV $e^{\pm}$ Linear Collider”
c) A. de Roeck, CERN	“CLIC, a Compact Linear Collider: Experimentation and Physics Potential”

d) K. Hübner, CERN	"New Acceleration Methods and Plans for High Intensity Proton Machines and VLHC"
e) K. Peach, RAL	"Neutrino Factories"
f) M. Tigner, Cornell	"Perspectives and Experimental Environment of a Muon Collider"

Meeting 4 21 –22 February, 2001, CERN

The working group listened to presentations by P. Sphicas and F. Gianotti on the Physics Potential of the LHC, and of the physics potential of possible future upgrades to the LHC. In addition P. Janot described the advantages of a sub-TeV muon collider, and A. Skinsky gave the viewpoint of the Russian Particle Physics community.

a) F. Gianotti, CERN	"Physics Perspectives with the LHC within the Minimal Standard Model"
b) P. Sphicas, CERN	"Physics Perspectives with the LHC: SUSY and other physics beyond the Minimal Standard Model"
c) P. Janot, CERN	"What Physics at Muon Colliders?"
d) A. Skrinsky, Budker	"Russian HEP Activity: Status and Perspectives"

Meeting 5 23 March, 2001, DESY

The working group attended the presentation of the TESLA Technical Design Report at DESY. The working group also listened to the viewpoint of the American particle physics community.

a) J. Bagger, Johns Hopkins	"HEPAP Sub-Panel on Long Range Planning for U.S. High Energy Physics"
b) F. Gilman, Carnegie-Mellon	"The U.S. High Energy Physics Advisory Panel White Paper"

Meeting 6 4 April, 2001, CERN

This meeting was devoted to internal discussions.

Meeting 7 8-9 May, 2001, CERN

This meeting was devoted to internal discussions.

Meeting 8 1 June 2001, DESY

This meeting was devoted to internal discussions.

Meeting 9 29 June 2001, CERN

The Working Group listened to the viewpoint of the Japanese community.

a) S. Komamiya "Report on ACFA activities"

Meeting 10 5 July 2001, CERN

Final discussions and editing of the Working Group report.

A draft report was discussed at meetings of Restricted and Plenary ECFA on respectively July 13 and July 14, 2001. Comments on the draft report were received by the Working Group until August 20, and were taken into account in the final report. The above report was discussed and endorsed at a meeting of Restricted ECFA, on September 8, 2001.