Appendix A: Facilities

We describe in more detail the facilities that are summarised in the main report. In each case we give a context for the facility, relevant facility details, a summary of the UK track record and expertise, the current UK involvement, future opportunities for the UK, and relevant milestones and/or decision points.

A.1 Theoretical Particle Physics

A.1.1 Formal Theory

Context:
Supersymmetry and string theory are widely considered to be most promising ingredients in finding a single consistent quantum theory of all four forces including gravity. The solution of this very long standing problem would represent one of the crowning achievements of human intellectual endeavour. While experiments directly probing the Planck scale, the scale at which the unification with gravity should occur, are far beyond reach, it is possible that there will be imprints at lower energies. Moreover, such fundamental research frequently leads to theoretical developments which have an enormous, but unexpected, impact on lower energy experiments. For example, the recent discovery of a duality between supersymmetric field theory and topological string theory has directly led to developments in phenomenology such as the computation of the W+3 jet rate at the LHC. Another example is that the famous AdS/CFT correspondence, which has transformed our theoretical understanding of the relationship between gravity and quantum field theory, can be successfully used to model the RHIC thermal plasma by studying black holes in anti-de-Sitter spacetimes. Furthermore, supersymmetry and extra dimensions provide the eagerly expected signatures of new physics at the LHC.

Typical timescales for bringing new theoretical ideas to experimental realisation can be very long. The Higgs mechanism for electroweak symmetry breaking was proposed in 1964; Hawking radiation from black holes was proposed in 1975; supersymmetric field theories, together with their unexpected quantum properties, were found in the period 1974 to 1976. All three could be finally observed at the LHC. Even models with large extra dimensions were proposed more than a decade ago. Theoretical particle physics plays the strategic role of motivating new questions and experiments and, for example, provide the motivation for new physics at the Terascale.

UK history/expertise:
The International Review of UK Physics and Astronomy Research 2005 said:
"As stated in the 2000 report, the UK has a long history of excellence and leadership in string theory and general relativity."
The UK has made, and continues to make, very significant contributions and it is second only to the US. Examples of particular strengths are the study of black holes, symmetry breaking, supersymmetry 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.

Current UK involvement:
Many UK universities are involved and there has been significant recent university investment into this area. The number of university funded academic FTE (across all of theoretical particle physics) has risen from about 120 in 2005 to 155 in 2008 and many top international scientists have come to the UK. The fundamental nature of theoretical particle physics is excellent for recruiting and inspiring undergraduates to study mathematics and physics.

UK opportunity:
To play a leading role in developing the theoretical answers to many of the fundamental questions about the structure and evolution of the Universe.

Milestones/decision points:
2010 next theory special grants round
2011 next theory rolling grants round

A.1.2 Phenomenology

Context:
Physics is a subject that can only thrive when there is strong interplay between theory and experiment. New theoretical ideas lead to predictions that can be tested experimentally, and new experimental findings challenge theorists to produce better ideas. Particle physics phenomenology provides the theoretical basis for the experimental programme. It is a well established field with a long standing tradition in achieving major contributions to scientific knowledge. The 2006 CERN Council Strategy Document assigned theoretical physics a high priority: "Strong theoretical research and close collaboration with experimentalists are essential to the advancement of particle physics and to take full advantage of experimental progress. The forthcoming LHC results will open new opportunities for theoretical developments, and create new needs for theoretical calculations, which should be widely supported." In parallel, particle astrophysics connects experiment to the questions about our universe, such as the nature of dark matter, the longevity of protons or the origins and properties of the energetic particles reaching the Earth.

Phenomenology continues to play a crucial role in shaping and consolidating the Standard Model and in 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. It provides the crucial link between theoretical ideas and their experimental realisation, for example taking the ideas of spontaneous symmetry breaking and turning them into predictions for Higgs boson production and decay at high energy colliders through to complete simulations of Higgs boson events.

UK history/expertise:
There is strong UK activity in all areas of phenomenology - Monte Carlo, QCD, Electroweak and Higgs, Beyond the Standard Model (BSM), Flavour Physics, Neutrino Physics, Particle Astrophysics/Cosmology, Lattice Phenomenology and Model Building with particular strength and depth in Monte Carlo (HERWIG, SHERPA) and QCD. The UK has a strong record of participation in studies for future accelerators – having led many of the CERN working groups on LEP and the LHC, and with leading contributions to the interpretation of HERA and TEVATRON data. There is significant leadership of Linear Collider and Neutrino Factory design studies, as well as strong input to the European strategies for particle physics and astroparticle physics.

Current UK involvement:
There has been a substantial upsurge in phenomenology across the whole country since the turn of the millennium. Many UK groups have expanded and overall, the number of university funded academic FTEs has risen to about 60 with many top international scientists coming to the UK. There are several strong initiatives including the Institute for Particle Physics Phenomenology (IPPP) in Durham, the Scottish Universities Physics Alliance (Edinburgh, Glasgow) and the NExT Alliance (RAL, RHUL, Southampton, Sussex). In some institutions close collaboration with experiment is stimulated by overlapping interests and research activities (e.g. Cambridge, Sheffield), or embedding (Manchester) phenomenologists within the experimental group.

UK opportunity:
To lead the theoretical efforts that will add value to the investment in all types of experimental measurements and provide the vital link between particle physics and cosmology; and to play a leading role in developing the theoretical answers to many of the fundamental questions about the structure and evolution of the Universe.

Milestones/decision points:
2010 next theory special grant round
2011 next theory rolling grants round

A.1.3 Lattice QCD

Context:
The primary aim of lattice field theory is to compute non-perturbative physical quantities with sufficient precision to have impact on experiment. Using lattice QCD, first-principles results with few-percent accuracy have been obtained for notable ‘gold-plated’ quantities, demonstrating consistency with experiment. Parameters of QCD such as quark masses and the strong coupling constant have been determined to higher precision than other methods allow. Precise predictions for hadron masses have also been made, subsequently confirmed by experiment. New formulations and computers will enable these calculations to be improved further and extended to a wide range of strong-interaction matrix elements, allowing any inconsistencies between the Standard Model and experiment to be exposed at this level of accuracy. In many interesting cases the experimental errors are smaller than the current theoretical (lattice) errors and to exploit the full potential of the measurements, increased computing power and improved algorithms/methods are needed.

It is now possible to perform realistic lattice QCD calculations that include the effect of up, down and strange quarks in the sea and a number of different formulations for doing this are being exploited in the UK. The best current lattice results (all with strong UK involvement) have errors of 6% for B meson decay constants, 1% for K meson decay constants, 3% for ratios of B mixing parameters and 5% for the K mixing parameter. This gives an error of around 1% on $|V_{us}|$, and 2.5% on $|V_{td}/V_{ts}|$.

UK history/expertise:
Over the last 20 years lattice field theory calculations in the UK have been led by the UKQCD Consortium, via a twin-stranded approach of both procuring world-class computational facilities, and through enabling and fostering collaborative projects among members of the constituent institutions and their overseas collaborators, most notably the international ETMC, HPQCD and RBC/UKQCD Collaborations. During this period UK physicists have established themselves in the front rank of lattice QCD research across a broad range of phenomenologically important areas: precision hadron spectroscopy; determination of fundamental Standard Model parameters such as quark masses and the strong coupling; hadron decay constants and form factors; operator matrix elements; heavy quark physics; and the nature of the quark/hadron phase transition at high temperature and small baryon density. An important UK facility for some of this work has been the QCDOC computer. When commissioned in January 2005 with sustained performance of 5 Tflops, it was the 64th fastest computer in the world. It reached the end of its life in 2009.

Current UK involvement:
The UK effort is coordinated by the UKQCD Consortium comprising Edinburgh, Cambridge, Glasgow, Liverpool, Oxford, Plymouth, Southampton and Swansea. Dedicated facilities such as QCDOC are the most cost efficient source of HPC, but the UK lattice community can and has made good use of general purpose HPC such as GRIDPP and HECToR.

A £7M bid by UKQCD was recommended for approval by PPRP in September 2007, but the final outcome has still not been announced. As a result, the UK reputation in lattice QCD is largely driven by 'people-power' with the computational power coming from abroad. This is not a sustainable model in the medium term. The UK is playing a leading role in a number of international collaborations, but to capitalise on UK expertise and intellectual capacity, adequate funding in the UK is vital.

UK opportunity:
To lead the lattice calculations that will add value to the investment in flavour physics measurements, and to complete our understanding of the CKM picture of flavour-changing quark interactions. To study new physics effects via matrix elements of additional quark and gluon operators at low energies. To study hot and dense systems of baryonic matter. To explore strongly-interacting quantum field theories that may help to interpret LHC results. To drive KE exchange with computing industry - see for example development of IBM Blue-Gene machines (Edinburgh).

Milestones and decision points:
2009 outcome from PPRP bid in 2007
2010 next theory special grant round
2011 next theory rolling grants round
2012 next generation lattice machine

A.2 LHC GPDs and their upgrades

Context:
The LHC was conceived in the 1980s to provide the definitive test of the Higgs mechanism for generating masses for fundamental particles. Unitarity arguments indicate that either the Higgs is discovered at the LHC GPDs, or some other new physics must be observed. Limits from direct Higgs searches at LEP, coupled with indirect electroweak constraints, suggest that the Higgs mass must be less than 157 GeV, well within the range accessible at the LHC. Inconsistencies in the Standard Model point towards additional new physics at the TeV scale, also potentially observable at the LHC. Among the most attractive proposals for such new physics is SUSY, which, if observed, could also have profound implications for cosmology by providing a dark matter candidate. Still more exotic physics such as extra spatial dimensions might also be found. The unprecedented technological challenge presented by the LHC has led to the development of a wide range of new technologies, many of which will be of immense benefit to wider society. Examples include new detectors revolutionising medical imaging, and Grid computing technology (via GridPP) enabling seamless access to global computing resources.

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. Exploitation of the LHC was identified as the top priority for UK particle physics in the 2009 STFC Vision Document. Following huge investment in the current machine CERN is already committed to limited (‘phase-1’) upgrades and will likely support more extensive (‘phase-2’) upgrades for operation in around ten years time. At hadron colliders such as the LHC an increase in luminosity enables access to higher energies. For a relatively modest cost such upgrades would therefore not only enable consolidation of LHC discoveries, but would also generate an extended mass reach for new particles and enhance access to very rare processes.

The facility:
The LHC makes full use of the existing CERN accelerator infrastructure, with the SPS acting as the injector/pre-accelerator and the machine itself occupying the 27km tunnel originally built for LEP. First beams circulated on 11th September 2008 although an incident on 19th September terminated the run before first collisions could be achieved. The LHC is expected to restart with 3.5 TeV beams in November 2009 following repairs and consolidation work. The beam energy is anticipated to rise to 5 TeV in 2010 before rising further in 2011. The ultimate goal is to reach 7 TeV per beam, although it is unlikely that this

will be achieved in 2011. The development of the accelerator will be a long and continuous process. The maximum luminosity achievable with the initial accelerator is 10^{34} cm^{-2}s^{-1}. Limited phase-1 upgrades to the LHC injector lattice are planned for operation in 2014-16 onwards, leading to a factor 3 increase in luminosity. The more extensive phase-2 upgrades, leading to an overall factor 10 increase in luminosity, are proposed for operation from 2018-20 onwards.

The GPDs submitted Letters of Intent in 1992 and Technical Proposals in December 1994. Construction of the initial detectors was complete by mid-2008. Small scale upgrades will take place on the same time scale as the phase-1 machine upgrades, including new forward detectors and replacement of the innermost tracking layers. Larger scale upgrades including tracker replacement and new track triggering systems as well as upgrades to the existing trigger systems and electronics are planned for operation in 2018-20 onwards, matching the timescale of the LHC phase-2 upgrade. Irrespective of the decision to go ahead with the phase-2 machine upgrades continued detector operation beyond 2020 will require extensive replacement of GPD sub-systems. In order to minimise the impact of upgrade installation on detector operation it is essential that sufficient time is allowed for sub-system construction to be completed before installation begins.

UK history/expertise:
The UK has been a major player in previous hadron collider experiments including those at the ISR, SPS and Tevatron. UK physicists were founder members of both ATLAS and CMS, and have made leading contributions from the outset to their design and construction, particularly in the areas of charged particle tracking, electromagnetic calorimetry, computing and trigger systems. The UK currently provides the Spokesperson of CMS, a Deputy-Spokesperson of ATLAS, Project Leaders of major detector sub-systems and convenors of flagship physics analysis groups. The UK is also very prominent in the international R&D programmes preparing for the detector upgrades, and has provided many of the key technical advances required for operation in the challenging phase-2 radiation environment. It is worthy of note that many of the CERN accelerator physicists responsible for building the LHC originated in the UK, including both the LHC Project Leader and CERN’s Director of Accelerators and Technology.

Current UK involvement:
The UK provides 10% (4%) of the scientific authors of ATLAS (CMS). Work on the GPDs and their upgrades occupies ~40% of the UK particle physics community. Physics exploitation and M&O activities are supported by the PPGP, while initial upgrade R&D for both ATLAS and CMS is currently supported by the PPRP. Further R&D is proposed from 2010 onwards leading to phase-2 TDRs in 2012-13. Upgrade construction is anticipated to take 6-7 years. The total cost, including staff, to STFC of R&D and construction of both GPD upgrades is likely to be ~£100M-£150M over the next decade. Upgrade SoIs have been submitted by both ATLAS-UK and CMS-UK and approved by PPAN.

Direct UK involvement in the accelerator upgrade programme has been less prominent in the past. CERN is however very open to collaboration with UK accelerator physicists and several such collaborations with CI and JAI are currently being set up.

UK opportunity:
To contribute to the discovery of the origin of mass, supersymmetry and/or extra dimensions. To maintain UK leadership in energy frontier physics and fully exploit the massive prior UK investment in the LHC machine (via the CERN subscription) and GPDs. To maintain world-leading UK expertise in collider detector construction, vital also for future lepton collider projects and delivering societal benefits such as improved medical imaging and hadron theraphy. To capitalise further on extensive global interest in the LHC to promote particle physics and science in general to the wider population. To build UK domestic accelerator expertise by contributing to the LHC machine upgrade programme.

Milestones/decision points (dependent upon LHC schedule):

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

A.3 Tevatron experiments

Context:

The Tevatron at Fermilab (Chicago) is currently the world's highest energy collider, with a proton-anti-proton centre-of-mass energy of 1.96 TeV. Two general purpose detectors, CDF and D0, monitor the collisions. These experiments offer the best prospects for finding evidence of the Higgs boson until the LHC GPDs have accumulated significant datasets. The experiments are of limited duration and the future cost to STFC of UK participation is relatively modest.

The facility:

The Tevatron initially commenced operation in the late 1980s and has been steadily upgraded since then, resulting in the flagship discovery of the top quark in 1995. The current phase of operation, referred to as "Run-II", started in 2001. Instantaneous luminosity initially rose slowly, however the machine is now exceeding design goals and routinely provides luminosities of 3×10^{32} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The integrated luminosity delivered to each experiment now exceeds 6 fb^{-1}. The experiments have published world's best measurements of many Standard Model observables in the electroweak, top quark and flavour sectors, and hold the world's best limits on many classes of new physics including SUSY (via limits on squark and gluino production), extra spatial dimensions and, most importantly, the Standard Model Higgs boson. Current limits on the latter obtained by the Tevatron experiments exclude masses in the region of 160 GeV to 170 GeV. It is anticipated that by 2011, when the Tevatron is scheduled to cease operation, the experiments should be able to exclude the remaining mass range currently allowed by electroweak precision measurements and direct searches. There is >30% probability that $>3\sigma$ evidence could be obtained for Higgs masses below 130 GeV or in the range 150-180 GeV given 10 fb^{-1} of data per experiment.

UK history/expertise:

The UK did not participate in the early "Run-I" Tevatron experiments, however several groups (Glasgow (CDF), ICL (D0), Lancaster (D0), Liverpool (CDF), Manchester (D0), Oxford (CDF) and UCL (CDF)) joined the Run-II experiments in 1998-2000. In addition to physics analysis, participation has mainly been focused in the software, computing and trigger areas, with some involvement in Silicon tracking. UK physicists have held many senior leadership positions in the collaborations over the past decade, including Spokesperson.

Current UK involvement:

UK physicists hold significant leadership positions in these experiments and the UK drives some of the most important physics analyses, particularly Higgs searches. There is also major UK involvement in the area of electroweak precision measurements, and UK physicists led the analyses which obtained the world's best measurements of the mass and width of the W boson.

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

Milestones:

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

A.4 High-energy lepton collider

Context:
In 1999 the International Committee for Future Accelerators (ICFA) recognised the importance of a next-generation electron-positron collider:

'To explore and characterize fully the new physics that must exist will require the Large Hadron Collider plus an electron-positron collider with energy in the TeV range… Just as our present understanding of the physics at the highest energy depends critically on combining results from LEP, SLC, and the Tevatron, a full understanding of new physics seen in the future will need both types of high-energy probes.' The 2006 CERN Council Strategy Document accordingly assigned the electron-positron collider a high priority:

'It is fundamental to complement the results of the LHC with measurements at a linear collider. In the energy range of 0.5 to 1 TeV, the ILC, based on superconducting technology, will provide a unique scientific opportunity at the precision frontier; there should be a strong well-coordinated European activity, including CERN, through the Global Design Effort, for its design and technical preparation towards the construction decision ... In order to be in the position to push the energy and luminosity frontier even further it is vital to strengthen the advanced accelerator R&D programme; a coordinated programme should be intensified, to develop the CLIC technology …'.

It is likely that the linear collider 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.

Facilities:
The most advanced technical design is for the International Linear Collider (ILC), whose first-phase target energy is 500GeV, with an upgrade path to 1 TeV. The ILC Global Design Effort is preparing a TDR for release in 2012. The Compact Linear Collider (CLIC) being pursued at CERN is less technically mature and aims at a target energy of 3 TeV. A TDR is planned for 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. A longer-term prospect for multi-TeV scales is a muon collider, which requires significant further R&D and design studies to validate the concept.

UK history/expertise:
The UK has a long history of leading in physics and detectors at high-energy electron-positron colliders (TASSO, JADE, PLUTO and CELLO at PETRA; ALEPH, DELPHI, and OPAL at LEP; and, SLD at SLC). In the past decade the UK has made significant investments in R&D for the linear collider, in detector technologies as well as in a targeted programme of accelerator R&D for key systems. The investment amounts to more than £25M. In the detector area R&D was supported on silicon pixel technology for vertex detectors and trackers (LCFI), as well as calorimetry (CALICE-UK), including mechanical aspects and drive/readout electronics. For the accelerator, R&D was supported principally in the beam delivery system, positron source and damping rings (LC-ABD). All of the UK investment was deliberately targeted at areas that are applicable to both the ILC and CLIC designs. Following implementation of the 2007 Delivery Plan the funding for CALICE-UK and LCFI was terminated, and LC-ABD funding was cut to a minimal programme that supports a few key individuals with leadership roles and a small amount of generic linear collider R&D at a total annual cost of c. £1M.

Current UK involvement:
Despite the drastic reduction in funding the UK has managed to hold on to positions of international leadership and responsibility in the linear collider detector concept studies and in the Global Design Effort. Without ongoing investment we will lose this leadership.

There is considerable UK community interest in participating in the linear collider; there are more than 100 members of the LCUK consortium. The SPiDER (silicon pixel) and LowMass (low-mass tracker support structures) generic detector R&D projects, recently approved by STFC, support a modest, focussed detector R&D effort that has potential applications to linear collider detectors. UK phenomenologists continue to do targeted, significant theoretical work on linear collider physics processes.

A muon collider is seen as a possible extension of a neutrino factory. The UK's leading work on MICE and neutrino factory design (see section A15), as well as the linear collider detector R&D, and aspects of the accelerator R&D, are applicable to a muon collider.

UK opportunity:
To lead in key accelerator and detector systems and position the UK for a leading role in the physics exploitation. To capitalise on UK expertise in building large detector systems.

Milestones/decision points:

2012: ILC TDR.
2012/2013: future linear collider project direction based on LHC results.
2015: CLIC TDR.
2015-20: possible start of linear collider construction.
2022-27: possible start of linear collider operation.
>2030: muon collider?

A.5 High-energy lepton-hadron collider

Context:
An LHeC would be a successor to the HERA lepton-hadron collider which ceased operation in 2007. Such a project would extend the LHC facility to allow electron-proton and possibly electron-heavy ion collisions. The UK has strong and leading involvement in this project, which is currently investigating the possibility of extending the LHC capability through this expansion of facilities at CERN.

An LHeC would be capable of providing complementary information to the current LHC programme. The observation of leptoquarks at the LHC would provide a strong case for building an LHeC which would be able to study the properties of such a manifestation of new physics in great detail. Other possible evidence for new physics such as excited leptons or supersymmetry could also be studied at such a machine. An LHeC would be the ideal place, and provide a unique opportunity, to probe the structure of the nucleon and nuclei in areas of parameter space relevant to the LHC.

The facility:
There are two possible designs for an LHeC. The first would involve adding an electron ring in the LHC tunnel on top of the current proton ring. The possible beam energy and luminosity are limited by synchrotron radiation losses and available RF components and the luminosity and energy achievable are correlated. An example realisation of an electron ring configuration could be a 50 GeV beam at 50 MW power delivering $5\text{x}10^{33}$ $\text{cm}^{-2}\text{s}^{-1}$, a factor of 100 beyond the highest luminosity achieved at HERA. An alternative solution for the electron beam is a linear accelerator, which has the advantages of installation

being relatively decoupled from the existing LHC and potentially larger electron beam energies. The luminosity in the linac case is more weakly dependent on electron beam energy for fixed power. Energies up to 150 GeV are therefore under consideration, the limitation being mainly civil engineering costs. More efficient use of power may be possible if energy recovery techniques can be applied to such a high energy beam configuration. At the Cockcroft Institute, the UK has one of only two energy recovery linac prototypes operating in the world.

UK history/expertise:
UK physicists made major contributions to the construction and exploitation of both experiments at the HERA collider. Main leadership roles were taken including four of the Spokespersons of H1 and Zeus. The UK provided major detector components including forward and central tracking systems, muon detectors and significant elements of the triggering and DAQ systems. Highlights of the extensive physics analysis activities include major publications on inclusive structure functions, parton densities and diffractive physics.

Current UK involvement:
The UK is currently a leading player in the LHeC concept, chairing the international steering committee, on behalf of ECFA, NuPECC and CERN, which is steering the Conceptual Design Report of the LHeC. The UK provides over a quarter of the membership of the steering committee and provides convenors of four out of the six working groups. For a number of years NuPECC has been chaired by leading UK nuclear physicists.

UK opportunity:
The UK has an opportunity to build on the leading role it has established in the concept of an LHeC. If LHC results were to support such an extension of the LHC this would enable the UK to further capitalise on its investment in the LHC machine. This would also be an opportunity to further capitalise upon and invest in electron accelerator technology.

Milestones/Decision points (dependent upon LHC schedule):
2010: LHeC CDR
2012: LHeC TDR.
2012/2013: results from LHC.
2020: possible installation of magnets, in the LHC tunnel or in a separate linear accelerator.

A.6 LHCb and its upgrade

Context:
LHCb is designed to exploit the large b-quark-antiquark production cross-section at the LHC in order to make precision tests of the flavour-changing interactions of the b quark. Measurements from LHCb will dramatically improve our knowledge of one of the least well-understood sectors of the Standard Model, and also have excellent new physics discovery potential. Virtual particles with masses far beyond the direct search reach can have significant effects in loop diagrams where Standard Model contributions are suppressed. Among the most important measurements for the first stage of LHCb are: (i) the search for the decay $B_s \to \mu\mu$, (ii) measurements of CP violation in B_s and D^0 mixing, (iii) studies of kinematic distributions in the decay $B \to K^*\mu\mu$, (iv) the precise measurement of the angle γ of the CKM unitarity triangle. LHCb will also search for the Higgs boson in multibody decay channels – topologies that are difficult to reconstruct at the GPDs.

In the initial phase of running, the focussing of the LHC beams at the LHCb interaction point is intended to achieve a nominal luminosity of 2×10^{32} cm^{-2}s^{-1}. The LHCb upgrade will enable an increase in the luminosity to 2×10^{33} cm^{-2}s^{-1}; the LHCb upgrade is thus independent of the LHC machine luminosity upgrade. The statistics provided by the LHCb upgrade are essential to fully exploit the potential of rare hadronic and radiative b→s loop transitions (in decay channels such as $B\to K^*\mu\mu$, $B_s\to\varphi\varphi$ and $B_s\to\varphi\gamma$), which are theoretically clean and therefore highly sensitive to New Physics. The physics programme of the LHCb upgrade also includes precision studies of CP violation in the charm sector, as well as searches for exotic states. In order to operate efficiently at such high luminosity, a displaced vertex trigger is required at the first level of the trigger system. This upgrade requires the full detector to be read out at the LHC beam crossing frequency of 40MHz, with the trigger to be executed in a CPU farm. Major components of this detector upgrade are the replacement of the existing read-out electronics for all detectors with a 40MHz readout system, the construction of a radiation hard Vertex Locator (VELO), the development of a photon detector for the Ring Imaging Cherenkov (RICH) counters which can be read out at 40 MHz and the development of algorithms to trigger at very high rates.

The facility:
See under LHC GPDs for the LHC machine.

The LHCb Letter of Intent was submitted in 1995, with the Technical Proposal following in 1998. A series of Technical Design Reports (for each subsystem) were published in 2000-2005. The Expression of Interest for the LHCb Upgrade was submitted to the LHCC in April 2008. A Statement of Intent for the LHCb Upgrade by LHCb UK was submitted to PPAN in December 2008. An R&D proposal will be submitted to the PPRP in autumn 2009.

UK history/expertise:
The UK has a very strong history in flavour physics, including kaon physics (NA31, CPLEAR, NA48) and b physics (LEP experiments, BaBar, CDF and D0). The UK is a founder member of the LHCb collaboration, with responsibility for two of the most critical subdetectors, namely the ring imaging Cherenkov (RICH) detector and the vertex locator (VELO) as well as for elements of the core computing infrastructure. The UK provided the first LHCb upgrade coordinator.

Current UK involvement:
The UK is leading the preparation for physics exploitation of the LHCb experiment and provides the current LHCb spokesperson as well as the physics coordinator elect, and conveners of several physics working groups. UK physicists have pioneered the LHCb upgrade efforts, and all LHCb UK groups (Bristol, Cambridge, Edinburgh, Glasgow, Imperial College, Liverpool, Manchester, Oxford, RAL, Warwick) are involved in the upgrade proposal.

UK opportunity:
To lead the physics exploitation of the LHCb experiment, and maintain UK leadership in the field of flavour physics; to participate in studies that will complete our understanding of the CKM picture of flavour-changing quark interactions; the potential to discover physics beyond the Standard Model. To fully exploit the potential of the LHC to study quark-flavour physics. To provide measurements that, combined with measurements from the GPDs, will allow different new physics models to be disentangled; to promote LHC results to the general public, building on the public interest in antimatter research; and to maintain world-leading UK expertise in detector technologies, and to enhance the capabilities of relevant UK industries.

Milestones/decision points:
A decision on R&D funding for the LHCb upgrade should be made soon (2009-10). Following a 3 year R&D phase, culminating in a TDR for the upgraded detector, a decision to proceed with construction should follow. Operation of the upgraded LHCb detector is planned to commence in 2016.

A.7 High-luminosity flavour factory

Context:
Following the successes of the asymmetric e^+e^- B factories PEPII/BaBar and KEK-B/Belle, a next generation of experiments is being planned. The concept is that, with significant increases in luminosity, new 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 copious production of tau leptons and B and D mesons in 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. Apart from flavour physics, precision electroweak studies and direct searches for light Higgs and dark matter candidates can be performed.

Facilities:
There are currently two proposals for a Super Flavour Factory. SuperKEKB/BelleII is based on an upgrade of the KEKB accelerator, while the SuperB proposal is for a new facility in Italy that would make significant savings by reusing PEPII/BaBar hardware. The SuperB accelerator design (initially inspired by concepts developed for linear colliders) achieves high luminosity through the use of low emittance bunches, while maintaining a stable dynamic aperture with a "crab" of the focal plane. The SuperKEKB design combines some aspects of the low emittance scheme while simultaneously increasing the beam currents. The anticipated peak luminosities are few 10^{35} $cm^{-2}s^{-1}$ (SuperKEKB) to 10^{36} $cm^{-2}s^{-1}$ (SuperB), which would allow the accumulation of at least tens of inverse attobarns of data within five years operation.

UK history/expertise:
The UK has a very strong history in flavour physics, including kaon physics (NA31, CPLEAR, NA48) and b physics (LEP experiments, BaBar, CDF and D0). UK physicists were actively involved in early workshops promoting the idea of very high luminosity e^+e^- B factories. The UK provided an editor of the physics chapter of the SuperB Conceptual Design Report, and is providing an editor of the corresponding chapter of the forthcoming Technical Design Report.

Current UK involvement:
There is currently a small but committed group of UK physicists working on SuperB, with prominent roles in the international proto-collaboration. The interests include physics studies and the development of a silicon detector (QMUL, RAL) and accelerator R&D (Cockcroft). A PRD proposal for accelerator R&D for SuperB is currently under review by the PPRP. There is currently no active UK involvement in the SuperKEKB/Belle-II project.

UK opportunity:
To take a prominent position in the construction of a major new particle physics facility in Europe (SuperB). To participate in R&D that may have significant ramifications for future high luminosity accelerators. To maximise return on the UK's investment in silicon detectors by constructing a critical subdetector.

Milestones/decision points:
A decision from the Japanese government on whether to proceed with SuperKEKB/Belle-II construction is expected soon (2009/10). If a positive decision is forthcoming, operation will begin in 2013. INFN recently (2009) decided to support the TDR phase of SuperB. Delivery of the TDR is expected in 2010/11, but a decision by the Italian government on construction funding may be made on the basis of a restricted TDR version as early as the end of 2009 or the beginning of 2010.

A.8 High-precision charm experiments

Context:
The charm sector provides a unique potential to study flavour-changing interactions of up-type quarks. Precise studies of charm mixing, CP violation 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.

Facilities:
Charm physics can be (and historically has been) studied in both hadronic and e^+e^- environments, in dedicated experiments as well as at experiments designed primarily for other purposes. LHCb (and its upgrade) and high-luminosity e^+e^- machines both have strong charm physics potential. BESIII is a dedicated tau-charm physics experiment at the BEPCII electron-positron accelerator that has recently started operation. The PANDA experiment at FAIR will study charm and charmonia in a gluon-rich environment. In the longer term there are proposals for fixed target charm experiments at FNAL and worldwide there are several possible sites for super tau-charm factories, the most advanced proposal being at BINP.

UK history/expertise:
See above for the UK's strength in flavour physics. UK physicists have led the charm physics programme at BaBar and are leading charm studies at LHCb. A subset of LHCb UK institutes (Bristol, Oxford, RAL, Warwick) are involved in the exploitation of CLEOc, making measurements that improve the physics reach of LHCb. Nuclear physics groups at two UK institutes are involved in PANDA.

Current UK involvement:
Except for the above mentioned involvement in CLEOc and PANDA, there is little UK involvement in dedicated charm physics experiments at this time.

UK opportunity:
There is an excellent opportunity for the UK to exploit the charm physics potential at LHCb and/or any future high-luminosity flavour factory. If, in the future, a specific need for measurements from a dedicated experiments becomes apparent, there may be an opportunity for a small-scale, but high value-for-money, UK investment.

Milestones/decision points:
N/A

A.9 High-precision kaon experiments

Context:
Studies of kaon physics have been essential to develop the Standard Model, from the understanding of GIM suppression, the discovery of CP violation, and the search and eventual discovery of direct CP violation. A few very rare kaon decays could be equally important for the discovery and understanding of physics beyond the Standard Model. Specifically, $K^+ \to \pi^+ \nu\nu$ and $K_L \to \pi^0 \nu\nu$ are considered golden modes in this sector, having unique sensitivity to new physics. They pose the experimental challenge of achieving a decay sensitivity to branching ratios at the level of 10^{-11} or less.

Facilities:
The NA62 experiment at CERN (approved in 2008) should observe at least 100 $K^+ \to \pi^+ \nu\nu$ decays if the branching fraction is at the Standard Model level. The NA62 physics programme also includes tests of

lepton universality. Upgrades could possibly improve the precision to the few % level of the theoretical uncertainty, and/or move to the $K_L \to \pi^0 \nu\nu$ decay. The KOTO experiment at J-PARC (successor of KEK-E391) should observe the $K_L \to \pi^0 \nu\nu$ decay (at the Standard Model branching fraction); an upgrade is planned to allow a precise measurement. There is a proposal called KLOD at IHEP (Protvino) to search for the same mode. There are proposals for rare kaon decay experiments at FNAL. The TREK experiment at J-PARC is a proposal to search for transverse muon polarisation in the $K \to \pi\mu\nu$ decay – a positive signal would indicate a beyond the Standard Model source of T violation. An upgrade of the KLOE detector is planned in parallel with an upgrade of the DAPHNE accelerator; its physics programme includes tests of CKM unitarity and lepton universality.

UK history/expertise:
The UK has a very strong history in kaon physics (NA31, CPLEAR, NA48). The UK has provided physics coordinators to NA48, and is prominent in NA62, having recently led an important analysis testing lepton universality.

Current UK involvement:
Birmingham, Bristol, Glasgow and Liverpool submitted a Statement of Intent of UK involvement in NA62 to PPAN in 2009, proposing UK involvement in particle ID (CEDAR), trigger and computing. There is currently no significant UK involvement in any of the other kaon physics projects mentioned above.

UK opportunity:
To make a major contribution to an important physics measurement, with a fairly modest investment, with a return on a relatively short timescale. To broaden the UK's participation in CERN's particle physics programme. To capitalise on the longstanding UK investment in kaon physics.

Milestones/decision points:
Decision on UK involvement should be taken imminently (2009). R&D and construction 2010-2012. Data taking to start 2012-13.

A.10 High-precision muon experiments

Context:
Precise studies of muons provide a fascinating probe of the Standard Model and its possible extensions. The most interesting measurements are (i) the anomalous magnetic moment $(g\text{-}2)_\mu$ and (ii) signatures of lepton flavour violation. There is currently a 3.1σ discrepancy between the Standard Model prediction and the measurement of $(g\text{-}2)_\mu$; if interpreted as a signal, this places severe constraints on new physics models. The origin of flavour quantum numbers within the Standard Model is not understood, and most generic models of new physics (eg. SUSY, GUTs, Majorana fermions) predict observable signatures of lepton flavour violation. Interest in charged lepton flavour violation has enjoyed a resurgence following the discovery of neutrino oscillations. The strongest existing limit on such processes is on $\mu \to e\gamma$ decays. The MEG experiment will improve the sensitivity of previous experiments, and could observe a signal if the rate is as predicted by some models. Further improvements require background-free channels, motivating a focus on $\mu \to e$ conversions, following muon trapping on nuclei. Current and future experiments will reach a level of sensitivity where signals predicted by many models could appear.

Facilities:
A new g-2 experiment is proposed at FNAL – sensitivity four times better than that of the previous (BNL) experiment is anticipated. The MEG experiment is currently in operation at PSI. There are proposals for $\mu \to e$ conversion experiments at J-PARC and FNAL. The COMET experiment, which recently received stage 1 approval from the J-PARC PAC, aims for an improvement of four orders of magnitude compared to the current limits. A second stage, called PRISM, would deliver a further two orders of magnitude in

sensitivity (the possibility of going directly to PRISM without COMET is currently under discussion). The FNAL proposal, mu2e, is conceptually similar to COMET (indeed the two collaborations are working closely together), and with similar performance. This experiment could benefit from ProjectX to gain further sensitivity.

UK history/expertise:
The UK was involved in early $(g-2)_\mu$ experiments at CERN, but has not been involved in the more recent experiments. Similarly, the UK has not participated in recent muon lepton flavour violation experiments (UK physicists have, however, been involved in lepton flavour violation searches at BaBar). The next generation muon experiments are critically dependent on high-intensity proton beams, precision muon beamlines and high-rate detectors: areas in which the UK leads through experience from the neutrino factory (FETS, MICE) and LHC detector components. The UK is developing significant expertise in FFAGs, which are the technology behind the PRISM proposal.

Current UK involvement:
UK institutes (Imperial College & UCL) are signatories of the COMET conceptual design report (Glasgow has recently joined). Together with RAL, DL, CI, JAI and ASTeC, these institutes are also prominent in the international design effort for PRISM. A submission to STFC is in preparation.

UK opportunity:
To gain experience in the field of muon flavour violation and to develop leadership in this field in the long-term. To participate in potentially groundbreaking physics measurements. To enhance UK investment into R&D of FFAGs, and to exploit synergies with other applications of this technology.

Milestones/decision points:
A decision on future UK participation in this field should be made after the proponents submit an SoI. The COMET TDR will be submitted in 2011-12, at which time J-PARC will make a decision on stage 2 (final) approval. If successful, COMET construction would run in parallel with further R&D for PRISM until 2015, when COMET operation and PRISM construction would commence. PRISM operation could begin by 2018. In an alternative scenario, a direct route to PRISM may be possible, depending on the conceptual design report from the PRISM task force, due in 2010.

A.11 Long-baseline neutrino experiments

Context:
The study of neutrino oscillations in long-baseline experiments provides access to the parameters governing neutrino flavour transitions at the "atmospheric" mass scale, Δm^2_{32}. The second generation of experiments will employ off-axis detectors and intense neutrino beams to target the measurement of sub-dominant $\nu_\mu \rightarrow \nu_e$ oscillations, and thus provide access to θ_{13}.

Facilities:

Of first generation of long-baseline neutrino oscillation experiments, K2K confirmed the Super-Kamiokande observation of atmospheric neutrino oscillations; MINOS provided a precise measurement of Δm^2_{32}; and CNGS/OPERA are searching for direct evidence of $\nu_\mu \rightarrow \nu_\tau$ oscillations through the observation of tau appearance in muon neutrino beam. MINOS and CNGS/OPERA are running experiments. There are two second generation, off-axis experiments, T2K in Japan and Nova in the US. T2K is due to start physics data taking within the next few months and Nova will start operation in a few years time. Phase I of the T2K experiment will have sensitivity to $\sin^2 2\theta_{13}$ down to 0.01 by 2014. A measurement of θ_{13} would represent a major breakthrough in the field; it will determine the future direction of long baseline neutrino oscillation experiments. T2K will also provide a precise measurement/lower limit on θ_{23}. This is theoretically interesting as the current data are consistent with maximal mixing. In addition, T2K will make a few % measurement of Δm^2_{32}. The Nova experiment is likely to commence in 2013/2014. Because of the long baseline, the sensitivity to matter effects complements the T2K physics goals, allowing a possible determination of the mass hierarchy.

UK history/expertise:

UK played a leading role in the design, construction and continued operation of the MINOS experiment and is playing a leading role in the T2K experiment where the UK has a major hardware involvement in the near detector (ND 280).

Current UK involvement:

UK physicists (Cambridge, Oxford, RAL, Sussex, UCL) played a leading role in the MINOS experiment, making up approximately 20% of the collaboration and holding many leadership positions within the collaboration (two of the three candidates in the current Spokesperson election are from the UK). MINOS is expected to run until 2011/2012. The funding for exploitation of the MINOS experiment was cut by approximately 50% in the last programmatic review. The current cost to STFC is at the level of £0.5M per annum. A significant further reduction would affect the operation of the experiment as the UK is responsible for the DAQ and a significant part of the readout electronics.

The UK (Imperial, Lancaster, Liverpool, Oxford, QMUL, RAL/Daresbury, Sheffield and Warwick) plays a leading role in the T2K collaboration, and provides the current T2K International Spokesperson.

UK opportunity:

MINOS is commencing running with anti-neutrinos rather than neutrinos; this will allow a measurement of Δm^2_{32} for anti-neutrinos, thus providing a new test of CPT in the neutrino sector. In addition, MINOS currently observes a small excess in its $\nu_\mu \rightarrow \nu_e$ appearance analysis (1.5σ). If this is due to a large value of θ_{13}, rather than a fluctuation of the background, with additional data MINOS may be able to claim a significant evidence for a non-zero value of $\theta_{13.}$

T2K will be the world-leading neutrino experiment for at least the next 5 years. Its results on θ_{13} and θ_{23} are important for the field and out understanding of the neutrino. If θ_{13} is sufficiently large there is a strong case for phase-II of the T2K experiment which would have the potential to discover CP violation in the neutrino sector.

Milestones/decision points:

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

T2K: 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 $\theta_{13.}$

A.12 Reactor neutrino experiments

Context:

The world’s best limit on θ_{13} was obtained from the Chooz reactor neutrino experiment. Due to the short baseline reactor neutrino experiments can directly measure θ_{13}, i.e. without dependence on the CP violating phase δ and the mass hierarchy. The next generation of reactor experiments aim for sensitivity down to $\sin^2 2\theta_{13} \sim 0.03$.

Facilities:
There are three major international projects being constructed: Double Chooz in France, Daya Bay in China and Reno in Korea.

UK history/expertise:

UK physicists (Oxford/Sussex) received STFC seedcorn funding for the Braidwood project which was subsequently cancelled. Sussex contributed to the Double Chooz experiment through this seedcorn funding. A proposal from the Sussex group to join the Double Chooz experiment was not funded.

Current UK involvement:

Sussex is a member of the Double Chooz collaboration, however their contribution is almost complete and it is unclear whether they will remain on the collaboration author list beyond the first publication.

A.13 Precision neutrino mass experiments

No history of STFC funding.

A.14 Neutrinoless double-beta decay experiments

Context:
The quarks and charged leptons are Dirac in nature with distinct particle and anti-particle states. The neutrino is unique amongst the Standard Model particles as it is possible that it is its own anti-particle, a Majorana particle. Whether the neutrino is Dirac or Majorana in nature is one of the most important open questions in the neutrino sector. If neutrinos were Majorana in nature, the process of neutrinoless double beta-decays (nuclear $\Delta Z=2$ transitions without the emission of neutrinos) would occur at a very low rate. The observation of neutrinoless double beta decay would represent a major, potentially Nobel prize-winning, breakthrough in science and would greatly enhance our theoretical understanding of the lepton flavour sector. There are a number of possible mechanisms for neutrinoless double beta decay, but the most commonly discussed is the exchange of a light Majorana neutrino. The expected signal depends on the effective mass $|m_{ee}|$ which depends on the three neutrino masses, the PMNS mixing matrix and the neutrino mass hierarchy. The largest decay rate is obtained in the case where the neutrino masses are quasi-degenerate, i.e. $m_1 \approx m_2 \approx m_3$, here $|m_{ee}|$ is in the 100-500 meV range. If the neutrinos are not quasi-degenerate, the expected values for $|m_{ee}|$ are in the ranges 10-60 meV and <5 meV for the inverted and normal hierarchies respectively. To date the only claim for a neutrinoless double beta-decay signal comes from part of the Heidelberg-Moscow collaboration (Klapdor-Kleingrothaus), although this result is not widely accepted.

Facilities:

The search for neutrinoless double beta decays is an active area worldwide. There are four approved projects CUORE, EXO-200, GERDA, and SNO+ which intend to commence operation within the next two years. SuperNemo, which builds on the existing Nemo-3 experiment, is in an advanced R&D/prototyping phase and a TDR is expected in 2011/2012. The ultimate sensitivity of the above experiments are in the range $|m_{ee}| \sim 50 - 100$ meV. The experiments use different isotopes (CUORE ^{130}Te; EXO ^{136}Xe; GERDA ^{76}Ge; SNO+ ^{150}Nd; and SuperNemo ^{82}Se (baseline). All experiments have sensitivity to the disputed Klapdor-Kleingrothaus claim, with the GERDA experiment using the same isotope. The UK is primarily interested in the SNO+ and SuperNemo experiments. The strength of the SNO+ experiment is that it is relatively cheap (re-using the SNO experiment) and, providing the technique works, has the potential to provide world leading results on a relatively short timescale, potentially within 3 years. The strengths of the SuperNemo experiment are i) if a signal is observed, it is the only experiment with the potential to confirm conclusively that the observed signal is neutrino-less double beta decay and ii) ability to change if one of the other experiments observe a signal. In the longer term, sensitivity down to 10 meV is an important goal, as it would fully cover the Majorana hypothesis in the case of the inverted hierarchy. To reach this sensitivity a multi-ton experiment is likely to be required. It is not clear that either SNO+ or SuperNemo are sufficiently scalable to reach this sensitivity.

UK history/expertise:

UK physicists first became involved in neutrinoless double beta decay experiments in the Nemo-3 experiment. UK physicists have a long history in the SNO solar neutrino experiment and have expertise in radiochemical purification necessary to meet the low background requirements of the SNO+ experiment.

Current UK involvement:

The UK (Imperial, Manchester, UCL, UCL-MSSL) is playing a leading role in the SuperNemo R&D project and provides the current co-spokesperson. SuperNemo is predominantly a UK/French collaboration. The UK has a long history in the SNO experiment and participation in SNO+ (Leeds, Liverpool, Oxford, Sussex, QMUL) is a natural extension. Ultra-high chemical purity is essential for the SNO+ experiment an area where the UK has a wealth of experience.

The SuperNemo R&D is currently being reviewed by the UK implying a likely investment at the level of £3-4M over the next three years. If the full SuperNemo project were approved this would imply a future capital investment at the £10M level and 8-10 year exploitation programme. SNO+ has recently been approved in Canada. The UK participation in the SNO+ double beta decay programme would imply a total UK investment of approximately £2.5M for the five year programme (2010-2015).

UK opportunity:

To make leading contributions to the discovery of neutrinoless double beta decay. For example, both SNO+ and Super-Nemo will have sensitivity to the Klapdor-Kleingrothaus claim on a relatively short timescale: 2011/2012 in the case of SNO+ and end of 2014 in the case of Super-Nemo.

Milestones/decision points:

Super-Nemo: proposal for prototype module 2009/2012 (under review); TDR 2011/12; begin construction 2012 (proposed); running with first module 2013/2014 (proposed); end of construction 2016; completion 2018/2019 (500 kg yr).

SNO+: R&D proposal (awaiting decision) 2009; Full UK proposal 2010; phase-I operation 2011-2012 (expected); phase-II operation 2013-2015 (current schedule); possible operation of SNO+ with a different isotope if there is the physics case.

A.15 Neutrino Factory

Context:

The future facilities fall into four main categories: Super-beams with off-axis detectors, higher power versions of T2K and Nova; Conventional high power wide band (WB) beams; beta-beams, from the decays of stored radio-isotopes; and a neutrino factory. The main aim of these facilities is to study CP violation in the neutrino sector. Currently all four types of facility are under consideration. If θ_{13} is “large” ($\sin^2 2\theta_{13}>0.01$), the conventional facilities (super-beams and WB beams) may provide the necessary sensitivity to CP violation. If θ_{13} is “small”, then either a beta-beam or neutrino factory facility would be required. The physics goals of a neutrino factory extend beyond CP violation and include the precise measuement of θ_{13} and the sign of Δm^2_{32}.

Facilities:
Possible sites for the more conventional facilities are: JPARC in Japan, Project-X at Fermilab or the SPL at CERN. The SPL could also provide input to a beta-beam facility or neutrino factory at CERN. A future neutrino factory could be hosted on a relatively compact site such as RAL, where an upgrade of ISIS could form the basis of a proton driver.

UK history/expertise:
UK physicists played the leading role in the International Scoping Study of a future Neutrino Factory and super-beam facility (the ISS) and play the leading role in the International Design Study for the Neutrino Factory which aims to produce a RDR in 2012. The international MICE experiment aims to provide a demonstration of muon cooling which is essential to a future neutrino factory, which in turn could be the pre-cursor to a muon-collider. MICE is hosted by the UK using a muon beam derived from the ISIS facility.

Current UK involvement:
UKNF: (ASTeC, Brunel, Daresbury, Durham, Imperial, Lancaster, Liverpool, Manchester, Oxford, Sheffield, RAL, Warwick, York). The main projects under the umbrella of UKNF are: the front-end test stand, target studies and MICE (demonstration of muon cooling). Whilst not part of the UKNF activities, EMMA (R&D project for a muon FFAG accelerator) is highly relevant to R&D for the neutrino factory. In addition, the UK is playing the leading role in the International Design Study (which includes physics, accelerator and conceptual detector studies). The UK also leads the EUROnu design study, which is part of the CERN strategy and is studying three possible alternatives for the 2nd generation facility in Europe: CERN to Frejus superbeam, a beta beam and the neutrino factory. Excluding MICE, the total cost of the UKNF activities is approximately £1M per annum. There UKNF accelerator R&D programme has a number of synergies that should be mentioned: the development of EMMA (at the Daresbury Laboratory) offers a significant KE opportunity as FFAGs have major medical applications in proton/hadron therapy; and both the front-end test stand and target studies are relevant to the future of ISIS.

MICE: MICE will use a muon beam produced from the ISIS facility at RAL. The experiment is proceeding in a number of stages, with an expected completion date of 2014. The UK as host country is playing the leading role in the international MICE collaboration and, consequently, bear a significant fraction of the total cost. The ongoing cost of MICE to the UK is estimated to be approximately £3.5M per annum for the next 5 years.

UK opportunity:
The UK is leading the neutrino factory IDS. Due to the compact nature of the neutrino factory RAL is a possible host site. One of the aims of UKNF and MICE is to put the UK in the position where it could bid to host this facility. Nevertheless, the strong neutrino physics community places the UK in the position to take a leading role in whatever future neutrino facility/detector is selected, whether it is in the UK or elsewhere.

Milestones/decision points:
Neutrino Factory: 2012 RDR; 2013-14, measurements/limits on θ_{13} determine direction of next step in neutrino physics programme.

A.16 Direct dark matter search experiments

Context:
The nature of the dark matter is one of the most important unanswered questions in science. Direct searches for particle dark matter are motivated by the observation that many models, for instance supersymmetry,

predict weak-interaction scale couplings between dark matter particles and atomic nuclei, leading to potentially observable rates of elastic nuclear scattering. Experiments searching for such processes are challenging due to the required low energy thresholds (<10 keV) and significant backgrounds from Compton scattering and neutron interactions. Experiments must be located deep underground to shield them from cosmic rays and natural radioactivity generating these backgrounds. Dark matter particles can interact through spin-independent (scalar) or spin-dependent (axial-vector) interactions. Sensitivity to the former typically exceeds sensitivity to the latter by factors ~10^6 due to nuclear coherence effects.

Facilities:
The search for dark matter is a thriving area worldwide. The field has pushed down the limits on the dark matter scattering cross-section by roughly an order of magnitude every 3-4 years. Numerous groups have pursued particular detection technologies. Recently there has been coalescence into larger consortia which aim at eventual detectors in the ton mass range and beyond using multiple event signatures (scintillation, ionization, phonons) to reject backgrounds. Current world-best limits on the spin-independent cross-section with minima around 4×10^{-8} pb have been published by the CDMS (ionization/phonons) and XENON10 (scintillation/ionization) collaborations, although currently there is debate over the validity of the latter result.

UK history/expertise:
UK physicists were among the first to recognise the importance of elastic nuclear recoil searches for dark matter. The UK Dark Matter Collaboration led the field in the 90's, pioneering the use of NaI and liquid xenon scintillator detectors. The UKDMC subsequently evolved into the ZEPLIN collaboration focused on double-phase xenon detectors (scintillation/ionization). These detectors were/are operated at a dedicated science facility at the Boulby Mine in North Yorkshire. In parallel, the UK has been a key collaborator in the CRESST experiment at Gran Sasso in Italy. This experiment uses a cryogenic calcium tungstate calorimeter with dual scintillation/phonon read-out. The SQUID-based amplifiers developed for this experiment have been spun-out to enhance the sensitivity of the neutron EDM searches.

Current UK involvement:
The UK plays a leading role in dark-matter search experiments. It leads two international consortia: EURECA (Oxford, Sheffield with EU collaborators; possibly located at Modane in France) and LUX-ZEPLIN (IC, RAL, Edinburgh and Daresbury with mainly US collaborators; possibly located at DUSEL in US) for development of large-scale detectors based on phonon/scintillation and phonon/ionization (EURECA) and scintillation/ionization (LUX-ZEPLIN). Both consortia propose to obtain sensitivity to signals at the 10^{-10} pb level. There is additional interest in R&D on directionally-sensitive detectors (CYGNUS/DRIFT – Edinburgh, Sheffield) and liquid argon detectors (ArDM - Sheffield). The directional detectors would be designed with capability to measure the 'WIMP wind' as a function of diurnal position, crucial for conclusively identifying a signal. Future tonne-scale detectors will cost at least £12M. At current pro rata this might imply UK investment of at least £6.5M.

UK opportunity:
To exploit existing expertise to make leading contributions to the discovery of dark matter. Use of pioneering new UK commercial photosensor technology in future experiments. Potential future exploitation of UK facility at Boulby.

Eureca Milestones:

2009-12: CRESST/Edelweiss exploitation;
2009-10: TDR;
2011-14: Construction and installation (proposed);
2015: Operation - 0.1t (proposed);
2018: Operation – 1t (proposed).

LUX-ZEPLIN Milestones:

2010: ZEPLIN-III (6kg) second science run ends;

2010: LZ3 (3t) construction start (proposed);
2012: LZ3 operation (proposed);
2013: LZ20 (20t) construction start (proposed);
2018: LZ20 operation (proposed).

A.17 Nucleon decay experiments

Context:
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. Supersymmetric 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 100kt range, which may give enhanced sensitivity to this channel. This technology might also be suitable for a future long baseline neutrino experiment and it is likely that a full-scale detector would be designed to fulfil both roles.

Facilities:
See Long Baseline Neutrino Experiment

UK history/expertise:
See Long Baseline Neutrino Experiment

Current UK involvement:
See Long Baseline Neutrino Experiment

UK opportunity:
To exploit existing expertise in liquid argon detectors to contribute to the first observation of evidence for the unification of forces.

Milestones/decision points:
See Long Baseline Neutrino Experiment

A.18 Electric dipole moment search experiments

Context
The search for neutron and electron electric dipole moments provides a complementary window on possible new physics effects via loop contributions; Standard Model effects typically enter at 3-loops and are of the order of 10^6 times smaller than possible beyond-SM contributions from, for example, SUSY, which enter at 1-loop. Critical to these BSM signals is a new source of CP-violation. Electric Dipole Moment (EDM) experiments consequently give sensitivity to a wide range of Beyond the Standard Model CP violation mechanisms. Neutron EDM signals can be sought with cold neutron beams from reactors or spallation sources while electron EDM signals can be identified with cold molecular beams. Experimental limits on the electron EDM are roughly an order of magnitude smaller than those on the neutron EDM, but so are the predictions for many BSM theories (although not all), so the physics reaches of the two approaches are broadly similar (although model dependent).

Facilities:

In the past the principle experiments in the neutron EDM field have been performed at neutron sources in the US, Russia and France (at the ILL reactor). The world’s best limits now come from the ILL experiment, which is largely a UK collaboration. The latest phase of this experiment, now called CryoEDM, is being commissioned with results expected in 2011-12 at the sensitivity level of $3\text{x}10^{-27}$ *e*cm. A proposal is in preparation for a possible future phase, leading to a limit of $3\text{x}10^{-28}$ *e*cm by 2016. There has been considerable competition in the recent past in the electron EDM field, with current world-best limits of $1.6\text{x}10^{-27}$ *e*cm published in 2002 by the Commins group at Berkeley. The eEDM experiment at ICL, which uses a cold YbF beam, is now clearly the world-leader since Commins has retired. It has the capability to improve its current limit from 10^{-26} *e*cm to 10^{-29} *e*cm within about 5 years.

UK history/expertise:

The UK has historically been a leader in this area. Over the last decade the best nEDM limits came from the ILL experiments, while the eEDM project developed a new technique that produces the world's best sensitivity for the electron.

Current UK involvement:

Both CryoEDM and eEDM are almost exclusively UK collaborations. Both are STFC funded.

UK opportunity:

To maintain UK leadership in an area which could generate results of fundamental importance for BSM physics. To fully exploit past UK investment in this area.

nEDM Milestones:

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

eEDM Milestones:

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

Appendix B: PPAP Membership

Philip Burrows, John Adams Institute, Oxford University (Linear Collider).
Cinzia da Via, Manchester University (LHC detectors).
Tim Gershon, Warwick University (LHCb).
Nigel Glover, IPPP, Durham University (Theory).
Claire Shepherd-Themistocleous, Rutherford-Appleton Laboratory (CMS).
Mark Thomson, Cambridge University (MINOS, ATLAS upgrade, Linear Collider).
Dan Tovey, Sheffield University (ATLAS).

Appendix C: Programme of Community Reviews

C.1 Flavour-changing physics and QCD

Programme committee:
Nigel Glover (IPPP) - Chair
Tim Gershon (Warwick) - Deputy
Christine Davies (Glasgow)
Val Gibson (Cambridge)
Cristina Lazzeroni (Birmingham)
Steve Playfer (Edinburgh)
Chris Sachrajda (Southampton)
Maria Smizanska (Lancaster)
Guy Wilkinson (Oxford)

Monday 13 July 2009:
`http://conference.ippp.dur.ac.uk/conferenceDisplay.py?confId=273`

Speaker	**Institution**	**Topic**
Philip Burrows	JAI/Oxford	Welcome
Jordan Nash	Imperial College	PPAN context
Gino Isidori	INFN Frascati	Flavour-changing physics beyond the Standard Model
Jonas Rademacker	Bristol	CKM matrix elements and CP violation
Jonathan Flynn	Southampton	Lattice QCD
Patrick Koppenburg	Imperial College	Rare decays
Fergus Wilson	STFC/RAL	Lepton universality and lepton flavour violation
Chris Parkes	Glasgow	LHC upgrades (LHCb and GPDs)
Adrian Bevan	QMUL	e+e- machines (SuperB, Belle upgrade, tau-charm factories)
Cristina Lazzeroni	Birmingham	NA62 + kaons at JPARC/FNAL
Yoshi Uchida	Imperial College	COMET + muons at FNAL

C.2 Energy frontier physics

Programme committee:
Claire Shepherd-Themistocleous (STFC/RAL) - Chair
Cinzia da Via (Manchester) - Deputy
Grahame Blair (RHUL)
Craig Buttar (Glasgow)
Rob Edgecock (RAL)
Jerome Gauntlett (IC)
Dave Newbold (Bristol)
Paul Newman (Birmingham)
Dan Tovey (Sheffield)
Georg Weiglein (IPPP)
Terry Wyatt (Manchester)

Tuesday 14 July 2009:
`http://conference.ippp.dur.ac.uk/conferenceDisplay.py?confId=274`

Speaker	Institution	Topic
Philip Burrows	JAI/Oxford	Welcome
Jordan Nash	Imperial College	PPAN context
Georg Weiglein	IPPP, Durham	Theory review
Marc Weber	STFC/RAL	LHC upgrades - physics & detectors
Steve Myers	CERN	LHC upgrades – accelerator
Andrei Nomerotski	Oxford	Linear collider - physics & detectors
Jim Clarke	STFC/Daresbury	Linear collider – accelerator
Ken Long	Imperial College	Future colliders & generic detector R&D
John Dainton	CI/Liverpool	LHeC
Nick Dorey Jerome Gauntlett	Cambridge Imperial College	Formal theory

C.3 Neutrino and non-accelerator-based physics

Programme committee:
Mark Thomson (Cambridge) - Chair
Phil Burrows (JAI/Oxford) - Deputy
Paul Harrison (Warwick)
Ed Hinds (IC)
Ken Long (IC)
Simon Peeters (Sussex)
Ruben Saakyan (UCL)
Silvia Pascoli (IPPP)
Subir Sarkar (Oxford)
Neil Spooner (Sheffield)
Christos Touramanis (Liverpool)

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Speaker	Institution	Topic
Philip Burrows	JAI/Oxford	Welcome
Philip Burrows p.p. Jordan Nash	Imperial College	PPAN context
Steve King	Southampton	Neutrino theory
Elisabeth Falk	Sussex	Current neutrino oscillation experiments
David Wark	Imperial College + STFC/RAL	Future neutrino oscillation experiments
Yorck Ramachers	Warwick	Non-oscillation neutrino physics
Alex Murphy	Edinburgh	Report from PAAP
Subir Sarkar	Oxford	Non-accelerator theory
Hans Kraus	Oxford	Dark matter experiments
Philip Harris	Sussex	EDM experiments
Gary Barker	Warwick	R&D for detectors
Rob Edgecock	STFC/RAL	Accelerator R&D