Input from the Netherlands to ESPP 2026

March 2025

Introduction

The process of shaping the input from the Netherlands for the European Strategy Update has been led by the Dutch National Institute for Subatomic Physics Nikhef. It has been a structured and iterative effort, starting with getting our community broadly informed. The formal process kicked off early-2024 with a half-day staff meeting on future colliders, serving as an introduction to the various options and discussing their strengths, weaknesses, opportunities and threats. Throughout 2024, a dedicated series of colloquia covered a range of future collider topics, including amongst others, the Future Circular Collider, linear electron-positron colliders, muon colliders and energy recovery linacs, as well as their physics motivations. Each of these colloquia included up to half an hour of discussion time. Early career researchers were further engaged through a three-day lecture series dedicated to future colliders, and they organized a joint one-day event with Belgium. They have summarised their statements in a dedicated section in this input document.

The next phase consisted of discussions, surveys and converging on the Dutch input. A straw poll was conducted under all of Nikhef with above hundred respondents to gauge initial opinions on different aspects of future colliders. Subsequently, a full-day meeting was held to discuss physics motivations for future colliders, other elements affecting the choice of a future collider, and scientific diversity within the European landscape. Three more strategy days were organized in the beginning of 2025 focusing in more depth on scientific diversity, technology and future collider options, respectively. These open meetings each had a similar format with pitches and discussion sessions. At the end of each day a survey was conducted and discussed, revolving around potential statements for the Dutch input. All meetings were attended by 50-100 people, with a background in particle and/or astroparticle physics. We concluded the process with an additional open session to refine the statements that arose from the previous sessions, which now form the basis of this document.

Nikhef and its considerations for the next collider

Nikhef is a partnership between the Institutes Organisation of NWO (NWO-I) and six Dutch universities: Maastricht University, Radboud University, University of Amsterdam, University of Groningen, Utrecht University, and VU University Amsterdam. Nikhef coordinates and leads the Dutch experimental activities in the areas of accelerator-based particle physics and astroparticle physics.

The mission of Nikhef is to study the interactions and structure of all elementary particles and fields at the smallest distance scale and the highest attainable energy. Two complementary approaches are followed. Accelerator-based particle physics studying interactions in particle-collision processes at particle accelerators, in particular at CERN, as well as astroparticle physics studying interactions of particles and radiation emanating from the universe. Research at Nikhef relies on the development of innovative technologies. The transfer of knowledge and technology to third parties, i.e. industry, society and the general public, is an integral part of Nikhef's mission.

Currently, Nikhef is involved in the ALICE, ATLAS and LHCb experiments at the Large Hadron Collider (LHC) at CERN. The LHC explores particle physics in hadronic collisions at high energies and luminosities which allow studies of dense environments, Higgs boson couplings, electroweak and top-quark sectors, as well as flavour physics with beauty and charm. In addition, searches for new particles are made through direct production, indirect detection via precision measurements, and missing energy in collisions. This is complemented by experiments searching for dark matter scattering with the XENONnT experiment, and in the future potentially with XLZD; studies of neutrino properties with the KM3NeT telescope and the near-future long-baseline DUNE experiment; precision studies of the electron electric dipole moment with eEDM; studies of high-energy cosmic rays with both charged particles at AugerPrime and neutrinos with KM3NeT; and the observation of gravitational waves with Virgo and the preparations for LISA and the Einstein Telescope. An extensive in-house theory group, electric and mechanical engineering departments and a scientific computing group completes the Nikhef portfolio. Finally, Nikhef collaborates with SARA to host a Tier-1 site of the Worldwide LHC Computing Grid (WLCG).

In view of our mission, we are convinced that a new flagship collider is essential and that it should be located at CERN, but it should not affect the completion of the high-luminosity phase of the LHC (HL-LHC). From our discussions, it followed that we see physics as the primary motivation for a future collider, with the study of the Higgs boson and the search for physics beyond the Standard Model as main targets. While physics is the primary driver, other considerations were also viewed as important in deciding on the next collider: it should offer an attractive and innovative R&D programme and the time gap between the HL-LHC and the next flagship collider has to be small or there should be an attractive physics programme in the gap.

Flexibility is important to adapt to new physics results and new technologies, and environmental impact must be addressed. Furthermore, sufficient career opportunities are essential to continue to attract and foster physicists and technologists, and a strong communication strategy is imperative for the viability of our field.

Finally, there was a strong sentiment that non-collider (astro)particle physics should be included in the ESPP, and that the next collider project should not come at the expense of a diverse scientific programme in Europe in terms of resources.

Future colliders

Completing the full HL-LHC programme must be the main present priority for CERN. Reducing its programme to implement a next flagship collider would be disruptive to both the planned physics reach of HL-LHC and the detector R&D programme.

It is essential that the next flagship collider is located at CERN. We discussed various promising future collider options, including the Future Circular Collider (both FCC-ee and FCC-hh), a linear e^+e^- collider, a muon collider and an ep collider. Awaiting the detailed ESPP inputs for the future collider options that will become available after the March deadline, the discussion focussed on what considerations are viewed as most important in deciding on the next flagship collider.

The primary physics motivations for a future collider are to conduct a detailed study of the Higgs boson and to explore physics beyond the Standard Model. The groundbreaking discovery of the Higgs boson opens new territory which we only started to explore. A key target is improving the precision on the Higgs self-coupling and on its couplings to other Standard Model particles beyond the expected potential of the HL-LHC. In the exploration for physics beyond the Standard Model, both the indirect search enabled by precision measurements in electroweak, Higgs and top-quark sectors, and the direct search at higher collision energies are important. The Standard Model Effective Field Theory serves as a valuable framework for interpreting measurements, but any signal will require direct searches at higher energy.

It is important that the next flagship collider supports a broad physics programme, also because it is not clear where the next major advancement in particle physics will come from. This includes diverse areas such as electroweak precision, top-quark physics, flavour physics (including heavy quarks, light quarks, leptons) and quantum chromodynamics (quark-gluon plasma, jets, small-x).

In the pursuit of both precision and high energy, flexibility to integrate technological innovations and adapt to new discoveries is highly valued, even if it comes at the cost of not having an integrated plan upfront.

Feasibility studies of linear collider options at CERN should be seriously considered. In addition to the FCC feasibility study, alternative options must be considered, in particular a feasibility study of a linear collider at CERN.

It is important to carefully scrutinise the physics motivations, when considering extensions of future colliders. The FCC-ee offers extremely high luminosities at lower energies, benefitting precision measurements. Exploring the $t\bar{t}$ threshold, which requires an upgrade, is viewed as important, though perhaps not critical. After an update, a linear collider can reach higher energies, with the ZHH threshold deemed very important, providing direct access to the Higgs self-coupling. An upgraded linear collider also offers the opportunity to use polarised beams, unlocking additional physics knowledge.

If a gap emerges between the HL-LHC and the next flagship collider at CERN which is too long, there should be impactful physics experiments in this gap.

This is seen as critical to keeping the community engaged and retain talent. One feasible and impactful bridge is the LHeC, a high-energy, high-luminosity *ep* collider at the LHC.

An integral part of achieving future colliders is advancing accelerator technologies. Specifically, we recommend that CERN continues to play a leading role in accelerator R&D, in particular for high-field magnet R&D and in support of a future muon collider. In addition, the long-term roadmap for accelerator R&D must have the ambition to attract and retain talent in the field. This implies taking some risk to achieve impactful technical innovations.

Long-term sustainability should be a guiding principle and supported by international agreements. The Energy Recovery Linac technology should be further developed to achieve the best physics for the least power.

We value global collaboration in science and we should strive to retain it. However, for the implementation of future colliders the risks due to the dependence on (substantial) financial contributions from outside Europe should be considered.

Scientific Diversity

To enable the full synergy of science and technology, many European institutions, like Nikhef, are organised to embrace both particle and astroparticle physics. Accordingly, Nikhef is committed to the long-term success of both, and resources are coupled.

To sustain a vibrant research community with the greatest impact, the particle physics community in Europe and also CERN should support relevant non-accelerator particle and astroparticle initiatives where synergies exist:

Non-collider (astro)particle experiments should be included in the European Strategy for Particle Physics. Many of today's puzzles considered in the particle physics domain are related to observations of the universe, such as dark matter and the matter versus antimatter asymmetry. In addition, fundamental properties and interactions of matter are studied in experiments outside of the accelerator domain. The (astro)particle physics experiments studying these topics provide complementary information to the insights obtained at colliders and should be taken into account in the European particle physics strategy.

A future accelerator should not happen at the expense of scientific diversity. The community in the Netherlands is strongly of the opinion that a future flagship accelerator at CERN should not further constrain the expert capacity and financial resources for non-accelerator (astro-)particle physics experiments in Europe.

It is important for CERN to have a diverse physics programme. CERN is seen as the European centre for particle physics. Therefore, CERN should strengthen its programme to further connect to experiments at European particle physics laboratories that have a major discovery potential. This guarantees visibility for CERN in advancements in the field that do not directly originate from accelerator-based research.

Our ideal European landscape encompasses community support for a broad range of experiments in various stages of operation. The Dutch community would like to encourage the support in the ESPP of the following projects in which Nikhef is involved:

Neutrino experiments probe fundamental properties of the lepton sector complementary to collider experiments. Measurements of neutrino masses and mixings, the CP-violating angle in the neutrino sector, tests of the three-flavour paradigm, and searches for new physics in the neutrino sector are crucial for the progress of particle physics. In addition, cosmic neutrinos offer independent and complementary access to the study of astrophysical and cosmological phenomena. It is important to measure these neutrino properties with a large variety of methods and experiments. These objectives are the goal of the DUNE experiment, as well as the European KM3NeT project and the Ptolemy initiative. Furthermore, the potential of a future European (tagged) neutrino beam in the context of a muon storage ring could provide Europe with an interesting expansion of physics potential.

Gravitational wave detection provides unique and paradigm-shifting opportunities for fundamental physics. Gravitational waves are a powerful new messenger from cosmic objects that are otherwise hard to observe, and provide unique experimental data for fundamental physics, astrophysics and cosmology. Earth-based detectors such as Virgo are fundamental in the near future, while the sensitivity of the future Einstein Telescope as well as the space-based LISA antenna are required to fully realise the potential of gravitational wave science. The Einstein Telescope will provide Europe with a flagship project besides a future collider, and will operate for at least 50 years. TheETpathfinder in Maastricht is a major centre for the development of low-frequency detection technologies.

Underground facilities for dark matter searches have a unique sensitivity for a WIMP-nucleon scattering discovery. The European particle physics community should support underground facilities for diverse (astro)particle physics research, such as XENONnT, and work towards the construction and operation of the ultimate Xenon-based direct-detection dark matter experiment, XLZD, reaching the "neutrino-fog" and enabling a precise exploration of neutrinoless double beta-decays.

Low-energy precision experiments, like those measuring electric dipole moments, are powerful probes of physics beyond the Standard Model complementary to high-energy experiments. These experiments provide strong limits on new physics such as CP-violating operators in the context of effective field theory, and should be supported technically and in terms of long-term funding in Europe.

Next-generation facilities to study cosmic rays enable access to the highest (EeV) energies unreachable by earth-based colliders. Similar to AugerPrime, next-generation facilities to study the EeV universe with cosmic rays will require accurate low-cost low-power sensors. It is desirable to benefit from the synergistic (hardware) developments with experiments in particle physics. Coordination among observatories, including the high-energy neutrino KM3NeT observatory, is essential in the realm of multi-messenger astronomy.

CERN is a technology and organizational hub for the (astro)particle physics community. This can be further facilitated, among other things, by:

Strengthening the concept of 'recognized experiments'. One of CERN's strengths lies in catalysing European collaboration and coordination within the particle physics community. There is an opportunity for CERN to also collaborate in astroparticle physics experiments in Europe. This can be done by strengthening the concept of recognized experiments and expanding its scope. For example, for projects like the ones mentioned above.

Establishing common technology platforms at CERN. The *neutrino platform* is a great example of the impact CERN can have on the success of an off-site experiment. Along those lines we propose CERN to consider further technology platforms, where shared interests with mutual benefit could be pursued, while keeping scientists involved that otherwise might migrate to nearby fields. Suggested topics would be: low-power electronics combined with the cosmic ray community; vacuum technology jointly with gravitational wave detectors; electronics and mechanical design prototyping with the neutrino community; and quantum sensors for a variety of future applications.

Supporting accelerator-based diversity. LHC far-forward experiments such as FASER and the Forward Physics Facility (FPF) enable a significant extension of the HL-LHC physics portfolio. Furthermore, forward physics facilities in fixed-target mode are essential for developing hadronic interaction models for cosmic ray and heavy-ion collision experiments.

A broad experimental exploration of new physics through precise measurements and direct searches at high energies goes hand in hand with in-depth theoretical guidance to leave no stone unturned:

The ongoing physics exploitation at the (HL)LHC and other experiments, as well as preparation for future facilities, mandates the continuation of a strategic and vibrant research programme in theory. This programme should be broad, ranging from abstract aspects of particle physics to those supporting and preparing for experiments at present and future colliders. This includes investments that relate to theory developments directly relevant for ongoing and future experiments, involving both predictions and methods to push their precision to the required high levels, and synergy through for example effective field theory. In addition, we recommend structural support for theorists working on backbone infrastructure, such as Monte Carlo generators and precision calculation tools like FORM.

Technology

The advancement of particle physics depends on cutting-edge technological developments. As part of the ESPP, it is crucial to promote the development of a clear and ambitious technological roadmap that ensures alignment with broader European technology and industrial strategies. We recognise the added value of strategic roadmaps, such as the previous detector R&D roadmap, in helping to prioritise research efforts and guide the allocation of resources in the community. To remain at the forefront of particle physics, Europe must adopt a proactive approach to technological development.

A coordinated and forward-looking technology strategy is essential to maintain Europe's leadership in particle physics. The ESPP technology roadmap should align with broader EU and national technology strategies, including the Dutch Technology Strategy, to enhance collaboration and funding opportunities. It must maintain a balance between incremental detector improvements (higher precision, lower material budget, increased data bandwidth) and long-term, paradigm-shifting R&D.

The ESPP should prioritise long-term investment in key areas, including artificial intelligence (AI), quantum computing and quantum sensing, whilst also recognizing the need for sustained support and maintenance of existing technologies. A well-structured collaboration between research institutes, CERN, and industry will be essential to ensure that European particle physics remains a global leader in these and other technological innovations. The Technology Platforms, as referred to in the previous section, are a powerful tool in this regard.

The European particle physics community should continue to actively define specific use cases for quantum computing in high-energy physics (HEP), leveraging synergies with industry and academia to ensure its relevance in emerging computational paradigms.

The European particle physics community should take a leading role in developing AI initiatives for fundamental physics, by investing in research, fostering collaborations, and developing dedicated AI infrastructure and expertise. As part of this, ESPP should support the development of large-scale AI-driven computing infrastructures, provided they are built upon scalable data infrastructures. The development of physics-specific large-scale AI models should be prioritised over attempts to leverage commercial and specialized AI models. Training in AI and data science must be an integral part of HEP education and research.

A concerted European programme on quantum sensing should be developed to remain competitive in the field, and to attract both physics students and technical staff. Dedicated teams of scientists, engineers, and early-career researchers should be allocated to quantum sensing research. Also here, a dedicated Technology Platform could be a good instrument to support these developments.

CERN should take an active role in planning, coordinating, and even leading the efforts required for long-term maintenance of experiments hosted at the laboratory. This is particularly important as long-term experiments require stable and well-planned maintenance strategies, for both their hardware and software. An optimal balance between technology R&D, production, and maintenance is essential to sustaining both large-scale facilities and the appeal of the field to researchers and society. It must be noted that technological innovation is required to improve on production and maintenance capabilities.

Fostering expertise in a broad portfolio of critical detector and electronics technologies must remain a core priority within the ESPP with a view to further these technologies. Areas that are essential for the future success of particle physics experiments are for example wafer-to-wafer bonding and the integration of MAPS and hybrid technologies. They should receive dedicated attention within R&D programmes. Pixel detector technologies must continue to evolve, but this will require secured funding to ensure access to smaller process nodes. To maintain technological leadership and flexibility, the ESPP should ensure strong in-house electronics development capabilities at CERN and major laboratories, rather than relying entirely on outsourcing to industry. In addition, the further development of end-to-end digital twins for future detectors will be crucial to optimise design, simulation, and analysis workflows.

The ESPP must actively ensure the field remains competitive and attractive for technologists. As technology evolves, it is becoming increasingly difficult to attract and retain talented engineers and instrumentalists in HEP unless career conditions remain competitive with industry. At the same time, development cycles for large experiments should be streamlined to reduce inefficiencies and accelerate implementation, ensuring that technological progress is not hindered by overly long timelines.

Early Career Researchers

While early career researchers (ECRs) in the Netherlands express different preferences for the next collider, they share clear priorities and a strong preference for a European location. Physics considerations are fundamental in choosing the next collider, and environmental impact and sustainability are equally important factors in the decision.

Beyond scientific and environmental considerations, ECRs are also deeply concerned about job security and long-term career prospects. Programme flexibility should be a key component of the plan for the next machine, ensuring adaptability to any future developments or discoveries, while maintaining enthusiasm within the physics community. ECRs express concerns about rigid planning and operation start dates set far in the future, as they could result in the loss of expertise. Additionally, ECRs fear that long timelines and financial uncertainty could limit career opportunities, increasing the risk of talent loss to other fields where societal impact could be more immediate and substantial.

ECRs stress the importance of uniting as a community to define a cohesive research programme beyond the Higgs boson, ensuring comprehensive progress across multiple fields, including flavour physics, electroweak precision measurements, and detecting or constraining physics beyond the Standard Model. A broad scientific vision is necessary to maximize future collider potential and maintain long-term engagement in the field.

There is a strong agreement among ECRs on the importance of the HL-LHC, with a clear consensus to prevent its programme from ending earlier than planned (2041) to accommodate a future collider. The HL-LHC is crucial in maintaining scientific progress, while ensuring the field is prepared for the next generation of colliders.

Science communication

Outreach and clear science communication have consistently sparked enthusiasm for fundamental research with the wider public. They foster a sense of curiosity, broaden scientific understanding, and help to inspire new generations of scientists. As such, they should be recognised as an essential component of the particle physics strategy moving forward. However, it's clear that society faces unprecedented global challenges, from geopolitics to climate change and from struggling economies to migration. Growing distrust in science and polarisation in society become pressing issues, often fuelled by mis- or disinformation and social media bubbles.

In this complex and challenging global situation, particle physics is at a critical point for its long-term future. A big future project will undoubtedly need enormous funding, relying on support and contributions from many stakeholders at local, national, European and global level. Communications and outreach play a crucial role in this context when it comes to rebuilding trust in science, engaging and inspiring people, fostering curiosity, and ensuring support for particle physics.

To this end, a coordinated approach is vital, including the following recommendations:

- **Ensure adequate support and funding for communications and outreach** as an integral part of science research. Professional communicators are crucial for effective and consistent communication. Scientists are needed to actively participate in outreach. Every member of the particle physics community should become an ambassador for the field.
- **Adopt a common and coordinated European vision and strategy for communications, outreach and public engagement** and implement joint initiatives.
- **Engage directly with diverse and new audiences**, including underprivileged and young audiences, and foster dialogue, discussions and participation.
- **Demonstrate societal benefits arising from fundamental research** including, for example, training new generations and valorisation/knowledge transfer.
- **Communicate transparently about efforts to reduce environmental impact**, showing commitment to environmentally responsible research.

Annex

- Early Career Researcher input document from the Netherlands.