# Update to the Particle Physics Advisory Panel Report

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## 1. INTRODUCTION

In October 2009 the Particle Physics Advisory Panel (PPAP) issued a 'roadmap' report in which we identified the scientific challenges and opportunities for the UK in particle physics. We made a number of recommendations aimed at a broadly-based, but focussed, world-leading UK particle physics programme. The financial context for the STFC programmatic review of 2010 resulted in support for a small set of very high priority projects, but curtailment of (even modest) investment in several significant areas that add breadth and diversity to the UK programme; in some cases STFC support for R&D in projects that could be the future life-blood of the field was halted. Although the financial support for the few highest-priority projects was welcomed, the narrowing of opportunity to the UK is a matter of great concern to the community, as acknowledged by STFC.

Here we issue a brief update to our 2009 report to indicate, where relevant, changes in status, schedules and/or external funding for the respective projects. Most notably the LHC is producing its first crop of exciting physics results, and over the next couple of years these will be expected to have a major impact on planning future strategy in the field. In addition there are early indications of a possibly large value of the $\theta_{13}$ neutrino mixing parameter, and interesting signals in several dark matter search experiments.

The next CERN Council European Strategy exercise is now starting up, and is expected to make recommendations on the European particle physics strategy by mid 2013. It is vital that we in the UK fully engage with the strategy process, maintain our own strategic options and capabilities, and ensure we are in a position to influence, be aligned with, and capitalise on, the evolving European strategy.

## 2.1 Energy frontier physics

### 2.1.1 LHC GPDs and their upgrades

The LHC is performing spectacularly well. With the current operation at 7 TeV, the peak luminosity to date has reached $3.4\times10^{33}$ $cm^{-2}s^{-1}$. The ATLAS and CMS experiments have already reached an integrated luminosity of ~5 $fb^{-1}$ per experiment. The detectors are coping very successfully with up to 20 pile-up interactions per event. The current projection for 2012 is at least an additional 5 $fb^{-1}$ per experiment, and, given the programme of on-going LHC luminosity improvements, there is a strong possibility that a larger data sample will be accumulated, possibly at the higher energy of 8 TeV.

With the data collected in 2010/11 the GPDs have, combined with LEP2 and precision electroweak data, disfavoured the whole SM Higgs boson mass range below 115 GeV and above 130 GeV. Moreover both ATLAS and CMS observe small excesses of events consistent with a SM Higgs boson of mass around 125 GeV. The additional data to be collected in 2012 should either provide confirmation of this observation with high statistical significance or rule out the SM Higgs, though some discovery room will remain for non-SM Higgs bosons. No beyond-SM new physics signals have yet been observed, and the mass reach for many SUSY particle (and other new physics) searches is being pushed towards (and in some cases beyond) the 1 TeV scale.

The current plan is that LHC will be upgraded ('High Luminosity'-LHC) to deliver ~3000 $fb^{-1}$ integrated luminosity in the 2020-30s to increase significantly its discovery potential. The timeline to reach this goal involves three long shutdown periods. The first, in 2013-14 (Phase 0) will be used to increase the LHC energy to close to the design value of 14 TeV and the peak luminosity to $1\times10^{34}cm^{-2}s^{-1}$. The second in 2017-18 (Phase 1) will upgrade the peak luminosity to $\sim2.5\times10^{34}$ $cm^{-2}s^{-1}$, and the last one foreseen (after collecting 300$fb^{-1}$) in 2021-22 (Phase 2) will be used to upgrade the luminosity to $\sim5\times10^{34}$ $cm^{-2}s^{-1}$ with luminosity levelling, which roughly increases the integrated luminosity per year by a factor of 10 over nominal. UK participation in the machine upgrade R&D programme is supported via the HiLumiLHC EU FP7 project.

Both the ATLAS and CMS experiments will use the LHC upgrade downtime to change the detectors most damaged by radiation or simply to replace detectors with improved versions. ATLAS upgrades will start in 2013 with the installation of a new pixel layer (IBL), to improve the primary vertex reconstruction. A new electronics chip and two sensor technologies (thin planar and 3D) will be used for the IBL. Construction of the IBL should be completed by the end of 2012 and installation is foreseen in summer 2013.

In Phase 1 both ATLAS and CMS are planning to upgrade the muon detectors, while CMS is planning the substitution of the entire pixel system and some part of the hadron calorimeter and ATLAS proposes also to make changes to calorimeter electronics. Phase 2 will require significant upgrades (detector, data acquisition and trigger systems) necessary to retain performance at increased luminosity. In particular, the tracking systems will need replacement to be able to withstand the integrated doses implied by 3000 $fb^{-1}$. For both detectors there will be a staged programme of upgrades to the triggering throughout the Phase 0, Phase 1 and Phase 2 shutdowns.

R&D has already started for Phase 1 and Phase 2 upgrades. Both experiments have been funded in the UK to perform a substantial R&D programme on detectors, Level 1 trigger, computing and simulation studies.

**Milestones:**

2012: LoI on Phase 1 upgrades
2013: TDRs for Phase 1 upgrades – decision on upgrade construction
2014-15 TDR on Phase 2 upgrades

### *2.1.2 Tevatron experiments*

UK involvement in the Tevatron experiments has provided excellent value for money over the past 13 years in terms of both scientific output and leadership roles. The Tevatron has recently delivered its last proton-antiproton collisions to the CDF and D0 experiments and a rather rapid wind-down of activities is expected. Previous UK funding has been based on the premise of a 2010 end to operations and thus expired in September 2011. The Tevatron-UK groups plan to request one further year of STFC support at a modest level to cover the remaining travel needs. This will support the completion of the remaining LHC-competitive analyses with significant UK leadership, specifically the search for a low mass Higgs boson, precision measurements of the W boson mass and measurements of top and bottom quark properties which are favoured by Tevatron kinematics.

### *2.1.3 High-energy electron positron collider*

The two international design projects for a next-generation $e^+e^-$ collider, ILC and CLIC, are proceeding with their R&D programmes. Collaboration between the two project teams on common technical issues has been ongoing for many years, and since 2008 formal collaborative working groups on relevant technical systems have been in place. In 2010 an annual international workshop series was started to review progress in both projects jointly. There is now an ICFA-led working group that is aiming to set up a single framework for the governance of both projects, in preparation for the realisation of a globally-agreed design for a future collider whose parameters (most notably the energy reach) will be determined by LHC physics results.

The ILC Global Design Effort is on track to deliver a Technical Design Phase (TDP) report to ICFA by the end of 2012. This will present an optimised design, taking account of extensive R&D since the 2007 Reference Design Report, including a revised cost estimate. CLIC is preparing its Conceptual Design Report (CDR) for submission to the CERN SPC by early 2012. CLIC is planning a next-stage 5-year R&D programme to advance the design, aiming towards an updated design document scheduled for 2016; this effort calls for greater participation from international collaborators and this is now being organised.

Through previous substantial investment the UK had built up significant technical expertise and leadership in a number of key linear collider detector and accelerator systems. Essentially all STFC funding for detector R&D ended in 2011, though small residual efforts survive via participation in EU FP7 projects. Nevertheless the UK retains a number of leadership roles within the ILC and CLIC detector and physics community. STFC support for the accelerator

(LCABD) project also ended in early 2011, though UK leadership of some key areas continues with CERN support via the CLIC-UK project, as well as via FP7 projects.

**Milestones:**

2012: CLIC Conceptual Design Report
2012: ILC Technical Design Phase report
2012/2013: future direction guided by LHC results and European PP Strategy Review
2013-20: possible decision on LC project and start of construction
2016: CLIC updated design report

### *2.1.4 High-energy muon collider*

The idea of a high energy muon collider, building on the muon storage ring of a possible future neutrino factory, remains a technology option for a very far-future multi-TeV lepton collider. The concept remains at a very early stage of development and requires considerable R&D in order to demonstrate its feasibility. In 2011 the US DoE formally launched a ‘Muon Accelerator Program’ to pursue critical R&D on the accelerator, coordinated by Fermilab, with funding currently foreseen at roughly the level of $10M/annum.

### *2.1.5 A high-energy lepton-hadron collider (LHeC)*

The HERA electron-proton collider ceased operation in 2007 and STFC support ended soon afterwards. Several UK institutes have continued to be involved in the analysis of the final H1 and ZEUS data and, in particular, in the measurments of the structure functions and parton densities which are extensively used at the LHC. This activity is now close to completion. The future of deep-inelastic scattering may lie in the LHeC project, which aims to supplement the CERN machine infrastructure with a (nominally 60 GeV) electron accelerator, producing electron-proton scattering at an instantaneous luminosity of order $10^{33}$ $cm^{-2}s^{-1}$ simultaneously with the existing proton-proton collisions. An electron-ion programme is also foreseen. An LHeC offers potentially unique sensitivity to new particles such as lepto-quarks, the discovery and exploration of gluon saturation, as well as precision electroweak and strong interaction measurements at the TeV scale and measurements of parton density functions with a full flavour decomposition over an extended range of momentum fraction.

A Conceptual Design Report is currently under review by CERN-appointed referees. The future of the project will depend on LHC results and the European particle physics strategy. The UK provides the spokesman and several other leading project members. The project receives a modest level of financial support from CERN. No UK funding is in place yet.

**Milestones:**

2011: CDR
2011-12: decision on electron linac versus ring
2012-13: future direction guided by LHC results and European PP Strategy Review
2012-15: prototype development and preparation of Civil Engineering
2013-14: TDR
2016: target date for start of mass production and construction

2022: possible operation alongside High Luminosity LHC

## 2.2 Flavour physics

### *2.2.1 LHCb*

The initial data taking of LHCb has proved the concept of a dedicated flavour physics experiment at a hadron collider. The detector is working to design specifications and is recording luminosity at levels 50% higher than the nominal design values. In particular, the (UK-built) VELO and RICH sub-detectors, which are critical to the LHCb physics programme, work as anticipated. Unique results are being delivered across the physics programme of the experiment, providing significant new constraints on physics beyond the Standard Model, with discovery potential in the next round of updates and beyond. For example, LHCb is now providing the most precise results on the rare decays $B_s \rightarrow \mu\mu$, $B_d \rightarrow K^*\mu\mu$, as well as on CP violation in $B_s \rightarrow J/\psi\varphi$ and $B_{d,s} \rightarrow K\pi$. In addition, LHCb has recently announced initial evidence for CP violation in the charm sector. UK leadership in LHCb remains exceptionally strong (current and next Physics Coordinator, ex-Spokesperson, ex-RICH and ex- and current VELO project leaders, Editorial Board chair). Support for UK activity on LHCb comes from the ERC and the Royal Society, as well as STFC.

The Letter of Intent for the LHCb upgrade was submitted in March 2011. It has been reviewed by the LHCC, who found the case “compelling”. The proposal is to upgrade the trigger, electronics and necessary subdetector components in order to read out the experiment at 40 MHz and collect a total integrated luminosity of around 50 $fb^{-1}$. The upgraded detector would be installed during the LHC long shutdown in 2018, and would operate for a decade thereafter (the project is compatible with, but does not require, the HL-LHC machine upgrade). The UK has held leadership roles since the inception of the upgrade plans, and was responsible for several sections of the LoI, including the physics case. The UK groups intend to lead in the vertex detector and particle identification subdetector upgrades, and in physics exploitation. A Statement of Interest was submitted in May 2011, but PPAN felt it premature to recommend the submission of a full proposal.

**Milestones:**

2012: technical review of upgrade and choice of technology
2013: Technical Design Report
2018: installation
2019: start of data-taking with upgraded LHCb detector

### *2.2.2 High-luminosity flavour factory*

UK involvement in BaBar exploitation continues at a low level. The UK provides the Chair of the Collaboration Council and the Deputy Chair of the Publications Board, as well as one of the co-editors of the Physics of the B Factories Book that will describe the legacy of BaBar and Belle.

At KEK, funding of $110M for upgrades to KEKB was announced in June 2010. Work is progressing on designing the Belle II detector. Upgrading the accelerator has begun and ground-breaking too place in November 2011 (both were delayed due to the March 2011 earthquake). The accelerator will now adopt the crab-waist and narrow beam design originally created for SuperB. The goal is to collect 50 $ab^{-1}$ over 5 years starting in 2015. No UK involvement is foreseen currently.

White papers on the physics, detector and accelerator for SuperB were published in summer 2010. SuperB was approved by the Italian parliament in December 2010 with €50M funding per year for 5 years with additional funding from in-kind contributions. The Nicola Cabibbo laboratory will be established on the campus of Tor Vergata University, Rome. The baseline design luminosity is $10^{36}$ $cm^{-2}s^{-1}$ with options to increase that by factors of 2 in later years. Unlike KEK, the accelerator will be able to operate at energies from the $\psi(3770)$ to the $\Upsilon(5S)$ and the electron beam will be 80% polarised. The goal is to collect 75 $ab^{-1}$ over 5 years at the $\Upsilon(4S)$ and ~500 $fb^{-1}$ in a few months at the charm threshold, starting around 2016/2017. SuperB will reuse the BaBar detector, with upgrades. There is some UK interest in the silicon pixel vertex detector and the accelerator design; the UK provides one of the physics coordinators. A Statement of Interest was submitted to PPAN in 2011 but was not successful.

**Milestones:**

- 2012: ground-breaking for SuperB
- 2015: commissioning of SuperKEKB
- 2016: earliest possible commissioning of SuperB

### *2.2.3 High-precision dedicated e+e- charm experiments*

CLEO-c has completed operation, and is publishing a range of results with data taken in the charm threshold region. The CLEO-c UK group remains active, exploiting charm threshold physics as input for LHCb, though its STFC funding has come to an end.

BES-III has commenced operation, and has already exceeded the CLEO-c data samples at various energies. The peak instantaneous luminosity continues to increase, and operation is planned until at least 2015. Thus significantly better precision than CLEO-c is anticipated across the programme that spans spectroscopy, production and measurements at charm threshold, exploiting quantum correlated D-Dbar pairs. No UK involvement is foreseen currently.

A proposal for a tau-charm factory in Novosibirsk, that would have luminosity exceeding that of BES-III, has been met positively by the Russian government. A Conceptual Design Report was submitted in 2012, with a funding decision expected around the end of 2012. If positive, data taking could commence as early as 2017/8.

**Milestones:**

- 2011-15: BESIII data-taking
- 2012: funding decision by Russian government on Novosibirsk tau-charm factory
- 2017: possible commissioning of Novosibirsk tau-charm factory

### 2.2.4 High-precision dedicated kaon experiments

The CERN NA62 experiment aims to reach a new level of sensitivity to rare kaon decays, down to branching ratios of around $10^{-11}$. UK involvement is supported mainly by a recently awarded European Research Council (ERC) Advanced Investigator grant. This award funds the design, construction, installation and first operations of the upgraded CEDAR detector. Additional support comes from the Royal Society. STFC has agreed to cover the Common Fund contributions for 2011 and 2012, with future funding to be requested via the next consolidated grants round. UK positions of responsibility include the CEDAR project leader and the chair of the Conference Committee. The NA62 physics programme requires prototype testing and commissioning runs until the SPS is shut down at the end of the 2012 LHC run. Data-taking will resume once the accelerator complex starts up again thereafter.

The J-PARC K0T0 experiment has been approved. Its construction is underway, with initial projections for data-taking in 2012 expected to be delayed by not more than 12 months due to the earthquake and tsunami. Other projects being discussed internationally include TREK at J-PARC and the KLOE-II upgrade at Frascati, while precision kaon experiments are foreseen as part of Project-X at Fermilab. No UK involvement is foreseen currently in any of these.

**Milestones:**

2012: NA62 engineering runs; K0T0 engineering run and start of data-taking; upgrade of detectors for KLOE-2
2013: K0T0 first physics results; KLOE-2 start of data taking
2014-17: NA62 data-taking

### 2.2.5 High-precision dedicated muon experiments

Two proposals for new g–2 experiments are being discussed. Fermilab proposes to ship the Brookhaven magnet to Illinois, and hope for CD0 in 2012 towards a goal of running for two years from 2015. A J-PARC proposal employs a novel technique that was developed at RIKEN/RAL and elsewhere for producing ultra-cold muons. Both aim to improve on the current error by a factor of four or so.

MEG have reported an upper limit of $2.4\text{x}10^{-12}$ (90% CL) on the branching fraction of $\mu \to e\gamma$, which is five times stronger than the previous limit set by MEGA. Improvements down to a few times $10^{-13}$ are foreseen with the complete 2012 data.

The proposed Mu2E experiment at Fermilab gained CD0 in 2009, and is currently preparing a conceptual design, aiming for CD1 in 2012. The longer-term timescale (aiming for data-taking in 2018 and 2019) is similar to COMET, which gained Stage 1 approval at J-PARC in 2009. Research and development since then has included irradiation studies of superconducting cables, beam extinction measurements at J-PARC and commissioning of the prototype pion production and muon transport experiment (MUSIC). This work has satisfied several of the J-PARC PAC's requirements towards full approval. The PRISM Task Force has published refereed work towards a conceptual design, also contributing to the Project-X muon physics proposals. Both scaling and non-scaling FFAG designs continue to be pursued, with studies at EMMA being highly promising for demonstrating the feasibility of the latter. Several UK groups are active in research and development towards muon conversion experiments, but are currently unfunded by STFC.

**Milestones:**

2012: COMET & Mu2E Technical Design Reports
2012: final MEG data-taking
2013: start of COMET construction
2014/5: start of data-taking for g-2 experiments at J-PARC/FNAL
2018/9: start of data-taking for COMET & Mu2E

## 2.3 Neutrino physics

### 2.3.1 T2K

T2K will be the leading experiment in neutrino physics for the next 5 – 10 years. 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 $\theta_{23}$. The initial operation of T2K was interrupted by the earthquake in March 2011. Using data taken prior to that point T2K reported $2.5\sigma$ evidence for $\nu_\mu \rightarrow \nu_e$ oscillations, which if confirmed suggest a relatively large value of $\theta_{13}$. The experiment now has been largely restored and is on schedule to resume data-taking early in 2012.

If the experimental measurements from T2K and reactor experiments confirm that $\theta_{13}$ is large it opens up the possibility of searching for CP violation with the existing experiment. This would require an extension to the run and operation with anti-neutrinos. Leadership within T2K, including the international co-spokesperson, places the UK in a strong position to play a leading role in the future Japanese neutrino programme.

**Milestones:**

2012: restart of T2K phase-1 operation
2016: end of T2K phase-1.
2016/2017: possible start of T2K phase-2 depending on magnitude of $\theta_{13.}$

### 2.3.2 MINOS/MINOS+

MINOS has produced two important results in 2011: a search for $\nu_\mu \rightarrow \nu_e$ oscillations with a similar sensitivity to that of T2K yielding an excess of just under $2\sigma$ and an updated measurement of the oscillations of anti-neutrinos at the “atmospheric” neutrino mass scale. MINOS is expected to finish running in mid-2012. The final analysis of MINOS data will continue through 2012/2013. The MINOS+ phase of the experiment will commence running for three years in the NOVA beam. The main physics goals are a high precision study of neutrino oscillations in the energy range 4-10 GeV and a search for non-standard neutrino interactions predicted by a number of models beyond the Standard Model. In addition, with a relatively small investment MINOS/MINOS+ will be able to make a precise measurement of the neutrino velocity which will provide a test of the recently observed $6\sigma$ claim of super-luminal neutrinos by the OPERA collaboration. The UK has a number of leadership roles within MINOS including the current co-spokesperson.

**Milestones:**

2012: end of MINOS operation.
2012-2013: final analysis of MINOS data.
2013-2015: MINOS+ operation.

### *2.3.3 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 that wishes to be involved in the next long-baseline experiment, whether it is T2K phase 2 or LBNE, a super-beam facility, a beta-beam, or a neutrino factory. Information on the value of $\sin^2 2\theta_{13}$ will improve in the coming years and it is likely that the route to the discovery of leptonic CP violation will be better understood by around 2015. The UK is making significant contributions to the future neutrino programme through a leading presence in T2K, leadership of the International Design Study for the Neutrino Factory (the IDS-NF) and by hosting MICE and EMMA.

The Accelerator Strategy Board recently considered proposals for the completion of MICE and the proton driver Front-End Test Stand (FETS) and for a programme of high-power target R&D. The Board recommendation is that the completion of MICE and FETS is the highest priority and that a target R&D programme should be funded.

With limited funding from Fermilab, the UK is also involved at a low level in the proposed LBNE project which aims to send an intense neutrino beam from Fermilab to a detector in the DUSEL. Whilst this project is central to the Fermilab future strategy the funding issues surrounding DUSEL are not yet resolved. Several UK institutes have received substantial FP7 funding to participate in the European LAGUNA/LBNO study for a neutrino beam from CERN (either a super-beam facility with a very long baseline, or a shorter baseline beta-beam to a detector in the Frejus mine).

**Milestones:**

2012: neutrino factory RDR.
2013/2014: improved knowledge of $\sin^2 2\theta_{13}$, enabling the future direction to be defined.
2015: completion of MICE Step V; demonstration of muon cooling.

### 2.3.4 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. Super-Nemo has comparable sensitivity to SNO+ but its main strength is the unique topological signature that would be required to demonstrate that an observed signal is indeed neutrinoless double-beta decay. In the UK Super-Nemo is funded by STFC to develop the Demonstrator module. UK involvement in SNO+ is funded through STFC and an ERC grant.

**Milestones:**

2012: SNO+ commissioning.
2011-2013: construction and commissioning of the Super-Nemo demonstrator module.
2013: SNO+ double beta decay operation.
2014: Super-Nemo demonstrator running.
2017: Completion of full Super-Nemo detector.
2020: Super-Nemo target sensitivity reached.

### 2.3.5 Reactor neutrino experiments

The current generation of reactor experiments (Double-Chooz, Daya Bay and RENO) all commenced operation in 2011 and will have sensitivity to $\sin^2 2\theta_{13}$ down to approximately 0.03 within a few years. 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 role in this area. The potential for future improvements in reactor-based experiments currently appears limited.

## 2.4 Non-Accelerator Experiments

### 2.4.1 Direct dark matter search experiments

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.

The final results of the EDELWEISS-II (4kg) dark matter search were presented in early 2011 leading to a combined limit from CDMS/EDELWEISS data in summer 2011. The next phase of EDELWEISS-III will run during 2012-14 using a 24 kg array of cryogenic germanium detectors. EURECA follows on from the pioneering EDELWEISS-II and CRESST cryogenic dark matter detectors. The EURECA TDR is expected to be completed in 2012. A new cavern to host EURECA (and Super-Nemo) will be excavated at the Laboratoire Souterrain de Modane simultaneously with the construction of a first stage 100 kg detector ready for operation in 2015. The full 1t detector will start data taking in 2018.

The LUX-ZEPLIN programme is based on two phase noble gas technology pioneered by the UK. ZEPLIN-III (6 kg) completed its second science run in May 2011 (collecting roughly four times the exposure of the first science run) leading to an improved limit that is comparable to the limits obtained by CDMS-II and EIDELWEISS-II. The ZEPLIN programme has now reached its conclusion at Boulby. The LUX350 detector (350 kg) was deployed on the surface in 2011. The UK groups will formally join the LUX collaboration in time for the first underground deployment in the newly excavated and outfitted Sanford Underground Laboratory at Homestake in spring 2012. The aim is to start taking data in 2012-13. The 1.5t LZS detector is in its design phase with construction/installation in 2013-14 and aims to start taking data in 2015. The third generation 20t LZD detector aims to commence operation in 2020.

The DRIFT (Directional Recoil Identification From Tracks) experiment at Boulby Mine has recently produced limits on the WIMP spin-dependent cross-section from 1.5 kg days of running with the DRIFT II detector. Funding for the Boulby Palmer Laboratory is secured for 3 years under the STFC environment programme, while the NSF is supporting a three-year continuation and expansion of operations at Boulby and CPL (the mine operators) supports new excavation to scale up to a 24 $m^3$ 4kg target DRIFT III module.

A new UK group funded by an ERC Starting Grant is part of the DEAP/CLEAN collaboration which is engaged in several experiments to search for dark matter using liquid argon and/or liquid neon as a single-phase scintillator experiment.

The STFC strategic approach and funding for direct dark matter searches are currently being reviewed.

**EURECA milestones:**

2012-14: EDELWEISS-III operation
2012: EURECA TDR.
2012-14: Excavation at LSM.
2015: EURECA operation (0.1t).
2018: EURECA operation (1t).

**LUX-LZ milestones:**

2012: LZ350 installation and start of data taking.
2013-14: LZS construction and installation (1.5t).
2015: LZS operation.
2016-19: LZD construction and installation (20t).
2020: LZD operation.

**DRIFTII/DTM milestones:**

2012-2013: DRIFTIIe construction; low WIMP mass directional search.
2012-2014: DTM 24m3 design R&D, Boulby excavation.

**DEAP/CLEAN milestones:**

2012-14: MiniCLEAN data taking.
2014-19: DEAP-3600 data taking.

### *2.4.2 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 EDM experiments which have now set the world's best limits on both the neutron and electron EDM.

The CryoEDM nEDM experiment is currently being commissioned at ILL with an anticipated improvement in sensitivity, by up to a factor of three, by 2013. At this point the ILL is scheduled to shut down for a year and the experiment will move to a new beamline; a proposal is in preparation to fund an upgrade along with this move, which will lead to a further factor of three improvement in sensitivity.

In 2011, the eEDM experiment at ICL set a new world-best limit of $10.5x10^{-28}$ ecm using a cold YbF beam. It has the capability to improve its current limit by an order of magnitude to $10^{-28}$ ecm in the next three years or so with the possibility of a further order of magnitude improvement in sensitivity after that.

The CryoEDM and eEDM experiments are expected to yield an order of magnitude increase in experimental sensitivity which 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 experiments are relatively small scale and inexpensive. Both are almost exclusively UK collaborations. CryoEDM is STFC funded. eEDM has received STFC funding in the past, but is not currently funded.

**nEDM Milestones:**

2013: sensitivity at the level of $2x10^{-26}$ ecm / year.
2014: commissioning and start of data taking in new beamline.
2016: sensitivity at the level of $5x10^{-27}$ ecm / year.

**eEDM Milestones:**

2012: aim for restoration of STFC funding.
2014: sensitivity an order of magnitude below the current limit.

## *2.5 Theoretical 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.

### 2.5.1 Formal Theory

The UK continues to lead in all aspects of Formal Theory (such as 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).

There has been a major expansion at Kings College London, as well as recruitment at Cambridge, Nottingham, Oxford, Queen Mary and Southampton as well as support from the ERC. As in the past, the UK is able to attract strong people through the STFC Advanced Fellowship scheme. Nevertheless, the community is now under severe strain because of EPSRC's decision to stop funding research fellowships in all areas of the mathematical sciences other than statistics and applied probability. Furthermore, EPSRC has indicated that it will no longer be funding topics in Mathematical Physics that are at the interface of the EPSRC Mathematics programme and the STFC programme, that historically they did in the past. With the continued focus of STFC funding towards exploitation of the investment in particle physics experiments, the net effect is that formal theory is now significantly underfunded in terms of postdoctoral support compared to the past and this will lead to a consequent reduction in the UK's volume of leading scientific output. This may also result in many of the best UK students being deterred from starting PhDs in formal theory.

### 2.5.2 Phenomenology

There continues to be strong UK activity in all areas of phenomenology - QCD, Electroweak and Higgs, Beyond the Standard Model (BSM), Flavour Physics, Neutrino Physics, Monte Carlo, Particle Astrophysics/Cosmology, Lattice Phenomenology and Model Building. In phenomenology relating to the LHC there is particular strength and depth, for example in event simulations (Herwig++ and SHERPA) and tuning (Professor/Rivet), parton distributions (MSTW and NNPDF) and higher order QCD corrections (BlackHat and ROCKET). There have been significant UK contributions to the early LHC analyses, particularly those connected with soft physics (minimum bias and underlying events), vector boson plus multi-jet events, jet algorithms and other QCD-motivated analysis techniques (such as boosted Higgs searches) and searches for new physics such as supersymmetry.

The community has received a recent boost through the return of John Ellis to the Clerk Maxwell chair at Kings College London, which, together with increased funding through Ellis's ERC Advanced Investigator Award and an appointment at UCL has revived particle physics phenomenology in London. There has also been healthy growth elsewhere in the UK through recent appointments in Cambridge, Durham, Edinburgh, Glasgow, Oxford and Sussex.

### 2.5.3 Lattice QCD

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. Recent best UK-led measurements with few-percent accuracy include B meson decay constants (error of 6%), the ratio of K to pi meson decay constants (0.5%), ratios of B mixing parameters (3%, which gives a 6% determination of the branching fraction for $B_s \to \mu\mu$,which is a key search mode for the LHC), and K mixing parameter (3%, leading to errors of around 0.5% on $|V_{us}|$, and 2.5% on $|V_{td}/V_{ts}|$). Constituent quark masses are now determined to 1-2% and the strong coupling to 1%.

In 2009 the DiRAC facility was funded in the UK to provide high performance computing services to the theoretical particle physics and theoretical astrophysics communities, with a £12.3M Large Facilities Capital Fund grant from BIS and additional funding from STFC, the universities involved, and industry. The provision for lattice QCD involves several machines, the largest of which are the Darwin cluster at Cambridge and a BlueGene/P machine in Swansea. A

800 Tflops BlueGene/Q machine is planned to arrive in Edinburgh in late 2011. These facilities have allowed theorists in the UKQCD consortium to perform significant lattice QCD calculations, adding computing resources to the 'people-power' on which the UK reputation was largely based (and which has recently been enhanced through the award of an ERC Starting Investigator grant in Southampton and an appointment in Glasgow). It is now important to maintain this level of computing provision into the future as the reach and scope of lattice QCD calculations is expanded around the world.

**Milestones**:

2011/12 Install the BlueGene/Q machine in Edinburgh
2012/13 Seek funding for upgrade to DiRAC facility
2013 next theory rolling grants round

## *3. RECOMMENDATIONS*

We reaffirm and update our recommendations given in the 2009 report. It is essential that the UK pursues a broad particle physics programme focussed on high-priority science questions. In particular the UK should:

**LHC**

- fully exploit its investment in the GPDs and LHCb by maintaining a leading role in the science exploitation of the current detectors;
- invest in R&D on the LHC GPD upgrades to accommodate higher luminosity on a timescale commensurate with the LHC upgrade schedule; and participate in the upgrades at an appropriate level;
- pursue R&D towards the LHCb detector upgrade and participate in the upgrade at an appropriate level;

**Next-generation collider facilities in planning:**

- pursue world-leading accelerator and focussed detector R&D through to a decision point on the future direction for the linear collider, and maintain a watching brief on muon collider developments;
- maintain a leading role in the conceptual design studies for the LHeC through to a decision point on the project;
- support key individuals to participate in design studies for a high luminosity flavour factory; if significant UK interest emerges, tension possible participation against other flavour physics projects at a level justified by the physics case;

**Other flavour experiments:**

- provide the modest support necessary to leverage the external EU funding obtained so as to enable a lead role in the NA62 experiment;
- maintain a strategic watching brief on future high-precision kaon and muon experiments;

**Neutrinos:**

- fully exploit its investments by leading the science exploitation of MINOS and T2K;
- pursue R&D towards a next generation long-baseline neutrino oscillation experiment;
- maintain UK leadership in R&D towards a future neutrino factory;
- pursue a coherent and world-leading programme of research in neutrinoless double beta-decay experiments;

**Non-accelerator experiments:**

- maintain involvement in a current-generation direct dark matter search experiment and pursue a coherent and world-leading long-term programme of research in this area;
- exploit its world leading position by investing in both electron and neutron dipole moment search experiments;

**Exploitation of datasets from facilities that have completed data-taking:**

- provide appropriate support to allow full exploitation, through to publication, of data from experiments where analysis is ongoing and the UK has made major previous investments, such as CDF and D0, BaBar, ZEUS and H1;

**Theory:**

- continue to support a world-leading long-term programme in theoretical particle physics, particularly in formal theory, phenomenology and lattice theory.