UK input to the European Strategy for Particle Physics Update

18th December 2018

Abstract

This document sets out the input from the UK Particle Physics community to the update of the European Strategy for Particle Physics. It is submitted by the UK Particle Physics Advisory Panel and represents the consensus view of the UK community.

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1 Introduction

This document sets out the input from the UK Particle Physics community to the update of the European Strategy for Particle Physics. It is submitted by the UK Particle Physics Advisory Panel and represents the consensus view of the UK community. A series of community meetings was held in the UK to discuss the UK input to this document. The Particle Astrophysics Advisory Panel and the Nuclear Physics Advisory Panel have provided input.

2 Future Colliders

The discovery of the, or indeed a, Higgs boson at the LHC is a great achievement and was recognized in the award of a Nobel prize in 2013. The detailed study of the properties of this particle should be one of the key objectives of the future European particle physics programme. The LHC is the world's flagship exploration facility at the energy frontier and energy-frontier colliders will remain an essential tool for the exploration of the fundamental properties of matter. The potential to produce new particles is one of the primary strengths of such colliders and one of the key methodologies for advancing particle physics knowledge.

The UK particle physics community has long standing, prominent and large contingents on the ATLAS and CMS general purpose detectors (GPDs), with UK scientists occupying a number of leading positions of responsibility within both collaborations. The HL-LHC has very strong support within the UK and the community has for some time been engaged in preparations for major upgrades to the detectors to enable them to perform effectively in the new and challenging environment that the HL-LHC will present. The major project for CERN until the late 2030's is without question, the HL-LHC. It will explore new territory in the search for physics beyond the standard model (SM) and enable much more precise Higgs sector and standard model measurements. Its construction, operation and exploitation should be Europe's highest priority.

Recommendation

Exploitation of the investment in the LHC and upcoming HL-LHC is the highest priority of the UK community.

It is fundamental to the pursuit of particle physics in Europe that CERN retains a competitive and timely high energy collider programme into the future, beyond the HL-LHC. This is necessary to ensure CERN remains at the forefront of Particle Physics research and is also vital to allow Europe to retain the expertise that would be capable of supporting major projects elsewhere in the world.

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The decision on the subsequent project could and should be made in the early 2020's. There is a clear scientific case for an e^+e^- machine to study the Higgs, including its self-coupling. There is also very strong physics motivation for a new hadron machine at the high energy frontier. CERN has expertise in both areas. The future global strategy for exploring the particle physics landscape should include both e^+e^- and hadron colliders.

Linear and circular e^+e^- colliders have complementary strengths and both options are being pursued. In both cases a staged system is possible where the ultimate capability could be realized through an energy upgrade. The UK is active and playing leading roles in both accelerator and detector aspects of a possible future linear collider. Should such an accelerator be realized, this community would engage in both of these activities. The CLIC RF technologies should be industrialised, and the development of medium-scale accelerators (for example a FEL) could help to progress this.

During this process of updating the European Strategy for Particle Physics, other areas in the world should be revealing their commitments to major projects in their regions. Were a strong e^+e^- programme to emerge on a non-European stage, then CERN has a clear direction towards the next generation of energy frontier hadron colliders. The extended physics reach of an FCC-hh is very attractive, with an order of magnitude increase in energy opening the door to very many new physics scenarios as well as enabling a high precision measurement of the Higgs self-coupling. Furthermore, this activity would be a major driver of new technologies. The UK community strongly supports the objective of building a hadron collider with a centre of mass energy around 100 TeV.

Were a future hadron collider to be Europe's objective then to achieve this goal CERN must pursue a vigorous high-field magnet R&D programme. CERN leads the world in the development of high-field magnet technologies, and this pre-eminence must continue for any future hadron collider project to succeed. This is challenging technology to develop and the CERN accelerator R&D programme would need to be optimally organized to achieve the required goals in as time efficient a manner as possible.

As an interim project, the LHeC, a project with significant UK leadership, remains a potential relatively low-cost option that extends the LHC programme. Accelerator technologies required for such a development could be of use to other projects, and these should be maintained where possible. The overall decision on an LHeC should be driven by the physics case, the cost and the effort required.

In the coming decade, the accelerator-focused nuclear physics community in the UK will concentrate its exploitation efforts on the high precision electron beam experiments that have become possible at the upgraded facility at JLab and on the opportunities presented by the upgraded ALICE detector at the LHC. In parallel, the community will be strongly engaged in defining the physics case for a future intermediate energy, high luminosity Electron Ion Collider (EIC) in the US and in fostering its strengths in the development of detector and trigger systems for the EIC detector systems.

Regardless of the final CERN project decision, CERN should maintain an active involvement in major projects elsewhere in the world, although the vast majority of the CERN budget should be spent on the projects at the CERN host laboratory.

Recommendation

In CERN, Europe has the world's leading accelerator laboratory and the European strategy for particle physics should enable this pre-eminence to continue. CERN should host a future collider to follow on from the HL-LHC. Such a facility should exploit CERN's accelerator expertise whilst recognising any potential accelerator developments elsewhere in the world. A timely decision on the nature of such a facility should be made such that its operation could follow on without excessive delay from the operation of the HL-LHC.

3 Flavour Physics

Measurements that explore the flavour properties of interactions have the potential to provide evidence of physics beyond the SM, most notably at mass scales well above those accessible via searches for direct particle production. Precision measurements have been critical in the development of the SM, from the first hints of the existence of the charm quark through the GIM mechanism and the first estimation of the top quark mass from B mixing to the elucidation of the CKM structure in the SM.

A number of precision measurements are currently displaying disagreement with the SM at the level of 2-3 standard deviations for individual measurements leading to intriguing patterns that give combined deviations at a level of 4-5 standard deviations. Examples of these are lepton flavour universality tests, electroweak $b \to sl^+l^-$ transitions and the anomalous dipole moment of the muon. Such measurements provide valuable methods of testing the SM. Flavour physics also includes studies of processes that are forbidden or vanishingly rare in the SM such as charged lepton flavour violation or electric dipole moments. These provide powerful null-tests of the SM. Heavy quark flavour physics also provides opportunities to explore the quark model and QCD through spectroscopy of expected and exotic states and through measurements of their properties and decay modes.

The LHCb experiment has clearly demonstrated that the LHC is an excellent laboratory for quark flavour physics, illustrating the importance of experiments designed to be dedicated to flavour physics at hadron colliders. It has produced world-leading results across a broad range of topics. ATLAS and CMS benefit from their very large integrated luminosity and can make leading measurements in, for example, decay modes involving muons such as $\mathrm{B}_s \to \mu\mu$. The very large production cross-section of the full spectrum of beauty and charm hadrons at the LHC enables a multitude of measurements that are unique to this facility and that are not possible at e^+e^- colliders. The installation of the first phase of the LHCb upgrade will start in 2020 and there is a programme for a detector consolidation in LS3 and a second phase upgrade around 2030, potentially resulting in unrivalled precision on many parameters. Examples of these are a precision on the CKM angle γ of $0.35°$, a sensitivity to CP violation in charm of $\mathcal{O}(10^{-5})$ and a precision on the B_s^0 mixing phase of 3 mrad. The upgrades of LHCb will enable the full exploitation of the flavour physics potential of LHC and HL-LHC.

Recommendation

Exploitation of the LHCb experiment and approved upgrades is the UK community's highest priority in flavour physics. We recommend the full exploitation of the flavour physics potential of the HL-LHC.

The UK particle physics community strongly supports a diverse programme of non-collider experiments that appropriately complements the collider programme. The Physics Beyond Collider (PBC) review being undertaken by CERN is very welcome and highlights the wide range of experiments that can be used to explore fundamental physics questions, and the UK particle physics community is supportive of a continuation of this programme of experiments.

The NA62 experiment is the world's leading kaon physics experiment with sensitivity to probe very high mass scales. There are several promising strategies for future precision kaon physics measurements within the PBC programme, and the UK particle physics community is supportive of a continuation of this programme.

The SHiP experiment designed to explore a possible hidden sector has leadership from the UK. This experiment plans to use a beam dump to produce copious quantities of heavy flavour particles, which could decay into lepton-flavour violating heavy neutral leptons, or other long-lived particles from a hidden sector. The UK community recognizes the potential of this proposed experiment.

Lepton flavour and charged lepton flavour violation measurements are excellent probes of physics beyond the SM. Physicists from the UK have a strong involvement in such experiments at CERN, at other European laboratories and further afield. Dedicated LFV experiments include Mu2e, COMET, Mu3e and MEG. The UK community recognizes the importance of these experiments and encourages CERN to support them.

Recommendation

The European particle physics community should ensure that the breadth of the field is maintained with a diverse range of experiments. The Physics Beyond Colliders initiative at CERN has highlighted what CERN has to offer to non-collider experiments. The UK community strongly supports a continuing programme of such experiments.

4 Neutrino Physics

4.1 Long-baseline Neutrino Physics

The 2013 update to the The European Strategy for Particle Physics noted that there was a "strong scientific case for a long-baseline neutrino programme exploring CP violation and the mass hierarchy in the neutrino sector." There have been significant developments since this time with the establishment of the DUNE and Hyper-Kamiokande (HK) collaborations and the approval of running T2K until the start of the HK experiment (T2K-II). All of these experiments have significant UK participation.

The neutrino platform, established at CERN following the recommendations that emerged from the 2012 process, has been very useful to the UK community; particular contributions of note include participation in the construction of the Long-Baseline Neutrino Facility (LBNF) in the United States, hosting the single-phase and dual-phase ProtoDUNE detectors and supporting the upgrade of the T2K near detector ND280.

Recommendation

The European particle physics community should continue to support the engagement of European physicists in the worldwide neutrino programme. Furthermore, we recommend that CERN continues to support the neutrino programme, both in terms of worldwide participation and through the neutrino platform facility at CERN.

4.2 Neutrinoless double beta decay

Neutrinoless double-beta decay experiments ($0\nu\beta\beta$) are, currently, the only way to address a fundamental question in particle physics, namely the fermionic nature (Majorana or Dirac) of the neutrino and hence the mechanism of neutrino mass generation. They are also highly sensitive probes of lepton number violation by other non-Standard Model mechanisms. The UK has a long history of involvement in such experiments that continues to the present day, with support for SNO+ and SuperNEMO.

The European particle physics community should develop further the programme of activity in this important area of neutrino physics. This requires involvement in more than one experimental effort in the near to medium term given the variety of technological approaches and the sensitivity of different isotopes. Such a programme should include at least one major experiment at a European underground laboratory and major involvement in other international projects. These experiments should have the capability to explore the inverted hierarchy range. Support should also be provided for the development of technologies that have the potential to eventually lead to a practical experiment capable of exploring the non-degenerate normal neutrino mass hierarchy. We note that there are strong technological synergies with direct dark matter detection and recommend coordination of R&D that could benefit both communities.

Recommendation

We recommend that the European Strategy includes the further development of an overall programme of $0\nu\beta\beta$ experiments. Such a programme should include at least one major experiment at a European underground laboratory and major involvement in other international projects. The programme should also include R&D for technologies that have the potential to eventually lead to a practical experiment capable of exploring the non-degenerate normal neutrino mass hierarchy.

5 Dark Matter and Particle Astrophysics

Understanding the nature of the dark matter (DM) that makes up 85% of the mass of the Universe is internationally recognized to be one of the highest priorities in science. Direct detection experiments utilizing ultra-low background targets in deep underground laboratories are key to the unambiguous identification of galactic DM particles in the GeV to TeV mass range. These particles could be WIMPs or other types of particle that arise in many extensions of the SM. The UK has been at the forefront of direct detection activities for decades, pioneering the use of liquid xenon time projection chambers (LXe TPCs), which is now the leading WIMP detector technology. The UK has made significant investments in the area of DM searches, including in the underground infrastructure at the Boulby Underground Laboratory. This facility currently supports a number of international projects. All international roadmaps, including those of STFC, APPEC, and P5 in the US recommend construction of '3rd generation' (G3) detectors to increase sensitivity by a further order of magnitude over near-future searches. Such G3 experiments are expected to include LXe TPCs that would be sensitive to a range of alternative DM candidates and BSM physics, in addition to WIMPs. Liquid argon (LAr) detectors may also be deployed at G3. Evidence from multiple targets will be required to confirm the WIMP hypothesis. These noble targets will require significant R&D that the existing infrastructure within European laboratories is well placed to support. CERN's expertise in cryogenic purification of LXe and LAr is well aligned with this R&D. The G3 experiments will also require large anti-coincidence outer detectors. LAr is a natural choice for such veto systems. CERN's expertise in LAr and cryostats for prototype long baseline neutrino experiments can be readily re-purposed towards this area.

Recommendation

We recommend European involvement in at least one LXe TPC at G3 and support for the development of LAr detectors towards G3. Expertise at CERN in the cryogenic purification of LXe and LAr could help to support the European effort.

A well-motivated alternative to the WIMP hypothesis is that DM consists of particles from a hidden sector. An example is the axion, whose discovery would also solve the long-standing strong CP / neutron EDM problem. The UK is involved in several DM axion search experiments, including the world's most sensitive axion-photon coupling experiment, ADMX, as well as efforts to probe axion-fermion couplings at higher masses. Next generation resonant axion searches will require improvements in quantum-limited RF/microwave electronics and applied magnetic fields. Further developments of ever-more-sensitive experiments to probe the hidden sector and ultra-light DM candidates have many overlaps and synergies with more general developments in the field of quantum sensing, which is also of wide interest in quantum computing, quantum electronics, and atom interferometry. The exploitation of quantum technologies for fundamental physics is a growing area in Europe.

Europe is involved in many searches for dark matter with multiple complementary techniques, including accelerators; direct searches; fixed targets; ground- and space-based indirect searches, and astronomical and cosmological probes. The interpretation of results from any one technique can have important implications for the others.

Astroparticle physics, at the intersection of particle physics, astronomy and cosmology, addresses fundamental and frontier physics including, in addition to DM, gravitational wave astronomy, gamma-ray astronomy, and neutrino astronomy. These areas can probe for evidence of BSM physics, and astroparticle facilities provide access to processes otherwise inaccessible to complementary accelerator-based particle physics. Improved coordination between these activities will enable better advantage to be taken of the opportunities multi-messenger physics provides.

Finally, we note the technical synergies between particle physics and astroparticle physics areas, including photodetectors, electronics, and fast computing. We recommend that R&D be coordinated in such technology areas to the benefit both communities.

6 Underground Laboratories

Europe possesses a number of underground laboratories and infrastructure that are crucial for several areas of research. These include searches for dark matter and neutrinoless double beta decay.

In the UK, the Boulby Underground Laboratory provides a low-background clean room facility that can be used for the development of next-generation techniques for rare event searches for dark matter and neutrinoless double beta decay. Additionally, with a cosmic ray muon reduction an order of magnitude greater than at Kamioka, providing the lowest radon rate of any underground facility, and with plans to excavate a cavern for a detector larger than SNO+, it may be possible to host a next-generation dark matter or $0\nu\beta\beta$ search at Boulby.

Recommendation

Europe possesses a number of underground laboratories, such as the Boulby underground laboratory in the UK, with important capabilities for DM and neutrinoless double beta decay experiments. We recommend that these laboratories be well supported to benefit this type of experiment.

7 Theory

Theoretical particle physics is a crucial part of the research programme. It has been instrumental in devising and recently verifying the Standard Model to exquisite precision and it will be vital for the formulation of possible BSM extensions and for the interpretation of discoveries. It is clear we need to concentrate on maximally increasing the accuracy of Standard Model predictions to determine unambiguously, any deviations seen in the increasingly precise experimental data expected in the coming years. This will require a concerted effort to maximise precision for e.g. Higgs physics, flavour physics, and the neutrino sector. Continued work is necessary in improving the accuracy of predictions for the strong and electroweak components of the Standard Model, and in particular to continue improvements in Monte Carlo generators to make them fully suitable for the HL-LHC. However, it is necessary to also pursue a wide-ranging programme of theoretical physics encompassing formal theory, which can potentially lead to paradigm shifts and sudden advances in our understanding, and phenomenology focussed on possible signs of BSM physics, e.g. model building. Since the Higgs discovery there has been a general move in theory towards understanding the high-energy physics underlying electroweak symmetry breaking, which remains extremely mysterious. Novel ideas such as scale invariance, split-supersymmetry, asymptotic safety, clockwork, relaxion, higgsplosion and so forth are being actively explored. A unifying feature of these proposals is that although they are often driven from the top-down by formal considerations, energies up to 100 TeV are a crucial testing ground. A similar scale is suggested by anomalies currently seen in measurements in flavour physics. It is also around the 100 TeV scale that non-perturbative aspects of field theory can begin to become important. Therefore, from a theory perspective, a crucial element of the programme is to maintain strong support for CERN, at the LHC and beyond, ultimately aiming towards these higher energy levels.

The recent increased interaction between BSM physics and dark matter physics is a natural evolution, which we believe should be further developed. Lattice theory remains a crucial ingredient of any future particle physics programme, as it contributes in an essential fashion to precision calculations in the Standard Model, particularly in flavour physics, which cannot be performed by other means. It is also key to understanding alternative scenarios of BSM physics, for example the crucial determination of the so-called conformal windows of quantum field theory, relevant for asymptotically safe theories. This requires the maintenance and development of powerful lattice computing facilities. Increased engagement of nuclear theorists with neutrino research would be of benefit, as this would facilitate the best exploitation of the wide variety of neutrino experiments either running or under construction or development. In addition, increased engagement of nuclear theorists would benefit heavy ion physics.

Particle phenomenology within the UK has a very strong international profile, facilitating the full exploitation and development of the current and future experimental programmes, and the UK hosts a dedicated phenomenology research centre, the Institute for Particle Physics Phenomenology in Durham. Formal theory activity in the UK also has a significant international profile, with a long history of successful innovation. Lattice gauge theory plays a vital and increasing role in understanding flavour physics and other areas and the UK continues to invest in high performance computing for particle physics via the DiRAC (Distributed Research utilising Advanced Computing) facility. Particle theory and astrophysical research are becoming more closely entwined, and the UK is expanding research in cosmology.

Recommendation

For exploitation of the experimental particle physics programme it is essential for Europe to maintain and further develop a world-leading long-term programme across theoretical particle physics in its broadest sense. We must confront data with the maximal theoretical precision to test fully the standard model and interpret any deviations from expectations, and to guide future experimental developments towards energy scales that can test a broad raft of underlying BSM ideas. This requires phenomenology (both SM and BSM), formal theory, astro-particle and lattice theory and further developing interactions between these areas.

8 Detector R&D

A strong detector R&D programme is vital to ensure a long-term world-leading experimental particle physics programme. This activity tends to be at a scale that is funded primarily from national funding bodies, at least in the early stages of such R&D work. The RD programme at CERN is a useful vehicle for supporting collaborative activity. While this programme is effective, re-evaluating its structure and function could make it more effective at facilitating the R&D activities of the particle physics communities of the CERN member states. The CERN experimental physics department has recently undertaken a welcome review of proposed research activities. Putting in place structures that will enable continued consultation and interaction with members states to identify research areas and enable well defined modes of interaction is desirable. The CERN programme has access to materials funding and this should be used to benefit all member state participation in RD programmes.

Facilities available in various European laboratories, such as test beams and low background facilities, are an important resource for the development and implementation of new detector technologies. The UK supports the accessible provision of such facilities to the European particle physics community.

Recommendation

Detector R&D activity is vital for the future of experimental particle physics and should be strongly supported. We recommend a revamp of the CERN RD programme to better support and interact with the member states particle physics communities. The new structure should be defined in consultation with delegated representatives from the member states.

Most particle physics experiments have considerable software and computing needs. The evolution of computing technologies and the resultant need for different approaches to software engineering are developments that mean it is more important than ever that planning for new experiments take full account of the development work and costs associated with this component of experimental work. We encourage CERN to remain actively engaged with community wide projects to deliver computing and software in an efficient manner, and to engage with communities beyond particle physics where mutual projects are beneficial.

Supporting many experiments across a diverse range of topics will provide excellent opportunities to explore new detector technologies and to train new generations of physicists. This is very important for the health and future of our field.

9 Accelerator R&D

The incremental development of accelerator technology and the innovation of novel techniques underpins future discoveries. A vibrant accelerator R&D programme is therefore vital to ensure the long-term future of experimental particle physics.

Exploration of physics at the highest possible energies has been the historic vehicle of discovery in the field of particle physics and should remain at the heart of the European Strategy for Particle Physics. The future energy-frontier accelerator R&D programme must be designed to create opportunity, and mitigate technical and financial risks. Therefore, the future programme must prioritise technology development (for example in high-field superconducting magnets, superconducting RF and novel accelerating structures, and energy-efficient acceleration) and the development of novel high-gradient acceleration, especially the very promising proton driven plasma wake field technique pioneered by the AWAKE collaboration. The resurgence of interest in muon colliders should also be noted.

Dedicated programmes are required to carry forward the investigation of the physics of flavour in the quark, neutrino, and charged-lepton sectors. In view of the expertise that exists in European laboratories, a distributed R&D programme, perhaps modelled on the "RD" programme that has been successful in coordinating detector development in Europe, should be established to develop the technologies and capabilities necessary to take the quark, neutrino, and charged-lepton flavour programmes beyond the sensitivities of the next generation of experiments in Asia, Europe, and the US. This "accelerator-RD" programme should encompass and exploit novel facilities such as nuSTORM and dedicated technology-development programmes such as RaDIATE.

Recommendation

A distributed R&D programme, perhaps modelled on the "RD" programme that has been successful in coordinating detector development in Europe, should be established to develop the technologies and capabilities necessary to take the quark, neutrino, and charged-lepton flavour programmes beyond the projected sensitivities of the next generation of experiments in Asia, Europe, and the US. CERN should play a coordinating role within Europe for this R&D activity.

10 Conclusion

There is a vibrant and successful worldwide particle physics research endeavour. Over the next few years major decisions must be made about future facilities that cater to this worldwide activity. Discussion on a global scale will be required to arrive at a set of facilities that can meet the challenges that particle physics research poses. Non-collider experiments should complement any major new collider facility and the increasing size of these activities means that they would benefit from a European wide strategy on which of these to pursue. A strong and well supported R&D programme is required to develop the technologies that will enable future accelerators and experiments to be built. CERN is the world's flagship Particle Physics Laboratory and the European Particle Physics strategy should aim to ensure that it maintains this position.