PRAMANA — journal of physics
© Indian Academy of Sciences
Vol. 79, No. 5
November 2012
pp. 953–962

Long-baseline experiments, now and soon!

JENNY THOMAS
Department of Physics and Astronomy, University College London, Gower St, London WC1E 6BT, UK
E-mail: jthomas@hep.ucl.ac.uk

Abstract. The new results available this year from a number of neutrino experiments bring into stronger focus the details in the 'Standard Model' of neutrino oscillations described by the PMNS mixing matrix. However, the parameters are still not known to very high precision. The next few years look bright for accelerator neutrino experiments, with much action occurring in the near future. We still have to wait a little longer, however, to be sure, but making educated guesses is needed to make plans for the future.

Keyword. Neutrino oscillations.

PACS Nos 10; 13.15.+g; 95.85.Ry

1. Introduction

The study of neutrino oscillations through long-baseline experiments has moved the field forward since the acceptance of the neutrino oscillation hypothesis following the results from Super-Kamiokande in 1999. The simplest Pontecorvo–Maki–Nakagawa–Sakata (PMNS) construction of the 3-flavour mixing, analogous to the quark mixing, is widely accepted and a number of parameters of that mixing model are measured with varying degrees of accuracy. However, none of the parameters are known with accuracy better than about 10%. So we are presently not in a precision phase where we can look for deviations from this neutrino mixing 'Standard Model' yet. It is essential that we continue to look very critically at the data. We do not have definitive proof yet that the PMNS model is correct, and our present measurements still have much scope for other interpretations.

In the recent years, there were a number of very important developments in the field. Technologically, the big step for mankind is the proof of the liquid argon (LAr) detector technology from ICARUS, which now has neutrino measurements at CERN Neutrinos to Gran Sasso (CNGS). OPERA has analysed double their data but is yet to find more tau events. MINOS has new results on antineutrino oscillations and θ_{13} and T2K have made their first measurement of θ_{13}.

The future looks very exciting, with the potential of a large value of $\sin^2 2\theta_{13}$ (>0.01) allowing investigation of CP violation and mass hierarchy in the next decade. Also an opportunity unique to Fermi National Accelerator Laboratory (FNAL), to study high precision and high energy at the on-axis NuMI beam will provide a far reach into the sterile neutrino sector as well as non-standard interactions and even extra dimensions!

The study of neutrino oscillation physics could prove to be as exciting as the LHC results in the coming decade.

2. Technical steps forward

A new revolution in neutrino experiment has risen from the liquid argon detector concept. This has been around for a number of years, but has been gaining recognition with a number of R&D and small detector proof of concepts such as ArgoNeuT at FNAL. However, the major pioneer for this technology is ICARUS which has this year published analysis of the CNGS neutrinos using the 600-tonne liquid argon detector. Figure 1 shows first a 'typical event' where the phenomenal resolution on the event is evident. The approach to particle identification is using $\mathrm{d}E/\mathrm{d}X$ which is shown in the lower right-hand figure where electrons and neutral pions are shown clearly separated. Another novel concept is that of measuring the muon momentum using multiple scattering which has been demonstrated to work (at least with long tracks) as evidenced in the middle and right plot. As of the summer 2011, 3.4×10^{19} protons-on-target (POT) had been analysed with 115 charged current and 46 neutral current ν_μ events identified. ICARUS expects to see 2 tau events in the next two years of data taking, to augment the five events expected in that time from the OPERA experiment.

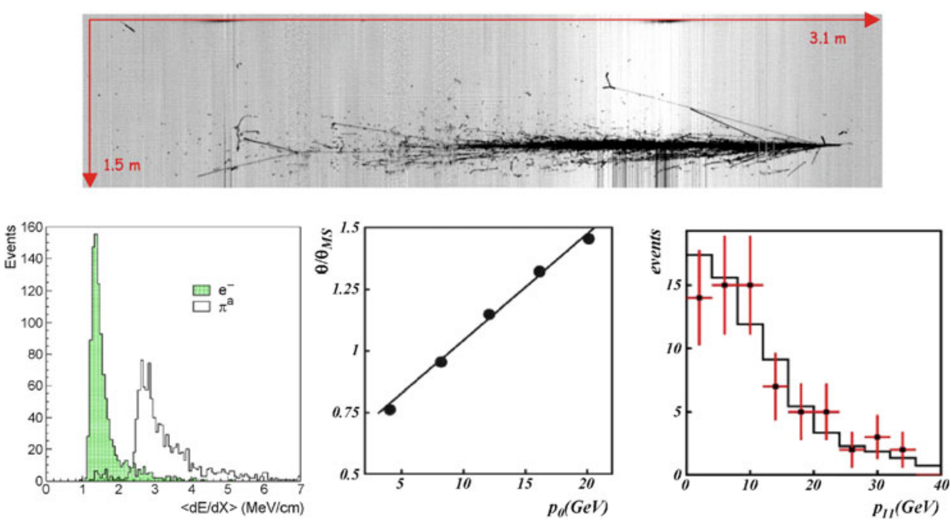

Figure 1. *Top*: A typical neutrino event from the ICARUS detector. *Left lower*: $\mathrm{d}E/\mathrm{d}X$ for electrons and neutral pions, *middle lower*: muon momentum vs. multiple scattering extent and *right lower*: muon momentum distribution for events.

3. Precision oscillation measurements

The OPERA experiment has been running since 2006. It is a combination of electronic and emulsion experiments whose main objective is to search for the appearance of tau events from the oscillation of muon neutrinos to tau neutrinos. Last year, the first OPERA tau candidate event was announced with a rather high energy of 44 ± 12 GeV at an energy where the flux is extremely low.

At the time of LP11, OPERA had collected a total of 12×10^{19} POT and analysed about 40% of them. They have vastly improved their event reconstruction to the tune of about 20%, but as yet have found no new tau candidates (although at the time of writing, there is news of two more events having been sighted).

MINOS has produced a number of very important results this year. MINOS was the first experiment constructed with identical near and far detectors, which mitigated a large number of systematic errors such as cross-section and beam uncertainties. The first new result is a stark reminder of the effect of the very low bar in the neutrino field used in presenting confidence levels (CL). Typically, neutrino experiments quote a 90% CL limit, but this of course means that it has a 10% probability of being incorrect. The MINOS experiment measured the oscillation parameters for muon antineutrinos last year [1] and came up with a very surprising contour. Figure 2a shows 68%, 90% and 99% contours for the neutrino and antineutrino mixing parameters which one would naively expect to be the same for neutrinos and antineutrinos. The 90% CL contours were worrying in that there was only a 2% probability that they hailed from the same underlying mixing parameters. However, the 99% CL contours (also shown) were still consistent. Figure 2b shows what happened when the new tranch of antineutrino data taken this year was analysed. The new data had an upward fluctuation in the number of events observed (at about the same level as the previous data had a downward fluctuation!) with the net result being that the 90% CL contour is now in much better agreement with its neutrino counterpart. MINOS had also published an updated version of the neutrino mixing parameter measurement [2] and the best-fit values are $\Delta m^2 = 2.32^{+0.12}_{-0.08} \times 10^{-3}\,\mathrm{eV}^2$, a precision of about 5% and $\sin^2 2\theta > 0.90$ (90% CL) with a precision of about 10%.

T2K announced its first results this year. With only 31 events, they have managed to produce a very impressive contour of Δm^2 and $\sin^2 2\theta_{23}$, shown in figure 2c, and while not yet competing with MINOS, draws attention to another lesson: the value of new information given the exact value of Δm^2 was known, the choice of the experimental parameters L (baseline) and E (energy) allowed the experiment to focus on the maximum oscillation probability. At the time of the MINOS construction, the most likely value of Δm^2 was somewhat larger and although the uncertainty of this value was larger too, it led to the MINOS detector being optimized for a higher energy regime than it eventually was used at.

Both these experiments produced results for θ_{13} this year [3,4]. This measurement is the one which has the biggest impact on the future direction of this field. In long-baseline experiments, the CP violating parameter δ_{CP} is always multiplied by a function of θ_{13} and so observing a large enough value of θ_{13} is paramount to studying CP violation in the lepton sector. The best-fit values of $\sin^2 2\theta_{13}$ range between 0.04 and 0.11, but more concisely, the results would be given as limits as in table 1. Super-Kamiokande have also announced limits on θ_{13} which are also included [4a]. The limit contours for MINOS and

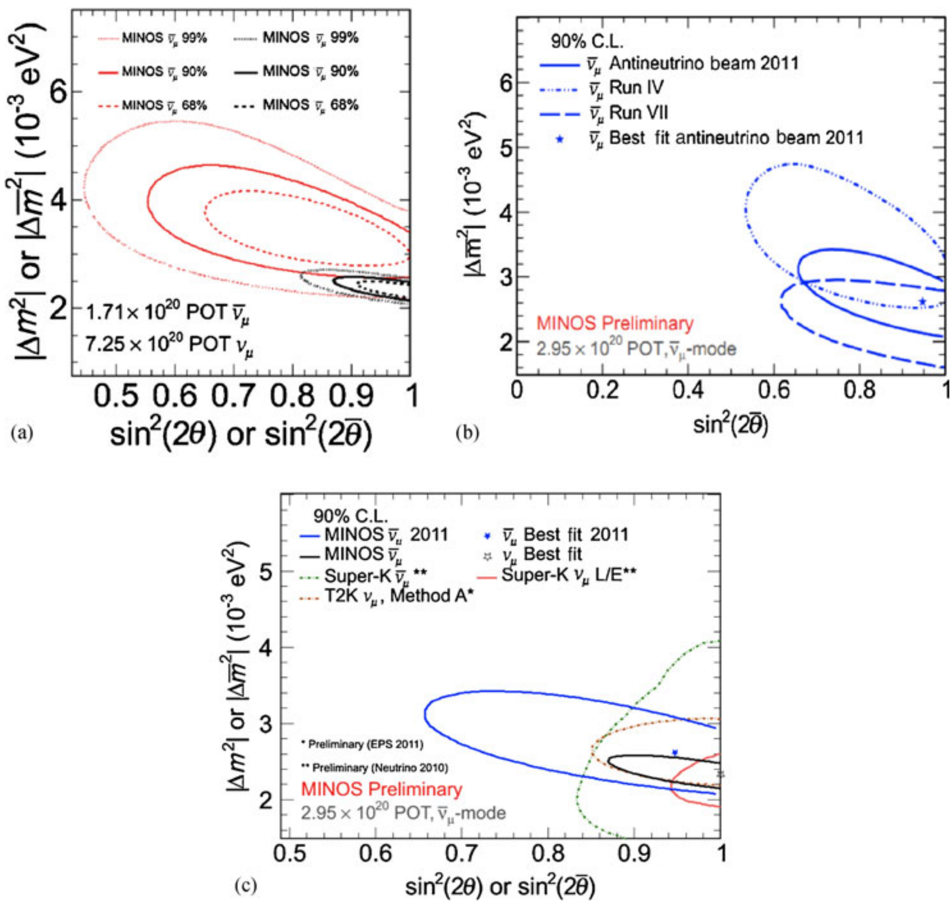

Figure 2. (**a**) Previous MINOS results for neutrino and antineutrino mixing parameters. (**b**) How the new data taken in 2011 compared with the previous data. (**c**) The MINOS neutrino and antineutrino contours in context with other experiments.

T2K are shown in figure 3, where the MINOS result is clearly the most precise, whereas the T2K result excludes zero with higher confidence level. The overarching conclusion is that θ_{13} is 'large' and this will undoubtedly help the future experiments. It should be noted that shortly after the conference, Double Chooz (a reactor experiment) announced their

Table 1. Recent limits placed on θ_{13}.

Experiment	Limit on θ_{13}	CL (%)
Super-Kamiokande	$<11.5^o$	90
MINOS	$<10.1^o$	90
T2K	$>5.4^o$	90

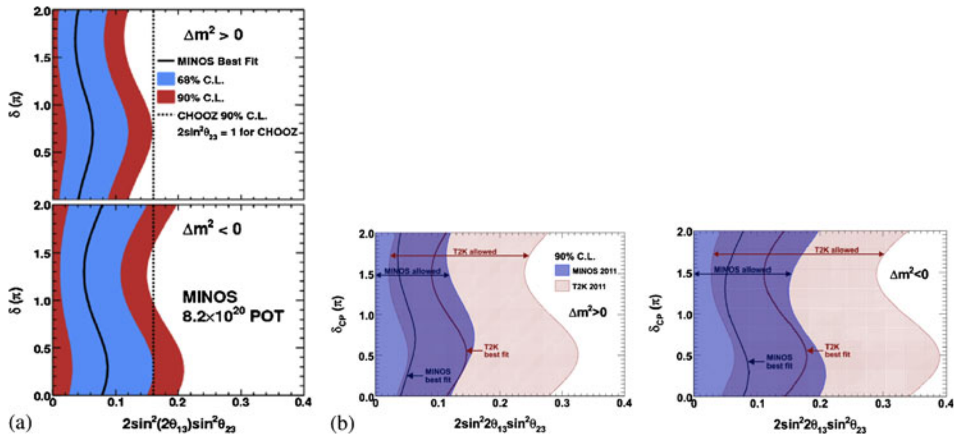

Figure 3. (**a**) New results from MINOS and (**b**) overlaid with T2K for θ_{13}.

first measurement of θ_{13} which, although not very precise, indicated a value consistent with the long-baseline experiments.

The future plans for these two experiments are as follows. MINOS will analyse the antineutrino ν_e data, which is already collected and will also analyse another tranch of data being collected from now until the spring 2012 shutdown. This will increase the effective size of the dataset by a further 30% and will lead to one more measurement of θ_{13}. T2K will start taking data again in the new year once a full recovery from the earthquake is affected. It is expected that by the end of 2012, θ_{13} will be well-known enough to cast in stone the experimental parameters of the next generation experiments.

4. Medium-term precision experiments

The NOνA experiment presently in construction, is an experiment which is situated off-axis by 2.5° in the NuMI beam at Ash River in Minnesota. It also has goals similar to T2K, that of a precise measurement of θ_{13}, but also the start of a study into CP violation in the neutrino sector. NOνA is a two-detector experiment like MINOS, but has a 16 kT, low-Z, 65% active far detector at 810 km and a 220 near detector at 800 m from the target. It is designed to have high efficiency for identifying ν_e events as well as being able to measure charged current ν_μ events as shown in figure 4a. The main objective though is to run NoνA with neutrinos and antineutrinos and look at the difference in the probability of oscillation between them. This gives information about δ_{CP}, although it is not that simple! Because of NOνA's long baseline, matter effects come into the oscillation probability from the forward-scattering interaction that electron neutrinos have with the electrons in the atoms they pass by inside the Earth. T2K are not affected by this because their baseline is much shorter (275 km) and so fewer electrons are seen by the neutrinos as they pass through the Earth. This is a blessing and a curse for NOνA, but together with T2K, the disentangling of CP violation effects from matter effects could be possible within the next 7–8 years. Figure 4b shows how the effect of CP violation is separated from the matter effects as a function of θ_{13}. Given what we know about θ_{13}, it is possible that six

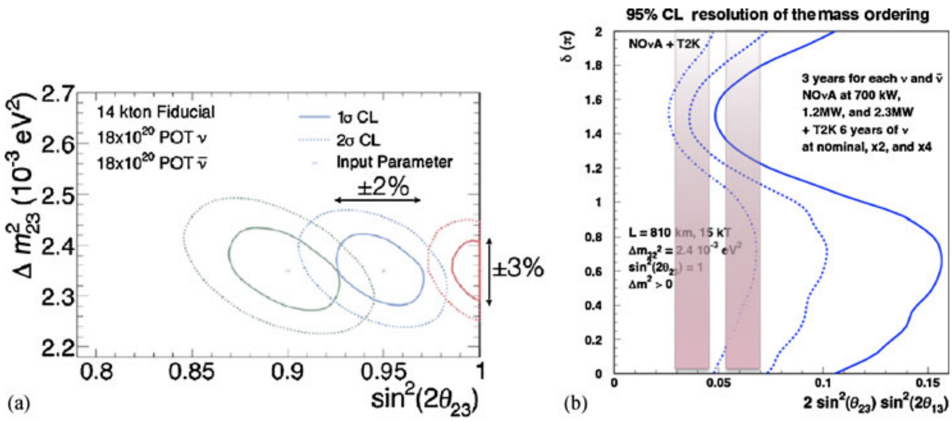

Figure 4. (**a**) Expected precision on $\sin^2 2\theta_{23}$ and Δm^2 with three years of running NOνA. (**b**) 95% CL contours for the mass hierarchy along with two potential reactor measurements of θ_{13}, also using T2K information.

years will not be enough for NOνA to see the mass hierarchy with a beam power of 700 kW, but it should be stressed that NOνA is not systematics-limited, and more mass, or higher beam power, will lead to improvements in reach. A potential outcome is shown in figure 4b, where with a longer NOνA (6+6 years, equivalent to running with between 1.2 and 2.3 MW) run period, the mass hierarchy could be resolved by a combination of NOνA, T2K and the reactor experiments if θ_{13} was 5.7° and δ_{CP} was between 1 and 2π. Taking into account the latest combination of results for θ_{13} which includes the Double Chooz result (not available at the time of the conference) and gives a most probable value of about 0.065 (or 7.6°), the reach of the NuMI beamline for the mass hierarchy is even more extensive.

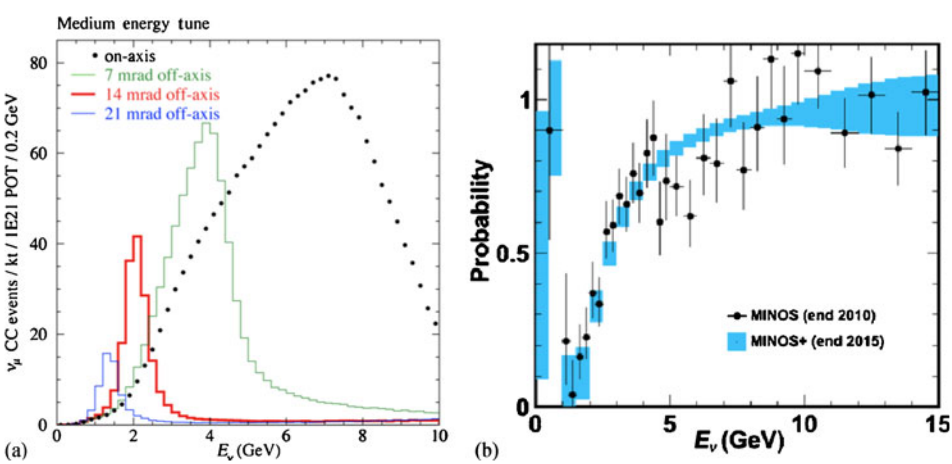

Figure 5. (**a**) Flux going to MINOS during the MINOS+ phase in black. (**b**) Present measurement of oscillation ratio with MINOS (points) and expected precision with MINOS+ (blue shading).

Running concurrently with NOνA will be the on-axis MINOS experiment, in a new phase known as MINOS+. The physics accessible to MINOS+ with higher intensity and higher energy neutrinos is very diverse, but it will also provide a very important cross-check of the assumptions generally now believed to be true about the PMNS neutrino mixing model. Figure 5 shows the event spectrum seen in the MINOS detector in black while the red spectrum is that produced in the NOνA detector during the NUMI/NOVA running period. Figure 5b shows our present precision on the ratio of oscillated to non-oscillated muon neutrinos (black points), while the shaded region demonstrates our expected precision on that ratio after three years of running MINOS+.

5. Sterile neutrinos

The sterile neutrino does not belong to the 3×3 PMNS 'Standard Model' of neutrino mixing. However, it is a subtopic which has attracted a lot of attention. What is referred to here as a sterile flavour should not be confused with the standard theory nomenclature of a sterile neutrinos referring to the right-handed non-weakly interaction version of the three known neutrino flavours. Because the sterile flavour which we seek is by definition non-interacting, its presence must be inferred by its interference with the oscillation of the three known flavours. Different experiments have different observables, and therefore probe different couplings. In the simplest framework of 3+1(sterile) neutrinos, there are a number of angles which can be probed. Those experiments which look at electron neutrino appearance (LSND, MiniBoone, ICARUS) probe a mixture of θ_{14} and θ_{24}. The experiments which look at the change in the rate of neutral current events over distance (MINOS and MINOS+) probe the mixture of θ_{24} and θ_{34} while the experiments that look at ν_μ disappearance (MINOS+, MiniBoone, CDHS, CCFR) are sensitive only to the angle θ_{24}.

The first hint of a sterile neutrino flavour surfaced more than a decade ago. LSND reported evidence for an oscillation of muon antineutrinos into electron antineutrinos with a probablility of about 0.2% and a mass squared difference of about 1 eV^2. This measurement was repeated using the FNAL booster beam and the MiniBoone scintillator Cherenkov detector and there still appears to be some evidence of a small excess in both the neutrino and the antineutrino signal regions echoing the former LSND signal. This is shown in figure 6 where the spectra for neutrinos (upper) and antineutrinos (lower) are shown along with the resulting exclusions (right).

MINOS has published new limits looking for the disappearance of neutral current events [5], a rate which is unaffected by standard oscillations, but which could be reduced if sterile neutrinos, which would not interact via the Z boson exchange, were being produced in place of a standard neutrino flavour. Figure 7a demonstrates the dependence of the measurement on both angles θ_{24} and θ_{34}, which is characteristic of this particular measurement, while figure 7b shows the reach in θ_{24} which comes from the constraint of muon neutrino disappearance and is compared to the existing limits on that angle.

ICARUS will be contributing to the exclusion (or otherwise) of sterile flavour neutrinos over the next two years also, and their predicted sensitivity is shown in figure 6, the red on the bottom right-hand corner of figure 6.

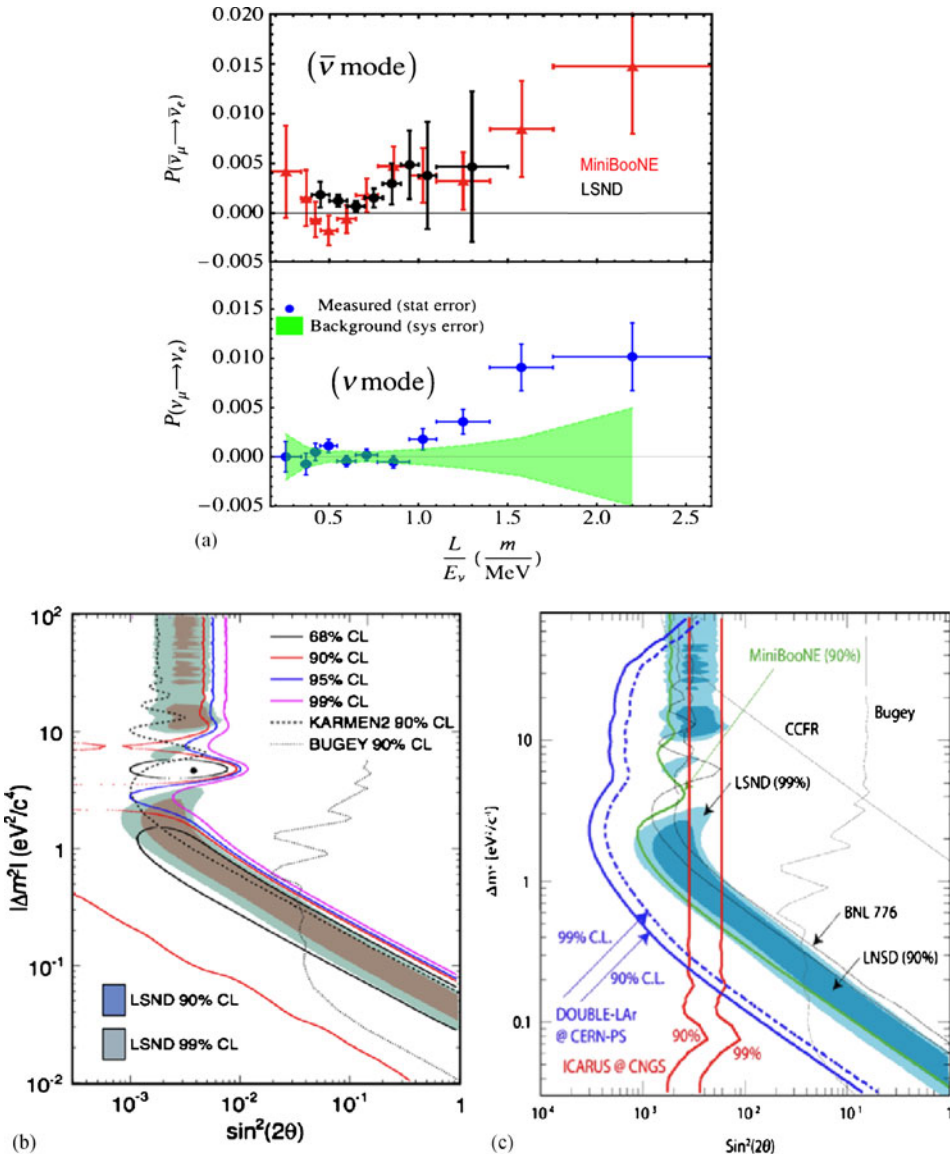

Figure 6. (**a**) Latest results from the MiniBoone experiment showing the ratio of expected-to-observed rate with neutrinos and antineutrinos together with LSND results, (**b**) the limit contours for antineutrinos and (**c**) neutrinos spectra and associated contours.

MINOS+ will be able to impose wide ranging limits by looking not only in the far detector for ν_μ and NC disappearance with very high precision, but also by looking in the near detector for distortions in the energy spectrum which are larger than the level of systematic flux uncertainty. The reach for neutrinos and antineutrinos are shown in figure 8.

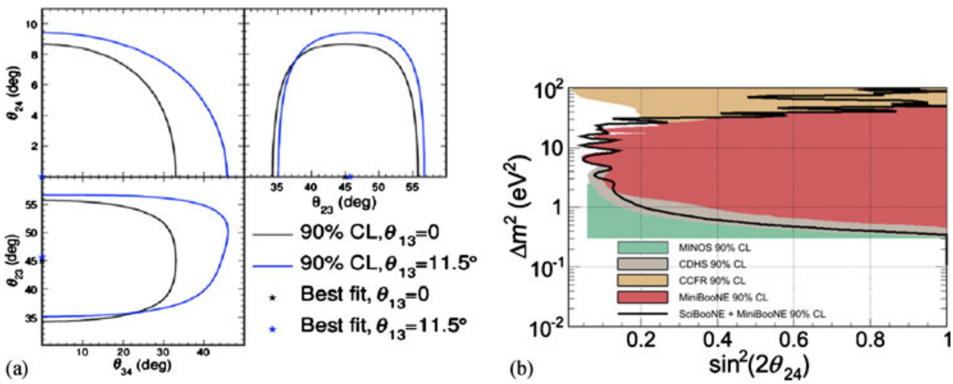

Figure 7. MINOS limits on sterile mixing angles. (**a**) 2D contours for the different mixing angles which could account for any loss in NC rate. (**b**) Contour from MINOS in green of θ_{24} vs. Δm^2.

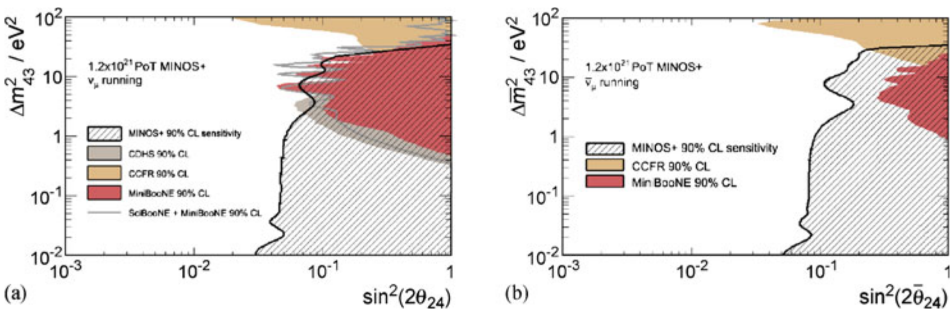

Figure 8. The sterile neutrino limits for (**a**) neutrinos and (**b**) antineutrinos expected with three years of MINOS+ using ν_μ disappearance.

This set of experiments will continue to provide the state-of-the-art information about neutrinos for the next decade while future study is being prepared.

6. Longer-term precision experiments

The main future programme being planned (at the time of the conference) is the Long-Baseline Neutrino Experiment project in the US. The conceptual design will have a far detector in a deep underground facility (Sandford Underground Research Facility), 1300 km from the beam source at FNAL. The experiment will measure $\delta_{\rm CP}$ and the mass hierarchy. Since the conference, there has been a letter of intent published for Hyper-K, a 0.5 MTon (fiducial) detector in the JPARC neutrino beam which has similar goals.

7. Conclusion

The last year has been one of real excitment given the new results from a number of neutrino experiments. The next few years will hopefully provide us with a precision measurement of θ_{13} and hints of δ_{CP} and mass hierarchy if we are lucky. Very high-precision measurements of the atmospheric parameters will be produced as well as precision tests on the whole PNMS matrix parametrization itself, including searches for sterile neutrinos. The future looks bright.

References

[1] MINOS Collaboration: P Adamson *et al*, *Phys. Rev.* **D84**, 071103 (2011)
[2] MINOS Collaboration: P Adamson *et al*, *Phys. Rev. Lett.* **106**, 181801 (2011)
[3] T2K Collaboration, *Phys. Rev. Lett.* **107**, 041801 (2011)
[4] MINOS Collaboration: P Adamson *et al*, *Phys. Rev. Lett.* **107**, 181802 (2011)
[4a] arXiv:1002.3471v2
[5] MINOS Collaboration: P Adamson *et al*, *Phys. Rev. Lett.* **107**, 011802 (2011)