Strategic Review of Particle Physics

Contents

I. Introduction

1. The Particle Physics Strategic Review Committee (PPSRC) was formed in the spring of 2022. Its composition is given in Appendix A. Its terms of reference can be found in Appendix B and its schedule of meetings in Appendix C.
2. The purpose of the Particle Physics Strategic Review is to 'provide guidance in the form a series of recommendations on a refreshed strategic framework that will ensure the long-term health of UK particle physics and maximise the scientific benefits to the UK within a range of realistic financial scenarios'. It should be noted that the PPSRC discussion is high level, focussed on general strategic priorities and specifically does not consider any tensioning of scientific areas.
3. Particle physics is an inherently international endeavour and so must be considered in an international context (for example, the health of UK particle physics is closely linked to that of CERN). The recommendations therefore necessarily range beyond the conduct of particle physics in the UK.
4. This report is organised in three main sections. The first, 'Findings', is intended to set out the most important factual information that has been considered by the committee. It contains the experience of the last decade since the previous strategic review [1] and a survey of the current status of particle physics with specific reference to the situation in the UK. The PPSRC intends that the 'Findings' section should be a relatively uncontroversial collection of factual information, although the selection of topics reflects the committee's own opinions on relative importance; it is necessarily incomplete. The second section 'Comments' gives some of the most important threads that the committee has drawn from the factual basis considered and forms the basis for the condensation in the concluding section, 'Recommendations'. The Appendices contain information on aspects and background of the review, including committee membership, input solicited, and received, from the community and an outline of the current committee structure relevant to particle physics.

II. Findings

Overview

5. Particle physics reveals the profound connections underlying everything we see, including the smallest and largest structures in the Universe. Discoveries have been made that have transformed our understanding of the Universe. These have been achieved by collaborating globally to develop new detector and accelerator technologies to probe ever-higher energy, intensity and precision, as well as smaller distance scales. Many of these technologies have a broader impact in society.
6. Nevertheless, many of the mysteries about the Universe are still to be explored, such as the nature of dark matter, and the preponderance of matter over antimatter. The Higgs boson can act as a portal to new physics and the European Strategy for Particle Physics update has identified the detailed study of the Higgs boson as the most pressing priority for the field. The Astroparticle Physics European Consortium (APPEC) Roadmap identifies the discovery of Dark Matter as one of the key priorities.

UK Particle Physics within the International Context

7. Despite substantial international planning efforts over the past decade, the strategic outlook for particle physics, particularly at the energy frontier, has not been so uncertain since the 1960s. Although there is a consensus that the next collider should be an electron-positron Higgs factory, as expressed in the European Strategy for particle physics update, there is no consensus as to how this should be achieved. There is also the ambition to build a proton-proton collider at the highest achievable energy. All current proposals have major question marks relating to feasibility, cost and political will.
8. The recent very large increase in electricity costs has called into question the ability to operate the CERN suite of accelerators within the current budget. This has implications for the strategic planning at CERN discussed above.
9. The fraction of UK Gross Domestic Product (GDP) devoted to Research & Development, even assuming the Government's target of 2.4% by 2027 is reached, remains significantly smaller than many competitors, in particular Germany, Japan and the US. The recent Government Spending Review (SR) outcome for the next three years is therefore very welcome in terms of providing more funding to the research councils. In particular, for the first time in a decade of 'flat cash' settlements, there will be uplifts to their base programmes. The financial scenarios for the particle physics programme that the PPSRC was asked to consider were: 'flat cash', 2% indexation, and 2.5% and 5% increases above indexation year on year for the next decade.
10. The effects of Brexit, such as greatly increased fees for European PhD students, increases in import/export charges, and in particular the failure so far to join the Horizon Europe programme, are still playing through the system. Even if the UK joins Horizon Europe at some point, significant opportunities will have been lost. If the UK does not join, leadership and integration opportunities with other European countries are lost. Whether the promised replacement UK schemes would be as favourable to research such as particle physics, which has done extremely well from in particular European Research Council grants, is a matter of concern. So far, the UK has received £119M from the 'Fundamental Constituents of Matter' programme for Horizon 2020, which corresponds to ~15% of the total.
11. In contrast to comparable countries such as Germany, France and Italy, research in the UK is overwhelmingly done in universities, with national laboratories and similar establishments playing a smaller, albeit important role. This means that the volume of research in the UK is particularly sensitive to the research overheads charged in universities. In the last ten years,

this has resulted in the cost of e.g. a postdoctoral research associate (PDRA) having increased by 40%.

12. In comparison to other countries for whom broadly comparable data is accessible[1], the UK particle-physics community of ‘permanent academics’ is roughly similar to that of Germany, smaller than Spain and substantially smaller than France and Italy.
13. The number of PDRAs in the UK is similar to that of Spain but dwarfed by that of France, Germany and Italy. A very similar picture pertains for the total cohort of students supported by the Science and Technology Facilities Council (STFC) compared to the student cohort in the aforementioned countries. The ratio of PDRAs/permanent academics is 0.3 in the UK, 0.3 in France, 1.1 in Germany and 0.5 in Italy. The ratio of students/permanent academics varies more widely: ~0.9 for the UK, 0.5 for France, 1.9 for Germany and 0.7 for Italy.
14. The relative funding in these comparator countries is very difficult to establish. For example, countries such as France and Italy pay the salaries of a substantial fraction of ‘permanent’ academics, whereas in Germany it is split more equally between universities and national labs (predominantly DESY) and Max Planck. The UK funds almost all ‘permanent’ academics via universities. Attempting to deconvolute academic salaries from total expenditure is not straightforward but a reasonable estimate would be that UK non-academic-salary domestic expenditure is larger than Spain, a factor of two smaller than France and Germany and a factor of four smaller than Italy.
15. The estimates above, combined with the fact that the CERN subscription of the UK is comparable to France, ~40% larger than Italy and 40% smaller than Germany, imply that the ratio of our domestic spend/CERN subscription is much smaller than any of these countries. It seems unlikely that sufficient new money will enter the field in the UK to reduce this ratio significantly. Schemes whereby CERN funds activity it requires in institutions in the UK have been exploited with some success in the field of accelerators.

Particle Physics in the UK

16. In the last decade, the number of academics applying for funding has grown significantly while the fraction of their time funded by STFC has reduced precipitously.
17. The UK particle-physics budget is saturated with commitments for the next decade[2]. While a level of overcommitment is necessary for efficient management of the programme, the headroom for new initiatives is very limited. For example, there is currently no funding within the baseline particle physics programme for Quantum Technologies for Fundamental Physics (QTFP), desirable to complement the substantial targeted UK Research and Innovation (UKRI) funding, which has been awarded as part of a joint programme with the Engineering and Physical Sciences Research Council (EPSRC) and is administered within STFC. The funding devoted to Dark Matter experimentation is low by international standards and scarcely compatible with UK ambitions to host future major experiments in this area.
18. Overall, the ‘flat cash’ settlements over the past decade have resulted in a steep decline in the amount of exploitation across the UK programme. For example, for particle physics experiment, the total number of PDRAs funded on the Consolidated Grant (CG) has declined by 25% over the past decade giving a ratio of PDRAs/academic of ~0.3. For theory, however, there has been a slight increase from a historical low, giving a ratio of ~0.2.

[1] Gathered from sources submitted to RECFA on recent country visits. It should be emphasised that different countries count statistics in different ways and this means that comparisons are necessarily broad brush. The UK numbers are those funded by STFC.

[2] It should be noted that the current inputs to the figures are limited to those presented to e.g. RRB for CERN experiments, but which only give projections three years ahead.

19. The UK particle physics programme is now considerably broader than it was at the time of the 2012 review [1], fulfilling one of its recommendations. ‘Flat cash’ settlements in this period mean that resources have been necessarily spread more thinly and in some cases activities may be sub-critical. The Large Hadron Collider (LHC) experiments, particularly the HL-LHC construction, by far dominate the current expenditure and financial commitments for the future. Over the last decade, there has been a ~50% reduction in LHC exploitation that is mostly due to the decrease in “responsive” PDRAs funded on the CG.

The Support of UK Particle Physics

20. There is a strong consensus, as expressed in submissions to this review, that the CG system represents a good mechanism to support the UK particle physics programme, both in the experimental and theoretical communities. It gives the medium-term security and stability essential to retain a core of expertise in construction and Maintenance and Operations (M&O) in the UK. It also gives some continuity to exploitation. Nevertheless, there is always room for improvement in its management and implementation[3]. For example, a limitation of the current system is the lack of opportunities for academics to take a PI role in a grant.
21. Currently it is essentially impossible for effort in R&D not attached to a particular experiment or programme to be funded in either particle physics experiment or accelerator R&D. A new scheme for ‘Early Stage Research and Development[4]’ has now been launched, which will improve the situation. Many submissions pointed to the desirability of increasing the flexibility available to CG holders to vire between items on the grant.
22. The current risible level of investigator time granted on the CGs is not sustainable and patently cannot be reduced further. A similarly parlous situation exists for travel, Small Research Facility (SRF) and computing costs. Since these reductions have been an important contribution in retaining the current minimally viable level of technical and postdoctoral staff, an infusion of money in the CG line by the next grants round is essential. It is therefore very welcome to note that, following the Spending Review announcement, an additional £5.1m will be allocated to the CG Line from FY23/24, rising to £6m from FY24/25 and baselined thereafter.
23. Submissions to this review, in particular from PIs in both theory and experiment, indicate that the number of retirements and expected losses of technical, engineering and computing staff are roughly what would be expected given the age profile of those employed. There appears to be no ‘cliff edge’ of retirements of these staff. Many submissions pointed to a difficulty in recruitment caused by the level of salaries available and the perceived lack of job security of CG posts. There was a consensus that addressing this issue was the most important component in ensuring that the UK retains its ability to contribute to new projects at its current high reputational level.
24. There is a broad consensus in the theory community that the mix of activities across the theoretical spectrum is reasonable. There was also broad support, with some exceptions, for decreasing both the frequency of CG applications and the length of PDRA posts supported on them. In contrast, however, several submissions pointed out the comparative rigidity of the CG system in responding rapidly to new developments in particle theory and its tendency to concentrate hires into a short period. The special role of the Institute of Particle Physics Phenomenology (IPPP) seems to be generally appreciated, especially its work in building bridges between the experimental and theoretical communities[5].

---

[3] Note that a recent review of consolidated grants recommended adding a shorter, individual grant type. The implementation and its implications are currently being worked through.
[4] Development of Basic Technologies Capital Funding call
[5] As recognised in the IPPP Core Programme Review of the IPPP.

25. There is considerable support for the role of the STFC national laboratories, in particular Particle Physics Department (PPD) and the Accelerator Science and Technology Centre (ASTeC), in supporting the programme and its delivery in both experimental particle physics and accelerator R&D. In the latter, the university-based Accelerator Institutes, Cockcroft and John Adams (JAI), play a vital role not only in R&D but in particular in training the next generations of accelerator scientists. However, in the last decade, no accelerator scientist has been successful in obtaining an Ernest Rutherford Fellowship.
26. The institution of the UKRI Infrastructure Advisory Committee (IAC) adds another potential source of funding for particle physics. The Committee has been amenable to interpreting infrastructure rather broadly, agreeing to fund several STFC projects including detector construction of two 'mainstream' particle-physics experiments. It is a matter for STFC to make internal priorities among its submissions to IAC; these priorities have great weight within the IAC. It is incumbent on STFC to ensure that successful bids can be accommodated within the baseline programme in terms of future downstream running and other costs. Some concern about how STFC priorities, and the budgets requested, were arrived at was expressed in submissions to this review.
27. The long time horizons necessarily considered by the IAC increase the chances of a bid for an international facility based in the UK both being made and subsequently being successful. Success however will require government to develop and stick to a plan over several Parliaments and many changes of ministerial personnel.
28. While there seems to be a consensus among the theory community as expressed in submissions to this review that the high-performance computing provision is good, the situation with regard to the experimental community is challenging. It can be assumed that computing requirements there will be dominated by the LHC experiments. The General Purpose Detector (GPD) experiments predict a substantial rise in both CPU cycles and storage of roughly a factor of 2-3 by 2027 and roughly a factor of 10 by 2032. It is clear that there will also be a major additional cost from power consumption. An estimate derived from numbers provided by PPD is that hardware and power costs could double in the next decade. These estimates are very uncertain, particularly relating to power costs, and are likely to be asymmetric in the wrong direction. They also assume significant effort is devoted to improving software efficiency.

The Administration of UK Particle Physics

29. One of the submissions to this review mentioned that there are no international panel members in the Particle Physics Grants Panel (PPGP). This was raised as a potential conflict of interest, in that all committee members have either direct or indirect interest in the outcome.
30. A wider information gathering of financial projections is desirable across the entire experimental programme. For example, financial planning of the programme for experiments at CERN is hampered by the fact that future commitments judged from Resource Review Board information only have a three-year horizon. Similarly, the downstream commitments generated by IAC decisions should be included in financial forecasts in a well understood manner.
31. The relatively recent separation inside STFC of particle physics from particle astrophysics, although intellectually rational from some viewpoints, has not necessarily increased the efficiency in use of available funds. While the emergence of particle astrophysics is in many ways a welcome development and has improved visibility and collaboration in cognate areas, this does not mean that a similar partition should necessarily be reflected in funding mechanisms, particularly with reference to Dark Matter, included in this review. It has been recommended for more funding in two previous reviews [6, 7] but has been limited by being in a smaller overall silo of funding.

32. The role of particle physicists in the strategic direction of the subject at the research council level is significantly smaller in the UK than e.g. in the US or in France, where it is common for seconded researchers to enter the higher echelons of e.g. US Department of Energy (DoE) and particularly National Science Foundation (NSF) for a fixed term of typically five years to play a role in developing future strategy as well as guiding the development of aspects of the programme. Germany is rather different, with a complex interplay between universities and the national laboratory leading to a much more diffuse system with devolved decision making.
33. The UK is unusual, although not unique, in that both of its delegates to CERN Council are from governmental or quasi-governmental bodies. It is fortunate that currently the Executive Chair of STFC is a particle physicist but this will not always be the case.
34. The above lack of researcher involvement in all issues from the treatment of new proposals of whatever size, to prioritisation of STFC particle-physics bids to the IAC, to major strategic decisions, leads to a feeling of disengagement within the researcher community and an expressed wish by STFC staff for more strategic steer from the community. The mechanisms by which new projects enter the system and the entire provision of strategic advice within STFC requires examination. The UK input to the recent European Strategy is an illustration that mechanisms by which a *prioritised* strategy could be discussed and decided in a way that both involves and would be widely accepted by the particle-physics community do not currently exist. Such mechanisms are beyond the remit of bodies such as the Particle Physics Advisory Panel (PPAP).

Other considerations – Societal & Impact

35. The composition of the particle physics community is a matter of concern, in that it does not reflect that of the UK public. Of course, this is not specifically a particle physics problem but one of physics in particular and even, at least for ethnicity, one of science as a whole. The number of senior female researchers in the subject has improved somewhat over the last twenty years but there is still substantial room for improvement.
36. Many particle physics experiments, particularly using particle accelerators at the energy frontier, consume large amounts of power. The pressure to decrease the carbon footprint and the cost of particle physics activity, both facility power and travel, will only increase in the future. The Covid pandemic necessitated qualitative improvement in abilities for remote conferencing and meetings. Further developments that must result in a reduction in the necessity to travel long distances will be required. It should be noted that this imperative to minimise travel runs counter to the tendency in science in general and the necessity in particle physics, to concentrate resources into fewer, more powerful and by definition therefore on average less accessible, facilities.
37. Another important source of impact in the wider community is Public Engagement, which is vital for the future of particle physics. There has historically been a strong activity in the UK in this area, initially stronger and more successful than other comparator countries. For example, the number of UK school visits to CERN prior to the Covid pandemic was larger than any other country.

III. Comments

International Strategic Considerations

38. The current strategic uncertainty on the next collider is a sheet-anchor on planning in particle physics. The Future Circular Collider (FCC) cannot be afforded within the CERN budget with its current Member-State basis but the possibility of additional funding is

currently being explored on the timescale of the next European Strategy. Higgs factories based on the International Linear Collider (ILC) or Compact Linear Collider (CLIC) technology could be built at CERN but this would require a major change of strategy. The prospects of building the ILC in Japan recede year on year. The prospects of Circular Electron Positron Collider (CEPC) in China are uncertain. New ideas such as the Cool Copper Collider (CCC) scheme promoted by SLAC may gain traction in the USA but converting this into a feasible project that would have to have international involvement is surely years away. The US ‘Snowmass’ report will be an important milestone.

39. Hadron colliders, such as SppC or FCC-pp require substantial R&D before they can be realised. A muon collider or a plasma-wakefield-based linear collider are clearly decades away.
40. The programme for other areas of particle physics beyond 2040, including flavour physics, neutrino physics, dark matter searches and LFV studies is similarly unclear.
41. The key future milestone during the next three years will be the next European Strategy discussion. At the conclusion of this, it will be essential for CERN to put on the table for Council approval a realistic plan that fits within the budget constraints of the time. The first stage at least must be technologically achievable with acceptable uncertainty so that it results in a new facility within a minimal period after the eventual end of LHC running.
42. The recent completion of the European Technology Roadmaps [4,5] should engender a response from the UK. The end of LHC upgrade construction will provide a possibility for strategic redirection.
43. It is worth recalling the situation around 20 years ago when there was much activity around the ILC. The UK devoted a very large sum to ILC R&D, mostly concentrated on accelerator R&D but also on detectors. While this catalysed a renaissance in UK accelerator R&D, from the point of view of its aim at the time, *viz*. giving the UK a leadership position in the realisation of the ILC project, in retrospect it was premature. However, the research undertaken by the UK groups was deliberately tailored to be as far as possible of a generic nature and applicable to other projects.
44. Given this strategic outlook, it would be premature for the UK to make a major commitment to any particular scheme or machine. Fortunately, much at least of the particle-physics development is relatively generic. The European Detector [4] and Accelerator [5] roadmaps define generic strategies that are important factors in determining UK involvement.
45. ‘Green’ accelerator R&D to improve efficiency and thereby reduce power consumption and carbon emissions towards Net Zero for all accelerators is becoming a priority in the global particle-physics community. This is particularly important for energy-frontier machines, since their luminosity must grow to compensate for the fall with energy of the point-like annihilation cross-section. The UK is playing an important part in such developments.
46. While the UK has prominent roles in many international science projects, it has had limited success in attracting international facilities. With the exception of the Joint European Torus (JET), no major international science project has ever been constructed in the UK. Obtaining a major international facility in the UK requires a least a decade of coherent commitment and planning.
47. The advent of the IAC gives UKRI the potential to take a much longer planning perspective, which benefits subjects like particle physics, where such long horizons are in any case necessary. It is important that the depth and breadth of experience on the IAC is retained, ideally including representation from the particle-physics community to bring the wider international research infrastructure perspective.

48. The loss of involvement in European Union (EU) Horizon programmes would cut off the UK from important funding sources, potential to broaden and strengthen the programme and leadership opportunities. For example, the number of LHC GPD exploitation PDRAs currently funded via ERC grants is roughly comparable to that funded by STFC.

UK Particle Physics Considerations

49. Although formally outside this committee's Terms of Reference, the issue of university overheads cannot be ignored. As mentioned in the 'Findings' section, the UK is unusual in that the great majority of its research is concentrated in universities. Unless the persistent inflation in university overheads can be addressed by a UK-wide re-evaluation, at the highest levels of government, of the methods of funding university research, the current system will break down. Indeed, it could be argued that it already has broken down and that the current unrealistic project and research time for academics funded on the CGs further distorts the university research-funding environment.
50. The current UK particle-physics programme is broader than a decade ago. However, the scarce resources are relatively concentrated in a few projects. The room for new initiatives within the core programme is now highly constrained. It is essential to find headroom to begin new activities in the UK and to fund at an appropriate level those that have already been approved. Most future financial commitments are in the LHC area. New experiments and upgrades in the next decade are likely to be in areas of the intensity frontier such as neutrino physics, rare decays, astroparticle physics including dark matter and dark energy, and quantum technologies. Although the latter are at a relatively early stage, it is already clear that there are a number of exciting new possibilities. Special cross-disciplinary funding opportunities that were available have been exploited with particle physicists playing leading roles; 'seed-corn' particle-physics funding could leverage resources.
51. The recently announced STFC scheme to encourage early stage R&D is welcome. However, its level, of £1.3M over 3 years, among all STFC communities, is patently insufficient to meet the likely pent-up demand and the response to the European Technology Roadmaps. The particle physics community has been starved of any significant possibility of innovative project-independent detector development for a decade. Such a development also holds the promise of subsequent impact generation and further industrial involvement in the CERN programme. The accelerator R&D environment would also benefit from increased funding towards particle-physics applications. This would certainly be in line with the European accelerator roadmap.
52. The UK particle physics community has historically been very strong in the area of Public Engagement. As the excitement of the Higgs discovery fades, it is more important than ever to continue to highlight particle physics and engage the public with its excitement. Role models who are enthusiastic about public engagement can catalyse progress in making the particle physics research community more representative.

The UK and CERN

53. The UK's top priority is the full exploitation of the current LHC programme and the high-luminosity LHC. There is a tension here between this imperative and the gradual decrease of exploitation effort on LHC-related activity. Reversing this trend would require an increase in PDRA and student numbers to work with academics on LHC analyses, which could be achieved by rebalancing investment versus exploitation as the construction phase ends. However, the imperative to retain expertise in core funding

may impede this natural correction. Strategic direction will be required to resolve this problem.

54. In addition to the planned increase in the particle-physics baseline from the relatively favourable SR settlement, it is essential to consider mechanisms that can result in a significant rebalancing of UK domestic activity compared to that taking place at CERN. An example of such a mechanism could be contracting out work on detector development and construction, M&O, software, etc. currently carried out by CERN staff, to UK groups. That currently already taking place in accelerator areas could be increased and form a long-term and coherent commitment. For example, an area that would be mutually beneficial for the UK and CERN would be sustainability of accelerators. Another possibility is provision of in-kind contributions.
55. It is notable that UK citizens are not represented in any category of CERN staff at a level commensurate with the UK subscription. A scheme whereby staff necessarily based at CERN are provided by the member states from their own staff on long-term attachment might also be attractive to other Member States. It would provide many advantages, not only improving the UK's return but also reducing costs. Naturally, implementing such a scheme would require negotiation with CERN management and agreement from the other Member States.
56. It is necessary to increase in the UK's industrial return from CERN. Since this has been a problem ever since the UK joined CERN, it clearly does not admit of an easy solution. Nevertheless, it is good to note the efforts currently being made by STFC, Department of Business, Energy & Industrial Strategy (BEIS) and CERN to address this issue. The increasing involvement of particle and accelerator physicists in various industrial applications well beyond the traditional areas that would arise from increasing blue-skies R&D may promise some improvement. The Innovate UK remit extends to collaboration with STFC to improve the industrial return from CERN; ARIA should also be involved.

Administration of Particle Physics in the UK

57. The CG system sits at the heart of the implementation of particle physics, since it is the means of funding the university groups that are the drivers of UK particle physics both in theory and experiment. While there seems to be little appetite in the community for major changes in this area, some changes would be welcomed. It is difficult to get funding on the CG for activities not related to an approved project.
58. A mechanism whereby academics have an opportunity to bid for PDRAs and/or other support for projects outside the three-year CG cycle would be valuable. Projects could be in accelerator or detector development, or exploitation. This was discussed in the recent CG review.
59. Increasing the involvement of university staff with the work of STFC national laboratories would benefit both parties, e.g. by enhancing skills of university staff, particularly engineering and technical.
60. The ability of university groups to undertake sizeable detector-construction projects is essential to the future health of the subject. This also depends on the ability to retain skilled technical and engineering staff. While there does not seem to be an imminent 'cliff-face' of retirements or resignations, it has been widely noted that salaries for such staff, and also job security for those funded on the CGs, are both unattractive and grossly uncompetitive. Difficulties with retention and in particular new recruitment are currently occurring. Salary increase, improved career security and progression would be part of a suitable response which would be facilitated by increased flexibility in university post grading. The maintenance of a pipeline of talent in all the areas that form

the foundation of UK particle physics, including accelerators, computing and detector development and project construction, is an essential element of future planning.

61. The paradigm for computing, which is dominated by the requirements of LHC, is changing. It will be necessary to increase the R&D effort to improve computing algorithms and thereby reduce computational requirements and improve sustainability. This may require a dedicated project. The more generic and less challenging parts of the current computing activity would be more efficiently delivered by the very large digital-research-infrastructure effort across UKRI. This could release resources for the R&D effort required.
62. Particle astrophysics is strongly linked to both astrophysics and particle physics. The division of research into various fields will always be relatively arbitrary. Generally speaking, the smaller the subdivision, the lower the efficiency in spending resources optimally. However, discipline-specific programme-management expertise and interactions with international bodies are valuable.
63. Perhaps the area that seems most unsatisfactory in the current administration of particle physics is the lack of appropriate prioritised strategic input from those actively involved in the experimental and theoretical programmes.
64. The UK lacks a *prioritised* particle physics roadmap and the means to produce it, nor does it produce a national strategy for scale of involvement in projects. There is no process to maximise scientific excellence in the programme. Such a roadmap would produce guidelines to which decision-making committees could tailor their decisions, leading to a more balanced programme.
65. The existing advice mechanisms and advisory committees would benefit from review. In accelerator physics, a community advisory panel at the appropriate level is currently missing.
66. It is important that issues of conflict of interest do not preclude experts from inputting important information while at the same time resolving real conflicts of interest. The inclusion of international members on most panels is an important element that can help to minimise institutional conflicts of interest.
67. The pathway for new projects from their inception to approval and the overall formation of strategy should be transparent and needs input from those with the appropriate knowledge of the latest developments in the field. Comments echoing this have been heard from the particle-physics community as well as from within STFC administration. Lessons can be learnt both from the practices of other countries and from the historical experience within the particle-physics community itself. The improvement of strategic insight to STFC at all levels and stages of projects will result in improved ability to react to new directions and to produce and regularly update a prioritised and strategic roadmap balancing current commitments with new initiatives.

Summary

68. In summary, the major problems currently to be addressed within particle physics in STFC predominantly stem from a decade of flat-cash funding. The most important concern is overcommitment of the programme with the concomitant lack of ability to begin exciting new programmes and address the imbalance between exploitation and construction. The room for strategic manoeuvre is limited by the uncertainty of the next steps at the energy frontier and the necessity of getting the best value from the CERN subscription. The importance of choosing generic topics in R&D is highlighted by the fact that early investment in major new unapproved accelerator projects has historically not delivered the outcome intended. The encouragement of 'blue skies' R&D with application to a wide range of possible new projects would be a positive development. The favourable SR settlement gives the opportunity to begin to address some of these

problems but any uplift will be insufficient in itself. The CG system for experimental, theoretical and accelerator-institute research is basically sound but can be improved by more flexible and responsive funding schemes. The strategic guidance that steers future initiatives needs to be improved to allow the production of a prioritised roadmap. The current separation of particle astrophysics and particle physics inside STFC is not optimal.

IV. Recommendations

International Strategy

69. The UK community, through STFC, should embark on a transparent process to develop a prioritised strategy for the next European Strategy Update with the aim of helping to set the agenda rather than responding to it. This update will be one of the most critical for the future of particle physics, so that both experimental and theory communities should work together and engage fully with the working groups that will be set up.
70. The UK community, through STFC, should as soon as possible press at CERN committees up to and including Council to deliver a decisive outcome at the European Strategy discussions. This should involve future collider plans that are both feasible and fit within the current and likely future levels of international investment.
71. The above plans must avoid a long period without substantial physics exploitation via CERN, since this plays a key role in sustaining a healthy and vibrant particle physics community in the UK. The proposed collider should ideally have a switch on as soon as possible after the closure of LHC.
72. STFC should also encourage the development of an exciting programme of non-collider physics at CERN and elsewhere to give continuity in physics exploitation.
73. The UK should have an R&D portfolio that contains elements that are generic, i.e. not specialised to a specific project proposal while aligning with the European technology roadmaps. It should also include targeted involvement in feasibility studies for new projects at modest cost. The UK should invest in research projects in sustainable energy usage, e.g. in accelerator R&D. The portfolio should have both low- and high-risk elements.
74. STFC should encourage government bodies to develop a coherent plan to attract a major international research infrastructure to the UK, preferably in particle physics.
75. STFC should use its influence to convince the UK government that the programme to replace ERC Starting, Consolidator and Advanced Grants should be as similar to the current ERC as possible, facilitating curiosity-driven physics and thereby the opportunity for continued success for particle-physics proposals. In particular, the number of studentships and postdocs should not fall precipitously in any ERC-replacement scheme, which must be attractive to prospective international students and postdocs.

UK Particle Physics

76. The balance of the UK programme should be improved, taking advantage of the increase in STFC funding from the CSR settlement. This would allow headroom for new strategic activities and appropriate resources for approved projects. There should be an increase in responsiveness via a mix of shorter-term and longer-term projects, evaluated by the usual metrics of scientific excellence etc. This could be facilitated by the announcement of a regular cycle of funding calls.
77. There should be an increase in resources available for generic R&D for detectors and accelerators. An indicative goal would be to approach a minimum of 5% of the core programme.

78. An improvement in project management, e.g. producing more realistic costings and timelines, should be effected by providing more and better help and advice to the community at an early stage with timelines and forward planning. This would be part of a proper pathway to approval. The PPSC is encouraged that progress in this direction is already being made within the Project Office at RAL.
79. Public Engagement in particle physics should be further encouraged and expanded by increasing the ability to access ad-hoc (~£1K) funding with minimal bureaucracy, e.g. as currently allowed from within the consolidated grant.
80. Equal opportunities are a challenge for the field. In consultation with STFC's Education and Training Committee, mechanisms should be devised to work towards a target % for under-represented minorities in particle physics. For example, this will require attention to PhD recruitment strategies. Any additional resources required should be provided as a high priority.
81. Members of the particle physics community should be encouraged by STFC and senior physicists to put themselves forward for membership of committees in STFC, UKRI and beyond, particularly important strategic ones such as the IAC.

The UK and CERN

82. There should be improved strategic direction in the UK's involvement at CERN. Highly constrained resources since LHC approval, among other factors, have exacerbated an imbalance between exploitation and construction. Future construction projects, at CERN and elsewhere, should be evaluated holistically, taking account of likely future running costs, M&O, exploitation and computing as well as initial capital cost. Mechanisms to do this more reliably should be explored, including capturing commitments over the next decade and changes in exploitation and, from the RRB, M&O costs.
83. The health of UK particle physics requires that the UK domestic programme is resourced appropriately relative to the CERN subscription. In part, this should be achieved by an increase in UK domestic spend In addition, STFC should negotiate with CERN to expend an appropriate fraction of the subscription via contracts appropriately to UK-employed groups and individuals to produce selected equipment, software etc., building on currently existing mechanisms. Where physical presence in CERN is essential, fixed-term Long-Term Attachment can be utilised. These proposals will be significantly more cost effective than the current situation.
84. Efforts to improve the UK's industrial return from CERN should be sufficiently resourced and STFC should strengthen the team dedicated to this end. For example, working with CERN to increase flexibility in procurement procedures and make them more attractive for UK companies should be pursued. STFC should also consult with Innovate UK and ARIA to put in place mechanisms to facilitate exploitation of CERN technology and drive innovation in the UK. Financial incentives that would increase the attractiveness of UK industrial involvement in CERN should also be explored.

Administration of Particle Physics in the UK

85. A new responsive scheme should be introduced so that any academic can access funding outside the three-year CG funding cycle. A similar recommendation also forms part of the recent CG review. This should be a small scheme, intended to add some flexibility to the CG system without in any way challenging its primacy.
86. STFC should incentivise universities to regrade critical posts in groups where staff retention and hiring are issues of concern. The cost of such regrading should be covered by STFC within CG settlements. STFC should differentiate these posts from others in the university

system by pointing out that particle physics (and astronomy) posts have a particular requirement for long-term continuity of expertise.

87. An over-arching and comprehensive strategy for particle physics computing should be put in place. Extrapolations of computing needs and costs reveal a need to find substantial efficiency savings. The strategy for the requisite software development should be formulated in terms of a project of similar scope and coherence as GridPP, which might be subsumed in the new project. Strong contacts with the evolving UKRI Digital Research Infrastructure initiative should be developed with a view to separating off those parts of particle-physics computing that are now sufficiently mature to be carried out inside a much larger framework, with concomitant increase in efficiency and reduction of costs.
88. The current funding ‘silo’ for Particle Astrophysics should end and those projects defined as being predominantly particle-physics related should be evaluated and funded within the particle-physics structures.
89. The provision of expert scientific and technical advice to STFC should be improved. Effective management of the large and complex PP/PA programme requires STFC in-house scientific and technical expertise at arm’s length from the community. This is currently often informally provided by STFC staff who happen to have personal expertise. Temporary secondment of qualified members of the community into STFC should be instituted. They would link to the community, advising on operational and management issues. Such a model is used in several other countries. Other university staff, particularly technical and engineering, should also be encouraged to gain valuable expertise by temporary secondment to STFC laboratories.
90. Strategic advice should also be improved and in particular, a prioritised roadmap should be produced. A small committee (Particle Physics Strategic Advice Committee, PPSAC) reporting to Science Board should be put in place. It would be charged primarily with the construction of a prioritised roadmap. This would include not only projects but also skills, training, and the shape of the community including the STFC national laboratories. The PPSAC will require community input, full financial information available to STFC including input via PPD on estimates for the running programme, and input from STFC and UKRI on government priorities and concerns. The STFC Advisory Structure should be rationalised accordingly.
91. The PPSAC should be constituted by nomination from the community through the normal STFC mechanisms. The committee should be between 5 and 7 in size. A chair should be elected for a 5-year term, non-extendable, and the committee members for 3,4 or 5 years, determined randomly, to allow smooth rotation. It would be advantageous to have representation from non-UK institutions. The committee should aim for a first prioritised roadmap to be published by the end of 2023, which should be revised and published on a regular basis. The amount of work required to carry out the prioritisation of the roadmap is substantial and will require sufficient support from STFC.
92. The PPSAC should be the primary source of advice reporting into Science Board on the programme, including particle-physics-related accelerator R&D, by classifying the current programme and its projects and activities under headings that are evidence based. It should form a view on what constitutes an ‘ideal’ UK programme and devise a plan to move towards it. Proposals and Statements of Interest (SoIs) for new projects should be commented on at an early stage by the PPSAC, which should advise how they fit into the prioritised roadmap.
93. As a further aid to increasing transparency, the process by which projects might be input to the IAC should be clarified. For particle physics, it should be steered by PPSAC, which should highlight areas of the prioritised roadmap that might be suitable.
94. The current portfolio of advisory committees can be confusing and in places overlapping. The PPSAC should fit inside a new reduced structure of advisory panels. For example, the role of PPAP will need to be redefined if it is to serve as an efficient channel into PPSAC. Its

remit should include accelerator science related to particle physics and those aspects of particle astrophysics administered through particle physics. Consideration should also be given to the advisability of adding international members to appropriate panels.

95. The PPSRC view is that exploitation is currently insufficient across the programme. It should in future be protected from an excessive concentration on capital spend including M&O. The PPSAC should devise a plan to transition from the current large number of FTEs devoted to capital construction to a substantial increase in exploitation while safeguarding core capabilities. There should be an aim of devoting up to approximately 5% of core activity towards non-project-specific R&D. The PPSAC needs to steer this process strategically. It should take account also of other sources of funding including ESF, IAC etc.
96. Finally, recruitment to all committees that have a bearing on particle physics, including CERN and UK government advisory committees, should be open and transparent and be for fixed terms of no more than a maximum of three, or exceptionally five, years. It should be emphasised that this is almost always the current practice; this recommendation is included simply to restate policy for completeness.

V. Appendices

Appendix A: Panel Membership

Chair	Professor Brian Foster	University of Oxford
Members	Professor Alfons Weber	University of Mainz
	Professor Jocelyn Monroe	Royal Holloway, University of London
	Professor Mark Lancaster	University of Manchester
	Dr Mitesh Patel	Imperial College London
	Professor Monica D'Onofrio	University of Liverpool
	Professor Nigel Glover	Durham University
	Professor Sinead Farrington	University of Edinburgh
Observers	Professor Dave Newbold	STFC
	Professor Jim Clarke	STFC
	Professor Mark Thomson	STFC
	Sarah Verth	STFC
	Professor Tara Shears	University of Liverpool
Additional participants	Becca Tanner	STFC
	Chris Wrench	STFC
	Dr Matthew Needham	University of Edinburgh
Secretary	Charlotte Jamieson	STFC
Admin	Rebecca Lyons	STFC

Appendix B: Terms of Reference

Terms of Reference

The review panel is asked to provide guidance in the form a series of recommendations, on a refreshed strategic framework that will ensure the long-term health of UK particle physics and maximise the scientific benefits to the UK within a range of realistic financial scenarios.

Scope of the Review

The review will cover particle physics, including direct Dark Matter searches, and the accelerator and computing disciplines that support the field. It will take account of how wider international developments affect the UK.

In the context of developing an overall strategic framework that will ensure the long-term health of UK particle physics, the considerations of the review committee should include the following questions:

1. Are there any lessons to be learnt from the last ten years regarding the scientific and/or investment decision-making processes within STFC? The committee should consider the balance between broad areas, capital investment, exploitation, R&D, etc., not individual scientific areas.
2. What are the considerations that determine the appropriate balance between R&D, capital construction, M&O and scientific exploitation and how should these considerations be included in the decision-making process?
3. How should the UK programme ensure that it effectively leverages the investment in the membership of CERN?
4. To ensure the health of the UK particle physics programme, what is an appropriate level of early-stage technology R&D funding.
5. Given the financial constraints and uncertain timescales, how and when should the UK engage in the R&D phase for the next generation of colliders/experiments?
6. In the context of three/four financial scenarios, what are the essential elements and what areas could potentially be traded-off against each other within the strategic framework?
7. What are the key international decision points in the coming decade that will affect forward planning and influence the shape of the future UK particle physics programme?

Outputs from the Review

Having considered the above questions, the review panel will present its recommendations for a refreshed strategic framework that will ensure the long-term health of the UK particle physics programme and any changes needed to deliver the best outcomes within the recommended framework.

The output of the review will be a report to the STFC Executive, presented in three main sections:

- Findings: summarising the main findings of the review, representing a factual playback of the information that was presented to the committee that supports the committee’s assessment.
- Comments: representing the committee’s assessment of what was learnt during the review, providing narrative background to the committee’s recommendations.
- Recommendations: presenting the main recommendations from the committee that will be used to inform the development of the strategic framework for UK particle physics and its delivery.

The findings and recommendations will be presented in separate sections addressing the seven questions for consideration and any broader issues discussed by the review committee.

The report will be used by STFC, in consultation with STFC Council, to develop a new strategic framework for UK particle physics.

Inputs to the Review

The review committee will be provided with:
• historical information on the evolution of the existing particle physics programme;
• financial modelling for the potential future programme in a few scenarios ranging from:

- pessimistic: flat cash (not adjusted for inflation) for the next ten years; to
- optimistic: 5% year-on-year above inflation increase for the PPAN budget for five years and the inflationary increases

Appendix C: Meeting Dates and Location

Date	Meeting	Location
11th May 2022	Initial meeting	58 Victoria Embankment, London
22nd-23rd June 2022	2 day – comment, findings & recommendations paper discussion and drafts	The Wesley Hotel and Conference Venue, London
1st September 2022	Final paper review	58 Victoria Embankment, London

Appendix D: Current Particle-Physics Structures within STFC

1. Within the STFC advisory panel structure each scientific community is represented by an advisory panel, who maintain a roadmap of current and potential future activities in their area. The relevant panels for this review are PPAP, who represent particle physics, and PAAP, who represent particle astrophysics. Dark matter is represented in both advisory boards. Their roadmaps, and any relevant strategic reviews, are taken into account by STFC panels when making funding recommendations.
2. STFC supports particle physics research with core funding awarded through the following mechanisms: consolidated grants, reviewed by the Particle Physics Grants Panel (PPGP) and which support academics and researchers in universities; project grants, reviewed by the Project Peer Review Panel (PPRP) and which support researchers in universities and STFC; institute grants, reviewed by ad hoc panels and which support academics and researchers at the two accelerator institutes and core activities within the Institute for Particle Physics Phenomenology.
3. Project funding is held in separate lines for particle physics and particle astrophysics. The particle astrophysics budget funds dark matter projects. Dark Matter exploitation is met within PPGP.
4. STFC national laboratories, in particular PPD and ASTEC, support the programme and its delivery in both experimental particle physics and accelerator R&D. In the latter, the university-based Accelerator Institutes, Cockcroft and JAI, play a vital role not only in R&D but in particular in training the next generations of accelerator scientists.
5. STFC also funds underpinning computing for the area – GridPP for the high throughput computing necessary for experiments, and DIRAC as the primary high performance computing facility used by theorists.

Appendix E: Group Leaders Surveys

<u>Experimental</u> Sent to 27 group leaders, 10 responses

Strategic Review of Particle Physics

As part of the STFC Strategic Review of Particle Physics considering the future health and vitality of the field, we are trying to establish some general information on community viewpoints, including specifically whether there are issues arising from the impact of retirements (and loss of expertise) and the career-progression and appointment of early career technicians, engineers, detector/software physicists and with the consolidated grants and project approvals. With this in mind, we'd be very grateful if could answer the following questions.

1. What is the number, and the overall %, of FTEs of your technical group: technicians, engineers, detector/software physicists, that are likely to retire in the next 10 years
2. Do you envisage issues in replacing any expertise that may be lost e.g. difficulties in recruiting and retaining early-career technical staff?
3. Are there areas of skills shortage that you envision within your group for building next-generation experiments in the 2030s?
4. Any general comments you may have, on the vitality of technical support into the next decade.
5. Do you consider the current procedure of supporting university groups via Consolidated Grants satisfactory? Please suggest ways in which you think it could be improved.
6. Do you think that the current method of gaining approval for new particle-physics experimental activities in STFC is satisfactory? Please suggest ways in which you think it could be improved.

Theory Sent to 25 group leaders, 15 responses

1. What does a healthy programme of theoretical particle physics in the UK look like?
2. Is the balance between Cosmology, Lattice, Phenomenology, QFT, Strings right?
3. Is the balance between academic staff, postdoctoral staff, postgraduate students right?
4. If new resources would be available what would be the best way of deploying them? Please rank
5. Is the consolidated grant a suitable mechanism for supporting PPT, and how might the CG scheme be improved? For example through 4 year grants rather than 3.
6. Is the current number of academics supported on the grant at the right level? And is the amount of academic time funded at the right level?
7. Is there a preference for 2 year or 3 year pdra awards?
8. Is the current mechanism for awarding PhD studentships adequate, or could the mechanism be improved?
9. Would there be any benefit to increasing the numbers of studentships?
10. What would be the benefit of having more international studentships?
11. Is the level of resource made available for HPC adequate? Could the current model be improved?
12. How can we improve interactions between different communities? for example, the interfaces between particle theory and particle experiment, or between particle theory and astroparticle theory/experiment?

There was also an open call for input from the community.

VI. Glossary

CCC	Cool Copper Collider concept that gives a new elevated baseline for electron acceleration
CEPC	Circular Electron Positron Collider a proposed collider with a circumference of 100 Km to be based in China
FCC	Future Circular Collider, a proposed collider with an energy significantly above that of previous circular colliders

CLIC Compact Linear Collider a proposed linear collider
DESY Deutsches Elektronen-Synchrotron an accelerator centre of the Helmholtz Association located in Hamburg and Zeuthen
GPD The 2 General Purpose Detector experiments, ATLAS and CMS, at CERN's Large Hadron Collider
HL-LHC High Luminosity-Large Hadron Collider
ILC International Linear Collider
JET Joint European Torus is the world's largest and most advance tokamak located at Culham
LHC CERN's Large Hadron Collider
PPAP Particle Physics Advisory Panel
RRB the Resource Review Boards for the LHC experiments, which meets twice a year
Snowmass US process for particle physics planning organised by DoE's Particle Physics Project Prioritization Planning groups
SoI Statement of Interest for new projects

VII. References

1. STFC Programmatic Review Report 2013
2. 2020 Update of the European Strategy for Particle Physics
3. BEIS research and development (R&D): partner organisation allocation 2022-2023 to 2024-2025
4. The 2021 ECFA detector research and development roadmap
5. N Mounet (ed.) 2021 European Strategy for Particle Physics – Accelerator R&D Roadmap *CERN Yellow Reports: Monographs* arXiv:2201.07895
6. STFC Balance of Programmes exercise: 2017 and 2020
7. STFC-01122021-2019-Dark-Matter-Strategic-Review.pdf (ukri.org)

September 2022