Particle Physics Roadmap Update 2019

1) Introduction

This is a revision to the last update to the Particle Physics Roadmap, which the PPAP published in 2016. The timing is not ideal, as we recently produced our input to the next 5-yearly review of the European Strategy, and that process will conclude in 2020. At that point, many open issues should be clearer. We are also writing only as the outcome of the latest grants round for experimental particle physics groups emerging. From the picture that has merged so far, this outcome will severely limit or descope the UK ambitions. We note it is explicitly not in our brief to prioritise projects; however, with the programme growing from seven to 11 approved projects between 2015 and 2018, while the purchasing power of the core funding has fallen by approximately 30% in real terms, some strategic review and tensioning is inevitable. We recommend a further PPAP roadmap review in late 2020 or 2021.

The sections in this report largely correspond to the main subdivisions of the previous document; however, where this would unbalance or incorrectly reflect the current status and ambitions across the community, we have adopted a slightly different structure. This is particularly the case for the future accelerator projects and for technologies.

2) The Energy Frontier

2.1 The LHC GPDs, ATLAS and CMS

The full exploitation of the LHC remains the top priority for the community. The HL-LHC has very strong support within the UK and the community has for some time been engaged in preparations for major upgrades to the detectors to enable them to perform effectively in the new and challenging environment that the HL-LHC will present. The major project for CERN until the late 2030's is without question, the HL-LHC. It will explore new territory in the search for physics beyond the standard model (SM) and enable much more precise Higgs sector and high-precision measurements testing the standard model. Both of the GPD upgrade projects are approved, with agreed STFC funding for the construction phase.

The LHC began 13 TeV collisions in May 2015 and recently concluded Run-2 after accumulating about 190 fb^{-1} overall for each GPD. The LHC operated beyond expectation, with excellent livetime and delivered a peak luminosity of 2.1 x 10^{34} $cm^{-2}s^{-1}$. Both GPDs have been running extremely well with data taking efficiencies of well over 90%. The increase in LHC energy from 8TeV at the end of 2012 to 13TeV for Run-2 has allowed searches for signatures of non-Standard Model physics to be made, probing deeper into the TeV-energy scale. LHC Run-3 will start in 2021. The LHC will increase its energy towards 14TeV and operate at 2.5 times its design luminosity, aiming for around 380fb^{-1} of integrated luminosity by the end of 2023 (at the time of the last update, only 300fb^{-1} were expected). Run-3 will extend analyses in the GPDs in terms of both energy reach and precision measurements.
HL-LHC Run-4 will start in 2026. The LHC will operate at around 7.5 times its design luminosity with the aim of reaching an integrated luminosity of 4000fb^{-1} by around 2038. The GPDs will undertake a broad programme of physics. A comprehensive study of the

properties of the Higgs boson including rare processes such as H→μμ and HH-couplings, ttH, direct searches for evidence of new physics at the TeV-scale, and indirect searches for evidence of new physics at the multi-TeV scale through a range of precision measurements; this is the only option proposed that can guarantee evidence and maybe lead to a discovery of the Higgs self-coupling.

ATLAS completed LHC Run-2 data-taking at the end of 2018 and is now analysing 139fb^{-1} of "good for physics" data. The large dataset has allowed ATLAS to produce their first results on the Higgs decaying to b-quarks, to tau leptons and in association with top quarks, and to make measurements of the properties of the Higgs' mass, couplings and fundamental CP parameters to make a broad range of precision measurements of Standard model processes to search for evidence of non-Standard Model physics. ATLAS is now starting to challenge the precision of LEP and the Tevatron in measurements of fundamental electroweak parameters such as the top and W mass and the electroweak mixing angle and is probing regions of phase-space sensitive to new physics through differential cross-section measurements. The Phase-1 Upgrades are progressing during LS2. The UK is providing the new electron feature extractor (eFEX) for the level 1 calorimeter trigger. The eFEX will be critical to maintain the trigger acceptance of LHC collisions with a x2 increase in instantaneous luminosity. The development of the eFEX is complete and production will start in 2019, with installation and commissioning in 2020. For the High-Level-Trigger, the UK has already provided new core and tracking software and will continue to upgrade and maintain the software for Run-3. There is UK effort integrating the new hardware fast tracker (FTK) into the High Level Trigger. The UK has worked on the core framework and on developing algorithms compatible with the multi-threaded architecture. The UK is also working on the development of fast simulation, which is critical to optimise the use of computing resources.
The major ATLAS Phase-2 construction projects have now been approved and the MoUs will be signed in 2019. The UK will begin construction of major parts of the tracker upgrade: half of the strip barrel tracker and a pixel endcap tracker. The UK components will be delivered to CERN in 2022-2024 for integration and commissioning. The UK contribution to the hardware elements of the trigger: Global Trigger and Hardware Track Trigger, will start in 2019. The R&D and development work will overlap and build on the Phase-1 Upgrade. Construction will be in 2021-2024, with integration and commissioning in 2024-2026. The ATLAS computing framework has moved to a multi-threaded architecture (AthenaMT), although further work needs to be done with decreasing effort. The HLT and Computing and Software will continue to evolve through Run-3 and into LS3, in preparation for Run-4 operations.

Updated Institute list
Birmingham, Cambridge, Edinburgh, Glasgow, Lancaster, Liverpool, Manchester, Oxford, QMUL, RAL, RHUL, Sheffield, Sussex, UCL, Warwick.

CMS has produced a record number of publications during Run-2, with 141 alone in 2018. Amongst others, highlights include the rapid progress on the characterisation of the Higgs boson, with the coupling to third generation fermions (taus, b quarks and top quarks) being confirmed in the space of a year. The breadth of the physics programme, and indeed CMS's flexibility, was illustrated by the UK initiated collection of a sample of b-hadrons exceeding the world's previous largest inclusive sample (some 10 billion) during 2018 for analysis during LS2, in particular targeting the recent flavour anomalies. The UK led the Phase-1 upgrade of the Level-1 Trigger, and this continued its excellent performance through 2017 and 2018, proving particularly flexible in the challenging conditions of the 2017 run. The concepts of 'time-multiplexing' and a generic, highly performant, FPGA processing platform instigated by the UK as part of this now form the baseline for the associated CMS and CMSUK Phase-2 HL-LHC upgrades. The Phase-1 pixel upgrade was carried out during the 2016-2017 year end stop, unfortunately resulting in reliability issues with an externally supplied DC-DC converter, proposed for many HL-LHC upgrades. The problem was fully understood, and rectified for 2018 running, with no repeat of the issue. The focus of LS2 will be the completion of the residual Phase-1 upgrades and the ongoing infrastructure changes for HL-LHC operations. The CMS computing model continues to evolve in response to the changing needs of the experiment, with one example being the successful use of dynamic and transient resources.

The major CMS Phase-2 construction projects have now been approved and the MoUs will be signed in 2019. As well as being responsible for key aspects of the tracker front end electronics and barrel calorimeter, the UK is playing a major role in the development of the common readout and trigger platform that will be used extensively within CMS, and underpins the UK lead in the Level 1 track trigger and readout, HGCAL trigger and overall Level 1 Trigger project. Prototyping and detector specification customisation will be completed in the next two years, before the EDRs in 2020-21. To take full advantage of evolving technology, the Level 1 Trigger TDR is planned for Q1 2020. Ongoing R&D builds on the highly successful, UK led, Phase-1 upgrade.

Updated Institute list

Bristol, Brunel, IC, RAL

Updated Milestones

2019-20: LS2, Installation of the ATLAS/CMS Phase-1 upgrades
2021-23: LHC Run 3 data taking (380 fb-1 integrated luminosity)
2024-26: LS3, Installation of the ATLAS/CMS Phase-2 upgrades
2027-29: LHC Run 4 data taking
2030-31: LS4
2032-: LHC Run 5/6 (4000 fb-1 integrated luminosity for HL-LHC running)

2.2 Future Collider projects

In our recent input to the current review of European Strategy, the PPAP noted that a CERN-led collider project is necessary to ensure CERN remains at the forefront of Particle Physics research and is also vital to allow Europe to retain the expertise that would be capable of supporting major projects elsewhere in the world. The choice of project should be made in the early 2020's. There is a clear scientific case for an e^+e^- machine to study the Higgs, including its self-coupling. There is also very strong physics motivation for a new hadron machine at the high energy frontier. CERN has expertise in both areas. The future global strategy for exploring the particle physics landscape should include both e^+e^- and hadron colliders.

However, both the UK and CERN can have an involvement in collider projects elsewhere and the UK would wish to engage with scientific exploitation opportunities elsewhere. Indeed, the UK has been prominent in the activities around the proposed linear collider projects.

Potential e^+e^- colliders

The number of potential e^+e^- collider projects have increased since the last roadmap, with two circular collider options being explored (FCC-ee in Europe and CepC in China) in addition to the longer-standing two linear collider options. Linear and circular e^+e^- colliders have complementary strengths and both options are being pursued. In both cases a staged system is possible where the ultimate capability could be realized through an energy upgrade.

The linear collider options remain the International Linear Collider (ILC) and the Compact Linear Collider (CLIC) development at CERN. The hoped-for confirmation of support from Japan for the ILC has yet to emerge. The CLIC RF technologies have the potential to be industrialised, and the development of medium-scale accelerators (for example a FEL) could help to progress this.

Potential Hadron Colliders

The extended physics reach of an FCC- hh is very attractive, with an order of magnitude increase in energy opening the door to very many new physics scenarios as well as enabling a high precision measurement of the Higgs self- coupling. Furthermore, this activity would be a major driver of new technologies. The UK community strongly supports the objective of building a hadron collider with a centre of mass energy around 100 TeV, and the required technology development to allow it to be realised. The Chinese Super Proton Proton Collider (SPPC) would, like the FCC-hh machine, capitalise on the existing infrastructure developed for the precursor electron positron collider and offer very similar physics opportunities.

Potential ep Colliders

As an interim project, the LHeC, a project with significant UK leadership, remains a potential relatively low-cost option that extends the LHC programme to electron-proton collisions. Such a machine would have competitive Higgs coupling sensitivities, alongside hadron structure, strong interaction dynamics and some BSM search sensitivity

The accelerator technologies required for such a development could be of use to other projects (e.g. the electron-ion collider in the US), and these should be maintained where possible. There is UK leadership in this project. At even higher energies, an electron-proton collider option for the European FCC project is under study.

Potential Muon Colliders

A muon collider offers a hitherto unexplored opportunity to construct a relatively compact circular lepton machine that emits almost no synchrotron radiation and couples strongly to the Higgs sector. It therefore uses the expensive RF accelerating cavities very efficiently and can fit on the site of an existing laboratory. UK expertise in muon ionisation cooling would be relevant to the development of a muon collider facility.

3) Flavour and related Physics

3.1 LHCb and the LHCb Upgrade

The first phase of the LHCb experiment was successfully completed in 2018 with a dataset of over 9 fb^{-1} collected. This exceeds the previous largest dataset of exclusive b- and c-hadron decays by far. First results from the full dataset, presented at Moriond 2019 include the first observation of CP violation in charm hadrons, precision tests of lepton universality in b-hadron decays, and new insights into the formation of pentaquark states. A rich harvest of new results is expected in the coming years. In parallel dismantling of the current detector and installation of the LHCb Upgrade I detector has commenced. This will allow to run the experiment at order of magnitude higher luminosity and collect up to 50 fb^{-1} of data by LS4 in 2030. Installation of the new detector is proceeding to schedule such that it will be ready for commissioning at the start of Run 3 in 2021. A key component of the upgrade project is a full software trigger capable of running at the proton-proton interaction rate of 30 MHz. Valuable experience of performing calibration and alignment in real-time was obtained in Run 2, demonstrating it is possible to obtain offline quality results directly from the trigger. This allows to save a reduced amount of data offline making more optimal use of available computing resources.

The experiment is planning for a further upgrade that would allow it to continue to run until the end of HL-LHC operation, collecting data at around an order of magnitude higher instantaneous luminosity than with Upgrade I, leading to a total sample of at least 250 fb^{-1}. This Upgrade II would take place during LS4 (~2030), with preparatory work and consolidation of the Upgrade I detector during LS3 (referred to as Upgrade Ib). A key feature of the Upgrade II concept is the use of precise timing information to reduce pile-up background.

An Expression of Interest (CERN-LHCC-2017-003) and a detailed physics case document (LHCC-2018-027) for LHCb Upgrade II have been prepared. In September 2018, the LHCC recommended that the collaboration prepare Technical Design Reports for this project. A framework TDR is expected in 2020 followed by Upgrade II detector TDRs by 2024, with Upgrade Ib TDRs on a shorter timescale. UK groups have expressed interest in updates to the vertex detector, the particle identification system and the development of the new large silicon downstream tracker.

Improved measurements of charm strong-phase parameters provide critical input to the studies of the CKM angle gamma being made to LHCb. In 2017 the Manchester and Oxford groups joined BES3 to work on these measurements and to strengthen the interplay between the two experiments.

Updated Milestones

2019-20: LS2, Installation of the LHCb phase-1 upgrade
2021-23: LHC Run 3 data taking (2×10^{33} cm^{-2} s^{-1})
2024-26: LS3, LHCb Upgrade I consolidation and Upgrade II preparatory work (Upgrade Ib)
2027-29: LHC Run 4 data taking (2×10^{33} cm^{-2} s^{-1})
2030-31: LS4, LHCb Upgrade II
2032- : LHC Run 5/6 (1.5×10^{34} cm^{-2} s^{-1})

Updated Institute list

Bristol, Birmingham, Cambridge, Edinburgh, Glasgow, IC, Liverpool, Manchester, Oxford, RAL, Warwick

3.2 High Precision Kaon experiments

NA62 commissioned and ran successfully between 2014-2018 with STFC funding from 2015. Analysis of data 2016 data has shown that background rejection is sufficient to observe the $K^+ \rightarrow \pi^+\upsilon\upsilon$ signal and the 2016-2018 dataset should contain around 20 events of this decay mode. And analysis is ongoing with UK leadership. The UK provides the spokesperson and deputy spokesperson along many other posts and responsibilities.

CERN has approved funding for the next two years to prepare the experiment for running after LS2 in 2021, and a beam-time request will be submitted to the SPSC in April 2019. Post

LS2 running will allow both to complete and widen the current physics program. A longer term option for running at 4 times the nominal intensity is being investigated; and a proposal for a new experiment at CERN to measure $K_L \rightarrow \pi\upsilon\upsilon$ is has been presented within the Physics Beyond Collider programme. A detailed study of the beam line modifications to obtain a higher intensity of protons on target on the beam line relevant for NA62 and KLEVER has been studied extensively, with positive conclusions.

Updated Milestones
2019-20 Preparation for post-LS2 running
2021-24: NA62 Run 3

Updated Institutes
Birmingham, Bristol, Glasgow, Lancaster, Liverpool

3.3 High-precision dedicated muon experiments
The UK is at the forefront of four high-precision muon experiments: Muon g-2 and Mu2e at Fermilab, Mu3e at PSI and COMET at J-PARC. COMET, Mu2e and Mu3e will extend the search for charged lepton-flavour violation (cLFV) by up to 4 orders of magnitude on the timescale of the mid-2020s and can probe effective new physics mass scales above 10^3 TeV. The sensitivity offers genuine discovery possibilities in a wide range of new physics models with SUSY, Extra Dimensions, an extended Higgs sector, lepto-quarks, or from GUT models.
The UK has established significant roles in all these experiments, providing key detector systems for Muon g-2, and targets and detectors for Mu2e. It has made important contributions to the T/DAQ and offline simulation for COMET. The UK is building pixel layers and the clock and control system for Mu3e.

Within two years, the Fermilab Muon g-2 experiment will measure the anomalous magnetic moment of the muon to a precision four times better than the E821 BNL experiment and extend the sensitivity to a muon EDM by two orders of magnitude. If the existing E821 measurement is confirmed, the Fermilab experiment would establish a BSM muon interaction at a significance of 8σ.

The cLFV experiments will proceed in phases: COMET-I will have first beam in 2020 and extend the search for the neutrinoless muon to electron conversion by two orders of magnitude. Mu2e will extend this by a further two orders of magnitude in the same channel by the mid 2020s, with first beam in 2022. Mu3e will improve the $\mu^+ \rightarrow e^+e^-e^+$ sensitivity by over two orders of magnitude; the beam delivery, and design and construction of the experiment is on schedule for data taking to start in 2020.
Beyond this, upgrades in proton intensity offer the possibility of additional improvements. An upgrade to Mu2e that extends the sensitivity by another factor of ten or more, Mu2e-II, is proposed and would utilize about 100 kW of 0.8 GeV protons from the Fermilab PIP-II linac. An upgrade to COMET, COMET Phase-2, would utilize 56 kW of 8 GeV protons to reach a comparable sensitivity. At PSI a new high intensity muon beam (HiMB) is planned that would allow more than an order of magnitude improvement in the Mu3e sensitivity. These upgraded facilities would take data in the latter half of the 2020s.

Updated Institutes
COMET: IC, RAL
Mu2e: Liverpool, Manchester, RAL, UCL
Mu3e: Bristol, Liverpool, Oxford, UCL
g-2: Cockcroft, Lancaster, Liverpool, Manchester, UCL
Updated Milestones
2017-2020: Data taking for g–2
2020: Start of data taking for Mu3e
2020 Start of data taking for COMET Phase-1
2021 – 2025: Data taking for Mu2e
2024: Start Mu3e Phase-2

3.4 SHiP
The SHiP (Search for Hidden Particles) collaboration has grown to 54 institutes in 18 countries. A technical proposal (and physics paper) have been submitted and approved by the SPSC and CERN research board in 2015. The collaboration submitted a progress report in 2018 and will submit a conceptual design report during 2019. SHiP is included in CERN's medium-term plan, with a small amount of funding allocated for machine feasibility studies. The UK collaborators have identified three key areas in which they wish to contribute: the active muon shield, the target design and the data acquisition and trigger. Start of data taking is foreseen for 2026.

Updated Milestones
2019: CDR completed
2020-2026: Construction and installation
2026: Start of data taking

Updated Institutes
Bristol, IC, RAL, UCL, Warwick

3.5 MoEDAL
This experiment relies on mostly passive detection media and is situated in the LHCb experimental hall. Physics goals of MoEDAL include searches for magnetic monopoles and heavily ionising particles, and the UK has a number of leadership roles, including chair of the theory board, Physics coordinator and machine learning group leader. The spokesperson is a visiting professor at a UK institute.

Updated Institute list
IC, KCL, QMUL

4) Neutrino Physics

4.1 Current oscillation experiments: T2K, NOvA
Both T2K and NOvA continue taking data with respective beam power of 475 kW and 700 kW. Both experiments also take data in both neutrino-mode and anti-neutrino mode.

Over the past year, T2K has made two significant developments: adding a new far-detector sample of e-like 1-Michel electrons, and implementation of a new reconstruction algorithm that improves both efficiency and purity. The new event sample mainly consists of resonant pion interactions, and adds a new channel to constrain the oscillation parameters.

NOvA debuted a new analysis, including anti-neutrino samples, at the Neutrino 2018 conference in June. They have the first hints of anti-neutrino appearance; additionally, their disappearance results are now consistent with maximal mixing, thus reducing the tension with T2K, IceCube, and Super-Kamiokande.

Both experiments are currently indicating a preference for CP violation and a normal mass ordering of the mass eignestates e.g. T2K report a best fit value close to maximal CP violation for normal ordering, ruling out zero CP-violation at slightly more than two standard deviations.

Following recent upgrades to the Super-Kamiokande tank in summer 2018, it is anticipated that gadolinium will be loaded into the Super-K water in early 2020. This new phase of the Super-Kamiokande experiment, denoted 'SK-Gd', will add neutron capture capabilities to the detector, enabling discrimination between neutrinos and anti-neutrinos. Such event tagging relies on an accurate understanding of the neutron yield in neutrino interactions events; these measurements are being studied at Super-Kamiokande, as well as other experiments. If successful, the neutrino / anti-neutrino discrimination will enhance the sensitive of Super-K and T2K for discovering leptonic CP violation.

Updated Institutes
Glasgow, IC, Lancaster, Liverpool, Oxford, QMUL, RHUL, Sheffield, Sussex, UCL, Warwick

Updated Milestones
2019: Upgrades to J-PARC neutrino beam
2020: First operation with gadolinium in T2K far detector
2020: Joint T2K-NOvA oscillation analysis

4.2 Future oscillation experiments: Hyper-Kamiokande, DUNE
The UK continues to maintain strong involvement in both major next-generation oscillation experiments, the US-based Deep Underground Neutrino Experiment (DUNE) and the Japan-based Hyper-Kamiokande. Both build on existing UK efforts, with UK personnel holding key leadership roles in both collaborations. Hyper-Kamiokande will continue the Japanese preference for water Cherenkov detectors, whilst DUNE will push the emerging liquid argon (and dual-phase liquid / gas argon) technology to new levels. BEIS has committed £65M to support DUNE, and both projects receive STFC support. The realisation of the CERN-based single-phase liquid argon ProtoDUNE is a major milestone. Exploitation of ProtoDUNE continues, with analysis of beam data and continued collection of cosmic ray data.

Alongside the ProtoDUNE effort, the UK is deeply involved with two of the three experiments in the Fermilab short-baseline oscillation programme. Taken together, the Short-Baseline Near Detector (SBND), MicroBooNE, and Icarus form the ideal configuration for confirming or refuting the existence of light sterile neutrinos. The UK is active on the first two of these experiments. MicroBooNE now has several years of data accumulated, with SBND to begin its exploitation phase in 2020.

Finally, there is work on a concept for a mega-tonne water Cherenkov detector array, CHIPS, that aims to develop cheap and scalable detector elements to allow neutrino oscillation studies to be pushed beyond the ultimate limit of DUNE and Hyper-Kamiokande. UCL is a leading proponent of this.

Updated Institutes
Hyper-K: Edinburgh, Glasgow, IC, IPPP, Lancaster, Liverpool, Oxford, Sheffield, QMUL, RAL, RHUL, Warwick
DUNE: Birmingham, Bristol, Cambridge, IPPP, Edinburgh, IC, Lancaster, Liverpool, UCL, Manchester, Oxford, RAL, Sheffield, Sussex, Warwick

Updated Milestones
2020: First data with SBND
2021: Sterile neutrino analysis
202?: First DUNE module goes live
2026: Start of Hyper-Kamiokande data-taking

4.3 Neutrino-less double beta decay
Neutrino-less double beta decay (0νββ) experiments are currently the only way to the fermionic nature (Majorana or Dirac) of the neutrino and sensitive probes of lepton flavour violation. The results of 0νββ experiments may, in addition, provide insights into the mechanism behind the cosmological matter-antimatter asymmetry. It should be noted that the discovery potential of next generation 0νββ experiments is high, regardless of the neutrino mass ordering.

The UK currently plays leading roles in two 0νββ experiments. The liquid-scintillator based SNO+ detector in Canada has the advantage of hosting a potentially very large mass of isotope. The UK constitutes ~25% of the total SNO+ project effort and holds key leadership positions within the collaboration. The SuperNEMO experiment in France uses a much smaller mass of isotope but the full event reconstruction offers advantages including background suppression and insights into the mechanism of double-beta decay; the UK provided a current and previous spokesperson, along with other major roles.
Beyond these experiments, UK groups are also considering their joint longer-term strategy to retain leadership in this field. SNO+ and SuperNEMO groups are jointly engaged in R&D on the development of novel liquid scintillators and light collection devices aiming for sensitivity to the normal neutrino mass hierarchy in a future project. Another possibility being explored is LEGEND, a next-generation Ge-76 neutrinoless double-beta decay experiment, where UK particle and nuclear physicists currently have an initial involvement on the basis of their expertise in germanium-detector development and characterisation, radiopurity assays, simulations and analysis.

By 2022, SuperNEMO will achieve a sensitivity to the half-life of 0νββ in ^{82}Se of 6.5×10^{24} yr, corresponding to a sensitivity to the absolute neutrino mass of 200-400 meV (the range covering uncertainty on the nuclear matrix element).

The SNO+ physics goals include: a sensitive search for neutrinoless double-beta decay using ^{130}Te; low energy solar neutrinos; geo-neutrinos; reactor neutrinos (Δm_{12}^2); neutrinos from potential galactic supernovae; and search for “invisible modes” of nucleon decay. SNO+ is currently undergoing a transition to liquid scintillator and expects to begin loading tellurium for 0νββ by the end of 2019. First results are expected in 2020. Phase-1 operation of SNO+ is projected to provide a world-leading measurement with a sensitivity capable of probing the upper part of the inverted neutrino mass hierarchy below 50meV for the first time.

Recent highlights from the running experiments

In developing SuperNEMO, UK researchers achieved the best resolution ever obtained in a large-plastic-scintillator calorimeter; developed a novel radon detector has been developed with world-leading sensitivity at the 40 µBq level; and a suite of high-purity germanium detectors have been installed at the Boulby Laboratory, serving the double-beta and dark-matter communities. The UK have also led a number of analyses of data from NEMO-3, including the world’s first search for quadruple double-beta decay, the world’s most precise measurements of the half-life of 2νββ decay, and searches for 0νββ decay in 48Ca and 150Nd.

The SNO+ detector has been operating with water in its central volume since Spring of 2017 and recently published papers using some of this data on a low background measurement of ^{8}B solar neutrinos and setting world leading bounds on some forms of “invisible” nucleon decay modes.

A first limit on the Majorana neutrino mass was also published using a combination of 0νββ data from multiple isotopes and multiple experiments.

Updated Institutes (SNO+)

Lancaster, Liverpool, Oxford, QMUL, Sussex

Updated Milestones (SNO+)

2019: First scintillator data, updated results for water phase analyses
2020: First results for 0νββ, reactor neutrinos and geoneutrinos
2021: Consider potential loading increase
2022: Preparations for Phase-2

Updated Institutes (SuperNEMO)

IC, Manchester, UCL and Warwick

Updates institutes (LEGEND)

Lancaster, Liverpool, UCL, Warwick

Updated Milestones (SuperNEMO)

2019: beginning of physics data-taking
2021: end of Phase-1 running
2022: beginning of Phase-2 running

5) Non-accelerator Experiments

5.1 LUX-ZEPLIN (LZ) liquid xenon dark matter experiment

LZ is the largest Generation-2 (G2) project funded by the DOE and the only construction project funded by STFC in this area. It uses liquid xenon (LXe) technology, which was partly pioneered in the UK. The UK project concludes in September 2019 and the UK deliverables are essentially complete. The experiment is on track to take first data in mid-2020.
LZ will probe spin-independent WIMP-nucleon scattering cross-sections above 1.6×10^{-48} cm^2 at 40 GeV/c^2 WIMP mass. LZ is sensitive to a variety of dark matter models including spin-dependent scattering on Xe-129 and Xe-131 and other interactions causing nuclear recoils, and to leptophilic interactions too. It is also set to make interesting measurements in neutrino physics, including a first detection of boron-8 solar neutrinos by coherent nuclear elastic scattering, and it achieves competitive neutrinoless double-beta decay sensitivity in Xe-136.

Updated Milestones
April 2020: Start of operation

Updated Institute List
Bristol, Edinburgh, IC, Liverpool, Oxford, Sheffield, RAL PPD, RHUL, UCL

5.2 Dark Matter Generation-3 liquid xenon R&D

This project is aimed at R&D for the future construction of an ultra-low background 'rare event observatory' for the detection of WIMP dark matter and neutrino physics. A liquid xenon G3 experiment will aim to improve sensitivity by another order of magnitude in comparison to the LUX-ZEPLIN (G2) experiment, enabling discovery potential in still untested parameter space down to the so-called "neutrino floor". In case of a discovery by LZ, study of dark matter properties will become a very high priority. An exciting neutrino programme would also be possible at the 50-100 tonne target scale.
Dark Matter Generation-3 R&D is currently unfunded. An SoI has been considered by Science Board in October 2017.

Updated Institute List
Bristol, Edinburgh, IC, Liverpool, Oxford, RAL, Sheffield, RHUL, UCL

5.3 DarkSide (DS) liquid argon dark matter experiment

DS aims to detect dark matter (DM) particles (WIMPs) via scattering on argon (Ar). It employs a two-phase Liquid Argon Time Projection Chamber (LAr TPC) with the detector mass of 50 tonnes; Ar has the leading result at low masses, and DS is designed for leading sensitivity to masses above the energy scale accessible at the LHC. The LAr TPC sits inside an instrumented 770 tonne LAr veto in a cryostat designed by CERN, leveraging the cryostat technology development for DUNE. Construction has already begun.
An SoI was considered by Science Board on 12 December 2018. The proposed UK contributions to DS are in the areas of veto readout, calibration, distributed computing and searches for DM beyond WIMPS.

Updates Milestones
2021: Commissioning

2022-2018: Data taking

Updated Institute List
Durham, Glasgow, Birmingham, KCL, Lancaster, Liverpool, Manchester, RAL, RHUL, Sheffield, Sussex, QMUL, Warwick

5.4 DEAP-3600 liquid argon dark matter experiment
DEAP, at SNOLAB, has recently demonstrated pulse shape discrimination between electron vs. nuclear recoils in liquid Argon that is approximately an order of magnitude better than the projection. The full data set of this background-free dark matter search is expected to give an order of magnitude improvement over the current result. UK collaborators serve as the Software Coordinator, Dark Matter Search Analysis working group conveners, and have previously convened the Detector Calibration and Energy Scale working groups, as well as served as the Detector Calibration Coordinator.

Updated Milestones
Dec 2020: End of data taking

Updated Institute List
RHUL, RAL, Sussex

5.5 Other dark matter experiments
Other dark matter experiments with UK involvement include searches for low-mass WIMPs with cryogenic bolometers (SuperCDMS) axions using a resonant microwave cavity inside a superconducting magnet (ADMX-Gen2) and directional dark matter detection (CYGNUS, DRIFT). A new UK involvement has been initiated in GNOME, operating a network of optical magnetometers to detect stable topological defects of axion-like fields. Continuing on the theme of quantum sensors, the UK is a founding member of the MAGIS-100 programme at Fermilab to build large scale atom interferometers as tests of fundamental physics, including dark matter, and as gravitational wave detection.

Updated Institute List
SuperCDMS: Durham
ADMX-Gen2: Sheffield
DRIFT: Sheffield
CYGNUS: Sheffield
NEWS-G: Birmingham

5.5 eEDM experiment
The Imperial College (IC) eEDM project aims to measure the electron electric dipole moment by measuring the spin precession of polar molecules in an electric field. The upgraded is complete and has eEDM sensitivity close to the projected shot-noise limit. In 2019, characterisation of the systematic errors and reduction of systematic uncertainties to 10^{-29} e cm are planned. Then new eEDM data will be collected and derive a new result, aiming for a total uncertainty of 5×10^{-29} e cm. For 2020, a further upgrade of the detectors and an

increase of the electric field, followed by the collection of a final set of data is planned, aiming for a total uncertainty of 2×10^{-29} e cm. This is the limit of the current method. This work is supported exclusively by the IC consolidated grant.
Work on a new apparatus has begun that will use ultracold molecules to enhance the sensitivity to eEDM. The aim is to demonstrate a statistical uncertainty below 10^{-30} e cm by the end of 2022, reaching to 10^{-31} e cm in the longer term. This work is funded by an STFC PPRP grant (Oct 2018 – Sep 2022), and by the IC Consolidated Grant, with additional support from the John Templeton Foundation (Oct 2018 – Jun 2021).

The main recent highlight from the eEDM project is the development of methods to cool molecules to ultracold temperatures. This is the key new technology that will enable future sensitivity improvements. This work is published in several recent papers.

Updated Institute List
IC

Updated milestones:
2020: eEDM measurement with uncertainty of 5×10^{-29} e cm
2020: Molecules cooled to 50 microkelvin
2021: eEDM measurement with uncertainty of 2×10^{-29} e cm
2021: Completion of ultracold eEDM apparatus
2022: Demonstration of eEDM sensitivity below 10^{-30} e cm

5.6 nEDM experiment
The PSI-based nEDM collaboration has been working to upgrade the apparatus from the RAL/Sussex/ILL experiment that established the current world limit. Data taking began in 2016, and the statistical sensitivity fell below the milestone 10^{-26} ecm level. Publication of the existing nEDM data is expected in the second half of 2019. PSI then provided 2.5M CHF towards a next-generation experiment, n2EDM. It is anticipated n2EDM will have a year of commissioning in 2021 prior to full data taking with an experimental sensitivity in the low 10^{-27} ecm range. The UK has leadership roles in both projects.

The UK is also involved in the PanEDM project under development at ILL that uses a new type of cryogenic source for ultracold neutrons. The UK is working on development of new, potentially more efficient guide tubes and other aspects of ultracold neutron transport. For the medium- to long-term, development of technologies for a next-generation fully cryogenic nEDM experiment is continuing.

Updated Institute List
nEDM/n2EDM: Sussex
PanEDM: RAL

Updated milestones:
- 2019: Unblinding of nEDM analysis, final publication.
- 2021: n2EDM commissioning.
- 2022: n2EDM data taking.

6) Theory

Theoretical particle physics is a crucial aspect of the research programme and underpins the investment in the experimental effort. Its goals are broad and far-reaching. It aims to obtain the precision needed to exploit the data to identify any deviations from the Standard Model and to explore theoretical ideas to understand the physics responsible for electroweak symmetry breaking, the origin of neutrino masses and of the baryon asymmetry, and the flavour structure we observe in the quark and lepton sectors. Another focus is the nature of dark matter and more broadly the connection between elementary particles and their interactions with the physics of the Early Universe. On the more formal side, new developments are important as they can potentially lead to paradigm shifts. The UK hosts several world leading research activities in particle theory, which, according to the 2015 STFC Review of Particle Phenomenology, include the areas of PDF's, Monte-Carlo, lattice QCD and precision QCD, together with strong expertise in forward proton tagging, Higgs measurements, the anomalous magnetic moment of the muon, new physics searches and tools, model building and lepton flavour violation. UK particle phenomenology has a very strong international profile and the UK hosts a dedicated phenomenology research centre, the Institute for Particle Physics Phenomenology in Durham. This effort is essential to exploit the data from the LHC, neutrino, flavour and astroparticle experiments, and to guide future developments in the field. Formal theory activity also has a significant international profile, with a long history of successful innovation and new ideas. Lattice theory remains a very active area of research in the UK and it is essential for precision calculations in the Standard Model, particularly in flavour physics, and in alternative BSM scenarios, which cannot be performed by other means. The UK continues to invest in high performance computing for particle physics via the DiRAC (Distributed Research utilising Advanced Computing) facility. Connections between particle theory and astrophysical research are increasing, and the UK is expanding research in cosmology.

7) Technology Roadmap

7.1 Computing and Software

The experimental and theory programmes continue to fundamentally rely on computing infrastructure for their success. The High Performance Computing has been provided by DIRAC, which was funded in its DIRAC 2.5 bid and is now bidding for DIRAC 3. The High Throughput Computing is provided by GridPP, which is has just submitted its bid for GridPP6. IRIS now provides a common structure for DIRAC and GridPP to help service the wider STFC community and beyond, and capital resources have been allocated to help this. Resource remains scarce for such activities.

Some important changes in the general computing and software environment have occurred. Moore's Law growth seems to have almost stalled, which implies significantly increased cost for fixed computing resource. There is also a multiplicity of architectures available, and increasing pressure for some use of GPUs and similar for machine learning applications.

The increasing demand for computing coupled with the cost drives make the demands on software event greater. This effort is often underrated in grant reviews and also in academic recognition. Proposals have been made concerning software institutes and

Fellowships to partly address this, but the general funding routes also need to be addressed.

7.2 Detector Technologies

The limits and ambition of our science are often set by the achievable detector technologies. These are rapidly developing, and new technological approaches offer new opportunities for particle physics. For instance, a recent new STFC award for "Quantum Sensors for Fundamental Science and Society" aims to exploits aspects of the recent growth in quantum technologies. This is very welcome, but even in this area there are many and evolving further opportunities, ranging from imaging and characterisation at the nano-scale to quantum chronology. Another area with well evolved plans within the community is CMOS and thin films. These offer opportunities for the science and for impact.

Typically, the required expertise lies outside traditional particle physics groups, and often at institutions with little high energy physics involvement. Thus, links need to be made between particle physics and other groups. The recent H2020 ATTRACT seed corn funding opportunity is a good example of how this activity can be promoted. It is of continuing concern that the scope for new developments through previous schemes like the PRD are now very limited and driven by external funding opportunities, often (such as GCRF) with overly restrictive conditions.

Another strong detector involvement of the UK particle physics community is the implementation of trigger and DAQ systems to various particle physics projects. Whether for ATLAS, CMS or LHCb, the UK community is heavily involved in delivering novel trigger and DAQ technologies for both the Phase-1 and Phase-2 upgrades of those detectors. Current work is also ongoing on preparing other experiments DAQ, for example, the UK is hoping to deliver a significant fraction of the far detector DAQ for the DUNE collaboration. There is also long-standing involvement related with future linear collider detectors, and the current involvement of UK groups in the AIDA-2020 framework is an example of this activity. Finally, the UK is also involved in R&D involving DAQ systems, for example the novel use of FPGAs for pattern recognition and track fitting.

7.3 Accelerator Technologies

The construction of higher energy hadron colliders (including LHC energy upgrades) will require the development of a new generation of high field superconducting magnets. The challenges of building high energy electron-positron colliers (Higgs factory and beyond) are numerous and include the delivery of cost-effective high-power RF systems for acceleration and nanometre scale beams at the interaction point, two areas where the UK has considerable expertise to contribute.

The pursuit of compact very high field gradient alternative accelerator technologies is also a UK strength. The recent success of the AWAKE programme at CERN points the way to proton driven plasma wakefield acceleration as a potentially viable source of electrons (and positrons) at the 100 GeV+ scale, although a high energy proton source is an essential prerequisite for such a facility. Extremely high-power multi-stage laser-plasma wakefield accelerators could also be a route to high energy electrons (e.g. 10 GeV per stage) without the need of a proton driver but the difficulties of successfully operating dozens of back-to-back plasma cells are considerable. Dielectric accelerators offer yet another way to achieve high field gradients but are less likely to be suitable for very high energy applications. These technologies may take decades to perfect but the necessary R&D should certainly be undertaken.

2019 recommendations and modifications

Note: the main changes are the first few recommendations before the programme details. Some detailed recommendations have been retired because they have been folowed, and there are minor wording changes over ongoing projects. The future accelerator recommendation reflects the more diverse options now open and the attendant uncertainties, echoing the agreed position for the European Strategy process.

Recommendation 1: The UK must continue to pursue a world-leading particle physics programme, focussed on addressing the internationally acknowledged high priority science questions.

Recommendation 2: The core funding of the programme is essential for exploitation and innovation, but has fallen dramatically over the last decade. STFC must pursue every avenue to increase the core funding in real terms.

Recommendation 3: When new projects are initiated, the downstream impact on the core programme must be considered, including scenario planning for continued attrition of the core programme funding.

Recommendation 4: 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 5: It is important that basic R&D be continued in detectors to support the long-term programme. STFC should facilitate access to funding opportunities for these activities, where possible using external funding streams.

Recommendation 6: In the case of continued attrition to the funding, STFC should attempt to maintain minimal capability in areas that are otherwise defunded, to allow regrowth at a later stage.

Recommendation 7: 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 8: The UK must fully exploit its investment in ATLAS and CMS by maintaining a leading role in the science exploitation of the current detectors at the 13/14 TeV design energy *and high luminosity****.***

Recommendation 9: The UK must invest *throughout* ***the ATLAS and CMS upgrades so as to maximise the science output over the entire LHC lifetime, including the high luminosity phase.***

Recommendation 10: The UK must maintain its computing capability commensurate with the requirements of its experimental programme, including those associated with the LHC upgrades.

Recommendation 11: The UK is strong in providing theoretical and phenomenological input to the LHC. Continued commitment to this activity is essential to the full exploitation of LHC data.

Recommendation 12: *It is essential that the UK engages with future high-energy e^+e^- Collider initiatives and positions itself to play a leading role should such a facility go ahead.*

Recommendation 13: If the LHeC goes ahead, the UK should exploit its current position to maintain a leading role in its construction and exploitation.

Recommendation 14: It is essential that the UK maintains an involvement in developing ideas for future very-large-scale energy frontier projects such as the CERN FCC*-hh* ***and the Chinese CEPC-SppC, so as to be well positioned should any of them move towards realisation.***

Recommendation 15: The UK should support initiatives for novel acceleration techniques with a view to the long-term future of energy frontier and other accelerator- based science.

Recommendation 16: The UK must fully exploit its investment in LHCb by maintaining a leading role in the *development and* ***science exploitation of the current*** *and upgraded* ***detector.***

Recommendation 17: There is a strong science case for precision kaon physics and the UK should provide the modest resources required to enable its participation in the full exploitation of the NA62 dataset.

Recommendation 18: There is a strong science case for precision muon experiments. The UK community, both experimentalists and theorists, should be supported to best exploit the possible opportunities.

Recommendation 19: There is considerable UK leadership and emerging interest in SHIP, which potentially has high physics reward. This should be evaluated further and be reviewed should the project go ahead internationally.

Recommendation 20: The UK must fully exploit its investment in T2K by maintaining a leading role in the science exploitation.

Recommendation 21: The UK has a leading role in the MINOS+ experiment and should provide the modest support required to allow continuing participation.

Recommendation 22: The UK has strong leadership in planned next-generation long baseline neutrino oscillation experiments in the USA and Japan. It is essential that the UK continues to make a substantial contribution in this area, with a view to eventual exploitation of least one such experiment.

Recommendation 23: The UK should pursue a coherent and world-leading programme of research in neutrinoless double beta-decay.

Recommendation 24: The UK should maintain its involvement in world-leading electron and neutron electric dipole moment search experiments.

Recommendation 25: The UK must continue to support a world-leading long-term programme in theoretical particle physics, particularly in fundamental theory, phenomenology, lattice theory and particle cosmology.

Recommendation 26: The UK should continue to support the computing needs of the Theoretical Physics commu