

ROADMAP(S) FOR PARTICLE PHYSICS*

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During the last three years, various regional strategies for particle physics have been formulated. The highlights of the proposals will be briefly reviewed.

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1. Introduction

For many decades, experimental particle physics has been characterised by projects realised in international cooperation. With very ambitious scientific programmes and particle beams reaching higher and higher energies and intensities, accelerators are becoming even more sophisticated and very expensive. It further enhances the importance of international collaborations not only for performing experiments, but also for constructing accelerators. The Large Hadron Collider (LHC) at CERN with experimental groups from institutions located in more than 70 countries all over the world, participating in its experimental programme, is the first truly global accelerator. High Luminosity LHC (HL-LHC) should be global already in its construction phase, while International Linear Collider (ILC), since its design, has been realised in the framework of a global collaboration.

Recently developed local and regional strategies for particle physics — in Japan in 2012 [1], in Europe in 2013 [2] and in the U.S. in 2014 [3] — underline the large scale of the future facilities and the need for even stronger international cooperation resulting in the globalisation of experimental particle physics.

The global roadmap concerning a few flagship projects requiring significant resources, sizeable collaborations and sustained commitment of the world-wide particle physics community, is emerging from the regional roadmaps. Some of the highlights of those roadmaps are reviewed below.

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2. LHC and HL-LHC

The LHC experiments have started the data taking for physics analyses in March 2010 after more than two decades of the design and R&D work, prototyping, construction and commissioning of the accelerator and detectors. The LHC Grid had also been developed for processing and storage of an unprecedented amount of data. The LHC collider performance during Run I, which ended in February 2013, for proton–proton (p – p), lead–lead (Pb–Pb) and proton–lead (p –Pb) collisions had exceeded all expectations. The integrated luminosity of about 30 fb^{-1} , collected for p – p collisions at the energy of 7 and 8 TeV by each of the ATLAS and CMS detectors, allowed those experiments not only to discover the Higgs boson [4], confirming in this way the BEH mechanism [5] for acquiring mass by fundamental particles in the Standard Model, but also, based on the common full p – p data samples, to measure the Higgs mass with a precision of a few hundreds of MeV ($m_H = 125.09 \pm 0.21(\text{stat.}) \pm 0.11(\text{syst.}) \text{ GeV}$) [6].

The Long Shutdown 1 (LS1) period, following the Run I, had been dedicated to the large upgrade of the LHC and consolidation of its injectors to run at the LHC maximal design energy of 14 TeV. The Run II began on June 3, 2015 by the first physics data taking at the energy of 13 TeV. The aim of Run II is to collect 100 fb^{-1} of p – p data by each of the ATLAS and CMS experiments. This will allow those experiments to measure better the Higgs boson properties and to enlarge the kinematic region in searches for new particles from beyond the Standard Model. Other important parts of the LHC programme, like the study of flavour physics and the quark–gluon plasma, will also benefit from collecting more data at higher energies.

The European Strategy for Particle Physics [2] says: *Europe’s top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030.* The LHC physics programme concerning the Higgs boson and searches for new particles has also been considered the first priority in the American and Japanese strategies for particle physics. This shows that the common global strategy for particle physics is emerging.

Since the approval of the European Strategy in May 2013, the future upgrades of the LHC have been further elaborated in the framework of the rolling Medium Term Plan of CERN. The ultimate goal of collecting p – p data samples of 3000 fb^{-1} by each of the two large experiments corresponds to several periods of typically three years of data taking interleaved with long shutdowns typically two years long. More information about future LHC upgrades and, in particular, the HL-LHC can be found in the presentation of Siemko at this conference [7].

The key property of the Standard Model Higgs boson is that its couplings to each fermion and boson species are proportional to their mass. The huge amount of data collected at the HL-LHC will allow the measurements of these couplings with a precision of several per cent. This may lead to an observation of discrepancies between the measured values and those predicted by the Standard Model. In the case of no direct observation of particles from outside the Standard Model, this would be an indirect indication of physics beyond the Standard Model. However, this precision will not be sufficient to decide which particular model applies.

3. Post-LHC project for CERN

The long timescale for designing and constructing the new colliders, as illustrated by the LHC, causes that the work on the post-LHC collider for CERN has already been started. This is clearly indicated in the European Strategy document. *To stay at the forefront of particle physics, Europe needs to be in a position to propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy update, when physics results from the LHC running at 14 TeV will be available. CERN should undertake design studies for accelerator projects in a global context, with emphasis on proton–proton and electron–positron high-energy frontier machines.*

The two lines of developments indicated in the Strategy document correspond to the Future Circular Colliders (FCC) and to the e^+e^- Compact Linear Collider (CLIC).

The FCC will primarily be the hadron–hadron collider with the collision energy for p – p of the order of 100 TeV. This very demanding project at the cutting-edge of technology requires the collider tunnel’s circumference of 100 km (baseline, 80 km as an option) for dipole magnet field of 16 T (baseline, 20 T as an option). The e^+e^- circular collider (FCC-ee), aiming at precise studies of the Z , WW , Higgs and $t\bar{t}$ production, is considered as an option. Having two colliders in the same tunnel would allow other combinations of colliding particles, *e.g.* electron–proton collisions (FCC-ep) allowing studies of the proton structure with unprecedented precision. More information about FCC can be found in the presentations of Benedikt [8], Blondel [9] and Klein [10] at this conference.

The CLIC e^+e^- collider is based on the new two-beam acceleration concept where the main electron and positron beams are accelerated by transferring RF power from the high intensity drive beams going parallel to the main beams. This is the only technology which, at affordable cost, but with energy consumption close to socially acceptable limit, can yield e^+e^- collisions at energies above 1 TeV (the CLIC design is optimised for 3 TeV). The CLIC test facility has been developed at CERN for more than twenty

years. The CLIC Conceptual Design Report (CDR) was published in October 2012 [11]. The detailed information about CLIC can be found in Stapnes [12] presentation at this conference.

Since the FCC kick-off meeting on February 12–14, 2014 at the University of Geneva, this concept has quickly gained supporters in the research groups outside CERN and a strong international collaboration is being formed. It seems that the FCC starts to be considered a preferable option for the post-LHC project at CERN. The FCC's CDR is expected for the next update of European Strategy for Particle Physics, most likely in 2018.

4. Circular colliders CEPC-SPPC in China

Another concept of the future circular colliders has been developed in China. It is complementary to the FCC at CERN because the design is focused on the Circular Electron Positron Collider (CEPC) with the Super Proton Proton Collider (SPPC) considered as an option for further future. This approach is motivated by the discovery of the Higgs boson with a relatively low mass, which revived interest in large-circumference e^+e^- circular colliders.

The baseline design of the CEPC-SPPC facility assumes 50 km in colliders' circumference, but other possibilities of up to 100 km are not excluded. There will be 8 arcs and 8 straight sections, with four straight sections for the interaction regions and RF (two for experiments at CEPS and two for experiments at SPPC), and with another four for RF, injection and beam dump. It is assumed that the CEPC collision energy will be 240 GeV and the integrated luminosity per interaction region per year will be 250 fb^{-1} . This will give a sample of one million Higgs bosons after ten years of data taking. The basic parameters for the SPPC are less certain. The p - p collision energy of 70 TeV can be realised if the magnets can operate at 20 T. Of course, the achievable collision energy will depend on the final choice of colliders' circumference and on what can be achieved in the magnet R&D program.

A candidate site for the CEPC-SPPC facility near Qinghuangdao, a city in the so-called Chinese Tuscany, about 300 km east of Beijing, has been chosen. This is a *green field* project, which means that contrary to CERN the whole accelerator injection chain and other infrastructure has to be constructed. The CEPC-SPPC Pre-CDR [13] has been completed, reviewed by an international committee and recently submitted to the Chinese government to be included into the 13th Five-Year Plan for the years 2016–2020. The main goal is to secure funding for R&D for key technical systems.

More information about the status of work for CEPC-SPPC colliders can be found in the presentation of Geng [14] at this conference.

5. International Linear Collider

Different concepts of the future e^+e^- linear collider, based on the acceleration RF cavities, have been developed in Europe, Japan and the U.S. for more than twenty years, resulting in the choice of the superconducting RF technology for this collider. A global collaboration has been involved in performing necessary R&D and in designing the collider, called since the International Linear Collider (ILC). Its Technical Design Report (TDR) [15] was published on June 12, 2012 during the world-wide handover ceremony in all three regions. More information about the ILC can be found in the presentation of Stapnes [12] at this conference.

This potential next-generation collider, complementary to HL-LHC, should further advance the precision of the Higgs boson studies. In particular, the Higgs boson couplings could be measured with single per cent accuracy required for distinguishing between some of various theoretical concepts from beyond the Standard Model.

In 2012, the Japanese particle physics community expressed its wish to construct the ILC in Japan in agreement with one of the two main recommendations in the Japanese strategic document [1]: *Should a new particle such as a Higgs boson with a mass below approximately 1 TeV be confirmed at LHC, Japan should take the leadership role in an early realization of an e^+e^- linear collider. In particular, if the particle is light, experiments at low collision energy should be started at the earliest possible time.* In September 2013, the Science Council of Japan recommended to the Japanese government to take the decision on hosting the ILC in two to three years, after clarifying some scientific and organisational matters as well as financial contributions of other countries. The Japanese government has settled dedicated working groups and committees to answer these questions. In the case of a positive decision, the ILC would be constructed in phases, the first one at the energy of 250 GeV for precision studies of the Higgs boson properties. The maximal energy at the ILC would be 1 TeV.

The European Strategy for Particle Physics [2] says: *The initiative from the Japanese particle physics community to host the ILC in Japan is most welcome, and European groups are eager to participate. Europe looks forward to a proposal from Japan to discuss a possible participation.*

6. Accelerator-based neutrino projects

At present, accelerator-based neutrino studies are realised in Japan, based on the neutrino beam from JPARC, and in the U.S., based on two neutrino beams produced at Fermilab: NuMI (Neutrinos at the Main Injector) and BNB (Booster Neutrino Beam). The accelerator based neutrino research programme is aimed at the measurements of the remaining unknown

facts concerning the neutrino oscillations, which are the neutrino mass hierarchy and the phase related to the CP violation in the neutrino sector, at answering the question concerning the existence of sterile neutrino(s) and at precise measurements of the cross sections of various final states in neutrino interactions. The measurement of the CP violation phase is of the utmost importance because it may provide us with an explanation of the observed asymmetry between matter and antimatter in the Universe.

In the last year, one can witness a very fast and strongly supported by the U.S. funding agencies development of the neutrino programme at Fermilab. In particular, the Long Baseline Neutrino Facility (LBNF), with a new intense neutrino beam from Fermilab to a 40 kton Liquid Argon far detector (part of the DUNE experiment) at the Sanford Underground Research Facility in South Dakota at a distance of 1300 km, is becoming its flagship for the future. This reflects the statement in the Strategic Plan for the U.S. Particle Physics [3]: *Reformulate the long-baseline neutrino program as an internationally designed, coordinated and funded program with Fermilab as host.* The technically limited schedule for the LBNF and DUNE foresees the start of data taking with the first 10 kton detector module in 2024.

In parallel, the short-baseline programme (SBL) aiming at searches for sterile neutrino(s) is also being developed at Fermilab. In particular, the ICARUS detector, which in 2013 completed data taking in the Gran Sasso laboratory, will be transported to Fermilab in 2017 and will become a far detector for the SBL programme.

A detailed description of the U.S. accelerator-based neutrino programme is given in the presentation of Zwaska [16] at this conference.

The second of the two main recommendations in the Japanese strategic document [1] is: *Japan should aim to realise a large-scale neutrino detector through international cooperation, accompanied by the necessary reinforcement of accelerator intensity, so allowing studies on CP symmetry through neutrino oscillations. This new large-scale neutrino detector should have sufficient sensitivity to allow the search for proton decays, which would be direct evidence of Grand Unified Theories.* This statement concerns the HyperKamiokande water Cherenkov detector with a total mass of one megatons, *i.e.* twenty times larger than the SuperKamiokande detector and the future upgrade of the JPARC accelerators.

Concerning this important field of research, the European Strategy document [2] recommends: *CERN should develop a neutrino programme to pave the way for a substantial European role in future long-baseline experiments. Europe should explore the possibility of major participation in leading long-baseline neutrino projects in the U.S. and Japan.* For the last two years, this recommendation has been realised through the development at CERN

of the so-called neutrino platform with test beams and infrastructure for the dedicated R&D and development of detector prototypes. In particular, a large prototype of the double-phase Liquid Argon detector, aimed at the DUNE experiment, is being constructed and the ICARUS detector is being upgraded for its future use in the SBL programme at Fermilab.

7. R&D for accelerators and detectors

Realisation of the above ambitious programme requires a very intensive R&D in the domain of accelerators and detectors. In the case of hadron-hadron circular colliders, the main objective is the development of high-field magnets at affordable cost. Different materials and technologies are being studied aiming at 16–20 T magnets. In the case of linear e^+e^- colliders, the key parameters are high-gradient acceleration structures and maximal beam focusing. These issues have been discussed by several speakers at this conference.

High collider luminosity sets requirements for detectors and computing, which are usually at the cutting edge of technology. For example, a luminosity goal of 10^{35} for the SPPC in China opens a debate on the ability of future detectors to handle such luminosity. The European Strategy document [2] recommends: *Infrastructure and engineering capabilities for the R&D programme and construction of large detectors, as well as infrastructures for data analysis, data preservation and distributed data-intensive computing should be maintained and further developed.*

8. Important regional projects and synergy with other domains of physics

Some strategic projects in accelerator particle physics are being developed as parts of regional roadmaps. The SuperKEKB collider, constructed at KEK in Japan for unprecedentedly precise studies in quark flavour physics, is probably the most pronounced example of this kind of project. However, one should remember that the Belle II detector at SuperKEKB has been completed and will be run by a large international collaboration.

One should also mention a synergy between particle physics and other physics domains, in particular astrophysics and nuclear physics. Several examples, not pretending to exhaust the full list, could be given. Searches for Dark Matter particles performed at the LHC are supplemented by both direct and indirect searches in experiments performed in underground laboratories and in astrophysical experiments. Large neutrino detectors, like HyperKamiokande or DUNE, can be used not only for accelerator-based

long-baseline experiments, but also for studies of astrophysical neutrinos or in searches for proton decays. The yet unknown neutrino mass hierarchy, whose determination is one of the two main goals of the LBNF research programme, will also be a subject of measurements of the JUNO experiment exploiting the low energy reactor neutrinos. Studies of hydrogen antiatoms at CERN inscribe in the searches for physics beyond the Standard Model.

9. Summary and outlook

Direct observation at the LHC of particles from beyond the Standard Model would be the most exciting discovery in the future runs of the LHC. However, this cannot be guaranteed and the alternative approach is to perform measurements of properties of the known fundamental fermions and bosons as precisely as possible. The measurements of Higgs couplings to fundamental fermions and boson, aiming at looking for discrepancies between the measured values and those predicted by the Standard Model, are very suitable for this purpose. The full exploration of the LHC, including HL-LHC, is needed to achieve this goal.

Further progress will require the next generation collider(s). Two different approaches are envisaged. The first one is based on even more precise measurements than those at the HL-LHC, performed at e^+e^- colliders. The most mature solution, the ILC linear collider, has been developed for many years by a global collaboration; its hosting in Japan is currently being studied by the Japanese government. Discovery of the Higgs boson with a relatively low mass revived interest in large-circumference e^+e^- circular colliders. For a few years, this option (CEPC) has been developed in China, which starts to be an important partner in planning accelerators for particle physics. The second approach aims at enlarging the accessible kinematical region in searches for new particles by increasing the energy in $p-p$ collisions by a factor of about eight. This is a primary goal of the FCC-hh project at CERN and a possible SPPC project in China. The FCC-ee collider is considered as an option at CERN.

During the next few years: the results of the LHC Run II at 13–14 TeV, the Japanese government decision concerning the ILC and some results concerning design studies and R&D work for other concepts of the future colliders will be known. This should give a solid base for the next update of the European Strategy for Particle Physics envisaged in 2018 and for developing further the global roadmap for particle physics.

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