Initial report from the ICFA Neutrino Panel

Executive summary

The discovery of neutrino oscillations implies that neutrinos have mass and that the flavour eigenstates mix. Non-zero neutrino masses require new physics beyond the Standard Model. Revealing the physics behind neutrino masses and mixing is among the highest priorities for particle physics in the twenty-first century.

Measurements of the parameters that govern neutrino oscillations will have a profound impact on our understanding of particle physics, astrophysics and cosmology. Such a breadth of impact justifies a far-reaching experimental programme by which the properties of the neutrino that are presently unknown are determined, the three-neutrino-mixing picture is tested and the properties of the neutrino are measured with a precision sufficient to allow the physics that explains these properties to be understood. Accelerator-based neutrino-oscillation experiments are an essential component of this programme as they are the only way in which oscillations between all known flavours can be studied precisely.

The accelerator-based neutrino-oscillation programme is international in both scope and engagement. The approved programme will improve our knowledge of the mixing angles and the mass-squared differences and may be able to determine the neutrino mass hierarchy. In the medium term, the Long-baseline Neutrino Experiment (LBNE) and the Tokai (J-PARC) to Hyper-Kamiokande experiment offer complementary approaches to searching for the violation of the matter-anti-matter symmetry in neutrino oscillations. For these experiments to realise their full potential coordinated programmes of hadro-production and neutrino-nucleus cross-section measurements are essential. A design study of an alternative wide-band beam facility is underway: the Long-baseline Neutrino Observatory (LBNO) study will report by the end of 2014. New concepts such as the implementation of a neutrino beam on the European Spallation Source (ESSnuSB) and the use of muon decay-at-rest to search for the matter-anti-matter asymmetry (Daedalus) are also being studied.

The Neutrino Factory, in which electron- and muon-neutrino beams are produced from the decay of muons confined within a storage ring, has been shown to offer the ultimate sensitivity and precision. The staged implementation of the facility has been studied. The attractive first stage, "nuSTORM", has the potential to make detailed and precise studies of electron- and muon-neutrino-nucleus scattering and to make exquisitely sensitive searches for sterile neutrinos.

A small number of measurements do not fit the elegant three-neutrino-mixing model. These measurements can be interpreted as evidence for new "sterile neutrino" states. If confirmed, these measurements will revolutionise the field. An experimental programme is underway to investigate these anomalies. It is important that these anomalies are addressed. Short-baseline contributions to this programme should have clear synergy with the long-baseline programme.

This report presents the conclusions drawn by the Panel from three regional "Town Meetings" that took place between November 2013 and February 2014. The Panel recognises that to maximise the discovery potential of the accelerator-based neutrino-oscillation programme it will be essential to exploit the infrastructures that exist at CERN, FNAL and J-PARC and the expertise and resources that reside in laboratories and institutes around the world. Therefore, in its second year, the Panel will consult with laboratory Directors, funding-agency representatives, the accelerator-based neutrino-oscillation community and other stakeholders to:

- Develop a road-map for the future accelerator-based neutrino-oscillation programme that exploits the ambitions articulated at CERN, FNAL and J-PARC and includes the programme of measurement and test-beam exposure necessary to ensure the programme is able to realise its potential;
- Develop a proposal for a coordinated "Neutrino RD" programme, the accelerator and detector R&D programme required to underpin the next generation of experiments; and
- To explore the opportunities for the international collaboration necessary to realise the Neutrino Factory.

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1 Manifesto

1.1 Why is neutrino physics important?

The neutrino is the most abundant matter particle in the Universe; the number of neutrinos exceeds the number of protons, electrons and neutrons by a factor approaching ten billion. So, to understand the Universe we must understand the neutrino. The neutrino is the least understood matter particle; in contrast to all other fundamental fermions, some of the neutrino's properties are unknown while the properties that are known are poorly understood.

The discovery of neutrino oscillations, in which the neutrino type or flavour changes as the neutrino propagates through space and time, implies that the neutrino has mass and that the neutrino flavours mix. Theoretical interpretation of this result requires either that:

- Neutrinos are their own antiparticle, in which case they are an entirely new form of matter; or
- Neutrinos and anti-neutrinos are different particles. This case implies that lepton number conservation is a fundamental law of Nature.

Hence, neutrino oscillations imply that there are new phenomena beyond those described by the Standard Model. Consequently, when considering the programme required to understand the properties of the neutrino, we must assume nothing but aspire to a programme of sufficient breadth and precision to elucidate the underlying phenomena.

Progress since the seminal discovery of neutrino oscillations in 1998 has been rapid. Since then, the solar-neutrino anomaly has been resolved, mixing among all three neutrino flavours has been established and the magnitudes of the two mass splittings and the three mixings angles that characterise the strengths of the mixings have been measured. To complete our understanding we need to know:

- Whether mixing among the three neutrino flavours violates the matter-antimatter (CP) symmetry. Such leptonic CP-invariance violation (CPiV) would be something new and might have cosmological consequences;
- Why neutrino masses are so tiny, at least a million times smaller than any other known matter particle;
- What the ordering of the three neutrino mass eigenstates is. While there are constraints on the absolute neutrino-mass scale our knowledge of the mass spectrum is incomplete;
- Why the strength of mixing among the neutrino flavours is so much stronger than the mixing among the quarks;
- Whether empirical relationships between neutrino-mixing parameters, or between neutrino- and quark-mixing parameters, can be established; and
- Whether the few measurements of neutrino oscillations that are not readily accommodated within the elegant framework of three-neutrino mixing are statistical fluctuations, systematic effects or indications that there is even more to discover.

Neutrino physics is important. Not only has recent progress in neutrino physics been rapid and exciting, but the remaining questions to be addressed are fundamental. The discovery potential of the programme required to address these questions is substantial.

1.2 What must the neutrino program do?

If we are to understand neutrinos and their role in, and influence on, the Universe, we must:

- Determine the properties of the neutrino that are presently unknown;
- Determine whether the three-neutrino mixing picture (the "Standard Neutrino Model", SνM) is the whole story; and

- Measure the properties of the neutrinos with a precision sufficient to allow the physics that explains these properties to be understood.

This ambitious programme requires a comprehensive set of innovative experiments that have the potential to make discoveries and to provoke theoretical progress. Accelerator-based neutrino oscillation experiments play a critical role in this program. They provide the only means by which both neutrino and anti-neutrino transitions between all of the three known neutrino flavours can be studied precisely. In particular, accelerator-based neutrino-oscillation experiments are essential to:

- Complete our knowledge of the pattern of neutrino masses, which will constrain ideas about the underlying physics.

- Determine the last remaining unmeasured parameter that describes the mixing between the three neutrino flavours, the CP-phase δ, and determine whether there is observable CP-invariance violation in neutrino oscillations; this would constitute the discovery of leptonic CP-invariance violation;

- Clarify the origin of the present anomalies in accelerator-based neutrino-oscillation measurements—the few measurements that do not seem to conform to the SνM picture would, if established, imply the existence of additional neutrino states or interactions, and a mysterious new set of physical phenomena;

- Measure transitions between all neutrino and anti-neutrino flavours to see whether the three-neutrino mixing picture is self-consistent and to check that the oscillations depend only on proper time (L/E) rather than depending on the baseline (L) and neutrino energy (E) separately. A discovery that the SνM is inadequate would be a major breakthrough; and

- Make precise measurements of all of the mixing parameters to search for clues about the underlying physics. This may be the only way to provoke progress in understanding neutrinos.

This accelerator-based program is international both in intellectual interest, in engagement and in scope. It has tremendous potential to make discoveries that would have profound impact on our understanding of the physics of fundamental particles and the evolution of the Universe. The international program should encompass:

- The timely completion of the present generation of accelerator-based neutrino-oscillation experiments;

- The implementation of an appropriate programme of new "long-baseline" and "short-baseline" neutrino-oscillation experiments accompanied by a measurement programme by which systematic uncertainties are reduced such that they are commensurate with the statistical power of the oscillation experiments; and

- The accelerator and detector R&D programmes required to deliver the next generation of facilities culminating in the Neutrino Factory which is recognised to be the facility that offers the ultimate precision.

2 Review of the status of neutrino oscillations

The neutrino mixing matrix U translates neutrino-mass eigenstates into flavour eigenstates through the relation $(\nu_e, \nu_\mu, \nu_\tau)^T = U(\nu_1, \nu_2, \nu_3)^T$. The mixing matrix may be parameterised using three mixing angles $(\theta_{12}, \theta_{23}, \theta_{13})$, one "Dirac CP phase" δ, and two Majorana CP phases $(\alpha_{21}, \alpha_{31})$. In the three-flavour-mixing

Table 1: Summary of neutrino oscillation parameters [1]. In the table the abbreviation SK stands for Super-Kamiokande, KL for KamLAND, BOREX for Borexino, DB for Daya Bay, and DC for Double Chooz. Citations for the various experiments may be found in [1].

Parameter	Value ($\pm 3\sigma$)	Examples of Experiments
$\sin^2 \theta_{12}$	$0.312^{+0.052}_{-0.047}$	SK, SNO, KL, BOREX
$\sin^2 \theta_{23}$	$0.42^{+0.22}_{-0.08}$	SK, K2K, MINOS, T2K
$\sin^2 \theta_{13}$	$0.0251^{+0.0109}_{-0.0101}$	T2K, MINOS, DB, DC, RENO
Δm^2_{21}	$(7.58^{+0.60}_{-0.59}) \times 10^{-5}$ eV^2	SK, SNO, KL, BOREX
$\|\Delta m^2_{32}\|$	$(2.35^{+0.32}_{-0.29}) \times 10^{-3}$ eV^2	SK, K2K, MINOS, T2K
sign of Δm^2_{32}	unknown	SK, MINOS, T2K
δ	unknown	SK, MINOS, T2K

framework, U may be written [1]:

$$
\begin{aligned}
U &= \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \\
&= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \\
&\quad \times \mathrm{diag}(1, e^{i\frac{\alpha_{21}}{2}}, e^{i\frac{\alpha_{31}}{2}}) \, ;
\end{aligned}
\tag{1}
$$

where c_{ij} and s_{ij} represent $\sin\theta_{ij}$ and $\cos\theta_{ij}$, respectively. The probability for oscillations from flavour α to β as the neutrino propagates in vacuum may be expressed as:

$$
\begin{aligned}
P(\nu_\alpha \to \nu_\beta) &= \delta_{\alpha\beta} \\
&\quad -4 \sum_{i>j}^{3} \mathrm{Re}\left[U^*_{\alpha i} \cdot U_{\beta i} \cdot U_{\alpha j} \cdot U^*_{\beta j} \right] \sin^2 \left(\frac{\Delta m^2_{ij}}{4} \frac{L}{E} \right) \\
&\quad +2 \sum_{i>j}^{3} \mathrm{Im}\left[U^*_{\alpha i} \cdot U_{\beta i} \cdot U_{\alpha j} \cdot U^*_{\beta j} \right] \sin \left(\frac{\Delta m^2_{ij}}{2} \frac{L}{E} \right) \, ;
\end{aligned}
\tag{2}
$$

where $\Delta m^2_{ij} \equiv m^2_i - m^2_j$ is the difference of the squares of the neutrino masses. The probability for the oscillation of antineutrinos is the same as that for neutrinos with $U \to U^*$. This implies that the last line has a sign opposite to that of neutrino oscillations. The probability is further modified by the interaction of the (anti-)neutrinos with the matter through which they travel. Among the three phases, neutrino oscillations depend only on δ. CP-invariance violation (CPiV) occurs if $\delta \neq 0°$ and $\delta \neq 180°$. The present status of the determination of the mixing parameters is presented in table 1. Each of the three mixing angles have been determined: θ_{12} is known with an uncertainty $\sim 2\%$; θ_{23} is known with a precision of $\sim 5\%$; and θ_{13} with a precision of $\sim 5\%$. It is not known whether θ_{23} is more than $45°$ or less than $45°$, this is referred to as the "octant ambiguity". The magnitude of the mass-squared splittings are also known, Δm^2_{21} with an uncertainty of $\sim 3\%$ and Δm^2_{32} with an uncertainty of $\sim 5\%$. The sign of Δm^2_{21} is known from measurements of the energy dependence of the oscillation pattern of electron-neutrinos from the sun. The sign of Δm^2_{32} remains to be determined.

Of the parameters, the phase δ has not yet been determined and the sign of Δm_{32}^2 is not known. The "normal hierarchy" refers to the case in which m_3 is the heaviest mass state ($\Delta m_{32}^2 > 0$); the "inverted hierarchy" is the case in which m_3 is the lightest state ($\Delta m_{32}^2 < 0$). The normal and inverted hierarchies result in measurably different oscillation probabilities if neutrinos of sufficient energy are caused to travel an appropriately long distance through the earth. The determination of the mass hierarchy and δ is feasible if the transition $\bar{\nu}_\mu \to \bar{\nu}_e$ (or $\bar{\nu}_e \to \bar{\nu}_\mu$) can be detected with sufficient rate and cleanliness. The mass hierarchy may also be explored by experiments searching for neutrinoless double-beta decay, through cosmological observations and by measuring the energy dependence of electron-anti-neutrinos produced in nuclear fission. Whether $\sin^2 2\theta_{23}$ is maximal ($\theta_{23} = \pi/4$) or θ_{23} is in the first octant ($\theta_{23} < \pi/4$) or in the second octant ($\theta_{23} > \pi/4$) is another open question.

A number of measurements have been reported that do not fit into the three-flavour mixing scenario. These anomalous measurements can be interpreted as "hints" for the existence of neutrinos other than the three known species. Such states are referred to as "sterile" as they do not interact via the weak interaction. To explain the anomalous measurements, new states are introduced with masses such that the mass-squared difference to the three known states is $\sim 1\,\mathrm{eV}^2$. Oscillations between the known states and the sterile states govern short baseline oscillations such as electron-neutrino appearance in muon-neutrino beams over baselines of 0.03 km to 0.5 km, the deficit of reactor neutrinos at very short distance and the deficit of electron neutrinos from radioisotopes. The evidence for the existence of sterile neutrinos is controversial and a program to prove or refute the anomalous measurements is underway in Asia, the Americas and in Europe.

3 Elements of the future programme

The future programme must determine the parameters of the SνM and make the tests necessary to establish it as a precise and self-consistent description of nature. With these goals in mind, the elements of the future programme are identified in this section.

3.1 Headline measurements

3.1.1 Completing the picture

Searching for CP-invariance violation

The CP-phase (δ) can only be determined by measuring the rate of appearance of a neutrino flavour not present in the beam at source. The measurement must be made over a range of values of L/E at which there is significant interference between terms in the oscillation formalism that arise from θ_{12}, θ_{13} and θ_{23}. In the short term, searches for CP-invariance violation will be made by measuring the appearance of ν_e (or $\bar{\nu}_e$) in a conventional ν_μ ($\bar{\nu}_\mu$) beam. Of the experiments that will take data this decade, only NOνA and T2K have the ability to probe CP-invariance violation.

Since the sensitivity of long-baseline experiments arises from the interference of oscillation modes, sensitivity to δ arises from the product $\sin\delta \times \sin\theta_{12} \times \sin\theta_{23} \times \sin\theta_{13}$. Therefore, the determination of δ using long-baseline experiments requires that measurements of each of the mixing angles is available.

The proposed next generation long-baseline experiments fall into two classes: narrow- and wide-band beam experiments. Narrow-band beams deliver a narrow range of neutrino energies using the off-axis beam technique. Such experiments are able to make a model-independent search for leptonic CP-invariance violation by measuring the difference between the rates of neutrino and the anti-neutrino appearance. In order to reduce the

asymmetry introduced by neutrino interactions with the earth (the matter effect), the low-energy narrow-band beam is tuned to match a comparatively short baseline. The Hyper-Kamiokande experiment is an example of such a project that is sensitive to events at the first oscillation maximum. A concept to produce a neutrino beam at the European Spallation Source serving a detector placed at the second oscillation maximum has recently been proposed. Wide-band beams generate a broad band of neutrino energies with a larger mean energy of $\sim 3\,\text{GeV}$. By placing the detector at a distance of more than $1000\,\text{km}$ from the source it is possible to exploit the broad band of neutrino energies to study the energy spectrum of the oscillated neutrinos at both the first and the second oscillation maximum. By studying the difference between the oscillated neutrino and anti-neutrino spectrum, such experiments can make model independent searches for CP-invariance violation. The Long Baseline Neutrino Experiment (LBNE) proposed in the USA and the Long Baseline Neutrino Observatory (LBNO) proposal under development in Europe plan to search for CPiV in this manner. In addition, by studying the oscillated neutrino-energy spectrum, both narrow- and wide-band beam experiments are able to probe the description of CP-invariance violation provided by the SνM outlined above. The two techniques probe for CPiV in different oscillations regimes; as discussed below, the matter effect is significant in long-baseline experiments. Futher, the short- and long-baseline collaborations have converged on complementary detector technologies; water-Cherenkov detectors and liquid-argon time-projection chambers respectively. These factors mean that the measurements that can be made at narrow-band, short-baseline beams are complementary to those that can be made at wide-band, long-baseline beams. Systematic uncertainties arising from the modelling of neutrino interactions are challenging in both short- and long-baseline experiments. However, these systematics will be manifested in qualitatively different ways owing to the different energies and detector techniques used. And, as discussed in section 3.1.2, the study of oscillations as a function of baseline, L, and neutrino energy, E, separately will offer the possibility to observe non-standard effects. Therefore, the combination of results from short- and long-baseline experiments will be extremely valuable and should be studied further.

To search for CP-invariance violation in a conventional long-baseline experiment requires the detection of ν_e ($\bar{\nu}_e$). Greatly improved signal purity can be achieved using a technique that can deliver a large flux of electron (anti-)neutrinos since, in this case, sensitivity to CP-invariance violation requires the detection of the appearance of ν_μ (or $\bar{\nu}_\mu$) which is readily accomplished through the charged-current production of muons. In the Neutrino Factory, intense ν_e ($\bar{\nu}_e$) beams are produced from the decay of muons confined within a storage ring. The Neutrino Factory offers the best sensitivity to leptonic CP-invariance violation and the best precision on the determination of δ. The use of high-power cyclotrons to produce neutrinos from the decays of muons brought to rest in a large detector has recently been proposed. Such an experiment has the potential to measure δ from the L dependence of the oscillated neutrino beam.

Determining the mass hierarchy

The large value of θ_{13} means that the next generation long-baseline experiments have the potential to determine the mass hierarchy. Neutrinos interact with the earth as they propagate from source to detector. All neutrino flavours may undergo elastic scatters with the atomic electrons. In the case of the ν_e and $\bar{\nu}_e$, the charged current makes a contribution to the elastic-scattering amplitude. This leads to a "matter effect" through which the oscillation rate of neutrinos differs from that of anti-neutrinos. The way in which the oscillated, neutrino-appearance energy spectrum is modified depends on the sign of the large mass splitting (Δm_{32}^2). In the case of long-baseline experiments, good sensitivity to the mass hierarchy is obtained for small values of $|\Delta m_{32}^2|/E$ and appropriately long baselines. LBNE and LBNO seek to determine the mass hierarchy using this technique.

It is possible to determine the mass hierarchy by measuring with high precision the shape of the oscillated, neutrino-disappearance energy spectrum. Experiments are being developed that will immerse a large detector capable of measuring the incident neutrino energy with a precision of $\sim 3\%$ in the large flux of $\bar{\nu}_e$ produced in

nuclear reactors.

Atmospheric neutrinos remain an important probe of neutrino oscillations and provide a sensitive technique for the determination of the neutrino mass hierarchy. Supernova neutrinos detected in one or several of the existing or planned large neutrino observatories would allow the determination of the neutrino mass ordering although uncertainties in the models of particle production by supernovae make for a challenging analysis.

Resolving the octant ambiguity

Disappearance measurements using atmospheric and accelerator-generated beams are primarily sensitive to θ_{23} through a term in the oscillation probability proportional to $\sin^2 2\theta_{23}$. As a result, such measurements are able to determine $|\theta_{23} - 45°|$ but unable to determine the sign of $(\theta_{23} - 45°)$. The "octant ambiguity" refers to the fact that the octant in which the value of θ_{23} lies is not yet known. The sign of $(\theta_{23} - 45°)$ can be determined through a detailed analysis of the $\nu_\mu \to \nu_e$ oscillation pattern, where the first-order term in the oscillation probability is proportional to $\sin^2 \theta_{23}$, thereby giving rise to an enhancement in the transition if $\theta_{23} > 45°$ relative to the corresponding value if $\theta_{23} < 45°$ that gives rise to the same value of $\sin 2\theta_{23}$. In general, the effects of CPiV, the mass hierarchy and θ_{23} are intimately entangled in $\nu_\mu \to \nu_e$ oscillations. The complementarity afforded by studying the oscillations with different baselines and energies, along with the anti-neutrino channel, allows one to vary systematically the impact of each parameter in the oscillation pattern and extract each of their values.

3.1.2   Testing the standard three-neutrino mixing model

In the near term, the precision with which the oscillation rates are known will improve as the present generation of experiments accumulate data. Reactor experiments exploiting the $\bar{\nu}_e$ disappearance channel and operating at baselines of ~ 1 km are sensitive to θ_{13}. The appearance channels in accelerator-based experiments operating at baselines larger than ~ 100 km ($\bar{\nu}_\mu \to \bar{\nu}_e$) are sensitive both to θ_{23} and to θ_{13}, while the disappearance channel depends mainly on θ_{23}. Therefore, it is possible to check the consistency of the SνM by comparing the results of the reactor and long-baseline experiments. Assuming consistency between the results, constraints may be placed on the value of δ. A separate constraint on δ may be derived from the comparison of oscillation measurements using ν_μ and $\bar{\nu}_\mu$ beams. A check on the consistency of the SνM will then be afforded by the comparison of the allowed range of δ yielded by the two techniques. Taken together, the full data sets from reactor and long-baseline experiments will place stronger constraints on the mixing matrix than can be derived from any single experiment on its own.

Such complementarity in the oscillation-measurement programme will continue to be essential beyond the present generation of experiments. To confirm the SνM as the correct description of nature, or to establish the existence of entirely new phenomena, will require that consistency checks of sufficient precision be carried out. For the future accelerator-based neutrino-oscillation programme, this puts a premium on the study of neutrino and anti-neutrino oscillations, the measurement of the energy dependence of the oscillations and the verification that the SνM is able to give a consistent, detailed and precise description of at least two experiments at substantially different baselines.

It was noted in section 2 that there are a small number of measurements that are not readily described by the SνM. It is possible to interpret these results by postulating the existence of additional "sterile" neutrino states that are electro-weak singlets and that have masses such that the effective mass-squared splitting with the three known flavours of neutrino (Δm^2) is ~ 1 eV^2. To date it has not been possible to give a satisfactory, self-consistent description of all of the anomalous measurements.

Conceptually, the search for sterile neutrinos can be separated into experiments which seek to confirm or refute the existence of oscillations with a frequency corresponding to $\Delta m^2 \sim 1$ eV^2 and generic searches

which do not target a particular mass scale. Reactor- and radio-isotope-source based experiments are sufficient to study $\bar{\nu}_e$ disappearance channels at oscillation frequencies corresponding to $\Delta m^2 \sim 1\,\text{eV}^2$. Accelerator-based experiments will be required to test the sterile-neutrino interpretation of the observed excesses in the $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance and the $\bar{\nu}_\mu$ disappearance channels. Generic searches for sterile neutrino states should be developed in synergy with the neutrino-nucleus scattering programme that is required to support the future long-baseline neutrino-oscillation programme. Such a cross-section measurement programme will also be able to set limits on non-standard phenomena in neutrino-scattering.

3.2 Experimental programme required to deliver headline measurements

The long-baseline accelerator-based neutrino-oscillation experiments will rely on intense neutrino sources and very massive detectors to reduce statistical uncertainties. For the experiments to realize their potential, the systematic uncertainties will need to be controlled such that they are always commensurate with the statistical precision. A concurrent programme of neutrino-nucleus scattering and hadro-production measurement is therefore required.

3.2.1 Neutrino Interaction Measurements

Solar and reactor neutrino experiments operating at very low neutrino energies (several MeV) and scattering experiments at very high energies (100's of GeV), enjoy very precise knowledge of their respective neutrino cross sections (at the few-percent level). In the neutrino energy range of interest to accelerator based oscillation experiments, $0.2\,\text{GeV}$–$5\,\text{GeV}$, the inclusive $\bar{\nu}_\mu N$ cross section is known with precision between 5% and 10%, and the differential cross sections have uncertainties in the 30%–50% range. Further, the $\bar{\nu}_e N$ cross section has not been measured in the energy range of interest.

The phenomenology of neutrino interactions in the few-GeV energy region is a complex combination of quasi-elastic scattering, resonance production and deep inelastic scattering processes. Each of these processes has its own model and associated uncertainties. The models are based on neutrino cross section measurements that have substantial uncertainties, are not always consistent from one measurement to the next and which are often in conflict with theoretical predictions. Furthermore, current and future experiments will have to contend with significant nuclear effects which modify the composition and spectra of the hadronic final state as well as the observed neutrino-scattering rate. Recently, there has been a new appreciation of the importance of accounting for nuclear effects in the reconstruction of the incoming neutrino energy and in the calculation of the difference between neutrino and anti-neutrino cross sections.

Much of the neutrino-scattering data on which phenomenological models are based are rather old and obtained using target materials not relevant for modern oscillation experiments. Taking advantage of new intense sources of neutrinos, modern experiments have begun to remeasure these neutrino interaction cross sections, most importantly on nuclear targets relevant to the neutrino oscillation program. Such measurements are performed using near detectors associated with long-baseline neutrino projects as well as small-scale dedicated neutrino-scattering experiments. While recent data have been instrumental in driving progress, they often raised more questions than they have been able to answer. It is clear that additional measurements are needed to complete our understanding of the few-GeV energy region and the nuclear physics at play. In particular, it has been noted that not all nuclear effects cancel in the comparison of the event rates at the far detector with those at the near detector in long-baseline experiments.

A well-considered program of precision neutrino-scattering experiments in both low- and high-energy regimes on a variety of nuclear targets for both neutrinos and anti-neutrinos is required, combined with a dedicated theoretical effort to develop a reliable, nuclear-physics-based description of neutrino interactions in nuclei that can

be used in neutrino oscillation fits. The first step in this programme will be to establish a clear set of goals for the precision with which $\bar{\nu}_\mu N$ and $\bar{\nu}_e N$ cross section need to be measured. In addition, precise measurements on hydrogen or deuterium targets and the study of electron-neutrino cross sections will be needed to provide further confidence in our ability to constrain this complex physics for our future neutrino-oscillation program.

Hadro-production Measurements

All current accelerator-based neutrino oscillation experiments use either an on- or off-axis neutrino beam produced from meson decays. The uncertainty in the normalisation and the spectral shape of the neutrino flux ultimately limits the precision of neutrino-oscillation and neutrino-interaction measurements. It is therefore important to develop an improved understanding of the details of the production mechanisms that give rise to conventional neutrino beams. To improve the knowledge of the neutrino flux it is necessary to determine meson production rates and the underlying meson momentum and angular distributions. Such hadro-production measurements can then be combined with detailed simulations of the optics of the neutrino beam line. Measurements have already been performed in support of the present generation of neutrino experiments yielding flux predictions with uncertainties of $\sim 10\%$. Advancing beyond this to support the future accelerator-based long-baseline neutrino-oscillation program will require hadro-production experiments pushing to achieve an uncertainty of $< 5\%$ on the neutrino flux. This will require pion-nucleus scattering as well as proton-nucleus scattering measurements in order that secondary interactions in the target can be simulated with confidence.

3.3   Required R&D programme

An extensive, coordinated R&D programme is essential to deliver the accelerator and detector techniques and systems required to support the future programme. The programme must encompass the development of:

- A new generation of high-power, pulsed proton sources;
- Intense neutrino sources based on stored muon beams;
- Neutrino detector system of unprecedented size and granularity;
- Magnet systems that can produce an adequate magnetic field over a large detector volume in the absence of iron; and
- Simulation tools which encapsulate the physics of neutrino-nucleus interactions and models of the detector response.

Accelerators and beams

Next generation experiments are based on megawatt-class proton sources. The intensity of such a source introduces many challenges in accelerator and particle-production-target technology arising from thermal shock, heating, and radioactivity. While beam powers of close to 1 MW will be realised in the current generation of experiments, multi-MW power will be a new regime. Non-destructive beam monitoring technologies that can operate in this harsh environment are needed. In addition to production targets and absorbers that can withstand the thermal shock, the heat load on components makes the cooling of the components challenging. These issues are further exacerbated by such processes as acidification of air and contamination of, and hydrogen production from, cooling water. Such processes give rise to corrosive and/or explosive components in the environment. The high-power environment creates new challenges related to the maintenance and interchange of highly active components such as targets and horns.

Developments to realise muon storage rings that would be the basis for neutrino factories can be divided into two categories. For nuSTORM, pre-construction R&D and prototyping is required on the pion-capture magnet, the large-aperture transport magnets and the muon-beam instrumentation. Further R&D is needed to deliver the high-power target and pion-capture channel, ionization-cooling system and high-gradient RF cavities that are required for the Neutrino Factory.

The Panel notes that the promotion of an internationally coordinated R&D programme would maximise the impact of the efforts of individual countries and regions.

Detectors

Future multi-kiloton to megaton-class far detectors have converged on two technologies: liquid-argon time-projection chambers (LAr) and water Cherenkov (WC) detectors.

LAr is the newer technique. Though kiloton-scale single-phase detectors have already been realised, further developments are required to prove the dual-phase approach and to construct multi-kiloton detectors using either the single- or dual-phase technique. A separate item is the magnetisation of a large volume detector that contains no iron. Magnetising a large LAr detector will allow powerful sign-selection and momentum-reconstruction techniques that can be applied to data from LAr detectors, enhancing the ongoing long-baseline efforts. This capability is also essential for the exploitation of neutrinos produced by stored-muon beams.

The WC technique has matured over several generations of detectors of increasing volume. Significant opportunities remain to enhance photo-sensor and readout technologies in order to optimise detector performance for a given cost. R&D is required to improve light-collection efficiency, to increase the effective photo-sensitive area and to develop new amplification technologies that will significantly reduce the per-channel cost. A new generation of large-area photo-sensors based on micro-channel plates is also emerging. Other potential enhancements include water-based scintillators that may give WC detectors new capabilities for detecting and reconstructing particles with momentum below the Cherenkov threshold.

For near detectors, a wider range of options and higher levels of granularity are possible due to the relatively small size of the near detectors. Higher granularity and lower tracking thresholds are in principle desirable to advance studies of neutrino interactions. Options include gaseous detectors such as high-pressure time-projection chambers and finely segmented scintillator-based tracking detectors. In most cases, magnetisation allows sign selection, momentum-measurement and particle-identification capabilities that are either beneficial or essential depending on the application.

Again, the Panel notes that an internationally coordinated R&D programme would maximise the impact of the efforts of individual countries and regions.

Software and computing

Along with the hardware development for LAr, a vigorous program to realise reconstruction algorithms that can fully exploit the information provided by these detectors is needed. While reconstruction algorithms have been developed in the context of existing and past WC detectors, there are opportunities to develop and improve these algorithms, particularly if new photo-sensor or optical elements are introduced.

Neutrino event generators, which simulate the final states produced by neutrino interactions, are another area where significant development is needed. The reliability and robustness of the underlying models used in these generators is critical for the projected physics sensitivities in the next generation experiments to be achieved. New measurements of neutrino interactions from the current and upcoming generation of experiments, along with commensurate developments and improvements in the relevant nuclear theory, will provide the foundations for these improvements.

Due to the broad range of expertise that will be required, which spans fields that are traditionally outside the realm of particle physics, and the fact that this expertise is widely distributed geographically, international coordination and cooperation are essential for success. The Panel plans to take an initiative to promote cooperation and to share best practice in the software and computing required for present and future experiments.

Regional strengths

Accelerator and beam developments relevant for the next generation of neutrino experiments are being pursued in Asia, Europe, and in the Americas, and particularly at CERN, FNAL and J-PARC, each of which hosts, or has recently hosted, neutrino oscillation experiments. Expertise that is critical to the success of the accelerator R&D programme can be found in many other laboratories (e.g. targetry at RAL, remote handling at RAL and TRIUMF, superconducting magnets at BNL and FNAL, etc.).

Likewise, LAr TPC developments are occurring in all three regions. At CERN, a large, single-phase, prototyping effort based on the successful ICARUS project is in progress in the context of WA104. The WA105 programme seeks to realise a large ($6 \times 6 \times 6$ m^3) dual-phase detector and to expose it to charged-particle beams. At FNAL, several neutrino-physics collaborations (MicroBooNE and LAr1ND) are building LAr detectors, while the CAPTAIN and LArIAT R&D activities are investigating the performance of LAr in test beams. Efforts are also under way in Japan.

For WC detectors, Japan has a strong track record building on the success of the Kamiokande and Super-Kamiokande experiments. Antarctic and sea-based experiments such as PINGU, ANTARES and KM3NET, which detect Cherenkov radiation in sea water or ice, have similar photo-sensor, readout, and calibration requirements that may offer opportunities for cooperation. In addition, significant WC expertise exists in North America from SNO, Super-Kamiokande, and the R&D programme for LBNE.

In all regions, experiences from past experiments using a wide variety of different technologies are an invaluable repository of knowledge and expertise that may be applied to the development of the next generation of neutrino beams and the near and far detectors. The Panel believes that the development of a mechanism by which this expertise can be coordinated is essential to maximise the cost-effectiveness of the R&D programme.

3.4   Required theory and phenomenology programmes

Better Monte Carlo (MC) simulation tools are required to allow systematic uncertainties related to the poor understanding of neutrino-nucleus-scattering and hadro-production cross sections to be reduced in line with the statistical power of the oscillation measurements. The generators cannot be more precise than the cross-section measurements on which they are based; i.e. currently with precision not better than $\sim 20\%$ in the neutrino-energy range of interest. Some limitations arise from the fact that basic parameters such as the nucleon-Δ excitation transition matrix elements are poorly known. Such uncertainties can only be reduced through a programme of measurements. The use of outdated theoretical models implemented in the generators is also a source of substantial uncertainty. As an example, the Fermi Gas (FG) model, which is known to not capture relevant physics in neutrino-nucleus interactions, is often used to describe the behaviour of nucleons because it is simple to implement. These sources of systematic uncertainty can only be improved with a thorough theoretical programme. Coordination is necessary to ensure that appropriate models of the basic physics are implemented consistently across the suite of simulation tools.

It has become clear that nucleon-nucleon correlations (neglected in the FG model) must be properly included. Much useful information can be obtained from ab initio computations of nucleon-nucleon effects for nuclei such as carbon and oxygen. Even though such computations are limited by their non-relativistic character, they

put severe constraints on the approximate models that are widely used. Another element of the present suite of simulation tools that requires substantial improvement are the models of the final-state interactions (FSI). Typically, these modules rely on simplified cascade approaches. Electron-scattering data, for which the lepton kinematics is precisely known, is a rich source of information that can be used to validate the cascade models since hadronic FSI effects are the same in both neutrino- and electron-nucleus scattering.

The study of neutrino–nucleon and neutrino–nucleus interactions benefits from a number of international networking activities including the "NuInt" workshop series and new initiatives such as the NuSTEC collaboration. The development of a vigorous phenomenological programme to combine the world's neutrino-oscillation data is also important.

The ultimate goal of the neutrino oscillation programme is to over-constrain the parameters of the standard three-flavor mixing model in order to test the SνM paradigm, which can only be achieved through the careful combination of data from several different sources. Once experimental uncertainties are no longer dominated by statistical errors, global fits that can take into account correlations between the systematic uncertainties will play a crucial role.

There are many connections between neutrino oscillations and observables in other areas of particle physics, particle astrophysics and cosmology. Further theoretical and phenomenological exploration of such correlations is important to develop a deeper understanding of fundamental physics. These connections strengthen the case for the pursuit of neutrino-oscillation experiments.

4   Towards figures of merit beyond the Standard Neutrino Model

When considering the development of the accelerator-based neutrino-oscillation programme beyond the present generation of experiments it is necessary to articulate clearly the goals of the programme and the figures of merit against which proposed contributions to the programme can be judged. The SνM postulates the existence of three neutrino-mass eigenstates, linear-combinations of which couple to the charged leptons and the W-boson as prescribed by the Standard Model. The same states also couple to one-another and to the Z-boson and, except for the feeble gravitational interactions, do not directly interact in any other way. This picture, while sufficient to explain almost all neutrino data, is yet to be tested experimentally in any non-trivial way. Large deviations from the three-flavour paradigm are allowed, for example:

- There may be more than three neutrino-mass eigenstates. Theoretically, the number of neutrino types need not be the same as the number of charged-lepton or quark flavours. New, sterile-neutrino degrees of freedom are allowed; the properties of these new states are constrained only very weakly by data. Sterile neutrinos can only be "observed" via their mixing with the active neutrinos and, if their masses are small enough, will only manifest themselves in neutrino-oscillation experiments. Broadly speaking, evidence for sterile neutrinos can be searched for in two ways:

    1. New mass eigenstates imply the existence of new mass-squared differences and hence new neutrino-oscillation lengths, the existence of which can only be probed in oscillation experiments. The short-baseline anomalies are often interpreted as evidence for new neutrino-oscillation lengths. An integral component of the neutrino-oscillation programme must therefore be to perform experiments to establish or refute the existence of these new oscillation lengths for amplitudes large enough to accommodate the short-baseline anomalies. The confirmation of the existence of more than two oscillation lengths would revolutionise particle physics and open up a new window for exploration of the neutrino sector.

        Even if it becomes clear that the short-baseline anomalies are not a consequence of new oscillation lengths, the hypothesis that there are light sterile-neutrinos remains intriguing. In the absence of any experimental hints, however, it is important to evaluate whether there are parts of the mass–

mixing parameter space which are theoretically preferred. For example, light sterile neutrinos may be a "side-effect" of the elusive mechanism behind the very light neutrino masses. If neutrinos are Majorana fermions and the new mostly sterile mass states are heavier than the mostly active ones, then it may be expected that the new mixing angles θ_{new} are related to the new masses M_{new}; $\theta_{\text{new}}^2 \sim m_{\text{light}}/M_{\text{new}}$, where m_{light} are the mostly-active-neutrino masses. This relation provides a concrete target for sterile-neutrino searches. Another example is the possible evidence for new "neutrino" states from cosmology, which is currently in a state of flux. If these are indeed neutrinos, their properties will be constrained by cosmological data (including, perhaps, some currently-unaccounted-for interactions) and searching for them in accelerator-based experiments will be of the utmost importance.

2. The neutrino-mixing matrix, as defined within the SνM, is unitary only if there are no new neutrino states. New neutrino states imply that the "correct" mixing matrix is larger than three-by-three, so any sub-matrix is not constrained to be unitary. If the new oscillation lengths are too short, the presence of new states can only be revealed indirectly via detailed unitarity tests, which require precision measurements of neutrino oscillations in a variety of channels, including both appearance and disappearance modes;

- Neutrinos may participate in new, "weaker-than-weak", interactions. New neutrino interactions of the neutral-current type will mediate, at leading order, non-standard matter effects. These can only be directly probed in long-baseline neutrino-oscillation experiments. Usually, complete models for non-standard neutrino–matter interactions are also constrained by other types of precision experiments and by searches for rare processes involving charged leptons. However, there are scenarios, at least at the "existence-proof" level, that can only be constrained by neutrino oscillations; and

- Neutrino propagation may deviate from standard expectations. Neutrino oscillations require the existence of a macroscopically-coherent source of neutrinos and rely heavily on the fact that neutrinos obey the dispersion relation of fundamental fermions expected by special relativity. For this reason, neutrino oscillations are very sensitive and quite unique probes of Lorentz invariance and allow for searches for new sources of quantum-mechanical decoherence from hypothetical "neutrino–vacuum" interactions. The tiny neutrino masses also translate into some very stringent tests of the CPT-theorem, including the prediction that fermions and anti-fermions have exactly the same mass.

Regardless of whether new degrees of freedom, interactions, or fundamental principles are revealed, neutrino oscillation experiments will provide very precise measurements of the neutrino mass-squared differences and the elements of the leptonic mixing matrix. Neutrino masses and mixing angles, in turn, are basic pieces of the long-standing flavour puzzle—where do the observed values of fermion masses and mixing angles "come from"? There are many models and ideas proposed and discussed at length in the literature but we are far from a satisfactory answer to this question.

In the context of the Panel's initial report, it is more instructive to identify specific targets for the measurement-precision required of the future programme. While there are no unambiguous answers, a couple of options that can serve as "robust" targets, more or less independent of the would-be flavour model, have been identified:

- Predictions from flavour models often translate into algebraic relations among the different mixing parameters (e.g. $\theta_{23} = \pi/4 + \sqrt{2}\theta_{13}\cos\delta$). In order for these relations to be tested robustly, the precision of the different components of the relation should be known with similar precision. The smallest known mixing angle, θ_{13}, is of order a few percent, indicating that, in order to test different relations among mixing angles and the CP phase, δ, it is important to measure all mixing angles with a precision comparable to the precision with which θ_{13} will be known; and

- Some flavour models relate mixing angles, or their deviations from special values, to small parameters in the theory. In the neutrino sector there are a few small parameters, including $\sin^2\theta_{13}$, $\cos 2\theta_{23}$ and

the ratio of the mass-squared differences ($\Delta m_{21}^2 / \Delta m_{31}^2$). The ratio of the mass-squared differences, for example, provides successive targets for precision: $\sqrt{\Delta m_{21}^2 / |\Delta m_{31}^2|} \sim 17\%$; $\Delta m_{21}^2 / |\Delta m_{31}^2| \sim 3\%$; and $(\Delta m_{21}^2 / \Delta m_{31}^2)^2 \sim 0.1\%$.

Detailed exploration of the neutrino sector, combined with searches for new degrees of freedom at the LHC, the search for rare or forbidden processes and the precision measurement of the global properties of the Universe, to name a few, along with the necessary theoretical work to "tie" everything together, will all be required to construct a more satisfactory description of Nature at the smallest distance scales. Regardless of the nature of the new physics, accelerator-based neutrino-oscillation experiments will play a unique and fundamental role.

5 Opportunities

To carry out the ambitious experimental programme by which all of the properties of the neutrino are determined will require coordinated investment in the necessary facilities; including long- and short-baseline oscillation experiments and the infrastructures necessary to determine, with the requisite precision, neutrino flux and neutrino-nucleus scattering cross sections.

5.1 The approved program

The long-baseline oscillation programme is being taken forward by the T2K experiment in Japan and by the MINOS+ and NOνA experiments in the US. Over the next three years, MINOS+ will collect a data sample ~ 60 times that of MINOS with a neutrino-energy spectrum peaked between $4\,\mathrm{GeV}$ and $10\,\mathrm{GeV}$. The large event rate and the relatively broad energy spectrum will allow MINOS+ to search for evidence of oscillation phenomena not described by the SνM. T2K and NOνA exploit the kinematics of pion decay to obtain a narrow-band neutrino beam tuned to the separation between the source and the far detector. In the case of T2K, the beam energy is matched to the 295 km distance between J-PARC and the $22.5\,\mathrm{kT}$ fiducial mass Super-Kamiokande water Cherenkov detector. T2K has recently observed electron-neutrino appearance in a conventional muon-neutrino beam. Data taking over the next five to seven years will allow θ_{23} to be determined with a precision of $\sim 2\%$. The direct comparison of the T2K measurement with the θ_{13} determined through the reactor-neutrino $\bar{\nu}_e$ disappearance measurement will allow a first search for CPiV to be made with a sensitivity at the $\sim 1\sigma$ level for $-150^\circ \lesssim \delta \lesssim -30^\circ$. NO$\nu$A is a $14\,\mathrm{kT}$ liquid-scintillator detector placed at a distance of 810 km from FNAL and is illuminated with the NuMI beam. The comparatively long baseline gives NOνA sensitivity to the mass hierarchy. With an exposure of six years in neutrino and anti-neutrino modes, NOνA will be able to determine, at the 2σ level, that $\Delta m_{31}^2 \lesssim 0$ if $-150^\circ \lesssim \delta \lesssim -10^\circ$ or that $\Delta m_{31}^2 > 0$ if $20^\circ \lesssim \delta \lesssim 140^\circ$.

Neutrino fluxes are estimated using simulations that exploit parameterisations of the spectra of hadrons produced in pion- or proton-nucleus interactions. Following on from the HARP experiment at CERN and the MIPP experiment at FNAL, the NA61/SHINE experiment at CERN will provide measurements in the kinematic range of interest to the present generation of long-baseline oscillation experiments. The goal is to allow the absolute flux of the J-PARC neutrino beam to be estimated with a precision of $\approx 5\%$ and the ratio of the flux at the near and far detectors to be estimated at the $\approx 3\%$ level. Neutrino-nucleus scattering measurements are being made by the cross-section dedicated ArgoNeut and MINERvA experiments as well as by the oscillation experiments MINOS(+), MiniBooNE, NOνA, SciBooNE, T2K (ND280) and, in the near future, MicroBooNE. Single- and double-differential $\nu_\mu N$ ($\bar{\nu}_\mu N$) cross-section measurements with statistical and systematic uncertainties at the 10% to 30% level will be provided. By exploiting the small electron-neutrino contribution to the conventional-beam flux, the present generation of experiments will be able to determine single-differential $\nu_e N$ ($\bar{\nu}_e N$) cross sections at the 20% to 50% level over a limited range of the parameter space.

The short-baseline accelerator-based neutrino program is focused on elucidating the nature of the anomalies observed by the LSND and MiniBooNE experiments. These anomalies consist of the original evidence for $\bar{\nu}_\mu \to \bar{\nu}_e$ transitions from the LSND experiment, supported by the equivalent measurements of MiniBooNE, and an excess of ν_e-like interactions at low energies observed in the MiniBooNE experiment. The origins of these anomalies need to be understood. A new experiment, MicroBooNE, will begin taking data with a 170 Tonne liquid Argon TPC at the Fermilab Booster Neutrino Beam later this year. MicroBooNE will either confirm or exclude the excess of low-energy ν_e-like events seen by MiniBooNE and will be able to tell if these anomalous events are really ν_e interactions or some other unexpected type of events producing energetic photons. Within the coming four or five years these results are expected to guide our interpretation of the anomalous MiniBooNE low-energy events but are not expected to directly address the LSND anomaly.

5.2 Experimental opportunities: near-future

To step beyond the approved programme requires the unambiguous determination of the mass hierarchy and a first attempt to observe CPiV.

The Long Baseline Neutrino Experiment (LBNE) will measure ν_e ($\bar{\nu}_e$) appearance in a ν_μ ($\bar{\nu}_\mu$) beam using a 35 kT liquid-argon time-projection chamber. The neutrino beam from FNAL which will illuminate the detector will span a wide range of neutrino energies (a wide-band beam). The mean of the neutrino-energy distribution matches the baseline of 1300 km. For an exposure of ten years LBNE has sensitivity to the mass hierarchy at the $\sim 5 - 6\sigma$ level over the full CPiV parameter space. The same exposure will allow the energy spectrum of the ν_e-appearance signal to be investigated giving sensitivity to CPiV at the $\sim 3.5\sigma$ level over 50% of the CPiV parameter space. LBNE is being considered within the US Critical Decision (CD) process and has received CD0 and CD1 approval. A budget line for an investment of $867M in the LBNE programme from the DOE has been identified. To deliver the full science programme requires that additional, non-US partners join the effort. The Panel recognises that the LBNE collaboration and the FNAL management are in the process of negotiating non-US contributions to the programme and welcomes the recent positive developments in expanding the consortium.

The Tokai to Hyper-Kamiokande (Hyper-K) experiment will study ν_e ($\bar{\nu}_e$) appearance in a ν_μ ($\bar{\nu}_\mu$) beam using a water Cherenkov detector with a fiducial mass of 560 kT. Hyper-K will be illuminated by the J-PARC neutrino beam at a baseline of 295 km. Assuming that either the mass hierarchy is known or that it will be determined using its atmospheric-neutrino data, Hyper-K has sensitivity to CPiV at the 3σ level over 76% of all possible values of δ. Hyper-K has been identified as one of the high priority projects on the MEXT road-map. The necessary pre-construction R&D programme is underway. The Science Council of Japan has identified a planning line at the level of ¥80B for the far detector and ¥3B for a near detector system.

FNAL has articulated upgrade plans by which the proton-beam power serving the long-baseline programme will be increased to 1.2 MW and ideas to realize multi-MW beams at J-PARC are being discussed. In addition, the LBNE and Hyper-K collaborations are planning large detectors with large fiducial mass with the goal of bringing the statistical uncertainty of the oscillation measurement down to the per-cent level.

So, for the future long-baseline programme to realise its potential, the systematic uncertainties related to neutrino flux and neutrino-nucleus scattering cross sections must be reduced such that they are always commensurate with the statistical uncertainties. Since the signal for the headline measurements outlined above is the appearance of ν_e ($\bar{\nu}_e$), the accurate determination of the $\nu_e N$ ($\bar{\nu}_e N$) cross sections over the kinematic range of interest will become a priority.

Design studies for alternative facilities are also underway. The LAGUNA-LBNO consortium is carrying out a design study of the Long Baseline Neutrino Observatory (LBNO) which would illuminate a suite of detectors in a mine in Finland with a conventional, wide-band beam from CERN. The baseline of 2300 km would allow

the experiment to determine the mass hierarchy at the 5σ level for all values of δ in a few years of running. The wide-band beam would allow LBNO to study the neutrino energy spectrum in order to search for CPiV with a sensitivity at the level of 3σ over $\sim 55\%$ of the CPiV parameter space assuming a ten-year exposure of a $20\,\mathrm{kT}$ LAr detector with the nominal SPS beam power of $750\,\mathrm{kW}$. A number of other design studies are also under way. The "Cherenkov Detector in Mine Pits" (CHIPS) projects would instrument the water collected in disued mine pits which are in the path of the NuMI or LBNE neutrino beams. Results that are competitive with the combined T2K/NOνA sensitivity to δ can be obtained with six years of running. It has been proposed to provide a beam from the European Spallation Source (ESS) to illuminate a large water Cherenkov detector placed at the second oscillation maximum. The "ESSnuSB" experiment will benefit from the fact that the rate of events at the second oscillation maximum depends strongly on δ. Finally, it has been proposed to exploit the δ-dependence of the oscillation as a function of baseline length (L) by illuminating a single large detector with neutrinos produced by muon decay at rest (the "Daedalus" experiment). The concept calls for three, high-power cyclotrons placed at distances of $1.5\,\mathrm{km}$, $8\,\mathrm{km}$ and $20\,\mathrm{km}$ from the detector.

Turning to the short-baseline programme, there is general agreement that a new and as-yet-to-be-approved experiment is needed finally to resolve the origin of the LSND anomaly and that the new initiative should be designed to be definitive. Several candidate experiments have been proposed in Europe and in the US. The present accelerator-based proposals include using liquid argon TPCs at two or more baselines at either Fermilab or CERN; mounting an improved LSND-like experiment at ORNL; or building a dedicated low energy muon-decay ring with straight sections pointing at a Neutrino-Factory type detector (nuSTORM). Although the scope of these proposed initiatives could in principle be accommodated within a regional budget, the interest in doing the right experiment is international. The choice and execution of the next generation short-baseline experiment(s) would therefore seem fertile ground for fully international cooperation.

The contributions to the systematic uncertainties may be broken down into three broad classes. There are uncertainties relating to the particular detector configuration; these uncertainties must be addressed by each collaboration individually. Then, there are uncertainties relating to the estimation of the neutrino flux and uncertainties relating to the neutrino-nucleus-scattering cross sections. To manage the systematic uncertainties related to the flux it will be necessary to consider the hadro-production measurement programme that may be required to follow on from the NA61/SHINE experiment. Precise knowledge of the neutrino-nucleus-scattering cross sections and final-state spectra are required for the reactor, atmospheric, solar and cosmological neutrino programmes as well as the accelerator-based programme; the measurement of the cross sections is therefore an important service that the present and future accelerator-based neutrino-physics programme must provide. Neutrino detectors exploit water, liquid argon, liquid scintillator or iron as the material in which neutrinos are captured. To develop an understanding of the cross-section phenomenology sufficient to allow extrapolation using Monte Carlo techniques is likely to require the measurement of neutrino scattering on additional materials. The measurement of $\nu_e N$ ($\bar{\nu}_e N$) cross sections with the requisite per-cent-level precision will require the development of a novel neutrino source such as that proposed for nuSTORM. The development of an appropriate, systematic study of neutrino-nucleus scattering measurements will become of increasing importance to the field.

5.3   New experimental opportunities: long-term

The objectives of the neutrino programme identified in section 1 are:
  1. To determine the properties of the neutrino that are presently unknown;
  2. To determine whether the SνM picture is the whole story; and
  3. To measure the properties of the neutrinos with a precision sufficient to allow the physics that explains these properties to be understood.

The next generation of experiments will improve the precision with which the mixing angles and mass-squared differences are known and determine the mass hierarchy. With $\delta \in [-180, 180°]$, if $|\delta| \lesssim 25°$ ($|\delta| \gtrsim 155°$) a new and novel technique will be required to continue the search for CPiV. In any event, a new technique will be required to test the SνM and to determine the neutrino-mixing parameters with a precision sufficient to allow the underlying physics to be elucidated. The Panel therefore concludes that a programme of accelerator and detector R&D is needed to deliver the technologies required to drive the field beyond the sensitivity and precision offered by the next generation of experiments.

The Neutrino Factory, in which intense beams of electron- and muon-neutrinos are produced from the decay of stored muon beams, has been shown to offer the ultimate sensitivity to CPiV and precision on δ. The charge-to-mass ratio of the muon makes it possible to tune the stored-muon-beam energy to provide a neutrino beam matched to a particular choice of baseline, detector technology or to respond to changes in the understanding of the physics of neutrino oscillations. The incremental development of the Neutrino Factory has been studied by both the International Design Study for the Neutrino Factory (the IDS-NF) and within the US Muon Accelerator Program (MAP) by the Muon Accelerator Staging Study (MASS). Each of these studies has identified a staged implementation of the Neutrino Factory in which each step is capable of delivering first rate neutrino-physics and of supporting the R&D necessary to prepare the next step in the incremental programme. The first step in the programme is nuSTORM in which a stored muon beam with a central momentum of $3.8\,\text{GeV}/c$ and a momentum spread of 10% will:

- Deliver detailed and precise studies of electron- and muon-neutrino-nucleus scattering over the energy range required by the future long- and short-baseline neutrino oscillation programme;
- Make exquisitely sensitive searches for sterile neutrinos in both appearance and disappearance modes; and
- Provide the technology test-bed required to carry-out the R&D critical to the implementation of the next increment in the muon-accelerator based particle-physics programme.

The development of the nuSTORM ring, together with the instrumentation required for the νN-scattering and sterile-neutrino-search programmes will allow the next step in the development of muon accelerators for particle physics to be defined. Just as the Cambridge Electron Accelerator, built by Harvard and MIT at the end of the '50s, was the first in a series of electron synchrotrons that culminated in LEP, nuSTORM has the potential to establish a new technique for particle physics that can be developed to deliver the high-energy ν_e ($\bar{\nu}_e$) beams required to elucidate the physics of flavour at the Neutrino Factory. The development of muon accelerators for particle physics clearly requires international collaboration.

6 Initial conclusions and next steps

6.1 Initial conclusions

Following its initial consultations with the accelerator-based neutrino-oscillation community at the three regional Town Meetings, the Panel has drawn the following conclusions:

0. The study of the neutrino is the study of new phenomena that are not described by the Standard Model. Accelerator-based neutrino-oscillation experiments are an essential part of the neutrino-physics programme and offer exciting and unique insights into the physics of fundamental particles. The results of the accelerator-based experiments will have important consequences for particle astrophysics and cosmology. This breadth of impact justifies a far-reaching experimental programme;

1. The accelerator-based programme is vibrant and is international in both intellectual interest, engagement and in scope;

2. The optimal exploitation of the present and approved experiments will benefit from increased cooperation in the development of better models for neutrino-event generators, event-reconstruction algorithms for large-volume liquid-argon time-projection chambers and frameworks for the robust combination of results from different experiments;

3. LBNE and Hyper-K offer complementary approaches to the search for CPiV. The Panel welcomes the positive developments in the LBNE and Hyper-K approval processes. A dedicated, coordinated programme of measurement is required to ensure that systematic uncertainties are commensurate with the statistical power of these experiments;

4. Design studies are underway for conventional wide-band beams (LAGUNA-LBNO, which will report in 2014) and ESSnuSB. Potentially, these proposals offer attractive alternatives to LBNE and Hyper-K. In addition, the design of a novel experiment (Daedalus) to search for CPiV using neutrinos generated by muon decay at rest is being studied;

5. The Neutrino Factory in which intense electron- and muon-neutrino beams are generated from the decay of muons confined within a storage ring remains the facility that offers the best sensitivity. The incremental, or staged, implementation of the facility is being studied. The Panel recognises nuSTORM as an attractive first step;

6. The anomalies in neutrino-oscillation measurements that can be interpreted as evidence for "sterile" neutrinos are being investigated energetically through a programme of short-baseline experiments. The short-baseline programme required to resolve these anomalies convincingly must be developed such that it also benefits the long-baseline programme.

6.2 Next steps

To optimise the discovery potential of the future oscillation programme, thereby maximising the scientific return on investment, requires that the international neutrino community has timely access to a number of complementary, powerful neutrino-beam facilities. For the programme to reach its full potential requires that the "headline programme" be supported by a programme of measurement by which the systematic uncertainties can be made commensurate with the statistical power of the oscillation experiments. To ensure timely access to the necessary facilities it will be necessary to exploit to the full the infrastructures that exist at CERN, J-PARC and FNAL such that each region makes a unique and critically-important contribution to the programme. To maximise the impact on the programme of the expertise, experience, resources and infrastructure that exists in laboratories and institutes worldwide requires active coordination. Therefore, in its second year the Panel will consult with laboratory Directors, funding-agency representatives, the accelerator-based neutrino-oscillation community and other stakeholders to:

- Develop a road-map for the future accelerator-based neutrino-oscillation programme that exploits the ambitions articulated at CERN, FNAL and J-PARC and includes the programme of measurement and test-beam exposure that will ensure the programme is able to realise its potential;
- Develop a proposal for a coordinated "Neutrino RD" programme, the accelerator and detector R&D programme required to underpin the next generation of experiments; and
- To explore the opportunities for the international collaboration necessary to realise the Neutrino Factory.

The Panel's vision is that, taken together, the road-map and Neutrino RD programme will form the basis of the "International Neutrino Programme" (IνP) necessary to deliver the measurements required for the phenomena that explain neutrino oscillations to be discovered.

The Panel will exploit the XXVI International Conference on Neutrino Physics and Astrophysics which will take place in Boston in June 2014 to:

- Initiate a discussion amongst the international accelerator-based neutrino-oscillation community on its emerging vision for an International Neutrino Programme; and
- Launch a workshop, or a number of workshops, to promote cooperation on the topics noted in item 2 section 6.1.

References

[1] **Particle Data Group** Collaboration, J. Beringer *et al.*, "Review of Particle Physics (RPP)," *Phys.Rev.* **D86** (2012) 010001.

[2] The International Committee on Future Accelerators, "ICFA Neutrino Panel." http://www.fnal.gov/directorate/icfa/neutrino_panel.html, 2013.

[3] The International Committee on Future Accelerators, "ICFA Neutrino Panel: terms of reference." http://www.fnal.gov/directorate/icfa/files/Terms-Of-Reference.pdf, 2013.

[4] The ICFA Neutrino Panel, "ICFA Neutrino Panel." http://www.fnal.gov/directorate/icfa/.

A The ICFA Neutrino Panel

ICFA established the Neutrino Panel with the mandate [2]:

To promote international cooperation in the development of the accelerator-based neutrino-oscillation program and to promote international collaboration in the development a neutrino factory as a future intense source of neutrinos for particle physics experiments.

The membership of the Panel agreed by ICFA at its meeting in February 2013 is shown in table 2. The terms of reference for the panel [3] may be found on the Panel's WWW site [4].

Table 2: Membership of the ICFA Neutrino Panel.

Name	Institution
J. Cao	IHEP/Beijing
A. de Gouvêa	Northwestern University
D. Duchesneau	CNRS/IN2P3
R. Funchal	University of Sao Paulo
S. Geer	Fermi National Laboratory
S.B. Kim	Seoul National University
T. Kobayashi	KEK
K. Long (chair)	Imperial College London and STFC
M. Maltoni	Universidad Automata Madrid
M. Mezzetto	University of Padova
N. Mondal	Tata Institute for Fundamental Resarch
M. Shiozawa	Tokyo University
J. Sobczyk	Wroclaw University
H. A. Tanaka	University of British Columbia and IPP
M. Wascko	Imperial College London
G. Zeller	Fermi National Accelerator Laboratory

B   Reports on Regional Town Meetings

B.1   Asia

The Asian neutrino community meeting took place in the afternoon of November 13, 2013 on the last day of the NNN13 workshop at Kavli IPMU in Kashiwa city, Chiba, JAPAN. This meeting was organized by the Asian panel members (J. Cao, S.B. Kim, T. Kobayasi, N. Mondal, and M. Shiozawa) to collect input from the neutrino community in Asia and to receive reports from regional planning efforts. There were approximately 40 participants and the meeting program and presentation files have been made available on the web at: http://indico.ipmu.jp/indico/getFile.py/access?contribId=8&resId=0&materialId=slides&confId=26 . The meeting consisted of an introductory talk, a theoretical presentation on neutrino physics, and a series of talks about the status and planning of neutrino experiments in China, India, Japan, and Korea with an emphasis on international accelerator-based neutrino oscillation experiments. Following these talks there was an open discussion among the meeting participants. Opinions were solicited through the web page in advance to collect broad inputs to the meeting and this discussion.

Presentation Summary

- **Introduction** by Takashi Kobayashi (KEK)
  An introduction to the ICFA neutrino panel, including its objectives, charges and procedures, was given and the goals of the town meeting were explained. It was noted that the panel would like to carry out a review of:

  (a) The present status of the neutrino oscillation program within Asia and the developments that can be expected on a 4-to-7-year timescale;

  (b) The discovery opportunities for which the accelerator-based neutrino oscillation program must be optimized over a 7-to-25-year timescale; and

  (c) The measurements and R&D (including software development) that are required for the near-term (4-to-7-year) and medium- to long-term (7-to-25-year) program in order to fulfill that potential.

- **Why Neutrinos?** by Hitoshi Murayama (Berkeley & Kavli IPMU)
  Although the theory of the strong, weak, and electromagnetic forces appears to be complete after the discovery of the Higgs boson, there are still many unanswered questions in particle physics. There are at least five missing pieces in the standard model: non-baryonic dark matter, the lightness of the neutrino masses, dark energy, acausal density fluctuations in the early universe, and a mechanism to generate the baryon asymmetry in the universe. In this context, neutrino and nucleon decay experiments are unique probes of high energy (up to $O(10^{16})$ GeV) physics beyond the standard model. In order to explain the observed baryon asymmetry of the universe, for instance, new sources of CP violation, like CP violation in neutrinos, are needed. Similarly, proton decay searches may shed light on the manner in which particles convert to anti-particles, another piece of information essential to understand how the baryon asymmetry evolved in the history of our universe.

- **Neutrino Program in China** by Jingyu Tang (Institute of High Energy Physics, CAS)
  The Daya Bay experiment is now running and aims to achieve a 3% measurement of $\sin^2 \theta_{13}$ by accumulating data over the next four to five years. Its successor, JUNO, is a next-generation liquid scintillator detector whose primary physics target is the determination of the neutrino mass hierarchy using reactor antineutrinos over a $\sim$ 50 km baseline. It is also expected to measure Δm_{21}^2, Δm_{32}^2, and $\sin^2 \theta_{12}$ at the 1% level or better. High-precision measurements of supernova neutrinos, geo-neutrinos, and solar neutrinos are also anticipated. Additionally, the possibility of a CP measurement with a new neutrino beam facility based on muon decay, MOMENT, is under discussion.

- **Neutrino Program in India** by Sanjib Kumar Agarwalla (Bhubaneswar)
  Though the headline experiment of the India-Based Neutrino Observatory (INO) will be the ICAL neutrino detector, underground laboratories for double beta decay and direct dark matter detection experiments are available as well. ICAL will primarily study atmospheric neutrinos and is expected to have 2.5σ sensitivity to the mass hierarchy by itself and 3.4σ sensitivity in combination with T2K, NOνA, and reactor experiments. Further improvements in the ICAL event reconstruction lead to enhanced sensitivity of 3σ. It was also noted that many Indian institutions are involved in the FNAL neutrino program, including the MIPP, MINOS+, NOνA, and LBNE experiments.

- **Neutrino Program in Korea** by Kyung Kwang Joo (Chonnam National University)
  The short-baseline reactor neutrino experiment, RENO, is expected to improve its precision on its measurement of $\sin^2\theta_{13}$ to $\sim 5\%$ over the next five years. A longer baseline (~ 50 km) reactor experiment, RENO-50, is being pursued to perform high-precision measurements of Δm_{21}^2, Δm_{32}^2, and $\sin^2\theta_{12}$, and to determine the mass hierarchy. RENO-50 will also be capable of observing neutrinos from supernova, the Earth's interior, the sun, and J-PARC. Though a search for neutrinoless double beta decay is also within the scope of the detector, a dedicated double beta decay experiment, AMoRE, is being planned for a ten year run. Construction of a short-baseline neutrino oscillation experiment to study the reactor neutrino anomaly is also underway.

- **Neutrino Program in Japan** by Tsuyoshi Nakaya (Kyoto)
  With its approved 7.8×10^{21} POT, T2K by itself has a chance to exclude $\sin\delta = 0$ with an expected significance of $\sim 2\sigma$ if, as its latest data suggest, $\sin\delta = -1$. In that scenario the mass hierarchy could also be determined by the combination of measurements at T2K and NOνA. Additionally, the precision on its measurement of $\sin^2\theta_{23}$ will be 0.045 (2.6°) assuming $\sin^2\theta_{23} = 0.5$. High statistics studies of atmospheric neutrinos at Super-K will have $\sim 2\sigma$ mass hierarchy determination power and $\sim 2\sigma$ sensitivity to the θ_{23} octant if $\sin^2\theta_{23} = 0.6$. Sterile neutrino searches at KamLAND and the J-PARC/MLF (P56) are also in preparation.

  On a timescale of ~ 25 years the next-generation underground water Cherenkov detector, Hyper-Kamiokande (Hyper-K), is being proposed both to serve as the far detector for a long-baseline neutrino oscillation experiment using an upgraded J-PARC neutrino beam and as a detector capable of observing proton decay, atmospheric neutrinos, and astrophysical neutrinos. Hyper-K is expected to measure the CP phase with $10 - 20°$ precision and can establish CP violation with $> 3\sigma$ significance for 74% of the δ parameter space. The significance of the mass hierarchy determination is expected to reach 3σ or more using high statistics data from the J-PARC neutrino beam and atmospheric neutrinos. Additionally, if $\sin^2 2\theta_{23} < 0.995$, the θ_{23} octant can be resolved at $> 2\sigma$. Owing to its factor of 25 increase in fiducial volume, Hyper-K has sensitivity to nucleon decays exceeding what has been achieved at Super-K by an order of magnitude or more. Finally, discussions are underway within the community concerning ideas for new facilities to achieve a multi-MW neutrino beam, for the development of advanced neutrino detectors such as a large scale liquid Argon TPC, and for upgrades to KamLAND that will extend its sensitivity to $0\nu\beta\beta$ decay into the inverted hierarchy region and beyond.

Discussion Summary

Figure 1 summarizes a conceptual timeline of both running and planned experiments with (optimistic) estimates of expected measurement sensitivities. T2K is now entering an era of CP violation studies, which will be significantly expanded at Hyper-K with the upgraded J-PARC neutrino beam. Indeed, Hyper-K's test of CP violation in neutrinos represents a significant opportunity for discovery over the next 7-to-25-years. The effects of matter on neutrino oscillations mimicing CP violation are relatively small for ~ 600 MeV neutrinos from J-PARC over the 300 km Hyper-K baseline. Using well established water Cherenkov technology Hyper-

K consequently offers an experimentally clean and promising way to approach the question of neutrino CP violation. Moreover, this technology is the only known realistic detector option that can probe proton lifetimes of the order of 10^{35} years. High statistics measurements of atmospheric neutrinos at Hyper-K and ICAL, as well as measurements of reactor neutrinos over moderate baselines at JUNO and RENO-50, each have the potential to determine the mass hierarchy with $> 3\sigma$ significance. These measurements, in conjunction with high precision measurements of the neutrino mixing and mass parameters by these projects, highlight the strength and versatility of the neutrino program in Asia.

In order to achieve these goals, several essential R&D studies were discussed at the meeting. Improvements on the neutrino detection technology are necessary in the following areas: the development of fast, high quantum efficiency photo-sensors and gadolinium loading technology for large water Cherenkov detectors, the development of advanced liquid scintillators for scintillator experiments, and the development of other advanced detector technologies such as the liquid argon TPC. To achieve a high intensity neutrino beam, upgrades to the J-PARC beamline to allow for 750 kW and multi-MW operation must be developed and as a part of that program research into high power targetry is needed. Additionally, both the development of a 15 MW proton driver and advances in muon transportation are essential for the success of the MOMENT concept. Central to all upcoming measurements is the reduction of systematic errors and accordingly, improved hadron production and cross section measurements are critical.

Finally, all participants agreed that the Asian program can be successful and strengthened by the mutual support and participation.
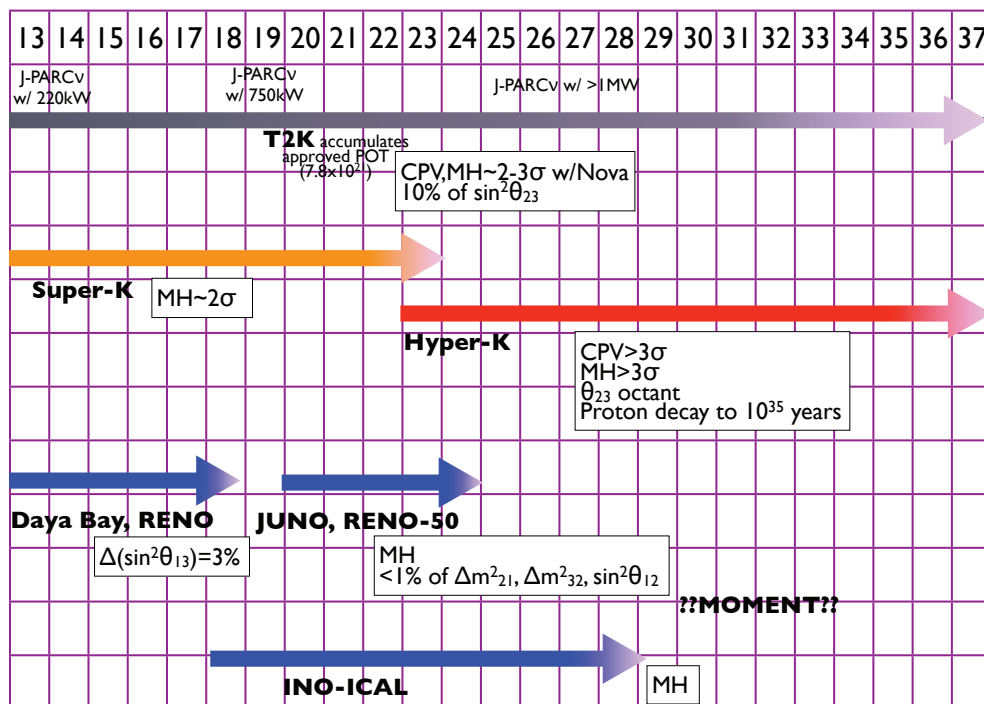

Figure 1: Working timeline of neutrino oscillation experiments in Asia and their expected sensitivities.

B.2 The Americas

The ICFA Neutrino Panel held a two-day Americas Town Meeting at Fermilab, 23–24 January 2014. The meeting was well attended with approximately 90 participants from the experimental and theoretical neutrino communities, and with representatives from the U.S., Canada, Mexico, and South America. There were also a few participants from Asia and Europe. The meeting agenda included 25 talks that explored the themes:

1. Present issues;
2. Regional study summaries and perspectives from the Americas;
3. International collaboration: experience from present experiments;
4. Opportunities for international collaboration.

In addition, there were three round table discussions that were moderated by distinguished members from the neutrino community. The round tables explored the questions:

1. What coordination is necessary for planning the short-baseline neutrino program?
2. How to increase collaboration across the Americas?
3. What do we need to do to further promote the long-baseline science case?

Discussion was encouraged throughout the meeting. The discussion associated with the presentations, together with the presentations themselves, and the round table discussions, revealed a great deal of consensus within the community about directions and priorities for the global neutrino program, as well as many suggestions for areas where increased global coordination might be fruitful.

B.2.1 General consensus

1. The presently running, or soon-to-be running, accelerator-based neutrino oscillation experiments will advance our knowledge of the properties of the neutrino by further constraining (or measuring) the θ_{23} octant, the mass hierarchy, and the CP phase /delta, and may also begin to elucidate the nature of the excess of the MiniBooNE low-energy neutrino events.

2. Beyond the present experiments, the highest priority for the future accelerator-based neutrino program is a new massive deep-underground long-baseline experiment. The candidate experiments are LBNE, LBNO, and Hyper-K. There has been significant recent progress in exploring the possibility of merging the LBNE and LBNO Collaborations. A new long-baseline possibility using the future European Spallation Source is also being explored.

3. One or more new accelerator-based short-baseline experiments are needed if we want to conclusively resolve the origin of the LSND and MiniBooNE anomalies. The new experiment(s) should be designed to be definitive.

4. New experiments to measure hadroproduction and neutrino and antineutrino cross-sections may be needed to enable the next generation of neutrino oscillation experiments to achieve their full potential. This deserves further consideration.

B.2.2 Increased global coordination

The discussions generated a number of suggestions for areas which might benefit from increased international and/or global coordination. The following is an unfiltered list:

- Support for a CTEQ-like group to develop a global understanding of neutrino cross-section measurements and the associated tools needed for Monte Carlo event generators;

- A forum, meeting series, or other mechanism by which laboratories can disclose and discuss their capabilities in the context of future neutrino projects and R&D;
- The organization of neutrino workshops and schools in Latin America;
- Early planning of new neutrino beam facilities, leading to a more global approach to constructing new facilities and R&D for subsequent upgrades (LARP-like R&D activities);
- Support for a globally coordinated CERN RD-like neutrino detector R&D program;
- Support for an international/global effort on liquid argon neutrino event-reconstruction;
- Planning the program of hadroproduction and neutrino cross-section experiments needed to fully exploit future long-baseline experiments; and
- R&D on targetry and horns.

B.3 Europe

The meeting took place from January 8th to 10th 2014 in Paris at the University of Paris Diderot.

The number of participants was 100.

The link to the web site is:

http://www.apc.univ-paris7.fr/APC/Conferences/ICFA_Neutrino_European_Meeting_2014/Home.html

B.3.1 Neutrino facilities discussed at the meeting:

ESSnuSB: (contribution to Snowmass white paper Sept. 2013)

The project Concentrates on second oscillation maximum with low neutrino energy around 0.5 GeV. When coupled to a 440 kton WC detector (Memphys) in a mine at 540 km it gives a competitive CP violation search potential. The proton beam power is about a factor 5-6 higher than any other planned proton driver for a neutrino beam. Following the ESS schedule, the proton beam will be ready in 2019-2022

A ESSnuSB Design Study will be prepared and submitted to EU (HORIZON2020) in September 2014.

NuStorm: (EOI at CERN May 2013 and proposal to Fermilab July 2013)

It is a muon based neutrino beam project with nue and numubar of about 2.5-3 GeV. This project can add significantly to our knowledge of neutrino interactions and cross sections, particularly for nue, since it can provide neutrino beams with fluxes known to <1%.

It offers good capabilities for study of sterile neutrinos with an accelerator beam with high sensitivity. A workforce is setup for nuSTORM to join CENF (CERN neutrino platform activity). The detector technology can profit for the foreseen R&D activities in this framework.

They seek to establish a 2-year programme to deliver a Technical Design Report (2016?).

The timescale of this facility is not well defined but the major R&D required and the accelerator modification (new proton driver) would suggest a realisation beyond 2020.

LBNO and CN2PY: (EOI at CERN June 2012, Laguna-LBNO FP7 Design study since 2011)

This is the Long Baseline 2300 km from CERN to Finland (Pyhasalmi) with a 700 kW neutrino beam of 1-10 GeV.

In a first stahe, a 20 kton Liquid Argon double phase detector is foreseen (run both nu and anti-nu for10-12 years) followed by a 70 kton in the second stage.

They claim to be the only facility to guarantee a mass hierarchy determination at 5 sigma level after few years running

LBNO has complementarity to HK by providing MH and measuring CP in a different way using L/E and the 2nd oscillation maximum

The European design study nearing completion should provide a very detailed costing by June 2014. Technical and engineering study work is done is a very serious and detailed way.

An R&D program is developed around the CERN neutrino platform for the double phase LAr TP: WA105=> goal is to build a large scale prototype from 2014 to 2016 and take data in 2017

The funding status of the experiment was not discussed in the meeting however the full costing of the project is expected in June.

The situation concerning the Finnish government's interest in the project was not reviewed during the meeting. It is, however, important to note that this issue would require additional discussion when the Laguna-LBNO project delivers a report with the full cost estimate.

B.3.2   European involvements in LBNE and HyperK:

LBNE:

The project overview was presented by M. Diwan with the US schedule

Europe in LBNE (A. Weber): 10 UK and 8 Italian groups are presented as collaborators

UK Areas of interest/activities: DAQ, 35 t prototype Operation, HV monitoring (2014-2017), R&D TPC components, reconstruction Software and neutrino generators

Italy Areas of interest/activities: Original developer of LAr TPC technology, precise scope being discussed, push technology: R&D and experiment, includes WA104 @ CERN

LBNO-LBNE Discussions are going on: joint physics task force, common R&D centred around WA105 at CERN (2014-2017) => comparison of single and double phase, prototyping common hardware like membrane cryostat

It should be noted that the project is funded in order to cover a 10 kton liquid argon detector on surface without a near detector

Sensitivities are computed with 1% systematic errors, which are considered too optimistic by the community (especially in the absence of a near detector ...)

Hyper-K:

The overview was presented by F. Di Lodovico.

Natural collaborative work emerges from previous European participation in T2K => UK groups showing significant interest.

Ideas to look at improved ND280, at a new near detector at 2 km (WC).

There will be an LOI submitted to J-PARC in April 2014.

The UK proposal to STCF will be submitted in May 2014

The areas of interest are: DAQ, electronics, calibration strategy, photodetector studies for both Hyper-K and new near detector.

Required R&D should take place from now to 2017 with a prototyping phase in 2016-2017.

A decision on HK will be taken in 2016. However there could be some "anticorrelation" with possible strong Japan involvement in ILC

The overall cost is estimated to be 800M$ (detector only, it does not include beam upgrades)

HK should get sensitivity to resolve MH by adding atmospherics to beam data.

B.3.3   Detector and Accelerator R&D in Europe:

- A broad range of activities have been presented on the main detector technologies that can be used for future neutrino accelerator projects: water Cherenkov R&D, Large liquid Argon TPC, liquid scintillator, magnetised iron-scintillator detector, large air core and iron spectrometers.

- Clearly the needed expertise exists in Europe for all the different technologies. R&D should be pursued to allow testing large scale prototypes to go beyond the different Design Studies.

In addition an active work is being done in various aspects of accelerators to produce neutrino beams.

The MICE experiment for R&D towards a Neutrino Factory and a Muon Collider.

Technological developments for multi-GeV MW-class proton drivers: CERN, ISIS and ESS are three European laboratories which could host a MW-class proton driver for a neutrino facility, profiting from existing machines or planned projects.

Target R&D: materials studies, conceptual designs, Prototyping, Heating/cooling tests, beam experiments are covered.

B.3.4   The CERN Neutrino Platform (CENF)

The development of the new neutrino platform at CERN is a real advantage for the community. Indeed it is very important that CERN is becoming involved in neutrino physics since it enhances the chances to develop a consistent European neutrino strategy.

CERN offers a platform for:

- Neutrino detectors R&D (2014-2018)
- Logistics and test beam infrastructures (2014-2016)
- Design of a possible neutrino beam.(2012-2014) for an eventual construction in 2015-2018. The cost is estimated to be 80-100MCHF.

- CERN created a budget line for neutrino projects in the Medium Term Plan. It will support this platform in an active way and will help WA104, WA105 and others in this initial phase.

- Both projects are finalizing their MOU and are preparing detailed plans. Approval is for R&D, but no neutrino beam has yet been granted.

- CERN planned involvements:

Construct a large neutrino test area (EHN1 extension) with charged beams capabilities, available in 2016 (and compatible with a future neutrino beam);

Continue the detailed studies towards a short baseline neutrino beam at CERN in particular for the secondary beam facility;

Assist the EU neutrino community in their long term common plans.

WA104:
- ICARUS-NESSIE is now the experiment WA104.
- The T600 will be transported at CERN where it will be overhauled.
- A new T150 detector will be constructed using the same technology of the T600 for the TPCs and new solutions for LAr purification, electronics, light collection and complemented with a magnetic field.
- It includes R&D for air core muon detector (ACM), testing in charged beam, tracking capabilities of the ACM detector with high energy muon penetrating LAr-TPC.

WA105:
- The project is to build a 6x6x6 m^3 double phase LAr TPC to validate the LBNO far detector proposal technology.
- The demonstrator will be exposed to charged hadrons beam in the North Area.
- The demonstrator will be constructed with all the techniques developed in LAGUNA-LBNO and needed for the affordable implementation of the far underground detector. It will represent a milestone for future long-baseline programs.
- The TDR and MoU are under preparation.

B.3.5   Conclusions:

During the meeting two long baseline European projects have been discussed and detailed. One is the ESSnuSB for which a design study will be prepared and submitted to EU (HORIZON2020) and the other one is the Laguna-LBNO project for which the design study is nearing completion. Several discussions took also place around the NuStorm project implementation in Europe and its physics reach and around the sterile neutrino program. This paragraph gives a synthesis of the points which have (nearly) reached some consensus during the round table or were mentioned and so should be taken into account.

General principles:

- Neutrino physics is very important. It is one of the fields providing evidence for "new physics".
- It provides important information also for several theoretical grounds.
- The link with cosmology is important and neutrino physics is used as a control piece of information.
- The MH and CP violation are major parameters to access and should be seen as priority. An optimal program requires more than 1 experiment; need to over constrain the oscillation parameters.
- Need 2 long baseline experiments with complementarity: Water Cerenkov detector on a few hundred km baseline, ESSnuSB or Hyper-K like) and LAr TPC on very long baseline (LBNO or LBNE like).
- Need short/medium time scale program in neutrino, not only long term.
- Long term project should be incremental with defined stages.
- It is important that European nu community arrives at the generally accepted scientific program of research
- If European contributions to neutrino physics will be realized in US- or Japan-located experiments, the needed size of the contributions will require formal international agreements.
- Cross-section measurements should be part of the neutrino program.

Sterile neutrino program:

- Must distinguish chasing anomalies near 1eV from searching for sterile neutrinos which can have any mass. However the anomalies at 1eV should be resolved. Confirmation of the LSND signal would completely change our picture of elementary particles.
- It is mandatory that any new accelerator program will have synergy with LBL experiments.
- Since there is no obvious theoretical guidance to look at them, it will be difficult to justify a project with only sterile neutrino goals.

nuSTORM

- NuStorm is a multi-topic project which can cover steriles as well as the very important topic which is the precise measurements of cross sections, especially nue.
- Nustorm should be looked carefully in the CENF. The CENF designs should allow upgrading to a NuSTORM front end.

Neutrino infrastructure:

- Neutrino program started at CERN. The steps are being defined.
- CENF should be seen as the infrastructure, with experiments a separate consideration.
- The community should support a program for detector R&D and critical measurements like cross sections and hadron production. The CERN neutrino platform is an important basis to fulfil these goals.
- A design study about the possibility of adding to ESS the capability of generating neutrino beams is supported by the community