Dear PPAP,

This covering letter and attached document are intended to draw your attention to the unique physics and technological opportunities that the long baseline neutrino program offers.

The document was written for the European Strategy for Particle Physics meeting in Krakow (10-12 September 2012) that was supported by the CERN Council; as such it has a very European focus. However, we also recognise, and would like to draw your attention to, other projects being initiated elsewhere in the world, which address some of the same physics questions.

The UK now has a long history of active and leading involvement in the international neutrino program through experiments in the US, Canada and Japan, thanks to the vision of the PPARC and STFC funding committees who saw these opportunities as providing the best physics reach at the time. The phenomenon of neutrino oscillation constitutes the first, and so far only, evidence of physics beyond the Standard Model and the new measurements of the oscillation parameters in the past year have produced a step change in the field. In this light proposals are already underway to build new experiments: T2HyperK in Japan, LBNE in the US, PINGU in the Antarctic as well as further exploitation of the existing NuMI beam in the US. There is already UK interest in all of these projects.

The UK community is growing quickly and it is unlikely that the entire community will contribute to only one project. The goal, however, is to both exploit existing R&D expertise to meet the technological challenges these new worldwide experiments provide and to position ourselves to drive a small number of selected projects. Continued involvement in these international endeavours will allow the UK to maintain and enhance its leading role in the neutrino domain.

In summary, the vibrant UK neutrino community will continue to play a leading role on the international neutrino scene. Continued and timely involvement in the worldwide experiments will guarantee the UK being able to deliver on the important new physics goals that the neutrino program is targeting in the next 10-20 years.

The UK neutrino community

European strategy for long-baseline neutrino-oscillation experiments;
The UK perspective

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Executive summary

Neutrinos are the only elementary fermions of which the properties are largely unknown. The phenomenon of neutrino-flavour oscillations, which implies that neutrinos have mass and mix, remains the only established physics beyond the Standard Model.

It is widely anticipated that the measurement of neutrino properties will provide insights into long-standing mysteries in particle physics and cosmology. In particular, understanding the neutrino may provide unique glimpses of physics at energy scales well above those that can be reached at any existing or planned collider and which might have been reached in the very first instants of the Universe. A dedicated experimental neutrino programme is therefore at least as important as, and is complementary to, the collider programme at the energy frontier.

Over the past 15 years, experiments measuring oscillations in solar, atmospheric, accelerator and reactor neutrinos have made tremendous progress in pinning down the neutrino-mixing angles and oscillation frequencies which parameterise the "Standard Neutrino Model". To complete the picture, demands that we now turn to the next generation of neutrino oscillation projects. In particular the next phase of experimentation must address:

- The determination of the mass hierarchy of the neutrino mass eigenstates;
- Searching for, and measuring the magnitude of, CP-violation in neutrinos; and
- Bringing the precision with which the neutrino mixing-matrix elements are known in line with the precision that exists in the quark sector as a precursor to the development of a genuine understanding of the physics of flavour.

At the time that the previous European Strategy for Particle Physics was devised, the unknown value of the mixing angle θ_{13} meant that the programme required to deliver these measurements was difficult to gauge. The recent measurement of (a large) θ_{13} by accelerator and reactor experiments has radically modified this situation. It is now clear that existing accelerator and detector technologies, with a well-defined R&D path, allow a programme of measurements to be planned immediately offering an excellent discovery potential by the middle of the next decade.

The UK neutrino physics community calls on the European Strategy for Particle Physics to endorse a programme which will provide European scientists and engineers with the opportunity to make decisive contributions to the physics programme outlined above. To achieve this, the strategy must focus on:

- Exploiting the unique accelerator infrastructure available at CERN and the opportunity to develop a deep underground neutrino detector at Pyhäsalmi in Finland, to create a long-baseline experiment capable of measuring the mass hierarchy within the next decade and with significant sensitivity to CP-violation;
- Backing a programme of R&D, that will allow:
  - The continued development of the CERN proton accelerator complex to provide high-power, pulsed, proton beams;
  - Prototyping of large-scale liquid-argon detectors and increased R&D into optimal near-detector configurations (to be hosted at the CERN North Area); and
- The demonstration of muon ionisation cooling through the timely completion of the MICE experiment, the implementation of a neutrino experiment based on a stored muon beam and European contributions to the programme required for the Neutrino Factory to be proposed as an option for the field.

1. Introduction

The study of neutrino oscillations provides a unique window on physics beyond the Standard Model through which it may be possible to elucidate phenomena at extremely high energy scales. Detailed, precise measurements of the properties of the neutrino are required to allow the theory of the physics of flavour to be developed and to test theories beyond the Standard Model. The study of neutrino oscillations is therefore as fundamental as, and complementary to, the high-energy-collider programme.

- The neutrino is unique among the fundamental fermions in that it has no conserved quantum numbers (except spin and possibly a global lepton number if they are Dirac particles).
- The established phenomenon of neutrino oscillations implies that: lepton-flavour is not conserved; neutrinos are massive; and that the neutrino mass eigenstates mix to produce the observed flavour eigenstates.
- The phenomenon of neutrino oscillations constitutes the first evidence of physics beyond the Standard Model. The tiny neutrino mass and large neutrino-mixing angles may be related to physics at energy scales beyond the reach of present or future colliding-beam facilities. Precision measurements are needed to test physics beyond the Standard Model.
- Oscillations are readily described through the introduction of three neutrino-mass eigenstates and a unitary mixing matrix ($U_{\rm PMNS}$) that defines the relationship between the mass and flavour eigenstates (the Standard Neutrino Model).
- Although great progress has been made, measurements of the parameters of the mixing matrix are not complete and do not yet rival the precision with which the analogous mixing-matrix in the quark sector (the CKM matrix) is known.
- The existence of three neutrino states admits the possibility of violation of the CP symmetry. This can be parameterised through $U_{\rm PMNS}$ by the presence of a CP-violating phase $\delta_{\rm CP}$, the value of which is currently unknown. This CP violation can help to explain the matter anti-matter asymmetry of the universe via lepto-genesis.
- The next generation of long-baseline neutrino-oscillation experiments will probe the phase space of $\delta_{\rm CP}$ in addition to establishing, for the first time, the neutrino-mass hierarchy.

By exploiting the strength of the European neutrino-oscillation community and the infrastructure and expertise available at CERN and at other European laboratories, Europe has the opportunity to make unique contributions to the experimental programme that will make precision measurements of neutrino oscillations.

- Europe has an established position of leadership in the international neutrino-physics community.
- The European community (comprising at least 600 physicists) is undoubtedly able to exploit the infrastructure and expertise in the provision of neutrino beams that is available at CERN, and in national laboratories such as RAL, to make decisive contributions to the international neutrino-oscillation programme.
- European, and indeed UK, physicists have played both seminal and leading roles in the current generation of long-baseline experiments (MINOS/MINOS+ in the USA, ICARUS/OPERA in Europe and T2K in Japan).
- The fact that the value of θ_{13} was unknown at the time of the last European strategy review made it inappropriate to define a long-term strategy for neutrino-oscillation physics. The measurement of θ_{13} combined with the outcome of the design studies (EUROnu, LAGUNA, LAGUNA-LBNO, and the IDS-NF) and maturity of the R&D programmes (the EMMA experiment at DL, the MERIT experiment at CERN, and the MICE experiment at RAL) means that it is now possible to define a powerful, long-term programme that may be implemented in stages offering guaranteed discovery potential at each stage.

2. Status of neutrino oscillations

Over the last 15 years there has been a revolution in our understanding of neutrinos. From having a solar- and an atmospheric-neutrino problem, we have gone to a state where we understand the neutrino detection rates in terms of solid flux predictions and the effect of neutrino-flavour transitions, the phenomenology of which is parametrised by $U_{\rm PMNS}$.

- Neutrino oscillations are readily described in terms of three neutrino mass eigenstate with masses m_1, m_2 and m_3. $U_{\rm PMNS}$, which may be parameterised using three mixing angles (θ_{12}, θ_{23} and θ_{13}) and a CP-violating phase parameter ($\delta_{\rm CP}$), relates the mass and flavour eigenstates.
- Many of the parameters have now been determined. Fits to solar-, atmospheric-, beam- and reactor-neutrino data have been used to determine that $\theta_{12} \simeq 34^\circ \pm 1^\circ$, $\theta_{23} \simeq 45^\circ \pm 3^\circ$, $\theta_{13} \simeq 9^\circ \pm 1^\circ$ and that $\Delta m^2_{21} = m^2_2 - m^2_1 \simeq (7.6 \pm 0.2) \times 10^{-5}\,{\rm eV}^2$. The absolute value of Δm^2_{31} is also known, $|\Delta m^2_{31}| = |m^2_3 - m^2_1| \simeq (2.4 \pm 0.1) \times 10^{-3}\,{\rm eV}^2$.
- The neutrino mass hierarchy (${\rm sign}(\Delta m^2_{31})$) and the value of $\delta_{\rm CP}$ are unknown.

3. Scientific imperatives for the long-baseline neutrino oscillation programme

To complete the description of neutrino oscillations afforded by the Standard Neutrino Model requires that the sign of Δm^2_{31} be determined and that the value of δ be established.

- The demonstration that $\sin^2 2\theta_{13} \sim 0.1$ implies that:
  - Matter effects are large and the mass hierarchy may be determined from the energy dependence of the oscillation probabilities or by comparison of the neutrino and anti-neutrino oscillation probabilities; and
  - The discovery of CP-invariance violation is possible. The long-baseline neutrino-oscillation programme must therefore be optimised to expedite the search for CP-invariance violation.
- To complete the exploration of the Standard Neutrino Model, it is necessary to:
  - Exploit existing and planned experiments (T2K, MINOS/MINOS+, NOvA) to obtain some indication of the mass hierarchy;
  - Prepare to bring forward a proposal for a long-baseline experiment on a conventional broad-band beam that is capable of exploiting the details of the oscillation spectrum to:
    (a) Determine the mass hierarchy with a confidence level of at least 5σ; and to
    (b) Provide first indications of CP-invariance violation.

The tiny neutrino masses and the large neutrino-mixing angles, so different to those of the quarks, hint at a rich seam of physics beyond that described by the Standard Model. To fully expose this seam would require a Neutrino Factory. Precision measurements are required to:

- Test the Standard Neutrino Model by searching for, e.g., non-unitarity of the neutrino-mixing matrix, sterile neutrinos and non-standard interactions;
- Measure with precision the oscillation parameters and establish whether θ_{23} is maximal (i.e. $\theta_{23} \simeq 45^\circ$) which would hint at an as-yet-undiscovered symmetry; and to
- Allow relationships between quark- and lepton-mixing parameters, which may arise in theories of the physics of flavour, to be tested quantitatively. In the absence of an unambiguous theoretical steer, the experimental imperative is to make measurements of the neutrino parameters with a precision at least as good as the precision with which the quark-mixing parameters are presently known.

4. Strategy for development of European contributions to the long-baseline oscillation programme

The European Strategy for Particle Physics must provide for European scientists and engineers to make decisive contributions to the strategic priorities of the long-baseline programme: the search for leptonic-CP-invariance violation and the determination of the mass hierarchy. Europe is well placed to make leading contributions to the field by exploiting the unique infrastructure available at CERN and developing a deep underground neutrino detector at Pyhäsalmi in Finland. Such developments offer the potential to build a powerful long-baseline programme encompassing a wide-band conventional beam and the staged implementation of the Neutrino Factory.

- Europe has established a strong, world-class, long-baseline activity that encompasses CNGS, MINOS/MINOS+, NOvA and T2K. European personnel have played seminal roles in the establishment of the international programme and individuals and groups enjoy internationally-recognised positions of leadership. The European Strategy for Particle Physics must maintain and enhance this vibrant and influential programme.
- With $\theta_{13} \sim 0.1$, the strategic priorities for the long-baseline neutrino-oscillation programme are to expedite the search for leptonic-CP-invariance violation (CPV) and the determination of the mass hierarchy. The European strategy must be optimised to allow European scientists and engineers to make decisive contributions to the priority programmes.
- European contributions to the international programme should exploit:
  - The unique infrastructure that exists at CERN and other European national laboratories;
  - The uniquely-long baseline offered by a large underground detector at Pyhäsalmi in Finland served by a neutrino beam from CERN; and
  - The warm and effective collaborations that have been established with Japan and the USA.
- The European Strategy for Particle Physics should therefore provide for:
  - The development of a proposal for a large detector at Pyhäsalmi served by a wide-band conventional neutrino beam from CERN;
  - Preparatory work, including detector and accelerator R&D, towards a long-baseline neutrino programme in Europe, which would also underpin European contributions to, and leadership in, programmes in Asia and the Americas (MINOS+, NOvA, LBNE, GLADE and T2HK); and
  - European contributions to the programme required for a Neutrino Factory proposal to be prepared in time for the next update of the European Strategy. This programme must encompass the experimental demonstration that stored muons can serve a first-rate neutrino programme; the necessary hardware and system R&D, including completion of the MICE experiment; and all relevant design work, including consideration of the implementation of the facility at CERN.

Central to the success of such a strategic programme is R&D, which addresses the key issues that underpin the strategy. The future long-baseline programme requires the development of high-power, pulsed proton beams and particle production targets to match. Large volume neutrino detectors can, in principle, provide the excellent spatial and energy resolution required. To make the Neutrino Factory an option for the field, it is important to demonstrate the ionisation cooling technique and essential to mount a world-class neutrino experiment using a stored muon beam.

- The future of the long-baseline neutrino-oscillation programme at CERN is underpinned by the incremental development of the proton-accelerator complex and therefore of the neutrino beams that can be delivered. The development of the SPS, already planned for the high-luminosity LHC, will be capable of delivering an instantaneous beam power of 770 kW. Concepts for the further development of the proton accelerator complex that will allow the staged implementation of beams with powers in excess of 1 MW have been developed. The European strategy should provide for the R&D programme that underpins these developments to be taken forward.

- To demonstrate the feasibility of large-volume liquid-argon detectors, prototyping and test-beam exposures are essential. CERN is uniquely well placed to host such an activity by appropriate development of the North Area.
- The control of systematic uncertainties related to neutrino flux and interaction cross-sections, will be key to the precision measurement of neutrino properties long-term and the use of near detectors will be essential. Increased R&D into their optimal configuration and location needs to begin now. Once again, by appropriately developing the North Area, CERN will be able to accommodate the vibrant, international activity that will be required.
- Continued support for the hadro-production experiment NA61/SHINE and possible successors will be important to constrain the uncertainty associated with the beam flux in conventional beams.
- The essential proof of the principle of ionisation cooling will be provided by the MICE experiment. The timely completion of the MICE programme is therefore essential.
- An increased focus on neutrino-interaction cross-section measurements is crucial in order to reach the sensitivities needed to probe CP-invariance violation. In particular, the nuSTORM project has the potential to determine the $\nu_e N$ scattering cross sections and fill the gaps in current cross-section results in addition to providing definitive sterile neutrino studies. nuSTORM will also be capable of supporting essential accelerator and detector R&D. The European strategy should encompass European contributions to such a programme.