The Particle Physics Advisory Panel
to STFC

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1. INTRODUCTION

The Particle Physics Advisory Panel (PPAP) to STFC is charged with liaising with the UK particle physics community, maintaining an overview of its activities, continuously developing a roadmap and advising STFC on relevant matters as and when appropriate. It meets typically once every two months to exchange and review news and hosts an annual 1-2 day community meeting as well as ad hoc grant-holders fora when there is a need.

In November 2012, PPAP released its latest roadmap document\(^1\), identifying current and future scientific challenges and opportunities for the UK in particle physics. It made a set of recommendations for a balanced programme, both in terms of breadth of science and timescale of projects, from the exploitation phase of running experiments to the longer-term R&D phase. It also emphasised that a healthy particle physics programme should include both a sizeable commitment to the largest scale worldwide ‘flagship’ projects such as the LHC and a portfolio of ‘high risk, high reward’ projects, i.e. those with a limited physics focus, but where a paradigm-changing result is possible, which might not be accessible through other experiments. This 2012 document was used as input to the 2013-14 UK Programmatic Review\(^2\), which broadly followed its recommendations.

There have been a number of important developments since November 2012. Internationally, the updated CERN Council Strategy for European Particle Physics\(^3\) and the HEP Prioritisation Panel P5 document in the US\(^4\) both placed their highest priority on the full exploitation of the LHC. In the UK, significant new scientific opportunities and initiatives are being pursued by particle physics academics.

In this document, PPAP provides an update on its 2012 roadmap report, with emphasis on projects with substantial UK involvement which have newly appeared or developed significantly since that time. The content is two-fold:

- A compilation of information on projects in which UK particle physicists are currently engaged, summarising leadership roles, main responsibilities and opportunities, giving indicative timescales and providing information on funding status and sources. The main scientific motivations for each project are also summarised, especially where there is relevant information which was not already discussed in the 2012 roadmap document.
- A series of PPAP recommendations, as given in bold font. These either reiterate, expand upon, or replace those in the 2012 document.

Although not explicitly repeated here, the general motivation for pursuing particle physics remains unchanged and is neatly summarised in a set of fundamental questions with textual elaboration in the 2012 document. We do, however, reiterate the final recommendation of the 2012 roadmap report:

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\(^1\) http://www.stfc.ac.uk/resources/PDF/PPAPreportFINALNovember2012.pdf
\(^2\) https://www.stfc.ac.uk/files/3067/3067_res_2.pdf
\(^4\) http://www.usparticlephysics.org/p5/


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

The CERN laboratory remains at the centre of the landscape of world particle physics and is the location of the experiments on which a large majority of UK particle physicists work. We therefore also reiterate the recommendation from 2012:

**Recommendation 2:** 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.

The remainder of this document provides a survey of current UK activities. Its contents are derived from presentations and extensive discussion at our UK community meeting in July 2014, further discussions between PPAP members, project leaders and a circulation to the UK community. Since there is overlap of interests and personnel between the two areas, this document includes projects within the remit of the Particle Astrophysics Advisory Panel (PAAP) where they relate to elementary particles. For reference, the projected 2015/16 distribution of STFC resources in the particle physics and particle astrophysics areas are shown below, based on the 2013 Programmatic Review.

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2. Private Communication, STFC
2. THE ENERGY FRONTIER

2.1 ATLAS and CMS (‘LHC GPDs’) and their upgrades

The 2012 roadmap document followed quickly after the discovery of the Higgs boson. Since then, the LHC General Purpose Detectors (GPDs) have begun work on determining the properties of the Higgs. It is almost certainly spin-parity $0^+$ and its couplings to ZZ, $\gamma\gamma$ and WW are in line with Standard Model expectations to current precision. There is also now strong direct evidence, through the $\tau\tau$ channel, for Higgs boson decays to fermions. GPD searches for physics beyond the Standard Model have excluded a wide range of possibilities up to new physics scales of typically 1-2 TeV. The restart of data taking with a higher centre-of-mass energy of 13 TeV (compared with 8 TeV previously) is eagerly awaited in 2015. This increase in energy will substantially enhance the sensitivity of the GPDs to new phenomena beyond the Standard Model.

The first LHC run obtained approximately 1% of the total target integrated luminosity at around half the design energy. The current detectors are performing well at luminosities and multiple-event pile-ups beyond their original specification, but have a limited lifetime and will certainly not cope with the ultra-demanding environment of the high luminosity LHC (HL-LHC, expected from mid-2020s). The detector upgrades in the present long shutdown (LS1) were relatively modest. UK work is well underway towards the more extensive upgrades during LS2 (~2018-19) and the very major upgrade programme planned for LS3 (~2024 - for HL-LHC). The instrumentation requirements to meet the severe technological challenges of the HL-LHC (radiation dose, data rates and pile-up) motivate significant international R&D activities.

By the start of the HL-LHC data taking period a number of scenarios are possible: direct evidence for new physics may have been discovered in the form of new particles or missing energy signatures; deviations from Standard Model expectations may have been observed - for example in Higgs branching ratios; or no deviations from Standard Model expectations may yet have been made manifest. In all of these scenarios the HL-LHC will provide critical information, enabling the disentangling of possible origins of observed new physics or providing a major increase in sensitivity in the search for its evidence. The UK involvement in ATLAS and CMS is funded mainly by STFC through Consolidated Grants and Experiment Grants.

Scientific Goals:
Broad exploration of the multi-TeV energy frontier using pp collisions, including characterisation of the Higgs boson and searches for new physics in uniquely accessed new kinematic domains. Also precision studies and tests of the Standard Model, often in areas, such as top quark production and multiple weak boson production, where there has been little or no previous exploration.

UK Leadership (ATLAS):
The current spokesperson (ex deputy-spokesperson and physics coordinator) and recently retired physics and upgrade coordinators are from UK institutes, as well as the incoming physics coordinator. In addition the UK provides multiple leaders of physics analysis working groups and sub-groups, and of many operational aspects of the experiment, including the coordinators of both the current and upgrade Inner Detector projects and of Data Preparation.

UK Responsibilities (ATLAS):
ATLAS is the largest UK particle physics activity by some distance, with 300 authors (about 10% of the collaboration). The UK performs a wide range of pivotal roles and delivered substantial components of the tracking, triggers, DAQ, computing resources and software for Run 1. The main UK involvements in the upgrade programmes are a substantial part of the I Tk (new all-silicon inner tracker for installation at LS3), the LS2 and LS3 phases of the first
level calorimeter trigger (L1Calo), a new first level track trigger (L1Track) for LS3, plus computing, software and Higher Level Trigger upgrades.

UK Institutes (ATLAS):

UK Leadership (CMS):
The UK has provided the spokesperson, deputy spokesperson, deputy tracker project manager, upgrade coordinator, ECAL endcaps project manager and will be providing the next project leader for the ECAL (starting 2015). In addition the UK has and is providing various leaders of physics coordination and analysis groups.

UK Responsibilities (CMS):
The UK provides about 4% of CMS authors. The UK led the design and delivery of the ECAL end-caps, the front-end readout of the Silicon Tracker (including the readout ASIC used for both the tracker and the ECAL) and the calorimeter trigger. The UK provides significant computing resource to the experiment. It also has a major and leading role in the calorimeter trigger upgrade for installation at LS2 and is performing R&D towards LS3 upgrades in the trigger and tracker.

UK Institutes (CMS):
Bristol, Brunel, Imperial College, RAL.

Milestones:
2015: LHC restart at 13 TeV.
2023-2025: LHC LS3, leading to HL-LHC.

The LHC is the world’s flagship energy frontier facility. With only around 1% of the planned total data sample collected to date, it has already yielded a major, Nobel prize-recognised, discovery. With the expected future programme of energy and luminosity upgrades, further significant discoveries are likely.

Recommendation 3: 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.

Recommendation 4: The UK must invest in the ATLAS and CMS upgrades so as to maximise the science output over the entire LHC lifetime, including the high luminosity phase.

The UK GridPP project has played a leading role in the development of the LHC computing grid, which has succeeded in meeting the very large data volume and processing requirements of the LHC. The demand on Grid resources will increase significantly in the future, as LHC data samples and corresponding simulation requirements grow.

Recommendation 5: The UK must maintain its computing capability commensurate with the requirements of its experimental programme, including those associated with the LHC upgrades.
As discussed in more detail in section 5, the full exploitation of the complex LHC data requires that the experimental and theoretical communities work closely together to design analyses and interpret the observations.

**Recommendation 6:** 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.

### 2.2 Possible Future Linear e⁺e⁻ Colliders

The International Linear Collider (ILC) is a proposed linear electron-positron collider designed to operate at centre of mass energies of 200 – 500 GeV, and with potential to be upgraded to 1 TeV. The energy and luminosity would allow an excellent model-independent characterisation of the Higgs boson. Many BSM models predict only small deviations from the predicted Higgs couplings in the Standard Model. The ILC can measure Higgs boson branching ratios more precisely than HL-LHC and can provide sensitivity to invisible Higgs decays at the sub-1% level. It is also sensitive to many other processes, including precision top-quark physics (e.g. precise top quark mass determination via $e^+e^- \rightarrow t\bar{t}$ at threshold). The ILC design uses superconducting linear accelerator technology, as deployed already in the European XFEL at DESY. Two detector concepts, the International Large Detector (ILD) and the Silicon Detector (SiD), are being developed using state of the art detector technologies.

Japan is the most probable host for the ILC; a potential host site has been indentified at Kitakami in northern Japan. In 2014, MEXT, the relevant Japanese government ministry, initiated a two year review of the project; in 2016 Japan could be in a position to formally commit to the ILC. In 2014, a consortium including representatives of all experimental particle physics groups in the UK was awarded modest STFC funding in order to re-engage with the ILC and with the Japanese initiative in particular.

CLIC (Compact Linear Collider) is a proposed $e^+e^-$ collider, using a novel beam-driven accelerating technique. The aim is for a centre of mass energy of 3 TeV, using a 48km accelerator. The CLIC collaboration is engaged in studies of staging options, with the intention of producing machine designs for intermediate energies around 380 GeV and 1.5 TeV, as well as the ultimate target of 3 TeV.

**Scientific Goals:**

An ILC, operating between $\sqrt{s} = 250 – 500$ GeV, would offer unique capabilities for precision Higgs physics, including model-independent measurements of the Higgs boson couplings. It would also make precision measurements of top quark properties and would directly probe any new physics up to a scale of $\sqrt{s}/2$.

CLIC would achieve broadly similar physics goals, but would be able to probe to substantially higher energies. Should the ILC not be built, CLIC could also be designed with a lower initial-stage energy to address the ILC Higgs and top-quark physics programme.

**UK Leadership:**

A UK physicist is the spokesperson of the CLIC accelerator collaboration and chair of the SiD Institute Board; another is the European director of the Linear Collider Collaboration; another leads the ILD physics and detector design studies. In addition, the UK provides several physics coordinators and work package leaders for ILC-related projects.

**UK Institutes:**

Birmingham, Bristol, Cambridge, Edinburgh, Glasgow, Imperial College, Lancaster, Liverpool, Manchester, Oxford, QMUL, Open University, RHUL, Sheffield, Southampton, Daresbury, RAL, Sussex, UCL and Warwick all signed the 2014 Lol.
Milestones:
2016: completion of MEXT reviews (physics case and TDR validation) of ILC.
2016-17: decision on proceeding with ILC Higgs Factory in Japan.
2018-20: possible start of ILC construction.
2018: CLIC Project Plan for energy-staged implementation.
2019: European Strategy update: decision on future direction for CLIC.
2024-5: earliest possible start of CLIC phase 1 (~380 GeV) construction.
2028-30: possible start of ILC operation.
2035: earliest possible commissioning of CLIC phase 1.

Recommendation 7: It is essential that the UK engages with the Japanese Linear Collider initiative and positions itself to play a leading role should the facility go ahead.

Recommendation 8: The UK should continue to lead in developing key systems vital for demonstration of CLIC feasibility.

2.3 A possible high-energy lepton-hadron collider
The Large Hadron electron Collider (LHeC) project aims to upgrade the capabilities of the LHC by colliding its protons with electrons produced in a new 60 GeV energy-recovery linear accelerator, resulting in the highest resolution microscope for nucleon and nuclear matter ever built using clean lepton probes. As an upgrade to the LHC rather than a complete new facility, the LHeC is a significantly (factor ~10) smaller scale project than other possible future energy-frontier projects. New developments since the Conceptual Design Report publication in 2012 have increased the design luminosity from $10^{33}$ cm$^{-2}$s$^{-1}$ to $10^{34}$ cm$^{-2}$s$^{-1}$, opening a precision Higgs programme and increasing the synergy with the HL-LHC programme. A prototype for the Energy Recovery Linac (ERL) is included in CERN planning. The key element (a high quality superconducting cryo module at 802 MHz frequency) is under design at CERN and Jefferson Laboratory. CERN has also set up a renewed project structure, to further develop the physics case, the detector and accelerator concepts and the collaboration. The LHeC project receives modest funding from CERN and a low level of UK funding through academic time on Consolidated Grants.

Scientific Goals:
Broad goals across particle and nuclear physics, including precision investigation of the Higgs boson in production and decay modes not easily accessible at the LHC. Also, significant improvement of our knowledge of proton parton densities at high Bjorken-x, as required for a full exploitation of the HL-LHC BSM potential, and at intermediate Bjorken-x, as required for precision LHC Higgs physics. In addition, precision investigation of the strong and electroweak interactions at the TeV scale, including the expectation of new parton dynamics at low Bjorken-x.

UK Leadership:
The International Spokesperson of the LHeC is a UK physicist, as are two further coordination group members (out of 11) and four physics group conveners (out of 11).

UK Institutes:
Birmingham, Cockcroft, Liverpool, Oxford, QMUL. Also interest in eA programme from several nuclear physics groups and collaboration on ERL test facility and other accelerator topics from ASTeC and Universities.
Milestones:
2015: Physics report update to CERN. Design of the ERL Test Facility
2017: Conclusion of physics, detector and accelerator design as input to 2019 European Strategy Update.
2019: Earliest possible ERL test facility start date.
2025 (post LS3): Earliest possible ep operation alongside pp data-taking at HL-LHC.

Recommendation 9: If the LHeC goes ahead, the UK should exploit its current position to maintain a leading role in its construction and exploitation.

2.4 Other Possible Future energy-frontier colliders
With a view to the longer term future, the CERN Future Circular Collider (FCC) study will report on potential post-LHC energy frontier options in time for the next CERN Council European Strategy evaluation in 2018. Organised by ECFA, the goal is a Conceptual Design Report for a hadron collider with a centre of mass energy of 100 TeV in a 80-100 km tunnel, also including a lepton collider with a centre-of-mass energy up to 350 GeV and an electron-proton option. A design study for the hadron machine called EuroCirCol is receiving European funding through Horizon 20:20.

There is a proposal for a circular $e^+e^-$ collider based in China (CEPC), with data-taking proposed in the 2030s, and a related proton-proton collider (SppC), with data-taking proposed in the 2040s. The machine parameters are broadly similar to FCC, and the intention would be to design and construct the machines with international participation.

A muon collider remains a long-term possibility for future exploration of the energy frontier through lepton collisions, with an additional application for producing intense neutrino beams (see section 4.6).

Looking towards completely new acceleration techniques, the AWAKE experiment aims to demonstrate proton-driven plasma wakefield acceleration for the first time. Electrons will be accelerated by wakefields of about 1 GV/m generated by protons from the CERN SPS in a plasma column. AWAKE was approved as a CERN project in August 2013, with significant resources, personnel and capital, invested. AWAKE-UK groups received a modest 2-year project grant from STFC in October 2012, which has been extended by one year to bridge the period of the accelerator review.

Scientific Goals:
FCC: Exploration of energy frontier collider options in the post-LHC era, tightly linked to the physics goals following LHC results from Run 2.
AWAKE: Demonstration of proton-driven plasma wakefield acceleration as a future technology for particle physics.

UK Leadership:
FCC: The MDI work package of the machine design study EuroCirCol is led by JAI. A UK physicist coordinates studies for the electron-proton option (FCC-he).
AWAKE: Deputy Spokesperson; publications and speakers committee member; task leaders for electron energy spectrometer, DAQ, discharge plasma source and the electron source linac.

UK Institutes:
FCC: All HEP groups are watching long-term future collider developments with interest; most have low-level involvement in evaluating one or more of the cases. Involvement in EuroCirCol from the accelerator institutes.
AWAKE: Central Laser Facilities (plasma physics), Cockcroft Institute, Imperial (JAI plasma physics), JAI Oxford, Strathclyde (plasma physics), UCL.
Milestones:
2016–18: Initial AWAKE data taking
2020– : Second phase of AWAKE data taking

Recommendation 10: 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 and the Chinese CEPC-SppC, so as to be well positioned should any of them move towards realisation.

Recommendation 11: 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.
3. Flavour Physics

The focus of flavour physics today is probing physics beyond the Standard Model through high precision measurements which are sensitive to “off-shell” virtual particles, providing a unique window on mass scales far exceeding those probed through the search for the direct production of new particles in colliders. The information on physics beyond the SM obtained in this way is thus complementary to that accessible at ATLAS and CMS. While there are some intriguing hints of BSM physics in the flavour sector, no clear signal has yet been observed. This indicates either a BSM sector with a very specific, fine-tuned flavour structure, or a very high mass scale. Both scenarios require detailed study of the flavour sector with the highest precision possible. The field attracts considerable international interest, with approved/operating high profile projects in Asia, Europe and the US. In the following, the emphasis is placed on those in which the UK is engaged.

3.1 LHCb and the LHCb Upgrade

LHCb is the dedicated flavour physics experiment at the LHC; it is able to perform a broad flavour physics programme with unrivalled BSM sensitivity in the beauty and charm sectors. Its forward acceptance and instrumentation also permit unique measurements in electroweak physics and QCD

Key results from LHCb’s run 1 include the first observation of CP violation in B$^+$ mesons, measurements of the key CP violation parameters $\gamma$ and $\phi_b$ at a precision substantially better than previous world averages, a world-leading determination of $|V_{ub}|$ using exclusive baryon decays, the first observation of charm mixing in a single measurement, and the best constraints on CP violation in charm. The first observation/evidence of the very rare decays $B_d \rightarrow \mu^+\mu^-$ and $B_d \rightarrow \pi^+\nu\bar{\nu}$ was achieved in close collaboration with CMS. While these and many other results are consistent with the Standard Model, intriguing hints of BSM physics have emerged in LHCb’s study of decays mediated by electroweak penguin diagrams such as $B_d \rightarrow K^*\mu^+\mu^-$. Results beyond LHCb’s core flavour physics programme have also received considerable attention, such as the recent discovery of a new B-baryon. As a consequence of more favourable running conditions and an improved High Level trigger scheme, Run 2 is expected to approximately quadruple the available data from Run 1.

The LHCb upgrade will improve statistical precision and thus BSM sensitivity by significantly increasing the data acquisition rate, allowing the experiment to operate at roughly an order-of-magnitude higher luminosity, also with significantly increased signal efficiency. These improvements will take place during LS2 and do not require, but are compatible with, further planned LHC upgrades. The LHCb collaboration is currently exploring the physics opportunities and possible detector designs for a potential further upgrade at LS3. LHCb-UK is currently funded predominantly by STFC with additional contributions via ERC grants.

The UK theory community plays a leading role in heavy flavour phenomenology and provides crucial theory input to LHCb’s analyses. Progress in Lattice QCD, in which the UK is internationally leading, is a vital ingredient in LHCb’s programme of probing for BSM physics with precision measurements.

Scientific Goals:
Discover and characterise, or heavily constrain, physics beyond the Standard Model at mass scales far exceeding LHC energies, through a broad programme of measurements of unprecedented precision. LHCb/upgrade will also pursue a programme beyond flavour physics, such as cross section measurements in a forward kinematic regime inaccessible to other LHC experiments.
UK Responsibilities:
LHCb’s most innovative and critical components (VELO and RICH) are UK-built. A substantial UK contribution to the upgrades of these components has been approved. The UK also delivers significant computing resource to LHCb.

UK Leadership:
UK physicists have held many key leadership positions, including Spokesperson (twice), Collaboration Board Chair and Physics Coordinator (twice). Current UK leadership positions include the LHCb Spokesperson, RICH project leader (and deputy), VELO project leader (and deputy), Editorial Board Chair, Operations Coordinator, Deputy Operations Planning Group Chair, Deputy Computing Coordinator, 5 out of 16 physics analysis working group conveners and other positions of responsibility.

UK Institutes:
UK physicists represent 24% of the LHCb collaboration. - Birmingham, Bristol, Cambridge, Edinburgh, Glasgow, Imperial College, Liverpool, Manchester, Oxford, STFC-PPD/TD, Warwick. All UK LHCb institutes are also part of the LHCb-upgrade.

Milestones:
2015: LHC restart at 13 TeV.
2018: LHCb-upgrade installation.
2020: Start of data-taking with upgraded LHCb detector.

LHCb is the world’s flagship flavour physics experiment. The planned detector upgrade programme will expand the potential for significant BSM discoveries.

Recommendation 12: The UK must fully exploit its investment in LHCb by maintaining a leading role in the science exploitation of the current detector.

Recommendation 13: The UK must invest in the LHCb upgrade so as to maximise the science output over the lifetime of the experiment.

3.2 High-precision dedicated kaon experiments
UK involvement in kaon physics is currently limited to the NA62 experiment at CERN. Precision studies of rare kaon decays in theoretically precisely understood modes such as $K^* \rightarrow \pi^\pm \nu\bar{\nu}$ to be measured at NA62, could provide clear signatures for physics beyond the Standard Model. The experiment also has a wider programme of searches for physics beyond the Standard Model. After successful engineering runs and detector development over the last couple of years, the baseline NA62 detector was ready for beam when the SPS turned on after the LS1 shutdown. The UK involvement has been primarily funded by an ERC Advanced Investigator grant. Once finished, the UK groups will seek STFC funding in order to capitalise on the UK’s key role in the NA62’s construction by playing a leading role in its exploitation.

Other currently foreseen major kaon experiments with no UK involvement include the K0T0 and TREK experiments at J-PARC. The KLOE and KLOE-II experiments at Frascati also continue to publish results.
Scientific Goals:
Measurement of the rare kaon decay, $K^+ \rightarrow \pi^+\nu\bar{\nu}$ and extraction of a 10% measurement of the CKM parameter $|V_{td}|$. Several other searches for new physics.

UK Responsibilities:
The UK is responsible for the CEDAR/KTAG detector, which identifies kaons in the mixed-particle unbunched beam and is vital to the success of the experiment. This has been delivered and is performing well.

UK Leadership:
Coordination of and full responsibility for CEDAR/KTAG detector. Coordination of software and reconstruction. GRID implementation and lepton flavour and exotics analysis group coordination. Co-responsibility for development and maintenance of rare-kaon trigger and run control system.

UK Institutes:
Birmingham, Bristol, Glasgow, Liverpool (including theory).

Milestones:

Recommendation 14: 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.

3.3 High-precision dedicated muon experiments
The importance of searches for charged lepton flavour violation has been highlighted for example in the recent report from the US HEP prioritisation panel (P5). UK engagement in this area presently takes place through the COMET (J-PARC) experiment, which searches for muon-to-electron conversion ($\mu^- N \rightarrow e^- N$) and aims to extend the previous best limit by four orders of magnitude by the beginning of the next decade. Work on COMET is ongoing on detector prototypes and beamline construction in order to start Phase 1 data taking in 2016, followed by Phase 2 in 2019. The UK effort is supported via staff in the Consolidated Grant.

There is UK interest in joining the Mu2e experiment at FNAL, with a view to constructing the Xray detector and beam monitors from 2017. There is no UK involvement in the MEG and Mu3e experiments at PSI, but a joint Mu2e and COMET collaboration (AlCap), seeking to characterise the Mu2e / COMET backgrounds using a PSI muon beam has significant UK contributions.

The g–2 experiment at FNAL aims to measure the anomalous magnetic moment of the muon to unprecedented precision using polarised muon decays, following on from a closely related experiment at BNL, which observed a difference between experiment and theory which has been evaluated at up to 3.5$\sigma$. The level of precision is potentially sensitive to a wide range of BSM interactions. The experimental programme is backed up by close collaboration with UK and other theorists in minimising theoretical sources of uncertainty in the Standard Model predicted value. The BNL magnet was successfully shipped to FNAL and is now housed in the newly-constructed experimental building. A data sample matching the BNL experiment in size will be accumulated in 2017 and one twenty times larger is expected by the end of 2019. UK groups were awarded a three year PPRP experiment grant in April 2014.
Scientific Goals:
COMET / Mu2e: Search for neutrinoless conversion of muon to electron, an unequivocal signature for physics beyond the Standard Model.
g–2: Measurement of anomalous magnetic moment of the muon with a precision of 0.14 parts per million.

UK Responsibilities:
COMET: The UK has delivered the Fast Control Board electronics and takes responsibility for offline software.
g–2: The UK is responsible for the design and construction of the straw trackers, including the data acquisition system and will provide an independent technique to measure the magnetic field calibration. Work on simulating the beam dynamics of the ring has also been supported by Liverpool/Cockcroft. Theoretical work on improving the Standard Model prediction is underway in several UK groups.

UK Leadership:
COMET: Collaboration Board Chair, Executive Board and Speakers Board members, coordinators of trigger, data acquisition, offline software systems and proton targetry.
g–2: Chair of publications/speakers board, straw tracker construction, backend readout and DAQ, ³He magnetometer, beam dynamics and offline tracker reconstruction and calibration and alignment software.

UK Institutes:
COMET: Imperial, Manchester, RAL, UCL
g–2: Cockcroft, Liverpool, Oxford, UCL
Mu2e: Liverpool, Manchester, RAL, UCL

Milestones:
2015: Start of Mu2e construction.
2017: Data taking for COMET Phase 1.
2017–19: Data taking for g–2.
2019-23: Data taking for COMET Phase 2.
2020–24: Data taking for Mu2e Phase 2.

Recommendation 15: 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.

3.4 SHiP
SHiP is a proposed general-purpose fixed-target facility based on a new beam-line at the CERN SPS. It will initially be used by the SHiP experiment to search for hidden particles as predicted by a large number of models of Hidden Sectors which are capable of accommodating dark matter, neutrino oscillations and the origin of the full baryon asymmetry in the Universe. The physics capabilities also extend to Standard Model measurements such as those of tau neutrinos. This initiative was put forward to CERN’s SPS committee in October 2013. The SHiP Collaboration was formed in December 2014 with over 40 institutes as founding members. CERN approval of the project is being sought in 2015.

Scientific Goals:
Search for hidden particles in new physics models which incorporate candidates for dark matter, neutrino oscillations, etc.; measurements of Standard Model physics such as tau neutrinos and direct search for dark matter using a neutrino-type detector in the beam-line.
UK Leadership:
Collaboration Spokesperson.

UK Institutes:
Bristol, Imperial, UCL, Warwick, (RAL)

Milestones:
2015: Technical proposal and CERN project approval.
2023: Possible start of SHiP data taking.

Recommendation 16: 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.
4. Neutrino physics

4.1 T2K

T2K is the first off-axis long baseline neutrino experiment and is steadily running with a beam power above 320 kW in both neutrino and antineutrino beam configurations, sending neutrinos from the Japanese J-PARC site to Super-Kamiokande. T2K will continue to be the leading experiment in neutrino physics for the next 5 – 10 years. The main UK contribution to the experiment has focused on the near detector. In the past three years, T2K has delivered the world’s first statistically significant neutrino oscillation appearance signal, and in the coming three years the main physics programme will focus on improved measurements of $\theta_{13}$, $\theta_{23}$ and $\Delta m^2_{23}$ in both neutrino and antineutrino modes. There is also a world-leading programme of near detector cross-section measurements. The anticipated data set by 2020 will represent a factor ~10 increase relative to today. With the full data set, T2K will have 3$\sigma$ sensitivity to CP violation in the neutrino sector, which will be strengthened by combining it with NOvA data. The collaboration is currently studying upgrades to the near detectors. Leadership positions within T2K, including the former international co-spokesperson, have led the UK to leading roles in the future Japanese neutrino programme (Hyper-Kamiokande).

The UK contribution to T2K is funded mainly by the STFC through Experiment and Consolidated Grants, but has also attracted ERC grants and Royal Society awards.

Scientific Goals:
T2K is focussed on the discovery of $\nu_\mu$ to anti-$\nu_e$ oscillation and world-leading measurements of oscillation parameters in $\nu_\mu$ and anti-$\nu_\mu$ disappearance. Other goals include searches for sterile components in $\nu$ and anti-$\nu$ disappearance by observation of neutral-current events, and world-leading contributions to neutrino-nucleus cross-section measurements.

UK Leadership:
The UK has provided the international co-spokesperson, the near detector project manager, the ECal project manager, and an Executive Committee member. In addition the UK provides multiple leaders for physics analysis working groups and sub-groups, and for many operational aspects of the experiment, including one of the near detector coordinators.

UK Responsibilities:
T2K is the UK’s largest neutrino project, with 102 authors (21% of the collaboration). The UK performs a wide range of pivotal roles and delivered the off-axis near detector ECal, the DAQ for the on-axis near detector and much of the off-axis near detector, as well as crucial components of the neutrino beamline. The UK provides significant computing resource to the experiment.

UK Institutes:
Imperial College, Lancaster, Liverpool, Oxford, QMUL, Sheffield, STFC/Daresbury, STFC/RAL, Warwick.

Milestones:
2015: Operation at 400 kW.
2018: Operation at 750 kW.
2020: End of T2K operation.

Recommendation 17: The UK must fully exploit its investment in T2K by maintaining a leading role in the science exploitation.
4.2 MINOS/MINOS+

MINOS+ is an extension of the MINOS run using the medium-energy FNAL NuMI beam for NOνA. MINOS+ took $3 \times 10^{20}$ protons on target in the run period up to September 2014 and may double that by 2015. MINOS+ has world-leading sensitivity to sterile neutrino searches in the region of $\Delta m^2$ from $10^{-3}$ to $10$ eV$^2$, though the disappearance channels. Combination of the antineutrino disappearance data with that from the Daya Bay collaboration is being pursued.

The experiment is supported by STFC through a Spokesperson’s RA.

**Scientific Goals:**
Searches for non-standard 3x3 neutrino mixing, sterile neutrino searches, and non-standard interactions.

**UK Leadership:**
The UK provides the co-spokesperson, Analysis Coordinator and Deputy Analysis Coordinator, in addition to other committee and analysis convenorships.

**UK Institutes:**
Cambridge, Manchester, Oxford, Sussex, UCL.

**Milestones:**

*Recommendation 18: The UK has a leading role in the MINOS+ experiment and should provide the modest support required to allow continuing participation.*

4.3 NOνA

NOνA is the second FNAL off-axis long baseline neutrino experiment. Because of the longer baseline and higher neutrino energy, it has sensitivity to the mass hierarchy as well as neutrino appearance and disappearance oscillation searches. NOνA began taking data in 2013, and completed the far detector in 2014.

UK involvement in NOνA is funded through an ERC grant.

**Scientific Goals:**
NOνA is currently focussed on observation of muon to electron neutrino oscillation, as well as muon neutrino disappearance and determination of the mass hierarchy.

**UK Leadership:**
The UK plays a leading role in the NOνA analysis working groups.

**UK Institutes:**
Sussex.

**Milestones:**
2014: start of NOνA operation.
2020: end of NOνA operation.
4.4 Future Long Baseline Neutrino Oscillation Experiments

The primary physics target of all next-generation long baseline neutrino oscillation projects is to measure a possible CP violation signal in the lepton sector of the Standard Model. This, as well as the neutrino mass hierarchy, are currently the main open questions in neutrino oscillation physics. In addition, other fundamental physics targets such as proton decay and astrophysical neutrinos form part of the rich physics programme for these large volume detectors.

UK involvement in the next generation of long baseline oscillation projects centres on the Hyper-K and DUNE experiments. These projects are currently in the development phase, but the final goal is to deliver multi-kiloton scale detectors, partnered with MW-class neutrino beams, capable of measuring the neutrino mass hierarchy, searching for CP-violation in neutrinos across most of the phase space and taking our knowledge of neutrino oscillation parameters to new levels of precision.

DUNE will observe the upgraded (PIP-II) 1.2 MW beam at FNAL with a liquid argon TPC. Hyper-K, a new, next-generation, megaton-scale water Cherenkov detector to replace the existing Super-Kamiokande, will be exposed to an upgraded J-PARC neutrino beam. UK institutes were awarded funding by the PPRP in October 2014 to participate for the next 3-years in the preparatory phase of Hyper-K and DUNE. Hyper-K also received EU funding through the Marie Curie RISE programme. Beyond the current phase, funding will be sought to play a full role in the construction of these experiments. Both projects are expected to be ready for data taking around 2023.

Scientific Goals:
Measurements of CP violation in the leptonic sector of the Standard Model and the neutrino mass hierarchy. Precision measurement of neutrino oscillation angles. Also measurement of neutrinos from supernovae and searches for proton decay.

UK Responsibilities:
DUNE: Physics programme, LAr-TPC reconstruction, DAQ and trigger, TPC wire-plane design and construction, first for prototype projects (35 ton detector, SBND), then for the far detector.
Hyper-K: Physics programme, computing, DAQ, calibration, photosensor R&D, near-detector design, beam.

UK Leadership:
DUNE: Co-Spokesperson and one member of executive committee, Leadership in several work packages.
Hyper-K: Steering committee co-chair, Project management co-chair, Institutional Board Representative chair, Leadership in several work packages.

UK Institutes:
Milestones:
**DUNE:**
- 2015: First data from 35t prototype.
- 2015: CD-2a/CD-3a review of far site excavation
- 2017: WA105 and DUNE single-phase prototype operational at CERN.
- 2023: Completion of first DUNE 10 kt far detector module

**Hyper-K:**
- 2017: First data from WC prototype.
- 2018-23: Construction of Hyper-K.

Since the publication of the 2012 PPAP Roadmap, the UK neutrino community has developed a coherent and focussed programme for participation in next generation long baseline neutrino experiments.

*Recommendation 19: 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 engages with R&D in this area, with a view to participation in at least one such experiment.*

### 4.5 Neutrinoless double-beta decay experiments

The motivation to search for neutrinoless double-beta decay remains compelling, with no other way to answer questions regarding the nature of the neutrino and additionally, gain access to the absolute neutrino mass scale.

The UK has interests in two projects, SNO+ and SuperNEMO. SNO+ reuses the existing SNO facility and thus offers a timely and cost-effective neutrinoless double-beta decay experiment. Recent UK-led investigations on the use of tellurium in SNO+ have the potential to give world-leading sensitivity, with the possibility to begin probing the inverted hierarchy in the next 3-5 years. SuperNEMO will have sensitivity near this range, but its main strength is the unique topological signature that would demonstrate neutrinoless double-beta decay if a signal is found. The UK SuperNEMO effort is funded by STFC to develop a demonstrator module. UK involvement in SNO+ is funded through STFC and an ERC grant. SNO+ also has a programme of other measurements including the study of solar neutrinos.

**Scientific Goals:**
Determination of the nature of neutrinos (Majorana or Dirac) and measurement of the effective neutrino mass. Also constraints and guidance in the search for the neutrino mass mechanism.

**UK Leadership:**
SuperNEMO: Co-spokesperson, Chair Institute Board, several work package leaders.
SNO+: Chair Scientific board, Coordinator speakers committee, lead several work packages.

**UK Institutes:**
SuperNEMO: Imperial College, Manchester, UCL, Warwick.
Milestones:
SNO+:
2015: Finish water running, transition to scintillator, construct Te purification system.
2016: Introduce isotope, first results.
2017: New proposal to upgrade detector and loading aimed at bottom of IH
2018/2019: Finish Phase I (sensitivity approaching 50 meV)
SuperNEMO:
2016: Commissioning of the SuperNEMO demonstrator module.
2017: Demonstrator module demonstrates sensitivity.
2018: Demonstrator module reaches target 0νββ sensitivity using Selenium-82.
2018/19: Full detector construction planning

Recommendation 20: The UK should pursue a coherent and world-leading programme of research in neutrinoless double beta-decay.

4.6 Further Neutrino Projects

The issue of the possible existence of sterile neutrinos with Δm^2 near 1 eV^2, prompted by the electron appearance results in the LSND, and later miniBooNE, experiments, and bolstered by the reactor neutrino flux anomaly, has yet to be settled. A number of programmes are in development which will test the sterile neutrino hypothesis. Experiments such as SoLiD in Belgium, SBND plus microBooNE at Fermilab, SHiP and possibly nuSTORM (see below) at CERN, are capable of testing this hypothesis at the required mass splitting. The UK is involved with strong current leadership positions on all of these experiments. UK participation in MicroBooNE and SBND is strategically aligned with the future DUNE LAr-TPC-based long-baseline programme.

Muon acceleration and storage has considerable physics potential for neutrino physics, including high precision oscillation parameter and CP violation measurements. However, this is an ambitious and long-term programme, which must be seen in the context of the future long-baseline neutrino oscillation experiments described above. The principal UK contribution is the international Muon Ionisation Cooling Experiment (MICE) which is being commissioned at RAL with a view to demonstrating the feasibility of muon beam ionisation-cooling by 2017/18. An incremental approach to delivering science has been articulated, starting with nuSTORM, a facility which is capable of measuring the electron- and muon-neutrino-nucleus cross sections with neutrino flux uncertainties at the per-cent level and making sensitive searches for sterile neutrinos. UK contributions to nuSTORM have been funded through collaborative agreement with FNAL, consolidated grant and individual awards.

PINGU is part of the proposed IceCube-Gen2 atmospheric neutrino project, with a focus on issues of interest to particle physics. It will use atmospheric neutrinos interacting in the Antarctic ice shelf to measure key properties of neutrinos. Using the established IceCube technology, PINGU will be able to determine the neutrino mass hierarchy at high significance after only three years of data taking. The UK is leading work to utilise the existing IceCube/DeepCore detector to demonstrate the concept of measuring the mass hierarchy using neutrino interactions in ice. PINGU will also be able to test whether the mixing angle θ_{23} is maximal, and observe tau neutrino appearance with greater than five standard deviation significance after only a few months. UK institutions are taking a lead in aspects of the development of the physics programme, including the study of atmospheric neutrino flux uncertainties and neutrino cross sections. The UK groups, in collaboration with European partners, are looking to develop a significant contribution to the production of optical modules and the experiment’s software.
The UK is also engaged in the CHIPS experiment, an R&D project to test the feasibility of situating a water Cherenkov detector in a ground level freshwater lake/mine pit. The first CHIPS module will be exposed to the FNAL NUMI neutrino beam. CHIPS is currently funded in the UK (through a Leverhulme Foundation award) and in the USA to deploy and operate a demonstrator module.

**Scientific Goals (Sterile Neutrinos):**
High significance tests of the $\sim 1$ eV$^2$ (LSND and reactor flux) anomalies through appearance and disappearance channels and of the standard three-neutrino paradigm.

**UK Leadership (Sterile Neutrinos):**
SoLiD: Spokesperson.
SBND: Level-2 TPC construction manager, Analysis group convenerships.
microBooNE: Analysis group convenerships.

**UK Institutes (Sterile Neutrinos):**
SoLiD: Bristol, Oxford.
SBND: Cambridge, Lancaster, Liverpool, Manchester, Oxford, Sheffield, UCL.
microBooNE: Cambridge, Manchester, Oxford.

**Milestones (Sterile Neutrinos):**
2015: microBooNE first data taking
2016: SoLiD data taking and oscillation search
2017: SBND commissioning

**UK Responsibilities and Leadership (MICE and nuSTORM):**
As well as providing the international Spokesperson, the international Project Manager, the Physics Coordinator and many work-package and analysis-package leaders for MICE, UK personnel have led the evaluation of the physics performance of nuSTORM and the preparation of the Expression of Interest to mount the experiment as part of a possible Neutrino Platform at CERN.

**UK institutes (MICE and nuSTORM)**
Brunel, CI, Glasgow, Imperial College, IPPP, Lancaster, Liverpool, Oxford, Sheffield, STFC RAL, UCL, Warwick

**Milestones (MICE and nuSTORM)**
2017-18: Completion of MICE demonstration of muon cooling.
2018: Feasibility study of implementation of facility as part of a CERN Neutrino Platform.

**Scientific Goals (PINGU):**
Determination of the neutrino mass hierarchy, detection of tau neutrino appearance, precision measurement of the neutrino oscillation angle $\theta_{23}$, searches for dark matter and detection of supernova neutrinos.

**UK leadership (PINGU):**
Convener of the PINGU mass hierarchy analysis group.

**UK Institutes (IceCube-PINGU):**
Manchester, Oxford (theory), QMUL.
Milestones (PINGU):
2015: Submission of MREFC proposal, with accelerated timeline to approval.
2017: Approval of MREFC funding. Commence full procurement and construction.
2018: First drilling activities and PINGU string deployment.
2019: First physics data with partial detector.
2021: Data taking with full PINGU detector.
2023/24: Mass hierarchy known at high significance.

Scientific Goals (CHIPS):
Ultimately, measurements of CP violation in the leptonic sector of the Standard Model.

UK Responsibility and Leadership (CHIPS):
The CHIPS Spokesperson is a UK physicist.
The UK is delivering the PMT system design and characterisation and the calibration system.

UK Institutes (CHIPS):
UCL.

Milestones (CHIPS):
2017: First neutrino events in NuMI beam.

Recommendation 21: Involvement in small scale neutrino projects should continue to be considered in the context of a coherent UK neutrino physics programme. Where the UK has strong leadership roles, such experiments should be given the modest required support where possible.
5. Non-Accelerator Experiments

5.1 Direct dark matter search experiments

Shining light on dark matter is one of the most important and popular aspects of contemporary science. Astrophysical probes have indicated for decades that this unknown substance dominates the dynamics and matter content of galaxies including our own. Direct dark matter experiments search for dark matter composed of new elementary particles. Of the proposed dark matter candidates, UK activity is focused primarily on those colloquially named WIMPs (weakly interacting massive particles), from which experiments aim to detect extremely rare elastic interactions with ordinary nuclei at the core of very sensitive radiation detectors. There is also some interest in searching for weakly interacting slim particles (WISPs) such as axions.

The UK has a leading role in the LUX-ZEPLIN (LZ) consortium, which aims to develop a multi-tonne detector at the SURF facility in South Dakota, based on the two-phase xenon technology pioneered by the UK-led ZEPLIN collaboration. Some institutes also participate in the LUX experiment, which has the current world-leading sensitivity. In addition, the DRIFT and DMTPC gas TPC technologies have directional capability and may be able to determine whether the Dark Matter flux is correlated with the Earth's galactic motion. Funding for LZ has recently been approved through the experiments grants line and is being sought through Consolidated Grants for exploitation. DMTPC is supported in the UK through Consolidated Grants.

Scientific Goals:
Discover and study WIMP dark matter particles with world-leading sensitivity.

LZ UK Leadership:
Institute Board Chair, members of the Executive and Technical Boards, leadership in several work packages.

LZ UK Institutes:
Edinburgh, Imperial College, Liverpool, Oxford, Sheffield, STFC/Daresbury, STFC/RAL, UCL.

LZ milestones:
2015: LZ approved by DoE and STFC; start of construction.
2016: LUX operation completed.
2018: LUX analyses completed.
2018/19: LZ commissioning; start of exploitation.

Since the publication of the 2012 PPAP roadmap, the UK Dark Matter Community has converged on a coherent approach towards R&D for a next-generation Dark Matter search experiment, focused on LUX-ZEPLIN.

Recommendation 22: The UK should provide capital-phase support for construction of the tonne-scale LUX-ZEPLIN Dark Matter experiment and continue R&D towards directional sensitivity.
5.2 Electric dipole moment search experiments

Measuring electric dipole moments is a background-free, sensitive probe for BSM physics, which is complementary to searches using high energy colliders, because many reasonable extensions to the Standard Model predict measurably large values, corresponding to energy scales much higher than those achievable at the LHC. The UK has a long history of world-leading work on both electron and neutron EDM searches.

The electron EDM (eEDM) experiment at Imperial College held the world record sensitivity until 2013. A new approach based on a fountain of YbF molecules is under development. Participation in the eEDM search is currently funded through EPSRC (which will end in 2016), an ERC grant, and the STFC Consolidated Grant.

UK neutron EDM (nEDM) effort is focused in the short-to-medium term on operation, analysis of data, and subsequent upgrading of a room-temperature experiment at PSI, based on largely UK-designed and built apparatus that set the current world limit. The UK group is renowned for its detailed analysis of systematics. With a view to the longer term, UK scientists have joined a new ILL-based collaboration aimed at further development of a cryogenic nEDM apparatus, building on the substantial UK expertise in that area, expected to begin running in 8-10 years.

Scientific Goals:
Complementary studies of CP (i.e. time-reversal) symmetry violation to those in the quark and neutrino sectors, sensitive to BSM models including non-minimal SUSY and with relevance to baryogenesis.

UK Leadership and Responsibilities:
Historically, UK-led and based experiments have been at the cutting edge. The eEDM experiment remains under development at Imperial College. The UK is developing a cryogenic nEDM insert to be placed inside the magnetic shield for the ILL experiment and is taking responsibility for magentometry in the PSI experiment, as well as core design issues in its upgrades.

UK Institutes:
eEDM: Imperial College
nEDM: RAL, Sussex

eEDM Milestones:
2014: measurement with 1-sigma uncertainty reduced to $8 \times 10^{-29}$ ecm.
2017/8: establish laser-cooling technique, reduce sensitivity to $10^{-30}$ ecm

nEDM Milestones:
2017: Measurement with sensitivity at the level of $\sim 5 \times 10^{-27}$ ecm from PSI
2020: Commissioning of upgraded PSI apparatus, aiming at $\sim 1 \times 10^{-27}$ ecm sensitivity.
2023: Start of running of cryogenic experiment at ILL.

Recommendation 23: The UK should maintain its involvement in world-leading electron and neutron electric dipole moment search experiments.
5.3 The Large Synoptic Survey Telescope

The LSST will be the most ambitious deep optical survey of the Universe yet conducted. It addresses a scientific programme which is primarily within the traditional remit of the Astronomy Advisory Panel. There is participation from UK particle physicists, who are interested in LSST’s sensitivity to major questions in cosmology and particle astrophysics, particularly Dark Energy. Potential constraints on dark matter and the sum of neutrino masses are also of interest. Skills and expertise developed in the particle physics community which are potentially valuable to the project include large scale data processing, large scale detection systems and DAQ. The construction project was approved in the US in 2014 and a large consortium including a small particle physics contingent has recently been awarded experiment funding in the UK. Some groups have also requested support through Particle Physics Consolidated Grants.

Scientific Goals:
Broad goals: the primary astroparticle physics aspect is dark energy, with potential constraints on dark matter and the sum of neutrino masses.

UK Leadership and Responsibilities:
Former Executive Director of the LSST Corporation

UK Institutes:
Edinburgh, Liverpool, Manchester, Oxford, UCL.

Milestones:
2020: Commissioning.
2022-2032: Data taking.
6. Theoretical physics

Scientific Goals:

The UK’s programme in theoretical physics has two key elements – supporting and informing the on-going and planned programme of high energy experimental physics; and in parallel pushing forward new and more speculative ideas that may frame our future understanding of fundamental questions in physics. Four areas of research have been delineated below. There is strong overlap between them however, and the boundaries can shift rapidly with new experimental results.

UK Leadership:

The UK holds a strong position internationally in all the major areas cited below. Where long-term international collaborations exist (for example in the area of lattice QCD) the UK has leadership roles.

UK Institutes:

There were 23 UK group applications to the PPGP (Theory) grants round in 2013, with 180 academics in total, split according to universities as follows: Durham (17), Edinburgh (16), Kings (15), Cambridge (14), Southampton (12), Imperial (12), Swansea (12), Liverpool (10), Nottingham (10), Oxford (10), Queen Mary (8), Sussex (7), Surrey (7), Manchester (5), Lancaster (4), Sheffield (4), Heriot-Watt (3), Glasgow (3), Plymouth (3), UCL (3), City (2), RHUL (2), Newcastle (1).

The fractions of funded academics and PDRA awards (a total of 28) made in 2013 were split, respectively, into: Strings/Conformal Field Theory (45%, 30%), Phenomenology (24%, 39%), Cosmology (20%, 13%) and Lattice (11%, 19%).

Note: these data do not include PDRA numbers (typically 8) associated with the Institute for Particle Physics Phenomenology (IPPP) in Durham, which has direct STFC support. With these posts added the split of PDRA posts in Theory is: Strings/Conformal Field Theory (25%), Phenomenology (53%), Cosmology (8%) and Lattice (14%).

Overview

Theoretical physics has been pivotal in shaping and consolidating the Standard Model of particle physics and our theories of the Universe and is essential for formulating scenarios for future discoveries. Whilst UK research in these areas remains highly competitive with worldwide excellence, there are continuing concerns at the effects of major cuts in the funding supporting this research. UK universities have made significant investment in this area with an increase in academic staff numbers of 50% since 2005. Despite this, there has been a 30% reduction in STFC Consolidated Grant funding for PDRAs, combined with a retraction of significant elements of EPSRC support. Current average support through the Consolidated Grant is less than one RA per six academics. These cuts will impair the UK’s ability to provide wide-ranging theoretical support for its experimental programme into the future and are sapping morale.
6.1 Fundamental Theory

UK research in formal theoretical physics continues to be world-leading, evidenced by multiple ERC awards in this area. Strengths are across the spectrum and include the study of symmetry breaking, supersymmetry and string theory, the study of duality symmetries, solitons and branes in quantum field theory, supergravity and string theory, the holography between gauge theories and gravity, strongly interacting theories, mathematical applications of string theory, new developments in scattering amplitudes, quantum gravity, black holes and string phenomenology.

UK involvement: ~80 staff from 15 institutions.

6.2 Phenomenology

There continues to be internationally excellent UK activity in all areas of phenomenology: QCD, Electroweak and Higgs, BSM, flavour physics, neutrino physics, Monte Carlo simulations, Astroparticle Physics, Lattice QCD Phenomenology and Model Building. For LHC there is particular strength and depth in event simulations (Herwig++ and SHERPA) and tuning (Professor/Rivet), parton distributions (MSTW, NNPDF and LSS), higher order QCD corrections (BlackHat and ROCKET) and precision NNLO calculations, with overlap with formal theory in scattering amplitude developments.

Phenomenology is a strategic priority for the UK with joint activity between experimentalists and theorists enhancing LHC analyses. The UK hosts a dedicated phenomenology research centre, the Institute for Particle Physics Phenomenology in Durham.

UK involvement: ~60 staff from 15 institutions

6.3 Lattice QCD

The primary aim of lattice QCD/lattice field theory is the nonperturbative computation of physical quantities such as hadron masses and matrix elements with sufficient precision to have impact on experiment. The field has now broadened to reach beyond the Standard Model as well as into nuclear physics.

The advent of STFC’s DiRAC High Performance Computing Facility, with capital funding from BIS and now in Phase 2 (2012-2015), has allowed UK lattice theorists to make huge strides forward with their international collaborators. Calculations are now possible for the first time with up and down quarks at their physical masses for fully realistic QCD. The UK has particular strength in flavour physics and the determination of Standard Model parameters (such as quark masses and CKM elements), studies of QCD at high temperatures and/or large baryon densities and searches for viable technicolor scenarios. Currently the UK represents around 10% of the world community but 20% of recent top-cited papers in this field have a UK author.

Funding for phase 3 of DiRAC is now being sought, focussing on 3 architectures to support the range of calculations planned across theoretical particle physics and astrophysics.

UK involvement: ~20 staff from 8 institutions
6.4 Particle Cosmology

Particle cosmology addresses fundamental questions from the early universe such as the origin of the matter/antimatter asymmetry, the composition of the dark matter, the origin of the primordial density fluctuations that seeded galaxies, and the nature of the Big Bang itself. It aims to determine the cosmological implications of data from LHC and other particle physics experiments, and to test fundamental theory against cosmological observations. This is an area in which the UK excels on the international stage with particular strengths in string and extra-dimensional cosmology, inflation model building (and observational tests), phase transitions including formation and evolution of topological defects, baryo/leptogenesis, the cosmology of neutrinos and of unstable particles in BSM physics, candidates for dark matter and dark energy, and modified gravity models. The generation of primordial gravitational waves is also part of particle cosmology.

UK involvement: ~35 staff from 11 institutions

Recommendation 24: 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 25: The UK should continue to support the computing needs of its Theoretical Physics community.
7. Generic Instrumentation and Accelerator R&D

The UK has a long tradition in the design and construction of particle physics accelerator and detector systems. These are key components of the UK particle physics programme. In particular, our expertise in areas such as semiconductor tracking systems, fast electronics for triggering and data acquisition and noble liquid detectors underpin our capability to participate in new projects. These aspects are being separately assessed in accelerator and technology reviews, so will not be described further here. However, we repeat and update the recommendation from the 2012 PPAP roadmap report.

**Recommendation 26:** The UK should exploit its leading position in generic instrumentation and accelerator technology in focused areas. This is essential to the long-term future of the field and provides substantial Knowledge Exchange opportunities.

8. Summary

The roadmap summary table below positions the primary projects outlined in this report in terms of indicative timescales and (in blue) main scientific drivers. Flagship elements are indicated in boldface. Experiments receiving STFC experiment grants are indicated in red.

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