Summary of the German strategy workshop "The Future of Collider Physics" in preparation of the ESPP update

27-29 November 2024, Hamburg

This document reflects the final discussion of the workshop which was attended by 178 registered participants. The workshop was organized by a committee of representatives of the involved communities and open to everyone interested in the field. The agenda is available here: https://indico.desy.de/event/45276/.

The Standard Model (SM) of particle physics, which describes the basic components of matter and the forces that govern their interactions, has seen an impressing success story. Not only has it been tested to great accuracy, it also has been structurally completed with the discovery of the Higgs boson. Still, there remain **open questions that cannot be answered within the SM**. Among these, the most prominent ones are those for the nature of Dark Matter (DM) and why there is more matter than antimatter in the universe. While the existence of DM is deduced from numerous astrophysical and cosmological observations, the SM cannot explain the observed DM. A dynamical mechanism for the generation of the matter-antimatter asymmetry is provided by electroweak baryogenesis, but cannot be realized by a SM-like Higgs boson with a mass of 125 GeV. Another puzzle is the lightness of the Higgs mass in view of large energy scales up to which the SM may potentially be valid. Most, if not all of these questions, are profoundly connected to the Higgs sector. The precise study of the Higgs boson and its properties will give us deep insights into the mechanism underlying electroweak symmetry breaking and thereby guide us to the answers of our open fundamental questions. In this context, the precise measurements of the Higgs couplings and in particular its self-couplings are crucial.

Answering the open questions requires a **diverse research programme**, at the highest energies, at the highest intensities, from the next large-scale project at CERN to specialised experiments on individual questions. A good balance between projects on different scales and timescales is essential for the success of the research programme. The timely construction of an e^+e^- Higgs factory and in the longer-term a collider with access to the multi-TeV energy range are essential components of the strategy for the field.

CERN is the world's leading laboratory for accelerator-based particle physics and a beacon for Europe's international competitiveness, as highlighted in the report "The future of European competitiveness" by Mario Draghi. CERN's leading role is to be secured by a flagship collider project after the LHC, which can be used to search for answers to our fundamental questions. CERN has repeatedly proven that it can successfully realise large-scale technological projects. CERN's strength in accelerator research and development is essential for the realization of the future flagship project. The diversity of the research programme at CERN must be maintained.

As the German national laboratory for particle physics, **DESY** plays an important role for the particle physics community in Germany. Apart from its exciting on-site program, DESY enables collaborative contributions of the German community to outside flagship projects by providing technical infrastructures, facilities and expertise for large scale projects. DESY's cooperation with the universities on the one hand and with CERN on the other is an essential ingredient of the long-term strategy of the German particle physics community.

The **LHC** with its upgrade to the HL-LHC represents an extremely important and successful research infrastructure for our field, the potential of which must be fully utilised. It enables an excellent physics programme. It is currently, and at least for the next decade, the only facility at which Higgs bosons can be produced and their properties studied with precision. The HL-LHC will significantly improve on the Higgs physics results and provide access to the fundamental measurement of the Higgs boson self-coupling. The LHC has achieved a plethora of important results in electroweak, top quark, and flavour physics. It is a unique facility to search for heavy new particles and facilitates a comprehensive search program for physics beyond the Standard Model, including indirect searches through precision observables. As a proton and ion collider the LHC has a particular virtue to investigate the strong interaction from small to high scales, from hadron spectroscopy to the quark gluon plasma and to interactions at the TeV scale. The HL-LHC will boost progress in all these investigations towards our fundamental questions and will provide a wealth of new and important physics results. A strong and sustained effort in particle physics theory is mandatory for the analysis and interpretation of LHC results as well as for the further development of research directions at the LHC. Beyond its past and future achievements in particle physics the LHC and HL-LHC strongly promote technological developments, such as the broad use and further development of artificial intelligence, innovative technologies opening the door to the exascale computing frontier, and the development of novel detector technologies, with a wide range of potential applications in science, industry and society. The ongoing Phase 2 upgrades of ATLAS and CMS are critical to the success of the HL-LHC. They are strongly supported by the German community and must be successfully completed on schedule. The community strongly supports the Phase 2b upgrade of the LHCb experiment to fully exploit the unique flavour physics potential of the LHC. The Phase 2b upgrade of the ALICE experiment (ALICE3) is a future flagship project in the recently published NuPECC Long Range Plan and is supported by a strong German community. Both Phase 2b upgrades are currently under review at CERN. The German community is fully committed to make the upgrades towards HL-LHC a success and is very much looking forward to exploiting the great physics potential of HL-LHC.

The **Belle II** experiment has an excellent physics programme that is complementary to the LHC. The German community strongly supports the full exploitation of this programme. It requires that the anticipated luminosities beyond 1E35/cm^{2}s are achieved. CERN and national labs should continue collaborating with KEK to further advance e^+e^- collider technologies and to help in achieving this goal.

While we expect significant progress on physics results at HL-LHC and Belle II and other experiments, **important fundamental questions will remain open.** These cannot be answered without a future large collider project.

Future Collider Flagship project at CERN

To maintain Europe's international competitiveness in particle physics CERN's leading role after the successful completion of the high-luminosity LHC program must be ensured through the timely realization of **a future collider flagship project at CERN**. Such a project will require a very strong commitment of the particle physics community in all relevant areas, namely detector and accelerator development as well as construction, computing, data science, and artificial intelligence. Theoretical developments are indispensable for its success. The project must have the ambition to be innovative while at the same time achieving the highest standards in sustainability.

An e^+e^- collider, which explores the Higgs, top and electroweak sector, will open up a new window to address our open questions with unprecedented precision. Such **a Higgs factory remains the highest priority of the German community**.

The German community assesses the physics performance (and future options) of the FCC-ee and of linear e^+e^- colliders with a centre-of-mass energy of up to 500 GeV (LC500) in the following way:

- For electroweak measurements at the Z pole and at the WW threshold the FCC-ee provides the best accuracy due to its extremely high luminosity.
- Both circular and linear Higgs factories provide an excellent potential to measure the Higgs couplings to SM particles at very high precision. A FCC-ee run at the Higgs mass would give access to the Higgs coupling to electrons. At the LC500 the trilinear Higgs self-coupling can be measured directly in Higgs pair production.
- Through a scan at the top pair threshold the top mass can be measured to excellent precision at the FCC-ee and at linear colliders. Better sensitivity to deviations from the SM is achieved at higher energies, however.
- For both circular and linear e^+e^- colliders the sensitivity to beyond-SM (BSM) physics is complementary to the LHC BSM searches. At lower energies light resonances can be probed directly and precision measurements allow indirect sensitivity to heavy new physics. The sensitivity to BSM physics increases with energy and luminosity.
- The clean environment and extremely high luminosity at the FCC-ee enable high precision tests of QCD. In addition, its flavor program is complementary to the measurements at existing flavor experiments.
- As for future options, the tunnel built for the circular e^+e^- colliders can be reused for a high-energy hadron collider. Linear e^+e^- colliders on the other hand can be upgraded to higher center-of-mass energies and be used as a photon-photon collider.

Following these considerations, the German community concludes that the FCC-ee provides an excellent potential to explore Higgs physics as well as the electroweak sector. It can perform QCD and flavor measurements, test BSM physics and, after an upgrade, make important measurements in top physics. With this program the FCC-ee will offer an exciting experimental approach towards answers to the fundamental open questions.

It offers high luminosity at up to four interaction regions. The FCC-ee concept was developed at CERN and its feasibility studied in depth, with no showstopper reported so far. The tunnel to be built for the FCC-ee could be re-used for a future FCC-hh. Clearly, CERN has the required expertise to run this integrated program.

The German community supports the FCC-ee as the next flagship project at CERN with highest priority. The German community will be fully committed to engage in all aspects of this project. Its realization requires the timely development of a solid and affordable financial plan by CERN.

Considerations if China proceeds with the CEPC

With the CEPC project the Chinese particle physics community promotes an ambitious collider project to be built in China which provides a physics reach comparable to that of the FCC-ee**. If China proceeds with the CEPC on the announced timescale**, physics results from this machine are expected to become available about 10 years earlier than results from a future flagship project to be built at CERN. In this case the FCC-ee as well as a linear e^+e^- collider operating at a centre-of-mass-energy around 250 GeV are not considered competitive enough by the German community to serve as the next flagship collider project at CERN. To secure the European leadership in collider-based particle physics, **CERN then has to aim for a more ambitious next flagship collider project**. Two projects are considered mature enough for a timely realisation after the HL-LHC. Both offer a world-leading physics program securing European leadership in particle physics on the long-term:

- **A hadron collider with magnet technology expected to be available at the end of the HL-LHC, installed in a tunnel of about 100 km circumference,** will provide a huge improvement of the physics potential in comparison to the expected status after the HL-LHC and largely complementary to the physics reach of the CEPC. It offers superb perspectives for precision studies of the Higgs boson (e.g. very precise access to the trilinear Higgs coupling) and opens a completely new territory in the search for new physics at the energy frontier not accessible at other colliders. Like the LHC today, this collider would offer a world-leading, very broad physics program lasting for several decades.

- **A linear e^+e^- collider facility with a centre-of-mass energy of initially 550 GeV** offers a highly competitive physics program in the area of Higgs physics (e.g. with its unique opportunity of direct access to ZHH production) and in the top sector. With its upgrade options to higher energies, either by extending the tunnel length or by installation of improved technologies (CLIC-like, plasma wake-field acceleration), this collider could access the high energy region with remarkable precision. This makes this option highly attractive for a high-level physics program at CERN lasting for several decades.

Considerations if the FCC is not financially feasible

The FCC-ee – and even more so a hadron collider in a tunnel of about 100 km circumference – will require significant resources and there is a **risk that the currently ongoing substantiation of the financial plan will lead to the conclusion that FCC is not feasible**.

An e^+e^- **Linear Collider** provides an attractive alternative path to a Higgs factory. It has complementary interesting additional features (polarization of both beams). Prospectively, it provides an upgrade path to TeV lepton collision by extending its length or installing more powerful acceleration devices. The foreseen luminosity at 250 GeV and below is lower than for the FCC-ee and can provide up to two interaction regions sharing the luminosity. It offers a reduced electroweak program and much reduced flavour program at the Z pole. The tunnel cannot be reused for a hadron collider. **The ongoing cost analysis of different linear collider stages will give important input to balancing the financial and scientific aspects in the decision for a next flagship project if the FCC-ee is not financially feasible.**

At this time, a **hadron collider option** as next flagship project is either not more affordable (FCC-hh, medium energy hadron collider in FCC tunnel) than the FCC-ee or not suitable as next flagship project (HE-LHC). Nevertheless, a rigorous accelerator R&D program towards enabling the exploration of the energy frontier should be pursued.

The LHeC as an intermediate project

The **LHeC**, i.e. an electron-proton collider using the LHC proton beam and an e^- beam from a to-be-built energy recovery linear accelerator, would offer the possibility to explore the proton structure to even greater precision – as prerequisite to exploiting the full potential of a new hadron collider. It has a well justified physics program which, in combination with LHC, will help to address fundamental questions of the field, in a way complementary to the EIC. It is being considered as a potential **intermediate project** between HL-LHC and a later next flagship project provided technical feasibility is established. However, the technological challenges for an energy recovery linac of the required performance as well as the practical and financial implications on the timelines of LHC operation and a future flagship need to be understood better.

Accelerator R&D for colliders

As Europe's leading laboratory for accelerator based particle physics CERN must strengthen the R&D efforts in technologies critical for future collider projects

- A **muon collider** (potentially installed with accelerating structures in the existing LHC tunnel) is a highly interesting and sustainable option for studying a broad range of fundamental physics questions following a largely different experimental approach. While important steps towards its technical realisation have been reached in recent years, more R&D work is needed in crucial areas (muon production and cooling, magnet technology, to name just two) before it can be regarded as a potential flagship project for CERN on the required timescale. On the longer term, the physics potential remains superb and R&D should be intensified to enable its realisation.

- The achievable energy of future hadron colliders directly depends on the magnetic field values that can be technically reached. While promising results have been obtained during the last years, **a dedicated R&D program for high field magnets** remains crucial for any future progress in this direction with potentially very large impact on particle physics. In addition, it offers interesting links to developments in industry and other applications.

- The concept of particle **acceleration using plasma wake fields** offers a highly attractive experimental approach to reach higher energies in much shorter accelerators than conventional technologies. Potentially this could lead to enormous reduction of costs and needed resources for colliders at the high-energy frontier. Current R&D efforts have led to very promising results, but the proof of principle for the usage of these methods in a particle collider still requires significant R&D efforts in the community.

- **Energy Recovery Linacs** offer the opportunity of considerable power reduction and/or luminosity increases. Interesting conceptual ideas for profiting from ERL technology exist for circular and linear colliders, however also here the proof of principle for the usage of these methods in a particle collider still requires significant R&D efforts in the community.