PHYSICS RESULTS AT THE LHC AND IMPLICATIONS FOR FUTURE HIGH-ENERGY PHYSICS PROGRAMMES

Rolf-Dieter Heuer
Director-General, CERN, Geneva, Switzerland

Abstract

This paper presents the latest physics results from the LHC and describes high-energy colliders at the energy frontier for the years to come. The contribution also describes the various future directions, all of which have a unique value to add to experimental particle physics, and concludes by outlining key messages for the way forward.

THE LARGE HADRON COLLIDER PHYSICS PROGRAMME

The Large Hadron Collider (LHC) [1] is primarily a proton-proton collider (see Figure 1) with a design centre-of-mass energy of 14 TeV and nominal luminosity of 10^{34} $cm^{-2}s^{-1}$, but also operated in heavy-ion mode. The high 40 MHz proton-proton collision rate and the tens of interactions per crossing result in an enormous challenge for the experiments and for the collection, storage and analysis of the data.

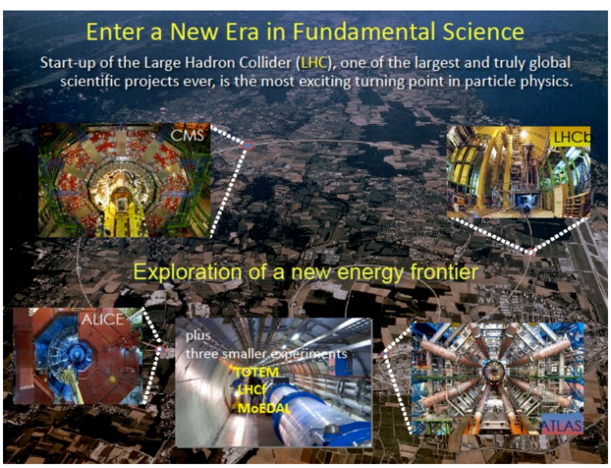

Figure 1: The LHC accelerator and the ALICE, ATLAS, CMS and LHCb experiments. There are also three smaller experiments - LHCf, MoEDAL and TOTEM.

By colliding unparalleled high-energy and high-intensity beams, the LHC is opening up previously unexplored territory at the TeV scale in great detail, allowing the experiments to probe deeper inside matter and providing further understanding of processes that occurred very early in the history of the Universe.

Of central importance to the LHC is the elucidation of the nature of electroweak symmetry breaking, for which the Higgs mechanism and the accompanying Higgs boson(s) are presumed to be responsible. In order to make significant inroads into the Standard Model Higgs boson search, sizeable integrated luminosities of several fb^{-1} are needed. However, even with a few fb^{-1} per experiment, discovery of the Standard Model Higgs boson is still possible in mass regions beyond the lower limit of 114.4 GeV from direct searches at LEP2.

Moreover, the reach for new physics at the LHC is considerable already at LHC start-up. In Supersymmetry (SUSY) theory, due to their high production cross-sections, squarks and gluinos can be produced in significant numbers even at modest luminosities. This would enable the LHC to start probing the nature of dark matter.

All LHC experiments are taking data of excellent quality and with high efficiency and they have been coping well with multiple interactions per crossing. The physics analyses have so far re-measured the science of the Standard Model of Particle Physics, in many instances superseding limits set at the Tevatron while taking the LHC's first steps into new territory. As a result, a plethora of physics papers were published and conference presentations were made by the LHC experiments. The performance of the Worldwide LHC Computing Grid (WLCG) is also outstanding, exceeding the design bandwidth and allowing a very fast reconstruction and analysis of the data.

ATLAS has produced a rich set of physics results. The ATLAS search for the Standard Model Higgs boson is well underway, with ATLAS currently reporting an excess of events being observed around a Higgs mass of ~126 GeV. ATLAS has also performed a variety of searches for physics beyond the Standard Model and has placed stringent limits. SUSY limits are now approaching 1 TeV or beyond in many search channels, while mass limits on singly-produced new particles from other non-Standard-Model scenarios are beyond 1-2 TeV in many cases. Thus far, no significant signs of non-Standard-Model physics have been shown. ATLAS has an impressive top quark programme, releasing a broad variety of results, including top quark mass and cross-section results as well as its own observation of "single-top" produced through the electroweak interaction. There are ATLAS papers on a range of QCD and electroweak physics, including recently a broad range of di-boson results, diffractive physics, as well as a successful heavy-ion set of publications.

CMS has also produced a plethora of physics results. The CMS search for the Standard Model Higgs boson is well underway, with CMS currently reporting an excess of events being observed around a Higgs mass of ~124-125 GeV. The physics analyses are going well—with results shown for top, SUSY, Exotics, and Higgs channels as well as a successful heavy-ion set of publications. Results from CMS show that SUSY limits are now approaching 1 TeV or beyond in many search channels. CMS has also published results on a range of QCD and electroweak physics, including recently a broad range of di-boson results, diffractive physics, as well as a successful heavy-ion set of publications.

The main physics results of LHCb include the world's best measurements of Br($B_s \rightarrow \mu+\mu-$) < 1.5 × 10^{-8} (95% C.L.), thus vastly improving the exclusion plots for simple TeV-scale SUSY models at large tan(β), which now look practically ruled out; of ϕ_s (phase of the B_s oscillation amplitude) at ±0.18 rad; of the forward-backward asymmetry A_{FB} in $B \rightarrow K^*\mu+\mu-$ and the first evidence of CP violation in D→KK, D→ππ charm decays.

The ALICE experiment has produced results of considerable interest, such as new findings on flow, on the production of heavy quarks and on the energy loss of fast partons in Pb-Pb collisions. New proton-proton physics results include measurement of the inclusive J/ψ production cross-section at 2.76 TeV centre-of-mass energy (CME), measurement of J/ψ polarisation at 7 TeV CME, inclusive D-meson production cross sections at 7 TeV CME, the observation of Λ_c at 7 TeV CME and J/ψ production versus charged particle multiplicity in proton-proton collisions at 7 TeV CME. First results from the Pb-Pb running show that J/ψ statistics will be sufficient for a measurement of the elliptic flow. Increased statistics for open charm will provide an improved measurement of the nuclear modification factor R_{AA} and of the elliptic flow v2 for heavy flavours.

In addition, the smaller of the LHC experiments have also made considerable progress. TOTEM has measured the total, elastic and inelastic cross-sections in proton-proton collisions. The LHCf measurement of the zero degree single photon energy spectra was completed. The MoEDAL monopole-search experiment installed a subset of their Nuclear Track Detectors.

The LHC is poised to clarify the mechanism by which elementary particle acquire mass. A definitive answer will have to wait for the 2012 LHC run. Either way, finding or excluding the Standard Model Higgs boson will be a discovery.

THE LHC MACHINE

The performance of the LHC machine has been outstanding, delivering integrated luminosities considerably exceeding expectations for both the proton-proton and Pb-Pb running and matched by record peak luminosities. In proton-proton mode, the LHC machine delivered an integrated luminosity exceeding 5 fb^{-1} to each experiment ATLAS and CMS in 2011, significantly above the 1 fb^{-1} goal for 2011 and with record instantaneous luminosities exceeding 3 × 10^{33} cm^{-2} s^{-1}. For Pb-Pb running, the LHC machine delivered in 2011 an integrated luminosity of more than 140 μb^{-1}, more than an order of magnitude greater than that in 2010. These record luminosities are due to the increased experience in operating the LHC machine and to the better understanding of the machine's beam dynamics.

The 2012 physics run has started very well, with more than 3 fb^{-1} of data having already been delivered to each of the experiments ATLAS and CMS.

The coming years will lay the foundation for the next decades of high-energy physics at the LHC. The LHC research programme until around 2030 is determined by the full exploitation of its physics potential, consisting of the design luminosity and the high-luminosity upgrade (HL-LHC). Together with R&D on superconducting higher-field magnets for a higher-energy proton collider (HE-LHC), if necessitated by the physics, these initiatives will position CERN as the laboratory at the energy frontier.

LHC Consolidation

The state of the LHC has continuously been evaluated, leading to the following decisions:

- The LHC will be operated during 2012 with the aim of reaching an integrated luminosity at least 15 fb^{-1} at 4 TeV/beam for each of the experiments ATLAS and CMS. A proton-Pb heavy-ion run is scheduled for the end of the year and will be of about 4-weeks' duration.
- This 2012 operations period will be followed by a long shutdown (of about 20 months beam-to-beam) starting at the end of 2012 to repair and consolidate the inter-magnet copper-stabilizers (splices) to allow for safe operation up to 7 TeV/beam for the lifetime of the LHC.
- In the shadow of the inter-magnet copper-stabilizer work, the installation of the pressure rupture disks (DN200) will be completed and around 20 magnets which are known to have problems for high energy will be repaired or replaced. In addition, PS and SPS consolidation and upgrade work will be carried out.

High Luminosity LHC

The next few years of LHC operation will lay the foundations for the next 20 years of high-energy physics at the LHC:

- In the years 2015 through 2017, the LHC will be operated starting at 6.5 TeV/beam and progressively increased towards 7 TeV/beam with increased intensities and luminosities.
- In 2018, the next long shutdown is scheduled to connect LINAC4 [2], to complete the PS Booster energy upgrade, to finalise the collimation system enhancement and to install LHC detector improvements. After this shutdown, a further period of three years of LHC operation at 7 TeV/beam and at least the design luminosity is planned (with short technical stops around the end of each year).
- Maintenance and improvements will be made continuously, including modifications to elements in the insertion regions of the machine whose performance will have deteriorated due to radiation effects, such as the inner triplet quadrupole magnets.

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These items are needed to ensure the LHC exploitation and are part of the high-luminosity performance improving consolidation.

- The ambitious longer-term plans include a total integrated luminosity of the order of up to 3000 fb^{-1} (on tape) by the end of the life of the LHC. This HL-LHC implies an annual luminosity of about 250-300 fb^{-1} in the second decade of running the LHC. The HL-LHC is scheduled for the 2022 long shutdown and it is expected that the upgrade will be partially funded from considerable external contributions through international collaboration.
- LHC detector R&D and upgrades to make optimal use of the LHC luminosity.

Higher Energy LHC

Increasing the beam energy beyond the 7 TeV nominal energy of the LHC can be obtained by raising the mean field in the dipole magnets. The main parameter of the HE-LHC machine is the 16.5 TeV beam energy, and is based on the hypothesis of substituting all the present dipoles with new, more powerful ones, capable of operating at 20 T with beam. The success of the HE-LHC study depends critically on the success of the magnet R&D to reach dipole fields around 20 T in a useful bore. Despite the variety of superconducting materials and the continuous new discoveries, the practical superconductors (i.e. with good physics characteristics, good workability and suitability to cabling) are limited. The candidate materials are NbTi, Nb_3Sn, Nb_3Al and high-temperature superconductor (HTS). Additional open issues that require continuing R&D include high-gradient quadrupole magnets for the arcs and the interaction regions; fast-cycling superconducting magnets for a 1-TeV injector; emittance control in the regime of strong synchrotron damping; cryogenic handling of the synchrotron radiation heat load; and a study of the dynamic vacuum. The HE-LHC studies have started at CERN within an international collaboration and a first estimate provides a timeline of between 2030-2033 to start the realisation of the HE-LHC machine project.

COLLIDERS AT THE ENERGY FRONTIER BEYOND THE LHC

Great opportunities are in store at the TeV scale and a fuller understanding of Nature will come about through a clearer insight at this energy level. The LHC will provide a first indication of any new physics at energies up to several TeV. First results from the LHC will be decisive in indicating the direction that particle physics will take in the future. Many of the open questions left by the LHC and its upgrades may be addressed best by an electron-positron collider, based on technology developed by the Compact Linear Collider (CLIC) [3] and International Linear Collider (ILC) [4] collaborations. Options for a high-energy electron-proton collider (LHeC) [5] and a muon collider [6] are also being considered. As in the past, there is a synergy between collider types that can be used to advantage. The discovery of the Standard Model over the past few decades has advanced through the synergy of hadron-hadron (e.g. SPS and the Tevatron), lepton-hadron (HERA) and lepton-lepton colliders (e.g. LEP and SLC). Such synergies should be continued in the future and thus a strategy has been developed along these lines. The above effort on accelerators should advance in parallel with the necessary detector R&D.

Linear Electron-Positron Collider

The Compact Linear Collider (CLIC) CLIC is based on using lower-energy electron beams to drive high-energy electron and positron beams (see Figure 2). The fundamental principle is that of a conventional AC transformer. The lower-energy drive beam serves as a radiofrequency source that accelerates the high-energy main beam with a high accelerating gradient. The nominal centre-of-mass energy is up to 3 TeV, the nominal luminosity exceeds 10^{34} $cm^{-2}s^{-1}$, the main linear accelerator frequency is 12 GHz, the accelerating gradient is 100 MeV/m and the total length of the main linear accelerators is up to 48.3 km.

The mandate of the CLIC team is to demonstrate the feasibility of the CLIC concept, to be published by 2012 in a Conceptual Design Report. If this effort is successful, and if the new physics revealed by the LHC warrants, the next phase of R&D on engineering and cost issues will be launched. This would serve as the basis for a Technical Design Report and a request for project approval.

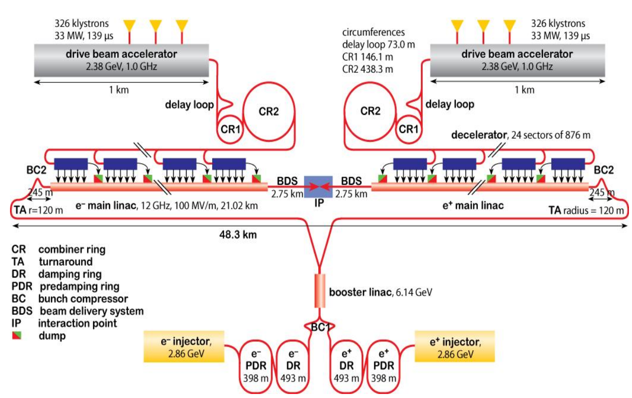

Figure 2: The CLIC general lay-out.

The International Linear Collider (ILC) The ILC is an option for a linear electron-positron collider at lower energies than CLIC and is based on a more conventional design for acceleration using superconducting standing wave cavities with a nominal accelerating field of 31.5 MeV/m and a total length of 31 km at 500 GeV centre-of-mass energy (see Figure 3). A two-stage technical design phase during 2010-2012 is presently underway, culminating in a Technical Design Report.

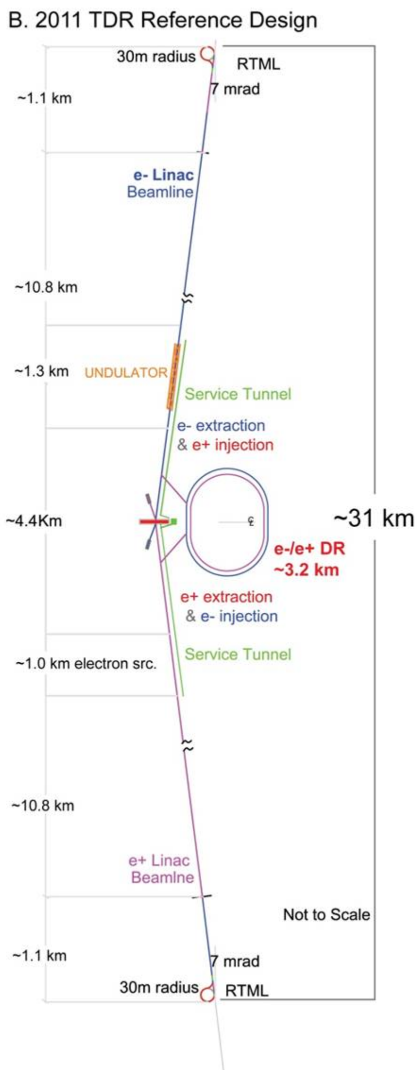

Figure 3: The ILC general lay-out.

Towards a Single Linear Collider Project The strategy to address key issues common to both linear colliders involves close collaboration between ILC and CLIC. Such close collaboration facilitates the exchange of concepts and R&D work between the ILC and CLIC in the future. In the meantime, items to be addressed as a matter of high priority for both linear collider projects include the construction costs, power consumption and value engineering.

Detectors Challenges R&D on key components of the detector for a linear collider is mandatory and is also well underway. High-precision measurements demand a new approach to the reconstruction. Particle flow, namely reconstruction of all particles, is thus proposed and requires unprecedented granularity in three dimensions of the detection channels.

Lepton-Hadron Collider

The option of a high-energy electron-proton collider - the Large Hadron Electron Collider (LHeC) - is being considered for the high-precision study of QCD and of high-density matter at the energy frontier. The LHeC design consists of an electron beam of 60 GeV (to possibly 140 GeV) colliding with protons of 7 TeV energy from the LHC. Assuming an electron-proton design luminosity of about 10^{33} cm^{-2} s^{-1}, the LHeC could exceed the corresponding HERA values of integrated luminosity by two orders of magnitude and the kinematic range by a factor of 20 in the four-momentum squared Q^2 and in the inverse Bjorken x. Both a ring-ring option - consisting of a new ring in the LHC tunnel with bypasses around the LHC experiments - and a linac-ring option - based on a re-circulating linac with energy recovery or on a straight linac - are being considered.

Muon Collider

Another proposal as a successor to the LHC is a muon collider [6]. The collider would accelerate muons, which are about 200 times heavier than electrons, into beams that would collide with each other. A benefit of muons over electrons is that, since they are heavier, they do not emit as much electromagnetic radiation in the form of synchrotron radiation (and thus lose less energy) when going around a circular accelerator ring. The muon collider would consist of a compact facility accelerating muons with re-circulating linacs. The major challenges include muon generation and cooling; cost efficient acceleration; and backgrounds from muon decays.

Generic Accelerator R&D

In addition to continuing focused R&D on the above collider projects, R&D should also be supported for generic accelerator studies. For example, R&D for high-power proton sources, such as the high-power superconducting proton linac (HP-SPL), in line with European participation in neutrino physics, should continue. Moreover, studies for novel acceleration techniques based on plasma acceleration is mandatory, as such machines could potentially provide the high acceleration gradients to reach the high energies required by the physics at future colliders.

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 early 2006, a final workshop in Zeuthen in May 2006 and with

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the strategy document being signed unanimously by Council in July 2006 in Lisbon [7]. CERN considers that experiments at the high-energy frontier to be the premier physics priority for the coming years. This direction for future colliders at CERN follows the priorities set in 2006 by the CERN Council Strategy Group. The first years of LHC operation are seeing the start of the LHC physics exploitation leading to important input for the update of the European strategy for particle physics planned for 2012-2013.

KEY MESSAGES

Particle physics will need to adapt to the evolving situation. Facilities for high-energy physics (as for other branches of science) are becoming larger and more expensive. Funding for the field is not increasing and the timescale for projects is becoming longer, both factors resulting in fewer facilities being realised. Moreover, laboratories are changing their missions.

All this leads to the need for more co-ordination and more collaboration on a global scale. Expertise in particle physics needs to be maintained in all regions, ensuring the long-term stability and support through-out. It would be necessary to engage all countries with particle physics communities and to integrate the communities in the developing countries. The funding agencies should in their turn provide a global view and synergies between various domains of research, such as particle physics and astroparticle physics, should be encouraged.

Particle physics has entered a new and exciting era. The start-up of the LHC allows particle physics experiments at the highest collision energies. The expectations from the LHC are great, as it would provide revolutionary advances in the understanding of the microcosm and a fundamental change to our view of the early Universe. Due to the location of the LHC, CERN is in a unique position to contribute to further understanding of the microcosm in the long term.

Results from the LHC will guide the way in particle physics for many years. It is expected that the period of decision-making concerning the energy frontier will be in the next few years. Particle physics is now in an exciting period of accelerator planning, design, construction and running and would need intensified efforts in R&D and technical design work to enable the decisions for the future course and global collaboration coupled with stability of support over long time scales.

The particle physics community needs to define now the most appropriate organisational form and needs to be open and inventive in doing so, and it should be a dialogue between the scientists, funding agencies and politicians. It is mandatory to have accelerator laboratories in all regions as partners in accelerator development, construction, commissioning and exploitation. Furthermore, planning and execution of high-energy physics projects today require world-wide partnerships for global, regional and national projects, namely for the whole particle physics programme. The exciting times ahead should be used to advantage to establish such partnerships.

CONCLUSIONS

In this paper, we have reported on the latest physics results from the LHC and described high-energy colliders at the energy frontier for the years to come, such as the status and future plans of the LHC machine and experiments and also presented the strategy for future electron-positron linear colliders, an electron-proton collider and a muon collider.

The past decades have seen precision studies of 5% of the Universe, which has led to the discovery and study of the Standard Model. Now, the LHC is delivering data and particle physics is at the beginning of exploring the remainder 95% of the Universe.

ACKNOWLEDGEMENTS

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