Statement by the German Particle Physics Community as Input to the Update of the European Strategy for Particle Physics

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Abstract

This is the national statement by the German particle physics community, which is based on the results of four open community workshops.

The German community agrees that Europe's leading role in particle physics is to be secured by a flagship collider project at CERN after the LHC, which is essential to search for answers to the fundamental questions in particle physics. A Higgs factory remains the highest priority of the German community. The German community supports the FCC-ee as the next flagship project at CERN with highest priority. Its realization requires the timely development of a solid and affordable financial plan by CERN. Recommendations are made for scenarios in which the FCC-ee is considered not financially feasible or in which international competition calls for a complementary and more competitive collider at higher energies at CERN and related accelerator R&D efforts.

The German community considers a diverse experimental landscape of non-collider experiments essential. Furthermore, strategic considerations are presented on CERN, DESY, and the German research landscape, on theory, on sustainability, on enabling technologies and detector development, on computing, software, algorithms, and data science, on early-career researchers, on diversity, equity and inclusion, as well as on outreach.

1 Scope of this document

This is the national statement by the German particle physics community which is based on the results of four workshops[1,2,3,4] that were held between May 2024 and January 2025. These workshops were open to everyone in the community, with active participation of researchers at all career levels, including early career researchers, as well as representatives of the neighbouring fields of accelerator physics, hadron and nuclear physics, and astro-particle physics. The statement represents the consensus reached at these workshops. It was agreed on by the participants of the final workshop[4], and approved by the elected German committee for particle physics, KET[5].

The national committees representing the fields of accelerator physics (KfB), hadron and nuclear physics (KHuK), and astro-particle physics (KAT) in Germany submit statements on their own, to which we refer where appropriate. The statements in this document about areas of mutual interest and regarding the future of CERN have been agreed on at the final workshop[4].

The preparation of this statement involved consultations with the Federal Ministry of Education and Research, BMBF, who were, however, not participating in the approval process.

2 Open questions and how to address them

Discoveries and measurements in particle physics have laid the foundations of the understanding of the fundamental laws governing nature at the smallest distance scales. These laws are essential to explain phenomena at microscopic, astronomical, and cosmic scales. The discovery of a Higgs boson is a major, but only a first step, in revealing the mechanism of electroweak symmetry breaking and its implications on the early universe. The Large Hadron Collider (LHC) direct search programme, successfully pushing the energy frontier into the TeV energy range, as well as the broad particle physics landscape at lower energies, are only starting to challenge the naturalness of the separation of energy scales. Outstanding questions remain unanswered. What is the nature of the detected Higgs boson? Is it a composite particle like all other known scalars? How does it interact with itself? What is the structure of the quantum theory of gravity that combines the principles of quantum mechanics and general relativity and what are the quantum properties of space-time? Why is there such a large discrepancy in the strength of the fundamental forces? Are there new symmetries at high energies that unify the three forces of the Standard Model (SM) of particle physics and can one compute the parameters of the SM? What is the origin of the observed dominance of matter over anti-matter in the universe, which cannot be explained within the SM? What are the fundamental properties of neutrinos and what is their role in the evolution of the universe? Is there a reason for the large flavour mass hierarchy? What is the nature of Dark Matter (DM) and the mysterious Dark Energy? Why are the nucleon electric dipole moments so small? Why is the electric charge quantised and why are the charges of the proton and that of the electron equal and opposite?

The precise study of the Higgs sector and the properties of the detected Higgs boson will provide deep insights into the mechanism underlying electroweak symmetry breaking and thereby guide us to the answers to many of the 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. Studies of high-energy particle collisions are indispensable to provide insights into the open questions. 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.

[1] Future Collider @ CERN Community Event, Bonn, 22.-24.05.2024

[2] German strategy workshop "The Future of Non-Collider Particle Physics" in preparation of the ESPP update, Bad Honnef, 22.-24.11.2024

[3] German strategy workshop "The Future of Collider Physics" in preparation of the ESPP update, Hamburg, 27.-29.11.2024

[4] Concluding Workshop in preparation of the input to the ESPP update, Bad Honnef, 19.-22.01.2025

[5] ketweb.de

3 Future of collider physics

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. **Europe's leading role in particle physics is to be secured by a flagship collider project at CERN after the LHC. Such a project is essential to search for answers to the fundamental questions in particle physics.** CERN has repeatedly proven that it can successfully realise large-scale technological projects. CERN's strength in accelerator research and development is pivotal for the realization of the future flagship project. However, the diversity of the research programme at CERN must be maintained.

3.1 HL-LHC and Belle II

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 their 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 their successful completion on schedule is of highest priority. 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 and their schedules are currently under review at CERN. The German particle physics community is fully committed to make the HL-LHC a success and is very much looking forward to exploiting its great physics potential.

The Belle II experiment has an excellent physics programme that is complementary to the LHC. **The German community strongly supports the full exploitation of the Belle II programme**. It requires that the anticipated luminosities beyond $10^{35}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ are achieved. CERN and national laboratories should continue collaborating with KEK to further advance e^+e^- collider technologies and to help in achieving this goal.

3.2 Future Collider Flagship project at CERN

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

To maintain Europe's international competitiveness in science and technology, 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.

3.2.1 Higgs factories

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 550 GeV (LC550) 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 could give access to the Higgs coupling to electrons. At the LC550 the trilinear Higgs self-coupling can be measured directly in Higgs pair production.

– Through an energy scan at the top-quark pair production threshold the top-quark 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 flavour program is complementary to the measurements at existing flavour experiments.

– Regarding future options, the tunnel built for the circular e^+e^- collider can be reused for a high-energy hadron collider. Linear e^+e^- colliders on the other hand can be upgraded to higher centre-of-mass energies and be used as a photon-photon collider.

3.2.2 FCC-ee as highest priority

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 will allow us to perform QCD and flavour measurements, test BSM physics and, after an upgrade, to 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 technical 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 carry out this integrated programme.

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.

3.2.3 Considerations in case 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 complementary and competitive next flagship collider project at higher energies** in order to extend the reach to answer the open questions. 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 90 km circumference**, will provide a huge improvement of the physics reach in comparison to the expected status after the HL-LHC and will be largely complementary to the physics potential of the CEPC. It offers superb perspectives for precision studies of the Higgs boson (e.g. very precise measurement of 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 at least 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.

3.2.4 Considerations if the FCC-ee is regarded as not being financially feasible

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

In case China proceeds with the CEPC on the announced timescale, a Linear Collider at a centre-of-mass energy of 250 GeV is not considered competitive; it would need a minimum energy of 550 GeV to be considered as a flagship project; see Sect. 3.2.3.

A hadron collider in a tunnel of about 90 km circumference is more expensive than the FCC-ee.

In any case, a vigorous accelerator R&D program is required to enable a future high-energy flagship project as detailed in Sect. 3.3.

3.2.5 Considerations on the LHeC as an intermediate project

An electron-proton/ion collider using the LHC proton (ion) beam and an e^- beam from a to-be-built energy recovery linear accelerator (LHeC) has been proposed. It would offer the possibility to improve the knowledge about the proton and nuclear structure, which can be used to obtain further insights into the fundamental questions when combined with the LHC data. It has a well-justified broad physics program complementary to the EIC project in the US and would give additional input that helps exploiting the full potential of a new hadron collider.

For a scenario with a longer time gap between the HL-LHC and the future flagship project at CERN, the LHeC could be considered as a potential intermediate project provided technical feasibility is established. However, the technological challenges for an Energy Recovery Linac of the required performance need to be overcome. Furthermore, the practical and financial implications on the timelines of LHC operation and a future flagship project need to be understood better. A timely realisation of the next flagship project remains the highest priority.

3.3 Accelerator R&D for colliders

The European community must strengthen the R&D efforts in technologies critical for possible future high-energy collider projects. These technologies also offer important synergies with applications in particle physics, other fields of science as well as in industry.

R&D in the following areas is of particular importance. This requires a concerted effort within the established structures of the Accelerator R&D Roadmap process.

– The achievable energy of future hadron colliders directly depends on the magnetic field strength 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 particular, high temperature superconductors (HTS) offer an interesting path forward.

– **Superconducting radiofrequency cavities** are a key technology for both linear and circular accelerators, including FCC-ee. The technology has been successfully demonstrated in several large scale projects including colliders. In view of promising recent results, European R&D towards significantly higher gradients and quality factors should be intensified and pushed towards application-readiness together with industry. This will extend the energy reach and luminosity-to-power-ratio of future colliders.

– The concept of particle **acceleration using plasma wake fields** offers a highly attractive 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 demonstration of the applicability of these methods in a particle collider still requires significant R&D efforts in the community.

– A **muon collider** (potentially installed with accelerating structures in the existing LHC tunnel) is a highly interesting 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 longer term, the physics potential remains superb and R&D should be intensified to enable its realisation.

– **Energy Recovery Linacs** (ERL) 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.

A strong effort in accelerator R&D for colliders is of very high importance. The extent of the European commitment in these areas should be adjusted taking into account the outcome of the decision on the next flagship collider at CERN and developments of other global HEP projects.

4 Future projects complementary to colliders

4.1 Promoting a diverse experimental landscape of non-collider experiments with a high physics potential

To address the fundamental questions of particle physics, the German community considers a diverse experimental landscape of non-collider experiments, with a complementary physics potential with respect to collider experiments, as essential.

– There is a rich set of theoretical ideas regarding the nature of Dark Matter (DM), some of which address known deficits of the Standard Model (SM) of particle physics. Candidates are Weakly Interacting Massive Particles (WIMPs, which can be searched for e.g. by looking for annihilation signals from the cosmos, missing energy/momentum or scattering signatures at collider or non-collider experiments, and at direct detection experiments), axions (related to the so-called strong CP problem) and ultra-light bosonic dark matter, keV sterile neutrinos (related to the neutrino mass problem).

– Various SM problems are addressed by beyond-the-SM (BSM) theories predicting feebly interacting particles (FIPs, e.g. neutral leptons, dark photons/scalars, ALPs, but also light and ultra-light dark matter). Dedicated beam-dump or scattering experiments at lower energies with extremely high beam intensities can achieve unprecedented sensitivities to search for FIPs, respectively, light dark matter particles. Specialized experiments, often relying on quantum sensing technologies, are able to search for signals from ultra-light dark matter.

– Precision particle physics experiments, such as NA62, Mu3e, and LUXE, play a critical role in testing the SM and are a tool to probe BSM physics.

– Neutrino physics is a dynamic field with strong discovery potential providing a unique window to BSM physics. The major scientific questions include the ordering and absolute scale of neutrino masses as well as their particle-antiparticle properties. The measurements of mass ordering, oscillation parameters and leptonic CP violation require complementary experiments using neutrinos from reactors and accelerators as well as atmospheric neutrinos.

– Gravitational wave (GW) detectors offer a unique opportunity, enabling the exploration of both early universe cosmology and late universe sources. Signals from the early universe, along with high-frequency signals from late universe sources, provide direct evidence for the existence of BSM physics. Low-frequency signals (e.g., PTA, LISA) are particularly sensitive to QCD and electroweak BSM phase transitions. Meanwhile, high-frequency signals hold the potential to uncover BSM phenomena and, with future technological advancements, might eventually probe energy scales beyond the reach of colliders.

Besides their complementarity, non-collider particle physics experiments operate on distinct timescales compared to large-scale collider projects and therefore ensure a continuous flow of scientific results and technological advancements. Non-collider experiments provide an excellent platform for training the next generation of researchers, which is essential to retain and develop expertise in forefront detector technologies and experimental techniques. They often have a size and complexity that makes it easier for early-career researchers to take part in all stages of an experiment, from the detector design, the detector construction and operation, to the data analysis and the publication of the physics results. They heavily rely on and profit from the infrastructure provided by the European laboratories for particle physics with respect to technology, coordination, and organisation. We recommend to continue this support as already provided by CERN (e.g. the fixed-target program) as well as at the European and national level (in Germany in particular: KATRIN and the Tritium Laboratory at KIT, the Axion Platform at DESY, MAMI/MESA in Mainz, ELSA in Bonn) and welcome new initiatives to strengthen and coordinate the European efforts in this area.

These national infrastructures, in particular at DESY, should receive the necessary funding to guarantee a competitive non-collider particle physics research program in the future.

4.2 Priorities

To search for feebly interacting particles, **the German community prioritizes the SHiP experiment**, hosted in a new beam-dump facility, thereby fully exploiting the investment into CERN's north area.

To search for axion(-like) particles, **the German community prioritizes the two complementary concepts of MADMAX and IAXO together with its precursor experiment BabyIAXO** as large-scale experiments on an international level.

Next generation non-accelerator based neutrino experiments are important to determine the neutrino masses, particle-antiparticle properties, oscillation parameters and possible BSM effects in the neutrino sector. Future non-collider experiments on WIMP searches are important to cover the full WIMP parameter space. Both areas are considered in a separate input document by the German committee for astroparticle physics KAT.

Dedicated high-intensity/precision experiments at national laboratories with a unique physics case are important to support, for example Mu3e and LUXE.

The community considers the long-baseline accelerator neutrino oscillation experiments DUNE and Hyper-Kamiokande but also long-term projects like ESSnuSB important. Besides a currently targeted participation in DUNE, the German community is actively watching developments in this field.

The community encourages identifying fundamental particle physics questions that can be advanced through GW research and recognizes the importance of supporting smaller-scale high-frequency GW experiments and fostering technological synergies with particle physics research.

Given the priority of the HL-LHC and a future flagship collider project at CERN on one hand and the importance of a diverse physics programme on the other hand, **CERN should maintain its non-collider activities at the current level.** Support of the fixed-target programme and strengthening the support of magnet development for non-collider experiments are considered of particular importance.

Technological support by CERN for enabling future neutrino experiments should be continued within the envelope of CERN's non-collider activities and in close collaboration with the national particle physics laboratories in Europe.

5 Additional strategic considerations

5.1 CERN, DESY and the German research landscape

CERN is the European and international centre for particle physics and is vital for the German community. Germany contributes about 20% of the CERN budget, and its particle physics strategy is tightly linked to CERN and its projects. In 2023, nearly 1300 students, scientists and engineers from more than 25 German research institutions were registered as users of CERN. A continuing challenge is to ensure that German scientists and engineers are represented in CERN's staff commensurate with the funding level of Germany, to optimally leverage the German investment in CERN.

Particle physics in Germany is based on a strong community of university groups and research institutions from Max Planck Society and Helmholtz Association. Activities at DESY, GSI, KIT, Max Planck Institutes and the universities are central to the success of CERN.

DESY plays a special role in this as the largest particle physics laboratory in Germany, and with its role as a national hub for particle physics. DESY strongly contributes to the CERN program, and has also developed an ambitious local experimental program of mid-scale particle physics experiments, with a broad international participation. This complements the scientific reach of the large collider facilities and focuses on axion physics (ALPS II, Baby IAXO, MADMAX) and precision studies of QED (ALPS II, LUXE). It significantly adds to the scientific reach of the non-collider program at CERN.

CERN and DESY share a long tradition of collaboration in particle and accelerator physics and computing, with the success of these activities rooted in the ability to design, construct, and operate large accelerators and detector systems.

A strong and well-coordinated cooperation between CERN, DESY and other national laboratories in Europe and beyond is essential to ensure that large and mid-size particle physics projects can be realised in a timely manner, and to foster a diverse and compelling particle physics research landscape in Europe.

5.2 Theory

Theoretical physics is an indispensable driving force in particle physics, addressing fundamental questions about the inner working of our universe and the smallest building blocks of matter. It opens new research directions, motivates and guides experimental searches for novel phenomena, and provides the tools necessary to fully exploit and interpret experimental results. It also plays a crucial role in capturing the public's imagination and inspiring young researchers.

The success of particle physics relies on dedicated theoretical work and close collaboration with experimental communities. The precision anticipated from future experiments necessitates a "quantum leap" in theoretical predictions. Achieving this level of precision can only be accomplished through the development of conceptually new methods and computational tools, ranging from the mathematical aspects of scattering amplitudes to phenomenological predictions and event generators. Identifying the effects of new particles through their quantum imprint requires a concerted effort from theorists working on different aspects of extending the Standard Model, experts in precision calculations in QCD and electroweak theory, and those developing simulation tools. This requires improved support structures, as well as training opportunities and career prospects for young theorists.

Theory also forges vital connections to fields such as cosmology, astroparticle physics, and nuclear physics, which are essential for interpreting experimental results. Moreover, innovative methods from artificial intelligence are transforming theoretical physics, opening up new research directions and opportunities.

Europe should continue to vigorously support a broad program of theoretical research that covers the entire spectrum of particle physics, from abstract theoretical frameworks to phenomenological applications. The German community recommends ensuring long-term and substantial support for theoretical work, which is crucial for strategic decision-

making, for data interpretation aimed at advancing towards a new, more complete theory of the quantum world, and for the overall success of the scientific program.

5.3 Sustainability

As scientists and as part of our society, the German HEP community is committed to building a sustainable future. Our research activities and research infrastructure must aim to minimize resource consumption and negative impacts on the environment, while exploring how research and development through our international collaborations can further contribute to the UN Sustainable Development Goals.

Any future project, while catering to the needs of the current generation, must consider the needs of future generations. In view of global climate change, this requires resolutely reducing carbon-equivalent emissions through novel and widely usable developments such as High Temperature Superconductors and bringing forward net-positive technologies like heat re-use. Future projects need to perform life cycle assessments, aiming to optimize their carbon footprint. The latter implies no future use of gases with high global warming potential (if leak-tightness cannot be guaranteed), phase-out of other environmentally harmful materials such as forever chemicals (PFAS), and transitioning to carbon-neutral energy supply together with its optimized efficient use (also regarding computing). When new infrastructure (buildings, tunnels, etc.) is built, major efforts must be undertaken to use carbon-minimized construction materials, in particular, related to concrete; existing infrastructure needs to be improved. Improvements extend also to institutes and research centers participating in future projects who need to transition to environmentally sustainable procurement, computing, travel and hiring practices. Maintaining our international networking and personal exchange culture requires creative and flexible solutions to effectively reduce frequency and accumulated distances by air-based travel. Achieving sustainability must become an integral part of particle physics research.

5.4 Enabling technologies and detector development

Advances in particle physics instrumentation are a core driver of discoveries and are recognized as a major source of societal impact and technology transfer. The physics goals of the proposed future particle physics projects demand innovative detectors beyond the present state-of-the-art. Strategic developments – as defined in the ECFA Roadmap for Detector R&D – are needed, and the R&D collaboration structure created in response to the previous ESPPU should be fully exploited. **With the completion of the ongoing upgrade projects and the identification of a future flagship collider, detector development must be intensified and adequately resourced at CERN, at national laboratories and at universities. Emerging technologies, leveraging on synergies with other fields, should also be explored to open up hitherto unimagined experimental opportunities.**

The German community has made substantial investments in the creation or upgrade of performant infrastructure for the development, construction and test of detectors, including test beam facilities. It has built up expertise in large ongoing construction projects, for example in silicon detectors, calorimeters and large-area gas detectors for the upgrade of the LHC experiments, and in advanced trigger and DAQ electronics systems. Non-collider experiments are also in preparation, some of which serve as incubators for novel technologies such as quantum sensors. **The expertise of CERN is unique in a number of cutting-edge technology areas and should be strengthened for the benefit of both collider and non-collider projects located at CERN and national laboratories**.

Detector development is an excellent training ground for early career researchers and an opportunity for hands-on experience with advanced technologies. Training researchers in the field of instrumentation is essential to enable any flagship project.

5.5 Computing, software, algorithms, and data science

The full exploitation of the unique physics potential of the European particle physics programme requires the development and application of state-of-the-art software and machine learning methods and the provision of extended computing and storage resources beyond the increase provided by technological evolution. At the same time scientific computing has to become CO_2-neutral by 2050 at the latest in order to mitigate the impact on climate change and to meet the agreed-on climate goals within the European Union. Hence, a timely development of novel computing concepts and innovative algorithms for data handling, event generation, detector simulation, reconstruction and analysis, taking into account the magnitude of the to be collected data, the required computing power, and the aspect of environmental sustainability is imperative.

WLCG, using mainly dedicated hardware resources, has been a great success over the last two decades. Nevertheless, the option of an interdisciplinary usage of large IT infrastructures (e.g. NHR[6] in Germany, EOSC at the European level) shall be investigated and be carefully evaluated. Necessary software frameworks for orchestration and accounting shall be developed and maintained. The full costs for provisioning and operation of the required hardware resources shall be included in the financial planning of future experiments.

Artificial intelligence is transforming the field, enabling unprecedented improvements in precision predictions, event generation, detector simulation, event reconstruction, and data analysis. Its exploitation and further active development by the community alongside other modern disruptive technologies is essential. A flexible common experiment-overarching software ecosystem for all these tasks, such as the turnkey software-stack KEY4HEP, and the use of state-of-the art concepts is vital for the development and optimisation of the next generation of detectors at future colliders. It is mandatory that the seamless and easy integration of modern AI algorithms in the relevant frameworks is provided from the start. The development and maintenance of new concepts and software libraries for the above tasks shall continuously be supported.

Interdisciplinary cooperation on national (e.g. NFDI[7], DIG-UM[8] in Germany) and international level (e.g. WLCG, JENA, EOSC, EuCAIF) exploits synergies with neighbouring fields which face similar challenges and shall be strengthened.

The data and research results of the particle physics community create a unique legacy. Hence, it is mandatory to develop technical solutions for sustainable Open Science, Data Preservation and scientific reuse strategies in accordance with FAIR principles.

To be able to carry out flagship projects and to drive future technological developments in computing, software and data analysis, which may be fundamental and disruptive, it is essential to keep the relevant expertise in the community. This can only be achieved by a recognition of work in this area, in particular conducted by early career researchers, at the same level as for other areas in particle physics.

Meeting the computing needs of major future projects in an environmentally sustainable way requires embracing of new technologies and enhanced interdisciplinary use of IT infrastructures and cooperation. The implementation of FAIR principles, the retention of expertise, and the recognition of work are priorities.

5.6 Outreach

Outreach and science communication are essential activities in particle physics, contributing in multiple ways to securing the field's future. Ongoing activities, such as "Netzwerk Teilchenwelt",[9] have proven to be successful and require sustained and adequate financial support and commitment from the community. An integral part for the success of any future project will be uniting different efforts into a coordinated approach. Key components should be the already existing outreach networks, such as EPPCN (Communication), IPPOG (Outreach), and the Teacher and Student Forum (Education), and closer collaboration and communication of existing outreach organizations with the research community is desirable.

A major task is to inspire the general public and to raise interest in STEM disciplines. Early career physicists are especially valuable role models for inspiring young people to become scientists. Outreach efforts to all audiences should go beyond professional communicators, and commitment to outreach, education, communication, and transfer efforts should be acknowledged as part of a strong academic profile. Interdisciplinary collaboration to excite different communities should be supported.

The future particle physics flagship project requires a major and timely outreach campaign, and sufficient resources for outreach, education, and communication must be provided to the research community. These activities will need to target a broad range of stakeholders, ranging from policymakers, scientific peers, journalists and influencers, all the way to the general public

[6] National High Performance Computing Alliance
[7] National Research Data Infrastructure
[8] Digital Transformation in the Research of Universe and Matter
[9] https://www.teilchenwelt.de

including future generations. Particularly more ‘soft’ topics such as environmental sustainability, diversity and decision making processes need to be communicated beyond the direct stakeholders. This includes ambassadorship of scientific methods to help society manage disinformation.

5.7 Diversity, equity and inclusion

The particle physics community commits to placing the principles of diversity, equity and inclusion at the heart of all its activities. We propose to implement target-based and leadership-led strategies to actively improve and monitor diversity, equity and inclusion benchmarks across the different dimensions of diversity.

Diversity, equity and inclusion are strategic necessities for the future of particle physics, because they enhance innovation, broaden perspectives, attract and retain the best talents globally, and improve decision-making.

Core diversity dimensions include the social background, age, ethnic background and nationality, gender and gender identity, physical and mental abilities, religion and world view, and sexual orientation as defined in the “Charta der Vielfalt”.[10] Individuals are furthermore affected by outer diversity dimensions such as family status or parenthood, as well as organizational diversity dimensions that shape their diversity profile.

Our community stands for promoting scientific collaboration across borders, inclusiveness and open science, transcending political and other conflicts as stated in CERN’s main objectives document. We have the unique opportunity as a global, highly innovative, respected and influential research community, to advocate for policies that promote diversity, equity and inclusion on societal level in e.g. education, research, and industry. This can include supporting initiatives that address systemic barriers to entry for under-represented groups, such as scholarships, mentorship programs, and inclusive hiring practices.

5.8 Early career researchers

Particle physics provides exciting opportunities for exploring cutting-edge technology and performing forefront research. **To ensure the attractiveness of particle physics in Europe, a timely decision on the next flagship project is critical for early career researchers (ECRs). The long pathway towards a future collider and its decades-spanning operations make it essential to foster and retain expertise of ECRs, which calls for more long-term positions.** At the same time, this provides a clear career path for ECRs. Recognizing achievements equally across all disciplines – whether in accelerator physics, computing, detector development, data analysis, or theory – is vital to sustaining innovation and for advancing the field.

A future collider project will be realized by the current and next generation of scientists. **The German community supports transparent and comprehensible decision-making processes and ECRs being actively involved at all stages.** In particular, sustainability throughout the life cycle of all future projects is a core priority for ECRs.

Moreover, the German community advocates for working conditions that support the retention of talent and the continued attractiveness of careers in particle physics. This includes promoting scientific visibility, fostering a healthy work-life balance, and ensuring a family-friendly, proactive, supportive work environment for all.

[10] https://www.charta-der-vielfalt.de/en/