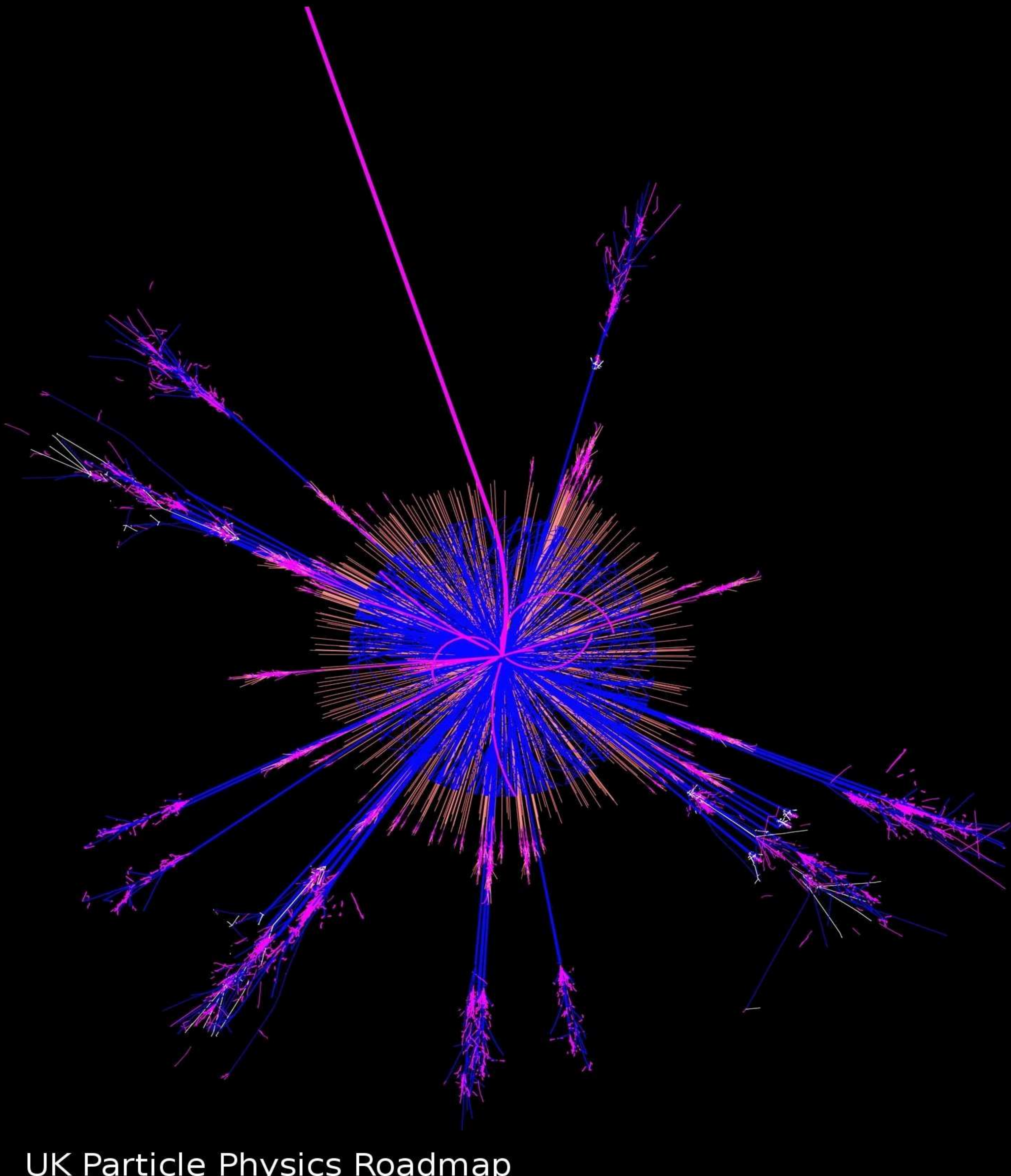

UK Particle Physics Roadmap
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Particle Physics Advisory Panel

# Report of the Particle Physics Advisory Panel

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## 1. INTRODUCTION

In the next 20 years Particle Physics will make great strides in answering many of the most important questions in fundamental science: the LHC will unveil the nature of physics at the TeV scale; the origin of a matter anti-matter asymmetric universe will be probed with unprecedented precision in both the quark and lepton sectors; and the dark matter content of the universe will be explored at both the LHC and in dedicated experiments.

Particle Physics focuses on addressing our curiosity-driven questions about the Universe through large scale facilities. These require international cooperation and stable funding over long timescales to develop the appropriate advanced technology, to expand the industrial base for the construction phase and to support the science base for the exploitation phase. Within this global framework, the UK has systematically and strategically limited its investments to those facilities that are best suited to unravelling the mysteries of nature. We have focussed on areas where the UK can have a large impact; as a result UK particle physicists hold senior leadership positions in many of today's major experiments (e.g. ATLAS, CMS and LHCb at CERN; D0 and MINOS at Fermilab; and T2K at KEK).

In order to continue to lead we must invest in a broad but well focussed programme in current and future world-class experimental and theoretical Particle Physics. The UK must also maintain an ability to react rapidly to developments, whether these will be discoveries at the LHC which steer the future direction of Particle Physics, or the emergence of novel accelerator or detector technologies which open up new avenues of research and new opportunities for knowledge exchange (KE) [1].

The UK must invest in and utilise facilities around the world to reap the optimal scientific and technological return. Most important of these is CERN, the world's pre-eminent Particle Physics laboratory and host laboratory for many of the UK's highest priority research activities. The UK continues to drive CERN's scientific programme and hence the direction of Particle Physics globally. Continued membership of CERN is essential; it provides a platform for us to pursue cutting-edge world-leading science.

Particle Physics research is about to enter a new and exciting era with the start of data taking at the LHC. We stand poised on the brink of exploring uncharted territory and, over the next two decades, we anticipate a revolution in the way we see the Universe. Our understanding will be challenged; new theories will need to be developed and new experimental facilities constructed. The UK is well placed to lead in the areas likely to be central in unveiling the fundamental laws of nature.

**Recommendation: The UK must lead in establishing the new laws of physics.**

We present a roadmap that encapsulates the aspirations of the UK community and the projects required to find answers to fundamental questions about the Universe we live in. The major scientific challenges are described in Section 2. The required facilities are discussed in Section 3 with the UK involvement described in Appendix A. The main scientific issues and our recommendations are given in Section 4.

# 2. MAJOR SCIENTIFIC CHALLENGES

The major scientific challenges for particle physics have been elucidated in a number of recent reports [2,3,4]. Particle Physics seeks answers to fundamental questions about the Universe, including:

- What are the most basic building blocks of matter?
- Can the forces between particles be understood in a unified framework? How does gravity fit in?
- What unknown properties of these particles and forces drove the evolution of the universe from the Big Bang to its present state?
- Why is there more matter than antimatter in the Universe? What is the origin of this asymmetry?

## 2.1 The Energy Frontier

Accelerators at the Energy Frontier, such as the LHC and a future Linear Collider, will survey a new energy regime, the Terascale, by producing directly the new particles which are the messengers of new phenomena. Major outstanding questions will be addressed, including:

1. How do elementary particles acquire mass? Does the Higgs boson exist, or are new laws of physics required?
2. What is the new physics that solves the problems of the Standard Model? Are there new particles or new principles? Are there as-yet undiscovered symmetries of nature such as supersymmetry (SUSY)? Are there extra dimensions of space or time? Are leptons and quarks really distinct, or simply separate manifestations of a single type of matter?
3. Can we understand the phenomena produced by strongly interacting systems?

**Recommendation: The UK must lead in exploring the Energy Frontier.**

## 2.2 The Flavour Sector

Why does the Universe contain so little anti-matter? Rare decays of particles like the kaon show that a matter-antimatter asymmetry can be produced by a mechanism called CP-violation. Our present understanding associates CP-violation with the property of "flavour" which allows us to assemble the family and generation structure of quarks and leptons. But why are there three families? Intriguingly the observed CP-violation does not account for the matter-antimatter asymmetry of the Universe. Nature must be hiding some new phenomena that explain why the Universe contains so little antimatter; almost all ideas for physics beyond the Standard Model predict much larger flavour-violating effects than have been observed so far. Major outstanding questions will be addressed, including:

4. How many generations of elementary particles are there? What principle determines this number?
5. Does new physics introduce new sources of flavour- and CP-violation beyond those of the quark sector of the Standard Model? If not, what principle explains the uniqueness of the Standard Model couplings?
6. Is charged lepton flavour violated? If so, what new physics causes charged lepton flavour violation?

The LHCb experiment and experiments at high intensity flavour factories that produce large amounts of matter and antimatter are the most direct routes for addressing these fundamental questions. They, and other flavour experiments at the high intensity frontier, will allow us to study the link between particles associated with new phenomena at the Terascale and the matter-antimatter asymmetry of the Universe.

**Recommendation: The UK must lead a coherent and focussed programme to understand the flavour sector.**

## 2.3 Neutrino and Non-Accelerator Physics

Measurements of the properties of neutrinos are fundamental to understanding physics beyond the Standard Model and may have profound consequences for our understanding of the evolution of the universe. Having mass but no charge, neutrinos could be their own antiparticles, a property possessed by no other fundamental fermion. The small neutrino masses could provide an exciting and direct link to very high energy scales that may be associated with the unification of interactions, and thereby a window back to the Universe at the very earliest times. CP-violation in the neutrino sector could play a key role in producing the observed matter-antimatter asymmetry of the Universe. Major outstanding questions will be addressed, including:

7. What are the masses and properties of neutrinos and what role did they play in the evolution of the Universe?
8. Is the neutrino its own antiparticle?
9. Is CP violation realised in the neutrino sector? How are neutrinos connected to the matter-antimatter asymmetry?

Neutrino oscillation experiments and neutrino-less double beta decay experiments will answer some of these questions by making major discoveries about the nature and properties of the neutrino.

Astrophysical measurements have revealed that dark matter makes up about one quarter of the contents of the universe. Experiments at the LHC may be able to produce Dark Matter particles directly in the laboratory, while experiments deep underground could detect Dark Matter in the solar system. These experiments try to answer:

10. What is the Dark Matter that makes up about one quarter of the contents of the universe? Can we make and study it in the laboratory?

**Recommendation: The UK must lead a coherent and focussed programme to determine the nature and properties of the neutrino and Dark Matter.**

# 3. FACILITIES

The theoretical physics programme addresses all of the key scientific questions described above. It underpins the Particle Physics programme by devising new theories and models for testing, and in assessing and determining the right sorts of experimental tests to validate them. Table 1 lists the main experimental facilities, together with their relationships to the major scientific questions described above. A summary of each facility and the UK involvement is given in Appendix A.

Exploitation of the facilities listed in Table 1 relies upon access to large-scale computing resources. The UK has been instrumental in developing the Grid computing infrastructure which underpins global Particle Physics, and through the GridPP project is a major contributor in particular to the worldwide LHC Computing Grid. GridPP enables UK researchers to take the lead in LHC physics analyses and its continued support is absolutely vital for the field.

| Experimental Facility | Key science question | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| **Energy frontier physics:** | | | | | | | | | | |
| ATLAS/CMS and their upgrades | ✓✓✓ | ✓✓✓ | ✓✓✓ | ✓ | ✓ | ✓ | | | | ✓✓✓ |
| Tevatron experiments | ✓✓✓ | ✓ | ✓✓✓ | ✓ | ✓ | ✓ | | | | ✓ |
| High-energy electron-positron collider | ✓✓✓ | ✓✓✓ | ✓ | ✓ | ✓ | ✓ | | | | ✓✓✓ |
| High-energy muon collider | ✓✓✓ | ✓✓✓ | ✓ | | | | | | | ✓✓✓ |
| High-energy lepton-hadron collider | ✓ | ✓✓✓ | ✓✓✓ | | | ✓ | | | | ✓✓✓ |
| | | | | | | | | | | |
| **Flavour physics:** | | | | | | | | | | |
| LHCb and its upgrade | ✓ | ✓ | ✓ | ✓✓✓ | ✓✓✓ | ✓✓✓ | | | | |
| High-luminosity flavour factory | | ✓ | ✓ | ✓✓✓ | ✓✓✓ | ✓✓✓ | | | | |
| High-precision dedicated charm experiments | | ✓ | ✓ | ✓ | ✓ | ✓ | | | | |
| High-precision dedicated kaon experiments | | ✓ | ✓ | ✓ | ✓✓✓ | ✓ | | | | |
| High-precision dedicated muon experiments | | ✓ | | ✓ | | ✓✓✓ | | | | |
| | | | | | | | | | | |
| **Neutrino physics:** | | | | | | | | | | |
| Long-baseline neutrino experiments and/or a neutrino factory | | ✓ | | ✓✓✓ | | | ✓✓✓ | | ✓✓✓ | |
| Reactor neutrino experiments | | ✓ | | ✓✓✓ | | | ✓✓✓ | | ✓ | |
| Direct neutrino mass experiments | | ✓ | | | | | ✓✓✓ | ✓ | | |
| Neutrinoless double-beta decay experiments | | ✓✓✓ | | | | | ✓✓✓ | ✓✓✓ | ✓✓✓ | |
| | | | | | | | | | | |
| **Non-accelerator-based physics:** | | | | | | | | | | |
| Direct dark matter search experiments | | ✓✓✓ | | | | | | | | ✓✓✓ |
| Electric dipole moment search experiments | | ✓ | | ✓ | ✓✓✓ | ✓✓✓ | | | | |
| Nucleon decay experiments | | ✓✓✓ | | | | | | | | |

**Table 1:** The relationships between international experimental facilities and the major science questions discussed in Section 2. Three ticks implies that the facility is expected to have a major impact in answering this question. A single tick implies that the facility is capable of making a significant contribution to addressing the question. No tick implies that the facility is likely to have little or no impact on that question.

# 4. RECOMMENDATIONS

We highlight the areas of research that we consider likely to be the most important over the next 20-30 years. In order to enable the best possible programme within constrained resources we recommend that the following principles are adopted:

- A broad and diverse particle physics programme focussed on high priority science questions is an essential pillar of the UK science and technology base.
- Optimal scientific return on long term investment should be supported during the exploitation phase of experiments.
- Participation in projects that are likely to form major components of the future global Particle Physics programme should be kept at viable levels.
- The potential to engage in possible future activities should be kept open, especially where key decision time frames can be identified. Where the UK is playing a leading role in design studies, appropriate funds should be made available to support these activities. Minimally, a watching brief should be kept on other promising future projects.
- A strong technological R&D base must be maintained to enable a world-leading UK Particle Physics science programme and future knowledge exchange opportunities. This should include generic R&D as well as that more focused on specific experiments.

We summarise below how the facilities map onto the roadmap for the next 20 years or so. Where milestones are listed the dates represent current best projections; they may be subject to revision as international plans evolve. For each facility we summarise the impacts of non-participation, or withdrawal, as relevant.

## 4.1 Theoretical Particle Physics

Theoretical physics has been pivotal in shaping and consolidating the Standard Model and is now crucial for formulating possible scenarios for future discoveries. It directly addresses the key scientific questions in this area and provides many of the scientific justifications for designing and constructing new experimental facilities.

### 4.1.1 Formal Theory

The UK has leadership in all aspects of Formal Theory [5] and is considered to rank second only to the US in terms of scientific output. Examples of particular strengths are the study of black holes, symmetry breaking, SUSY and string theory, the study of duality symmetries, solitons and branes (higher dimensional localised objects) in quantum field theory, supergravity and string theory and, in particle cosmology, especially the evolution of the Universe just after the big bang.

### 4.1.2 Phenomenology

There has been a substantial upsurge in UK phenomenology since the turn of the millennium. It is now firmly established as internationally leading and adds significant value and impact to the experimental programme. The Institute for Particle Physics Phenomenology has been a particularly successful initiative in this field, together with several other groups which also contribute to cutting-edge research.

### 4.1.3 Lattice QCD

Over the last 20 years lattice field theory calculations in the UK have been coordinated by the UKQCD consortium which has achieved major advances in the understanding of observations from worldwide particle physics experiments. Supported by HPC, such as the QCDOC supercomputer, UK physicists have achieved highly visible predictions with few-percent accuracy for a number of notable ‘gold-plated’ quantities, demonstrating consistency with experiment.

**We recommend that the UK should support a world-leading long-term programme in theoretical particle physics, particularly in formal theory, phenomenology and lattice theory.**

**Impacts of reduced funding**: i) Loss of major science opportunity in areas where the UK has international leadership; ii) failure to support adequately the UK experimental programme; iii) serious impact on a large number of Physics/Mathematics departments (over 150 University FTE); iv) negative impact on undergraduate recruitment and training of highly qualified personnel; and v) loss of KE opportunity with the computing industry (e.g. IBM Blue-Gene development).

**Milestones:**

2009: outcome from lattice QCD PPRP bid in 2007.
2010: next theory special grant round.
2011: next theory rolling grants round.
2012: next generation lattice machine.

## 4.2 Energy frontier physics

### 4.2.1 LHC GPDs and their upgrades

The LHC is the world's flagship particle physics project and was identified as the highest priority for European particle physics in the 2006 CERN Council Strategy Document [2]. The general purpose detectors (GPDs), namely ATLAS and CMS, are guaranteed to find either the Higgs boson or other new physics related to the generation of masses for the Standard Model particles. They offer the best prospect for exploring the mechanism of electroweak symmetry breaking and provide an outstanding chance to discover new phenomena such as SUSY and extra spatial dimensions. The results from the GPDs will shape the future direction of particle physics. The UK made major strategic investments in the LHC and the GPDs from the outset, enabling UK physicists to occupy many of the senior leadership roles in the collaborations and to drive many of the important physics analyses. The UK GridPP project provides the Grid computing infrastructure upon which these analyses are crucially dependent.

CERN is committed to an initial LHC luminosity upgrade in around 2014 and is likely to support a more extensive ('phase 2') luminosity upgrade in around ten years time. These upgrades are an integral part of the LHC physics programme, enabling full exploitation of earlier investment by consolidating LHC discoveries and extending the sensitivity to new particles and very rare processes. The UK is already prominent in the international R&D programmes preparing for the necessary GPD upgrades, and has provided many of the key technical advances required.

**Recommendation: it is essential that the UK should fully exploit its investment in the GPDs as its highest priority via:**

- **Completion and science exploitation of the design-luminosity detectors.**
- **R&D on detector upgrades to accommodate higher luminosity on a timescale commensurate with the LHC upgrade schedule.**

**Milestones:**

2009/2010: start of LHC operation.
2012-13: TDRs for upgrades – decision on upgrade construction.
2018-20: start of operation of phase 2 upgraded detectors.

**Impacts of withdrawal:** i) Catastrophic for UK particle physics: would imply termination of energy frontier physics in the UK and failure to capitalise on UK investment and leadership; ii) highly damaging impact on the wider GPD physics programme through failure to honour major UK deliverables; iii) cause immense harm to the UK's international reputation; and iv) loss of significant KE/training opportunity.

### 4.2.2 Tevatron experiments

The Tevatron experiments (CDF and D0) offer the best prospects for finding evidence of the Higgs boson until the LHC GPDs have accumulated significant datasets. UK physicists hold significant leadership positions in these experiments and the UK drives some of the most important physics analyses, particularly Higgs searches. These experiments are of limited duration and the future cost to STFC of UK participation is relatively modest. Consequently, they represent excellent value for money.

**Recommendation: it is essential that the UK should continue to exploit the science opportunities for as long as the Tevatron remains a world-leading energy frontier facility.**

**Milestones:**

2011: end of Tevatron operation (depending on LHC performance).

**Impact of withdrawal:** failure to capitalise on UK investment and leadership at the time when the experiments stand a chance of making a major discovery.

### 4.2.3 High-energy electron positron collider

A high-energy electron positron linear collider has been internationally recognised as the highest-priority next global major particle physics facility [2,3]. It is likely that it will be the facility for exploitation and extension of the LHC physics discoveries. It would be complementary to the LHC, bringing incisive precision and significant additional discovery potential. Early LHC physics results will guide the choice of the design energy range for the collider. The ILC is the most mature technical design (TDR in 2012) and addresses the energy range 0.5 – 1.0 TeV. The CERN based CLIC concept aims to address energy scales up to several TeV, but requires significant further R&D (TDR expected in 2015). It is important to note that in the past 18 months a formal collaboration has been launched between ILC and CLIC for a coherent strategy to realise a linear collider. This naturally extends CERN's role in the global planning process for the linear collider. The UK has made significant investments in R&D on both the accelerator and detector technologies and key systems, and continues to hold positions of international leadership and responsibility. All of the UK investment was deliberately targeted at areas that are applicable to both the ILC and CLIC designs.

**Recommendation: it is essential that the UK should pursue both accelerator and focussed detector R&D through to a decision point on the future direction for the linear collider.**

**Milestones:**

2012: ILC TDR.
2012/2013: future project direction based on LHC results.
2015: CLIC TDR.
2015-20: possible start of construction.
2022-27: possible start of operation.

**Impacts of non-participation:** i) loss of UK influence/opportunity in the world's next forefront particle physics project; ii) failure to engage in world-leading detector and accelerator R&D, with loss of related KE opportunity; iii) failure to capitalise on previous investment, and loss of international leadership; and iv) further damage to the UK's international reputation.

### 4.2.4 High-energy muon collider

In the long-term, a high energy muon collider, building on the muon storage ring of a future neutrino factory, might provide a route to a multi-TeV lepton collider. By accelerating muons, rather than electrons, it could be possible to construct a high energy/high intensity collider on a compact site. Nevertheless, the development of the concept of a muon collider is at a relatively early stage and there are a number of major technological challenges which need to be solved to demonstrate its feasibility, including the necessary muon cooling which is being addressed via the MICE project (see also Section 4.4.3). UK involvement in both accelerator and detector R&D could build on existing Neutrino Factory and Linear Collider R&D programmes.

**Recommendation: Accelerator and detector specific R&D which is naturally part of the neutrino factory and linear collider R&D programmes also supports the development of a muon-collider. No additional significant specific investment in a muon collider is appropriate at this time. Modest funds to maintain a watching brief on international muon collider developments would be appropriate.**

**Milestones:**

2014/2015: physics motivation for the neutrino factory as the next long-baseline facility.
> 2030: muon collider realisation?

### 4.2.5 A high-energy lepton-hadron collider (LHeC)

The concept of a high energy lepton-hadron collider (LHeC) at CERN, using the LHC to provide the proton and ion beams, is currently being developed. LHeC would provide complementary information to the LHC and a linear collider, with unique sensitivity to the manifestation of new physics with lepton+quark quantum numbers. In particular, if a lepto-quark signal were observed at the LHC, the new-physics case for a high energy lepton-hadron collider would strengthen significantly. In addition the LHeC has the potential for precision strong and electroweak measurements at the TeV scale, and such a facility amounts to a possible extension of the LHC programme. The UK is playing a leading role in developing the concept of the LHeC in preparation for a TDR in 2012.

**Recommendation: appropriate funds should be made available to allow key individuals to maintain a leading role in the conceptual design studies for a possible LHeC.**

**Milestones:**

2012: TDR.
2012/2013: results from LHC.
2020: possible installation of magnets, in the LHC tunnel or in a separate linear accelerator.

## 4.3 Flavour physics

### 4.3.1 LHCb

LHCb will be the world's leading experiment in quark flavour physics for at least the next five years. Its measurements will radically improve our knowledge of several parameters that are crucial for our understanding of the quark flavour sector. These include the amount of CP violation in oscillations of $B_s$ and $D^0$ mesons, the rate of the rare decay $B_s \to \mu\mu$ and the size of the CKM unitarity triangle angle $\gamma$. Through virtual new particles which may contribute to loop processes that are suppressed in the Standard Model, LHCb has significant new physics discovery potential even if the scale of the new physics is above the direct reach of the LHC GPDs. The UK's leading involvement in LHCb capitalises on a decade of investment and builds on the UK's leadership in quark flavour physics. The UK GridPP project provides the Grid computing infrastructure upon which the data analyses are crucially dependent.

**Recommendation: it is essential that the UK should fully exploit its investment in the design-luminosity LHCb detector as its highest priority in flavour physics.**

**Milestones:**

2009/2010: start of LHC operation.

**Impacts of withdrawal:** i) Hugely damaging for UK particle physics; it would imply the withdrawal of the UK from one of the major and most active areas of research; ii) failure to capitalise on UK investment and leadership; iii) highly damaging impact on the international LHCb physics programme through failure to honour major UK deliverables; and iv) cause devastating harm to the UK's international reputation.

### 4.3.2 LHCb upgrade

After roughly five years of data taking the LHCb detectors will need to be upgraded. The LHCb upgrade will enable the experiment to operate at ten times the design luminosity and to increase the trigger efficiency by a factor of two for hadronic modes. This will enable a new era of precision measurements probing deeper into the physics of the flavour sector. The upgraded experiment will, for example, fully exploit the potential of rare hadronic and radiative $b \to s$ loop transitions (in decays such as $B_s \to \varphi\varphi$, $B_s \to \varphi\gamma$ and $B \to K^*\mu\mu$) and CP violation in D mesons. Such decays are highly sensitive to, and can distinguish between, different models of, new physics. The LHCb upgrade does not depend on the LHC luminosity upgrade. The UK is already leading in the international effort to establish R&D programmes preparing for the LHCb upgrade. At the current time, R&D is necessary into critical sub-detector components in areas of strategic UK interest: radiation-hard silicon pixel technology; fast photon detectors; algorithms to read out and trigger at very high rates.

**Recommendation: it is essential that the UK should pursue R&D on a possible detector upgrade. The UK should plan for participation in the upgraded LHCb detector and, if justified by the LHC physics results, should participate in the upgrade at an appropriate level.**

**Milestones:**

2009/10-2013: R&D phase.
2013: TDR for upgrade, decision on upgrade construction.
2016: start of upgraded LHCb data-taking.

**Impact of withdrawal:** i) huge loss of scientific opportunity; ii) loss of leadership of an experiment that is a key part of CERN's medium-term programme; iii) imperil the viability of the LHCb upgrade project; iv) loss of UK leadership of the field of quark flavour physics and v) loss of significant KE opportunity.

### 4.3.3 High-luminosity flavour factory

A next generation asymmetric energy $e^+e^-$ flavour factory, with a luminosity ten to a hundred times higher than the current experiments, could do for the understanding of the flavour sector of any TeV-scale new physics what BaBar and Belle did for the CKM paradigm of the Standard Model. The clean environment of an $e^+e^-$ machine enables a number of important measurements that cannot be performed at LHCb. These include inclusive studies of $b \to s$ loop transitions and measurements of the leptonic decay $B \to \tau\nu$. The sensitivity to lepton flavour violating tau decays also exceeds that expected at any other experiment. The ‘SuperB’ proposal for such a facility in Italy would represent a major new European scientific initiative. There is also a proposal for upgrading the KEK B factory in Japan. Decisions on the construction of these projects by the respective authorities are expected within the next year; this is an area where developments may occur rapidly.

**Recommendation: appropriate funds should be made available to allow key individuals to participate in design studies for a high luminosity flavour factory. If a facility is approved, and if significant UK interest emerges, possible participation should be tensioned against other flavour physics projects at a level justified by the physics case.**

**Milestones:**

2009/10: decision expected on whether/how to proceed with such a facility.
2011: ‘SuperB’ TDR.
2013: ‘Super KEK-B’ start of operation?
2014-2016: ‘SuperB’ start of operation?

**Impact of non-participation:** i) loss of scientific opportunity; ii) loss of potential UK leadership in a major new initiative and iii) loss of KE opportunity.

### 4.3.4 High-precision dedicated charm experiments

The charm sector provides unique potential to study flavour-changing interactions of up-type quarks. Precise studies of charm mixing and rare charm decays are highly sensitive to new physics in many models. Charm experiments also provide important results on spectroscopy and can help to improve our understanding of QCD. Charm physics represents a significant part of the programmes of LHCb, the LHCb upgrade and high-luminosity $e^+e^-$ flavour factories. Dedicated charm physics experiments, such as BES-III and proposals for fixed-target experiments at FNAL, offer some additional scientific opportunities.

**Recommendation: at this time interest in charm physics should be pursued through the UK's involvement in LHCb, and there should be no UK involvement in new dedicated charm experiments.**

**Impact of non-participation:** loss of scientific opportunity.

### 4.3.5 High-precision dedicated kaon experiments

Among a number of very rare decays of K-mesons, the decays $K^+ \rightarrow \pi^+ \nu\nu$ and $K_L \rightarrow \pi^0 \nu\nu$ have unique sensitivity to new physics in the quark-flavour sector. They pose the experimental challenge of achieving a decay sensitivity to branching ratios at the level of $10^{-11}$ or less. The NA62 experiment at CERN (approved in 2008) should observe at least 100 $K^+ \rightarrow \pi^+ \nu\nu$ decays if the branching fraction is at the Standard Model level, with corresponding discovery potential if the decay rate is affected by new physics.

**Recommendation: a limited investment in the proposed NA62 experiment could provide very interesting near-term science return at a modest cost. Beyond NA62, modest funds to maintain a watching brief on future high-precision kaon experiments would be appropriate.**

**Milestones:**

- 2009-10: decision on UK involvement in NA62.
- 2010-12: NA62 construction.
- 2012-13: start of NA62 data-taking.

**Impacts of non-participation:** i) loss of a significant science/leadership opportunity; ii) reduction in the potential diversity of the UK particle physics programme; iii) failure to capitalise on previous investment in the CERN kaon-physics programme.

### 4.3.6 High-precision dedicated muon experiments

Interest in the possibility of observable charged lepton flavour violating decays has enjoyed a resurgence since the discovery of neutrino oscillations. Such decays, which would be unambiguous signatures of physics beyond the Standard Model, would provide a new window on flavour and CP violation in the lepton sector. The highest potential sensitivity to charged lepton flavour violating processes appears to come from $\mu \rightarrow e$ conversions, following muon trapping on nuclei. The proposed COMET experiment aims for an improvement of four orders of magnitude compared to the current limits; this would extend into a theoretically interesting region. A second stage, called PRISM, based on FFAG technology, could have the potential to deliver a further two orders of magnitude in sensitivity. The UK does not have a recent track record in this scientific field, but there has been recent UK interest in participating in these experiments and the UK leads in development of FFAG accelerator technology.

**Recommendation: a limited investment in a future high-precision muon experiment, such as COMET/PRISM, could offer the prospect of significant scientific return.**

**Milestones:**

- 2010: decision on UK involvement.
- 2012: COMET TDR, J-PARC decision on COMET/PRISM.
- 2012-2015: COMET construction; PRISM R&D.
- 2015-18: COMET running; PRISM R&D/construction.
- 2018-20: PRISM running.

**Impact of non-participation:** i) loss of a significant science opportunity; ii) reduction in the potential diversity of the UK particle physics programme; and iii) loss of significant KE opportunity.

## 4.4 Neutrino physics

### 4.4.1 T2K

T2K will be the leading experiment in neutrino physics for the next 5 – 10 years. T2K will make seminal contributions to our understanding of the lepton flavour sector; it is well placed to make the first measurement of $\sin^2 2\theta_{13}$ with sensitivity down to 0.01 and will greatly improve the theoretically interesting measurement of $\theta_{23}$. If $\theta_{13}$ is sufficiently large, a second phase of T2K may have sensitivity to CP violation in the lepton sector which would represent a major discovery. Involvement in T2K places the UK in a strong position to play a leading role in a future Japanese Super-Beam experiment which, depending on the value of $\theta_{13}$, may represent the route to the discovery of leptonic CP violation.

**Recommendation: it is essential that the UK should participate strongly in T2K as its highest priority in neutrino physics.**

**Milestones:**

2009: start of T2K phase-1 operation.
2014: end of T2K phase-1.
2014/2015: possible start of T2K phase-2 depending on magnitude of $\theta_{13.}$

**Impacts of withdrawal:** i) hugely damaging for UK particle physics: loss of major science opportunity; ii) failure to capitalise on UK investment at the time when T2K is about to enter the exploitation phase; and iii) loss of reputation of the UK as a reliable international partner.

### 4.4.2 MINOS

MINOS will continue running until 2011/2012. There are two main physics goals in this period. Firstly, the measurement of the oscillations of anti-neutrinos at the "atmospheric" neutrino mass scale. This measurement will remain unique for the foreseeable future and will provide a test of CPT violation in the neutrino sector. Secondly, MINOS will extend its search for electron neutrino appearance, where MINOS currently observes a small (1.5$\sigma$) excess; thus with additional data there is the possibility of the first observation of $\nu_\mu \rightarrow \nu_e$ oscillations. This would represent a significant discovery, demonstrating for the first time that $\theta_{13}$ is non-zero.

**Recommendation: sufficient funding should be retained to enable the UK to exploit the last two years of MINOS operations with antineutrinos.**

**Milestones:**

2009/2010: start of anti-neutrino running.
2011/2012: end of MINOS operations.

**Impacts of withdrawal:** i) loss of science opportunity; ii) failure to fully capitalise on significant UK investment and leadership; and iii) seriously compromise the ability to operate the experiment.

### 4.4.3 R&D for future long-baseline neutrino experiments and/or a neutrino factory

In the last ten years the UK has built up a world-leading neutrino physics community and it is essential that the UK is involved in the next long-baseline experiment, whether it is T2K phase 2, a super-beam facility, a beta-beam, or a neutrino factory. By the middle of the next decade it will be known whether $\sin^2 2\theta_{13}$ is large or not, and the route to the discovery of leptonic CP violation will be better understood. The UK is making world-leading contributions to the future neutrino programme through a leading presence in T2K, leadership of the neutrino factory international design study, and by hosting MICE and EMMA. There is a case for new detector R&D into Liquid Argon TPC technology.

**Recommendation: it is essential that the UK should be involved in the next generation of long-baseline neutrino oscillation experiments and should continue to pursue a world-leading R&D programme towards this aim. Any new detector/dedicated accelerator R&D in this area should be tensioned against the existing neutrino R&D programme.**

**Milestones:**

2012: neutrino factory RDR.
2014: completion of MICE experiment; demonstration of muon cooling.
2014/2015: measurement of/tight limit on $\sin^2 2\theta_{13}$, enabling the future direction to be defined.

**Impacts of non-participation in R&D:** i) loss of leadership in future long-baseline neutrino facilities; ii) loss of leadership in the neutrino factory international design study; iii) loss of opportunity to participate in cutting edge neutrino detector and specific accelerator R&D; iv) loss of significant KE opportunity.

**Impacts of withdrawal from MICE:** i) failure to deliver a high-profile particle physics project hosted in the UK; and ii) a failure to honour international commitments.

### 4.4.4 Reactor neutrino experiments

The current generation of reactor experiments (Double-Chooz, Daya Bay, etc.) have sensitivity to $\sin^2 2\theta_{13}$ down to approximately 0.03. Due to the absence of matter effects, the measurements are (at least partially) complementary to those from long-baseline oscillation experiments. At this time, the UK is not playing a significant role in this area. The potential for future improvements in reactor based experiments currently appears limited.

**Recommendation: At this stage, reactor neutrino experiments should not form part of the STFC roadmap.**

**Milestones:**

2009/2010: Start of Double-Chooz experiment.

**Impact of non-participation:** loss of scientific opportunity.

### 4.4.5 Direct neutrino mass experiments

Neutrino oscillation experiments only provide information on the differences of the squares of the neutrino masses. The determination of the absolute scale of the neutrino mass is an essential measurement. The UK has only very limited involvement in the Katrin experiment.

**Recommendation: At this stage, future direct neutrino mass experiments should not form part of the STFC roadmap.**

### 4.4.6 Neutrinoless double-beta decay experiments

Neutrinoless double-beta decay experiments address a fundamental question about the nature of the neutrino and the observation of a signal would represent a major discovery. A number of experiments will operate in the next decade. These will begin to reach the theoretically interesting level of sensitivity. The UK has interests in two projects (SNO+ and Super-Nemo). The strength of SNO+ is that it reuses the existing SNO facility and thus offers a timely and cost-effective neutrinoless double-beta decay experiment with genuine discovery potential; there is a strong case for the UK to make the required modest investment to participate in SNO+. Super-Nemo has comparable sensitivity to SNO+ but its main strength is the unique topological signature for neutrinoless double-beta decay; this would be essential to demonstrate that an observed signal is indeed neutrinoless double-beta decay.

**Recommendation: it is essential that the UK is involved in a current-generation experiment and pursues a coherent and world-leading long-term programme of research in this area.**

**Milestones:**

2010: decision on UK involvement in SNO+.
2011-2013: SNO+ Phase I operation.
2011/2012: operation of the Super-Nemo prototype module.
2012: Super-Nemo TDR.
2013-2015: SNO+ Phase II operation.
2013/2014: Initial Super-Nemo running.
2016: Completion of full Super-Nemo detector.

**Impact of non-participation:** i) loss of the opportunity to participate in a potentially major discovery of the nature of matter; ii) UK withdrawal from Super-Nemo could lead to cancellation of the project; iii) failure to capitalise on previous SNO investment; iv) loss of KE opportunity.

## 4.5 Non-Accelerator Experiments

### 4.5.1 Direct dark matter search experiments

The nature of the dark matter is one of the most important unanswered questions in science and has profound implications for both particle physics and cosmology. The search for dark matter is a very active and competitive field worldwide, pushing down limits on the dark matter scattering cross-section by roughly an order of magnitude every 3 – 4 years. The UK has a leading role in two international consortia, EURECA and LUX-ZEPLIN, developing tonne-scale detectors intended to obtain sensitivity to signals at the $10^{-10}$ pb level. Such detectors should have sensitivity to a significant fraction of possible SUSY dark matter models.

**Recommendation: it is essential that the UK is involved in a current-generation experiment and pursues a coherent and world-leading long-term programme of research in this area.**

**EURECA milestones:**

2009-12: CRESST/EDELWEISS exploitation.
2009/10: EURECA TDR.
2011-14: EURECA construction.
2015: EURECA operation (0.1t).
2018: EURECA operation (1t).

**LUX-ZEPLIN milestones:**

2009: ZEPLIN-III (6kg) operation ongoing.
2010: LZ3 construction (3t).
2012: LZ3 operation.
2013: LZ20 construction (20t).
2018: LZ20 operation.

**Impact of withdrawal:** i) loss of major science opportunity with potential for maximum impact on cosmology and particle physics; ii) termination of an area of significant UK leadership; iii) loss of KE opportunity.

### 4.5.2 Electric dipole moment search experiments

Electric Dipole Moment experiments have sensitivity to a range of Beyond the Standard Model CP violation mechanisms. The UK is the world-leader in both electron and neutron EDM experiments. The

CryoEDM nEDM experiment and YbF-beam eEDM experiments will yield between one and two orders of magnitude increases in experimental sensitivity compared with the current best limits within the next 5 years or so. In both cases the projected experimental reach extends into a theoretically interesting region. These experiments are complementary to direct searches for BSM physics and are likely to remain at the forefront of this field until at least the end of the next decade. The CryoEDM and the YbF eEDM experiments are relatively small scale and represent excellent value for money.

**Recommendation: it is essential that the UK exploits its world leading position in both electron and neutron dipole moment search experiments. We note that for these relatively small, UK-dominated experiments, a small reduction in funding would be difficult to absorb and would have a disproportionate impact.**

**nEDM Milestones:**

2012: sensitivity one order of magnitude below current world limit.
2013: data taking in new beamline.
2016: sensitivity of $10^{-28}$ *e* cm; two orders of magnitude below current limit.

**eEDM Milestones:**

2009: publication of world leading limit.
2014: improvement in sensitivity by two orders of magnitude.

**Impact of reduced funding:** i) effective termination of the world-leading eEDM and nEDM experiments; and ii) missing out on a potentially major discovery.

### 4.5.3 Nucleon decay experiments

Nucleon decay is a generic prediction of Grand Unified Theories and a discovery would provide the first direct evidence for the unification of forces. Initial searches for the $p \rightarrow e^+\pi$ decay mode using water Cerenkov detectors have ruled out the simplest SU(5) models. SUSY GUT models predict significantly longer lifetimes and more challenging decay modes such as $p \rightarrow K^+\nu$ to which water Cerenkov detectors are less well suited. There is UK interest in a liquid argon detector in the 100 kt range, which may give enhanced sensitivity to this channel. This technology might also be suitable for a future long-baseline neutrino experiment (see Section 4.4.3) and it is likely that a full-scale detector would be designed to fulfil both roles.

**Recommendation: bids for nucleon decay experiment R&D should be tensioned against the rest of the future long-baseline neutrino experiment programme.**

**Impacts of non-investment:** loss of major science and KE opportunities.

## 4.6 SUMMARY OF RECOMMENDATIONS

We summarise our recommendations below. In each category the facilities are listed in alphabetical order.

### i) World leading/highest priority

The highest-priority areas are:

- LHC GPD exploitation and upgrades;
- LHCb exploitation;
- Neutron and electron EDM search experiments;
- Theoretical physics programme;
- T2K;

It is mandatory that the UK reap its investment in these facilities and maintains its world leadership. Withdrawal from these facilities is unthinkable.

Support for the GridPP project is essential for the exploitation of the LHC programme.

### ii) World leading/UK involvement essential

Programmes in which UK involvement is essential are:

- Direct dark-matter search experiments;
- LHCb upgrade R&D;
- Linear Collider accelerator and detector R&D;
- Long-baseline neutrino physics detector R&D/neutrino factory accelerator R&D;
- Neutrinoless double-beta decay experiments;
- Tevatron experiments.

All of these facilities offer world-leading science opportunities and are areas of UK excellence and/or leadership. Under no circumstances should the UK withdraw from any of them – some level of strategic investment needs to be maintained in all. If it proved necessary, modest reductions should be considered in allocations to the highest priority programmes (above) in order to maintain an appropriate level of strategic investment in these areas.

### iii) World leading/significant UK scientific opportunity

The following programmes are world leading and offer a significant scientific opportunity for the UK:

- High-precision muon experiments;
- MINOS;
- NA62.

Limited investment is highly recommended.

### iv) Significant future opportunity

The following projects offer exciting future scientific directions:

- High-luminosity flavour factory;
- Future high-precision kaon experiments;
- LHeC;
- Muon collider.

At this stage we recommend that modest funds be made available to allow UK leadership and participation in design studies. Where relevant, limited strategic investment in detector and accelerator R&D, e.g. via the PRD scheme, should be considered on its merits.

### v) UK engagement not foreseen at this time

Whilst the areas/projects below are scientifically interesting, no UK participation is foreseen at this stage:

- CNGS;
- Dedicated precision charm experiments;
- $g_\mu$-2;
- Belle;
- MEG;
- Nova;
- Precision neutrino mass experiments;
- Reactor neutrino experiments.

Whilst the above recommendations, **i) – iv)**, are based purely on scientific merit, **all** projects offer significant knowledge exchange opportunities: the forefront exploitation experiments provide an exciting training base for young physicists in advanced data processing/analysis techniques and computing skills; the R&D projects involve the development of high-technology solutions in detector and accelerator science which offer the potential for industrial engagement as well as spin-offs.

**In the unfortunate event that the STFC financial situation requires that major cuts be made to the UK Particle Physics programme, we request that no such cuts be implemented without a further consultation with the PPAP.**

It should be noted that we have not considered projects that we consider to be mainly within the remit of the other Advisory Panels. These include heavy ion experiments, high-energy gamma-ray experiments, and solar neutrino experiments.

## 4.7 A Roadmap for the STFC Particle Physics Programme

Based upon the above recommendations, a roadmap for the STFC Particle Physics programme is shown in Figure 1. The indicative timescales represent reasonable estimates based on the input to the PPAP.

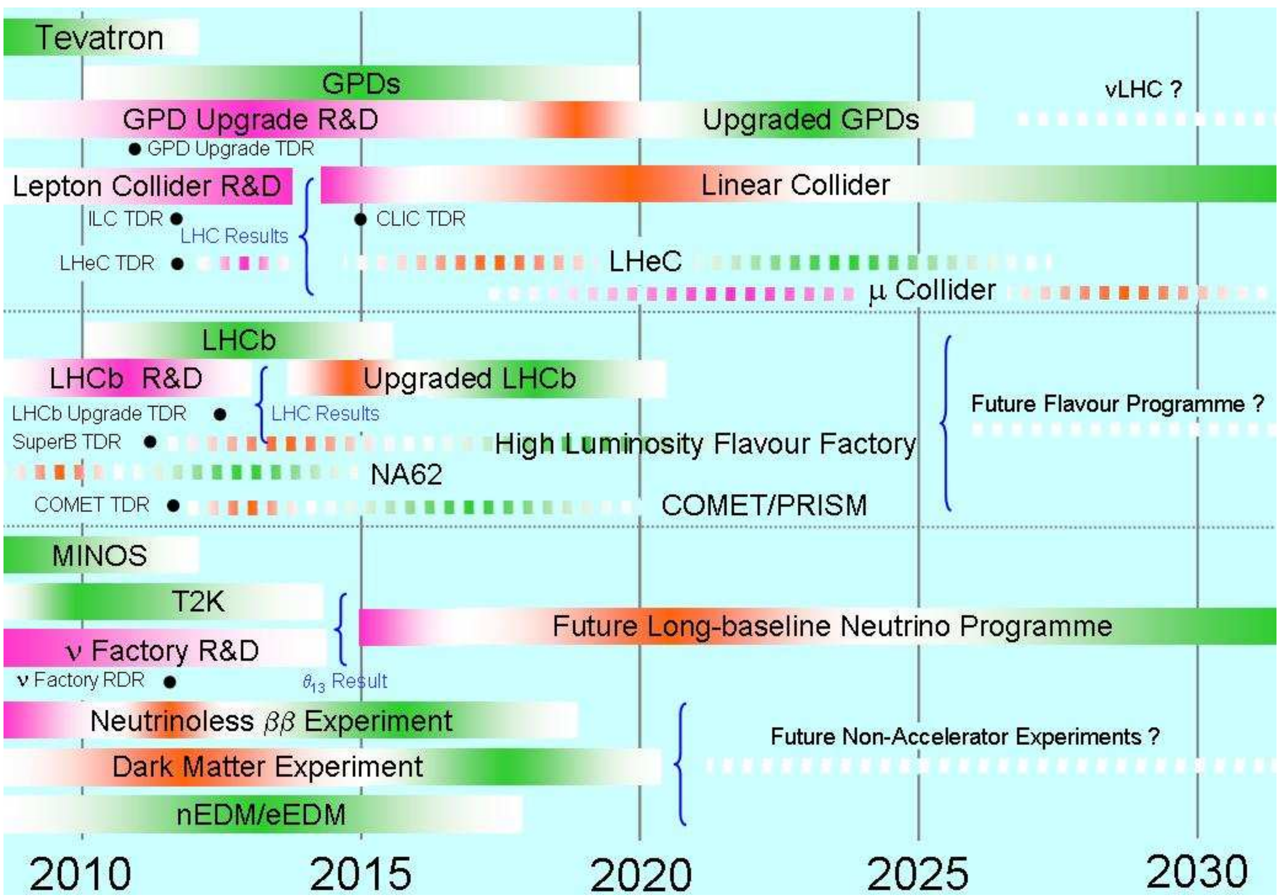


**Figure 1:** Proposed roadmap for UK Particle Physics showing the major milestones as understood now. The colours show the expected status of each facility as a function of time (as best understood now). Magenta represents the R&D phase, orange the construction phase and green the exploitation phase. The facilities shown by solid bars form the core of the recommended future UK Particle Physics roadmap. The facilities shown by the dashed-bars indicate potential future scientific opportunities not currently funded by STFC. Possible decision points are shown by the braces.

# 5. CONCLUSIONS

This report represents the conclusions of the Particle Physics Advisory Panel. These conclusions were reached via extensive consultation with the UK Particle Physics community. The proposed roadmap represents a diverse and coherent programme of research, focussed on the major scientific questions in Particle Physics, within the framework of constrained resources. Answering these questions is key to our understanding of the Universe. It is clear that Particle Physics is entering an exciting era; all projects on the roadmap have the potential to make major discoveries that will challenge our current understanding of fundamental physics.

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