CERN and the Future of Particle Physics

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Abstract. With the start-up of the Large Hadron Collider, particle physics is entering into an exciting period of research and discovery with high prospects for exciting advances in our understanding of Nature. The results from the initial running at the LHC will provide the directions for the future of particle physics and as host to the LHC, CERN is in a unique position to play a key role in the future course of particle physics. Future major facilities in particle physics require the formation of collaborations on a global scale, and to this end organisational structures are being put in place to oversee such extended endeavours. This paper reviews the characteristic features of particle physics and analyses the routes to be taken for the future advancement of the field.

1. Features of Particle Physics

Furthering our understanding of key questions in particle physics has relied on the interplay and synergy between various particle sources, such as accelerators, cosmic-rays and reactors, and a range of facilities, such as a lepton collider, a hadron collider and a lepton-hadron collider, at both the energy frontier and the intensity frontier. Of much topical interest presently is the synergy of lepton and hadron colliders in the elaboration of the origin of mass of elementary particles and the search for the Higgs boson. This interplay will continue to be central in extending our knowledge in other areas, such as the unification of forces, the fundamental symmetry of forces and matter, the number of space-time dimensions and the understanding of dark matter and energy. In addition to the development of the particle accelerators and particle detectors, advances in theoretical calculations should proceed in parallel.

Furthermore, the duration of large particle physics projects is measured in decades, from the time of making the initial science case, through the conceptual phase, R&D and design, to the final realisation and exploitation. These long-term projects serve as excellent training grounds, as they incorporate advanced and complex accelerator and detector technologies as well as high-performance computing. For example, preliminary performance estimates for a proton collider in the LEP tunnel were published in 1983 [1] and this was followed by the first LHC physics workshop in 1984. The long duration requires the timely development of the driving technology and a long-term strategy and stability of funding and course of action.

2. The European strategy for Particle Physics

European particle physics is founded on strong national institutes, universities and laboratories, working in conjunction with CERN. The increased globalisation, concentration and scale of particle physics require a well-coordinated European strategy. This process started with the establishment of the CERN Council Strategy Group, which organised an open symposium in...
Orsay in January 2006, a final workshop in Zeuthen in May 2006 and with the final strategy document being signed unanimously by CERN Council in July 2006.

The European Strategy for Particle Physics [2] includes several key areas. The highest priority rests with exploiting fully the physics potential of the LHC at its design performance. In parallel, a vigorous R&D programme for the LHC accelerator and detectors needs to be pursued with the aim of increasing the LHC luminosity, once motivated by the operation experience and findings at the LHC, by up to a factor of ten from the nominal design value of $10^{34}$ cm$^{-2}$s$^{-1}$, within the so-called super LHC (sLHC) effort. To this end, the 240 MCHF additional CERN funding during the years 2008–2011 will be partly used by CERN to gradually increase the performance of the LHC towards the sLHC specifications. This effort will be undertaken in stages. The first one will include new inner triplets around the ATLAS and CMS experiments and the construction of the new LINAC4. For the second stage, R&D for a Superconducting Proton Linac (SPL) and for a new PS2 accelerator is ongoing. It is very important that this effort is carried out within the framework of international collaborations.

The Strategy considers it to be imperative to complement the results of the LHC with a linear electron-positron collider. In the energy range up to around one TeV the International Linear Collider, ILC, based on superconducting technology, will provide a unique scientific opportunity. In addition, a co-ordinated effort should be intensified to develop the technology for a Compact Linear Collider (CLIC) to reach collision energies of several TeV. Furthermore, studies for the development of a high-intensity neutrino facility should be pursued with the aim of ensuring a co-ordinated European participation in a global neutrino programme.

3. THE Large Hadron Collider
The LHC first beam on 10 September 2008 and the period of beam commissioning in the days immediately after were a great success for both the machine and the experiments. However, the complete commissioning of the LHC machine and detectors, which are of unprecedented complexity, technology and performance, will be one of the biggest challenges in the next year and operation at the nominal luminosity will need continued effort. Recovery from the incident of 19 September 2008 is well underway and the LHC is expected to re-start again later in 2009. The incident was caused by a faulty electrical connection between two of the LHC accelerators magnets, resulting in mechanical damage due to a release of helium from the magnet cold mass into the tunnel.

The initial phase of the LHC experiments need sustained international collaboration and the experiments require continued assurance of manpower for the complete commissioning. Only with fully-commissioned LHC experiments will the new physics be able to be explored and the future directions of particle physics be gauged. Possibilities for exploring Nature beyond the LHC include the sLHC, a doubling of the LHC energy (DLHC), an electron-positron linear collider (ILC or CLIC) and a Large Hadron electron Collider (LHeC).

4. Future high-energy linear colliders
4.1. The Compact Linear Collider (CLIC)
Design of the CLIC high-energy collider is well underway [3]. The CLIC concept is based on a novel two-beam acceleration scheme, whereby the high acceleration gradient of about 100 MV/m is obtained from normal-conducting acceleration structures at high frequency, resulting in a linear collider of total length 50 km at 3 TeV centre-of-mass energy. It is the aim of the CLIC team to demonstrate all key feasibility issues and document them in a Conceptual Design Report by 2010 and to prepare a Technical Design Report earliest by 2015.
4.2. The International Linear Collider (ILC)

The ILC [4] is based on an accelerating system using superconducting standing wave cavities with a nominal accelerating field of 31.5 MV/m and a total length of 31 km at 500 GeV centre-of-mass energy, extendable to around 1 TeV. A two-stage technical design phase during 2010–2012 is presently underway.

A major contribution from Europe and from DESY to the ILC Global Design Effort is the European X-ray Laser Project XFEL at DESY [5]. The purpose of the facility is to generate extremely brilliant and ultra-short pulses of spatially-coherent X-rays. The electron energy is brought up to 20 GeV by a superconducting linac of length one-tenth that of the ILC superconducting linac. The project has much in common with the ILC. The strategy to address key issues common to both linear colliders involves close collaboration between ILC and CLIC. Recent progress has been encouraging in this respect and a first common meeting between ILC and CLIC was held in February 2008.

4.3. Detector challenges

R&D on key components of detectors for CLIC or the ILC is mandatory and is well underway. In particular, high-precision measurements demand a new approach to the reconstruction. In view of this, the particle flow method, i.e. the reconstruction of all particles in the event, is thus proposed and requires unprecedented granularity in three dimensions within all detector elements.

5. Electron-proton colliders

A possible electron-proton collider (LHeC) has been proposed as a successor to HERA at a higher centre-of-mass energy with the aim of studying QCD with high precision, electron-quark spectroscopy, quark substructure and high-density matter. The European Committee for Future Accelerators (ECFA) has recently endorsed a series of workshops for the study of electron-proton collisions in the LHC. Work towards a Conceptual Design Report is advancing with the aim of submission in 2010. LHeC’s electron energy would be between 40 GeV and 140 GeV while the proton energy would be between 1 TeV and 7 TeV. A lay-out based on electron and hadron rings with a luminosity reaching $10^{33}$ cm$^{-2}$s$^{-1}$ and a lay-out based on an electron linac and a hadron ring with a luminosity reaching a few times $10^{31}$ cm$^{-2}$s$^{-1}$ are under study.

6. The neutrino sector

Significant progress has been achieved in neutrino oscillation physics during the last years. However, the reason for the smallness of the $\theta_{13}$ neutrino mixing angle still remains an open issue. The T2K project [7] in Japan has the primary goal of measuring for the first time the mixing angle $\theta_{13}$ by observing the appearance of electron-type neutrinos from an initial beam of muon-type neutrinos that have traversed 295 km between J-PARC in Tokai and Super-Kamiokande. Moreover, $\theta_{13}$ will be measured at reactor-based neutrino experiments like Double Chooz [8], by measuring the survival probability of the electron antineutrinos emitted from the nuclear power plant. First indications of $\theta_{13}$ should be available in 2012 at either T2K or e.g. at Double Chooz.

In parallel, an International Scoping Study (ISS) for a Neutrino Factory [9] is progressing with the aim of producing a Reference Design Report by 2012 when the first indications of $\theta_{13}$ are available at either T2K or at Double Chooz. The Neutrino Factory would consist of a proton driver delivering the primary beam on a production target; a target and capture channel producing the pions and kaons which subsequently decay to muons; a cooling section to reduce the transverse emittance of the muon beam; a muon accelerator with an injection energy of 130 MeV and reaching a top energy of between 20 and 50 GeV; and muon decay ring(s) producing the muon-neutrino beam.
7. Concluding remarks and outlook

A number of trends in particle physics have emerged. Facilities for high-energy physics are becoming larger and more expensive; the overall funding envelope is not growing; the number of facilities being realised are fewer; the time scale for projects is becoming longer; and many laboratories are changing their mission becoming multi-purpose laboratories. Such trends point to the need for more co-ordination and collaboration amongst all stakeholders.

Consistent with the European Strategy for Particle Physics, future major facilities in Europe and elsewhere require a collaborative effort on a global scale. Achieving global collaboration involves maintaining expertise and ensuring long-term stability and support in all regions through national, regional and global projects. It also requires engaging all countries with particle physics communities. To this end the CERN Council Working Group on the geographical and scientific enlargement of CERN has been set up and a CERN Co-ordinator for External Relations has been established. Global collaboration would also require integrating particle physics developing countries and regions. A shift in the approach of the funding agencies is called for with a more global view to be undertaken, with the present Funding Agencies for Large Colliders (FALC) serving as a first step. Finally, a closer linkage between particle physics and astrophysics is to be encouraged.

Particle physics is entering a new and exciting era. The start-up of the LHC will make possible experiments at the highest collision energies. Revolutionary advances in the understanding of the microcosm and grand steps in our view of the Universe are therefore expected.

Results from the LHC will guide the way for the future of particle physics at the energy frontier. The field is now in an exciting era of accelerator planning, design, construction and running. The period of decision taking for the next steps in particle physics are expected during 2010–2012, for both the energy frontier and the neutrino sector. Intensified efforts on R&D and technical design work are needed in order to enable these decisions. This needs to be coupled with the formation of global collaborations and the guarantee of stability of funding on long time scales. The most appropriate organisational structure needs to be defined now and we need to be open and inventive in this process. It is mandatory to have accelerator laboratories in all regions as partners in the development, construction, commissioning and exploitation of future accelerators. The exciting times ahead should be used to establish such global partnerships.

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