Perspectives of Early-Career Researchers in Belgium and the Netherlands on the Future of Collider Physics

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Abstract

This document provides input from the Early-Career Researcher (ECR) communities of the Netherlands and Belgium for the next update of the European Strategy for Particle Physics. It includes responses from 41 participants to a survey, 68% of them from the Netherlands and 32% from Belgium, with 81% currently working on LHC experiments. Overall, participants expressed that they are happy in their current job and excited about the HL-LHC in the near future. In particular, 76% respondents do not want the HL-LHC program to end sooner than anticipated in preparation for the next flagship collider, for which they have much stronger reservations. Their primary concerns about the next machine relate to funding, long-term strategy, job security, career trajectories, and public perception.

When considering a new flagship accelerator, the ECRs identified environmental responsibility, timeline, enthusiasm, and flexibility as the most critical factors. Regarding the choice of the next collider, respondents favored innovative and exciting concepts, though they acknowledged the need for rigorous feasibility studies to objectively evaluate risks, costs, and challenges. Regardless of the specific choice, the majority (76%) prefer the next collider to be built in Europe, with CERN being the favored location (24%).

1 Introduction

The ECR representatives of the European Committee for Future Accelerators (ECFA) [1] in the Netherlands and Belgium organized a workshop in September 2024 to discuss among ECRs the topic of future colliders within the two ECFA member countries [2]. To ensure broader engagement and include ECRs who could not attend, a follow-up survey was conducted. The present document offers an overview of the workshop discussions in Section 2, and presents the survey results and highlights the perspectives of the Early-Career Researchers on the future direction of the field, in Section 3.

The workshop aimed to foster dialogue between both countries, inform ECRs on the next update of the European Strategy for Particle Physics (ESPP) and its implications (particularly important for ECRs), engage them in this process, and gather input to provide to the ESPP in the form of this document. The event followed the "Future Colliders for Early-Career Researchers" workshop [3] held at CERN on 27 September 2023, an initiative of the ECFA ECR Future Colliders Working Group. Due to their community sizes and geographical proximity Belgium and the Netherlands were combined for this initiative, while recognizing that many factors such as funding and career paths vary by country.

The search for the next flagship collider is not a new challenge, nor is the involvement of ECRs. In 1984, an ECFA Workshop [4] discussed a future electron-positron machine and a potential hadron collider in the same tunnel. It also happened before that ECRs provided input [5] hoping to be taken into account. This document aims to take a proactive role in collecting input from ECRs for the Strategy Update. As members of the community that will build, operate, and analyze the data of the next collider it is important for our voices to be heard. Decisions made without such input risk overlooking the long-term implications for those affected by them.

Given the long time scales between deciding, building, and operating a new collider, we emphasize the need for a clear trajectory, especially for those without permanent positions. This is crucial to ensure the continuity of particle physics research at CERN and to prevent the loss of current expertise and technical knowledge. The decision on the next machine must be realistic, with a commitment to sustainability and a global perspective, to maintain interest in the field and to prevent the migration of younger generations to other industries. Challenges are opportunities for innovation, not barriers. Meanwhile, the High-Luminosity LHC (HL-LHC), a future collider in many ways, must remain a priority.

2 Workshop summary

The workshop took place in Ghent, Belgium, on 12–13 September 2024. The first day featured a poster session on ongoing work among ECRs related to future colliders, providing an opportunity for initial exchanges. The main program took place on the second day, starting with a theoretical motivation and an insight into yet-unexplored physics phenomena, with a focus on the Higgs sector that future colliders can probe. The following part addressed key considerations when designing a collider with a brief overview of the current proposals for the next machine. The morning session concluded with a talk emphasizing the need for upcoming collider proposals to prioritize sustainability and energy efficiency, particularly in light of Europe's net-zero CO_2 policies. This first part is summarized in Appendix A. The second part of the program centered on the Dutch and Belgian involvement in future colliders and was followed by a panel discussion. A summary of this part is provided below.

2.1 Involvement in future colliders

Belgium and the Netherlands have not yet taken formal positions on future colliders, as their input for the ESPP is still under development. In the Netherlands, most contributions focus on current experiments, with some efforts also dedicated to future collider detector research and development (R&D) via contributions to DRD collaborations [6]. In Belgium, activities are more diverse, including feasibility studies and detector developments, while maintaining strong involvement in ongoing experimental programs. These efforts are conducted individually, involving existing experiments such as ATLAS and CMS. Below is a summary of the ongoing activities for each country.

2.1.1 The Netherlands

Researchers in the Netherlands are involved in multiple collider studies, with the involvement of ATLAS, LHCb and theory groups and engineering teams. The key areas of involvement include:

◦ Detector R&D:

- **ILC:** Development of technology for a pixel time projection chamber.
- **FCC-hh:** Advancements in accelerator magnets studies for a FASER-like experiment.
- **Cool Copper Collider (C^3):** Research into alignment techniques for the accelerator structures.
- **DRD contributions:** The Netherlands is involved in four DRD collaborations: DRD3 (Solid State Detectors), DRD5 (Quantum and emerging technologies), DRD7 (Electronics and Data Processing), DRD8 (Mechanics & Cooling of Future Vertex and Tracking Systems).

◦ Phenomenological studies:

- **FCC-ee:** Global Standard-Model effective field theory (SMEFT) analysis for Higgs, top and electro-weak (EW) sectors.

◦ Analysis sensitivity projections:

- Comparative studies of sensitivity projections across collider options, including HL-LHC, LHeC, ILC, CLIC, CEPC, and FCC.
- **Muon collider:** Studies focusing on Higgs, heavy neutrinos, and precision physics.

◦ ECFA studies: Co-convener of physics potential group for Higgs/EW/top factories.

2.1.2 Belgium

Belgian researchers are similarly engaged across a wide spectrum of activities, with contributions from CMS and theory groups and engineering teams. The key areas of involvement include:

◦ Detector R&D:

- **LHeC/FCC-eh:** Participation in the development of forward spectrometer and energy-recovery linear accelerators (ERLs).
- **FCC-ee/hh:** Contribution to MAPS-based vertex detector.
- **DRD1:** Involvement in RD51 collaboration designed to develop gaseous detector technologies for future applications.
- **Calorimeters for Linear Collider Experiments (CALICE):** Developing and testing calorimeter prototypes, with Belgian involvement in high-granularity semi-digital hadronic calorimetry.

◦ Phenomenological studies:

- Extensive studies on top quark properties, including precision measurements at the $t\bar{t}$ production threshold and searches for anomalous couplings.
- Phenomenological investigations into Higgs single- and self-couplings and their loop corrections.
- Effective field theory (EFT) studies focusing on EFT frameworks to probe deviations from the Standard Model (SM).

◦ Analysis sensitivity projections:

- **FCC-ee/hh:** Feasibility studies and flavor tagging development

◦ ECFA: Co-conveners of physics potential and analysis methods groups for Higgs/EW/top factories.

2.2 Panel discussion

The panel discussion was the final item on the agenda, closing the event with an opportunity for ECRs to engage directly with experienced researchers. During this session, participants raised critical questions about the future of particle physics and the challenges ahead. The discussion covered a broad range of topics such as feasibility and timeline, with the main points summarized as follows:

CERN's Feasibility Studies and Alternative Scenarios. Participants noted that while physics data for an e^+e^- collider is well understood, information on the FCC and other alternatives remains incomplete. **Feasibility studies are essential to assess risks, costs, and challenges, but due to inherent uncertainties, their goal is to guide decision-making by setting priorities and defining a plan rather than making final decisions.** Emphasis was placed on prioritizing high-impact studies at both the technical and physics levels to advance the process.

Impact of a Potential Collider in China. The discussion emphasized the importance of maintaining a diverse portfolio of projects and pursuing a complementary collider at CERN if China constructs the CEPC, rather than duplicating efforts. While adjustments to the decision-making timeline may be needed, participants stressed that the European strategy should remain independent of China's decisions. International collaboration, which has historically benefited CERN, was highlighted as essential for advancing particle physics, despite potential geopolitical challenges. Participants stressed that **all projects, regardless of location, contribute to the scientific community, reinforcing the need for CERN to set clear priorities while remaining adaptable to any developments.**

Physics Beyond the Higgs. Future colliders, such as FCC, offer significant opportunities for flavor physics, including rare decays. **An emphasis was brought on the importance of uniting as a community to define a cohesive program**, especially for critical areas such as flavor-changing neutral currents and kaon physics, ensuring comprehensive coverage and progress in these fields.

Bottlenecks for Future Progress. The discussion highlighted key challenges for particle physics including delays in launching the HL-LHC, which risk public trust and proving the field's ability to achieve ambitious projects. **Technical failures were noted as more harmful to the field's reputation than delays.** The lack of clear evidence for new physics poses challenges for funding and societal support, **reinforcing the need for effective public communication beyond Higgs discoveries**.

3 Survey summary

As part of the follow-up to the workshop, a survey was conducted to gather input from ECRs in Belgium and the Netherlands. This survey aimed to understand ECR perspectives on the current landscape of particle physics, including ongoing projects like HL-LHC and thoughts on the next flagship collider. The responses provide valuable insights into how ECRs view their current work and well-being, their expectations on future colliders, along with concerns they have.

3.1 Participants' Backgrounds

A total of 41 responses were collected, 68% from the Netherlands and 32% from Belgium. Participants are primarily involved in LHC experiments, 29% from ATLAS, 22% from CMS, 20% from LHCb and 10% from ALICE. Participants are also contributing to neutrino research (5%), FCC (2%), and gravitational wave studies (2%). Additionally, 10% are engaged in other areas, including precision top physics, theoretical research, or work outside specific experiments. The primary areas of focus for participants are physics analysis (71%), software development (39%), and hardware work (34%), with smaller groups engaged in theory (15%) and phenomenology research (2%).

3.2 Well-being & outlook

Part of the survey gauged the job satisfaction of ECRs, along with their outlook and concerns on both the short- and long-term developments within the field. **Generally it was found that while participants were happy in their current job and excited about the HL-LHC in the near future, they hold much stronger reservations when it comes to the long-term developments in the field**. The following paragraphs outline the survey results in detail.

Job satisfaction. Most participants are happy with their job. In a question where they were asked to rank their happiness they gave it on average an 8.12 out of 10, with a standard deviation of 0.89. The lowest recorded score was 6, which was chosen by only two participants. This is in line with the result that 86% of participants indicate that they would like to remain in the field. Those who answered that they did not want to remain in the field mentioned the lack of stability and relevance to society as reasons. Nonetheless, ECRs generally do see room for improvement. 25 participants answered the open question *"how would you like your job to be improved?"*, where they raised points relating to the following overarching themes:

- **Job Stability and Security:** Respondents prefer longer contracts, more permanent positions, and reduced pressure to relocate frequently.
- **Work-Life Balance and Well-Being:** Improved work-life balance, reduced time pressure, and better attention to mental health are common desires.
- **Inclusivity and Society:** Some express a desire for HEP to build stronger connections with society and to be more inclusive, with greater openness and involvement of ECRs in decisions.

HL-LHC (short-term). Nearly all participants were excited about the HL-LHC, with only three of them answering that they were not. Most (76%) also did not want the HL-LHC program to end sooner than anticipated in preparation for the next flagship collider. Approximately half (46%) currently are

involved in HL-LHC related activities. The following overarching themes were identified in answers to the question *"what is your opinion on the HL-LHC?"*:

- **Practical solution:** There is strong support for the HL-LHC as a sustainable and efficient way to maximize the potential of the existing LHC infrastructure.
- **Scientific potential**: Respondents expect mostly a refinement of our understanding of the standard model with higher precision, but not necessarily major discoveries. They also appreciate that it serves as a platform for advancing technologies for future colliders.
- **Concerns:** Some reservations include its high costs and energy demands.

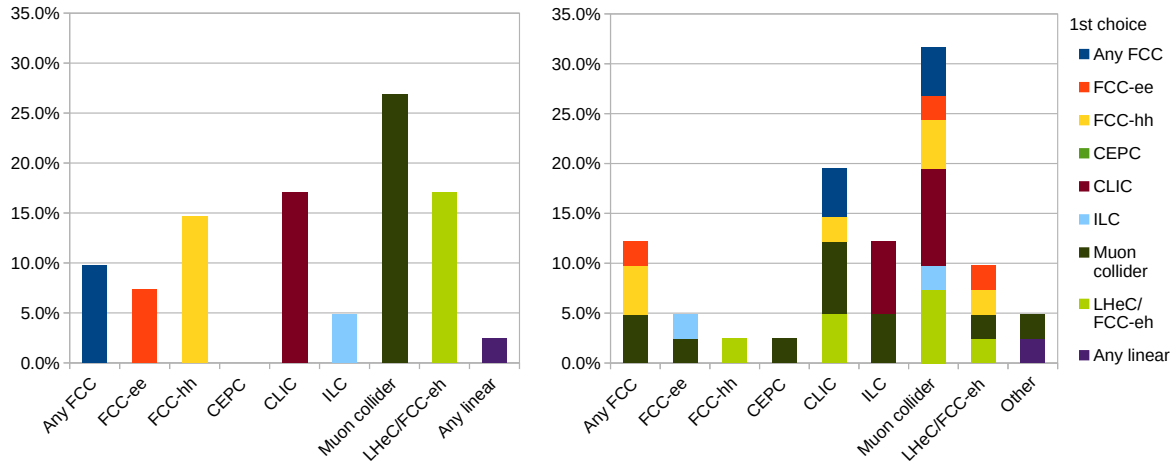
Long-term. 30 respondents answered the question *"what are your concerns about the future of our field?"*. Some overarching themes which were identified from the responses include:

- **Funding Concerns**: Respondents express concerns about securing funding for costly projects amid declining public interest, competition with other fields, and global challenges like climate change and economic instability.
- **Long-term strategy**: Concerns are raised about the reliance on ever-larger colliders. Some respondents call for a more open discussion about alternative strategies, prioritizing smarter, more cost-effective, and sustainable methods to achieve physics goals. Regarding focusing on larger collider projects (like FCC), there is a concern about the loss of flexibility.
- **Job Security and Career Trajectories**: Many fear the shrinking availability of academic positions, the insecurity of temporary roles, and the difficult career paths in academia.
- **Public perception**: Some worry that the field could lose relevance in the public view due to a lack of discoveries, overpromising on results, and decades-long timelines for future projects.

3.3 Preferences for the next flagship collider

This section summarizes the respondents general interest in the different future collider options, including whether they expect to work on future collider related projects in the near future. In addition, participants were asked to rank various aspects by their importance to make a decision on the next flagship collider. Opinions about potential host regions and prospects of European proposals in the context of other international projects were also surveyed. Finally, respondents were asked about their preferred timeline for the ESPP.

What is your favorite next collider? The results of this question are presented in Fig. 1a. Of the people surveyed, almost 27% indicated the Muon collider as their preferred project, which is the largest fraction of votes for any single project. The FCC projects accumulate 32% of the respondents between them, with almost half of them (15%) primarily interested in the hadron collider variant FCC-hh. The two linear collider options accrue over 24% in total, with most respondents (17%) favoring CLIC, which makes it the second most preferred single project. The electron-hadron collider projects LHeC / FCC-eh were also chosen by 17% of respondents. When asked for their second favorite choice, the results are similar to the first choice. However, the FCC projects lose a few points, mostly in favor of the muon collider and to a lesser degree CLIC.



(a) 1st choice.

(b) 2nd choice.

Figure 1: Preferred future collider options.

Apart from the physics which are the most important aspects to build a future collider? The surveyed persons were asked to rank the following aspects of any kind of future collider project from 1, being the most important aspect to 10 being the least important aspect. The numbers in brackets indicate the average rank ± the standard deviation among the surveyed people. The aspects are listed from most important to least important: Environmental impact and sustainability (3.49 ± 2.03), Time for decision making, construction, and getting it running (3.56 ± 2.32), Physicist enthusiasm (4.24 ± 2.56), Flexibility (4.49 ± 2.35), Cost (4.63 ± 2.66), Long-term (5.68 ± 2.54), Social impact (6.32 ± 2.17), Risks (6.46 ± 2.29), Public opinion (6.54 ± 2.23). The results reflect ECRs focus on environmental responsibility and concern about the timeline and flexibility of the projects. The importance assigned to "time for decision making, construction, and getting it running" seems to contradict the preference for a muon collider, as this is a project that would likely require a longer time until construction due to the need for extensive R&D. However, the respondents who indicate a preference for a muon collider indeed rank the timeline aspect significantly lower, at 4.9 ± 2.8 with a standard error of 0.8.

Do you expect to work on future colliders in the following years? 34% yes - 66% no

In which region/country would you prefer to have the next collider built? The majority of the people surveyed want the next collider to be built in Europe (76%), where the preferred location would be CERN (24%). A minority (one mention each) would favor Asia, US or Europe but not CERN. 12% of respondents did not have a preference for the location. Among the respondents who prefer the next collider to be a muon collider fewer (63%) prefer it to be built in Europe, whereas all (100%) of respondents who prefer an FCC as the next flagship collider would like it to be built in Europe.

Should CERN/Europe proceed with a circular/linear collider if another machine is build elsewhere? During the panel discussion summarized in Sec. 2.2, it was pointed out that a significant overlap between the projects could occur. Therefore, the community was asked for their opinions on

building a specific future machine, linear or circular, in Europe under the circumstance that a competing machine is built elsewhere. If Japan proceeds with the ILC in a timely manner, 66% of the surveyed persons agree that Europe should continue to build a circular collider but should not continue (80%) to plan or build a linear collider. If China proceeds with CEPC on the announced timescale only 39% of the surveyed persons believe that Europe should continue the efforts in a circular collider but 71% agree to continue the efforts for a linear collider in Europe. Moreover, Survey results indicate that 71% of participants believe construction of a circular collider should proceed in Europe, regardless of developments in the US, while only 56% support continuing efforts for a linear collider If there are major new, even unexpected, results from the HL-LHC, 56% (49%) of the surveyed persons would agree to continue building a future circular (linear) collider in Europe.

When would you like to have a decision made on the next future collider? Most respondents (41%) are happy with the proposed timeline of the ESPP. But a significant fraction (37%) would like a decision to be made within 2 years or earlier.

3.4 Opinions & concerns about future projects

This section contains a summary of the advantages, disadvantages, and concerns perceived by the respondents for each of the future collider projects surveyed. The topics range from the physics case of the individual project over the proposed timeline and connected career opportunities up to the environmental aspects.

Over all projects the opinions that were pointed out the most are related to:

- the funding and cost
- the timeline, e.g. being too far in the future for reasonable career prospects
- the work environment, e.g. the number of detectors possible or the location of the machine
- the technology, e.g. whether it is already available, its potential interest for the general public or whether new technology is needed with a higher risk to be successful in time

The community pointed out that the FCC projects (FCC-ee & FCC-hh) are more expensive than than the other collider projects. Especially FCC-hh is considered to be very far in the future and other projects have a more interesting timeline considering career perspectives. The CEPC project being built in China introduces concerns about the international access and collaboration. While most of the projects use known technology to some extent, the muon collider would offer significant room for new technology developments. However, this means its feasibility is not yet proven which adds additional uncertainty to the project. The possibility for polarized beams at CLIC and ILC is considered as an advantage with respect to the other e^+e^- projects.

While the aspects above are supported by a significant fraction of the respondents, the scale of the survey does not allow us to draw more concrete conclusions. Therefore, in the following a summary of all arguments raised for each of the projects is given.

FCC-ee. For the FCC-ee project respondents acknowledge that as a lepton collider it has a much cleaner collision environment compared to a hadron machine, allowing for high precision measurements of the SM. It is pointed out that this project offers good prospects for EW, Higgs and top physics,

and EFT interpretations. However, the proposed center of mass energy of 350 GeV is not sufficient to measure the Higgs self-coupling, and some do not see a huge rate at the Z pole as sufficient. The possibility to have multiple interaction regions is pointed out as an advantage compared to the linear colliders. The proposal to upgrade the machine to a hadron collider is received positively, since this guarantees a long-term perspective for high-energy physics (HEP) in Europe. However, many consider the FCC-ee to be very expensive for the physics perspective if FCC-hh is not built later. The lower flexibility in the energy range of this machine is seen as a disadvantage compared to the linear colliders. This is especially of interest when considering the long timeline to build this collider and with potential discoveries at the HL-LHC. It is pointed out that the timeline for this project is longer than the one for CEPC which could lead to conflicts already discussed in Sec. 2.2. It is also mentioned, that conceptually this project is very similar to LEP and no big technology innovation is foreseen. This makes the plan more realistic and achievable, but at the same time, the question is raised how to convey the innovation of this project to the public.

FCC-hh. The greatest advantage of the FCC-hh lies in its potential to achieve the highest collision energy, offering the greatest opportunity for direct discovery of new particles and enabling the most complex physics programs. It is pointed out that—similar to the LHC–this project will allow for further precision measurements of the SM. Also, the prospects for the continuation of the heavy ion program are seen as promising. However, it is pointed out that the machine might be too large and not very flexible given that the outcome of the HL-LHC is yet unknown. Many respondents consider the cost for this project to be too high, while at the same time some see it as not groundbreaking enough in terms of technology. Additionally, it is mentioned that there is no strong theoretical motivation for the chosen energy and no guaranteed deliverables that would justify the cost. Due to its large size, the FCC is expected to have a significant carbon footprint and environmental impact. Some respondents point out that this and the high cost will be difficult to communicate to the general public. However, it is seen positively that this project shares its civil infrastructure with FCC-ee and that the infrastructure of the LHC can be reused. As with FCC-ee, this project is seen as a guarantee for a long-term future of HEP in Europe. However, it is pointed out that it is very far in the future and that the projected timeline for the CEPC will be faster if the decision is made to build it. It is often also mentioned that the technology for this project is not yet ready, preventing an earlier start.

CEPC. The CEPC has more concerns raised. In terms of physics, mainly the limited energy reach is pointed out as a downside—in particular the fact that no Higgs self-coupling measurements are possible. Additionally, it is seen as a disadvantage that there is no potential for higher energies in the case of new discoveries at the HL-LHC, and a huge rate at the Z pole is not considered essential. It is pointed out that CEPC does not foresee any big advancements in accelerator technologies. While some view this as a drawback, others believe it makes the project more practical and feasible. CEPC is expected to be significantly cheaper than the other options, but political and ethical concerns are raised. The technical reliability and the know-how needed to build and operate such a machine are questioned. On the one hand, the location in China is seen as a chance for international collaboration and support, which however depends on the international access granted. On the other hand, it is expected to lead

to a reduction of the HEP community in Europe if it is the only collider built. Concerns about working and living in China are raised.

CLIC. The big advantage of the CLIC project is seen in the unique opportunity to reach the energy frontier with an e^+e^- collider. This would also allow to probe the top quark pair production threshold and the Higgs self-coupling. The possibility to provide a polarized electron beam is positively received, as it brings new channels to study electroweak physics. However, it is noted that this project will have a lower luminosity than a circular collider. The staged approach of this project is considered lower risk. The possibility to extend the energy of the machine or upgrade it with new technologies (e.g. C^3 or plasma-wakefield acceleration) is also mentioned. CLIC could therefore be used to immediately explore new (heavy) resonances discovered at the HL-LHC. While the proposed technology is ready, it is still considered novel. CLIC is cheaper and could be realized earlier than FCC [1], and its location in Europe is seen as an advantage. Yet it is pointed out that a linear collider would have fewer experiments and therefore fewer job opportunities. CLIC is considered to be in direct competition with the ILC project.

ILC. The ILC project is viewed similar to CLIC in many aspects. The staged approach is considered to be more flexible and therefore to offer lower risk. It is acknowledged that the technology for this project is ready. It is also mentioned that it could be build more quickly than the FCC. The accelerator can be extended to higher energies more easily by extending it or by upgrading with new technologies. However, a concern is that it will provide lower luminosity than a circular collider. It is pointed out that this project allows precision measurements both for top pair production and Higgs self coupling. The unique possibility of polarized electron and positron beams at the ILC is seen as an advantage, as this offers the possibility to study new channels in electroweak physics. It is pointed out that due to the partial funding by Japan this project might be cheaper for the European contributors compared to the other projects. However, it is also mentioned that the ILC has been under consideration for a long time and it is uncertain if it will be built. The limited number of experiments is seen as a disadvantage by some, as this offers fewer job prospects, with the additional downside compared to CLIC of the host country being located outside of Europe.

Muon Collider. Physics wise, it is considered to bring together the advantages of an e^+e^- collider and a hadron machine. It offers a clean physics environment like a e^+e^- collider while reaching energies similar to a hadron machine. It is received positively that it has a great potential for interesting physics due to its novel concept compared to previous lepton colliders such as LEP. A Muon collider is seen as a exciting new project with a higher interest from the general public. This offers a risk and a gain at the same time: interesting and new technology developments are attractive not only within the particle physics community. At the same time, this increases the uncertainty on the project. Timeline and cost are considered less reliable, due to the developments needed. It is acknowledged that, compared to the other options, the muon collider requires the smallest civil infrastructure and less electricity to achieve the same luminosity at a given energy.

[1] Nevertheless, neither the circular nor the linear option will be operational before the late 2040s.

LHeC & FCC-eh. Some respondents see the main point of the LHeC in precision measurements of parton density functions (PDFs). But others acknowledge that a wider physics case complementary to the other projects is present, although it partially overlaps with the lepton colliders. Overall, LHeC is not considered to be a big flagship project. But it is seen as advantage that the timescale is much shorter than the other projects, so that it could fill the gap between the end of HL-LHC and the start of the next future collider. Respondents appreciate that due to the reuse of the LHC infrastructure it is cheaper than the other projects and the environmental impact is lower.

The interest in FCC-eh is lower than for LHeC. But some see it as a worthwhile extension to the FCC program with similar benefits as LHeC. It is pointed out that it should not delay the FCC-hh program.

General remarks and concerns:

- Europe should take the Electron-Ion Collider (EIC) into account when discussing future projects.
- Better inclusion of ECRs in the discussion. Some feel like the decision has already been made in favor of FCC-ee.
- Focus on the development and application of novel technologies and techniques that could have wider benefits. This provides a stronger justification for building a future machine.

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A Summary of the talks during the workshop

This section includes short summaries of the morning sections on the second day of the workshop.

A.1 Current physics landscape and motivation for future colliders

The LHC has exceeded all expectations, unlocking insights far beyond the initial scope of its design. While many measurements align with the SM, certain phenomena—like the universe's puzzling matter-antimatter asymmetry—remain unexplained, hinting at physics beyond the SM. These mysteries suggest the existence of undiscovered particles, possibly at energies beyond the LHC's reach or hidden within subtle deviations in current measurements. The Higgs boson, a cornerstone of this endeavor, continues to reveal its secrets. While properties like its mass and width are increasingly well-measured, other aspects remain obscure. For instance, the Higgs mechanism for imparting mass is only explored for a subset of elementary particles, leaving much of its role unexplored. Even more intriguingly, the self-interaction of the Higgs boson—a process linked to the universe's early moments and the Baryogenesis era—remains untested. Remarkably, only about 7% of the projected LHC dataset has been analyzed, leaving vast potential untapped. However, achieving the next level of precision in the Higgs sector, with sub-percent uncertainties, demands a new generation of accelerators to surpass the LHC's capabilities and push the frontiers of discovery further.

A.2 Collider Options and Considerations

The LHC has been a monumental achievement in particle physics, with operations projected to last until 2040. However, when proposed in 1984, the LHC faced skepticism due to the substantial R&D needed, particularly in high-performance magnet technology. Today, similar challenges arise as future accelerator

projects demand long-term technological development. Selecting the next accelerator extends beyond physics, requiring careful consideration of factors like luminosity, energy, costs, and risks as failures could have irreversible consequences for the field. Regardless of the choice, any future accelerator will represent a significant financial investment yet such investments often brings new technologies and stimulate high-tech industries. Future accelerators fall mainly into two categories: linear and circular. Linear colliders (e.g. CLIC, ILC colliding electrons and positrons) offer possibility for energy scanning and minimization of synchrotron radiation. Circular colliders (e.g. FCC-ee, CEPC) offer higher luminosity, support multiple experiments, and enable upgrades to hadron colliders, broadening their energy and physics reach. Muon colliders, though technically challenging, promise transformative innovations that could impact science and technology broadly. Crucially, R&D knowledge from these efforts must be preserved to benefit both particle physics and other fields.

A.3 Impact of future colliders on society and sustainability

Addressing sustainability is critical as Europe targets net-zero CO2 emissions by 2050, coinciding with the timeline for future accelerators. Therefore, future collider projects must prioritize reducing their carbon footprint throughout their lifecycle—construction, operation, and deconstruction. A significant portion of CO2 emissions are expected to come from concrete production for civil engineering, power consumption relying on non-renewable sources, and detector operation. Even activities like air travel to conferences contribute to the overall impact. Awareness and reduction targets are needed at individual, infrastructure, and institutional levels. Given the increase in energy consumption and the global shift away from non-renewable sources, future accelerators must emphasize energy efficiency, re-use, and sustainable data management as they handle exponentially growing demands for storage and processing. Innovative approaches in power optimization and cooling systems will be essential to minimize environmental impact.