PPAP 2021 Roadmap

Particle Physics Advisory Panel

*B. Allanach, A. Bevan, M. D'Onofrio, R. Jones,
M. Needham, K. Palladino, S. Pascoli, J. Pasternak,
Y. Peters, R. Saakyan*

1 Introduction

The mission of the UK particle physics community is to push the limits of human understanding of the fundamental description of nature at the smallest scales and highest energies, leading and influencing global scientific efforts. Cutting edge data science, instrumentation, facilities and theoretical methods are required for this. Recent highlights on the experimental side include:

- Improved knowledge of the Higgs Boson properties and couplings from measurements at the LHC, as well as first measurements of rare Standard Model (SM) processes and stringent, world-leading constraints on new physics including supersymmetry, high mass new particles and dark matter.

- Improved precision on the knowledge of the neutrino mixing matrix from T2K and NOVA, with recent highlights including indications on the allowed parameter space for the CP violating phase and neutrino mass ordering.

- Hints of Lepton Flavour Universality violation by LHCb, improved knowledge of quark mixing matrix parameters such as the CKM angle, γ, and the discovery of many new hadronic states.

- Confirmation of tensions between theory and experiments by the Fermilab g-2 experiment in this important Standard Model observable.

- Successful construction of the LZ experiment, projected to have a world leading direct detection sensitivity to a wide range of dark matter masses.

Underpinning these experimental developments is a vital UK theory activity in phenomenology and lattice QCD. In addition, the UK development of the double copy of gravitation (originating from scattering amplitude techniques) is revealing a hidden, simpler side of gravity and enabling more accurate computation of gravitational wave signatures from black hole mergers.

Fundamental science breakthroughs are often the result of experiments that take decades of planning. They normally require access to large international facilities, although sometimes smaller instruments can provide focused opportunities. The challenges of current and future experiments require innovation: new ways to accelerate particles, detect radiation and innovative computing and data science solutions to harvest results. The fundamental nature of this research often requires application of subtle quantum effects that can provide powerful insights to guide applications of quantum theory. New ideas are generated continually and the UK must retain its agility to respond to emerging opportunities. The UK's leadership is ensured by its strength across the scientific life-cycle of new theoretical ideas being proposed, new facilities and instruments being constructed through to successful operation and finally data analysis. The particle physics community serves the wider interests of UK public, research, and commercial sectors by working with UK industry and public sector organisations on the development of new technologies and facilities, and by developing high quality scientists with a broad set of valuable transferable skills for the workforce. There are natural overlaps between the physics questions being addressed by the PPAP community and other areas that fall under the STFC programme remit, most notably Nuclear Physics, Particle Astrophysics, Technology and Accelerators.

The recent conclusion of the five-yearly European Strategy for Particle Physics update (ESPPU) presents an opportunity to update this UK particle physics roadmap. The time-range considered is longer than normal, looking to the 20-year horizon, as the major collider projects in particular require planning on that timescale. These considerations were also evident in the European Strategy process. We examine the possible opportunities as well as the technological requirements and drivers of the various Particle Physics (PP) projects. These may flag potential funding opportunities and possibilities for shared effort both with industrial partners and with other science areas.

The current exercise shows the strong leadership and capabilities of the UK community. There are many potential opportunities for science and technology emerging from the community. The current funding envelope allows for some of these opportunities to be realised with core funding, while others are opportunities for investment beyond the core. It is crucial that the UK delivers the science harvested from its previous investments and plays a leading role in the experiments and facilities that it has built. Increasingly, the challenge is to do this while supporting the work necessary for future projects; and to exploit opportunistic funding without compromising exploitation activity. This suggests that, where possible, new funding should be used to relieve pressure on the core programme.

The roadmap exercise is not intended to repeat the European Strategy process, in which the UK had an active and important role. The new European strategy presents a menu of activities for Europe while this PPAP 2021 roadmap aims to indicate how the UK will make its choices from that menu. At relevant points, we shall quote from the European strategy recommendations (and other documents) directly in *in italics*.

The community consultation exercise that resulted in this roadmap is described in Appendix A. The ordering of sections reflects a logical flow and does not indicate any prioritisation. We start with a section on colliders, followed by flavour, neutrino and dark sector concluding with the underpinning theory and technology sections. In discussing UK leadership we restrict ourselves to spokesperson level positions as these are common to all experiments, with a well defined meaning. In all areas the UK has significant leadership at lower-levels, where structures may differ.

2 Physics Challenges and the overall programme

The STFC physics strategy is built around a set of physics challenge questions listed here `https://stfc.ukri.org/research/science-challenges/`. The work of the PP community naturally addresses all of the STFC challenge questions under the high level question C: "What are the basic constituents of matter and how do they interact?".[1] However, we also address some of the A-type questions such as A1: "What are the laws of physics operating in the early Universe?". This section describes the mapping of projects in this report to the physics areas covered. In detail, the STFC challenge questions addressed are:

A1 What are the laws of physics operating in the early Universe?

A3 How is the universe evolving and what roles do dark matter and dark energy play?

A7 What is the True Nature of Gravity?

A8 What can gravitational waves and high-energy particles from space tell us about the universe?

C1 What are the fundamental particles and fields?

C2 What are the fundamental laws and symmetries of physics?

[1]This includes the question "What is the nature of nuclear matter?"; although it is predominantly covered by a parallel community, there are important contributions from our studies of quantum chromodynamics (QCD) and hadron structure, as well as from our technological developments.

C3 What is the nature of space-time?

C4 What is the nature of dark matter and dark energy?

C5 How do quarks and gluons form hadrons?

C6 What is the nature of nuclear matter?

C7 Are there new phases of strongly interacting matter?

C8 Why is there more matter than antimatter?

C9 What will precision measurements of the Higgs boson reveal about the Universe?

Table 1 attempts to survey how the activities in the roadmap are addressing the challenges. The level of coverage varies between facilities, but all those indicated make important contributions.

	A1	A3	A7	A8	C1	C2	C3	C4	C5	C6	C7	C8	C9
HL-LHC (GPDs)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
HL-LHC (LHCb)	✓	✓		✓	✓	✓	✓	✓	✓			✓	
Future e^+e^-	✓		✓		✓	✓	✓		✓			✓	✓
Future hh	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Future eh	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Non-collider flavour	✓	✓			✓	✓		✓	✓			✓	
ν osc.	✓	✓		✓	✓	✓	✓	✓				✓	
$0\nu\beta\beta/\nu$ mass	✓	✓			✓	✓	✓					✓	✓
e^-/n dipole moments						✓					✓	✓	
Direct dark sector	✓	✓		✓	✓	✓	✓	✓				✓	

Table 1: An indicative table of the physics coverage of the STFC challenge questions from different parts of the programme. GPDs refer to General Purpose Detectors ATLAS and CMS. Non-collider flavour refers to precise muon and kaon physics experiments. The row labelled Direct Dark Sector includes wave-like Dark Matter (DM) that is part of the Quantum Technologies call. Some complexity is obviously hidden. For instance, the e^+e^- collider physics coverage depends on the centre of mass (COM) energy achievable. Here, we have taken this to be 250 GeV as the first stage, expected to be a Higgs factory and with consequent limitations to the search reach.

The PP community has a detailed set of physics objectives that relate back to the challenge questions. The panel has looked to see how the ongoing and future activity areas in the European Strategy map on to those questions. Inevitably, the view of strengths and coverage of each has a subjective element: an activity may give superlative coverage of one aspect, but not of all places where the physics may apply; another may have broad coverage but not reaching the same precision and depth.

The panel looked broadly at: the Higgs sector; SUSY and other beyond Standard Model theories; dark matter and dark sector; QCD; CP violation; lepton universality; neutrino masses; and sterile neutrinos. The collider programmes each (and to varying degrees, dependent in part on the centre-of-mass energy considered) give good coverage of all except the neutrino mass questions. The non-collider flavour experiments give coverage of the dark sector, QCD, lepton universality and sterile neutrinos. The neutrino experiments cover CP violation, lepton universality, neutrino masses and sterile neutrinos. The dedicated dark sector and dipole moment experiments cover dark matter, CP violation, lepton universality and sterile neutrinos. Given the different scope and depths of coverage, it is important to have both the general and more dedicated facilities.

3 Overall programme recommendations

Since 2008 the core funding for PP has received flat cash funding, amounting to an effective cut of 30% in real terms. As recognised in the 2020 STFC Balance of programmes exercise[2], though excellent and world leading science is still being performed *'any further cut back of the programme's volume will cause severe damage to the UK's scientific output'*. A clear community concern raised during this exercise is that the balance between new projects, operations and exploitation has become distorted; an appropriate balance is essential to the health of the UK activity. In particular, there are concerns expressed about the ability to operate and exploit experiments throughout their lifecycle. Reversing this trend with an increase in core funding **is essential** to ensure that UK PP remains a strong part of the research portfolio ensuring that the UK fulfils its ambition to be a Science and Technology superpower by 2030. This will ensure that the science and technology skills pipeline required for fundamental science discovery continues to feed key industry sectors in line with Government policy.

The scientific life cycle of a project can sometimes last decades. To realise, take leadership and to harvest the big datasets generated by facilities and instruments requires that the community maintains a core set of experts across all these areas. To maintain this skills pipeline at the forefront of science and technology it is essential to have a broad portfolio of projects to efficiently balance R&D phases for future programmes from the dedicated production builds required for tomorrow's discovery physics. Maintaining a balanced portfolio is key to enabling technology and skills exchange between the community and UK industry partners collaborating on future experiments.

Careful planning is required to ensure that successful outcomes from initiatives that bring in new funding for R&D (i.e. the Quantum Technologies for Fundamental Physics, QTFP, programme or the DUNE experiment construction) translate into successful exploitation projects, particularly given the existing pressures on the core budget. Common projects, possibly cross-UKRI, that can liberate new funding to relieve that pressure need to be explored and exploited where possible.

The following overall recommendations remain largely unchanged from the 2019 roadmap exercise, and most predate that. The passing of time has made them more urgent.

Recommendation 3.1: The UK must continue to pursue a world-leading particle physics programme, focussed on addressing the internationally acknowledged high priority science questions.

Recommendation 3.2: The core funding of the programme is essential for exploitation and innovation, but has fallen dramatically in real terms over the last decade. STFC and the community must pursue every avenue to increase the core funding in real terms.

Recommendation 3.3: When new projects are initiated, the downstream impact on the core programme must be evaluated. Scenario planning should be used to help ensure the new programmes strengthen the core programme.

Recommendation 3.4: In the case of continued real terms attrition to the funding,

[2] See `https://stfc.ukri.org/files/balance-of-programmes-2020/`

STFC should attempt to maintain minimal capability in areas that are otherwise de-funded, to allow regrowth at a later stage.

Recommendation 3.5: CERN is the world's leading particle physics laboratory and the focus of most particle physics experimentation in Europe; UK membership of, and support for, CERN is crucial for the UK science programme.

4 Collider physics

The bedrock of the UK particle physics programme remains the LHC which will collect data well into the 2030s. As the following sections describe, there is current UK interest and involvement in various future collider possibilities. This reflects the broad physics engagement from the UK and the technical expertise it has developed. However, that diversity and the discussions through the consultations with the community come back to a strong endorsement of the recommendations in the 2020 ESPPU, namely:

- *'the PP 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* [3];
- *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 (EW) 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 PP community would wish to collaborate.'*

Our recommendations should be read in this context, and aim to ensure that UK activity provides the optimum benefit and leverage across projects. We also consider other collider projects that are less central to the PP domain such as the EIC, but to which the PP community can make important and synergistic contributions; and projects whose timescale is beyond the 10 year view of the 2020 ESPPU.

4.1 Current and near-term hadron collider programme: LHC and the HL-LHC

The LHC remains by far the major focus of effort and engagement of the UK PP community, with significant UK involvement in ATLAS, LHCb, CMS and ALICE, the latter formally falling under

[3] We note that the strategy document underlines also that, 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, developments for compact facilities with a wide variety of applications; an international design study for a muon collider; 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. Where appropriate the synergy between the PP programme with UKAEA and commercial fusion requirements of high field superconducting magnets should be explored.

the remit of the Nuclear Physics programme[4]. UK scientists and engineers have held and hold leading roles in all experiments, including the role of spokesperson in ATLAS, CMS and LHCb.

ATLAS and CMS are general purpose detectors (GPDs) and their extensive research programme addresses all major collider physics areas of interest, from searches for new physics at all accessible energy ranges, to precision SM measurements, also in the flavour sector. Both experiments present extensive UK involvement. In the Run 1 and Run 2 of the LHC, the GPDs have produced a dozen first observations of fundamental processes, including the discovery of the Higgs boson and the study of its properties, hundreds of first measurements and searches, and developed innovative performance analyses and methods. More than a thousand papers in international journals have been published by each experiment.

Complementary to ATLAS and CMS, LHCb is designed primarily to study beauty and charm hadrons that are produced at enormous rates in the forward region in high-energy proton-proton collisions. Over the last decade, the LHCb collaboration, which carries a very high UK fraction in its authorship, has published many precision SM tests using the integrated luminosity of $9\,\text{fb}^{-1}$ collected during Runs 1 and 2. Highlights include the discovery of the flavour changing neutral current decay $B_s \to \mu^+\mu^-$ (together with CMS) and the observation of CP violation in charmed meson decays. Intriguing discrepancies with Standard Model predictions are emerging in processes involving $b \to s l^+ l^-$ decays (the 'B anomalies') which beg further study.

The HL-LHC is scheduled to run until 2038 and it will allow the GPDs to collect an integrated luminosity of $3\,\text{ab}^{-1}$ in proton-proton collisions at a centre-of-mass energy of 14 TeV. As stated in the PP evaluation programme from 2019, the HL programme will maximise the potential of the LHC.

For GPDs, the determination of Higgs boson properties, and their connection to electroweak symmetry breaking (EWSB), is one of the primary targets. Outstanding opportunities have emerged for measurements of fundamental importance, such as the first direct constraints on the Higgs trilinear self-coupling and the natural width. The fundamental SM properties will be tested by performing measurements with unprecedented precision[5]. New phenomena up to a mass scale of 8 TeV could be discovered, thus testing many beyond the Standard Model (BSM) scenarios and possibly resolving big puzzles of fundamental physics. In most BSM scenarios the HL-LHC will increase the present reach in mass and coupling by at least 20–50%, and will allow, among others, to perform searches for additional Higgs bosons in EWSB scenarios and for hidden (dark) sectors.

The UK has committed to undertake substantial construction work for the GPD upgrades leading up to Run 4. These follow from the considerable technical knowledge built-up from the original construction, and our current operational responsibilities and expertise. The upgrade work for ATLAS is in the tracker, the level 1 and the high level triggers and the software and computing. For CMS, it is in the tracker and real time tracking electronics, high granularity endcap calorimetry, and a new level-1 trigger. These investments build the foundations for scientific exploitation and for high levels of future leadership in these world leading international endeavours. The R&D activities relevant for the HL-LHC should serve as a basis for the detector development relevant for future colliders. When operational these new facilities will result in exa-scale computing challenges that will require innovative data science and computing solutions.

The LHCb programme focused on the heavy flavour sector will continue throughout the era of

[4]This includes dedicated Heavy Ion studies, where often the analyses hinge on techniques developed in proton-proton running and comparison with reference proton-proton measurements.

[5]It is noted that further precision in the EW and QCD sectors, including the Higgs, would be achieved if an electron-proton facility is realised concurrently to the HL-LHC. The LHeC, based on the ERL technology for the electron beam, remains a viable option for CERN.

the HL-LHC. The 2020 ESPP recommends that *'full physics potential'* of the LHC in this area *'should be exploited'*. Operating at a luminosity of $2 \times 10^{33}\text{cm}^2\text{s}^{-1}$, from 2022 the Upgrade I LHCb detector will accumulate a factor five more data with further consolidation work for seen during Long Shutdown 3. The measurements driving the B anomalies include those from angular analysis of $B^0 \to K^{(*0)}\mu^+\mu^-$ and tests of lepton flavour universality: R_K and R_{K^*}. If the current central values hold, the Upgrade I dataset could establish lepton flavour universality violation. For the Upgrade I detector the UK has made major contributions to the particle identification, vertex detector and trigger. A second major upgrade (Upgrade II) is planned for the early 2030s to fully exploit the HL-LHC era by running a factor of five or more higher in luminosity allowing to collect a luminosity of $300\,\text{fb}^{-1}$ and is discussed in Section 5.1.

The continued flat cash in the core programme coupled with growth elsewhere has led to a decrease in the resource available for the current and HL-LHC activity. In particular, operational and data analysis effort has been eroded. This has now reached a floor level in the 2019-2022 experimental particle physics Consolidated Grants round below which further reduction would be inconsistent with the priority given to LHC exploitation in both the European and UK strategy.

Recommendation 4.1: The HL-LHC remains the highest priority for the UK community, with direct involvement from a large fraction of the experimental community; this, coupled with the large investments so far, mean that the UK must continue to give strong support to the ATLAS, CMS and LHCb upgrades, and their commissioning, and to the exploitation of the current and upgraded experiments, thereby maintaining its leadership in the LHC program.

4.2 Future colliders

High energy colliders provide direct access to the energy frontier and this area retains the largest active UK involvement in the current programme and with the largest fraction of institutes interested in its future plans. The proposed possible future collider options (including their running energies) have their own specific physics objectives, and could be discussed class-by-class. Since the various Future Circular Collider (FCC) options proposed by CERN have several common aspects to be considered, we consider the costs and timescales as part of a single programme for the purposes of this document. This does not imply that, for instance, the FCC-hh requires an FCC-ee in order to proceed. Pressures to economise and to leverage the maximum return on investment also encourage a more holistic view when making choices for the UK.

Recommendation 4.2 The UK community shares the vision of the European Strategy document to prepare an electron-positron Higgs factory as the highest-priority next collider; and a future hadron collider with sensitivity to energy scales an order of magnitude higher than the LHC. The latter requires development studies to address the associated technological and environmental challenges and opportunities. The UK community should establish a unified future high energy collider programme to be well positioned in a 20+ year plan for future accelerators.

This overarching programme should be built around existing UK strengths, including in physics exploitation, to inform instrument design and construction. This programme may present opportunities for new funding, but if budgets remain tight then consideration should be given where possible to supported activities that provide leverage with more than one of the facilities under consideration by the UK.

4.2.1 Future e^+e^- colliders

The UK view aligns with the conclusions of the 2020 ESPP listed above that a natural and highest priority next collider is an electron-positron Higgs factory. Several important precise measurements require a lepton collider with threshold of about 250 GeV, for example the measurement of the Higgs width, access to Higgs couplings to second generation fermions and probing for Higgs BSM. Further motivations of lepton colliders lie around higher-precision EW and flavour physics (Z and WW thresholds), precision measurements of top mass and width, and top-Higgs couplings. The latter requires centre-of-mass energies above that planned for circular electron-positron colliders but with would be reachable with future linear options. Higher-energy running opens further sensitivity to BSM scenarios.

These physics interests are common among the electron-positron collider proposals CepC, FCC-ee, and ILC, all of which have UK community interest and existing activity, with several institutes involved in more than one of the projects. The CLIC project featured in the previous European strategy and also shared these common interests and has UK community involvement and leadership in accelerator and detector development.

The common interests of all projects are reflected in the accelerator and detector technologies of all designs. In particular, accelerator R&D and beam delivery as well as CMOS MAPS technologies are mentioned, as well as UK expertise in trigger and data acquisition (DAQ), tracking, calorimetry and Grid computing. The requirements on detectors for any of the three putative e^+e^- collider projects are similar and would permit a more generic approach of the R&D detector efforts.

For all projects, the next major challenges are to establish international agreements and funding. Though there was funding for the ILC in the past, none of the projects has dedicated funding within the UK. Work is ongoing at a low-level through general detector R&D funds.

The various e^+e^- projects are in different R&D phases with first physics expected between around 2035 and 2045. The ILC published a TDR in 2013 focused on the 250-500 GeV option (extendable to 1 TeV), and is now in a phase which is preparatory to requesting approval. Recently, a proposal for a pre-lab structure has been released and endorsed by ICFA. The FCC-ee is entering a feasibility study phase, as recommended by the 2020 ESPP. Both FCC-ee and the ILC are endorsed in the European Strategy's recommendations. UK e^+e^- collider activities should therefore be supported to ensure broad engagement with the future options (CepC, FCC-ee, ILC, CLIC), so as to allow agility at the point where one of the facilities is realised.

Recommendation 4.3: The UK should engage in the realisation and exploitation of a future high-energy e^+e^- facility. Investment in appropriate R&D on detector and accelerator technologies/systems that capitalises on current UK strengths will position us to take a leading role in e^+e^- collider physics. Where possible, the programme should provide leverage with more than one of the facilities under consideration by the UK.

4.2.2 Future Circular Collider

The community consultation prompted three submissions on the FCC, reflecting the possible uses of a 100 km FCC tunnel at CERN: FCC-hh, FCC-eh and FCC-global, which includes the FCC-ee option detailed above. Overall, there is broad community interest in the FCC projects, with most institutes interested in more than one option.

The FCC is clearly central to the European and UK planning. It could be realised with an initial FCC-ee, or could proceed directly to an FCC-hh if another e^+e^- project goes ahead elsewhere, as recognised in the 2020 ESPP recommendations. There is a need for the UK to act now to be well positioned in the FCC multi-decade programme.

The hadron-collider phase of the FCC will it allow to collect an unprecedented proton-proton collision dataset in a decade of operations, with a centre of mass energy almost 8 times higher than that of the current LHC. It will also offer the possibility to have concurrent electron-proton collisions exploiting the addition of an electron beam produced through ERL technology.

The 100-TeV proton-proton collider offers several unique possibilities for a breakthrough in PP, such as precise measurements of the Higgs (triple) self-coupling, projected to be measured to 5%; quartic Higgs self-coupling at any level; direct searches for new physics, with the possibility to extend by an order of magnitude the LHC sensitivity above the EW symmetry-breaking scale.

FCC-hh requires technology far beyond the current state-of-the-art such as highly integrated low-mass and radiation-tolerant detector systems; substantially increased on-detector data processing and intelligence; development of new thin superconducting magnet technologies; and entirely new methods of controlling, powering and gathering data from billions of detector channels. This must build on the current expertise being deployed for the HL-LHC. Existing UK strengths on physics exploitation should be exploited to inform instrument design and construction.

In accelerator physics, work on enabling technologies such as high-field superconducting magnets should proceed involving the efforts of national labs, the community, and experts in HTS technology from industry and academia. The UK is also well placed to take a lead role in understanding the FCC-hh radiation environment given expertise developed through STFC investments to both the LHC and HL-LHC.

Recommendation 4.4: The UK community should identify a sub-set of key areas of technology that align with initiatives at CERN and will be informed by appropriate physics studies, that will allow the UK to capitalise on the expertise acquired through the HL-LHC construction and beyond, to carry forward its leading role to the FCC-hh.

Energy-frontier Deep Inelastic Scattering (DIS) can be realised through an ERL that would produce 60 GeV electrons to collide with the FCC hadron beams. It would deliver lepton-proton (ion) collisions with centre of mass energies in the range 0.8-3.5 TeV per nucleon, giving unique opportunities in terms of: QCD discoveries (*e.g.* physics at high and low-x); study of EW and vector boson fusion (VBF) production and forward objects; Higgs physics; Beyond SM searches (*e.g.* long-lived particles, heavy neutrinos, dark sectors). For the near and mid-term, the required work to prepare for a possible FCC-eh can essentially be undertaken in the context of the FCC-hh preparations. The physics programme has synergies with that of the FCC-hh allowing to further boost the FCC-hh potential. In terms of detectors, synergy with FCC-hh and FCC-ee in technologies is expected and should be exploited. Several aspects are common with precise detectors for e^+e^- and pp (e.g. CMOS Si technology and Si-W calorimetry).

On the accelerator side, ERL is considered green technology while allowing for the production of intense high energy electron beams and the UK has good expertise in this area. The PERLE Collaboration, with strong UK leadership, is currently developing and building a 500 MeV machine as demonstrator of this technology and it aims for start of operations in 2025.

Recommendation 4.5: As an adjunct to the FCC-hh studies, feasibility studies to inform accelerator and detector technology options for FCC-eh should be pursued by the UK focusing on common elements of the possible future facilities and their experiments.

4.2.3 Muon collider

Muon colliders could reach centre-of-mass energies of tens of TeV and high luminosity with shorter accelerator tunnels. A muon collider would allow accurate tests of the Standard Model to extremely high energy and searches for new physics. By exploiting the copious rate for VBF and vector boson scattering processes, it provides the opportunity to probe details of the EW symmetry breaking mechanism. Nonetheless, the technology is not mature enough to envisage such a facility in the medium term. The interest at the moment is focussed on nuSTORM. This facility, possibly to be hosted at CERN, could deliver a precisely known neutrino beam produced in a storage ring by the decay of muons. This could be considered as a technology demonstration platform for the construction of a muon collider. Such a facility would be an ideal tool for high-precision neutrino interaction cross-section measurements and to search for sterile neutrinos.

The CERN-led muon collider collaboration was formed in 2020 following publication of the ESPPU. The collaboration has entered a two year planning phase that will be followed by a three year study phase leading to a design report on a timescale consistent with the next strategy update. Nineteen UK institutes have expressed interest in nuSTORM, with that interest coming from both the neutrino and accelerator community. The UK has established leadership in this area and should maintain it, in case the Muon Collider would become a future direction.

Recommendation 4.6: The UK should maintain its recognized expertise in Muon Collider studies concentrating on medium-term projects focused on feasibility demonstration exploring synergies with neutrino physics such as nuSTORM.

5 Quark flavour and precise muon physics

The 2020 ESPP update highlights that *'the exploration of flavour and fundamental symmetries are crucial components of the search for new physics'*. The UK has a long tradition of leadership in flavour physics. The efforts of the UK flavour physics community are currently focussed in three areas: precision studies of heavy quark flavour physics with LHCb, rare kaon physics with NA62 and precision muon physics.

5.1 Flavour at Colliders

The UK heavy quark flavour programme is focussed on the large samples of beauty and charm quarks produced at the LHC where the UK has strong leadership in both the LHCb experiment and the flavour programmes of the GPDs as discussed in Section 4.1. More recently, a smaller effort on the BES III experiment in Beijing has started, funded by Royal Society and ERC grants. With a relatively modest investment, this has allowed measurements that are key to fully exploit the precision of the CKM angle γ measurements being made with LHCb and Belle 2 as well providing important inputs to the charm physics programme. The UK community is currently not involved in the Belle 2 experiment now taking data in Japan.

The LHCb experiment and its upgrade programme are discussed in Section 4.1. For many decays of interest the experimental sensitivity remains limited by the data sample size. Hence, more stringent tests of the Standard Model and tests of observed anomalies can be made by pushing to higher luminosities and collecting more data. The ESPP supports the exploitation of the heavy programme into the HL-LHC era. The LHCb Upgrade I detector will commence data taking in 2022.

The LHCb Upgrade II dataset will reduce the uncertainties in observables related to the current B-anomalies to below the 1% level. The precision on other flavour observables in the beauty and charm sector will also be improved. The high pileup in the Upgrade II environment gives many challenges. To meet these, the UK groups will build on their existing expertise and leadership in tracking and particle identification. A new 4-d vertex detector is planned exploiting timing information to associate tracks to primary vertices. UK groups also lead the development of the new downstream tracking system. This will use CMOS MAPs technology, originally developed for ATLAS and Mu3e. In particle identification the UK groups are leading an R&D programme to produce a RICH with excellent timing as well as the development of a new time-of-flight detector (the TORCH). To exploit the move towards 4-dimensional reconstruction, new paradigms will also be needed.

Scanning the horizon beyond the lifetime of the LHC, several opportunities in flavour physics at colliders may arise in the coming years. Further upgrades to the Belle physics programme in Japan are being considered and a new tau-charm factory has been approved in China following on from BES III. In the longer term, future collider projects such as FCC-ee have significant heavy flavour capabilities when running on the Z-peak.

Recommendation 5.1: The UK must continue to invest in the LHCb Upgrade II program and investigate the potential for flavour physics at future collider facilities.

5.2 Precise kaon physics

Measurements of the rare kaon decays $K^+ \to \pi^+\nu\overline{\nu}$ and $K^0 \to \pi^0\nu\overline{\nu}$ allow to make precision tests of the Standard Model and to indirectly probe for New Physics up to high mass scales ($\mathcal{O}(100\,\mathrm{TeV})$). The UK has strong involvement and leadership in the NA62 experiment and currently holds the spokesperson role. NA62 has already provided the first 3σ evidence for the $K^+ \to \pi^+\nu\overline{\nu}$ decay and aims to measure its branching fraction to 10% precision with data collected up to 2024. Upgrades building on the success of NA62 are being studied as part of CERN's Physics Beyond Colliders programme. A comprehensive future programme is being studied with the aim of measuring $K^+ \to \pi^+\nu\overline{\nu}$ to 5% precision, $K^0 \to \pi^0\nu\overline{\nu}$ to 20% precision and to study other rare decays. The proposed programme will over-constrain the CKM triangle using kaon measurements alone, allowing to probe for new physics through a precision test of the Standard Model.

The UK part of the NA62 collaboration aims to build on current leadership and responsibility (e.g in particle identification and novel photon detection) to make a major contribution to the NA62 upgrade programme. There are synergies with other UK activities related to single-photon direction and DAQ. Initial seed funding has been obtained from the Cockcroft Institute to investigate radio-frequency beam separation.

Recommendation 5.2: The UK has a leading role in the scientific exploitation of the current generation of kaon experiments. The UK should participate in the exploitation of the future CERN High-Intensity Kaon Beam Facility, and invest into the future CERN kaon experiments - for example by exploiting its expertise in beam-line, trigger and DAQ development.

5.3 Precise muon physics

Since the 2012 roadmap, a significant muon physics programme has developed in the UK. This complements direct searches for new physics at the LHC and is one of the few handles we have on physics at the PeV scale, which is addressing the fundamental questions STFC is focusing on. The UK's investment will provide a stream of the world's most precise measurements or limits in this sector over the coming decade.

First results from the Fermilab g-2 experiment were reported in April 2021. With a fraction of the dataset collected so far, a similar statistical precision to the previous generation experiment at Brookhaven is achieved. The combined experimental results differ by 4.2σ from the accepted theoretical value (where the hadronic vacuum polarisation is calculated from e^+e^- scattering data) and have attracted considerable attention. With the complete dataset the experiment aims to improve the precision by a further factor of four. If the central values of both experiment and theory persist this would indicate New Physics with high significance. In addition to measuring g-2, the experiment aims to improve the sensitivity to the muon electric dipole moment (EDM) by four-orders of magnitude. The experiment will cease data taking in 2022 with the analysis of the full dataset completed by 2024. The UK has several key responsibilities, for example, the straw tracker. There will be a modest request for further funding in the next CG round to cover the end of the exploitation period of the experiment. There is a proposal for a new experiment at PSI that will improve the sensitivity to the electric dipole moment of muon by a factor of 100 compared to the Fermilab experiment. Should this LoI be favourably reviewed, a UK LoI will be submitted to STFC for the project in 2021. First data taking could be expected in 2025/26.

The second strand of the precision muon physics programme is related to the search for lepton flavour violation with the Mu2e experiment at Fermilab via a muon-to-electron conversion process in the field of a nucleus, $\mu^- N \to e^- N$. Commissioning will start in 2022 with physics exploitation from 2024. Data taking will continue until 2030, with a 30 month shutdown for an accelerator upgrade required for DUNE. An upgrade is planned from around 2032 that will increase the sensitivity by an order of magnitude. The UK is solely responsible for the stopping target monitor detector, DAQ, slow-control and large parts of analysis modules. It is also utilising expertise from the g-2 experiment to optimise the reconstruction and alignment of the straw tracker.

There is also UK involvement in the COMET $\mu^- N \to e^- N$ conversion experiment being built at J-PARC. Commissioning is foreseen in 2022 with data-taking in 2023, improving the current sensitivity by a factor of a hundred in the first phase and further factor of a hundred in the second phase. Physics exploitation would extend until the late 2020s. COMET is funded in the UK via the STFC Newton Fund and Horizon 2020. The UK has responsibilities in the DAQ/triggering/software and beam. There is a proposal for a follow-on experiment (PRISM) developed in synergy with worldwide accelerator and detector developments, with UK leadership, which would extend the sensitivity by a further two orders of magnitude. A decision on PRISM is foreseen towards the end of this decade.

Finally, the Mu3e experiment at PSI will search for charge lepton flavour violation using the decay $\mu \to 3e$ with the aim to reach a sensitivity to branching ratios of 2×10^{-15} in its first running. Detector commissioning will start in 2023 with running for three years from 2024. A second phase of the experiment is dependent upon a further upgrade to the detector and beam during the late 2020s and would have a sensitivity below 10^{-16}. The UK is responsible for clock distribution, and the outer and curl layers of the MuPix sensor-based tracker. The latter has a synergy with the LHCb Phase 2 upgrade programme. Mu3e is supported by a PPRP grant till September 2021. Support beyond that date will be requested in the current CG round and beyond.

Recommendation 5.3: The UK should exploit its investment in the ongoing round of precision muon experiments and seek opportunities to support and invest in future charged lepton flavour violation experiments, targeted such that it exploits its expertise

and technological interests. The UK should aim to consolidate its involvement in future muon-electron conversion experiments, taking into account the global situation as regards the activity and synergies with accelerator and detector development.

5.4 Electron and Neutron Dipole Moments

Measurements of electron and neutron EDMs are exceptionally sensitive probes of new physics. They provide direct, background-free searches for BSM physics up to very high scales. Current model-dependent limits constrain new physics at energy scales up to 30 TeV. The next generation of experiments will improve on these by two-orders of magnitude.

The UK has long been at the forefront of electron and neutron EDM measurements. However, over the last decade the constrained nature of UK funding has meant that STFC support has been limited to CG academic time. For the neutron EDM, there is UK involvement in both the n2EDM experiment at PSI that is in the commissioning phase, and the cryogenic EDM experiment at ILL which will be fully operational from 2025.

Measurements of the electron EDM are being made by the UK Ultracold eEDM experiment. Construction of this experiment will take place over the next year leading to a programme of exploitation and upgrade over the next decade. This will lead to a measurement of the electron EDM at the 10^{-31} e cm level and improve constraints on P,T-violating electron-nucleon interactions. The experiment is funded by a PPRP grant.

Recommendation 5.4 The UK should exploit its world class expertise in EDM science and its investment in EDM experiments. The UK EDM community should evaluate the wide-range of EDM experiments world-wide so as to converge on the opportunity that maximises the chance for discovery.

6 Neutrino physics

The 2020 ESPP update identifies experimental neutrino physics as a high priority area in the quest to address the shortcomings of the Standard Model. In the next 20 years the key questions for neutrino physics are measuring the parameters that govern neutrino mixing, establishing whether the neutrino is its own anti-particle (i.e. whether neutrino is a Majorana or Dirac particle), measuring the absolute masses of neutrino states and understanding whether a sterile neutrino could contribute to anomalies in oscillation data observed by some experiments.

Answering these questions will have profound implications for particle physics. The currently unknown mixing parameter δ_{CP}, which governs the level of CP-violation in neutrinos may be linked to the observed matter-antimatter asymmetry of the Universe. The establishment of neutrino as a Majorana particle would open the way to understanding the neutrino mass generation mechanism, completely different to the Higgs mechanism and explaining the smallness of neutrino masses.

The UK has a large neutrino community with many world-leading contributions and interest in a number of future projects.

The observation of neutrino oscillations indicates that neutrinos possess a finite neutrino mass and mix, calling for a new physics scale, new particles and interactions. The UK has been an active player in this area in the past 20 years. It has recognised, world-leading expertise and has made strong contributions to key projects. It plays a prominent role in the currently running NOvA and T2K experiments and has significant leadership in the two future flagship neutrino oscillation experiments, DUNE and Hyper-Kamiokande (Hyper-K).

The Fermilab based experiment, NOvA will run until 2025/6 tripling the current exposure in both the neutrino and anti-neutrino beam and providing accurate measurements of a number of oscillation parameters and significant sensitivity to the neutrino mass ordering and CP-violation. The UK community has leveraged its expertise to spearhead physics studies in 3-flavour oscillation analysis and neutrino-nuclear interactions.

The T2K experiment based in Japan has provided significant results in neutrino oscillations including some interesting hints on CP-violation with UK groups playing a critical role in flagship oscillation and neutrino-nuclear interaction analyses. The UK delivered substantial elements of the ND280 near detector and the neutrino beam target. The UK community has significant leadership having provided two of three international Co-Spokespersons. The upgraded version of the experiment, T2K-II, will run until 2026.

The NOvA and T2K experiments, operating at different neutrino beam energies and different baselines, provide an important complementarity that boosts the sensitivity of the physics they address. By 2026-28 NOvA and T2K between them could provide evidence of a non zero δ_{CP} and an indication of the neutrino mass ordering at around 3σ level, depending on the true value of the parameters. Significant gains can be made by combining the two experiments' datasets and the UK community is strongly engaged in this process.

Future long-baseline neutrino oscillation experiments

An almost complete coverage of the parameter space for CP-violation and neutrino mass ordering at a 5σ level will be provided by the next generation experiments, DUNE in the US and Hyper-K in Japan. In addition, these major experimental endeavours will act as general purpose observatories. Both DUNE and Hyper-K will be the largest and most sophisticated neutrino detectors underground offering, in addition to long-baseline neutrino oscillations, sensitivity to a range of new physics phenomena and astrophysical processes, such as the proton decay, neutrinos produced by core-collapsed supernovae, solar and atmospheric neutrinos etc.

DUNE is top priority for the US High Energy Physics programme with a $2.6 billion investment from US funding agencies. It is also a flagship future neutrino physics programme for the UK. Substantial government capital funding (£65M) has secured a major part of the project for the UK that includes contributions to PIP-II SRF cavities, neutrino target, anode plane assemblies for the first two modules, leadership of DAQ and establishing UK as a chief developer of the neutrino interaction reconstruction software framework. The UK has provided two international Co-Spokespersons.

The establishment of the CERN Neutrino Platform, strongly influenced by the previous ESPP update in 2013, has allowed Europe and the UK in particular to become key players in the DUNE programme. The UK played a leading role in the successful realisation of the ProtoDUNE programme that demonstrated the feasibility of very large liquid Ar TPC.

The UK is also involved in MicroBooNE and SBN experiments at FNAL. These detectors provide the necessary step in a phased programme towards the construction of kiloton-scale liquid Ar TPC detectors for DUNE. In addition, they have an important science programme to address current anomalies pointing towards the possible existence of a sterile neutrino and provide much needed data to constrain neutrino-nucleus interaction cross-sections.

Building on its T2K involvement the UK is a major international partner in the Hyper-K project that will use a water Cherenkov detector with a fiducial mass of 187 kT and an upgraded J-PARC neutrino beam. The experiment was approved in the host country, Japan, in 2020 and the construction of facilities has commenced. Hyper-K plans to start data taking in 2027 with physics exploitation extending over a period of 20 years. Hyper-K will have the highest sensitivity to the neutrino CP-violation phase. It will be the most sensitive detector for the proton decay in the "golden channel" ($p \to \pi^0 e^+$). Leveraging its expertise the UK has a major involvement in critical areas of Hyper-K: the Hyper-K Outer Detector (OD), DAQ and calibration tools for OD and Intermediate Water Cerenkov Detector (IWCD), high-power target design, as well as leading a number of physics studies.

The 5σ coverage of the CPV and mass ordering parameter space with DUNE and Hyper-K requires uncertainties on neutrino fluxes and interaction cross-sections to be reduced to a few percent level. This is one of the major areas of UK expertise and focus in the currently running experiments NOvA and T2K, as well as in SBND. UK teams are also spearheading the design and physics studies of the nuSTORM project, as discussed in Section 4.2.3. In addition, UK members are involved in the NuSTEC initiative that promotes collaborative work between Nuclear Physics and PP communities, both theory and experiment, to improve our understanding of neutrino interactions with nucleons and nuclei.

Finally, we note that new initiatives are arising to study the interactions of high-energy neutrinos produced at a collider. The ForwArd Search ExpeRiment (FASER) experiment at CERN, designed to extend GPDs and LHCb searches for light and weakly-interacting particles at the LHC in the far-forward region, has been recently complemented with FASERν, an emulsion detector sensitive to neutrinos in the GeV-TeV energy range. A similar proposal, Scattering and Neutrino Detector at the LHC (SND), has been approved by CERN to exploit another underground tunnel connecting the LHC to the Super Proton Synchrotron, and it will start recording data in 2022 like FASER. Both FASERν and SND allow for detailed studies of ν_e and ν_τ at the highest energies yet explored and ν_μ neutrinos in a currently unexplored energy range between experimental data available from accelerator neutrino experiments and astrophysical neutrino observatories such as IceCube. Both experiments foresee a possible upgrade for the HL-LHC. The UK has some involvement in these initiatives, and should ensure that opportunities in this area are exploited further in the next decade.

Recommendation 6.1: The UK should maintain its leading role in long-baseline neutrino oscillation experiments. Exploitation of the currently running experiments should be supported. In the next 10-20 years the main priority will be on measuring the CP-violating phase of the mixing matrix and the neutrino mass ordering with the long-baseline programmes in Japan and USA. The UK should continue to engage with both programmes. In particular, it should maintain its leading involvements in LBNF/DUNE.

Recommendation 6.2: To extract the most physics out of the long-baseline neutrino experiments the UK should build on its existing expertise to pursue a complementary programme of precision measurements of neutrino interaction cross-sections and neutrino fluxes. In addition, recently emerged opportunities of detecting collider neutrinos, that allow measuring neutrino cross sections at energies where they are currently unconstrained, should be pursued.

6.1 Determination of neutrino mass and nature

At present, the only feasible way to prove the Majorana nature of neutrinos is to observe the rare neutrinoless double beta decay ($0\nu\beta\beta$) transition. There are strong technological and physics synergies with DM experiments, primarily in ultra-low background aspects and underground laboratory infrastructure. There are also significant synergies in detector technologies with nuclear physics.

The UK has strong leadership and expertise in this area. It has had a major involvement in the NEMO-3/SuperNEMO and SNO+ experiments, and more recently in the LEGEND experiment. SuperNEMO will take first data in 2021 and run until 2025 reaching a sensitivity to the Majorana neutrino mass, $\langle m_{\beta\beta}\rangle$, at a level of 0.2-0.4 eV and, crucially, will provide unique measurements of $2\nu\beta\beta$ that will shed light on the underlying nuclear mechanism and potentially constrain the quenching of the weak axial-vector coupling, g_A. SNO+ will begin physics data taking in 2022 reaching a sensitivity of 40-150 meV in 5 years in its first phase. Further upgrades with higher Te loading and improvements in detector performance may allow this technology to push the sensitivity further towards 10 meV. The SNO+ has a broad science programme including solar neutrinos, reactor and geo anti-neutrinos, and supernova neutrinos. LEGEND-200 will start physics data taking in late 2021 and will reach a 3σ discovery sensitivity to $\langle m_{\beta\beta}\rangle \sim$ 28-57 meV by 2026/7. Its next phase, LEGEND-1000 will require a new underground infrastructure. It will have a 3σ discovery sensitivity of 9-18 meV in 10 years of running fully covering the inverted neutrino mass ordering and exploring a significant range of the parameter space for the normal ordering. The UK has provided leading contributions to all three projects (tracking detector and radio-purity assays in SuperNEMO, Te-loading and calibrations in SNO+, detector characterisation and analysis framework in LEGEND).

Presently, there is an ongoing effort between Europe and USA, to coordinate the selection of 2-3 future "tonne-scale" $0\nu\beta\beta$ projects. In Europe, the Astroparticle Physics European Consortium (ApPEC) has identified a roadmap for the field focusing on the most prominent projects with strong European leadership: CUPID, LEGEND and NEXT. In the US, the Department of Energy initiated a portfolio review in summer 2021 to select the next $0\nu\beta\beta$ project for funding among CUPID, LEGEND and nEXO. A joint North American – European summit is planned for Sep-Oct 2021 at LNGS to coordinate the funding effort across the Atlantic.

Recommendation 6.3: The study of the neutrino mass nature (Dirac or Majorana) and its absolute value is the other key priority of the field. The UK should continue to support its current engagement with $0\nu\beta\beta$ experiments entering the exploitation phase. Going forward, the UK should leverage its expertise and technical capabilities to actively engage with international strategies, being formulated in Europe (APPEC), the US (DOE) and Asia, that aim to cover the inverted neutrino mass ordering parameter space, and should consolidate around the $0\nu\beta\beta$ experiments with the most promising discovery potential on the shortest timescale, and where the UK can have the maximum impact.

While the main focus of the $0\nu\beta\beta$ field is currently on covering the inverted ordering of neutrino masses (10-20 meV), the technology used in these upcoming experiments may not always be scalable to increase the sensitivity further to address the normal ordering scenario (1-10 meV). A rigorous R&D programme is necessary to understand modifications needed for existing technologies, or to identify completely new techniques that can lead to <10 meV sensitivity in case of the absence of a signal in the next generation experiments.

The most model independent way of measuring the neutrino mass is by analysing electron spectra near the end point of a beta decay. The effective electron neutrino mass measured by this method can not be smaller than 50 meV and 9 meV for the inverted ordering and normal ordering respectively (while the current upper limit from the KATRIN experiment is 0.8 eV). The UK has become involved in these studies under the recently established UKRI QTFP programme. The long term aspiration of the programme is to capitalise on recent advances in quantum sensors to reach a phased sensitivity to the absolute neutrino mass measurement from ^{3}H β-decay of 100 meV→50 meV→10 meV.

Recommendation 6.4: The UK should continue to pursue an R&D programme that can address the questions of the nature and absolute value of the neutrino mass within the normal ordering with $0\nu\beta\beta$ and single-β decay experiments using latest advances in particle detectors, quantum sensors and data processing technologies.

7 Dark Sector

Dark Sector physics has emerged as a strongly compelling area of PP and cosmology. The Dark Sector, encompassing DM, dark energy, and a wide variety of hidden sector theories, inherently crosses borders between PP and astronomy, as well as utilising detector technology developed in quantum and solid state physics.

The UK has long provided internationally recognized leadership in Dark Sector experiments, and an increasing number of UK researchers have joined dark sector collaborations. UK involvement has grown in both large experiments pursuing > 5 GeV DM, and in smaller scale collaborations utilising quantum technology, several of which are planned to operate in the UK. Compared to other fields, experiments in this area have relatively faster timelines and smaller budgets.

The Dark Sector uniquely spans astronomy and PP, and involves experts in technologies and materials usually supported by the EPSRC. Growth in funding this area at a national level will require coordination between multiple stakeholders. Such effort is well motivated by the underlying questions of the fundamental constituents of the universe, as well as technology development and training provided in this area. PP experiments are well positioned to take advantage of a broader expansion of funding to the dark sector.

7.1 Particle Dark Matter

UK leadership in weakly interacting massive particle (WIMP) searches is long established. For the high mass canonical WIMPS of masses over 5 GeV, the UK is a major participant in the liquid argon and xenon programmes. The liquid xenon LUX-ZEPLIN (LZ) detector will be in exploitation from $2021 - 2025$, and the liquid argon DarkSide-20K detector will be in exploitation $2025 - 2030$. However, the fast pace of this field leaves little downtime for exploitation analysis activities. A next generation xenon experiment could begin data taking in 2030 and a next generation argon experiment could be in operation soon thereafter. Maintaining leadership in these international projects requires continued detector development during earlier exploitation phases. In this area of new proposals, projects must demonstrate their uniqueness, complementarity nature and/or world-wide competitiveness, in addition to having critical mass if the project is brought forward.

These experiments are also more than simple WIMP DM detectors and, as they grow, so do their science portfolios and broader impacts. These techniques are also sensitive to lower mass or electrophilic DM candidates, and solar and astrophysical neutrino detection and novel neutrino properties. Xenon offers multiple target isotopes, especially ^{136}Xe, for neutrinoless double-beta decay. The liquid argon programme has ties to the Si detector community and industry, as well as the neutrino-beam field.

The 2020 ESPP update states in point 4A, *'The quest for dark matter and the exploration of flavour and fundamental symmetries are crucial components of the search for new physics. A diverse* *programme that is complementary to the energy frontier is an essential part of the European particle physics Strategy."* The PP Programme Evaluation was in agreement with this recommendation.

Commonalities in detector technology also allows for shared resources, most notably in radio-assaying for low background experiments, an area that has leadership in the UK. Past capital support continues to require expert personnel to realize the full utility of the radio-assay programme.

Low mass DM candidates have drawn additional interest from theorists in the last decade. In direct detection, new techniques and technologies are being developed both independently and as outgrowths from other projects. This is an area of study that may quickly grow for smaller scale experiments which may be built and operated in the UK fairly economically. Boulby Underground Laboratory is a key facility for this research, as well as supporting higher mass WIMP searches and a wider science programme. The outcome of the ongoing feasibility study should inform the long-term strategy for the Boulby Underground Laboratory as a potential host facility for future major international rare event search experiments.

Recommendation 7.1: The UK should maintain leadership during R&D, construction and exploitation of Direct DM Detectors over a wide range of DM masses that demonstrate their uniqueness, complementarity, or world-wide competitiveness, and should seek opportunities to grow funding to support projects, including those planned to be constructed within the UK.

7.2 Wavelike Dark Matter and the wider Dark Sector

Dark Sector candidates beyond the WIMP include lighter mass wavelike options including the QCD axion, dark photons, scalar particles, and a variety of models that span several orders of magnitude in mass. Theoretical models continue to be developed and provide motivation to explore new parameter spaces; the models worthy of investigation and technology capable of accessing them will continue to evolve over the next few decades.

Many promising techniques for detection depend upon advances made in quantum sensing, and the recent UKRI Strategic Priorities Fund in QTFP, a part of the National Quantum Technology Programme (NQTP), has initiated projects that include expertise from both STFC and EPSRC. With international partners, these novel UK projects are ambitious with their technology and sensitivity to new physics, and are seeking construction in the UK.

In the search for DM, these experiments use atomic interferometers, a network of atomic clocks, microwave cavities and low-atomic-mass, low-temperature targets with quantum sensors to search for axion-like, scalar, and very light particle DM. These experiments are also sensitive to new parameter spaces of gravitational waves, models of gravity, and the underlying cosmology. These studies are strongly tied to the particle astrophysics field. Quantum-enabled experiments can also probe exotic fundamental physics such as time variations in the fine-structure constant and the electron-proton mass ratio, and the holographic or quantised nature of space-time. Some of the QTFP initiatives, for example the Atom interferometric Observatory and Network (AION) project in the UK and the MAGIS-100 experiment at FNAL, are large-scale particle-physics-like experiments that enter physics exploitation in the next few years, and have long-term goals to build km-scale terrestrial and future space-based detectors.

Recommendation 7.2: The UK should secure future support outside the current STFC core programme (for example NQTP or other cross-UKRI funding) of dark sector experiments based on successful demonstration of quantum technologies seeded by the QTFP programme. If a growth of funds is not achieved, pursuing the broad

scientific goals in the dark sector will need to be tensioned with other areas of the core programme.

7.3 Complementarity to other areas

Dark Sector studies are strongly linked to multi-messenger astronomy and cosmology. Evidence for DM comes from astronomical surveys, and indirect detection through DM annihilation to SM particles provides a third complementary method for searching for DM particles. Gravitational waves also probe the matter distribution of the universe. The discovery of DM at direct and indirect detection experiments is necessary to ascertain the cosmological connection if there is a collider discovery, which in turn could provide information on the nature of the DM–SM interaction.

The comparison of sensitivities across direct detection, indirect detection and collider experiments is possible within a given theoretical framework, and strongly depends on the choices of model and parameters. These comparisons nevertheless give an idea of the potential parameter space for a DM discovery if DM is realised in one of those example models. For instance, the complementarity of collider and indirect detection searches within the wino and higgsino DM models is most evident at relatively high mass. Interestingly, the cross section of many of these models would be lower than the neutrino background for direct searches, emphasising the need for different experimental approaches. In addition, above 10 GeV DM mass, next-decade direct detection experiments are more sensitive than future colliders to DM signals. Future collider experiments, instead, are well suited to explore models with mediators decaying to lighter DM candidates as well as possibly reaching DM masses up to a TeV from the decays of multi-TeV-mass mediators. In the intermediate DM mass range the combination of future high-energy colliders, direct detection and indirect detection programmes will complement each other and shed light on the nature of a DM candidate at reach in the next decades.

Non-collider smaller experiments which depend upon the (HL-)LHC complex and are currently under construction (FASER, and the recently approved SND) also offer complementary coverage to the dark sector, especially for dark photons, dark scalars, axion-like particles and heavy sterile neutrinos. Plans for upgrades of these detectors are under consideration by CERN, and their added value for the UK GPDs and direct DM experiments programme should be examined carefully.

Another technique to explore the dark sector utilises accelerator-based beam-dump experiments to search for long-lived WIMP and dark sector particles like dark photons. Designed for this purpose, the projected sensitivity of such projects, most notably NA62 but also the Beam Dump Facility at the SPS, SHiP, would be world-leading across multiple portals. Though SHiP is funded by CERN for R&D and there is UK leadership, the deliberation document of the ESPP notes, a beam dump facility at the SPS as required for SHiP *'would be difficult to resource within the CERN budget, considering the other recommendations of this Strategy'*.

Finally, dark photons and axion-like particles can be sought in high electromagnetic field environments, such as those in the electron beam and laser of the LUXE experiment, currently under design. This project, planned to be located at DESY, is primarily focused on strong-field non-linear QED, which itself has astrophysical implications.

Combining direct and collider search results has been a very successful avenue to constrain new physics. A similar approach should be used for a wider range of DM searches. The international dark sector community of experimentalists and theorists demonstrates the need for greater shared understanding and dialogue.

Recommendation 7.3: The UK community of theorists and phenomenologists, collider

experimentalists, and direct and indirect detection experimentalists should establish a interdisciplinary programme to explore a synergic approach in DM studies, with greater communication and idea exchange.

8 Theory

Theoretical high energy physics is an essential part of research into PP and it provides a compass for far-future experimental research directions. A healthy theoretical PP programme requires breadth and flexibility since the subject is fast changing and aspects are unpredictable on long time scales. It provides support for the experimental programme in terms of the precise calculation of observables, as well as guidance as to which processes may be illuminating to search for or measure. It is via theoretical physics that bridges are built between high energy physics and other scientific areas such as nuclear physics, cosmology, gravitational research and condensed matter physics.

We follow the 2020 ESPP recommendation *'Europe should continue to vigorously support a broad programme of theoretical research covering the full spectrum of PP 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.'*

The UK has strengths across most areas of theoretical PP, whose topics can be categorised as more formal theory or phenomenology. On the phenomenological side, there is a vibrant programme in the UK. Some phenomenological work in the UK (particularly event simulation and data interpretation) cuts directly across both theoretical and experimental PP, adding value to the PP programme. The 2015 STFC phenomenology exercise identified several areas which remain UK strengths today: Monte-Carlo event generation, lattice and analytic QCD, Higgs measurements, searches for new physics and associated model building, computational software and parton distribution functions. Standard Model flavour phenomenology is one area that has recently diminished and could benefit from more support. This would act as a scientific impact multiplier for the large UK experimental effort in this area. A national centre for phenomenology (currently the IPPP in Durham) plays an important role, providing both leadership and a mouthpiece for UK phenomenologists. It also supports and links the experimental and theoretical communities.

Recommendation 8.1: The UK's world class strength in phenomenology, which aids the UK's experimental programme, should continue to receive robust support. A national centre for particle phenomenology is a scientific impact multiplier and should remain a priority.

Lattice QCD remains an essential ingredient for extracting Standard Model measurements, particularly in flavour physics, and is another area of strength of the UK programme. Lattice field theory enjoys attention in the wider UK theoretical physics community. The wider lattice community and the lattice QCD communities benefit from sharing computing resources, *e.g.* DiRAC (Distributed Research utilising Advanced Computing) in order to enable this. The recently started STFC Virtual Centre for Lattice Field Theory provides a useful point of contact and activity in the area.

Recommendation 8.2: Lattice QCD plays an crucial role in particle physics and the UK should continue to support the world class UK contribution as well as the required computing facilities.

On the formal side of STFC theoretical physics, there is leading expertise in more mathematical aspects of quantum field theories such as the AdS/CFT correspondence, string/M-theory and on quantum gravitational theory. The UK has made significant and innovative contributions to these areas in recent history; one highlight is the development of the double copy of gravitation, coming from scattering amplitude techniques, revealing a simpler hidden side to gravity and enabling more accurate computation of gravitational wave signatures from black hole mergers. Formal theory can lead to paradigm shifts and so can be particularly important for the long-term direction of the subject. The recently started STFC Fundamental Physics UK Virtual Centre provides a useful point of contact and activity in the area. More mathematical aspects of the fundamental physics programme have sometimes fallen, in harsher funding environments, in between the remit of different panels both within STFC and between different UKRI councils, despite being considered to be important. Within STFC, mathematical work in the area between cosmology and PP has sometimes had this problem, for example. Work on the cross-over between string theory, formal quantum field theory and condensed matter theory has also often fallen between the cracks of STFC and EPSRC.

Recommendation 8.3: STFC should support the already strong and broad formal fundamental theoretical physics programme (including mathematical aspects) to seed paradigm shifts and/or exploit current developments. STFC through UKRI should consider how best to prevent some areas of mathematical work 'falling between the cracks' of different panels and research councils.

There are emergent opportunities in the exploitation of quantum technologies (for example quantum computation) to answer fundamental questions in PP. Members of the UK STFC theoretical physics community are interested in studying (for example) lattice field theory, false vacuum decay and axions around black holes using such technologies. Current seed funding is producing useful nascent work in this direction (see, for example, the pro-forma Quantum Simulators for Fundamental Physics submission), and effort would be well-placed in enabling these new directions and cross-overs to develop into the medium-term future, where the activity is expected to grow in importance and maturity.

Recommendation 8.4: UKRI and STFC should consider how best to enable ongoing development in the exploitation of quantum technologies to help theory answer fundamental physics questions.

9 Technology and skills

9.1 The role of technology for Particle Physics

Unlocking the potential to contribute to fundamental science discoveries requires that the UK community provides a significant contribution to the instruments and facilities that are used to achieve those scientific goals. These endeavours are collaborative spanning university, national laboratory and industrial sectors across the UK. This allows for essential multidisciplinary collaborations of technicians, engineers and physicists to ensure that instruments are designed, constructed and operated to fit scientific goals. The community benefits from advances in other relevant science and technology fields, for example from the QTFP programme. This has launched seven projects that utilise new technologies to probe many of the physics challenges. The STFC should continue to engage with the community to horizon scan for future opportunities, and to support generic R&D on the CG, that provides agility for university research groups to engage with an appropriate level of high-risk, high-gain technology development. This is aligned with UK policy[6] and allows researchers to leverage funding and expertise from other sources. There are several committees established in this area with which the community is engaged (see Section 9.2 for more detail).

The knowledge, skills and understanding required for PP projects are highly valued in industry, providing an opportunity for fundamental science to support and maintain a valuable skills pipeline. Data science is ubiquitous across all phases of projects, from conception through to harvesting scientific results for publication. This includes computing infrastructure (high performance and high throughput, HPC and HTC, respectively), and software development. Simulated data is a vital part of validating the performance and accuracy of hardware systems, of analysis codes and methods used. The technical and engineering skills required to construct new instruments are varied in scale and scope. Often new solutions are developed that push the limits of capability. This spans a diverse range of areas from all forms of sensor technology, services, interconnects, electronics and even the materials used in each of those components and assemblies. New projects often present challenges in data rates that demand progress in the field of computing.

A vital function of universities and national laboratories is to train people with valuable transferable skills for research and industry. National laboratories also provide access to unique central facilities essential for project completion, and a diverse set of technical expertise that can be called upon as required. STFC should incentivise universities to support the career path for researchers in this area.

UK industry plays an important role, both in collaborative research and as a part of the wider supply chain. Supporting ways to strengthen that relationship will ensure UK industry is well placed to leverage commercial opportunities from the scientific sector and generate intellectual property.

With experiments that have long design, construction, and operation lead times, there is a need to explore ways to ensure the UK maintains its core expertise in instrument integration. This is an essential task, not to be overlooked because of its largely technical nature.

Innovative accelerator technology underpins the physics reach of many PP experiments, including colliders, accelerator-driven neutrino experiments, etc. It is also a powerful driver for many accelerator-based fields of science and industry. Accelerator developments in turn feed back into the need for developments in instrumentation that have many industrial benefits. The UK community should continue and support the R&D programme on technologies such as high-field magnets, high-temperature superconductors, plasma wakefield acceleration and other high-gradient accelerating structures, bright muon beams, energy recovery linacs, and the instrumentation required to fully harvest the benefits of those new technologies for science. The PP community has a long tradition of using simulation [7] to optimise its bespoke instruments. Such tools are vital to ensure that instruments remain functional over the full life cycle of a given project and usages include predicting performance, understanding operating environments through to validating analysis methods used for science that is harvested.

9.2 Synergies

The UK community has excelled in the application of new technology to fundamental science, and that forward looking exploration continues with the QTFP programme. This is also evident

[6]Global Britain in a Competitive Age: the Integrated Review of Security, Defence, Development and Foreign Policy

[7]The PP community uses simulation models extensively for understanding sensor performance, circuit designs, mechanical and thermal stability of structures, right through to simulating large quantities of synthetic data required for data analysis.

with members of the community working in collaboration with companies to develop new types of sensor and to improve existing technologies, and similarly in regard to cutting edge DAQ and trigger activities. PP technology has application in sectors of applied science and other areas of the STFC portfolio, as well as having synergies with UK industry and public sector needs. One specific example is understanding radiation environments and materials testing capability. These skills can be used by space, the nuclear industry and in medicine amongst others. The UK currently has world leadership in this area through work with CERN for the HL-LHC, and that lead should be maintained. PP tools developed for simulation to determine radiation fields, such as FLUKA and GEANT4, are widely used in the medical and nuclear industries. Similarly, data obtained from materials testing for the HL-LHC is unique and of value to UK industry. The community explores opportunities to ensure translation of PP knowledge for the wider benefit of the UK wherever practicable. The next generation projects requires development of novel, efficient, and fast methods for the UK to maintain leadership in this and other technology areas over the coming decades. The skill sets and capability of the STFC instrumentation community is aligned with areas of the EPSRC portfolio, for example the Energy and Quantum Technologies themes. The PP data science capability is ubiquitous across the EPSRC portfolio. This presents opportunities for impact generation and cross-cutting research for both STFC and EPSRC.

9.3 Computing and data science

Exascale computing challenges cut across scientific disciplines, including PP, astronomy and nuclear physics, and the community actively engages with sectors that have similar challenges to ensure that investments are harmonised across the STFC portfolio. Both the GridPP and IRIS programmes have a successful track record in this regard. The community also has the forward-looking SWIFT-HEP activity targeting this issue. Commercial and other non-STFC long-term research endeavours face similar exascale computing challenges and knowledge transfer between scientific fields and industry should be encouraged. The long track record of data-centric engineering in PP instrument and accelerator design places the community in a unique position to lead on or help guide the development of novel instrumentation in other fields. Both HPC and HTC requirements exist for the PP community, and it is important appropriate levels of resource and expertise be maintained for both. The Excalibur strategic priority fund programme supports exascale computing developments in the UK, and the SWIFT-HEP project has focused efforts on developing new methods for efficient computing. The UK lacks the level of investment seen in some other countries, such as the US and its IRIS-HEP community hub programme. There is scope for an equivalent model of investment in the UK if the core funding for the programme were to increase.

Data processing and a wide range of Machine Learning (ML) and AI methods (including Deep Learning) are a core part of the toolkits required for PP analysis. These methods enhance PP scientific output in accelerator, experimental and theoretical areas. The community has a role to train new generations of experts in data science in concert with industry to the benefit of the UK economy. The rapid development of data science necessitates implementation of comprehensive continuing professional development (CPD) opportunities for early career researchers. Other technology areas also have CPD requirements, however those areas generally experience a more modest rate of change. There are synergies with the EPSRC that can lead to impact, and PP has some unique data science problems related to the interpretability of results. Solutions to this issue may have applications outside of PP. Where possible, software developed for the STFC programme should be released under open source licenses to maximise the potential for impact and help the STFC community engage with other data science engineering fields.

9.4 Funding ecosystem

The long-term viability of technology generation relevant for future PP infrastructure projects needs a carefully thought out ecosystem ranging from more speculative low-TRL concepts through to those that can be matured over time to align with an STFC infrastructure project investment. That ecosystem should be compatible with the existing impact offerings such as IPS, CLASP, Innovate UK etc., in order to maximise the benefit to the UK economy as well as UK science. However scientific and commercial drivers are usually different and one can not simply rely on the existing commercialisation routes to fulfil an equivalent role for technology development for scientific application. Other countries have schemes that provide appropriate continuity for technology development, and UKRI would benefit from working with STFC and the community to find a viable solution to realise the full potential of the PP community to impact on the Global Britain policy.

9.5 Skills

PP relies on technical expertise from an aging workforce, and researchers often command a higher salary in industry than academia. The community needs to maintain a sufficient pool of opportunities for technical and physics researchers to maintain critical mass for fundamental science, and to feed the skills pipeline demands of the UK public sector and industry. Careful consideration of appropriate CPD opportunities and incentives for staff retention is essential to underpin the future leadership of the UK PP community. The STFC is encouraged to consider possible incentives to help the community maintain an appropriate career pipeline for technical, engineering and physics staff for design, construction and operation of instruments. One possible way to do this would be to allow for technical apprentices to be included on project grant applications. The existing core post component in the consolidated grant plays a vital role and helps achieve this goal. Several gaps have been identified including a lack of technical schools targeting PhD and early career researcher audiences to provide CPD. There is also a clear need for a specialist capability of expert Research Software Engineers (RSEs). These roles, in analogy with engineering posts, are focused on software design, implementation, and operations. Unlike the physicist programme role the RSEs do not engage with harvesting results from data. Core positions complement responsive posts for projects and exploitation that provide a mechanism for the community to be agile with resource allocation in order to respond to new opportunities. In particular long term instrument operation and data harvesting relies on a sustainable pipeline of experts who often have unique skill sets and are hard to replace.

9.6 Recommendations

We start by re-iterating two relevant recommendations from the previous report, before continuing with a set of new recommendations related to technology.

Recommendation 9.1: There is a systemic problem with career paths in detector and computing areas. STFC should consider initiatives that provide incentives for Universities to retain such academics, while maintaining paths through the national labs.

Recommendation 9.2: It is important that basic R&D be continued in accelerators and detectors to support the long-term programme. STFC should facilitate access to funding opportunities for these activities, where possible using external funding

streams.

Our new recommendations are as follows:

Recommendation 9.3: The core funding component of the consolidated grant programme provides an important path for career progression of scientists and engineers who have vital skills required for instrument development and operations. An equivalent path for research software engineers should be established, on a par with the established engineer core roles to provide balanced support.

Recommendation 9.4: Alternative funding streams for additional PhD students working on the strategic technical priorities of the community should be sought to maintain this pipeline in line with the needs of scientific goals and industry and public sector stakeholders. In parallel STFC should consider ways to incentivise universities and national laboratories to strategically manage technical staff attrition to retain capability and capacity of the community when individuals leave the field.

Recommendation 9.5: The STFC should continue to invest in areas of strategic importance to maintain leadership, such as accelerator technology for high energy and high intensity beams, detector technology for colliders, fixed target, neutrino and dark matter experiments. This includes infrastructure, instrumentation, computing, software, and data science technologies.

Recommendation 9.6: The UK should continue to support both high performance and high throughput computing in line with the evolving needs of the theoretical and experimental community.

Recommendation 9.7: The UK should continue to invest in new techniques, such as quantum technologies, to explore radically new ways to address fundamental particle physics questions. It should consider establishing a sustained funding stream to seed development of emerging technologies and to solve the technical requirements for the next generation of instruments needed for future experiments.

Recommendation 9.8: Where possible software developed by the UK PP community should be released as open source, and effort to maintain open source tools should be regarded as fundable and related to the wider impact agenda.

10 Links to other areas and panels

The UK Particle Physics community has strong links with the Nuclear Physics community. There is an opportunity to strengthen these in the context of the EIC, and capitalise on UK expertise to maximise physics exploitation. The EIC concept is to build the first ever collider of polarised electrons with nuclei or polarised protons. The target centre of mass energy (20 – 140 GeV) is substantially smaller than that achieved at HERA, but the target luminosity is foreseen to be 1000 times higher. Though the scope of the physics is largely in the nuclear physics domain, significant elements of hadron structure and significant technical expertise are of interest to the PP community. There are also synergies with the Nuclear Physics community in areas such as neutrinos and dark matter. As an example, LEGEND has collaboration between nuclear and particle physicists.

Similarly, there are considerable overlaps with the PAAP remit, which is producing an updated roadmap in parallel. Direct DM detection is under the purview of both panels, and the broader non-accelerator dark sector that has grown through the quantum technologies programme includes experiments that address open physics questions in both PP and particle astrophysics. High energy cosmic rays and neutrino astronomy also interface with the parton distribution functions and simulation tools developed by collider and neutrino beam particle physicists.

Strategic advice on accelerator science and technology and their connection to innovation and industry falls into the remit of the Technology and Accelerator Advisory Board (TAAB). Nonetheless, R&D efforts focused on advanced accelerator technologies including high-field superconducting magnets, high-temperature superconductors, plasma wake-field acceleration, energy recovery linacs and bright muon beams are very relevant for the future of particle physics and are part of the community focus for the next 10-20 years.

This year, in response to the 2020 European Strategy for Particle Physics, the Particle Physics Technology Advisory Panel (PPTAP) was convened to produce a roadmap for active technological R&D and skills development. This process has been carried out in close collaboration with ECFA in the case of detector R&D, and the European Laboratory Directors Group (ELDG) for the critical technologies associated with accelerators, which are also producing roadmaps.

The particle physics, astrophysics and nuclear physics communities are involved in the QTFP programme, which is already being exploited to deliver technologies that will serve the future needs of Dark Sector projects, absolute neutrino mass studies, gravitational wave studies and more. The existing close links to ensure the science needs and opportunities feed into the technology planning need to be maintained.

Beyond STFC there are links to challenges faced with the realisation of the next generation of nuclear reactors, space, medicine and national security including defence, through many of the technology areas that underpin PP. Expertise in computing and data science, including AI, has the potential for impact across both industry and the public sector. The community should work with the STFC to realise impact of the field more broadly both on the UK stage and globally.

11 Outlook

This document contains the updated roadmap for UK Particle Physics. As with previous iterations it is a snapshot of opportunities and community interests in time, and should be updated as the situation evolves. The UK has maintained leadership and technological expertise in the field in these challenging times. Compared to a decade ago the community is more diverse and involved in a wider range of projects. Going forward care is needed that UK community does not spread itself too thinly.

As well as maintaining the roadmap, during this process it has become clear that PPAP should proactively undertake sector reviews and horizon scanning exercises in each of the areas discussed in the roadmap. These would involve targeted calls for information and mini-workshops to help identify future opportunities for stakeholders in the community at an early stage, or to preempt emerging opportunities so that the UK can position itself to take the lead globally where appropriate. Such exercises will help area planning and identify future opportunities and synergies so as to focus the communities efforts toward strategic priorities.

Early stage researchers represent the future of the community. To ensure that they have a strong voice and are actively engaged in shaping the vision for their future, it is important to include early career researchers at the PDRA and PhD levels, more directly in community activities. This engagement could be encouraged by the institution of a Early Career Scientist Forum or by having PDRA representation on committees, and can be viewed as an investment in future leaders.

Recommendation 11.1: An *Early Career Scientist in Particle Physics* Forum should be established by the community to help support and represent the views of the PDRA and PhD students in the UK. STFC should consider the inclusion of PDRA-level representation on its panels.

A Consultation process

The consultation leading to this report proceeded via a series of community meetings, and by two rounds of requests for written submissions. The first round of written submissions were to solicit general descriptions of UK activity and interest. These were free format, and combined with topic by topic discussions in a community meeting. The written contributions received are listed in Appendix B. As an output of that process, a proforma response was requested from projects (Appendix C); those pro formas will also be of use to the panel for subsequent reports, and should be refreshed on a regular basis.

A subsequent community meeting discussed putative recommendations that were being considered in the various topical areas. This allowed the community feeling to be tested, and lead to many valuable correctives which have been applied.

A close-to-final draft of the report was circulated to the various CG holders for comment, and to other stakeholders. Their comments have been digested, and in many cases adopted. If there was disagreement that dissent is indicated in the surrounding text.

B Written contributions

The list of written contributions received is summarised below.

- *COMET/PRISM PPAP Update 2020*
- *AION: A UK Interferometer Observatory and Network*
- *The CEPC Input to the Particle Physics Advisory Panel*
- *Input to the PPAP roadmap for Particle Physics from the UK liquid argon dark matter direct detection community*
- *EDM contribution to PPAP roadmap*
- *UK Particle Physics and the Electron Ion Collider*
- *PPAP roadmap input: FCC-ee*
- *PPAP Roadmap input: preliminary FCC-ee resources estimate*
- *FCC-eh and LHCeC - Energy Frontier-Hadron Scattering*
- *PPAP Roadmap Input: FCC-hh*
- *PPAP Roadmap input: FCC*
- *Hyper-Kamiokande Contribution to the PPAP community consultation on European Strategy Outcome*

- *LBNF/DUNE-UK status report for the next update of the PPAP Roadmap*
- *UK participation in the International Linear Collider*
- *The LEGEND Neutrinoless Double-Beta Decay Experiment*
- *LHCb Upgrade II: Maximising HL-LHC Discovery Potential*
- *Light dark matter searches at the Boulby Underground Laboratory*
- *The timely case for a Liquid Xenon Rare Event Observatory*
- *The MAGIS-100 Experiment input to the PPAP update*
- *PPAP Roadmap Input: LHC GPD Experiments*
- *LHCb and LHCb Upgrade II: PPAP 2020 Roadmap Update*
- *Rare decays at the CERN high-intensity kaon beam facility*
- *Nuclear physics and multi-messenger astronomy*
- *Quantum Consortium contribution to PPAP Roadmap*
- *QSNET Contribution to PPAP Roadmap*
- *QTNM Consortium: Determination of Absolute Neutrino Mass Using Quantum Technologies. PPAP Submission 2020*
- *Quantum Sensors for the Hidden Sector*
- *Quantum Simulators for Fundamental Physics contribution to PPAP Roadmap*
- *Input from the SHiP collaboration*
- *The Future of SNO+: A Scalable and Cost-effective Approach to Achieve Sensitivity to the IH and Beyond*
- *Statement to PPAP on HV-CMOS R&D*
- *The SuperNEMO Neutrinoless Double-Beta Decay Experiment*
- *Swift-GridPP contribution to PPAP roadmap*
- *Studies of a Muon Collider and nuSTORM at CERN*

C Proforma contributions

The second element of written consultation was a proforma with the following questions:

- Please give a brief description of the physics objectives of your project (up to 200 words).
- Please give the status (planning/R&D, construction, exploitation, exploitation/upgrade, post data taking) and a timeline of the project from now until up to 20 years time.
- Please state the level of approval both nationally (consortium forming/SOI/Project R&D/Funded/...) and internationally (host lab approval level/funding of international project/etc).
- Please list the UK institutes + academics, ERF/URFs or similar full academics currently involved.
- Please briefly list the spread and scale of non-UK involvement.
- Please state the specific UK interests, highlighting those that are purely UK.
- Please give an indication of the overall cost and cost profile (both to the UK) of your project.
- Please detail the source and duration of existing funding.
- Please indicate your future funding plans.

The received proforma contributions are listed according to their primary area in Table 2.

Table 2: Contributions received by the panel, broken down by area. As underlined in this document the same facility/experiment can contribute to more than one area. For simplicity we list each submission once.

Area	**Submissions**
Colliders	ATLAS, CEPC, CMS, Electron Ion Collider (EIC), FCCe, FCCh, ILC, LHCeC-FCCeh, Muon beams
Neutrinos	DUNE, HyperK, LEGEND, MINERVA, NovA, NuSTEC, SuperNEMO, SND@LHC, SNO+ ,UK-UHEN
Flavour	COMET and PRISM, LHCb and LHCb Upgrade II, Precision Charm at Threshold, muon g-2, Mu2e, Mu3e, NA62, nEDM, Ultracold eEDM
Dark Sector	DarkSide-UK, DarkSphere, FASER-2+ν, LXeG3, LZ
Quantum Technology	Atom Interferometric Observatory and Network (AION), QSNET, Quantum Technologies for Neutrino Mass (QTNM), Quantum Enhanced Interferometry, QUEST-DMC, QSHS, QSFP
Other	Computing (GRIDPP and SWIFT-HEP), Laser Und XFEL experiment (LUXE), SHiP

D Recommendations

Recommendation 3.1: The UK must continue to pursue a world-leading particle physics programme, focussed on addressing the internationally acknowledged high priority science questions.

Recommendation 3.2: The core funding of the programme is essential for exploitation and innovation, but has fallen dramatically in real terms over the last decade. STFC and the community must pursue every avenue to increase the core funding in real terms.

Recommendation 3.3: When new projects are initiated, the downstream impact on the core programme must be evaluated. Scenario planning should be used to help ensure the new programmes strengthen the core programme.

Recommendation 3.4: In the case of continued real terms attrition to the funding, STFC should attempt to maintain minimal capability in areas that are otherwise de-funded, to allow regrowth at a later stage.

Recommendation 3.5: CERN is the world's leading particle physics laboratory and the focus of most particle physics experimentation in Europe; UK membership of, and support for, CERN is crucial for the UK science programme.

Recommendation 4.1: The HL-LHC remains the highest priority for the UK community, with direct involvement from a large fraction of the experimental community; this, coupled with the large investments so far, mean that the UK must continue to give strong support to the ATLAS, CMS and LHCb upgrades, and their commissioning, and to the exploitation of the current and upgraded experiments, thereby maintaining its leadership in the LHC program.

Recommendation 4.2 The UK community shares the vision of the European Strategy document to prepare an electron-positron Higgs factory as the highest-priority next collider; and a future hadron collider with sensitivity to energy scales an order of magnitude higher than the LHC. The latter requires development studies to address the associated technological and environmental challenges and opportunities. The UK community should establish a unified future high energy collider programme to be well positioned in a 20+ year plan for future accelerators.

Recommendation 4.3: The UK should engage in the realisation and exploitation of a future high-energy e^+e^- facility. Investment in appropriate R&D on detector and accelerator technologies/systems that capitalises on current UK strengths will position us to take a leading role in e^+e^- collider physics. Where possible, the programme should provide leverage with more than one of the facilities under consideration by the UK.

Recommendation 4.4: The UK community should identify a sub-set of key areas of technology that align with initiatives at CERN and will be informed by appropriate

physics studies, that will allow the UK to capitalise on the expertise acquired through the HL-LHC construction and beyond, to carry forward its leading role to the FCC-hh.

Recommendation 4.5: As an adjunct to the FCC-hh studies, feasibility studies to inform accelerator and detector technology options for FCC-eh should be pursued by the UK focusing on common elements of the possible future facilities and their experiments.

Recommendation 4.6: The UK should maintain its recognized expertise in Muon Collider studies concentrating on medium-term projects focused on feasibility demonstration exploring synergies with neutrino physics such as nuSTORM.

Recommendation 5.1: The UK must continue to invest in the LHCb Upgrade II program and investigate the potential for flavour physics at future collider facilities.

Recommendation 5.2: The UK has a leading role in the scientific exploitation of the current generation of kaon experiments. The UK should participate in the exploitation of the future CERN High-Intensity Kaon Beam Facility, and invest into the future CERN kaon experiments - for example by exploiting its expertise in beam-line, trigger and DAQ development.

Recommendation 5.3: The UK should exploit its investment in the ongoing round of precision muon experiments and seek opportunities to support and invest in future charged lepton flavour violation experiments, targeted such that it exploits its expertise and technological interests. The UK should aim to consolidate its involvement in future muon-electron conversion experiments, taking into account the global situation as regards the activity and synergies with accelerator and detector development.

Recommendation 5.4 The UK should exploit its world class expertise in EDM science and its investment in EDM experiments. The UK EDM community should evaluate the wide-range of EDM experiments world-wide so as to converge on the opportunity that maximises the chance for discovery.

Recommendation 6.1: The UK should maintain its leading role in long-baseline neutrino oscillation experiments. Exploitation of the currently running experiments should be supported. In the next 10-20 years the main priority will be on measuring the CP-violating phase of the mixing matrix and the neutrino mass ordering with the long-baseline programmes in Japan and USA. The UK should continue to engage with both programmes. In particular, it should maintain its leading involvements in LBNF/DUNE.

Recommendation 6.2: To extract the most physics out of the long-baseline neutrino experiments the UK should build on its existing expertise to pursue a complementary programme of precision measurements of neutrino interaction cross-sections and neu-

trino fluxes. In addition, recently emerged opportunities of detecting collider neutrinos, that allow measuring neutrino cross sections at energies where they are currently unconstrained, should be pursued.

Recommendation 6.3: The study of the neutrino mass nature (Dirac or Majorana) and its absolute value is the other key priority of the field. The UK should continue to support its current engagement with $0\nu\beta\beta$ experiments entering the exploitation phase. Going forward, the UK should leverage its expertise and technical capabilities to actively engage with international strategies, being formulated in Europe (APPEC), the US (DOE) and Asia, that aim to cover the inverted neutrino mass ordering parameter space, and should consolidate around the $0\nu\beta\beta$ experiments with the most promising discovery potential on the shortest timescale, and where the UK can have the maximum impact.

Recommendation 6.4: The UK should continue to pursue an R&D programme that can address the questions of the nature and absolute value of the neutrino mass within the normal ordering with $0\nu\beta\beta$ and single-β decay experiments using latest advances in particle detectors, quantum sensors and data processing technologies.

Recommendation 7.1: The UK should maintain leadership during R&D, construction and exploitation of Direct DM Detectors over a wide range of DM masses that demonstrate their uniqueness, complementarity, or world-wide competitiveness, and should seek opportunities to grow funding to support projects, including those planned to be constructed within the UK.

Recommendation 7.2: The UK should secure future support outside the current STFC core programme (for example NQTP or other cross-UKRI funding) of dark sector experiments based on successful demonstration of quantum technologies seeded by the QTFP programme. If a growth of funds is not achieved, pursuing the broad scientific goals in the dark sector will need to be tensioned with other areas of the core programme.

Recommendation 7.3: The UK community of theorists and phenomenologists, collider experimentalists, and direct and indirect detection experimentalists should establish a interdisciplinary programme to explore a synergic approach in DM studies, with greater communication and idea exchange.

Recommendation 8.1: The UK's world class strength in phenomenology, which aids the UK's experimental programme, should continue to receive robust support. A national centre for particle phenomenology is a scientific impact multiplier and should remain a priority.

Recommendation 8.2: Lattice QCD plays an crucial role in particle physics and the UK should continue to support the world class UK contribution as well as the required computing facilities.

Recommendation 8.3: STFC should support the already strong and broad formal fundamental theoretical physics programme (including mathematical aspects) to seed paradigm shifts and/or exploit current developments. STFC through UKRI should consider how best to prevent some areas of mathematical work 'falling between the cracks' of different panels and research councils.

Recommendation 8.4: UKRI and STFC should consider how best to enable ongoing development in the exploitation of quantum technologies to help theory answer fundamental physics questions.

Recommendation 9.1: There is a systemic problem with career paths in detector and computing areas. STFC should consider initiatives that provide incentives for Universities to retain such academics, while maintaining paths through the national labs.

Recommendation 9.2: It is important that basic R&D be continued in accelerators and detectors to support the long-term programme. STFC should facilitate access to funding opportunities for these activities, where possible using external funding streams.

Recommendation 9.3: The core funding component of the consolidated grant programme provides an important path for career progression of scientists and engineers who have vital skills required for instrument development and operations. An equivalent path for research software engineers should be established, on a par with the established engineer core roles to provide balanced support.

Recommendation 9.4: Alternative funding streams for additional PhD students working on the strategic technical priorities of the community should be sought to maintain this pipeline in line with the needs of scientific goals and industry and public sector stakeholders. In parallel STFC should consider ways to incentivise universities and national laboratories to strategically manage technical staff attrition to retain capability and capacity of the community when individuals leave the field.

Recommendation 9.5: The STFC should continue to invest in areas of strategic importance to maintain leadership, such as accelerator technology for high energy and high intensity beams, detector technology for colliders, fixed target, neutrino and dark matter experiments. This includes infrastructure, instrumentation, computing, software, and data science technologies.

Recommendation 9.6: The UK should continue to support both high performance and high throughput computing in line with the evolving needs of the theoretical and experimental community.

Recommendation 9.7: The UK should continue to invest in new techniques, such as quantum technologies, to explore radically new ways to address fundamental particle physics questions. It should consider establishing a sustained funding stream to seed development of emerging technologies and to solve the technical requirements for the

next generation of instruments needed for future experiments.

Recommendation 9.8: Where possible software developed by the UK PP community should be released as open source, and effort to maintain open source tools should be regarded as fundable and related to the wider impact agenda.

Recommendation 11.1: An *Early Career Scientist in Particle Physics* Forum should be established by the community to help support and represent the views of the PDRA and PhD students in the UK. STFC should consider the inclusion of PDRA-level representation on its panels.