

5 March 2020

Deliberation Document

on the 2020 update of the European Strategy for Particle Physics

The European Strategy Group
(prepared by the Strategy Secretariat)

The first European Strategy for Particle Physics (hereinafter referred to as “the Strategy”), consisting of seventeen Strategy statements, was adopted by the CERN Council at its special session in Lisbon in July 2006. A first update of the Strategy was adopted by the CERN Council at its special session in Brussels in May 2013. This second update of the Strategy was formulated by the European Strategy Group (ESG) during its six-day meeting in Bad Honnef in January 2020. The ESG was assisted by the Physics Preparatory Group, which had provided scientific input based on the material presented at a four-day Open Symposium held in Granada in May 2019, and on documents submitted by the community worldwide. In addition, six working groups were set up within the ESG to address the following points, and their conclusions were discussed at the Bad Honnef meeting:

- Working Group 1: Social and career aspects for the next generation;
- Working Group 2: Issues related to Global Projects hosted by CERN or funded through CERN outside Europe;
- Working Group 3: Relations with other groups and organisations;
- Working Group 4: Knowledge and Technology Transfer;
- Working Group 5: Public engagement, Education and Communication;
- Working Group 6: Sustainability and Environmental impact.

This Deliberation Document provides background information underpinning the Strategy statements. Recommendations to the CERN Council made by the Working Groups for possible modifications to certain organisational matters are also given. The structure of the updated Strategy statements closely follows the structure of the 2006 Strategy and its 2013 update, consisting of a preamble concerning the scientific motivation, followed by 20 statements:

1. two statements on **Major developments from the 2013 Strategy**
2. three statements on **General considerations for the 2020 update**
3. two statements on **High-priority future initiatives**
4. four statements on **Other essential scientific activities for particle physics**
5. two statements on **Synergies with neighbouring fields**
6. three statements on **Organisational issues**
7. four statements on **Environmental and societal impact**

Each Strategy statement gives a short description of the topic followed by the recommendation in italic text. Within the numbered sections there is no intention to prioritise between the lettered statements. In this Deliberation Document the Strategy statements are presented in blue indented text, and each statement is followed by some explanatory text.

Preamble

Nature hides the secrets of the fundamental physical laws in the tiniest nooks of space and time. By developing technologies to probe ever-higher energy and thus smaller distance scales, particle physics has made discoveries that have transformed the scientific understanding of the world. Nevertheless, many of the mysteries about the universe, such as the nature of dark matter, and the preponderance of matter over antimatter, are still to be explored.

This 2020 update of the European Strategy for Particle Physics proposes a vision for both the near-term and the long-term future. It aims to significantly extend knowledge beyond the current limits, to drive innovative technological development, and to maintain Europe's leading role in particle physics, within the global context. The 2013 update came shortly after the monumental discovery of the Higgs boson, which was a turning point for research in particle physics. The Large Hadron Collider (LHC) has established the crucial role of the Higgs boson in the acquisition of mass by the fundamental particles, but the observed pattern of masses remains an enigma. The Higgs boson is a unique particle that raises profound questions about the fundamental laws of nature. It also provides a powerful experimental tool to study these questions.

In the coming decade, the LHC, including its high-luminosity upgrade, will remain the world's primary tool for exploring the high-energy frontier. Given the unique nature of the Higgs boson, there are compelling scientific arguments for a new electron-positron collider operating as a "Higgs factory". Such a collider would produce copious Higgs bosons in a very clean environment, would make dramatic progress in mapping the diverse interactions of the Higgs boson with other particles and would form an essential part of a research programme that includes exploration of the flavour puzzle and the neutrino sector.

The exploration of significantly higher energies than the LHC will make it possible to study the production of Higgs boson pairs and thus to explore the particle's interaction with itself, which is key to understanding the fabric of the universe. Further, through the exploration of a new realm of energies, discoveries will be made and the answers to existing mysteries, such as the nature of dark matter, may be found. The particle physics community is ready to take the next step towards even higher energies and smaller scales. The vision is to prepare a Higgs factory, followed by a future hadron collider with sensitivity to energy scales an order of magnitude higher than those of the LHC, while addressing the associated technical and environmental challenges.

This Strategy presents exciting and ambitious scientific goals that will drive technological and scientific exploration into new and uncharted territory for the benefit of the field and of society.

1. Major developments from the 2013 Strategy

Four high-priority, large-scale scientific activities featured in the 2013 Strategy. Two of those, relating to the LHC and neutrino physics, form the basis of recommendations discussed in detail in this section. The other two concerned future colliders: one recommended research and development (R&D) for an ambitious post-LHC accelerator project at CERN, which led to detailed studies being made of two alternatives for an energy-frontier collider to be hosted at CERN: either electron-positron (the Compact Linear Collider, CLIC, for which a Project Implementation Plan has been prepared, following an earlier Conceptual Design Report) or hadron-hadron (the Future Circular Collider, FCC, for which a Conceptual Design Report has been prepared). Both of these studies include an electron-positron Higgs factory as a possible first stage, known

as FCC-ee in the latter case. These studies have informed the recommendations made in Section 3 of this Strategy concerning high-priority future initiatives.

The other statement in 2013 concerning future colliders related to the International Linear Collider (ILC) project in Japan, another possible implementation of an electron-positron Higgs factory, using a different technology to CLIC or FCC-ee. The corresponding recommendation was that “*Europe looks forward to a proposal from Japan to discuss a possible participation*”, but no such proposal has since been received, although interest in the ILC hosted in Japan remains high within the particle physics community. This is reflected in the recommendation made in Section 3 of this Strategy. A fourth possible implementation of an electron-positron Higgs factory has emerged since the 2013 Strategy was formulated, namely the Chinese electron-positron collider (CEPC) that would have a similar scope to FCC-ee. The technologies required for an electron-positron Higgs factory are mature and the scientific interest is very high. This has led to these four designs, albeit with different strengths, being considered in different regions of the world.

The highest priority in the 2013 Strategy was the full exploitation of the Large Hadron Collider (LHC) including the development of a high-luminosity phase (HL-LHC). Since the completion of the first run of the LHC with protons colliding at energies of 7 and 8 TeV, the accelerator has successfully delivered around 150 fb^{-1} of proton collisions in a second run at 13 TeV to each of the ATLAS and CMS experiments. Standard Model processes involving for example gauge and scalar bosons and top quarks have been measured over nine orders of magnitude in cross-section. For the first time, a window on the scalar sector has been opened through exploration of the interactions of the Higgs boson with vector bosons and third-generation particles. Nearly all the unsatisfactory aspects of the Standard Model and many of the open questions beyond the Standard Model are related to the scalar sector. The study of the scalar sector is therefore of central importance. New physics phenomena have been searched for with the LHC, directly reaching masses at and beyond the TeV scale for the first time. Creative ideas have emerged to make novel beyond-the-Standard-Model phenomena accessible with the LHC data, such as searches for long-lived particles.

- a) Since the recommendation in the 2013 Strategy to proceed with the programme of upgrading the luminosity of the LHC, the HL-LHC project was approved by the CERN Council in June 2016 and is proceeding according to plan. In parallel, the LHC has reached a centre-of-mass energy of 13 TeV, exceeded the design luminosity, and produced a wealth of remarkable physics results. Based on this performance, coupled with the innovative experimental techniques developed at the LHC experiments and their planned detector upgrades, a significantly enhanced physics potential is expected with the HL-LHC. The required high-field superconducting Nb₃Sn magnets have been developed. *The successful completion of the high-luminosity upgrade of the machine and detectors should remain the focal point of European particle physics, together with continued innovation in experimental techniques. The full physics potential of the LHC and the HL-LHC, including the study of flavour physics and the quark-gluon plasma, should be exploited.*

The HL-LHC programme was approved by the CERN Council in June 2016 with the objective of delivering a tenfold increase of integrated luminosity of proton collisions at 14 TeV to the ATLAS and CMS experiments. The envisaged increase of integrated luminosity with the HL-LHC will allow further precision measurements and searches and will directly challenge the understanding of particle physics at around the TeV scale, and indirectly at multi-TeV scales. Intensive accelerator R&D efforts over many years have culminated in the development of the essential short dipole magnets with niobium-tin (Nb₃Sn) superconductor, which will be tested in operation during the upcoming Run 3 of the LHC. They will replace

some of the existing long dipoles with niobium-titanium (NbTi) superconductor in order to make space for the additional collimators needed to reach higher luminosities at the HL-LHC.

The upgrades of the ATLAS and CMS experiments have been documented in a series of Technical Design Reports and have been approved, and the international collaborations are gearing up to commission these detectors by 2027, the scheduled start of the first HL-LHC run. The timely delivery of these upgrades is a milestone for the global particle physics community, and the continued allocation of adequate resources is a priority. Based on continued innovations in experimental techniques, the untapped physics that is surely awaiting in the third LHC run and the HL-LHC era can be unlocked. Incorporating emerging new technologies into trigger systems, computing and management of big data, reconstruction algorithms and analysis methods is the path to get the best out of these upcoming datasets. The passion to innovate should be nurtured and achievements recognised both inside and outside the field of particle physics, for example by strengthened attention to these topics in conference programmes.

In addition to proton collisions, heavy-ion collisions are also studied at the LHC, and the ALICE experiment is dedicated to this study. It is being upgraded towards Runs 3 and 4 of the LHC. Beyond this period, the heavy-ion community has the ambition to design a new experiment to continue with a rich heavy-ion programme at the HL-LHC. The flavour physics programme made possible with the proton collisions delivered by the LHC is very rich, and will be enhanced with the ongoing and proposed future upgrade of the LHCb detector.

b) The existence of non-zero neutrino masses is a compelling sign of new physics. The worldwide neutrino physics programme explores the full scope of the rich neutrino sector and commands strong support in Europe. Within that programme, the Neutrino Platform was established by CERN in response to the recommendation in the 2013 Strategy and has successfully acted as a hub for European neutrino research at accelerator-based projects outside Europe. Europe, and CERN through the Neutrino Platform, should continue to support long baseline experiments in Japan and the United States. In particular, they should continue to collaborate with the United States and other international partners towards the successful implementation of the Long-Baseline Neutrino Facility (LBNF) and the Deep Underground Neutrino Experiment (DUNE).

The discovery of neutrino oscillations is a compelling sign of new physics, because new particle states or new interactions are required to generate the relevant mass term in the theory. Neutrinos are known to be orders of magnitude lighter than charged leptons. The explanations for this lightness span many orders of magnitude in the scale of new physics. There could be light (sterile neutrinos) or heavier neutral leptons. Neutrinos could be their own antiparticles, in which case lepton number conservation would be violated. Such an extended neutrino sector could potentially be linked to the matter-antimatter asymmetry observed in the universe. Their mixing pattern is also very different from that observed for quarks, with some terms still not fully known. Neutrino physics is an integral part of the flavour quest. It is thus essential to pursue the exploration of the neutrino sector with accelerator, reactor, solar, atmospheric and cosmic neutrino experiments.

The first priority is the completion of the programme of measurements of the oscillation parameters, most notably the CP-violating phase of the mixing matrix and the neutrino mass ordering. Two strong and complementary approved experimental programmes are in preparation towards this goal in the United States and Japan, with the DUNE and Hyper-Kamiokande experiments. Following the recommendations of the 2013 Strategy, there is a strong participation of European physicists in both programmes, with CERN support, most notably through the Neutrino Platform. The latter has been very successful, in particular in

providing a large-scale demonstration of the liquid-argon time-projection chamber (TPC) technique that will be used for the DUNE experiment in the United States. This has involved the development of very large cryostats, suitable for the multi-kiloton scale of the envisaged DUNE detector. Other developments at the Neutrino Platform have included the refurbishment of ICARUS for use in the Fermilab short-baseline programme, as well as a magnetic spectrometer (BabyMIND) and the upgrade of the near detector ND280 for the T2K experiment in Japan. The community is very keen for the Neutrino Platform to continue operation at CERN for the benefit of the worldwide neutrino community.

To extract the most physics from DUNE and Hyper-Kamiokande, a complementary programme of experimentation to determine neutrino cross-sections and fluxes is required. Several experiments aimed at determining neutrino fluxes exist worldwide. The possible implementation and impact of a facility to measure neutrino cross-sections at the percent level should continue to be studied. Other important complementary experiments are in preparation using reactor and atmospheric neutrinos. They have the potential to discover the mass ordering and to perform other precision oscillation measurements. The study of the neutrino absolute mass and nature (either Dirac or Majorana) is the other priority for the field, covered by both laboratory and cosmology measurements. The design studies for next-generation long-baseline neutrino facilities should continue.

Balanced European support for this worldwide effort will make it possible to secure the determination of the neutrino masses, oscillation parameters, including the CP violation phase, and to test for possible deviations from the three-neutrino framework.

2. General considerations for the 2020 update

- a) Europe, through CERN, has world leadership in accelerator-based particle physics and related technologies. The future of the field in Europe and beyond depends on the continuing ability of CERN and its community to realise compelling scientific projects. *This Strategy update should be implemented to ensure Europe's continued scientific and technological leadership.*

With the construction and efficient operation of the LHC, CERN has established itself as the world's premier particle physics laboratory. The cooperation between the Member, Associate Member and non-Member States and the concentration of the European particle-physics effort at CERN have created a unique resource in terms of scientific accomplishments, human capital, international collaboration, technical expertise, and research infrastructure. The number of CERN users grew from 10,400 in 2013 to 12,600 in 2018 and about 35% are from non-Member States. In addition to the high-energy LHC programme, CERN exploits its full accelerator chain to provide world-leading facilities for beams of unstable isotopes, antimatter, and other studies. To maintain and improve these facilities, CERN and other accelerator-based laboratories worldwide use cutting-edge technologies, among them radiofrequency cavities to accelerate particles, superconducting magnets to steer and focus them, cryogenics to cool the magnets down and make them work, and high vacuum to allow the beams to circulate. A further particle physics expertise is the capacity to store, process and distribute large volumes of data. All of these technologies are shared throughout Europe for the benefit of the Member and Associate Member States.

- b) The European organisational model centred on close collaboration between CERN and the national institutes, laboratories and universities in its Member and Associate Member States is essential to the enduring success of the field. This has proven highly effective in harnessing the collective resources and expertise of the particle, astroparticle and nuclear physics communities, and of many interdisciplinary research fields. Another manifestation of the success of this model is the

collaboration with non-Member States and their substantial contribution. *The particle physics community must further strengthen the unique ecosystem of research centres in Europe. In particular, cooperative programmes between CERN and these research centres should be expanded and sustained with adequate resources in order to address the objectives set out in the Strategy update.*

The National Laboratories referred to in the Strategy are large and medium-sized infrastructures in Europe, which are operated, managed and financed by the respective national authorities. They collaborate, together with research institutes and universities, in large programmes at CERN and in activities of interest for this Strategy, performed locally and at other large laboratories.

European research institutes afford fruitful synergies with other communities that go well beyond the boundaries of particle physics (and hence of this Strategy). They provide strong links with networks such as LEAPS (League of European Accelerator-based Photon Sources) and LENS (League of Advanced European Neutron Sources), focused on R&D for accelerator and detector components. A vibrant and coordinated programme of initiatives in the National Laboratories can further support European R&D projects in advanced accelerator and detector technologies. Coordination of R&D activities is critical to maximise their scientific outcomes and to make the most efficient use of resources; as such, there is a need to strengthen collaborative R&D efforts in order to address the challenges in advanced accelerator and detector technologies and to provide the necessary expertise for future large infrastructures at CERN and elsewhere.

Moreover, the high visibility of European research institutes in supranational large projects is essential for their sustainability, i.e. to get stable national funding, better access to the EU opportunities, and a consolidated link with innovation. It is important to keep in mind the role played by Europe's National Laboratories, research institutes and universities also in terms of availability of a variety of large technical platforms dedicated to development, testing and production of accelerator and detector components. This European technology infrastructure also includes clean detector assembly areas, test beams, irradiation and low-background assay facilities, low-vibration and thermal test sites and high-power lasers, and the Strategy should endorse and guarantee the resources needed to operate them.

- c) *The broad range of fundamental questions in particle physics and the complexity of the diverse facilities required to address them, together with the need for an efficient use of resources, have resulted in the establishment of a global particle physics community with common interests and goals. This Strategy takes into account the rich and complementary physics programmes being undertaken by Europe's partners across the globe and of scientific and technological developments in neighbouring fields. The implementation of the Strategy should proceed in strong collaboration with global partners and neighbouring fields.*

The previous Strategy update pointed out that the increase in scale of the leading particle physics facilities and the resulting decrease in their number worldwide has led to the globalisation of the field, and to the need to involve potential international partners from all over the world in the planning of future endeavours. The timely realisation of complementary, large-scale projects in different regions of the world, each of them unique in pushing further the frontiers of particle physics, remains essential for the progress of the field, as well as for the development of the key technologies. With the neutrino programme, Europe has chosen to participate in the long-baseline programmes in Japan and the United States rather than building its own facility. Instead, it has secured reciprocal support for the timely realisation of the HL-LHC project. Europe's long-term vision is to maintain its leadership in pushing the exploration of the energy frontier, and this vision is supported by the other regions.

3. High-priority future initiatives

a) An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy. Accomplishing these compelling goals will require innovation and cutting-edge technology:

- *the particle physics community should ramp up its R&D effort focused on advanced accelerator technologies, in particular that for high-field superconducting magnets, including high-temperature superconductors;*
- *Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update.*

The timely realisation of the electron-positron International Linear Collider (ILC) in Japan would be compatible with this strategy and, in that case, the European particle physics community would wish to collaborate.

Following the discussions at the Open Symposium in Granada, as reported in the preamble, an electron-positron Higgs factory is the highest-priority next collider for the field, followed by a hadron collider at the energy frontier in the longer term. Two possible energy-frontier colliders have been studied for implementation at CERN, namely CLIC and FCC, introduced in Section 1. CLIC has the potential to reach 3 TeV in the centre of mass, while FCC could reach 100 TeV or beyond. In assessing their relative physics reach, it has to be borne in mind that in an e^+e^- collider, such as CLIC, the full energy is available for collisions, whereas the protons in a collider such as FCC are composite particles whose constituents interact with less than the total beam energy.

The design, technology, and implementation aspects of CLIC indicate that the first stage (a Higgs factory) could be realised on a timescale of 15 years and could be extended to higher energies subsequently. However, the dramatic increase in energy possible with a future hadron collider compared to the 13 TeV of the LHC leads to this technology being considered as the most promising for a future facility at the energy frontier. This would, however, require a large-scale infrastructure for the circular tunnel, as well as high-field magnets (assumed to be 16 Tesla in the current design) which are far from ready for series production. It is important therefore to launch a feasibility study for such a collider to be completed in time for the next Strategy update, so that a decision as to whether this project can be implemented can be taken on that timescale. The feasibility study should involve the following aspects: the possibility of constructing such a large infrastructure in the vicinity of CERN, the financial plan to complete and operate a project of this scale with international partners, its governance, and the handling of the energy consumption. For this future collider to reach sensitivity to new physics at scales ten times higher than the HL-LHC in a timely fashion, the development of high-field magnets, including the option of using high-temperature superconductors, coupled with other innovative accelerator technologies, has to be ramped up and the resources available within Europe and beyond need to be coordinated accordingly.

If the large circular tunnel for such a collider can be built, then it would also provide the infrastructure needed for an electron-positron Higgs factory as a possible first step, of the type that has been studied as FCC-ee. The FCC-ee also presents the option to provide, at lower centre-of-mass energies, huge numbers

of weak vector bosons and their decay products that can be used to make precision tests of electroweak physics and to investigate in depth the flavour puzzle.

b) Innovative accelerator technology underpins the physics reach of high-energy and high-intensity colliders. It is also a powerful driver for many accelerator-based fields of science and industry. The technologies under consideration include high-field magnets, high-temperature superconductors, plasma wakefield acceleration and other high-gradient accelerating structures, bright muon beams, energy recovery linacs. *The European particle physics community must intensify accelerator R&D and sustain it with adequate resources. A roadmap should prioritise the technology, taking into account synergies with international partners and other communities such as photon and neutron sources, fusion energy and industry. Deliverables for this decade should be defined in a timely fashion and coordinated among CERN and national laboratories and institutes.*

Accelerator R&D is crucial to prepare the future collider programme, and should be ramped up. To this end, the European particle physics community should develop an accelerator R&D roadmap focused on the critical technologies needed for future colliders, maintaining a beneficial link with other communities such as photon or neutron sources and fusion energy. This roadmap should be established as soon as possible in close coordination between the National Laboratories and CERN.

The accelerator community, led in Europe by CERN with partners in the United States and Japan, is investing efforts in the design of high-field magnets based on Nb₃Sn superconductor. First successful tests of dipole magnets with an 11 T field have recently been reported, and a full-size quadrupole magnet using Nb₃Sn technology has been constructed and successfully qualified in the United States. This is motivated by the needs of the HL-LHC upgrade programme. A focused, mission-style approach should be launched for R&D on high-field magnets (16 T and beyond); this is essential for a future hadron collider, to maximise the energy and to minimise the development time and cost. Development and industrialisation of such magnets based on Nb₃Sn technology, together with the high-temperature superconductor (HTS) option to reach 20 T, are expected to take around 20 years and will require an intense global effort. CERN's engagement in this process would have a catalysing effect on related work being performed in the National Laboratories and research institutions, and could lead to significant societal benefit. HTS technology has a wide variety of applications in medicine, science and power systems engineering as well as the high-field magnets, which are also used in fusion power plants. For example, HTS can be applied in the field of electric power systems in cables, motors, generators, and transformers where superconductors replace resistive conductors, plus superconducting magnetic energy storage (SMES) and fault-current limiters (FCL).

In addition to the high field magnets the accelerator R&D roadmap could contain:

- the R&D for an effective breakthrough in plasma acceleration schemes (with laser and/or driving beams), as a fundamental step toward future linear colliders, possibly through intermediate achievements: e.g. building plasma-based free-electron lasers (FEL). Developments for compact facilities with a wide variety of applications, in medicine, photonics, etc., compatible with university capacities and small and medium-sized laboratories are promising;
- an international design study for a muon collider, as it represents a unique opportunity to achieve a multi-TeV energy domain beyond the reach of e-e⁻ colliders, and potentially within a more compact circular tunnel than for a hadron collider. The biggest challenge remains to produce an intense beam of cooled muons, but novel ideas are being explored;

- a vigorous R&D on high-intensity, multi-turn energy-recovery linac (ERL) machines, promoting the realisation of a demonstrator with a view also to low-energy applications.

Reduction in energy consumption is an important consideration in accelerator design. Substantial progress has been achieved in the development of superconducting and normal-conducting high-gradient accelerating structures. This technology, which is needed for the e^+e^- colliders, is also driven by light source facilities all over the world.

4. Other essential scientific activities for particle physics

- a) The quest for dark matter and the exploration of flavour and fundamental symmetries are crucial components of the search for new physics. This search can be done in many ways, for example through precision measurements of flavour physics and electric or magnetic dipole moments, and searches for axions, dark sector candidates and feebly interacting particles. There are many options to address such physics topics including energy-frontier colliders, accelerator and non-accelerator experiments. A diverse programme that is complementary to the energy frontier is an essential part of the European particle physics Strategy. *Experiments in such diverse areas that offer potential high-impact particle physics programmes at laboratories in Europe should be supported, as well as participation in such experiments in other regions of the world.*

The observed pattern of masses and mixings of the fundamental constituents of matter, quarks and leptons, remains a puzzle in spite of the plethora of new experimental results obtained since the last Strategy update. Studying the flavour puzzle may indicate the way to new physics with sensitivity far beyond what is reachable in direct searches, e.g. the evidence for the existence of the top quark that followed from the study of B-meson mixing. In addition, flavour physics and CP violation, which play a vital role in determining the parameters of the Standard Model, are explored by a wide spectrum of experiments all over the world. These include measurements of electric or magnetic dipole moments of charged and neutral particles, atoms and molecules, rare muon decays with high intensity muon beams at PSI, FNAL and KEK, rare kaon decays at CERN and KEK, and a variety of charm and/or beauty particle decays at the LHC, in particular with the LHCb experiment. New results are expected in the near future from the Belle II experiment at KEK in Japan and from LHCb (currently undergoing an upgrade) at CERN.

There is ample evidence from galactic and cosmological observations that, within the context of general relativity, dark matter is the dominant form of matter in the universe. The existence of dark matter is another compelling evidence for physics beyond the Standard Model and detecting it in the laboratory remains one of the great challenges of particle physics. Given the present limits from multiple overlapping direct detection experiments, the mass of dark matter particles could be anything from as light as 10^{-22} eV to as heavy as primordial black holes of tens of solar masses. A comprehensive suite of experiments and techniques is required in order to cover the many possibilities. Accelerator-based beam-dump and fixed-target experiments can perform sensitive and comprehensive searches of sub-GeV dark matter and its associated dark sector mediators, complementary to high-energy colliders and other approaches.

An independent determination of the proton structure would be desirable to fully exploit the precision achievable with present and future hadron colliders. Detailed measurements of proton structure complement the investment in theoretical calculations and add sensitivity to searches for novel phenomena. A programme based on fixed-target experiments and on dedicated electron-proton machines, such as LHeC and FCC-ep, has been advocated in Europe. In the United States, the Department of Energy approved the “mission need” (known as Critical Decision 0) in December 2019 for an Electron-Ion Collider (EIC) at Brookhaven

Laboratory, which enables work to proceed on the conceptual design for this next-generation collider with the potential to map the three dimensional structure of the proton.

A dedicated Physics Beyond Colliders study group was set up at CERN to explore the opportunities offered by the CERN accelerator complex and infrastructure to gain new insights into some of the outstanding questions in particle physics through projects complementary to high-energy colliders and other initiatives in the world. This generated a lot of interest and became the *de facto* focal point for new research initiatives centred not only on the potential of the CERN facilities but also other facilities available throughout Europe in the National Laboratories and research institutes. Many of the proposals for new experiments at CERN are on a scale such that they could be considered for approval in the usual manner by the scientific committees and the Research Board. Among the proposals for larger-scale new facilities investigated within the Physics Beyond Colliders study, the Beam Dump Facility at the SPS emerged as one of the frontrunners. However, such a project would be difficult to resource within the CERN budget, considering the other recommendations of this Strategy.

Given the challenges faced by CERN in preparing for the future collider, the role of the National Laboratories in advancing the exploration of the lower energy regime cannot be over-emphasised. In addition to the examples already mentioned above, a broad programme of axion searches is proposed at DESY, a search for low-mass dark matter particles with a positron beam is under way at Frascati, and the COSY facility could be used as a demonstrator for measuring the electric dipole moment of the proton at Jülich. These initiatives should be strongly encouraged and supported.

Europe has the opportunity to play a leading role in this diverse scientific programme by supporting high-impact projects, which mostly require modest investment and play a crucial role in training and preparing a new generation of versatile scientists to address the challenges of the future.

b) Theoretical physics is an essential driver of particle physics that opens new, daring lines of research, motivates experimental searches and provides the tools needed to fully exploit experimental results. It also plays an important role in capturing the imagination of the public and inspiring young researchers. The success of the field depends on dedicated theoretical work and intense collaboration between the theoretical and experimental communities. *Europe should continue to vigorously support a broad programme of theoretical research covering the full spectrum of particle physics from abstract to phenomenological topics. The pursuit of new research directions should be encouraged and links with fields such as cosmology, astroparticle physics, and nuclear physics fostered. Both exploratory research and theoretical research with direct impact on experiments should be supported, including recognition for the activity of providing and developing computational tools.*

Theoretical particle physics in Europe is well developed and world-leading in many areas. European theoretical research spans a range of subjects, stretching from abstract ideas of string theory to the detailed simulation of collider physics processes. It is important for the future of the field that this broad approach be maintained.

Theoretical particle physics uses techniques that transcend one particular sub-discipline. Results from neighbouring fields, such as cosmology, nuclear physics and astrophysics, condensed matter and atomic physics, computation and quantum information enrich the scientific dialogue. This cross-fertilisation is essential for the progress of the field and is a particular strength of the universities and institutes in Europe. At the same time, experimental particle physics benefits from theoretical (as well as experimental) advances in neighbouring fields, such as superconductivity and computation.

Theoretical ideas, from the original concepts of quantum mechanics and relativity to the most recent breakthroughs in the understanding of the universe, have the power to inspire young minds, attracting young people to particle physics, and can act as a gateway to Science, Technology, Engineering, and Mathematics (STEM) subjects, thus fulfilling an important societal need. Outreach activities benefit from the special perspective that theoretical physicists bring.

There is great mobility in the field, with young researchers being trained in the universities and then going on to gain further experience as early career researchers, either within Europe or further afield. The CERN theory department acts as a focus point for research, both within Europe and worldwide.

The full exploitation of the LHC and HL-LHC, as well as future colliders, will require investment in theoretical methods and calculations. A case in point is the full characterisation of the Higgs boson, where the improved precision of experiments will require a concomitant improvement in theoretical calculations. Theory also plays an important role in assessing the strategic importance for the field of future investments in accelerators and experimental infrastructure.

Calculation-intensive areas such as precision phenomenology at colliders, lattice field theory or the development of Monte-Carlo event generators and other software tools require long time scales to yield results. Theorists involved in these challenging activities as well as other ambitious long-duration projects, should have career opportunities that take this into account, e.g. through postdoctoral positions of appropriate duration and the establishment of dedicated research appointments with career development opportunities.

c) The success of particle physics experiments relies on innovative instrumentation and state-of-the-art infrastructures. To prepare and realise future experimental research programmes, the community must maintain a strong focus on instrumentation. *Detector R&D programmes and associated infrastructures should be supported at CERN, national institutes, laboratories and universities. Synergies between the needs of different scientific fields and industry should be identified and exploited to boost efficiency in the development process and increase opportunities for more technology transfer benefiting society at large. Collaborative platforms and consortia must be adequately supported to provide coherence in these R&D activities. The community should define a global detector R&D roadmap that should be used to support proposals at the European and national levels.*

Innovations in detector instrumentation have been critical to deliver the novel designs of the current and upgraded detectors for the HL-LHC, allowing them to collect, reconstruct and analyse proton collisions at unprecedented luminosities. Delivering the near and long-term future research programme envisaged in this Strategy update requires advances in instrumentation through both focused and transformational R&D. Recent initiatives with a view towards strategic R&D on detectors are being taken by CERN's EP department and by the ECFA detector R&D panel, supported by EU-funded programmes such as AIDA and ATTRACT. Coordination of R&D activities is critical to maximise the scientific outcomes of these activities and to make the most efficient use of resources; as such, there is a clear need to strengthen existing R&D collaborative structures, and to create new ones, to address future experimental challenges of the field beyond the HL-LHC.

Organised by ECFA, a roadmap should be developed by the community to balance the detector R&D efforts in Europe, taking into account progress with emerging technologies in adjacent fields. The roadmap should identify and describe a diversified detector R&D portfolio that has the largest potential to enhance the performance of the particle physics programme in the near and long term. This community roadmap could,

for example, identify the grand challenges that will guide the R&D process on the medium- and long-term timescales, and define technology nodes broad enough to be used as the basis for creating R&D platforms. This will allow concerted and efficient actions on the international scale addressing the technological challenges of future experiments while fostering an environment that stimulates innovation and collaboration with industry.

Detector R&D activities require specialised infrastructures, tools, and access to test facilities. The National Laboratories and research institutes in Europe play a central and important role by providing access to these facilities and infrastructures, specialised expertise and user support. These technology platforms facilitate and stimulate strong engagement by industry.

d) Large-scale data-intensive software and computing infrastructures are an essential ingredient to particle physics research programmes. The community faces major challenges in this area, notably with a view to the HL-LHC. As a result, the software and computing models used in particle physics research must evolve to meet the future needs of the field. *The community must vigorously pursue common, coordinated R&D efforts in collaboration with other fields of science and industry to develop software and computing infrastructures that exploit recent advances in information technology and data science. Further development of internal policies on open data and data preservation should be encouraged, and an adequate level of resources invested in their implementation.*

The scientific outcomes of particle physics experiments are made possible by the development of an efficient computing and software infrastructure. Computing and software are profound R&D topics in their own right and are essential to sustain and enhance particle physics research capabilities. There is a need for strong community-wide coordination for computing and software R&D activities, and for the development of common coordinating structures that will promote coherence in these activities, long-term planning and effective means of exploiting synergies with other disciplines and industry. Some recently initiated examples are the HEP Software Foundation addressing the common computing and software challenges related to particle physics, and ESCAPE (European Science Cluster of Astronomy & Particle physics ESFRI research infrastructures) exploring the synergies in the areas of astronomy, astroparticle and accelerator-based particle physics.

Achievements in computing and software development with great impact should be recognised inside and outside the particle physics community. The skills required to perform computing and software R&D are a valuable part of the profile of a particle physicist. Recognition of this will do much to create interesting career opportunities and to retain the engagement of researchers in these R&D topics. More experts need to be trained to address the essential needs, especially with the increased data volume and complexity in the upcoming HL-LHC era, and will also help in experiments in adjacent fields.

It is becoming increasingly important to take a more holistic approach to detector design that includes the impact on computing resources during operation. The community needs to face the challenge of training experts that can bridge the growing gap between these activities. A significant role for artificial intelligence is emerging in detector design, detector operation, online data processing and data analysis. Important examples of developments in the field of computing and software with a large impact on particle physics results are the use of multicore CPUs, multithreading and accelerators such as GPUs. Event simulation, event selection and reconstruction and analysis software need to adapt to these and other emerging developments.

5. Synergies with neighbouring fields

There are many synergies between particle physics and other fields of research. Clear examples are nuclear and astroparticle physics, which address common fundamental questions and use common tools. Accelerator science connects to laser and plasma physics as well as to material science. There are also synergies with atomic physics, as exemplified by the antihydrogen experimental programme at CERN's AD antiproton decelerator and its upgrade, ELENA. Particle and laser physicists aspire to explore the strong field of QED by joining forces at the EU-XFEL facility in Hamburg.

- a) A variety of research lines at the boundary between particle and nuclear physics require dedicated experiments and facilities. Europe has a vibrant nuclear physics programme at CERN, including the heavy-ion programme, and at other European facilities. In the global context, a new electron-ion collider, EIC, is foreseen in the United States to study the partonic structure of the proton and nuclei, in which there is interest among European researchers. *Europe should maintain its capability to perform innovative experiments at the boundary between particle and nuclear physics, and CERN should continue to coordinate with NuPECC on topics of mutual interest.*

The synergies between particle and nuclear physics are driven by the ambition to achieve first-principle understanding of strong dynamics based on QCD. In addition, they share similar experimental tools. The CERN baseline programme includes not only the ISOLDE and n_TOF facilities but also the heavy-ion programme at the SPS and the LHC. Future European facilities such as FAIR, NICA and ESS envisage research programmes that are of interest to particle physics. The nuclear physics roadmap in Europe is coordinated by the Nuclear Physics European Collaboration Committee (NuPECC) and there are well established communication lines between the nuclear and the particle physics communities. NuPECC has expressed strong support for the extension of the heavy-ion programme into the HL-LHC era and beyond, should a high-energy hadron collider be built at CERN in the future. Electron-proton colliders, such as LHeC or FCC-ep, with the option of including ion-targets, are also of interest to NuPECC, which is preparing a support statement for the participation of Europe in the Electron-Ion Collider in the United States.

- b) Astroparticle physics, coordinated by APPEC in Europe, also addresses questions about the fundamental physics of particles and their interactions. The ground-breaking discovery of gravitational waves has occurred since the last Strategy update, and this has contributed to burgeoning multi-messenger observations of the universe. *Synergies between particle and astroparticle physics should be strengthened through scientific exchanges and technological cooperation in areas of common interest and mutual benefit.*

There are multiple synergies between particle and astroparticle physics, at the level of infrastructure, detectors, computing, interaction models and physics goals. These connections are through neutrino physics, dark matter searches, cosmic ray physics and, potentially in the future, gravitational waves. The precision measurements of the neutrino properties rely on solar and atmospheric neutrinos for the determination of several mass and mixing parameters. Large underground neutrino detectors are used both in long-baseline accelerator experiments and in astroparticle physics. Searches for dark matter are performed by dedicated underground experiments and by large astroparticle detectors like H.E.S.S., Antares or IceCube and, in the near future, the CTA observatory. The Astroparticle Physics European Consortium (APPEC) theory centre for astroparticle physics, EuCAPT, was established recently, and CERN was chosen as its first hosting hub. The need to foster these synergies has been clearly identified in the national inputs to the Strategy update.

CERN's "Recognised Experiment" status allows collaborations whose experiments do not take place at CERN but are in fields relevant to its scientific goals, to make use of CERN's infrastructure, e.g. to hold meetings, use offices or receive administrative support. It would be appropriate to establish a new procedure for such collaborations seeking CERN's technical support, which should be limited to providing technical expertise and infrastructure services in a cost-neutral way for CERN.

Links between accelerator-based particle physics and closely related fields such as astroparticle physics and nuclear physics should be strengthened through the exchange of expertise and technology in areas of common interest and mutual benefit. To further explore and enhance the synergies, a periodic joint seminar organised by APPEC, ECFA and NuPECC was recently established. For example, on the diverse topic of dark matter addressed with complementary experimental approaches, communication and results-sharing across communities is essential.

6. Organisational issues

- a) An ambitious next-generation collider project will require global collaboration and a long-term commitment to construction and operations by all parties. *CERN should initiate discussions with potential major partners as part of the feasibility study for such a project being hosted at CERN. In the case of a global facility outside Europe in which CERN participates, CERN should act as the European regional hub, providing strategic coordination and technical support. Individual Member States could provide resources to the new global facility either through additional contributions made via CERN or directly through bilateral and multilateral arrangements with the host organisation.*

The particle physics community is considering several large future projects, which, because of their size, complexity, duration and cost, will need to be planned on a global scale. This Strategy update builds on the statement on global projects in the 2013 Strategy, but also takes into account the better understanding of the current plans of the field worldwide. The issues to be addressed for the governance of global projects relate to governance and funding around either CERN hosting a next-generation collider as a globally funded project or a European contribution to a next-generation collider constructed outside Europe, and specifically the role that CERN would play.

For the case of a new global facility hosted at CERN, long-term commitments are needed from non-European states and must take account of both construction and operating costs. This level of cost-sharing between global regions goes substantially beyond the existing levels of in-kind contributions seen for the LHC. Non-European states might contribute to a new facility at CERN in two ways, either by becoming a CERN Member State, participating in the entirety of the CERN basic programme or in a new programme of activities (set up as part of the basic programme) encompassing the new facility and related infrastructure; or by participation at the project level, implemented through a long-term bilateral or multilateral agreement. CERN should engage now with potential non-European partners to explore which of these options is preferred. The discussion should recognise the need to provide a link between the level of participation and the level of influence on the project. The governance model for a new global facility hosted by CERN must be compatible with the provisions of the CERN Convention, amendment of which is not desirable.

For the case of a European contribution to a new global facility outside Europe, CERN should, if so decided by the CERN Council, provide strategic coordination and technical support for European contributions. The modalities of European participation remain to be decided, as and when the need occurs.

- b) The particle physics community and the European Commission have a strong record of collaboration. *The relationship between the particle physics community and the European Commission should be*

further strengthened, exploring funding-mechanism opportunities for the realisation of infrastructure projects and R&D programmes in cooperation with other fields of science and industry.

Participation in European networks devoted to development of future accelerator and detector technologies (AMICI, ARIES, EUROCIRCOL, TIARA, ATTRACT, AIDA2020, COMPACT XLS, EuPRAXIA, ALEGRO, LEAPS, LENS, etc.) has contributed to coherency of effort among CERN and the National Laboratories, and has facilitated success. The European particle physics community should work with the European Commission to shape and establish the funding instruments that are required for the realisation of common R&D projects, e.g. in the Horizon Europe programme.

- c) European science policy is quickly moving towards Open Science, which promotes and accelerates the sharing of scientific knowledge with the community at large. Particle physics has been a pioneer in several aspects of Open Science. *The particle physics community should work with the relevant authorities to help shape the emerging consensus on Open Science to be adopted for publicly-funded research, and should then implement a policy of Open Science for the field.*

Open Science promotes the sharing of research-based knowledge and facilitates the wide use of research findings, data, methods and infrastructures in the research community and in society at large. The goal is to accelerate the impact of research by increasing the societal and educational knowledge-base, which also contributes to innovation. Open science comprises open access to scientific publications and research data, preservation and reuse of research outcomes, sharing of infrastructures, as well as participation in the research process. The underlying principles are collaboration and transparency.

Open science policies are formed and implemented at the national and international levels by governments, international institutions, and research funders. The particle physics community in Europe and CERN have been pioneers in several aspects of open science, such as the open-access publishing initiative SCOAP3, the Zenodo archive and, not least, by establishing the worldwide web. It is the goal of the particle physics community to have a constructive engagement with policy-makers to shape an open science policy for the field.

7. Environmental and societal impact

- a) The energy efficiency of present and future accelerators, and of computing facilities, is and should remain an area requiring constant attention. Travel also represents an environmental challenge, due to the international nature of the field. *The environmental impact of particle physics activities should continue to be carefully studied and minimised. A detailed plan for the minimisation of environmental impact and for the saving and re-use of energy should be part of the approval process for any major project. Alternatives to travel should be explored and encouraged.*

In a world with increasing demand on limited resources and undergoing climate change it is crucial to keep energy consumption, sustainability and efficiency in mind when discussing the future of particle physics. A lot of attention has already been paid to these aspects and a large amount of work is being done at existing facilities and laboratories in refurbishing and updating old infrastructures and when designing new experiments or accelerators.

The next generation of high-energy particle colliders foresees power consumptions in the hundreds of megawatts of grid power, as compared to about 100 MW for the HL-LHC. The European accelerator laboratories, in particular CERN, ESRF and ESS, are actively discussing strategies to design new infrastructures that are more environmentally friendly. Such efforts need to be further supported, and the

results of the studies integrated in the design of upgrades of existing and new facilities. Many ways of improving the energy efficiency of particle physics accelerator complexes exist, such as waste-heat recovery, optimisation of cryo-cooling plants and beam-energy recovery, to name but a few. Investments in dedicated R&D for energy efficiency techniques will pay off already in the medium term, with a significant impact on the operating costs of accelerators. In the discussion of the optimal choice for a new facility, the energy efficiency of the accelerator should be considered alongside factors such as cost, timescale and physics reach.

The technologies required for detectors are themselves a potential source of greenhouse emissions, e.g. the special gases needed to operate certain types of detector. Significant efforts are already being invested in finding alternatives to gases that have large values of global warming potential (GWP). Research into environmentally-friendly alternatives for materials with high GWP for use in particle physics detectors should be strongly stimulated and supported. The use of closed recirculation systems needs to be included from the start of the design.

The greater the integrated luminosity, the greater the data volumes and computing needs. The energy efficiency of computer centres has improved markedly in recent years, an area in which particle physics should continue to take the lead. Good examples are GSI's Green Cube and CERN's planned new computing centre. In addition, dedicated efforts in software optimisation can also have a significant impact on resource requirements. The particle physics community is already engaged in these efforts, for example within the HEP Software Foundation. The community should invest in both hardware and software efforts to improve the energy efficiency of its computing infrastructures.

The international nature of the particle physics community and the concentration of the experiments at a few large facilities calls for a high level of coordination and inevitably results in people needing to travel to meetings. A significant fraction of travel is also associated with participation in international conferences and workshops, the latter being of particular importance for early-career researchers. The emission of greenhouse gases linked in particular to transport accounts for a significant fraction of the world's carbon footprint. The particle physics community has helped revolutionise the way in which information is shared by inventing the worldwide web. The community is thus expected to be in the vanguard of alternatives to physical travel such as virtual meeting rooms and should support low-carbon forms of travel and carbon offsetting, whenever travel is unavoidable.

b) Particle physics, with its fundamental questions and technological innovations, attracts bright young minds. Their education and training are crucial for the needs of the field and of society at large. *For early-career researchers to thrive, the particle physics community should place strong emphasis on their supervision and training. Additional measures should be taken in large collaborations to increase the recognition of individuals developing and maintaining experiments, computing and software. The particle physics community commits to placing the principles of equality, diversity and inclusion at the heart of all its activities.*

The exploratory nature of particle physics and its fundamental questions about the universe fascinates many inside and outside the field. It draws in talented students whose broad training touches many STEM subjects. Both aspects help strengthen the importance of science in society. Such training, through mentoring as well as dedicated schools (often with long traditions of excellence), should emphasise innovation in the broadest sense. Furthermore, training targeted towards people in leadership positions in collaborations should be made available, with special attention to managing the stress levels and work climate in the groups they are leading. It is important that recognition for individuals in large collaborations be improved, following the

guidelines of the corresponding ECFA study group. In particular, journals dedicated to technologies and theoretical and experimental methods should be supported. For particle physicists, the principles of equality, diversity and inclusion should be clearly and recognisably present in all of the field's activities. Training appropriate to this end should be available at CERN and other institutes, and best practices shared among them. Many of the topics mentioned above have been discussed amongst early-career researchers, and it is recommended they form a panel, under the auspices of ECFA, in which these subjects can be discussed and monitored.

National laboratories, research institutes and universities worldwide provide are the training ground of future young scientists. Education and training in key technologies are crucial for the needs of the field and society at large. Cooperative programmes among CERN and the National Laboratories should be fostered to increase the impact of particle physics and related technologies on new generations and society.

- c) Particle physics has contributed to advances in many fields that have brought great benefits to society. Awareness of knowledge and technology transfer and the associated societal impact is important at all phases of particle physics projects. *Particle physics research centres should promote knowledge and technology transfer and support their researchers in enabling it. The particle physics community should engage with industry to facilitate knowledge transfer and technological development.*

A large number of technologies developed or under development by the particle physics community exist with excellent potential to be transferred to other fields of science and industry. Accelerator and detector R&D and technology transfer can profit from the unique network of large facilities available at CERN and at the National Laboratories, relevant not only to particle, astroparticle and nuclear physics, but also to many interdisciplinary research fields.

Medical applications of accelerators for isotope production, radiotherapy and hadron-therapy benefit from developments being carried out in particle physics laboratories. Examples are the latest designs of superconducting gantries and medical detectors.

An important aspect of this Strategy update is to recognise the potential impact of technological developments in accelerators and associated fields on progress in other branches of science, such as astroparticle physics, cosmology and nuclear physics. Moreover, joint developments with applied fields in academia and industry have brought benefits to fundamental research and may become indispensable for the progress in the field, demonstrating that knowledge and technology transfer is not a one-way street.

A key aspect of the economic impact of physics, and of particle physics in particular, is also the coordinated effort on technology transfer to European industry, including industrial access to facilities at the National Laboratories.

- d) Exploring the fundamental properties of nature inspires and excites. It is part of the duty of researchers to share the excitement of scientific achievements with all stakeholders and the public. The concepts of the Standard Model, a well-established theory for elementary particles, are an integral part of culture. *Public engagement, education and communication in particle physics should continue to be recognised as important components of the scientific activity and receive adequate support. Particle physicists should work with the broad community of scientists to intensify engagement between scientific disciplines. The particle physics community should work with educators and relevant authorities to explore the adoption of basic knowledge of elementary particles and their interactions in the regular school curriculum.*

The particle physics community is highly active in public engagement, and the overall enthusiasm of the general public for the field testifies to the effectiveness of these actions. This high level of public engagement should be sustained, in both its bottom-up and top-down forms. Many of the public engagement activities rely on the efforts of individuals, and should be seen as an integral part of being a scientist and be properly valued in terms of career advancement. European funding agencies are urged to systematically and explicitly accompany research funding by providing resources for public engagement activities.

Good contacts between particle physicists and other research disciplines will lead to better mutual understanding of the importance and urgency of the open scientific research questions and will create opportunities for inter- and cross-disciplinary research.

The International Particle Physics Outreach Group (IPPOG) has been established as a structural collaboration between countries to streamline particle physics education at the high-school level and its role could be further augmented to that of providing public engagement material. The European Particle Physics Communication Network (EPPCN) has proven to be an effective network for the professional communication of particle physics. Its effectiveness would be further improved if the vacancies for EPPCN representatives for all Member and Associate Member States were filled. IPPOG and the EPPCN have excellent opportunities for synergy with APPEC.

CERN has thriving teachers and students programmes, which are also capable of generating valuable data that should be made available to the education research community. Education and training of the next generation of particle physicists and engineers are crucial to sustaining the field in the long term. Good particle physics university education is guaranteed by the many CERN users in academic positions. Vocational education in the fields relevant for CERN should also be encouraged. It is important to be inclusive for all students, and initiatives to address under-represented groups should be supported.

The Science Gateway, under construction at CERN, will offer a golden opportunity to reinforce particle physics public engagement and education, which should be made to radiate across the whole of Europe.

Concluding remarks

This 2020 update of the European Strategy for Particle Physics has focussed on both near and long-term priorities for the field. Given the scale of our long-term ambition, the European plan needs to be coordinated with other regions of the world. A further update of the Strategy should be foreseen in the second half of this decade when the results of the feasibility study for the future hadron collider are available and ready for decision.