National input from the United Kingdom to the 2026 Update to the European Strategy for Particle Physics

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This document has been prepared on behalf of the UK particle physics community to provide input to the 2026 Update to the European Strategy for Particle Physics (ESPPU). The UK process began with an initial workshop hosted by the IPPP in Durham in September 2024, aiming to bring together the experimental and theoretical communities to discuss the physics and technological opportunities and challenges associated with the future of High Energy Physics. This was followed by two community drafting days in November 2024 and January 2025. These drafting days focussed on the questions provided by the European Strategy Group (ESG) on both collider and non-collider physics along with additional topics outside the direct scope of the questions but relevant to the future roadmap. These include detector R&D; software and computing; attracting and maintaining talent and expertise; industrial return, and public engagement and outreach. The drafting was facilitated by a drafting team which had representation from both plenary and Early-Career Researcher (ECR) UK ECFA delegates and the STFC Particle Physics Advisory Panel (PPAP). For the first submission (31st March 2025) answers to most questions are provided (including q3a- the next high-priority collider at CERN) but prioritisation of alternative options if this is not feasible under various scenarios, and prioritisation of non-collider and complementary areas of exploration, is not provided. These will be discussed further in the next community drafting meeting on 28th April (when further information will be available following community submissions) and updated ahead of the Open Symposium. We anticipate one final community meeting following the release of the briefing book in September 2025 to discuss possible revisions/updates to the draft but we expect these to be minor.

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1 Executive Summary

The UK particle physics community strongly supports a bold and forward-looking European strategy that maintains CERN as the global centre for collider physics and ensures a balanced, vibrant, and innovative research ecosystem. It is paramount to fully exploit the High-Luminosity LHC (HL-LHC) to maximise scientific returns from this flagship facility. There is strong support in the UK for a new large circumference tunnel at CERN, the FCC tunnel, as a major infrastructure for the future of collider particle physics and the energy frontier. Beyond collider physics, the UK community emphasises the importance of a strong and sustainable non-collider particle physics programme, which has the potential for groundbreaking discoveries in the next 10–20 years.

The community calls for sustained investment in cutting-edge R&D in accelerator, detector, computing and environmentally sustainable technologies, recognising that, without a critical mass of support, the field will not be able to achieve its transformative potential. In addition the UK emphasises the importance of sustained and coordinated support for particle physics theory, which provides the foundation and vision for future discoveries, as well as emerging cross-disciplinary themes with the potential to transform particle physics. These include areas such as astroparticle physics, quantum technologies for fundamental physics, and other innovative fields that can drive breakthroughs in our understanding of the universe.

A key priority in UK discussions has been ensuring the needs and aspirations of ECRs are met by the future roadmap. The UK ECR community stresses the importance of a definitive decision made in this round of the ESPPU for the next European flagship collider project to ensure the retention of talent in particle physics. Additionally, ECRs strongly endorse the continued UK commitment to a breadth of non-collider projects.

The UK's input is structured as follows. Section 2 summarises our overarching priorities for the future and sets the context for the answers to the ESG questions provided in Sections 3 and 4 for the future collider programme and complementary areas of exploration, respectively. Section 5 presents additional considerations for the future roadmap that should be built into the planning.

2 Priorities for the future

Our strategy for the future is driven by our physics goals. As a field we have the ambition to thoroughly and systematically explore the limits of applicability of the Standard Model (SM) and push our experimental sensitivity to directly and indirectly search for Beyond-the-Standard Model (BSM) physics to the highest achievable energies. This includes establishing the nature of the Higgs potential, the origin of mass of some of the second (and maybe first) generation fermions, and furthering our understanding of electroweak symmetry breaking through detailed characterisation of the Higgs boson (including its self-coupling); establishing the stability of the EW vacuum (and its implications for cosmology); searching for dark matter across the broad range of available masses and couplings; searching for quantum imprints of BSM physics using the broad range of tools provided by the SM flavour sector; elucidating the mysteries of the neutrino sector (including understanding the origin and nature of neutrinos and their masses and probing CP violation in the lepton sector); and precisely characterising quantum chromodynamics (QCD) effects (especially in the non-perturbative regime) necessary to support all of the above.

Continuing in the spirit of the last ESPPU, as its highest priority the UK reaffirms its strong support for the full exploitation of the LHC and HL-LHC programme across the large experiments. This remarkable machine and its detector systems have a proven track-record in delivering, and often exceeding, their performance and research goals. Following a substantial investment of resources, the future LHC programme offers opportunities that will likely be unparalleled for several decades such as direct and indirect new particle searches, precision SM measurements, hadron spectroscopy, and heavy-ion physics. The probing of the Higgs self-coupling is a standout example of a measurement for which the highest attainable precision at the LHC should be pursued. Therefore, based on current projections (which will be updated by 31st March 2025), the delivery of a minimum of 3000 fb^{-1} at each of ATLAS and CMS and 300 fb^{-1} at LHCb should be a priority. The UK community encourages timely implementation of the upgrades required for full exploitation of the HL-LHC. The UK community also has significant involvement in proposed experiments and facilities to further exploit the HL-LHC, including the Forward Physics Facility (FPF) which provides unique opportunities to detect neutrinos at very high energy and enables searches for new physics scenarios that would otherwise be missed including light dark matter and dark sectors. For exploiting the broader LHC accelerator infrastructure, the UK has involvement in the SHiP experiment, which is the only

CERN-approved initiative beyond the LHC. Its physics programme will serve as a strategic cornerstone in the search for both hidden-sector particles and dark matter, as well as providing a world-class neutrino physics programme.

On the future collider front, many of the goals outlined above can be achieved through the priorities established in the previous ESPPU: that an e^+e^- Higgs factory should be the next highest priority machine and that the long-term aim should be to push the energy frontier exploration to the highest achievable level. There is a strong sentiment in the UK that CERN should remain at the forefront of the energy frontier exploration, crucial to address many of the questions above. An e^+e^- Higgs factory could be realised as a circular collider such as FCC-ee, or a linear collider such as CLIC or ILC; projections for all of these give similar core Higgs physics programmes and propose to run at an energy around the top pair production threshold. In addition, a Z-pole run would yield very high statistics with a circular machine with associated advantages for measurements of flavour physics and electroweak physics. A linear machine could also be staged to run at higher energies to study Higgs pair production. Options for an energy-frontier machine include a next-generation hadron collider, or a muon collider operating in the 10 TeV parton centre-of-mass (pCM) energy range; both necessitate extensive R&D.

An overarching theme in UK discussions was prioritising breadth of the programme to enable a combination of different approaches to maximise our sensitivity to new phenomena. As an example, whilst an e^+e^- collider provides a compelling programme of measurements in various sectors as highlighted above with indirect sensitivity to new physics at very high mass scales (O(50-100) TeV), complementary and unique sensitivity can also be accessed indirectly through dedicated quark-flavour, neutrino, and non-collider experiments including the precision muon/kaon and EDM programmes. In the quest for dark matter there is strong complementarity between the sensitivity of next generation direct dark matter experiments, energy frontier colliders (both general purpose detectors and additional forward and transverse detectors), and non-collider and beam-dump experiments targeting challenging scenarios (particularly lower masses and couplings) that would otherwise remain unexplored. Planned experiments exploiting quantum technologies can further extend dark matter/sector searches to very low and otherwise unattainable masses. Similarly in neutrino physics there is complementarity between the long-baseline programmes at DUNE and Hyper-K and the sensitivity to (absolute) mass measurements that can be achieved through single- and double-β decay experiments, while neutrino telescopes exploring ultra-high-energy neutrinos offer new opportunities to probe fundamental physics and astrophysical sources.

The timescales for future programmes discussed in this ESPPU mean that it is imperative that a future roadmap for high-energy physics has the support of ECRs, whose perspectives must be reflected in the priorities of the strategy that they will ultimately carry out. Our field produces exceptionally talented young researchers, which is beneficial for the UK as they contribute widely across various sectors. It is crucial to maintain the appeal of particle physics as a viable and attractive career path in order to sustain the population, expertise, and enthusiasm required to overcome the challenges that the next flagship CERN project will present. The ECR community needs certainty that collider physics has a future beyond the HL-LHC, a sentiment mirrored in the wider UK community's desire for CERN to remain a world leading collider laboratory. A continued lack of certainty around CERN's long-term future will seriously inhibit ECR participation in any future projects. Thus, it is essential that the next major collider project is decided upon and advances as quickly as possible. UK ECRs further stress the importance of a broad particle physics programme in Europe beyond collider projects, with extensive UK involvement. Smaller, shorter-timescale experiments carried out in parallel to, and in-between, major collider projects will offer continuity for ECRs during long stages of collider R&D in addition to their inherent valuable physics research potential. Collider and beyond-collider physics play crucial and complementary roles in training ECRs to develop critical skills, ensuring that we remain a community of researchers with great diversity of experimental and theoretical expertise.

A key theme in UK discussions was ensuring sufficient resources for the theoretical and technological R&D needed to deliver the future roadmap in an impactful and environmentally sustainable way. Particle physics is both inspired by and reliant upon theoretical developments which must be supported. Similarly, our future programmes are reliant on R&D activities across accelerator and detector technology and software and computing. For instrumentation the opportunities raised by the DRD collaborations and by quantum sensors have been stressed strongly in the UK community. These topics are discussed in detail in Section 5 (i.e. after the UK responses to the ESG questions) and support for these activities should be built into planning of the core programme.

3 Future collider programme

3.a Which is the preferred next major/flagship collider project for CERN?

There is strong support in the UK for a new large circumference tunnel at CERN, the FCC tunnel, as a major infrastructure for the future of collider particle physics. The community has a large contingent in support of the integrated programme of FCC-ee followed by FCC-hh , as well as a large contingent in favour of considering FCC-hh as the next collider at CERN. FCC-hh would also have additional opportunities for heavy-ion collisions and electron-proton collisions through FCC-eh. A key driver in UK discussions on this question was a desire for CERN to retain its position as a leading global centre for particle physics, which means investing in infrastructure for future colliders beyond the HL-LHC, combined with a strong request from the ECR community (noted in Section 2) to commit to a decision to move forwards. The opportunities and risks associated with committing to the FCC tunnel at this stage were discussed extensively. Inspiring and training the next generation of physicists is a key consideration, which can be well-served by a new large infrastructure if delivered in a timely manner. There were also discussions on the in-built risk-mitigation possible with FCC due to options to adjust the staging/timescales of the project in response to external factors (discussed further in later sections).

Given the need to minimise the time between the end of LHC data taking and the start of operations of the FCC, the immediate priority is to secure funding and begin civil engineering of the FCC tunnel. It is, however, critical that the extra resources required are not diverted from other parts of the European particle physics programme including HL-LHC exploitation and smaller-scale experiments; a healthy and robust European particle physics ecosystem requires a breadth of exciting smaller-scale experiments as well as a flagship collider. It is essential for both ethical reasons and public support that environmental concerns are fully taken into account. This includes ensuring that the negative environmental impacts of particle physics research and infrastructure are identified, minimised and mitigated, including comprehensive life cycle assessments of future experiments.

The FCC project presents risks related to the cost and schedule, international developments, the environmental sustainability, as well as the technical feasibility of some of its components and systems. It is therefore essential that a programme of R&D is established to address the risks and that the decision is kept under review. This will be discussed further in responses to subsequent questions.

3.b What are the most important elements in the response to 3.a?

The endorsement of FCC (subject to the boundaries mentioned in the previous section) is driven by the exciting potential of the physics programme and its fit with the future priorities outlined in Section 2. In this section, specific considerations across the categories provided by the ESG are highlighted but not prioritised (as they are all key considerations for the future programme).

i **Physics potential:** FCC-ee will enable detailed characterisation of the Higgs (improving and extending the progress that will be made at the HL-LHC) including measurements of the mass, width and couplings. The improvements in precision for Higgs/Top/EW/flavour measurements at FCC-ee are consistent with aims to push indirect sensitivity to the highest achievable level, whilst FCC-hh would provide unprecedented direct sensitivity to high-mass BSM (including full coverage of the relic surface for wino/higgsino WIMP dark matter and substantial discovery reach exceeding 20-50 TeV for heavy resonances). Accessing the Higgs self coupling should remain a priority for energy frontier exploration and the FCC-hh target of 5% for this parameter would represent a huge leap in our ability to understand electroweak symmetry breaking (EWSB). An electron hadron collider (FCC-eh) would be a natural accompaniment to FCC-hh, providing a compelling Higgs, Standard Model and BSM physics programme that complements FCC-hh and FCC-ee in many areas. Its sensitivity to proton structure extends to parton momentum fraction values, x, as low as 10^{-7}, providing the only realistic pathway to a well-understood initial state for the FCC-hh.

ii **Long-term perspective:** Provided it can be balanced with the breadth of the programme, FCC could provide decades of exciting high-impact energy frontier exploration shortly after the HL-LHC.

iii **Financial and human resources: requirements and effect on other projects** Preparations for the next collider at CERN need to be balanced with ongoing commitments to the HL-LHC. A schedule for the FCC has been developed taking constraints from the HL-LHC into account. However, in order for particle physics to remain exciting and attract new researchers, commitments to FCC should still leave resources for the smaller short/medium term projects (discussed later) needed to maintain the breadth of the programme.

iv **Timing:** Long gaps ($\gtrsim$ a decade) in CERN's accelerator programme will put retention of skills in accelerator and detector R&D at risk, and should be avoided, and the ECR community has expressed a desire for a decision on a future collider project. The FCC would provide a central long-term focus for collider physics.

v **Careers and training:** Particle physics must remain a desirable and viable career for aspiring scientists, providing attractive employment opportunities at all stages. If combined with a broad programme including shorter term smaller scale projects, FCC could provide an exciting long-term collider programme for the field.

vi **Sustainability:** Environmental sustainability is an underlying focus that must be properly funded and embedded into any flagship particle physics experiment. In such a flagship experiment Europe is provided with a unique opportunity to develop and lead environmentally sustainable construction approaches and therefore must embrace this. R&D to accomplish long-term sustainable accelerator, detector and computing infrastructure must be funded and we expect this to be built into future FCC plans.

3.c Should CERN/Europe proceed with the preferred option set out in 3.a or should alternative options be considered:

i If Japan proceeds with the ILC in a timely way?

ii If China proceeds with the CEPC on the announced timescale?

iii If the US proceeds with a muon collider?

iv If there are major new (unexpected) results from the HL-LHC or other HEP experiments?

The broad sentiment of the UK community's discussion is that Europe should take measures to maintain its global lead in collider physics regardless of decisions in other regions and without waiting for the final results from the HL-LHC. If major non-European collider projects proceed then the UK community would wish to collaborate on them. However, the next flagship collider at CERN should be complementary to major efforts elsewhere, and not an identical type of project.

With this in mind the UK community plans to discuss this question in the context of whether any of these developments would make proceeding with infrastructure for FCC an unfeasible route for CERN. The scenario where CEPC goes ahead is discussed in Q3.e below as this could create a scenario where the FCC-ee would be deemed unfeasible due to international developments (as there would be another circular e^+e^- collider being prepared on faster or similar timescales). The scenario of ILC being pursued in Japan will be further discussed in the April meeting. If the US were to proceed with plans for a muon collider, this would be complementary to FCC so unlikely to impact our answer to Q3.a. (The next step in the realisation of a muon collider is a 6D-cooling demonstrator which is highlighted in the next section). Furthermore, the possibility of a muon collider being pursued in Europe is discussed as one of the alternative scenarios in Q3.e.

Our response to major new unexpected results from the HL-LHC or elsewhere has not yet been discussed within the UK community and would depend on the nature of the results. In our next community meeting on 28th April, we aim to converge on specific answers to this question in the four scenarios above and prioritise the alternative options identified for the scenarios that FCC is deemed unfeasible or delayed in Q3.e.

3.d Beyond the preferred option in 3.a, what other accelerator R&D topics (e.g. high-field magnets, RF technology, alternative accelerators/colliders) should be pursued in parallel?

This section assumes no preferred option for a future flagship experiment, focussing instead on the accelerator R&D required to enable world leading particle physics experiments in Europe. Delivery of any world-leading accelerator-based facility requires sustained activity and global collaboration. Funding in accelerator R&D must be increased and secured to meet the demands of any European flagship accelerator-based facility and beyond.

Fundamental to the success of a future flagship experiment is funding more intensive R&D in several areas including high field magnets, high temperature superconductors, and efficient RF systems. Of particular importance is the increased emphasis on R&D focussed on improving the environmental sustainability of accelerators, in the areas of thin-film superconducting RF cavities, high efficiency klystrons, fast reactive tuners, permanent magnets, embedded re-use of energy such as waste heat, and leveraging A.I. Superconducting technologies are fundamental to all future flagship options. The development of a large scale cryogenics test facility is required as testing is a bottleneck in Europe for superconducting magnets and RF.

Significant scientific advancement is historically due to disruptive technology. To innovate and lead, Europe must commit to funding R&D in disruptive accelerator technologies, including but not limited to: muon acceleration, plasma based acceleration, high-energy recovery linacs, and terahertz acceleration. Novel acceleration techniques provide a route to future discovery potential within and beyond the current scope and meet the research criteria of ECRs. The realisation of novel accelerator technologies requires the development of demonstrators. Europe should pursue construction of proof-of-principle experiments such as, but not limited to, a muon cooling demonstrator, as well as exploiting the relevant existing accelerator test facilities, such as CLARA and EPAC in the UK. Funding and commitment to facility based experiments provide a path to wider collaboration and innovation.

The applications and benefits of accelerator R&D outside of particle physics should be emphasised to support arguments of funding synergy and return on investment. In addition to benefitting other research infrastructures, such as synchrotron light sources, free electron lasers, and spallation neutron sources, accelerator R&D has impact on the fields of fusion and medicine, where the requirements of future particle physics experiments overlap with the next generation of cancer treatment and energy production, with transformative capability in biomedical and clinical fields. Europe should maintain leadership and engage ECRs in synergistic multidisciplinary research. Greater links with supporting industries must be established and nurtured if Europe is to benefit from its own investment in any flagship accelerator-based particle physics experiment.

3.e What is the prioritised list of alternative options if the preferred option set out in 3.a is not feasible (due to cost, timing, international developments, or for other reasons)?

During the second community drafting day in January the decision was made to postpone any prioritisation of alternative options until the next community meeting on 28th April when additional information will be available. This section currently summarises key considerations raised on possible scenarios that might require adjustments to the preferred plan.

The constraints arising from the various possible scenarios could lead to different alternative options and so they should be considered separately:

i [**Cost/technical/environmentally unfeasibility**]- FCC is unaffordable or unfeasible on either cost or environmental grounds.

ii [**International developments**]- CEPC is realised.

iii [**Timing**]- Timescales for FCC are pushed back.

The following alternative scenarios have been highlighted for one, a subset or all of these possible scenarios, and will be prioritised in the discussion on April 28th.

a **Linear collider at CERN (relevant for i,ii):** A Linear Collider Facility is a less expensive alternative route to an e^+e^- Higgs factory at CERN, that could be realised on similar timescales and has the possibility for future energy upgrades. A linear collider facility at CERN with an initial collision energy $> 500\,\mathrm{GeV}$, could also provide a complementary facility to CEPC if it went ahead.

b **Pursue FCC-hh as next collider at CERN (relevant for ii):** If CERN committed to the integrated FCC programme but CEPC were realised efforts could be increased to realise FCC-hh on a shorter timescale; discussion would be needed on the technical roadmap required and the commercial availability, cost, and field-strength of magnets, and the corresponding collision energies that could be achieved.

c **Pursue muon collider at CERN in the LHC tunnel (relevant for i,ii):** this has not been extensively discussed in UK discussions to date but will be considered in UK discussions on 28th April.

d **Extend/expand the physics capabilities of the LHC (relevant for i,ii and iii)**: If FCC goes ahead but on a slower timeline or if an alternative route is chosen that would leave a significant gap in collider facilities at CERN, then it could also be desirable to pursue options that would extend the capabilities of the HL-LHC. Possibilities include the FPF (already introduced in Section 2) and the LHeC. LHeC could provide a compelling intermediate facility in scenarios with a longer gap between the HL-LHC and CERN's next major collider through utilising the LHC proton (ion) beam and a new energy recovery linear accelerator. This would significantly improve knowledge of proton and nuclear structure and provide crucial input for fundamental physics when combined with LHC data. Its physics programme would complement the EIC project in the US and enhance the physics potential of a future hadron collider.

e **Expand non-collider particle physics (relevant for i,ii and iii)**: If the FCC is deemed unfeasible or its timescales are delayed, the community could explore the option of expanding and further diversifying non-collider particle physics discussed in Section 4a including accelerator and non-accelerator neutrino physics, direct dark matter detection and the physics beyond collider programme.

Prioritisation of this programme will be discussed at the next UK community meeting on 28th April. In all cases, extra investment in accelerator technology R&D can be considered to bring forward further options for future colliders.

3.f What are the most important elements in the response to 3.e?

This section will be updated after the April community meeting to justify the prioritisation of alternative options that will be provided as answers to question 3.e. Currently, this section briefly lists considerations across the categories provided by the ESG that have been highlighted as important when reviewing alternative options.

i **Physics potential:** Alternative scenarios should remain compatible with the physics priorities set out in Section 2.

ii **Long-term perspective:** As was highlighted in question 3.a the UK community expressed strong concensus that CERN should remain a global centre for collider physics. It was also reinforced by the ECR community that if a future collider at CERN were delayed or unfeasible it is essential to provide a continuity of broad experimental opportunities to avoid the field shrinking, mitigate a loss of expertise and ensure continued, attractive job and training prospects.

iii **Financial and human resources: requirements and effect on other projects:** Alternative scenarios should remain compatible with current commitments (particularly the HL-LHC).

iv **Timing:** As in question 3.b, avoiding long gaps in the CERN programme should remain a priority, so programmes that sustain physics exploitation should be considered.

v **Careers and training:** As noted throughout our input, maintaining a broad programme with attractive opportunities for training and career development of researchers is key.

vi **Sustainability:** Environmental sustainability should remain a central consideration when comparing alternative options and should be embodied throughout the other (above) considerations.

4 Complementary areas of exploration and non-collider priorities

4.a What other areas of physics should be pursued, and with what relative priority?

A key message in UK discussions is that diversity of our physics programme should remain a priority in the coming decades. Due to the variation and complementarity of these projects, no prioritisation has yet been attempted, and instead this section highlights key areas the UK would like to see supported. This answer will be updated (including prioritisation where possible) following our next community meeting.

The discovery of neutrino oscillations, and thus the existence of non-zero neutrino mass, remains the most compelling evidence for BSM physics. Over the next 15 years, the field should focus on addressing fundamental questions in neutrino physics: understanding the nature of neutrino mass; measuring CP violation in the neutrino sector and its possible implications for the matter-antimatter asymmetry in the universe; determining the ordering of neutrino masses; increase the precision of determination of mixing angles and mass-squared splittings; and exploring potential connections to underlying symmetries. To achieve these goals, Europe should prioritise its leading contributions to the construction and scientific exploitation of the long-baseline neutrino oscillation experiments DUNE and Hyper-K, as well as to at least one, preferably two, neutrinoless double beta decay experiments capable of fully probing the inverted ordering parameter space for Majorana neutrino masses. This programme is highly complementary to the collider physics goals and should be regarded as a high priority for non-collider particle physics activities in Europe.

In the longer term, Europe should identify the scientific drivers for the neutrino physics programme beyond the currently planned oscillation and neutrino mass experiments. This long-term strategy should focus on achieving the precision needed in measurements of δ^{CP} and other oscillation parameters, as well as attaining absolute neutrino mass sensitivity that encompasses most of the normal ordering parameter space and provides insight into the fundamental nature of neutrino mass. Two promising future directions are the detection of cosmic neutrino background (CNB) and advances in neutrino telescopes. Detecting the CNB would be as groundbreaking as discovering the cosmic microwave background or gravitational waves. Neutrino telescopes offer a complementary approach to particle physics by accessing neutrino energies beyond terrestrial experiments, enabling PeV-scale interactions across kiloparsec baselines, and providing an independent probe of oscillation parameters and mass ordering in a distinct kinematic regime. A comprehensive R&D campaign is essential to advance this ambitious programme, focusing on innovative neutrino beam technologies, such as neutrino factories, and advanced absolute neutrino mass measurement techniques via double- and single-β decay, which also share synergies with CNB searches. The CERN Neutrino Platform should remain central, supporting DUNE and Hyper-K in the medium term while driving next-generation accelerator and detector technologies for future experiments.

Direct dark matter searches and collider searches offer complementary approaches to uncovering the nature of dark matter, each probing different aspects of potential dark matter interactions. While collider experiments explore dark matter production in controlled high-energy environments, providing insight into its possible particle nature and interactions, direct detection experiments aim to observe dark matter interactions with ordinary matter in underground detectors, probing astrophysical dark matter candidates. This synergy is crucial for a comprehensive search strategy, ensuring sensitivity to a wide range of dark matter scenarios. Direct dark matter detection must remain a key pillar of the European particle and astroparticle physics strategy, leveraging cutting-edge detector technologies and deep underground facilities to complement collider-based efforts in the quest to identify and understand dark matter. With significant advancements expected in the coming 10-20 years, this field holds the potential for a breakthrough discovery that could reshape our understanding of the universe. In this context, the UK has a strong ambition to host a next-generation dark matter experiment, XLZD, at the Boulby Underground Laboratory.

Incorporating emerging quantum technologies into this strategy will be critical for addressing a broad range of fundamental physics questions. Quantum sensors and precision measurement techniques can expand the scope of dark matter searches, enabling the detection of candidates such as axions and ultra-light dark matter, while also enhancing neutrino mass measurements and providing novel probes of fundamental constants and the laws of quantum mechanics. These advancements also strongly complement gravitational wave searches, which have produced some of the most groundbreaking discoveries in recent years. Looking ahead, next-generation gravitational wave observatories will play a key role in addressing major particle physics questions, including electroweak symmetry breaking and beyond.

In the next 25 years, Europe's physics beyond colliders (PBC) strategy should focus on a diverse set of experiments that complement and extend discoveries at energy-frontier colliders. These experiments uniquely probe BSM scenarios and parameter space that high-energy colliders cannot access, including Feebly Interacting Particles (FIPs), Freeze-In Massive Particles (FIMPs), Quirks, milli-charged particles, Long-Lived Particles (LLPs), Electric Dipole Moments (EDMs), dark-sector phenomena, and extremely rare muon and kaon decays. By leveraging existing and planned accelerator infrastructures at CERN, PSI, FNAL, J-PARC, ESS, and BNL, these experiments offer a cost-effective yet powerful approach to expanding the physics landscape, enhancing sensitivity to new physics in ways that energy-frontier colliders alone cannot achieve. A cohesive European strategy for PBC will ensure that these efforts remain well-integrated with collider programmes, maximising the potential for groundbreaking discoveries in particle physics.

4.b What are the most important elements in the response to 4.a?

This section will be further expanded following the community meeting in April, where an attempt at prioritisation will be made. For this draft, the key elements motivating a diverse programme of larger-scale and smaller-scale non-collider projects are briefly summarised using the same categories as Q3.b.

i **Physics potential:** The physics potential of non-collider experiments is often complementary to energy-frontier colliders in terms of direct or indirect BSM sensitivity, either through probing different processes or directly targeting BSM scenarios that are challenging in colliders.

ii **Long-term perspective:** Maintaining programme breadth is key for the long-term health of the field.

iii **Financial and human resources: requirements and effect on other projects:** Experiments that mostly use existing large-scale resources and infrastructure are cost-effective.

iv **Timing:** Several of the planned programs will continue beyond HL-LHC and will thus provide continuity in the particle physics programme, avoiding long gaps without running experiments which is important in attracting future students to the field.

v **Careers and training:** Smaller-scale experiments provide important training opportunities in R&D, construction and commissioning that will be required to realise the future energy-frontier collider programme. They also often have strong links to the theory community.

vi **Sustainability:** Similar to the cost-effectiveness mentioned above, the environmental impact of experiments that use existing infrastructure is reduced. The community agrees that maximising the environmental sustainability of future particle physics projects is essential, and this was particularly emphasised by ECRs.

4.c To what extent should CERN participate in nuclear physics, astroparticle physics or other areas of science, while keeping in mind and adhering to the CERN Convention?

CERN's role in nuclear physics, astroparticle physics, and other interdisciplinary fields has historically been shaped by its core mission in particle physics. Its unique accelerator infrastructure, expertise, and collaborative model have enabled impactful contributions beyond collider physics. The current level of CERN's engagement in these areas provides a valuable balance, leveraging existing facilities and capabilities without diverting focus from its primary objectives. The UK plays a key role in ISOLDE, which enables cutting-edge nuclear structure and reaction studies using the CERN accelerator complex. The fixed-target programme, which uses over 40% of the protons from CERN's injector complex, represents a significant scientific contribution, particularly in areas such as nuclear astrophysics and applied nuclear physics (e.g., through n_TOF). The UK also has strong engagement in antimatter research via the Antiproton Decelerator, as well as participation in ALICE, where heavy-ion collisions provide crucial insights into the quark-gluon plasma and fundamental nuclear matter properties.

CERN's involvement in astroparticle physics presents another important opportunity. Building on the success of the Neutrino Platform, which played a crucial role in advancing neutrino physics following the last European

Strategy update, CERN's expertise and infrastructure could similarly benefit key astroparticle initiatives. Close coordination with APPEC and its roadmap is essential to ensure CERN's contributions are strategically aligned with European priorities in astroparticle physics. Joint efforts between CERN and APPEC can enhance European leadership in areas such as dark matter searches, high-energy cosmic ray interactions, and precision tests of fundamental symmetries. CERN also possesses critical infrastructure and expertise that can significantly benefit astroparticle detector R&D, construction, calibration, and commissioning. CERN's test beam facilities provide unique opportunities for sensor development and performance validation in conditions relevant to astroparticle experiments. Additionally, CERN's cryogenic expertise and large-scale cryogenic infrastructure, developed for collider experiments, can play a key role in supporting the next generation of low-temperature detectors for dark matter, neutrino physics, and other astroparticle searches. Given this existing engagement, CERN's continued participation in nuclear physics, astroparticle physics, and related disciplines should remain at least at its current level. This ensures efficient use of its accelerator complex while maintaining alignment with its core mission in particle physics. The UK community strongly supports CERN's multi-disciplinary contributions, particularly where they provide unique scientific opportunities not easily achievable elsewhere.

5 Additional considerations for the future roadmap

5.a Equity, diversity and inclusion

The UK community has a strong commitment to addressing barriers to equity, diversity, inclusion and accessibility in High Energy Physics and it is important these considerations are incorporated into planning for the future roadmap. Additional inputs in this area will be reviewed in the April drafting meeting where we will discuss any additional statements to be added on this topic.

5.b Particle theory

Particle theory is a cornerstone of the future particle physics programme, providing the essential framework for formulating experimental goals and interpreting their results. A primary focus of theoretical research is precision calculations within quantum chromodynamics (QCD) and the electroweak sector. Accurate predictions for observables such as cross-sections and decay rates, rely on fixed-order and resummed perturbative quantum field theory calculations. These are crucial for precision tests of the SM and identifying potential signals of new physics. Equally important are parton distribution functions (PDFs), which describe the momentum distribution of quarks and gluons inside the proton. PDFs are indispensable for predicting hadronic collision outcomes and require continuous refinement through a combination of theoretical QCD input and experimental data.

Beyond the realm of perturbative techniques, non-perturbative physics plays an important role for state-of-the-art particle phenomenology. Lattice gauge theory provides a rigorous approach to calculating hadronic properties, confinement effects, and other strongly coupled phenomena that cannot be addressed through perturbation theory. Theoretical nuclear physics also contributes by modelling hadron interactions and multi-nucleon dynamics, which are particularly relevant in heavy-ion collisions and neutrino experiments.

In parallel, the field of particle theory is advancing data analysis and interpretation methods, for example, by incorporating modern machine learning techniques. These approaches enhance the ability to detect subtle patterns and increase sensitivity to rare or unexpected signals in large, complex data sets. At the same time, theorists continue to develop new physics models aimed at addressing fundamental questions in nature, such as the origin of dark matter, the structure of space-time, and the nature of EWSB. These models guide experimental efforts by predicting characteristic signatures of potential new phenomena.

To ensure that theoretical advances are practically applicable in experimental contexts, precise calculations must be implemented in Monte Carlo event generators. These generators provide a critical interface between theory and experiment, allowing for detailed simulations of particle interactions. They require the integration of fixed-order and resummed QFT calculations, along with PDFs, to produce accurate predictions of collider processes. As a result, they are indispensable tools for the global particle physics community.

This entire ecosystem of theoretical research is sustained by extensive collaborations involving researchers across European universities and institutions. These networks drive advancements in theory and play a vital role in training the next generation of physicists. Continued investment in theoretical particle physics is therefore essential to exploit the scientific opportunities of the future particle physics program fully.

5.c Detector R&D

The discovery potential of experimental particle physics is driven by the capabilities of the available technologies. A significant outcome of the previous European Strategy has been the establishment of Detector R&D (DRD) collaborations across all relevant technologies, which are providing a crucial forum for information exchange.

The opportunity now exists to build on this through the development of focussed programmes for key technology items, with long-term cross-European collaboration. This is envisaged in the DRD concept and the next stages should have more significant funding agency engagement in dedicated resource review boards, focussed MoUs for longterm projects, and active steering from CERN. The delivery of the programme relies on industry and relevant skills. This programme offers the opportunity for enhanced support for the development of innovation of technology with industry, leadership in developing detector technologies which minimize emissions, and the training of instrumentation scientists for societal benefits. CERN should remain open to engagement with national industrial plans (discussed further below).

Significant opportunities in fundamental physics are being created by the emergence of quantum technologies. We propose that the CERN QTI programme is reframed around the support of the technologies required for such a programme, particularly quantum sensing, and the coordination of dedicated international experimental proposals. The Physics Beyond Colliders initiative is a good example of how such a coordination can lead to the formation of a community and emergence of multiple physics proposals.

5.d Software & computing

Modern particle physics experiments rely heavily on advanced software and computing to operate and analyse the massive datasets they produce, already at the exabyte scale. Maximising the physics output of these requires leveraging cutting-edge computing technology for both real-time (trigger-level) and offline data processing. Progress in hardware and software is crucial for future research in our field, including its environmental sustainability. To remain competitive we must embrace emerging technologies and collaborate across research and industry, given the rapid pace of computational advancements. The application of state-of-the-art machine learning has already demonstrated that detectors can now surpass their originally envisaged performance. Sustaining this progress requires continuous monitoring of technological developments throughout the HL-LHC era, ensuring that the software and computing infrastructure developed in the coming decades serves as a foundation for future collider experiments.

Computing must be integrated into the planning and costing of experiments from the outset. This includes budgeting for software development, maintenance, and the necessary computing infrastructure. Long-term data preservation and accessibility, spanning decades, must also be considered.

Crucially, personnel are the most valuable asset. A dedicated career path (including appropriate training) for particle physics software engineers should be established, in order to ensure knowledge retention. This encompasses all personnel involved in managing the complex data pipelines, from online systems and distributed computing infrastructure operation to the development of software frameworks. Sharing common software and computing infrastructure, such as event generation and simulation tools, as well as generic reconstruction tools, across experiments can offer significant economies of scale.

5.e Industrial return

The second UK drafting meeting included a dedicated discussion on considerations related to industrial return in the context of the future roadmap. A key message was that engagement with industry is fundamental to the delivery of large scale experiments and facilities, and this requires communication of scientific and technological goals well in advance. With that in mind CERN and the European particle physics community should develop a coherent industrial plan to engage with national industrial strategies and help develop strategic industrial partnerships required to deliver future projects such as FCC.

5.f Public engagement and outreach

Whilst there will be more central community submissions on outreach and public engagement, its importance was highlighted in UK discussions in the context of “selling” the future collider roadmap to policy makers, funders and the public, and ensuring we continue to attract talented people into the field. Europe must invest in all forms of public engagement to improve public opinions of science, illustrate the wider impact of research in order to justify the funding of large scale experiments, and inspire the next generation of scientists.