Science and Technology Facilities Council

PARTICLE PHYSICS PROGRAMME EVALUATION REPORT

OCTOBER 2019

1. **Executive summary**

1.1. Particle physics (PP) aims to understand the fundamental constituents of matter and their interactions, and addresses STFC Science Challenges concerning the nature of and evolution of the Universe. Theoretical physics develops the mathematical structures that underlie the Standard Model and extensions, and provides tools to make concrete predictions of observable phenomena.

1.2. STFC's particle physics programme comprises five main science areas: energy frontier physics, flavour physics, neutrino physics and non-accelerator based physics, plus particle physics theory (PPT). These areas reflect the strengths and interests of the UK community and are aligned to the European Strategy for Particle Physics.

1.3. This review has evaluated the STFC funded PP Programme and under three financial scenarios (flat cash, and ±10%). The review includes a consideration of the breadth and balance of the programme and its future sustainability.

1.4. Overall, the panel considered the PP Programme to be a world class programme with potential for the future. However, flat cash funding continues to have a negative impact on the programme, both at universities and in the national laboratories, most notably in research and development (R&D) and on UK international maintenance and operations (M&O) responsibilities. Only increased funding scenarios would enable new opportunities to be pursued, whilst still maintaining STFC's international commitments and exploiting previous STFC investment.

1.5. The PP Programme has broadened since PR2013 as recognised by BoP1, and the panel agreed that it is vital that diversity is maintained. However, flat cash funding is insufficient to maintain the current programme, retain leadership and remain viable in areas that have previously been supported. Without an increase in funding, future programme diversity and balance is likely to be compromised.

1.6. A reduction in funding has serious implications for the future health and standing of the PP community; the quality and science output of the whole programme would be damaged irrevocably and would inflict severe reputational damage by withdrawing from major ongoing international commitments.

1.7. The panel therefore considered a 10% increase as the minimum amount required to maintain UK visibility and leadership in the current programme. Indeed, there is a sufficient queue of scientifically excellent proposals, with current or potential UK leadership, to usefully occupy funding far beyond this level for the foreseeable future.

1.8. The panel also raised concerns about the future diversity of PP beyond the STFC funded programme, given the uncertainties about future European Research Council (ERC) funding. This is likely to have a significant impact on both PPE and PPT communities and should be factored into the sustainability plans for the PP area.

1.9. While the panel recognises that the programme is entering a construction-heavy period, it also stressed the importance of funding R&D that supports the preparation of future experiments. This is important for the future health of the programme and to ensure that skills and capability are retained. This is also a crucial element in maintaining a pipeline of skilled people in detector development and computing.

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PARTICLE PHYSICS PROGRAMME EVALUATION REPORT

2. Introduction

2.1. The particle physics (PP) programme includes both experimental (PPE) and theoretical (PPT) activities. Theoretical particle physics develops the underlying framework necessary to interpret and predict experimental results, the Standard Model, and potential alternative ‘new physics’ models that describe phenomena beyond our current understanding. Experimental particle physics tests the limits of the Standard Model using data obtained from experiments and searches for evidence of new physics.

2.2. The PPE programme supports the exploitation and development of experiments to take data at the highest energies (‘energy frontier’), perform precision measurements of particle properties under the weak interaction (‘flavour physics’), study neutrino properties and behaviour, and perform measurements and searches through observation of very rare events (‘non-accelerator experiments’ – renamed dark sector in this report). Although using different experimental techniques, these areas have common scientific goals, and only through comparison of results in different experiments can a full picture be gained.

2.3. PPT supports a broad programme comprising five main theme areas: phenomenology, lattice gauge theory, particle astrophysics (PA)/cosmology, quantum field theory, and string theory. Support for phenomenology also includes investment in the Institute of Particle Physics Phenomenology (IPPP). These areas are closely linked and interdependent.

2.4. The purpose of the Particle Physics Programme Evaluation (PPPE) was to look at the current portfolio and science strategy to define a balanced programme of excellent science within a realistic financial planning envelope. A specialist panel was convened to consider the quality, effectiveness and impact of the PP Programme.

2.5. The role of the panel was to look at the current research programme and consider future opportunities and to make recommendations on how best to achieve an affordable and balanced programme over the next five years. Programme balance took account of health and breadth, return on past investments and the ability to exploit UK leadership and capability in strategically important areas and engage in future projects. The panel also examined the likely impact on the PP Programme of a number of funding scenarios between + 10% / -10%.

2.6. The PPPE looked at the scope of the programme following feedback from the 2016 Balance of Programmes 1 review (BoP1). BoP1 noted that the constant volume necessary to support the PP Programme cannot be maintained within the flat cash available. BoP1 therefore asked the PPPE to examine the relative balance between exploitation and development and between different experimental areas (energy frontier physics, neutrino physics, flavour physics and dark sector physics), as well as the balance between theory areas and between theory and experiment, with a view to ensuring that the programme is optimal, balanced, coherent and sustainable.

2.7. BoP1 also recommended that the programme should be evaluated in the light of developments in any area of the science programme, the European Strategy[1] review, any CERN review of computing resource requirements, and that this evaluation should be used as input to the next BoP2 exercise due late 2019 (now 2020).

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[1] The European Particle Physics Strategy Update process is underway (during 2019) and is due to conclude in the summer of 2020. The UK has representation on the European Strategy Group.

BACKGROUND

3. The current Particle Physics Programme

3.1. In 2016, BoP1 considered the relative balance of future and current PP experiments to be broadly correct. Since PR2013 it has been possible to broaden the programme following strategic reviews of energy frontier physics (2014 and 2016) and neutrino physics (2016), which provided guidance to the PP Programme on managing the costs associated with the future LHC upgrade programme and investments in long baseline neutrino R&D.

3.2. Since BoP1 STFC has committed funding to the ATLAS and CMS Phase II construction upgrades. Pre-construction phases have been funded for DUNE and Hyper-K and additional government funding has been secured for DUNE construction.[2] It has also been possible to make capital contributions to Mu2e and Mu3e, and to support eEDM, which includes funding from EPSRC. Lux Zeplin (LZ) and SBND (part of the DUNE R&D programme) have moved into exploitation in CG 2018. However, the 2018 consolidated grant (CG) will see a managed withdrawal from M&O commitments to SuperNEMO, and HepDATA is currently funded for only one year.

3.3. The PP Programme currently supports:

- PPE CG – provides support for the PP research programme to around 18 UK experimental groups, and comprises exploitation of previous STFC investment (physics analysis), international M&O commitments, support for new opportunities, and early stage R&D. CG funding also enables researchers to engage in discussions with their partners, even where STFC has not provided funding for an experiment.

- PPT CG – provides support for the PP research programme to around 19 UK theory groups also includes support for the Institute for Particle Physics Phenomenology (IPPP).

- Development (R&D and construction) projects:
    - Energy Frontier: ATLAS Upgrade Phase II construction, CMS Upgrade Phase II construction (installation of both in Long Shutdown 3 – LS3).
    - Flavour physics: LHCb Upgrade Phase I construction (installation in LS2), Mu2e, Mu3e, eEDM upgrade.
    - Neutrino physics: DUNE pre-construction/construction, Hyper-K pre-construction.
    - Dark sector: development projects funded primarily by the PA Programme.

- PA exploitation: unlike the PP, nuclear physics and astronomy programmes, PA does not have a consolidated grant to support its exploitation. Exploitation is through other programmes. The PP CG supports exploitation and M&O for accelerator based experiments including dark matter (both Xe and Ar).

- GridPP: Computing infrastructure is part of the worldwide LHC Computing Grid (wLCG), including the Tier 1 facility at RAL, which gathers, processes and analyses the massive levels of data both from the LHC and other experiments.

[2] STFC secured £65M capital investment in LBNF/DUNE for UK participation in the construction of LBNF/DUNE, of which up to £30M has been allocated to the DUNE detectors.

Note that PPT also makes considerable use of the DiRAC High Performance Computing infrastructure

- STFC Particle Physics Department (RAL PPD) baseline: Similarly to PPE consolidated grants, this provides core technology support to the UK national PP programme.[3] PPD funding also supports activities at the Boulby Underground Laboratory.

3.4. The PPE programme is closely aligned to the European Strategy for Particle Physics and has evolved in cognisance of the recommendations of the US Particle Physics Project Prioritization Panel (P5). The long-term picture of the programme is maintained via the Particle Physics Advisory Panel (PPAP) Roadmap. Many PP experiments are long term commitments, requiring R&D to develop new technologies to build new detectors, which once operational need to be maintained and exploited. International collaboration is essential in this endeavour and the UK frequently holds senior leadership positions in the majority of these experiments.

3.5. STFC provides investment in a number of overseas facilities and subscriptions. CERN (including the Large Hadron Collider (LHC)), is the world's foremost particle physics facility for research at the energy frontier, and during 2012 announced the discovery of the Higgs boson. UK investment provides access to unique technical capability and capacity in accelerators, computing and technical services, which supports broader applications, for example in medical and IT.

3.6. The majority of the experimental community are active in CERN-hosted experiments, and links with the theory community are strong. The UK has made major strategic investments in the LHC and all four of the LHC detectors; the two general purpose detectors, ATLAS and CMS (energy frontier physics), and the specialised LHCb (flavour physics) and ALICE (nuclear physics) detectors. Funding has also been provided to support smaller experiments such as NA62 and the work for ProtoDUNE.

3.7. UK research groups also participate in international research programmes at Fermilab (US) particularly supporting neutrino experiments (LBNF/DUNE), and precision muon experiments g-2 and Mu2e, and at J-PARC (Japan) through the currently world-leading T2K long baseline neutrino experiment. Mu3e is based at the Paul Scherrer Institute (PSI) in Switzerland.

3.8. The panel notes areas of significant overlap with other areas of the STFC programme, particularly with PA. Dark matter experiments like LZ (US) are funded via the PA Programme, but exploitation is supported through the PP Programme. The long-baseline neutrino experiments DUNE and Hyper-K have sensitivity to supernova neutrinos from across the galaxy, and neutrinoless double beta decay experiments (NDBD) like SNO+ and SuperNEMO have synergy with PA. There is a general and ongoing convergence between the methods and goals of the astrophysics, PA and PP programmes.

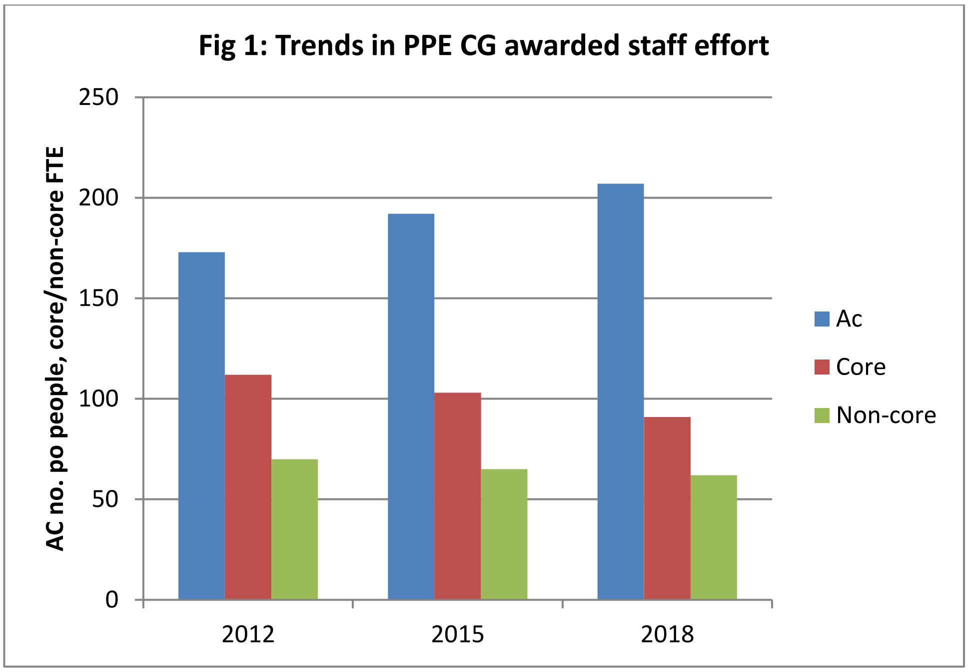
4. Size of the Particle Physics community

4.1. In the 2018 **PPE CG** the number of academics requested continued to increase, 218 were requested compared to 207 in 2015 and 180 in 2012. The number of academics awarded funding has also increased, 207 in 2018, 192 in 2015 and 173 in 2012.

[3] Note that RAL PPD is not referenced in this review, however it can be assumed that statements related to the CG can also be applied to RAL PPD baseline staff effort/funding.

However, the level of academic time awarded has decreased to an average of 8% in 2018 from 15% in 2015 and 17% in 2012.

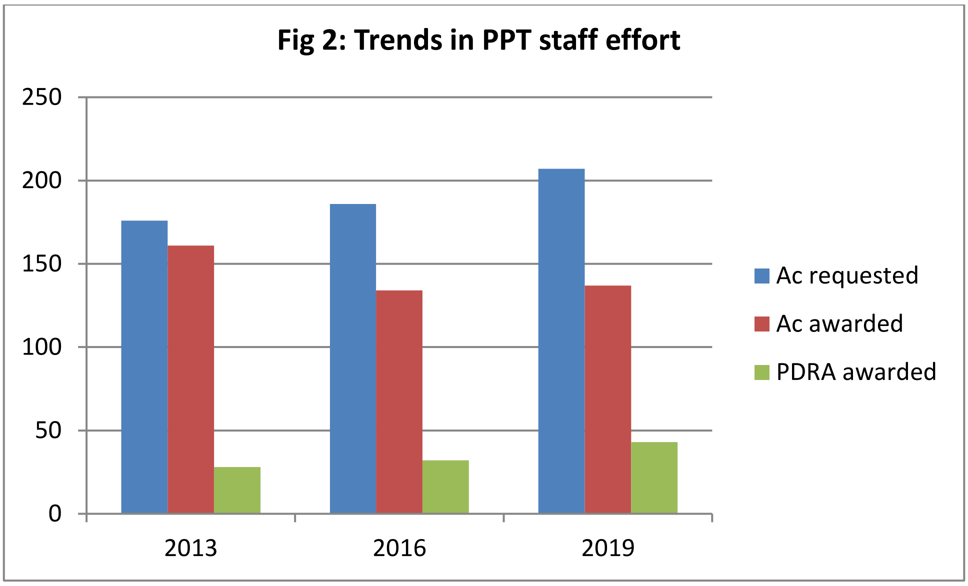
4.2. The awarded core FTE has decreased with 91 FTE awarded in 2018, 103 FTE in 2015 and 112 FTE in 2012. A further 12.75 core FTE was funded in 2018 as part of the ring-fence to support the LHC construction projects. The awarded non-core FTE has also decreased, 62 FTE awarded in 2018, 65 FTE in 2015 and 70 FTE in 2012. A further 1.20 core FTE and 2.67 non-core FTE was awarded in 2018 to minimise the risk of the UK defaulting on major international M&O commitments, particularly for CMS and LZ (not included in the chart below).



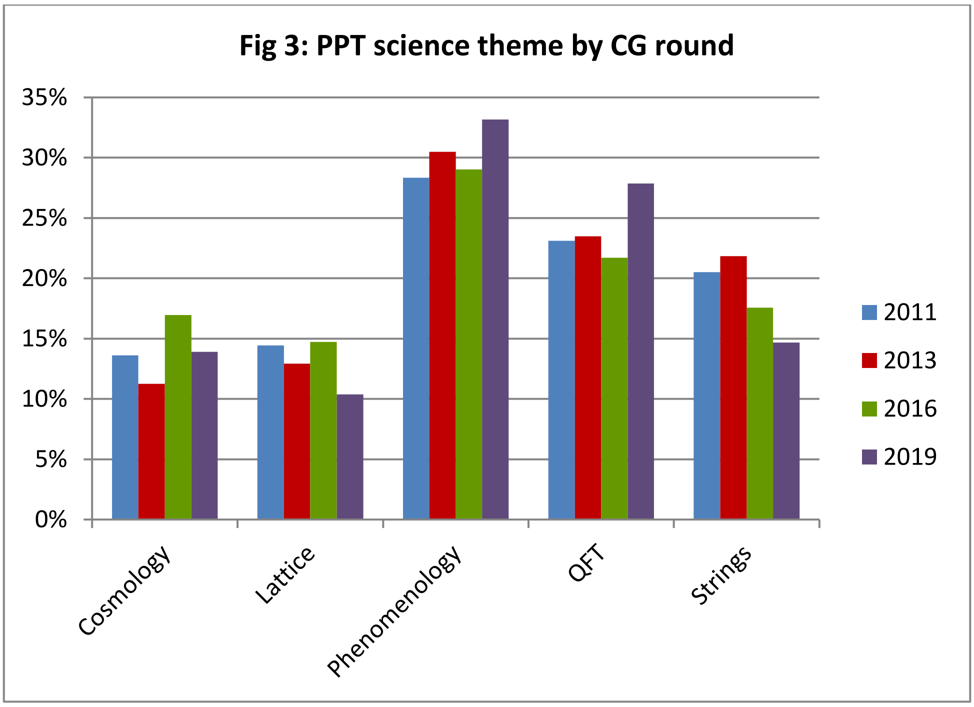
4.3. Further analysis of the experimental programme and the breakdown of FTE by experiment can be found in Annex 1. The panel noted the decrease in the FTE supporting operations for the LHC experiments, and the rise of support for neutrino experiments.

4.4. In the 2019 **PPT CG** the number of academics requested continued to increase, 206 were requested compared to 186 in 2016 and 176 in 2013. The number of academics awarded funding has remained stable with 137 funded in 2019 and 134 in 2016, but down from 161 in 2013. These numbers do not include the IPPP, a further 16 academics, which was incorporated into the PPT CG in 2018. The level of academic time has decreased to an average of 8% in 2019, from 13% in 2016 and 16% in 2013.

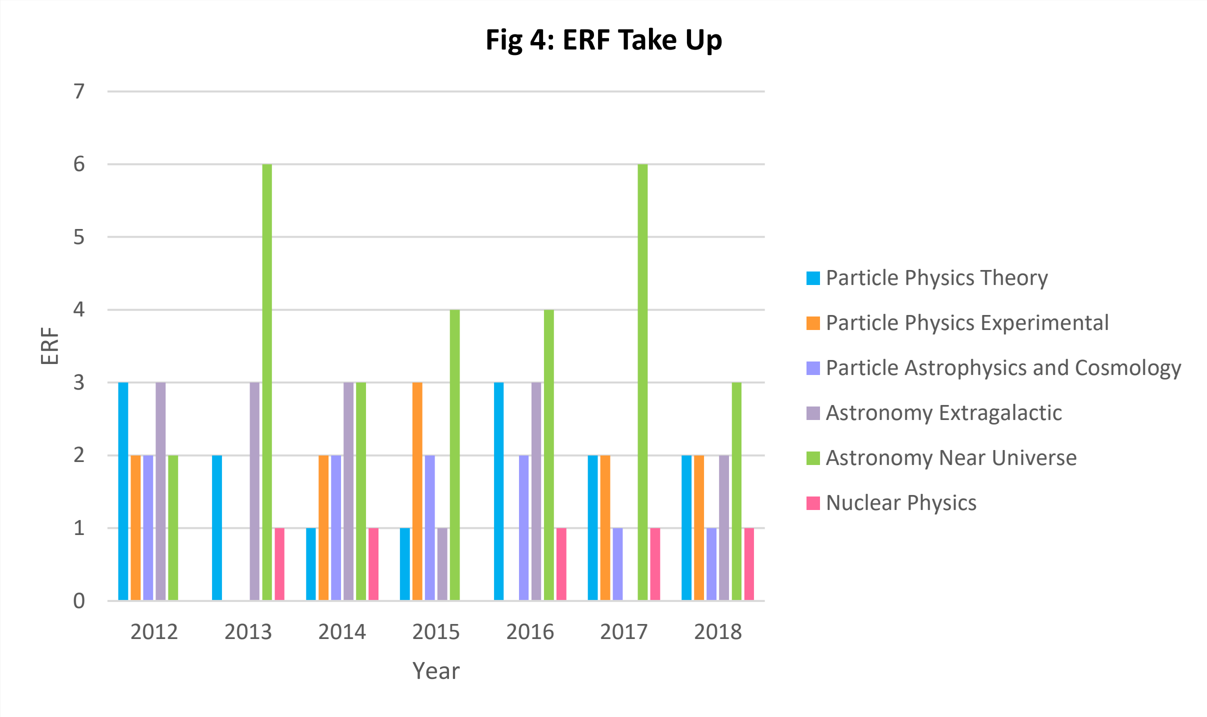
4.5. The awarded level of PPT PDRAs has increased recognising that the level of 28 FTE in 2013 was considered to be unacceptably low. In 2016 32 FTE was awarded and 43 FTE (including the IPPP). In 2016 the IPPP was awarded 8 PDRA FTE over two years during the transition to the CG. However, even with the increased level of PDRA effort, this is still considered to be low.



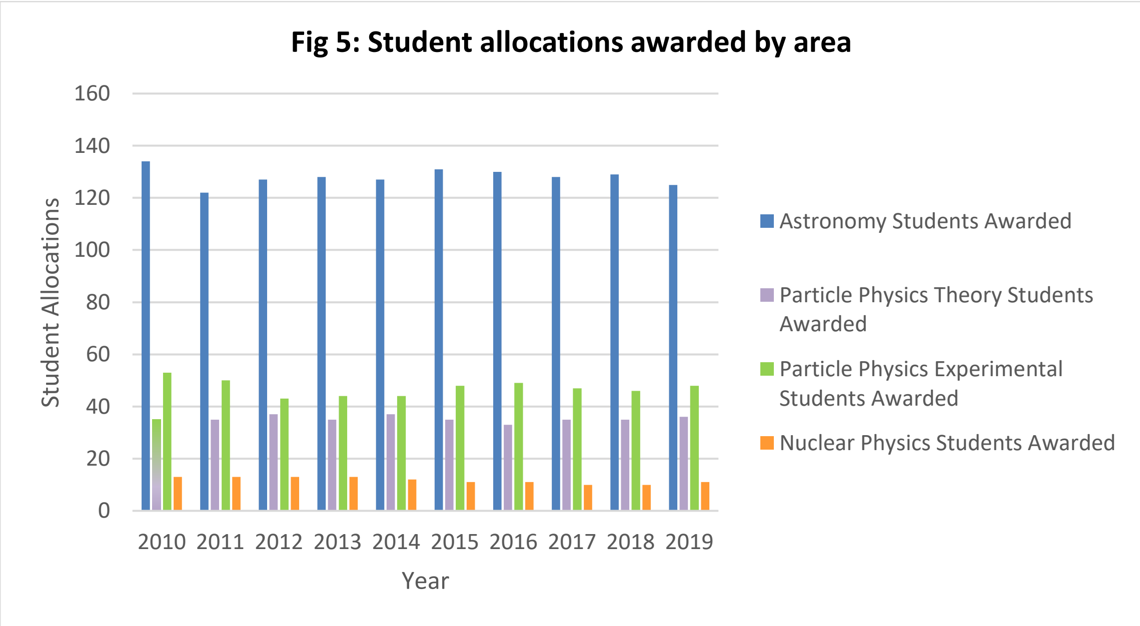
4.6. In PPT, the programme has been relatively stable with a slight increase in awards to phenomenology (though in 2019 this will be the inclusion of the IPPP) and QFT, with a reduction in awards to string theory.



4.7. **Fellowships:** In 2018 STFC were funding 54 **Ernest Rutherford Fellowships** (ERF), of which 13 fellows are listed as PP. The chart below shows how this compares with previous years and other disciplines in terms of uptake. The panel noted the decrease in PPE since 2015.



4.8. **Studentships**: In 2018, STFC funded 220 studentships of which 47 were related to PPE and 35 to PPT. The chart below shows how this compares with previous years and other disciplines.[4]



4.9. **Computing:** In addition to accessing computing support through GridPP the PP community also uses HPC machines including DiRAC. In the 2017 call of the DiRAC Resource Allocation Committee there were 20 applications for time on DiRAC; two were from the PP community and were funded. In the 2018 call 27 applications were funded, seven of which were classed as PP.

[4] The data includes the first cohort of CDTs

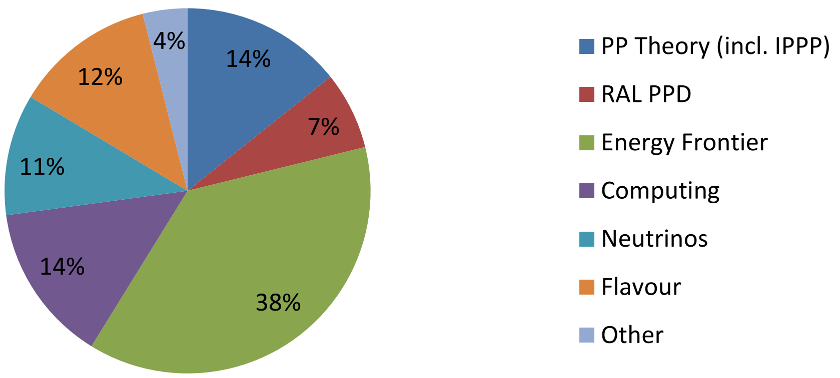
4.10. The panel also noted the gender balance of the area. In January 2019, there were 51 grants that were listed as PP. There are 10 female PI and 5 female CoI positions. This is roughly in line with the gender balance within the field, which is around 20% female.

5. Particle Physics Programme funding

5.1. In 2018/19 the Particle Physics budget was approximately £50M/year (including~£6M/year Capital/CGPS), and of this, 53% is committed to exploitation (experimental and theory consolidated grants, including support for IPPP), 33% to experiment operations, and 14% to future experiment development. The budget includes support for the RAL PPD. A further breakdown is below.

5.2. STFC secured an additional £1M to support the LHC upgrade construction from UKRI for the two financial years 2018/19 and 2019/20. It is essential that this uplift is retained and included in future years.

Fig 6: Particle Physics Programme funding



5.3. Note that the breakdown in Fig 6 does not include the funding for DUNE construction, which was in peer review at the time of the report. This will increase the percentage of spend in the neutrino area, which will no longer be modest with respect to the LHC experiments.

5.4. The RAL PPD staff budget allocation has, since 2011, been based on a nominal '50 core posts'. The percentage in Fig 6 is the portion of Programmes Directorate funding that supports that allocation, with overheads. In addition to this funding, RAL PPD also receives project-specific resources. These are included in the percentage shares of the other theme areas. Along with funding from external sources, this funding supports around 40% of RAL PPD staff.

6. Impact of continued flat cash funding

6.1. The overall volume of STFC grants programmes has reduced since the PR2013, and flat cash funding for the current CSR period to 2019/20 represents a significant and continuing cut in the volume of research. This has required careful management both by STFC and the PP community to try to minimise potentially negative long-term impacts on the health and balance of the programme.

6.2. BoP1 stated that "*the constant volume necessary to support the [PP] programme cannot be maintained within the flat cash available*" and that "*the current level of funding for future projects is already inadequate to support the full programme of world* *class particle physics projects the UK community is involved with."*[5] The panel agreed that the statements made by the BoP1 are still valid and that the impact of flat cash funding continues to have a negative impact on the programme.

6.3. The impact is evident in the contraction of the CG programme (see the reduction of effort in recent CG rounds in Fig 1). Balancing physics analysis, international M&O commitments, support for new opportunities and detector/early stage R&D is increasingly difficult and it is no longer possible for STFC to fully exploit its previous investments. Neither the experiment nor theory grants panels have been able to fund what they considered to be optimal programmes. The panel also noted that if funding reduces further, the areas of NDBD and neutrino astronomy in the next PPE CG, and IPPP core programme funding in PPT, are at risk. In the national laboratories, flat cash funding has meant it is no longer possible to support the nominal 50 posts at RAL PPD.

6.4. Funding for running experiments has reduced in the last three experimental CG rounds increasing risks to both UK science delivery and technical capability. This has resulted in the UK struggling to meet operational commitments to the experiments. This risk has increased following the 2018 CG, particularly for CMS and LZ. During this round it was also necessary for STFC to withdraw M&O funding for SuperNEMO. Consequently, there have been losses in leadership and expertise.

6.5. The challenge of meeting current M&O commitments, as a result of flat cash is also seen in the national laboratories. The effort available for CMS and LHCb M&O functions in RAL PPD is at a critically low level. Similar to many university groups, individuals work in parallel on M&O activities, upgrades and science exploitation, and in many cases have unique expertise in a particular area. Meeting UK responsibilities has been at the expense of science exploitation.

6.6. In PPT, the panel concurred with the views expressed in the Theory Review that the low level of PDRA support across particle physics is a threat to the programme and increased support was essential to maintain the quality of the current programme and its international competitiveness. Opportunities are being lost.

6.7. Both grants panels have tried to ensure a stable funding environment for high priority projects, and maintain strategic breadth to the programme. It has been necessary to reduce the level of academic time to mitigate the impact of reduced funding on core and responsive posts. However, this is now at a level that is increasingly difficult for universities to accept (although the number of academics requesting funding continues to grow). One impact, for some researchers, is an increased teaching load. In the long term, this could limit the programme's future scope and the responsiveness of the community to future opportunities.

6.8. In PPE, detector development and early stage R&D has been severely limited as a consequence of flat cash, which will inhibit future capability. The ability of the PP community to contribute to new initiatives and bring them to sufficient maturity to submit a Statement of Interest to Science Board for continued funding is at an increasingly low level.

6.9. The impact of flat cash funding is also seen in the development programme. The ATLAS and CMS upgrades have been funded at the minimum viable level, and Science Board has noted the UK's below-pro-rata 'fair share' contribution to cost of both experiments, around which the reputational risk must be managed. Only a capital contribution was made to Mu2e and Mu3e, with resource dependent on the CG.

[5] Balance of Programmes 1, p.26

SCIENCE PRIORITIES

7. Assessment

7.1. The panel considered each of the science areas identified in the PPAP roadmap. Each science area is described and evaluated and priorities assigned, but the ordering of the science areas is not significant. The panel considered the key science drivers in each area, the international context, how the science area has evolved since the last review, overlaps and synergies with other frontier science areas, and whether there are particular issues to address or where there are critical decision points.

7.2. The panel invited projects and running experiments to submit pro forma inputs to enable them to assess their relative research priorities. Note that accelerator projects were considered in the Accelerator Programme Evaluation and not this review. Likewise see the PA Programme Evaluation for a detailed assessment of PA experiments and the Computing Evaluation for DiRAC and GridPP.

7.3. The assessment criteria was based on that previously used in the PR2013, namely '**a**' ratings for projects and '**g**' ratings for science exploitation experiments. In addition, a new '**i**' rating was introduced to cover evaluation of impact for the economy and society. The rating definitions are listed in Annex 2 of this report. Projects submitted through the 2018 'Developing a World Class Research Programme' (also referred to as 'priority projects') exercise, were also noted.

7.4. The panel emphasised that their assessment is a snapshot in time (autumn 2018) when the proforma were invited, and recognise that priorities might change following the update to the European Particle Physics Strategy, which was ongoing during the time of the review (due to complete in May 2020). The panel also recognised the existence of a number of potential future projects or other areas of UK interest, which were not included in the call for input.

7.5. Projects were initially ranked on the basis of science excellence, taking into account synergies, economic and societal impact and leadership. The panel also assessed the impact of the programme. Ratings were based on the score of the highest quality piece of impact within each area and a broad assessment of the range of impact activity, i.e. volume measures of impact were not considered. The panel regard the impact ratings as indicative of activity rather than an absolute measure, and caution that they be treated accordingly.

7.6. The panel also redefined the PP Programme science areas and recommends that these classifications are used in future. Non-Accelerator physics has been replaced by dark sector, with the eEDM experiment moved to the flavour science area and the SHiP experiment to Dark Sector.

8. Energy frontier physics

8.1. The Large Hadron Collider (LHC) at CERN is the world's highest energy collider, and it will remain an essential tool for the exploration of the fundamental properties of matter in both the medium and long-term future. It is a unique facility, being the only operational hadron collider, and the only one expected to exist in coming decades and the highest priority in the European Strategy for Particle Physics. The LHC physics programme is one of the most successful experimental programmes in science and, in 2012, resulted in the Nobel prize winning discovery of the Higgs boson. This discovery was only one of the targets of the LHC, which aims at constraining and possibly discovering an incredible variety of new physics (NP) scenarios at the TeV scale. Searches for beyond Standard Model (BSM) scenarios are motivated by long-standing problems such as EW naturalness, dark matter, neutrino masses, the strong CP problem, and baryogenesis.

8.2. The scientific problems addressed by the LHC remain the core issues in the field. Whereas the discovery of the Higgs boson, and the confirmation of its properties as in complete accordance with the Standard Model, is a major breakthrough, this merely opens the door to a deeper and more difficult set of questions. Since evidence of new physics is manifest in both experimental (the existence of dark matter, matter-antimatter asymmetry) and theoretical terms (the hierarchy problem, the vacuum stability of the universe), there is no doubt that there is much more to be done and much more to discover. The LHC dataset current amounts to only around 5% of the final total, though it is clear that the challenge of extracting physics from a high luminosity environment will be significant.

8.3. The UK plays a major role in the operation and exploitation of both general-purpose detector (GPD) experiments, ATLAS and CMS. Both are large international collaborations; the ATLAS collaboration comprises around 4000 scientists from about 180 institutes, approximately 10% coming from the UK; and CMS has about 3500 from about 190 institutes, approximately 4% coming from the UK. Around 2000 peer-reviewed papers have been published by the ATLAS and CMS collaborations, with an average citation score of over 50.

8.4. The **ATLAS (g3 – mature, i4)** and **CMS (g3 – mature, i4)** programmes remain the highest priority for the UK PP community in the energy frontier physics area. ATLAS-UK delivered major parts of the experiment including substantial pieces of the central tracking detectors, trigger, data acquisition and computing and software infrastructure. CMS-UK provides crucial scientific and technical inputs in all the areas relevant to the experiment, covering detector operations, physics, upgrades and overall management. ATLAS and CMS UK scientists occupy a number of leading positions in physics analysis and science exploitation in both collaborations, including former ATLAS and CMS spokespersons, as well as in detector construction.

8.5. An upgrade of the LHC with increased luminosity, the High Luminosity (HL) LHC, is underway. It is scheduled to run until 2038 and collect an integrated luminosity of $3ab^{-1}$ in proton-proton collisions at a centre-of-mass energy of 14TeV. This will maximise the potential of the LHC to test the Standard Model by making very precise measurements of known processes, including exploring the Higgs sector in detail. It also has the possibility to discover new phenomena up to a mass scale of ~8TeV, thus testing many BSM scenarios and possibly resolving big puzzles of fundamental physics such as the nature of dark matter. In most BSM scenarios the HL-LHC will increase the present reach in mass and coupling by 20–50% and potentially discover new physics that is currently unconstrained. Even in the case of no new particle discovery, the HL-LHC will give access to the rarest phenomena and will be critical to reduce systematics or bypass their limitations with new analyses, leading to measurements of unanticipated and unprecedented precision of fundamental SM properties.

8.6. The experiments are also scheduled to undertake major upgrades, necessary to operate at the HL-LHC, during the long shutdown periods in 2018–21 (Phase I) and 2024–26 (Phase II). The UK plays a leading role in the **ATLAS Upgrade (a5 – construction, i4)** and **CMS Upgrade (a5 – construction, i4)**, and is well positioned for the subsequent science exploration.

8.7. The broad physics reach of the ATLAS and CMS programmes and their upgrades present synergies with other subject areas. Prospects for dark matter searches at the

HL-LHC offer excellent complementarity with direct dark matter experiments, mostly in the low DM mass range. Complementarities in neutrino physics include searches for sterile and heavy neutrinos at colliders. Strong links exist between the ATLAS and CMS UK physicists and the phenomenology community in the UK.

8.8. UK particle physics encompasses a wide variety of expertise in world leading technologies at both the universities and the national laboratories. Activities towards the upgrade of detectors and data acquisition systems have links to other particle and nuclear experiments such as LHCb, ALICE, CTA, LZ, Mu2e, Mu3e, DUNE and accelerator physics. ATLAS and CMS also generate a very large volume of data which requires extensive computing resources for data acquisition, processing, analysis and storage. In the UK, large scale distributed computing and storage are provided to the wLCG through the GridPP project.

8.9. **Continued involvement in both the ATLAS and CMS experiments is crucial for continued leadership, exploitation of UK investment in CERN and the LHC**, for providing data for the large UK community and for mitigating the risks associated with these complex, high technology experiments. **Investing in their programmes is vital to capitalise on previous investments and fully utilise the CERN subscription** which allows the UK to access this unique facility and profit from the CERN laboratories central role in particle physics.

8.10. Smaller experiments also depend upon the (HL-) LHC complex. Their physics programmes are complementary to that of the GDP (and LHCb) experiments and focus on a narrower set of science goals. These include Beyond Collider experiments like CODEX-b, FASER and MATHUSLA, targeting BSM scenarios characterised by the presence of long-lived, non-promptly decaying particles. Another is **MoEDAL (g1 – developing, a2, i3)**, designed to be sensitive to magnetic monopoles. It has produced the world's best limits on monopole searches from the LHC for a number of scenarios using its trapping detector studies. These projects offer deep coverage of a specific category of BSM physics; the added value for the UK GPD programme should be examined carefully.

9. Future developments in energy frontier

9.1. There are ambitious plans for future lepton and hadron colliders and, in the last few years, an intense activity worldwide has been carried out to assess the future of collider experiments beyond the HL-LHC. Proposals for future accelerators address similar questions with slightly different focus for lepton colliders (precision physics in SM and Higgs sector) and hadron colliders (new physics discovery, including dark matter).

9.2. Several options for future lepton colliders are under discussion. These include linear e^+e^- machines (ILC and CLIC), circular e^+e^- ones (FCCee and CepC), $\mu^+\mu^-$ colliders, or pp colliders such as an upgraded HE-LHC, a 50 − 100 TeV SppC, and a 100 TeV FCC-hh. A proposal for an e^-p collider, the LHeC, is also being considered to further upgrade the HL-LHC with a 60 GeV energy, high current electron beam by using novel Energy Recovery Linear Accelerator (ERL) techniques. The same facility could be hosted at the Future Circular Collider. Comparing the physics potential, the required technology and prospects for its availability, and the cost-to-benefit ratio of such machines is challenging, especially in light of the long approval process needed for new facilities and the huge and extended subsequent investment needed. This is also a major topic of discussion in the context of the European Particle Physics Strategy Update on-going until 2020: no consensus has been reached at this stage, although the community recognised that it is vital to plan one or more new accelerator complex, at CERN or elsewhere, for the next decades.

10. Flavour physics

10.1. Flavour physics is the study of the flavour structure of the Standard Model (SM) and can be divided into quark flavour and charged lepton flavour physics. Lepton flavour is conserved by all interactions whereas quark flavour is conserved in the strong and electromagnetic interaction, but not in the weak interaction. The nature of the quark flavour changes is described by the CKM mechanism, parametrised by the CKM matrix. This mechanism is one of the two known sources of CP violation in the SM, the other being the corresponding PMNS mixing matrix in the neutrino sector, where CP violation gives rise to a small but measurable difference in the behaviour between matter and antimatter.

10.2. Studying the observed spectrum of hadrons and measuring their properties (e.g. masses, lifetimes and branching ratios) and comparing them to predictions validates the quark model and tests our understanding of the strong interaction and the techniques used to make calculations of strongly interacting particles. Studying processes where both the theoretical calculations and the experimental measurements can be made with high precision are indirect probes for BSM physics. The CKM mechanism governs weak decays of hadrons and enables neutral mesons to mix with their anti-particles. Hence studies of hadrons, in particular those containing b, c and s quarks, are powerful probes to test if the CKM mechanism is a correct description of nature and if it is the only source of CP violation in the quark sector.

10.3. Charged lepton flavour (cLFV) is conserved in the SM, apart from the mightily suppressed path provided through neutrino oscillation, and hence an observation of cLFV would be a clear sign of BSM physics. The three charged leptons are predicted to behave exactly the same once their mass and CKM factors are taken into account. This lepton flavour universality (LFU) can be probed by e.g. comparing branching ratios of decays that are identical apart from an exchange of leptons. Any deviation from this universality would be a clear sign of BSM physics. Properties such as electric or magnetic dipole moments of the charged leptons can be measured with high precision. Since these quantities not only depend on the leptons themselves but also on the cloud of virtual particles that surround them, they are powerful probes of BSM physics.

10.4. There are no unambiguous signs of physics beyond the standard model, but a number of anomalies are seen in the flavour sector. It is difficult to identify the most crucial area in flavour physics before any anomaly is confirmed, so it is important to cast a wide net of measurements. This can be achieved by supporting the broad programme of the LHCb experiment and its upgrades and a few targeted experiments in the most promising areas. There are linkages to direct searches made by ATLAS and CMS that can address these anomalies should they persist.

10.5. In addition to the UK involvement listed here, there is a portfolio of medium sized experiments being developed targeting specific measurements in the flavour sector, which were reviewed in the physics beyond collider study at CERN. The physics potential for many of these experiments is very good and some flexibility may be required to adapt to a changing landscape depending on the evolution of the flavour anomalies and which projects that gain international support.

11. Hadron flavour experiments

11.1. **LHCb (g3 – mature, i4)** is the leading flavour physics experiment in the world with a major UK involvement and a strong UK leadership. LHCb has a broad physics programme with main focus on beauty and charm hadron decays but it also includes electroweak, heavy-ion, top and QCD physics and some hidden sector and exotics searches. The flavour physics programme addresses most of the science drivers listed above: spectroscopy and measurements of heavy flavour hadron properties; precision measurements of CP violation; precision measurements of decays with BSM sensitivity; tests of lepton flavour universality and searches for lepton flavour violation. The LHCb experiment finished its first phase in 2018 having recorded an integrated luminosity of 9 fb^{-1} and is currently undergoing a first upgrade. Data taking is expected to restart in 2021 with the upgraded detector at five times the current instantaneous luminosity to record 50 fb^{-1} by 2029. The UK has made significant investments in the LHCb upgrade and is well positioned to maintain its leadership in the subsequent science exploration.

11.2. Preparations are underway for **LHCb Upgrades 1b** and **2 (α5 – early, i4).** Upgrade 1b is a consolidation of Upgrade 1 to enhance the physics performance and is scheduled to be installed in 2025 with continued operation at the same luminosity in Run 4. Upgrade 2 is a second major detector upgrade to be installed in 2030 which will record 300 fb^{-1} at a further five to ten times higher luminosity. This will require an R&D programme to develop the technologies necessary to build the experiment, which have applications in other areas of the programme. A number of anomalies are currently seen in the flavour sector and even though it is not clear if they will persist when more precise measurements are made, it shows the power of searching for BSM phenomena by precision flavour measurements. **The breadth and depth of the physics programme provided by LHCb makes Upgrade 2 the highest priority development project in flavour physics and it is required to fully exploit the flavour potential of the HL-LHC**.

11.3. The main competitors to LHCb were the e^+e^- B-factory experiments that have completed data taking with UK involvement, and the Belle II super B-factory experiment that started physics data taking in 2019. Belle II can achieve a higher precision for certain measurements which give a desirable complementarity, but LHCb has a broader programme enabled by the full spectrum of hadrons produced at the LHC and achieves higher precision in the majority of measurements due to the much larger production cross-sections. Participation in Belle II is therefore not a priority in the UK.

11.4. There is a small UK involvement in the CLEO-c experiment (historically) and in the BES-III experiment (currently), both with a e^+e^- collider charm physics programme. The interest stems from the input they can provide to LHCb measurements, for instance determining strong phases needed for CP violation measurements and measurements of absolute branching ratios.

11.5. **NA62 (g3 – mature, i3)** is the leading kaon physics experiment at CERN with a sizable UK involvement and a strong UK leadership. NA62 studies rare or forbidden K^+ decays with primary focus on measuring the branching ratio of the $K^+ \rightarrow \pi^+ \upsilon\upsilon$ decay, which due to its challenging experimental signature requires a dedicated experiment. Data taking is planned until 2024, aiming for a precision of 10% on this branching ratio which would probe the SM up to mass scales of 100 TeV/c^2. KOTO is a complementary experiment without UK involvement that aims to measure the branching ratio of the isospin partner decay $K^0 \rightarrow \pi^0 \upsilon\upsilon$. The UK involvement in NA62 has mainly been supported through ERC funding, and is now supported through the consolidated grant.

12. Precision lepton experiments

12.1. **g-2 (g3 – mature, i3)** is a precision muon experiment at FNAL with a sizable UK involvement and a strong UK leadership. The experiment aims to measure the anomalous magnetic moment of the muon (g-2) with four times greater precision than the previous experiment and probe electric dipole moment (μEDM) with a sensitivity of 2-3 orders of magnitude better than the current limit. It is the successor of a similar experiment that measured a value that is in 3.7σ tension with the SM prediction and aims to reduce the uncertainty by a factor four to unambiguously confirm or refute this discrepancy. The first physics data was collected in 2018 and the experiment is expected to continue to run to 2021 with possible detector upgrades in 2020 to improve the sensitivity of the μEDM measurement. Internationally, an experiment using a complementary method is under construction at J-PARC in Japan, which is expected to achieve a similar precision on g-2 and μEDM but on a longer timescale. There is no UK involvement in this experiment or in the proposed scattering experiments that can provide input to the theoretical calculations.

12.2. The **Mu2e (g2 – mature, i3**) experiment at FNAL and **Mu3e (g2 – mature, i3)** experiment at PSI are searching for lepton flavour violating decays of muons. STFC has a modest involvement in these experiments. They are performing searches for three different LFV decays that have sensitivity to different extensions to the SM. Mu2e is searching for the process of μ^- to e^- conversion in orbit around a nucleus aiming for a sensitivity four orders of magnitude below the current limit. Data taking is expected from 2021 to 2025 and an upgrade is planned for the late 2020s to further increase the sensitivity by at least one order of magnitude. The COMET experiment at JPARC has a modest UK involvement and is searching for the same process with similar sensitivity in the mid-term but a more ambitious long-term upgrade programme. The Mu3e experiment is looking for the process $\mu^+ \rightarrow e^+e^-e^+$, with operation starting in 2020 aiming to reach a sensitivity 200 times better than the current limit after three years of data taking. An upgrade is planned for 2024 aiming to increase the sensitivity up to one order of magnitude further. The MEG II experiment, without UK involvement, is searching for the $\mu^+ \longrightarrow e^+\gamma$ decay with physics data taking starting in 2019.

12.3. The panel noted the interest in the “Precision Physics UK: next generation storage ring EDM and CLFV experiments” priority project, which seeks to establish a significant UK leadership role in several next-generation precision physics experiments that will have improved sensitivities to EDMs and rare charged lepton flavour violating decays, and will look for deviations from Standard Model predictions.

Recommendation 1: A review to evaluate the physics potential and return on investment of LFV experiments is recommended should funds become available for future investments.

12.4. The **eEDM (α4, g2 – mature, i2)** experiment measures the electric dipole moment of the electron and is a single institute experiment based at Imperial College, London. The experiment uses polarised YbF molecules and aims to reach a world-best sensitivity of $2\text{x}10^{-29}$ e·cm in 2020. The apparatus is being upgraded in parallel, with an ultimate sensitivity of 10^{-31} e·cm. There are three similar-sized collaborations internationally and the UK group is expected to set a world-best limit with the new apparatus.

12.5. Measurements of the electric dipole moment of the neutron (nEDM) are the subject of several project internationally. Although the UK withdrew from this area some years ago, these experiments continue to make use of previously developed UK technology, and exploit STFC-funded cold neutron sources. In addition, there are proposed future experiments to measure the proton EDM, e.g. at CERN.

13. Neutrino physics

13.1. The world particle physics community is united in classifying experimental neutrino physics as a high priority in the quest to extend the Standard Model to address the unanswered questions in fundamental physics. In the neutrino sector this means measuring the parameters that govern neutrino mixing (the phenomenon behind neutrino oscillations), establishing whether or not the neutrino is its own anti-particle (i.e. whether it is a Majorana or Dirac particle) and measuring the absolute masses of the neutrino states. Knowledge of these quantities will have profound consequences for fundamental physics e.g. one of the currently unknown mixing parameters δ_{CP}, which governs the level of CP-violation in neutrinos, is linked to a theoretical explanation for the observed matter-antimatter asymmetry of the Universe, and the possible verification of Majorana states would open the way to an understanding of neutrino mass through a mechanism completely different to the Higgs mechanism. There is important synergy with galaxy surveys and cosmic microwave background experiments that constrain neutrino mass and other neutrino properties.

13.2. The neutrino area was highlighted in the 2013 European Strategy and led to the establishment of the CERN Neutrino Platform. CERN also provides support for international projects such as the T2K near detector upgrade and the construction of cryostats for DUNE (the first time CERN funding has been used to deliver an experimental component outside of CERN). Domestic particle physics in the USA is dominated by the neutrino program centred on Fermilab and, in particular, on the DUNE project that will require a $1.5 billion investment from US funding agencies. Japan has a long association with neutrino physics, dating back over forty years to the original Kamiokande water Cherenkov experiment, which has led to two Nobel prizes.

13.3. A full understanding of neutrino properties and interactions requires neutrino oscillation projects over a range of baselines and neutrino energies and searches for the neutrinoless double beta decay process. The UK has recognised world-leading expertise making notable contributions to the key projects.

13.4. **T2K (g3 – mature, i3)** has provided significant results in neutrino oscillation and cross section physics and will continue to do so up to the planned start-up of Hyper-K in 2026. The UK delivered substantial elements of the ND280 near detector (the Electromagnetic Calorimeter, readout electronics and DAQ) and of the neutrino beam target. The UK has significant leadership, having provided two of three international Co-Spokespersons and dozens of convenorships. The ND280 is being upgraded as part of T2K-II upgrade project (which will run until 2026) to provide an experiment better equipped to handle neutrino-nuclear interaction systematics and so be ready to exploit the higher neutrino beam power of the T2K-II (up to 1.3 MW) and Hyper-K era. **Continued investment in T2K is important both to support UK responsibilities to ND280 into the upgrade period** and to maintain a training ground for early career physicists in preparation for the exploitation of the next generation projects.

13.5. The UK participates in the **NOvA (g2 – mature, i2)** experiment, a neutrino detection experiment based at Fermilab that will run until at least 2024. NovA has a higher energy neutrino beam than T2K and an almost three times longer baseline (810km) which results in a much higher sensitivity to the neutrino mass hierarchy (MH) than T2K can achieve. The small UK community enjoys considerable leadership which includes the co-convenors of the two main analysis channels and International Board (IB) chair.

13.6. Between them, T2K and NOvA could provide evidence of a non-zero δ_{CP} and an indication of the neutrino MH, at around the three-standard-deviation level of sensitivity, before the turn-on of the next generation of long baseline oscillation projects. There are also significant gains likely to be made by combining the two experiments' datasets, but work towards quantifying this is still in the preliminary stages.

13.7. The UK community is preparing for major roles in both of the international next-generation long baseline neutrino projects, which will undertake a comprehensive search for CP violation, along with measuring the mass differences to higher precision.

13.8. **Hyper-K (a5 – developing, i4)** represents an upgrade to the T2K project, replacing the far detector, utilising the beam upgrade and the ND280 upgrade. Super-K will be replaced with another water Cherenkov detector roughly 10 times larger (in 2 modules, 2 × 260 kton) and a new intermediate detector (E61) at 1-2km from the beam target. There is interest in the UK to deliver aspects of the DAQ, a water calibration system and photo-sensors for the far detector and UK personnel are leading work packages in these areas in the proto-collaboration. There is also significant UK leadership in the international management of the project (Co-project-lead, Chair of IB). Approval of the project in Japan is expected towards the end of 2019 and efforts to secure substantial UKRI capital funding for the UK contributions are on-going. **Hyper-K should be supported by STFC if bids to fund the capital project are secured. In the event this bid is unsuccessful, Hyper-K construction funding should be tensioned with other projects in the programme.**

13.9. **LBNF/DUNE (a5 - construction, i4)** is a long baseline (1300km) project between Fermilab and the Sanford Underground Research Facility (SURF) in South Dakota based on a 40k ton liquid argon TPC as far detector (in four modules). Substantial government capital funding (£65M) has secured a major part of the project for the UK: PIP-II SRF cavities, neutrino target, anode plane assemblies (APA) for the first two modules, leadership of the DAQ, and chief developer of the neutrino interaction reconstruction software programme. The UK has provided two Co-Spokespersons and leads three of the eleven 'detector consortia' plus numerous convenorships.

13.10. Both Hyper-K and DUNE have broadly similar sensitivities to the mixing parameters but with very different systematic uncertainties due to the very different technologies, baselines and beam energy profiles. This is an ideal situation in which to draw robust conclusions with a better precision than either experiment viewed in isolation. In addition, they both have a broader physics programme with complementary strengths e.g. super nova neutrinos in DUNE and proton decay searches in Hyper-K. The UK community has well established areas of responsibility in both projects and their participation exploits the full range of world leading expertise of UK personnel.

13.11. As part of the DUNE project, the UK is contributing to the construction of two smaller scale LAr TPC's to develop APA construction, DAQ and software methodology for the DUNE-Far Detector. **ProtoDUNE-SP** is a LAr TPC (420 ton active mass) based at the CERN neutrino platform. With key UK involvement, the run in 2018 was a convincing demonstration of the technology at large scale, and the detector will continue to collect cosmic ray data with a further test-beam run planned in 2021-22. ProtoDUNE-SP is a testbed for the DAQ and reconstruction software development and as such will continue to have UK involvement funded by the project grant. **SBND** is a 112 ton active mass LAr TPC forming part of the Fermilab Short Baseline Neutrino Programme, which has been designed to make a definitive measurement of whether a sterile neutrino could be contributing to oscillation anomalies seen by previous experiments. In order to fully exploit the UK deliverables to SBND, modest exploitation phase support should be made available for physics analysis once data taking starts around 2021.

13.12. There is also some UK activity in two detectors of reactor anti-neutrinos. The Solid experiment based at the Belgian BR2 reactor has sensitivity to sterile neutrino oscillation effects, and was funded by ERC. WATCHMAN is a homeland security project that will be hosted by AIT facility at the Boulby laboratory, and which will detect antineutrinos from the Hartlepool power reactor.

14. Neutrinoless double beta decay

14.1. In addition to the neutrino properties accessible via the oscillation experiments, it is also fundamentally important to measure the neutrino mass and to ascertain whether the neutrino and antineutrino are distinct quantum states (i.e. are neutrinos Majorana states). Answers to these questions link to cosmology, the large scale structure of the universe, and the theoretical understanding of the very earliest epochs.

14.2. The Neutrinoless Double Beta Decay (NDBD) process is proportional to the (effective) neutrino mass and is the only known way to experimentally probe the Majorana nature of neutrinos. The measurement of NDBD links to the long baseline (and reactor) oscillation experiments since at low neutrino mass it is a strong function of neutrino MH which is currently unknown. Nova and JUNO may be able to reach 3-4 standard deviation sensitivity to the MH in the period before DUNE and Hyper-K start-up, but it is these next-generation oscillation projects that will make the definitive measurements. From the perspective of fundamental neutrino physics, it is important that the UK has a role both in NDBD and oscillation physics. The UK community is currently involved in two projects in this area.

14.3. **SNO+ (g2 – commissioning, i5)** is the next phase of the SNO experiment, based on loaded liquid scintillator and builds on the significant role that the UK played in the original experiment. The UK are leading the critical scintillator loading with Te-130 but the start of the experiment has been subject to delays meaning it has lost significant ground to other projects (e.g. KAMLAND-Zen and EXO) in the race to reach the milestone of probing the upper part of the inverted neutrino MH scenario.

14.4. The **SuperNEMO (g1 – mature, i3)** project is unique in that it aims to reconstruct the full topology of the 0v2β process through the use of tracking detectors which the UK have provided for the Demonstrator Module – now beginning data-taking at the Laboratoire Souterrain de Modane. While the tracking technology will have a role to play in any attempt to characterise the physics mechanism behind the decay, the timescales and costs involved to scale-up the project to a competitive size have proven to be prohibitive and the project has now entered a period of managed UK withdrawal from M&O responsibilities.

14.5. The future of this area centres on large-scale enriched liquid Xenon and Germanium technologies. There are clear synergies with the extreme low background techniques being developed for dark matter experiments, which should be exploited wherever possible. Effort is now needed within the UK NDBD community to consolidate around a single project capable of covering the mass range indicated by an inverted MH (community interest in the LEGEND experiment has already been registered) and support R&D into an affordable solution that could probe the lower masses that a normal MH would suggest. Recommendations from international reviews, due from APPEC and DoE on NDBD, should also be considered before decisions are made.

Recommendation 2: The UK should be involved in a leading NDBD experiment and the community is strongly encouraged to take a strategic view of the subject in order to converge on a single future project.

14.6. Measurements of the absolute neutrino masses link with the recent bid to the Strategic Priorities Fund (SPF, Wave 2) by the Quantum Technologies for Fundamental Physics

Consortium (QTFP) where one work package is dedicated to utilising the precision of quantum sensors to probe the beta decay spectrum. There is also overlap with the astronomy programme, since the strongest upper limit on the neutrino mass sum comes from cosmological data (albeit with model dependencies).

15. Neutrino astronomy

15.1. The UK has continued to have an active role in neutrino astronomy through the IceCube and Anita-ARA projects based in Antarctica. This relatively new discipline is a component of a broad range of multi-messenger astronomy supported by STFC. The small UK community is in an excellent position to play a significant role in the planned upgrade to IceCube (IceCube-Gen2)[6] and in particular the low-energy extension (PINGU) where we provide a co-convener of the PINGU analysis group. There has been recent NSF funding for seven additional strings of PMT's for IceCube but the far larger Gen2 upgrades are still awaiting approval. There are links with the technology developed for the neutrino long baseline programme where the optical module idea used in PINGU is being investigated for application in Hyper-K and the use of GPU's for DAQ, pioneered in the UK for ANITA, is under consideration as a low energy trigger for DUNE. There is also synergy with the QTFP initiative where quantum optomechanical devices may have the potential to detect astrophysical neutrinos down to very low energy threshold.

Recommendation 3: Opportunities for new sources of funding for neutrino astronomy should be closely monitored. Existing UK leadership could be exploited to provide a high physics reward from a modest investment.

16. Dark sector

16.1. The nature of dark matter is one of the most fundamental open questions in science today. The Dark Sector programme in the UK aims to discover the nature of dark matter via direct detection in underground detectors, seeking to observe the interactions of ambient (galactic) dark matter, and in beam dump experiments searching for hidden particles through both visible decays and scattering signatures.

16.2. Globally, direct detection is a highly competitive field with many searches underway. The theoretically allowed range of dark matter masses and interaction cross sections spans many orders of magnitude, and therefore a broad search strategy is pursued to optimise discovery potential. The current leading constraints on the spin-independent and spin-dependent WIMP-neutron interaction cross sections above a few GeV/c^2 dark matter mass come from Xenon1T (Xe TPC, 2 tonnes total mass). The leading constraint on spin-dependent WIMP-proton scattering is from PICO-60 (60 kg C_3F_8 bubble chamber). At lower masses, ionisation-only signal searches are led by Xenon1T down to 3.5 GeV/c^2 and by DarkSide-50 down to 2 GeV/c^2 (Ar TPC, 50 kg). Planned searches using Xe are in advanced stages of construction (PandaX-xT, XENONnT and LZ, 4-7 tonne Xe TPCs), while the Global Argon Dark Matter Collaboration (GADMC) is constructing DarkSide-20k, a 50 tonne Ar TPC. Some of these next-generation projects have UK involvement, with the major UK contribution currently on the LZ experiment.

16.3. Different technologies have complementary reach: Xe TPCs have demonstrated the leading results for O(100 GeV/c^2) dark matter masses with 0.1-2 tonne detectors for several years, and have sensitivity to spin-dependent interactions through the Xe-129 and Xe-131 isotopes; Ar has a favourable nuclear form factor for high dark matter

6 Submitted to the Developing a World Class Research Base exercise in September 2018 and considered by the Particle Astrophysics Programme Evaluation.

masses (1 TeV/c^2 and above), and better ability to reject neutrino-electron scattering backgrounds through ppb-level particle ID. In the event of a dark matter discovery, combining measurements from sufficiently sensitive Ar and Xe targets strongly constrains the mass and cross section.

16.4. Above the tonne scale, direct detection searches have opportunities beyond WIMPs, with sensitivity to pseudoscalar dark matter and neutrino physics reach. LZ aims to make a first observation of solar and supernova neutrinos via coherent elastic neutrino-nucleus scattering (CEvNS), and has competitive sensitivity to $0\nu\beta\beta$ in Xe-136. DarkSide-20k aims to discover CNO solar neutrinos, as well as measure other components of the solar neutrino flux (pp, Be-7, B-8) with high precision, and has sterile neutrino sensitivity.

16.5. Several beam dump experiments are under development around the world to search for dark MeV–GeV particles via decay or scattering; these include SHiP which is being proposed for the CERN SPS, which has significant UK involvement. In these experiments dark particles produced in a beam dump can pass through surrounding shielding material and deposit energy in downstream detectors.

16.6. Since BoP1, the UK dark sector community has grown significantly. The UK invested in the LZ construction project, PRD and exploitation funding in the DEAP3600 experiment (3.6 tonnes LAr, now part of the GADMC), and UK academics are active in axion searches (ADMX), directional detection (DRIFT, DMTPC), low-mass searches (NEWS-DM), and DarkSide-20k. Most of the university PP groups, as well as RAL / Boulby, are now engaged in these dark matter direct detection efforts.

16.7. The **LUX-ZEPLIN (LZ) experiment (g3 – developing, i4)** features a 7-tonne LXe-TPC presently installed at SURF (USA). The international project is led by the DOE; the collaboration includes 250 physicists in 5 countries. There are nine collaborating UK institutions, which came together from the UK ZEPLIN programme (which played a key role in developing xenon technology) and EDELWEISS. This STFC funded project has just delivered contributions to the titanium cryostat, xenon detector, outer detector, calibration, materials screening, and offline data work packages. LZ was also assessed by the Particle Astrophysics evaluation panel.

16.8. A **next-generation ("G3") Xe-TPC (a4 – early, i3)** experiment aims to improve sensitivity by another order of magnitude, enabling discovery potential in still untested parameter space down to the neutrino floor, and also offers an attractive neutrino physics programme. An SoI has been submitted to Science Board for a preparatory R&D project in October 2017. The project objective is to enable the UK groups to engage in a global effort and bid for attractive work packages in a future G3 Xe dark matter search. Discussions have started between the various international collaborations using this technology. G3 was also assessed by the Particle Physics evaluation panel.

16.9. The **DarkSide-20k experiment (a4 – developing, i4)** features a 50-tonne Ar-TPC in a 770 tonne LAr outer detector deployed in LNGS (Italy). The collaboration includes 410 physicists in 11 countries. DarkSide-20k was approved in 2017, with capital funding from the INFN, NSF and CFI in 2018. DarkSide is a Recognized Experiment at CERN. There are 14 collaborating UK institutions delivering contributions to Veto Readout, Distributed Computing, Calibration Deployment, Veto Optical Simulation and Detector Simulations. An SoI was submitted to Science Board in November 2018 seeking funding to produce 25% of the DarkSide photo-detectors, building on the UK's deep expertise in silicon detectors for the LHC and developing capability for the future in silicon detectors and cryogenic integrated electronics. Darkside was also assessed by the Particle Astrophysics evaluation panel.

16.10. The panel noted that the PAPE had recommended that STFC undertake a review of dark matter. Subsequently, the Dark Matter Strategic Review was initiated and due to be undertaken in 2019. This will establish a clear strategy for longer term investment and, specifically, consider future UK participation in the DarkSide-20k experiment and R&D for UK participation in a next-generation (G3) LXe dark matter search, as both proposals are approaching critical decision points during 2019.

16.11. STFC has recently funded a feasibility study for hosting an international G3 dark matter experiment on the Boulby site. This study will examine the scientific potential and practicalities of such a project, and is supported by a range of UK institutions in additional RAL and Boulby.

16.12. Discovery of DM interactions would be a scientific achievement on par with the discovery of the Higgs boson. Given the large range of possible masses and cross sections, together with what we have learned thus far from the LHC, a broad search for dark matter is a scientifically excellent strategy with a relatively modest cost. In addition, combining direct and collider search results has been a very successful avenue to constrain new physics, and continuing to offer this complementarity into the LHC upgrade era is scientifically important.

16.13. The panel agreed that funding for dark matter is essential within the PP Programme. The scientific opportunity in direct detection represents excellent value, reflected in the alpha rankings – these fit into a category of priorities which is second only to the exploitation of the ongoing LHC experiments and their already-committed upgrades.

16.14. However, the lack of available capital funding for dark matter is severely limiting the field in the UK, and risks major loss of leadership. Direct detection experiments are now large, where international collaborations must ensure planning and capital investment is coordinated across multiple countries. European countries are moving rapidly to secure leadership in the next generation of dark matter experiments. **This panel finds that dark matter is important within the UK programme, and presents opportunities to nurture the next generation and build capability in detector R&D.** Investing now in future projects in direct detection is essential for both the PP and PA programmes.

Recommendation 4: The PPPE concurs with the assessment of the PAPE panel that participation in the dark sector area is essential, and that building capability for participation in future direct search experiments must be prioritised.

16.15. Dark matter has synergies across the STFC programme. The nature of dark matter is addressed by indirect detection experiments in the PAs and Astronomy programmes (e.g. CTA). Dark matter is a major focus of phenomenology in the UK theory programme. In addition to physics synergy with collider and fixed-target physics at CERN (e.g. SHiP) there is also strong technology overlap with other areas within the PP Programme, e.g. in cryogenics and photon sensing technology with DUNE and CTA, and in radioactivity assay facilities and controls with NDBD experiments.

16.16. The **SHiP (Search for Hidden Particles) experiment (a3 – early, i3)** aims to search for new particles produced in a dedicated fixed-target facility at CERN, with sensitivity to vector and pseudoscalar dark matter particles through both decay and scattering signatures. In addition, SHiP can perform new measurements with tau neutrinos and neutrino-induced charm production. The project has a large international collaboration composed of approximately 250 physicists from eighteen countries and has strong UK leadership. The experiment submitted a Technical Proposal to CERN in 2015. The CERN SPS committee has requested the production of a Comprehensive Design Study for 2019.

16.17. The funding for the necessary beam dump facility at CERN is still under review and the UK contribution to the design effort has received limited financial support to date. There is significant interest in this science in the UK.

16.18. The TERAS priority project (TEchnologies for RAre event Searches) was put forward by the direct detection and NDBD communities[7]. The TERAS aims are a new and ambitious low-background technology development and radio-assay facility for future rare event searches. This project leverages the UK's unique facilities at Boulby, and builds upon the expertise and infrastructure in silicon detectors developed for the LHC.

16.19. The AION project (Atom Interferometer Observatory and Network)[8] aims to develop a next-generation cold atom interferometer to explore to search for new fundamental interactions. It will provide a pathway for detecting gravitational waves from the very early universe in the unexplored mid-frequency band ranging from several milliHertz to a few Hertz, with potential sensitivity to ultra-light dark matter. The project cuts across several STFC science areas ranging from fundamental PP/PA to Astrophysics and Cosmology, and is closely linked to EPSRC technology development.

17. Particle physics theory

17.1. Theoretical particle physics studies the fundamental interactions of nature in the subatomic and cosmological regimes. Deriving predictions to test models against experiment is key. It is an exciting era because the Standard Model of Particle Physics reproduces experiment precisely, but is known to be theoretically incomplete. The Universe's dark sector is also not understood and is a rich field for exploration.

17.2. UK PPT has a history of world-class success: Maxwell and Dirac's work underpins the most successful physics theory, QED; Salam, Goldstone and Higgs contributed to the Standard Model; Hawking and Green's work to quantum gravity. The Higgs boson discovery highlights that experimental advances typically lead to a theory Nobel Prize – this is a prestigious international area.

17.3. UK theorists provide high-level mathematical training and flexibly teach many parts of undergraduate courses. There are strong links with industry (e.g. neural networks and AI development) yet much commercial impact is longer term (quantum mechanics of the 1930s is now an EPSRC priority area and relativity is now key to our functioning GNSS technology). The 2017 STFC Particle Theory Review found that of the STFC subject areas, PP theory places the most students into the private sector and teaching, and has the lowest Not-in-Work cohort.

17.4. Proforma submissions were not invited from the theory community. The panel instead drew on the Theory Review and reports from previous PPT CG rounds. The Theory Review noted that the field's international standing and relevance are very high. On average each theorist wrote 40 papers over ten years with 45 citations per paper. The community is very international – 50% of academics have PhDs from outside the UK. 80% of research postgraduates continuing in the field take up postdoc positions internationally. The review estimated the UK received 25% of all ERC particle theory

[7] Submitted to the Developing a World Class Research Base exercise in September 2018.
[8] Submitted to the Developing a World Class Research Base exercise in September 2018.

funding (5M€ per year), and the loss of this income is likely to have very serious impact.

17.5. The panel also noted that the number of particle theorists in UK universities has risen by 50% in ten years, driven by the REF and undergraduate demand. This demonstrates the strength of the field, which is growing across all five sub-fields below, but adds extra pressure on funding in a flat cash funding environment.

17.6. The panel noted that the UK theory community is highly regarded. The UK theoretical particle physics programme spans phenomenology, lattice gauge theory, quantum field theory, PA/cosmology, and string theory. The Theory Review highlighted the extreme interconnectedness of these areas with top academics shifting between them and work in one stimulating or reinforcing others.

17.7. **Phenomenology** computes original signatures of theoretical physics models for experimental searches and communicates the latest results between experimentalists and theorists. The UK has particular expertise in Monte Carlo development, parton distribution functions, precision calculations of the Standard Model (without which no precision experiment can be interpreted) and model building.

17.8. The world-leading **Institute of Particle Physics Phenomenology (IPPP) (g3, i3)** in Durham has fostered a sense of community and provides a central policy focus for UK phenomenology. While such a large enterprise cannot be reproduced in all five science areas, the PPGP(T) panel is currently seed funding virtual centres to play these roles in the other science areas to improve productivity, collegiality and connectivity.

17.9. **Lattice gauge theory** studies quarks using state-of-the-art supercomputing facilities (and has a distinguished history of chip design). The community is reaching 1% precision levels including QED and quark masses. UK expertise includes: nucleon structure, b-physics, g-2, finite temperature QCD, and non-QCD models.

17.10. **PA/cosmology**: Can the 85% of matter that is dark be understood by new physics, and can precision computations inform searches? The UK is involved in model building and detection simulation. 74% of the Universe's energy content is Dark Energy – leading work includes models of modified gravity. Gravitational wave data has led to new research on neutron stars and early universe phase transitions.

17.11. **Quantum Field Theory** develops the tool box for the Standard Model and Beyond. Imposing constraints e.g. supersymmetry has led to exact solutions at strong coupling. There is particular interest in conformality and integrability methods. New techniques beyond Feynman diagrams have provided new results relevant at the LHC.

17.12. **String theory** has been dominated by the discovery of holography – the equivalence of quantum gravity and gauge theory – suggesting a huge unification of ideas. These methods have been applied to generate new tools for studying the quark gluon plasma, QCD, black hole event horizons, superconductivity and the Big Bang singularity.

17.13. Consistent with the Theory Review, the panel agreed that each area is intimately linked and they positively reinforce each other, meaning that should any theme area be less well supported, there would be a negative impact on the whole.

17.14. Theoretical particle physics has synergy with other academic disciplines including astronomy (e.g. neutron star structure) nuclear physics (e.g. lattice and skyrmion computations), condensed matter physics (e.g. holographic superconductors), and mathematics (e.g. classification of geometries).

17.15. Future theoretical progress will include: more precise perturbative and non-perturbative computations, essential for precision experiments and beyond the Standard Model predictions; deeper understandings of the structure of new physics in the light of the Higgs discovery and dark sector observations (including the gravitational wave signals from such sectors); and the development of consistent quantum theories of gravity.

17.16. The panel concurred with the view expressed in the Theory Review that the low level of PDRA support across PP is a threat to the programme, and that increased support is essential to maintain the quality of the current programme and its international competitiveness. In 2008 there were 155 theorists applying, all of whom were funded at a 20% FEC level and sharing 35.3 PDRAs (0.23/bidding academic). By the current 2019 round there were 223 applying theorists but only 153 have been funded (though many of the other 70 being high-quality fundable academics) at 8% FEC and sharing 43 PDRAs. Although the number of PDRAs has risen reflecting the panel's response to the concern, it can still be seen as a drop to 0.19/bidding academic, the lowest STFC cohort (e.g. particle experiment ratio was 0.36).

17.17. A shortfall in theoretical activity limits the scientific output of the programme. Opportunities are being lost including over fifty academically excellent researchers who are unfunded, PDRA numbers at one for every five applying staff means a huge number of projects go unexplored (for example lattice studies of BSM physics was ill-funded in the 2019 CG round), and the IPPP funding has been reduced, and thus its ability to impact across the full international experimental programme.

17.18. The falling funding rate per academic, which will be worsened when ERC funding is lost, is reported to be demoralising. Scientific output is being lost, and there is a danger that PDRAs become so scarce that academics do not develop the skills to best use them. Whilst in part driven by rising academic numbers, the panel concludes that there is a strong and fertile community which could respond positively with a relatively modest extra investment. **Maintenance of the CG funding line at flat cash or above is essential and future reductions, as advised by the PPGP(T), will impact the IPPP's broad support for the full experimental programme and a loss of PDRAs across the five science areas.**

Recommendation 5: STFC should consider how to increase PDRA support in Particle Physics Theory to maintain quality and international competitiveness of the PP and PA programme.

17.19. The main priority infrastructure project that relates to particle theory is the DiRAC3 HPC facility. This major hardware upgrade will provide welcome world-class resources to the astroparticle/cosmology and lattice communities.

17.20. HEPData supports the experimental community and is the primary repository for publication-related data from particle physics experiments and contains data from more than 8500 experimental particle physics papers. It responds to a community need to share, manage and preserve data and is also one of the major elements in fulfilling the STFC and UKRI policies for the management and sharing of scientific data. Funding for HEPData was withdrawn in the 2018 CG. While the grants panel considered the HEPData work at Durham to be scientifically excellent and internationally competitive, given limited funding, it felt the strategic value of funding this work to be less important than maintaining international commitments on exploitation and M&O. Recognising HEPData's broader role as a service to the whole PP community, STFC decided to undertake a review of its future funding, and this is due to take place in 2020.

18. Computing

18.1. The entire STFC science programme depends on the availability of computing and software expertise and resources. The PPE area produces very large datasets that must be stored, curated, and made readily accessible for analysis. In PPT, there is a dependence on a variety of high performance and high throughput facilities. A significant fraction of programme resources (currently 14%) goes into computing.

18.2. The need for large-scale computing by PPE will strongly increase in the coming years, principally as a result of the HL-LHC upgrade. Other large-scale experiments such as DUNE will also have significant computing requirements, though the level of commonality with LHC is still under study. Since current investment is insufficient to meet future needs, it is clear that the cost of computing is directly in tension with that of current and future experiments, and that in the absence of any new strategy or funding uplift, the cost of HL-LHC computing is far beyond what is affordable.

18.3. There has been a historical shortfall in suitable computing resources to support PPT work, and in particular in finding a sustainable funding model for the DiRAC facility.

18.4. In addition to issues with computing resources, the panel agreed that the decline over recent CG rounds in the number of software expert physicists (‘physicist programmers’ or ‘research software engineers’) in favour of operations posts has been extremely damaging in the long term. Although the reasons for this shift (the start-up of LHC and the need to operate Grid computing centres efficiently) are clear and justified, this balance must be re-addressed with urgency. The UK is no longer able to think or develop its way out of resource problems in this area.

18.5. The panel noted the success of STFC’s ‘big data’ CDT scheme, and the new links with industry that have arisen through it. It is to be regretted that this scheme was unaffordable for more than a short time, since the skills pipeline in advanced software techniques is now depleted.

18.6. To ensure that the UK continues to lead in this area it is therefore important to ensure that we have the skilled people within all aspects of the programme to make effective use of the e-infrastructure available, and that there is a good interface between those analysing the data and those managing computing hardware.

Recommendation 6: STFC should consider how it should provide resources to address the long term software and computing needs of the programme, especially in the context of the challenge of the HL-LHC and other large experiments.

18.7. The panel noted that the challenges faced by PPT in particular are not unique, and that opportunities for co-development with the astrophysics and PA communities (and with emerging communities within UKRI dependent upon large-scale computing) were being missed due to lack of resource. These communities will also face significant issues with computing scalability in the medium- or long-term future.

18.8. It is clear that the HL-LHC computing problem must be addressed proactively, and in coordination with international partners. It is likely that a new common effort, distinct from current Grid computing projects, will be needed in software efficiency and new computing techniques, to reduce costs to a reasonable level. The panel agreed that an upfront investment of sufficient scale, even in tension with Grid computing and exploitation activities for current experiments, may be a necessary step to guarantee a sustainable energy frontier programme for the future.

18.9. Advanced statistical techniques ('machine learning' / 'artificial intelligence') are likely to be a key feature of future computing for STFC science, and are now a prominent feature of the research landscape across UKRI. There is the potential for STFC to lead in this area, given the significant experience with such techniques in both PPT and PPE, but in contrast with other research councils, there is currently no opportunity for funded research in this area.

Recommendation 7: STFC should examine the need and justification for a new initiative in computing efficiency and advanced techniques, focussed in the first instance on the needs of HL-LHC, and complementary to national projects in computing infrastructure.

18.10. The panel took note that STFC will not be able to fully exploit its previous investments due to the costs of computing not having been taken into account during the approval process for new projects. Outside the LHC programme, the DUNE project will soon be in a similar position. Computing is just one aspect of the costs of exploitation, and other areas of expenditure (M&O, exploitation RA effort) are also under pressure. It is important that computing and software needs (both hardware and skills) are recognised at an early stage.

Recommendation 8: STFC should revise its project evaluation and approval process, such that the estimated lifetime costs of all major projects are taken into account at the SoI and/or PPRP stages, i.e. before major capital expenditure is made. Projects should have credible estimates of exploitation costs before they are approved.

19. Skills and technology development

19.1. The panel discussed skills and technology in relation to both detector and accelerator development mostly in the context of the expertise required to deliver a future collider programme. On the detector-related aspects the discussions were partially, though not fully, aligned with the conclusions of the Strategic Review of Detectors and Instrumentation which was commissioned by STFC in 2018.

19.2. Many of the underpinning issues highlighted in that review were related to 'investment in people', including career progression, skills development, and retention. Central to these is the need to build in measures of recognition and esteem of non-academic researchers and technicians. The recommendations included the establishment of CDTs in detector research and development, noting the opportunity to forge new partnerships between the national laboratories and the universities; a Fellowship scheme tailored to detector-related activities, including engineering and instrumentation; and the targeting of apprenticeship schemes in these areas. The need to maintain well-funded laboratories was also highlighted. The PPPE panel noted additionally that the erosion of the size of the CG core threatens the capability of the UK to deliver long-term projects and exacerbates the issues highlighted above.

19.3. Other broad aspects involving skills relate to increasing the availability of Project Managers and Systems Engineers, which are key to delivering the large PP projects. This skills gap is well understood by STFC. These posts are very well remunerated in the private sector, but it should be noted that they have the potential to realise savings by ensuring that large projects are more likely to complete on time and within budget. It is, therefore, a false economy to recruit on uncompetitive salaries.

19.4. The need to re-establish a funding mechanism for R&D activities that is more responsive and agile (a replacement for the PRD funding line) was noted by the PPPE. This also addresses the present lack of opportunities for young academics in PP, which is regarded as a significant issue in the UK, where the breadth of the programme is still limited.

19.5. On the technology side, a number of detector and related technologies were discussed in the Detectors and Instrumentation review which the PP community identified as needing further development. The most generic include: data chain, detector interconnects, fabrication and testing facilities, FPGA and ASIC development, and CMOS detector technology. Electronics and DAQ have become real strengths of the UK PP programme, but STFC needs to invest to stay ahead. Some of this investment may also aid the realisation of impact in this area.

19.6. A theme specifically addressed by the PPPE was the expertise in accelerator and detector development needed for a future collider programme. **There is a need to balance different project phases in the STFC portfolio so that this is not lost between large projects.** Starting soon a low-intensive but sustained campaign of detector and accelerator R&D to this effect was regarded as strategically important.

19.7. A proposal for a UK Particle Physics Technology Centre, encompassing aspects of R&D, training and skills development, and industrial engagement, was considered by STFC as part of the Priority Projects process. A related proposal was selected for submission to SPF Wave 2, but was unsuccessful. Since this is one of the areas where there might be a chance to draw upon UKRI funding outside the core programme, further development of this proposal, including engagement with the whole STFC research community, may be relevant.

19.8. The panel noted the strong potential synergies between STFC technology development for its own programme and facilities, and the needs of other research areas (e.g. in the exploitation of quantum sensors, communications or computing).

Recommendation 9: STFC should consider, in light of the detector review and the UK-PPTC proposal, what routes to non-core funding of basic technology development should be prioritised, and to what extent these activities should be coordinated across communities and across research councils.

20. Societal and economic impact

20.1. The detector technology developed in the UK has led to numerous diverse applications and engagement with industry. Examples in the neutrino area include: photosensors where T2K helped develop the first large scale use of MPPC’s and the development of next generation photomultiplier technology is being driven by Hyper-K and SuperNEMO with companies such as ET-Enterprises in the UK. The calorimetry developed for SuperNEMO has enabled the speed and accuracy of the quality assurance to be improved in proton therapy. UK work with high power neutrino targets (T2K, Hyper-K, DUNE) has led to overlap with the UK nuclear industry experience with handling hot materials. Providing cryomodules for PIP-II (LBNF/DUNE) is driving UK industrial capability in Superconducting Radio Frequency (SRF) acceleration which is the key enabling technology behind next generation light sources vital to the advancement of soft material, biology and pharma-sciences.

20.2. In the energy frontier area, ATLAS UK silicon detector expertise is being exploited in beam characterisation systems for hadron therapy (Pravda project). ATLAS UK academics will provide beam instrumentation for an on-campus proton therapy centre. Patient outcomes will be improved by understanding energy deposition in a pre-treatment phase and monitoring neutron backgrounds close to the beam. In addition, the GDP Phase-II construction projects offer the possibility of direct economic impact through placing of contracts in UK industry, potentially as a primer for a further industrial engagement with CERN. As part of the upgrade R&D grant, CMS has a number of links with industry, including CASE studentships with Maxeler (interface of FPGAs/ML), and close interactions with assembly and PCB manufacturing companies.

20.3. An example of commercialisation comes from SNO+ who have commercialised two aspects of the R&D undertaken for the upgrade: A commercial DAQ product spun out from SNO+ work has been deployed in metrology instruments in conjunction with Etalon AG. The project has been supported by STFC and EPSRC, resulting in £2.5M of turnover, and is now being extended with a new commercial partner VadaTech. In addition Sussex are spinning out a company (PulserOptics), supported by STFC funding, which builds on the technology developed for the optical calibration of SNO+ and was used successfully in the DEAP-3600 experiment. Both VadaTech and PulserOptics are attracting first orders.

20.4. Academics in particle physics (both theory and experiment) provide inspiration and high quality teaching at the undergraduate level in physics and mathematics degrees which generate a significant part of the personnel for the UK science base. PPT attracts highly intelligent students (typically turning away students with lower 1st class degrees) and raises them to highly mathematically and computer literate experts with the ability to lead in a world class field. As well as progressing their field they move on to high tech IT, engineering and computing jobs underlying the UK economy.

20.5. Particle physics also has a significant media presence which is driven by the public's inherent appetite for the science that is pushing the envelope the most. This presents an opportunity to increase the "science capital" of all corners of society, particularly those under-served communities with the lowest university participation rates. Keeping particle physics in the public eye builds on the curiosity that all young people have, and it is this curiosity that studies[9] show can best drive academic achievement and attract the next generation of particle physicists.

Recommendation 10: The ongoing efforts by STFC and the community to define, track and publicise the societal and economic impact of projects and groups should be further expanded, and means found to integrate this into the project approval / review process whilst minimising the overhead to the science community.

OVERALL PROGRAMME

21. Programme breadth and balance

21.1. BoP1 asked the PPPE to examine the relative balance between exploitation and development, and between different experimental areas (energy frontier physics, neutrino physics, flavour physics and dark sector), as well as the balance between theory areas and between theory and experiment. Having assessed each science area, the panel considered the relative balance of the current PP Programme to be broadly correct, consistent with the view of BoP1.

21.2. While the panel considered the balance between experiment and theory exploitation to be broadly correct, flat cash funding has seen erosion in both the theory and experiment CG, and in support for the national laboratories and computing centres. Whilst the low level of PDRAs is recognised in PPT, levels have also reduced in PPE,

[9] Prachi E. Shah, Heidi M. Weeks, Blair Richards, Niko Kaciroti. Early childhood curiosity and kindergarten reading and math academic achievement. Pediatric Research, 2018; DOI: 10.1038/s41390-018-0039-3, see also Science Daily

and ensuring that PPE supports international M&O commitments is becoming more difficult. It was also noted the level of small-scale R&D has reduced significantly over the last 10 years. This was considered crucial for community engagement at the early stage of projects which helps to support the development of the future PP programme and future leadership.

21.3. The panel also considered the balance between exploitation and development to be broadly correct. However, within development the panel had concerns about the future balance between construction and R&D. Now that the LHC Upgrade programme and DUNE construction have begun, the future PP programme has less flexibility and so continued flat cash will risk future programme diversity. There are limited opportunities to support future R&D projects, crucial for the long-term health of the programme.

21.4. Whilst the panel recognised the pressures on both the CG lines, and with regard to funding new projects, **the panel did not recommend that funding be moved from development to support exploitation.**

21.5. The panel also noted, as did BoP1, that much of the programme's diversity is supported through non-STFC sources, which allow for a greater breadth in the portfolio than would otherwise be possible.

21.6. The panel supported concerns raised in previous reviews (BoP1, CG reviews etc.) surrounding UK exit from the EU and future access to ERC funding that supplements many activities of the UK PP programme, both in experiment and theory. **The uncertainties about future ERC funding should be factored into the sustainability plans for the PP area.**

22. Key decision points

22.1. Following the panel's assessment of the science areas, several high priority opportunities have been identified that have upcoming decision points:

22.2. Funding for **LEGEND** at the Gran Sasso National Laboratory (LNGS) in Italy has been requested at a cost of £1.7M over three years beginning in April 2020. This builds on UK expertise and previous investment in NBDB experiments and the Boulby Laboratory. Funding would enable UK participation in the 200kg phase of LEGEND, after which a decision would be taken on contributions to the 1-tonne phase (LEGEND-1T). A funding decision on the first phase is needed now.

22.3. Funding for **Hyper-K** pre-construction runs until September 2020, after which the project would like to pursue construction. While a bid for £20+M has been submitted to the UKRI FIC, the collaboration has also been asked to consider a small scale contribution that will still provide the UK with access to the physics data. Japan has not yet approved funding for Hyper-K, however it is their custom that once a project is approved, that funding is available immediately.

22.4. A statement of interest for the **LHCb Phase 1b Upgrade and 2** is expected to be submitted to Science Board in December 2019. The scale of the request is currently unknown, but is likely that funding will be required from April 2021.

22.5. The panel also noted that the **DarkSide-20k** experiment and R&D for UK participation in a **next-generation (G3) LXe dark matter search** are approaching critical decision points during 2019. These projects have been assessed by the PAPE and following recommendations in that evaluation, STFC has commissioned a Dark Matter Strategic Review to be undertaken in 2019 to consider UK participation in those experiments.

PROGRAMME FUNDING SCENARIOS

23. Assessment of funding scenarios

23.1. The panel was asked to recommend an appropriate PP programme in the following financial scenarios - Flat cash and Flat cash +/- 10% over the next five years (2020/21 to 2024/25) based on the current £50M pa flat cash envelope. **Based on the panel assessment, only the increased funding scenario would enable new opportunities to be pursued, whilst still maintaining STFC's international commitments and exploiting previous STFC investment.**

24. Flat cash (no inflation)

24.1. **At flat cash, the panel considers the PP Programme to be viable but severely compromised.** The panel assumes here that the £1M UKRI resource uplift to support the LHC construction projects is baselined. Without inflation this level of funding is a net reduction in volume in the research that can be funded through the programme. The uplift is necessary to support LHC commitments during construction.

24.2. **Exploitation:** The CG, along with national laboratory activities, ensures that previous investment is exploited and that current experiments are maintained. The panel agreed that exploitation grant lines should be well funded to ensure value for money for investment in PP and PA, and therefore agreed with the BoP1 statement that *"protecting exploitation budgets is the priority in a constrained funding environment"*.[10]

24.3. **At flat cash, the panel considered both the experiment and theory CG, along with corresponding national laboratory expenditure, to be the highest priorities and that they should be funded at least at the current level.** The healthy funding of exploitation grant lines remains a high priority for the PP Programme regardless of financial scenario.

Recommendation 11: Additional resource funding secured through UKRI to FY19/20 should be baselined within the PP Programme to maintain support for the LHC construction projects.

24.4. However, at flat cash difficult decisions will need to be made in future CG rounds. It seems inevitable that under these conditions, the next PPE CG will result in structural change to the programme rather than further 'salami slicing'. This will damage UK leadership and capability in key areas and several research groups may not be funded, affecting both PP and PA. With non-staff costs reduced below levels in 2012, academic time at a very low rate, and university costs sharply increasing (e.g. indirect rates and pension contributions), staff effort will inevitably continue to reduce, and some science areas will be lost (NDBD and neutrino astronomy were identified as at risk in 2018). The number of PDRAs in theory will drop below a level that is already considered to be critically low for the size of the community, and it will be necessary to reduce the level of funding provided to support the IPPP core activities.

24.5. The risk of the UK defaulting on its M&O commitments will increase. The panel also emphasised the need to support current investments and the UK's M&O commitments properly. While this review has a five year horizon, the panel notes that the costs of M&O are likely to increase in future, for example when the DUNE detector is operational in the mid-late 2020s. Although firm numbers are not known at this point,

[10] Balance of Programmes 1, p.26

estimates for the future M&O costs for future experiments should be included in STFC financial planning.

Recommendation 12: STFC should establish estimates for the costs of future M&O commitments and exploitation activities for future projects, e.g. following the ATLAS and CMS upgrades, and for the DUNE experiment.

24.6. With a focus on M&O, there is unlikely to be sufficient funding for the grants panel to comply with the guidance from Science Board, instructing them to consider small levels of funding to support small-scale R&D for future experiments. This is seen as important to support the long term health of the particle physics programme.

24.7. **Development and construction projects:** The panel considered flat cash funding for future development projects to be inadequate to support STFC's current portfolio of projects. The panel therefore agreed with the statement of BoP1 that *"Any reductions from the current level would inevitably curtail further the diversity of the programme in the UK, with consequences for the future of the subject."*[11]

24.8. At flat cash, the panel agreed that STFC should maintain its current portfolio of funded construction projects: ATLAS Upgrade, CMS Upgrade, and DUNE. These should be protected with high priority to secure the delivery of substantial UK responsibilities within the international collaboration. However, there is little headroom in the programme to support new opportunities. This includes the LHCb Upgrade (1b and 2) and Hyper-K, as well as other areas that have received previous investments including precision muon experiments and NDBD. The impact is felt beyond PP too. Dark sector physics cuts across both PP and PA programme areas, and while development funding for dark matter projects is primarily the concern of the PA Programme, there is added value for the PP Programme to contribute to projects with significant overlap. This is also true for projects in neutrino astronomy.

24.9. Therefore, at flat cash, the programme is viable but severely compromised. **The panel agreed that within the next five years, the programme will no longer be balanced**. As indicated in BoP1, the UK will move to a more limited programme that focuses on the highest priorities in energy frontier and long baseline neutrinos. The progress made since PR2013 in achieving a healthier breadth of activity will be lost. Known opportunities will be missed and the programme will have very limited scope to plan for the future and react to new opportunities.

24.10. **At flat cash it may not be possible to sustain leadership in each science area.** Without continued funding in flavour physics once the LHCb Upgrade Phase 1, Mu2e and Mu3e are complete, development funding for flavour physics could be lost from the programme. This will risk future UK leadership and expertise built up during over 30 years of participation in LHCb and prior experiments. The UK would fail to build on its past investment and it could be difficult to reinstate areas that are lost at a later date.

24.11. By the mid-2020s, the UK will have delivered its current project commitments, but will have lost skill and capability. This will limit the UK's ability to fully exploit the opportunities that the HL-LHC Upgrade and DUNE experiment will bring. **The panel therefore stressed the importance of retaining an R&D programme.**

24.12. The panel noted that the flat cash scenario makes no attempt to address the computing challenge for the PP Programme, without a resolution to which, HL-LHC exploitation may be unviable.

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[11] Balance of Programmes 1, p.26

25. Flat cash with inflation

25.1. In a flat cash scenario with inflation the priority would be to maintain the CG at least at constant volume and to retain R&D in the programme. Due to above-inflation cost pressures in several areas, as identified above, flat cash plus inflation does not equate to constant volume, and that difficult decisions will still need to be made.

26. Flat cash - 10% (£5M)

26.1. **A scenario of flat cash minus 10% would require a radical rethink about how the PP Programme is structured.**

26.2. **Exploitation:** While both experimental and theory CGs remain the highest priorities, reduced funding will reduce the size of the PP and PA community, in both experiment and theory, which could see a corresponding contraction of 10%. The potential implications for the CG programme, highlighted in the flat cash scenario, remain valid, including cessation of the IPPP core programme, and the risk of the UK defaulting on its intentional M&O commitments is increased.

26.3. **Development and construction projects:** With a reduction of 10%, the PP Programme would be severely limited, participation in areas of previous investment in flavour physics (including precision muon), and NDBD would not be possible. PP could not continue to support experiments in dark sector.

26.4. Funding at this level is insufficient to maintain the current construction programme. STFC would have to consider withdrawing funding from the CMS Upgrade, which is likely to also mean a full withdrawal from UK participation in the CMS experiment. Even this action is insufficient to support a 10% reduction and it would therefore be necessary to reduce funding for the ATLAS Upgrade and the PP Programme's contribution to DUNE. A reduction in funding on this scale would require further review of these three experiments to consider the implications fully and to agree the approach that limits the severity of reputational damage to the UK.

26.5. In a scenario at flat cash with a reduction less than 10% it would still be necessary to examine the different components of the LHC upgrades and DUNE, and weigh the consequences of withdrawing from major work packages in those experiments.

26.6. Reduced funding scenarios therefore have serious implications for the future health and standing of the PP community; the quality and science output of the whole programme would be damaged irrevocably. The UK will not be able to fulfil its international commitments, compromising leadership and return on long term investments. Such an action would result in severe reputational damage from pulling out of UK led activities and inability to extract value from international subscriptions.

27. Flat cash + 10% (£5M)

27.1. **In an increased funding scenario it is possible for the programme to keep up with inflation and cost increases, with limited headroom to plan for the future and respond to new opportunities.**

27.2. **Exploitation:** The panel recommended funding the CG at a sufficient level to maintain at least constant volume in the programme. This enables UK M&O commitments in both PP and PA to be maintained and current investments to be exploited. In PPT the current level of PDRA support and IPPP core programme is retained.

27.3. **Development and construction projects:** The panel recommended that funds should be used primarily to support the breadth of the programme in world-class projects where the UK is making key contributions and, in many cases, has already established leading roles (e.g. flavour, precision muon experiments and NDBD experiments).

27.4. Following the panel's concerns about the balance of construction and R&D in the development programme, it encouraged STFC to prioritise future investment in R&D projects that prepare for future experiments rather than construction, which should be focussed on future priorities e.g. in flavour and accelerator physics. **This means that without a substantial increase in programme funding i.e. above 10%, funding for Hyper-K construction, as currently proposed in the FIC bid, may be reliant on additional funding from UKRI.** This also recognises the importance of breadth in the programme and that the DUNE long baseline neutrino experiment is now funded.

27.5. The panel also recognised opportunities to contribute to dark matter experiments in the PA Programme, which have high discovery potential. This is an area where UK can develop leadership and technology outside of the CERN based programme, in smaller projects and at relatively low cost. Pooling resources with the PA Programme would benefit both PP and PA communities.

Recommendation 13: STFC should seek to maintain a balance of different project phases in the STFC portfolio so that R&D is not lost between large projects. STFC is therefore encouraged to prioritise future investment in R&D projects that prepare for future experiments

28. Additional funding opportunities

28.1. Additional funding schemes have been introduced through UKRI, which aim to ensure that the UK remains a leading science nation by building strong international partnerships, attract the best international talent and investing in strategically important research and innovation. This includes the Strategic Priorities Fund (SPF), FIC and similar 'grand challenge' initiatives.

28.2. The panel agreed that these new UKRI funding streams present a significant opportunity and provide a valuable route to funding excellent research that cannot be accommodated within the STFC's current flat-cash core programme. The panel welcomed the opportunity to secure additional funding for the programme, but noted that these routes do not guarantee funds and as such are not a replacement for core funding to underpin the long term health and viability of the PP programme and that STFC should maintain pressure for additional uplift to the core programme as part of its bid to the next Government CSR to underpin core capability and leadership and ensure a future pipeline for future skills and technology development and impact. The panel also noted the importance of ensuring that exploitation funding is sufficient to support these projects once they are in operation.

Recommendation 14: STFC should maintain pressure for an uplift to its core programme as part of the next CSR to underpin core capability and leadership for development and exploitation, and to ensure a future pipeline for future technology and skills development and impact. The uncertainties about future ERC funding should be also factored into the sustainability plans for the PP.

28.3. Following the introduction of the Global Challenges Research Fund (GCRF), the community has had limited success. This is perceived as being due to a combination of poorly written proposals and lack of alignment between the leading-edge activities of the PP Programme and the GCRF remit and criteria. As a result, it is possible that the community is disengaging from GCRF as a route to funding. The panel therefore encourages STFC to provide further guidance on writing proposals and case studies to reengage the community and encourage them to apply for GCRF funding. It was also noted that successful proposals tended to be for projects already funded through the core programme as opposed to establishing new activities. This further strengthens the case for STFC's core programme funding. **STFC is encouraged to provide further guidance on writing proposals and case studies to reengage the community and encourage them to apply for GCRF funding.**

28.4. The Industrial Strategy Challenge Fund (ISCF) is also a potential route to future funding. Given the nature of the LHC upgrade programme and other experiments that already work with industry on technology R&D, this could be explored in greater detail.

28.5. The Developing a World Class Research process stimulated significant discussion and work in the community towards the definition of aspirational proposals that may align with UKRI priorities. The panel noted the success of several proposals from STFC, though none of these are yet the result of this exercise. It is important that STFC provide feedback on the future of this process and how PPT / PPE proposals should be adjusted to attain maximum chance of success.

Recommendation 15: STFC should provide ongoing feedback on the Developing a World Class Research process via its advisory panels, and engage with the community to refine and re-focus proposals to maximise the chances of obtaining new funding.

SUMMARY OF RECOMMENDATIONS

29. Conclusion

29.1. Overall, the panel considered the PP Programme to be a world class programme with potential for the future. However, only the increased funding scenarios would enable new opportunities to be pursued, whilst still maintaining STFC's international commitments and exploiting previous STFC investment.

29.2. The PP Programme has broadened since PR2013 as recognised by BoP1, and the panel agreed that it is vital that diversity is maintained. However flat cash funding is insufficient to maintain the current programme, retain leadership and remain viable in all areas that have previously been supported. Future programme diversity and balance is therefore likely to be compromised.

29.3. UK capability to achieve proper scientific return on the significant investment in current programme areas could be severely reduced if less-than-adequate support is provided due to flat cash and reduced funding scenarios. At flat cash the programme is severely compromised. The programme can support only the ATLAS and CMS Phase II upgrades and maintain UK leadership in DUNE. It is not possible to continue support for precision muon and NDBD experiments or contribute to experiments in dark sector. There is insufficient funding to invest in the Hyper-K construction phase following pre-construction, and the LHCb Phase 1b Upgrade is at risk. UK leadership in at least one scientific area could therefore be severely damaged or lost.

29.4. A reduction in funding has serious implications for the future health and standing of the PP community; the quality and science output of the whole programme would be damaged irrevocably and would inflict severe reputational damage by withdrawing from major ongoing international commitments.

29.5. In the medium term, the panel emphasised the need to support current activity properly. Resources devoted to exploitation (operation and physics analysis) should be at a level that allows appropriate exploitation to ensure proper return upon the original investment, and international M&O commitments should not be compromised.

29.6. The panel also raised concerns about the future diversity of PP beyond the STFC funded programme, given the uncertainties about future ERC funding. This is likely to have a significant impact on both PPE and PPT communities and should be factored into the sustainability plans for the PP area.

29.7. While the panel recognises that the programme is entering a construction-heavy period, it also stressed the importance of funding R&D that supports the preparation of future experiments. This is important for the future health of the programme and to ensure that skills and capability are retained. This is also a crucial element in maintaining a pipeline of skilled people in detector development and computing.

29.8. The panel considered a 10% increase, assuming a baselined continuation of the uplift, as the minimum amount required to maintain UK visibility and leadership in the current programme. Indeed, there is a sufficient queue of scientifically excellent proposals, with current or potential UK leadership, to usefully occupy funding far beyond this level for the foreseeable future.

30. Recommendations

30.1. The panel has made a number of recommendations concerning the individual science areas and funding in different financial scenarios. These are listed below:

Recommendation 1: A review to evaluate the physics potential and return on investment of LFV experiments is recommended should funds become available for future investments.

Recommendation 2: The UK should be involved in a leading NDBD experiment and the community is strongly encouraged to take a strategic view of the subject in order to converge on a single future project.

Recommendation 3: Opportunities for new sources of funding for neutrino astronomy should be closely monitored. Existing UK leadership could be exploited to provide a high physics reward from a modest investment.

Recommendation 4: The PPPE concurs with the assessment of the PAPE panel that participation in the dark sector area is essential, and that building capability for participation in future direct search experiments must be prioritised.

Recommendation 5: STFC should consider how to increase PDRA support in Particle Physics Theory to maintain quality and international competitiveness of the PP and PA programme.

Recommendation 6: STFC should consider how it should provide resources to address the long term software and computing needs of the programme, especially in the context of the challenge of the HL-LHC and other large experiments.

Recommendation 7: STFC should examine the need and justification for a new initiative in computing efficiency and advanced techniques, focussed in the first instance on the needs of HL-LHC, and complementary to national projects in computing infrastructure.

Recommendation 8: STFC should revise its project evaluation and approval process, such that the estimated lifetime costs of all major projects are taken into account at the SoI and/or PPRP stages, i.e. before major capital expenditure is made. Projects should have credible estimates of exploitation costs before they are approved.

Recommendation 9: STFC should consider, in light of the detector review and the UK-PPTC proposal, what routes to non-core funding of basic technology development should be prioritised, and to what extent these activities should be coordinated across communities and across research councils.

Recommendation 10: The ongoing efforts by STFC and the community to define, track and publicise the societal and economic impact of projects and groups should be further expanded, and means found to integrate this into the project approval / review process whilst minimising the overhead to the science community.

Recommendation 11: Additional resource funding secured through UKRI to FY19/20 should be baselined within the PP Programme to maintain support for the LHC construction projects.

Recommendation 12: STFC should establish estimates for the costs of future M&O commitments and exploitation activities for future projects, e.g. following the ATLAS and CMS upgrades, and for the DUNE experiment.

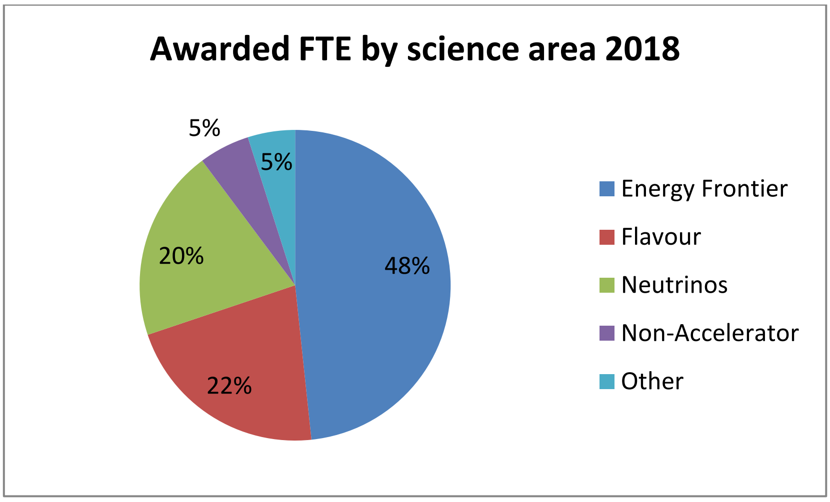
Recommendation 13: STFC should seek to maintain a balance of different project phases in the STFC portfolio so that R&D is not lost between large projects. STFC is therefore encouraged to prioritise future investment in R&D projects that prepare for future experiments

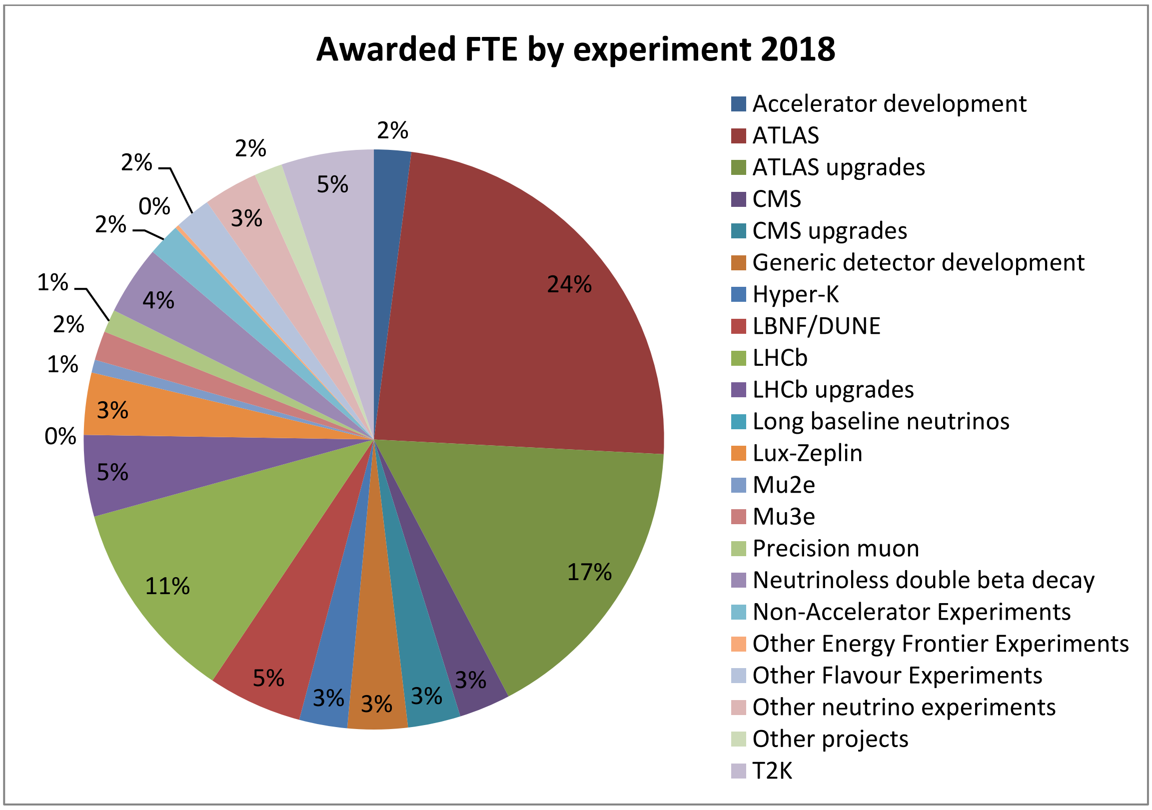
Recommendation 14: STFC should maintain pressure for an uplift to its core programme as part of the next CSR to underpin core capability and leadership for development and exploitation, and to ensure a future pipeline for future technology and skills development and impact. The uncertainties about future ERC funding should be also factored into the sustainability plans for the PP.

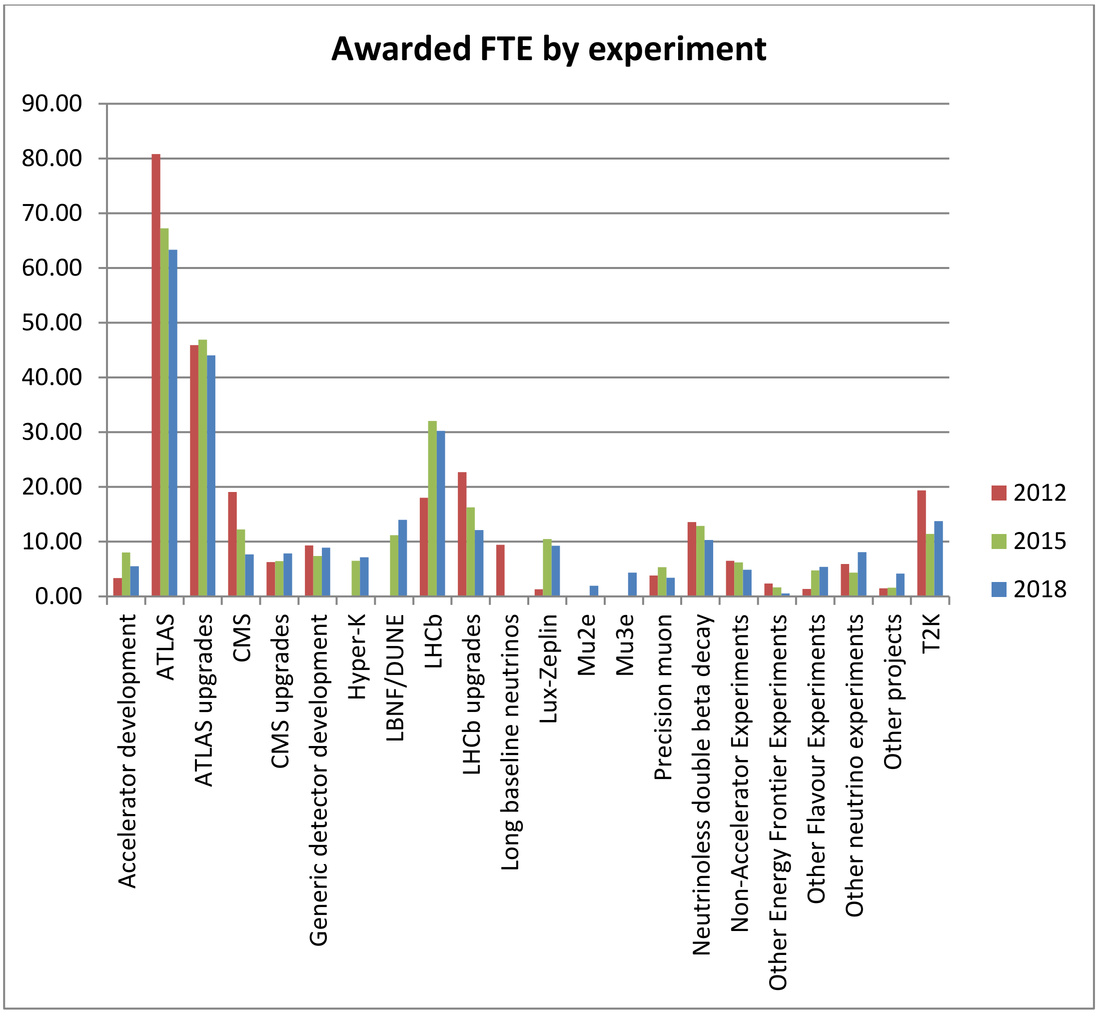
Recommendation 15: STFC should provide ongoing feedback on the Developing a World Class Research process via its advisory panels, and engage with the community to refine and re-focus proposals to maximise the chances of obtaining new funding.

ANNEX 1: PPE CG programme trends

The overall programme balance (in terms of total staff awarded) is shown in the pie charts, with a comparison to 2015 and 2012 shown in the bar chart.







The dominant uplifts are in the neutrino programme and flavour physics. The neutrino programme growth is due to the approval of the next generation DUNE experiment, the growth of T2K, the expansion of T2K-NoVA joint analysis work, the Hyper-K R&D programme, and the exploitation of SBND. However this has been accompanied by a decrease in effort in neutrinoless double beta decay. The growth in the flavour programme is due to the approval of three precision muon physics experiments (g-2, mu2e, mu3e), and the strong physics exploitation cases made by NA62 and LHCb.

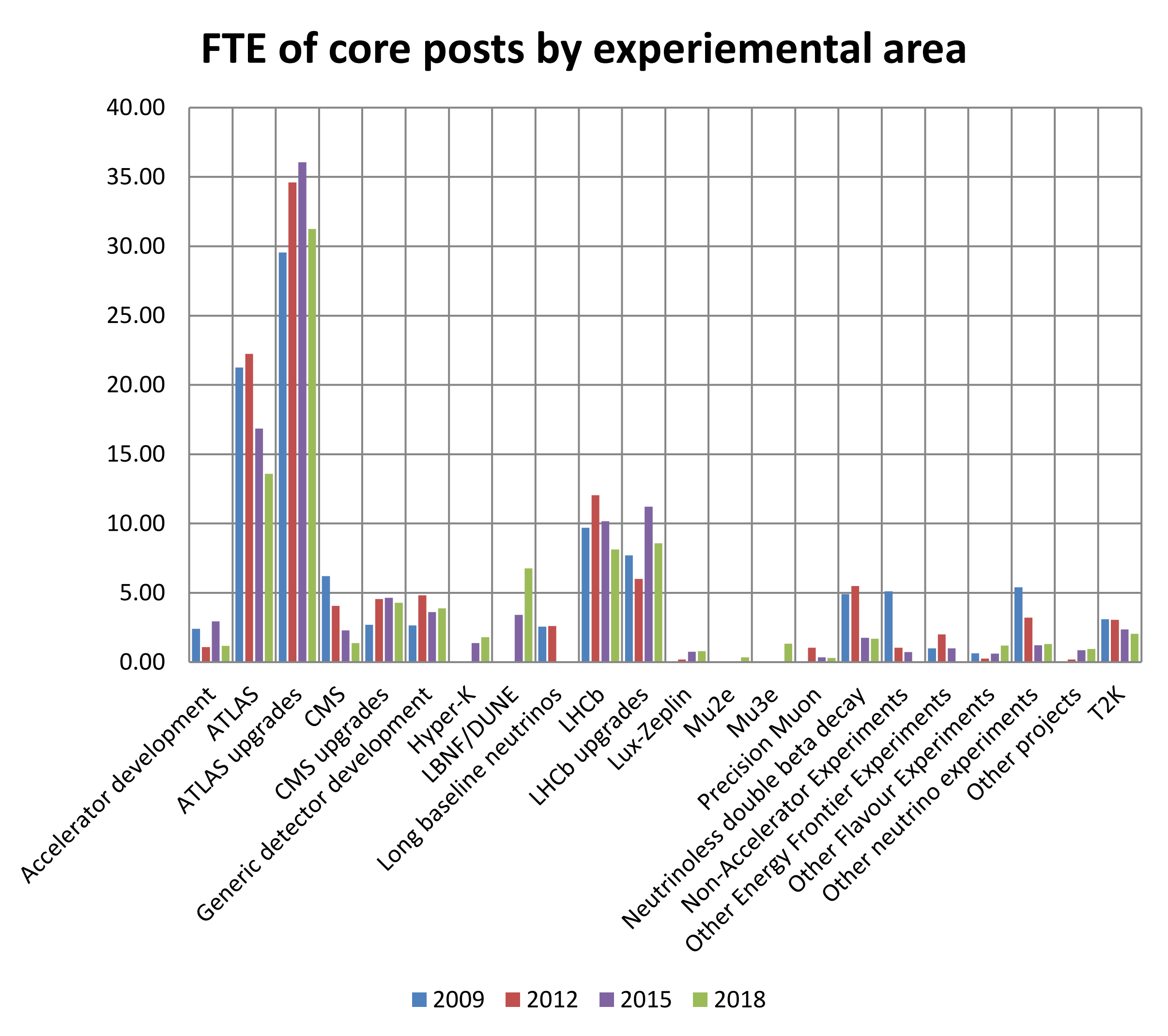
In a reduced programme these uplifts have been supported at the cost of exploitation support for the LHC experiments. The impact of these reductions has been mitigated by the additional ring-fencing supplement, which is necessary to fund LHC upgrade effort not currently in the panel's recommended programme. Therefore the main reduction is to exploitation and operations support and this represents considerable risk to high priority areas of the programme.

The 'Other Experiments" column includes small efforts on future projects such as SHIP. This is partially counter-balanced by a reduction in generic accelerator development.

Core staff

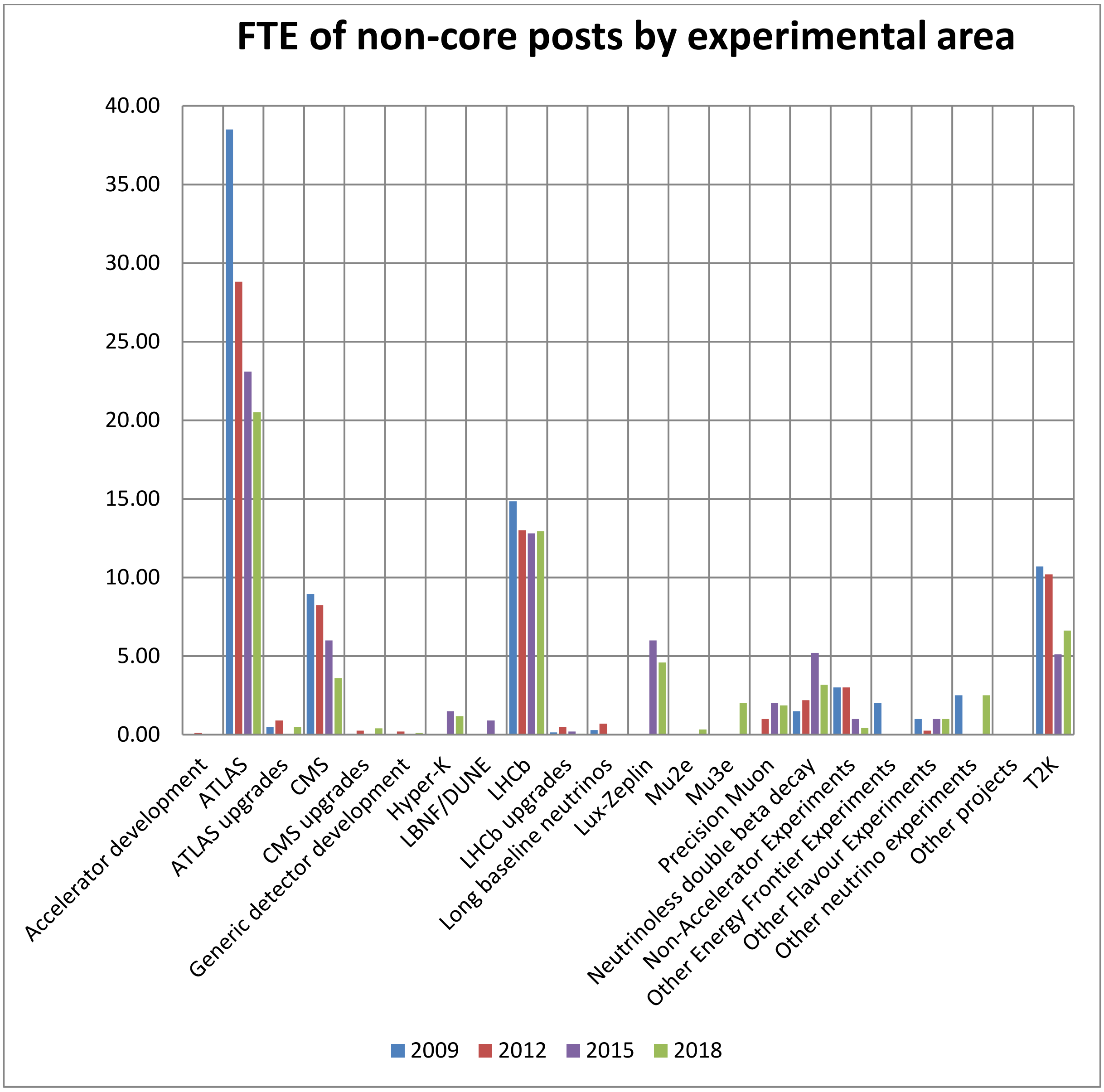
Core staff are those that possess specialist and difficult to replace skills that are key to underpinning the scientific programme of the university group covering both running experiments and upgrades planned or underway. Core posts are individuals who possess hard-to-replace skills needed at different stages of the experimental cycle, from initial design up until construction – and, during the exploitation phase, essential M&O. Typically, these will be experts in experimental development and detector building, software specialists, engineering and technical experts, etc. and will often work on more than one project at a time.

A comparison of the core FTEs awarded in 2012, 2015 and 2018 by experimental category, is shown here.



Non-core awards

A comparison of the non-core FTEs awarded in 2012, 2015 and 2018 both by experimental category, is shown here.


FTE of non-core posts by experimental area
40.00
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
Accelerator development
ATLAS
ATLAS upgrades
CMS
CMS upgrades
Generic detector development
Hyper-K
LBNF/DUNE
LHCb
LHCb upgrades
Long baseline neutrinos
Lux-Zeplin
Mu2e
Mu3e
Precision Muon
Neutrinoless double beta decay
Non-Accelerator Experiments
Other Energy Frontier Experiments
Other Flavour Experiments
Other neutrino experiments
Other projects
T2K
2009
2012
2015
2018

ANNEX 2: Ranking Criteria for Programme Evaluations

During the 2017/18 Programme Evaluations, projects/experiments/facilities within each discipline will be ranked. The ranking criteria will cover scientific excellence, exploitation within grants, and impact/industrial engagement. The exercise will look at all funded projects/experiments/facilities and ensure each is considered at whatever its stage of the exploitation cycle.

The panels will consider the merits or otherwise of supporting areas currently receiving STFC investment. This will include consideration of international engagement and subscriptions.

The ranking criteria will be largely based on that previously used by STFC, namely "α" rankings for projects/experiments and "g" rankings for science exploitation themes within grants as used in the last Programmatic Review. In addition a new "i" ranking will be introduced to cover evaluation of impact for the economy and society.

The Panel will be asked to consider the strategic value of the projects/experiments/ facilities that submitted proforma and how highly aligned they are to the mission of STFC. Consideration should also be given to the international standing and the potential for leadership of the area under review. Additional value, such as synergies within the STFC frontier science disciplines (Particle Physics, Astronomy, Nuclear Physics, Particle Astrophysics, Computing, Accelerators) programme should also be taken into account. The Panel will be asked to score each of the projects/experiments/facilities on the following criteria and submitted 2 days before the meeting.

The Panel member should complete section 1 and 4 below for each proforma. A marking should be given for either section 2 or 3 dependent on which is most appropriate.

The below wording is generic for the six evaluations and may be slightly modified to suit the specific requirements of the individual reviews.

1. **What is the life cycle stage of the Project/Experiment/Facility?**
   Early / Developing / Mature

2. **Scientific Excellence of Project/Proposal**
   α5 - Highly innovative and very likely to result in seminal changes in knowledge.
   α4 - Likely to substantially advance the subject.
   α3 - Likely to make an important contribution to the subject.
   α2 - Competent, worthy science.
   α1 - Interesting science but outcomes considered doubtful.
   β - Poor quality, flawed or unlikely to deliver meaningful or interesting results.

3. **Exploitation**
   Projects in the science exploitation phase are funded via grant panels. Three categories are defined, intended as strategic guidance to the peer review carried out by grant panels. Please consider the value of exploitation when the area under evaluation reaches maturity.

   g3 - A project with high strategic importance in the STFC programme, which has received substantial investment. We would expect to see it adequately funded via grants after peer review
   g2 - A project with high potential for excellent science which should be considered via peer review
   g1 - A project which is not well matched to the STFC programme, we would be surprised if it were to receive funding via the grants panel.

4. Impact and Engagement

Please consider if there is important impact within industry and/or wider society that STFC should be looking to exploit and that will otherwise not happen elsewhere.

i5 - Very exciting impact already under IP management or a close working partnership or exchange with non-academic partners is already in place.
i4 - Very exciting opportunities proposed, with some first connections made.
i3 - Interesting opportunities suggested but needs significant further work.
i2 - Little opportunity, although some could evolve in near future.
i1 - Little opportunity and unlikely to develop significantly in near future.
i0 - No apparent opportunities at all.