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Neutrino Experiments

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Abstract. We will start with a brief overview of neutrino oscillation physics with emphasis on the remaining open questions. Next we will review the current status and prospects of experiments probing the "solar" and "atmospheric" neutrino mixing parameters. Finally, we will describe the status and prospects of near and longer term neutrino oscillation experiments aiming to study the "cross" neutrino mixing parameters which, to date, are almost entirely unknown.

1. Introduction

Non-zero neutrino masses are perhaps the only experimental evidence we have so far for the existence of physics beyond the Standard Model. In the past ten years tremendous (experimental) progress has been made towards precisely measuring and better understanding neutrino mass differences and mixings [1–8]. However, there are still many open questions:

1) What is the value of the third neutrino mixing angle, θ_{13}, for which only a limit exists from the Chooz [9] experiment?
2) Do neutrinos violate CP symmetry and if so by how much?
3) What is the hierarchy of neutrino masses?
4) What are the absolute values of neutrino masses? Neutrino oscillation experiments provide information only on the mass differences between the different eigenstates.
5) Are neutrinos Majorana or Dirac particles?
These are important questions on their own, but they could also provide the necessary information in order to enable us to address perhaps even more fundamental issues:
• Why is neutrino mixing so much different from quark mixing, do they relate to each other and if so how, what is the underlying physics (if any) for the particular structure of the neutrino mixing matrix?
• Why are neutrino masses so much different from quark and charged lepton masses? What is the mechanism that generates them (maybe tautological questions)?
• What is the origin of the matter - antimatter asymmetry in the Universe, and do neutrinos play a role in that?
• Are there still more "surprises" to come in neutrino physics? Namely is there new physics involving neutrinos that will result in entirely "unexpected" experimental observations? Perhaps, for some of us, this is the most exciting scenario.

The first three of the five questions we can address with experiments using reactor and/or accelerator neutrinos, and the remaining two with natural neutrinos.

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Different neutrino oscillations experiments, involving different neutrino species, energies, and baselines can probe different parameters of the 3×3 unitary mixing matrix, U, which relates the neutrino weak eigenstates with their mass eigenstates. This matrix can be conveniently parameterized as a product of four (three if neutrinos are Dirac and not Majorana particles) sub-matrices as shown below:

$$|U| = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & -s_{23} \\ 0 & s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & -s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ s_{13}e^{-i\delta_{CP}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

For historical reasons the parameters of the first sub-matrix are called "atmospheric", the ones of the third sub-matrix "solar", and the ones of the second sub-matrix "cross" mixing, for which only an upper limit currently exists from the Chooz experiment [9]. Next we will present the status and prospects of the experimental measurements of the neutrino mixing parameters for each of these three sub-matrices.

2. "Solar" Mixing Parameters

The first evidence of neutrino oscillations came from experiments studying the number of solar neutrinos created by the photo-nuclear interactions at the centre of the Sun [10–13]. These experiments were sensitive to neutrinos of only one flavour (ν_e), which they were consistently finding in deficit with respect to expectations from the Standard Solar Model [14] (SSM). An unambiguous experimental signal that would verify the correctness of the expectation (SSM), and hence the correctness of the experimental deficit, would be to measure the flux of all active neutrino flavours from the Sun. This is precisely what the SNO [15] experiment did, and combinations of its measurements with Super-Kamiokande [15–17], shown in figure 1 (left plot), create a consistent picture of both the standard solar model, and oscillations of electron neutrinos from the Sun, as shown in figure 1 (right plot).

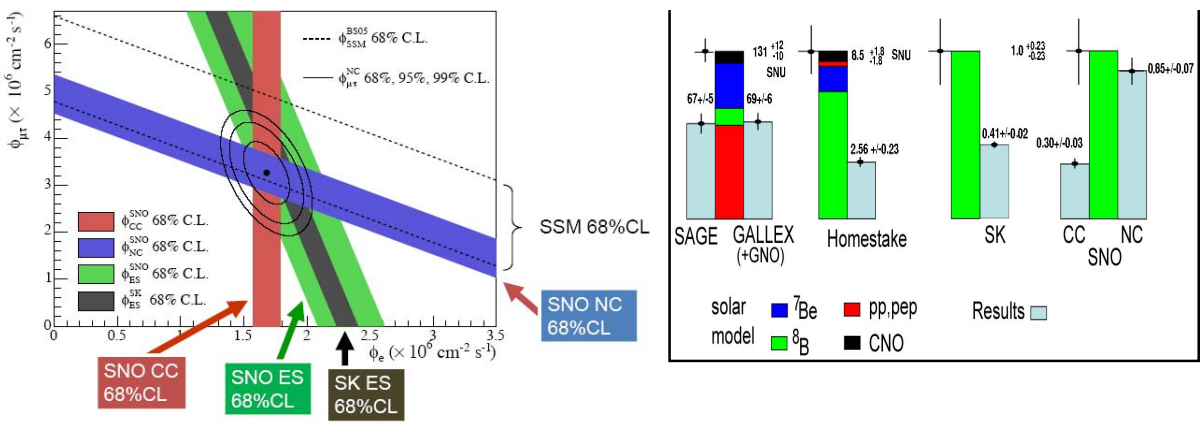

Figure 1. *Left plot*: Measurement of the flux of $\nu_\mu + \nu_\tau$'s versus the flux of ν_e's from the Sun by the SNO and Super-Kamiokande experiments. The total neutrino flux, as predicted by the SSM, is shown with dashed lines. The non-zero value of the non-ν_e flux provides strong evidence for neutrino flavour transitions, and the agreement between experimental measurements and theoretical expectations verifies the correctness of the SSM. *Right plot*: A pictorial summary of all solar neutrino experiment measurements, involving not only ν_e's but all three active neutrino flavours. The agreement between these different measurements provides a consistent picture for both the SSM and for the oscillations of electron neutrinos from the Sun to muon and tau neutrinos.

2.1. KamLAND

The goal of the KamLAND [18] experiment is to study oscillations of electron anti-neutrinos emerging in copious numbers from the nuclear reactors in Japan. If the solar neutrino experiments are indeed observing neutrino oscillations, then the same behavior (assuming that CPT is conserved) should be observed when studying electron anti-neutrinos from nuclear reactors. KamLAND is a 1000 ton liquid scintillator detector, with an outer water Cherenkov veto for cosmic muons, located in the Kamioka Mine in Japan. In figure 2 (left plot) we show the most recent [19] observed energy spectrum of the $\overline{\nu}_e$'s along with the best fit under the neutrino oscillation hypothesis, as well as the expectation in the absence of neutrino oscillations. There is a very significant deficit of $\overline{\nu}_e$'s observed ($> 5\sigma$), that has a characteristic shape as a function of energy. In figure 2 (right plot) we show the same measurement as a function of L/E which shows a clear oscillatory behaviour, and therefore excludes other theoretical models that predict neutrino disappearance like neutrino decay [24], and neutrino decoherence [25]) at high significance (3.9σ and 4.6σ respectively).

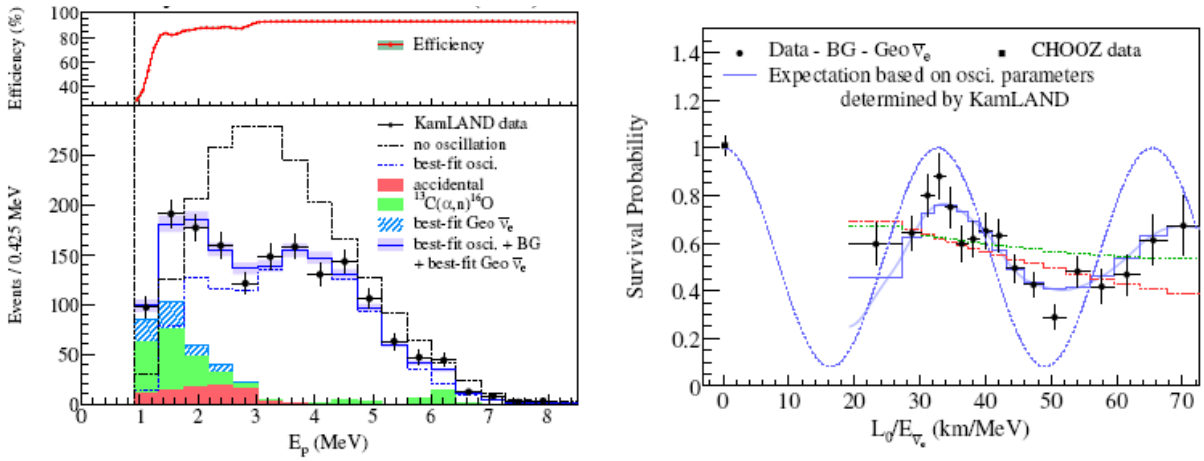

Figure 2. *Left plot*: Reconstructed energy spectrum of the observed $\overline{\nu}_e$ events in KamLAND. Black points correspond to the data, the blue continuous line to the best fit under the neutrino oscillation hypothesis and the dashed black line to the expectation under the no-oscillation hypothesis. *Right plot*: $\overline{\nu}_e$ survival probability (ratio of observation to expectation under the no oscillation hypothesis) as a function of L/E, with L taken as the average baseline of 180 km. The blue line represents the best fit under the neutrino oscillation hypothesis and the dashed green and red lines the best fits under the neutrino decoherence and neutrino decay hypothesis respectively.

The KamLAND measurements strengthen significantly the neutrino oscillation hypothesis, and in addition when combined with the solar neutrino experiment measurements provide precise determination ($\sim 5-10\%$) of the "solar" mixing parameters as shown in figure 3.

2.2. Borexino

The goal of the Borexino experiment [20] is to detect in real-time solar neutrinos in an energy range (below $\sim$ 4.5 MeV) that has never been observed before. Borexino is a liquid scintillator detector with an active mass of 278 tons and an outer water Cherenkov region to veto cosmic muons, located at the Gran Sasso laboratory in Italy. In figure 4 (left plot) we see the observed energy spectrum (without a statistical subtraction of the α peak at $\sim$ 500 KeV from the α emitting contaminants), its breakdown to the various components, along with the best fit. The best fit yields results that are consistent with the oscillation hypothesis, or equivalently

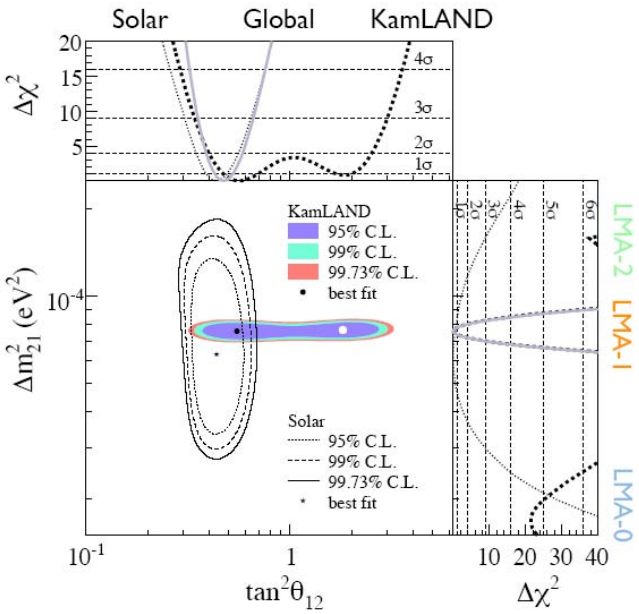

Figure 3. Allowed regions for the "solar" neutrino oscillation parameters when results from KamLAND and solar experiments are combined. The KamLAND data help in the precise determination of the mass squared difference, Δm^2_{21}, whereas the solar data help in the precise determination of the mixing angle, θ_{12}.

inconsistent with the no-oscillation hypothesis at the 4σ level. If one interprets the results in terms of oscillation probabilities, as shown in figure 4 (right plot) [21], then this result presents the first measurement of the survival probability of solar ν_e's in the transition region between matter-enhanced and vacuum-driven oscillations. This is an important result since, as shown in figure 4 (right plot), other theoretical models, like non-standard neutrino interactions [22], or mass varying neutrinos [23], are now more strongly disfavoured with respect to neutrino oscillations.

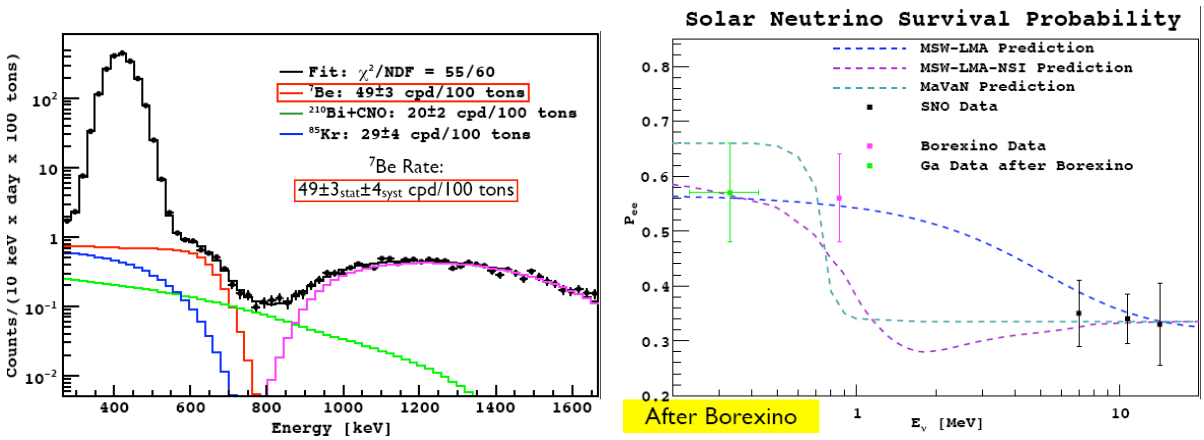

Figure 4. *Left plot* : Visible energy spectrum decomposed to signal (red line) and backgrounds (blue, green and magenta line) mostly from radioactivity, as measured by Borexino. *Right plot*: ν_e survival probability as a function of neutrino energy. The Borexino data (magenta point) are favouring the standard neutrino oscillation hypothesis (blue dashed line) and are disfavouring the non-standard neutrino interaction hypothesis (magenta dashed line) and the one of mass varying neutrinos (green dashed line).

3. "Atmospheric" Mixing Parameters

In the 1980's experiments like Kamiokande [26] and IMB [27] were designed and constructed in order to search for proton decay. These experiments were also measuring interactions of neutrinos created in the upper atmosphere, since those constituted one of the main backgrounds in a possible proton decay signal. By doing so, both experiments reported evidence for a significant deficit of ν_μ interactions with respect to expectation. The first strong evidence that this additional (to the solar one) neutrino deficit was due to neutrino oscillations came from the Super-Kamiokande experiment [4]. Soon after, several experiments [5]– [8] using both atmospheric and accelerator neutrinos reported consisted results, and now we are in a precision measurement era for the "atmospheric" mixing parameters, mainly due to the MINOS [6] and Super-Kamiokande [1] experiments. These are "disappearance" experiments in the sense that they measure the number of ν_μ's that oscillate as a function of L/E, but not the ν_τ's in which they are most likely re-appearing to, a measurement that the OPERA "appearance" experiment [31] will perform in the following years.

3.1. Super-Kamiokande

The main goal of the Super-Kamiokande [1] experiment was to perform a more precise study of the region of parameter space for neutrino oscillations indicated by the Kamiokande experiment. Super-Kamiokande is a 50 Kton total, (22.5 Kton fiducial) water Cherenkov detector located in the Kamioka mine in Japan. Super-Kamiokande announced its first results on oscillations of atmospheric neutrinos in 1998. Since then, collecting more data and improving both the apparatus, as well as the software and analysis techniques, increased the precision and the significance of the initial measurements, and obtained the most recent results shown in figure 5. The experiment performs two analyses. The first is the analysis of the zenith angle distribution of the muons originating from the atmospheric muon neutrino interactions, which yields the results shown in figure 5 (right bottom plot). The second analysis is the so called "L/E" analysis, in which the reconstructed L/E spectrum of the atmospheric neutrinos, shown in figure 5 (left plot), is fitted under the neutrino oscillation hypothesis, and compared against other alternative hypothesis like neutrino decay [24] and neutrino decoherence [25]. The results of the "L/E" analysis in terms of determining the "atmospheric" neutrino oscillation parameters are shown in figure 5 (right top plot), and the significance of discriminating against neutrino decay and neutrino decoherence is 4.1σ and 5.0σ respectively. Super-Kamiokande has the most precise measurement of the "atmospheric mixing angle θ_{23} which is of the order of $\leq 5\%$.

3.2. MINOS

MINOS [6] is a two detector long baseline neutrino oscillation experiment (baseline $L = 735$ km) with its near detector located at Fermilab and its far detector at SOUDAN Underground Laboratory. It utilizes an almost pure (98%) ν_μ beam produced by the Fermilab Main Injector (NUMI beam) with a mean energy $< E >\sim 3$ GeV. MINOS near and far detectors are magnetized segmented (steel/scintillator) tracking calorimeters. Muon neutrino charged current (CC) interactions are primarily identified by the presence of a muon-like track and neutral current (NC) interactions by the absence of it. There is a small contamination, $\sim$ 2%, of ν_e's in the beam whose CC interactions are distinguished from ν_μ CC and NC using the different characteristics of hadronic and electromagnetic showers. MINOS primary physics goals using accelerator neutrinos are the precise measurement of the dominant $P(\nu_\mu \to \nu_\tau)$ oscillation parameters, the comparison between neutrino oscillations and alternative disappearance hypotheses [24, 25], the existence of sterile neutrinos ν_s, as well as the study of the subdominant $P(\nu_\mu \to \nu_e)$ oscillations. The first ν_μ disappearance results were published [6] in 2006. In figure 6 we show the recent [29] MINOS ν_μ disappearance results, obtained with a factor of three higher statistics compared to the sample used in the first analysis, which present

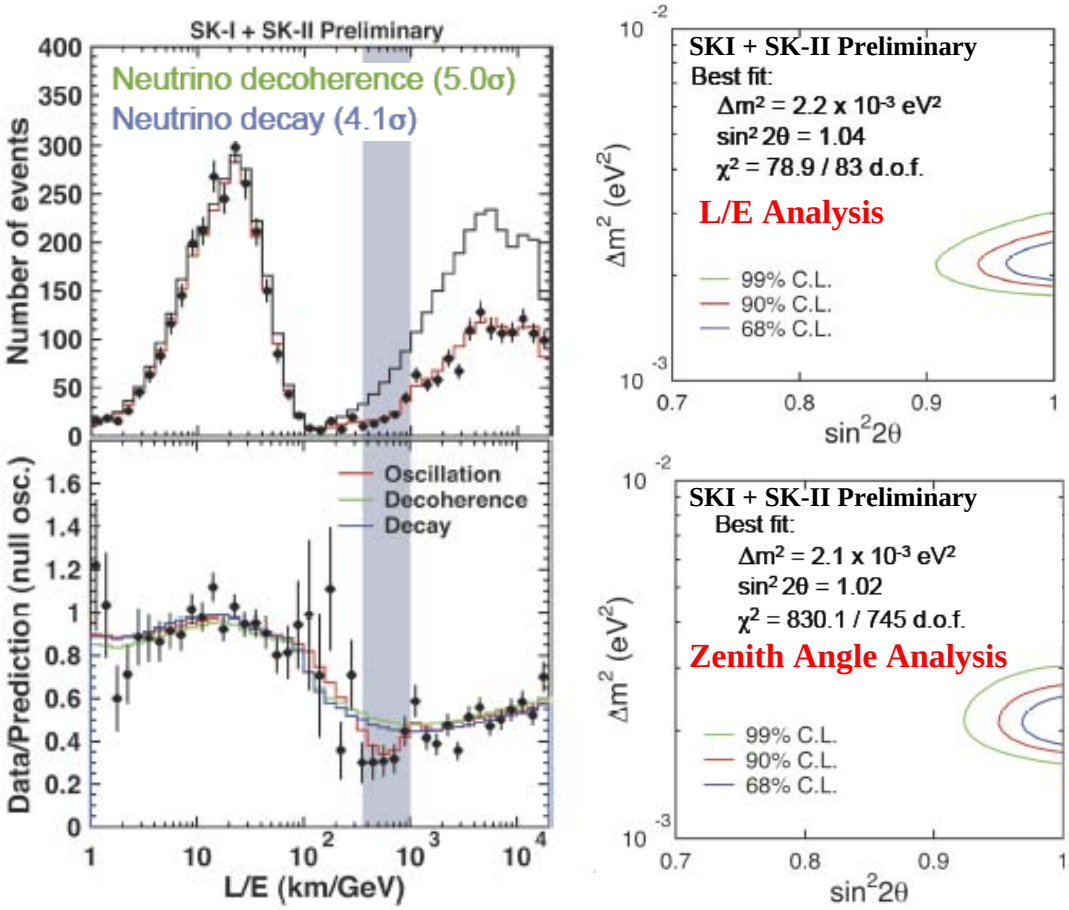

Figure 5. *Left plot*: The top plot shows the Super-Kamiokande reconstructed L/E distribution of charged current atmospheric ν_μ interactions (black points) along with the best fit under the neutrino oscillation hypothesis (red line) and the un-oscillated expectation (black line). The bottom plot shows the same information as the top one, but in the form of a ratio of data to the unoscillated expectation. Along with the best fit under the neutrino oscillation hypothesis (red line), the best fits under the neutrino decay (blue line), and neutrino decoherence (green line) are also shown. It is clear that in the dashed gray region the neutrino decay and neutrino decoherence hypothesis are failing to describe the data, whereas the neutrino oscillation hypothesis represents a successful description. *Right plot*: The top plot shows the most recent Super-Kamiokande measurement of the "atmospheric" mixing parameters obtained from the L/E analysis, and the bottom plot the results obtained from the zenith-angle analysis.

the most precise measurement of $|\Delta m^2_{32}|$. In addition, fitting the energy distribution shown in figure 6 under the pure neutrino decay and pure neutrino decoherence hypotheses and comparing it to the fit under the neutrino oscillation hypothesis, MINOS is able to disfavor them with a significance of 3.7σ and 5.7σ respectively.

MINOS has recently completed the first analysis of NC interactions in the near and far detectors [30]. Oscillations of ν_μ to ν_s would result in a depletion of the far detector NC-like data with respect to expectation. The magnitude of such a depletion would depend on the fraction, f_s, of active neutrinos that oscillate to sterile neutrino species with $f_s = \frac{P(\nu_\mu \to \nu_s)}{1-P(\nu_\mu \to \nu_\mu)}$. Fitting the NC-like far detector spectrum, shown in figure 7, under the assumption that ν_μ

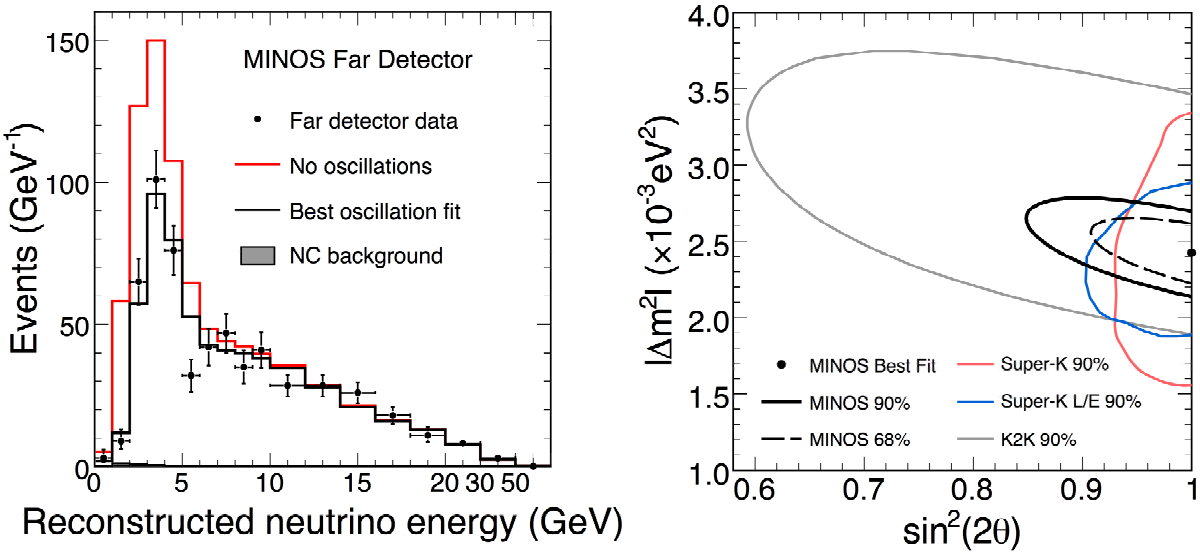

Figure 6. *Left plot*: MINOS Far detector reconstructed energy (GeV) spectrum for charged current-like events. Black points are the data, black solid line the unoscillated expectation and red solid line the best fit under the neutrino oscillation hypothesis. *Right plot*: MINOS two dimensional 68%$C.L.$ (black dotted line) and 90%$C.L.$ (black continuous line) contours along with Super-Kamiokande 90%$C.L.$ contours from both the zenith angle (red line) and the L/E (blue line) analyses and the K2K 90%$C.L.$ contours (gray line).

oscillate to ν_τ and ν_s with the same mass-squared difference, MINOS obtains an f_s limit of $f_s < 0.68$ at 90%$C.L.$.

MINOS analysis on ν_e appearance is on-going and results are expected soon (end of 2008, beginning of 2009). The potential of this analysis, for the current statistics as well as for the full statistics at the end of data taking, is shown in figure 8. If θ_{13} is at the current Chooz [9] limit MINOS has the potential of being the first experiment to observe it. If not, MINOS will further improve the current Chooz limit.

3.3. OPERA

OPERA [31] is a long baseline neutrino oscillation experiment (L = 730 km) located at the Gran Sasso Underground Laboratory (LNGS). It utilizes an almost pure (98%) ν_μ beam from the CERN SPS accelerator with a mean energy $< E >\sim$ 17 GeV, such that ν_τ's would have energies above the τ production threshold. The OPERA detector is a hybrid lead-emulsion spectrometer [31] with target mass of 1.25Ktons. The emulsion target provides the very high spatial resolution needed, $< 1\mu$, in order to observe and identify τ decays through the so called "kink decay topology".

The primary goal of the OPERA experiment is the direct, unambiguous, verification of ν_μ to ν_τ oscillations by the observation of ν_τ CC interactions originating in a pure ν_μ beam. OPERA is complementary to the MINOS experiment : MINOS has studied in detail ν_μ (to ν_τ) disappearance and OPERA will study in detail ν_μ to ν_τ appearance. OPERA will also study subdominant ν_μ to ν_e oscillations, the existence of sterile neutrinos, and alternative hypothesis to neutrino oscillations like neutrino decay and decoherence.

The direct observation of ν_τ in a hybrid emulsion spectrometer via the detection of the produced τ lepton in the ν_τ CC interactions has been successfully demonstrated by the DONUT

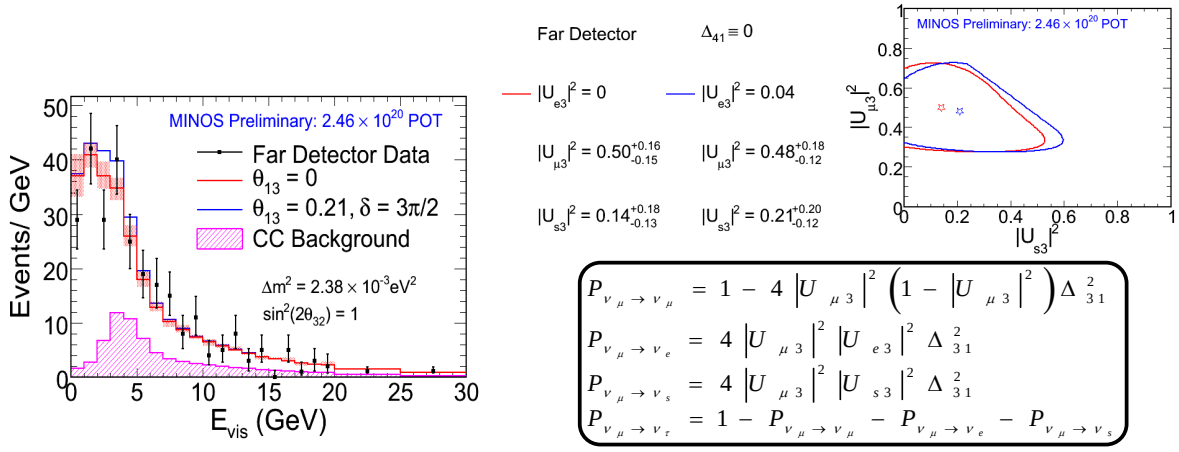

Figure 7. *Left plot*: MINOS Far detector reconstructed visible energy (GeV) spectrum for neutral current-like events. Black points are the data. Red solid line is the expectation under the hypothesis that ν_μ oscillate exclusively to ν_τ ($P(\nu_\mu \to \nu_s) = 0$ and $P(\nu_\mu \to \nu_e) = 0$). Blue solid line is the expectation under the hypothesis that ν_μ oscillate to ν_τ and ν_e with the latter allowed to have its maximal possible value (θ_{13} at the current Chooz limit, normal neutrino mass hierarchy and maximal CP violation with $\delta = 3\pi/2$). *Right plot*: MINOS two dimensional $90\% C.L.$ contours and best fit points resulting from fitting the reconstructed visible energy distribution shown in the left figure under the hypothesis that ν_μ oscillate to ν_τ and ν_s with the same mass squared difference (oscillation probabilities shown at the bottom of this figure)
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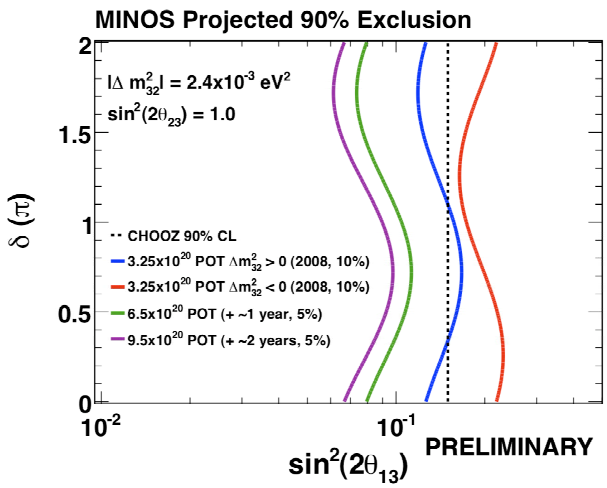

Figure 8. MINOS projections (Monte Carlo) of the $90\% C.L.$ exclusion limit on $\sin^2(2\theta_{13})$ as a function of the CP violating phase *delta* for the current and total foreseen integrated statistics (Protons on Target).

experiment [32]. OPERA, during the October 2007 GNGS run, has accumulated 369 neutrino interactions, 38 of which were recorded and reconstructed in the emulsion target. In figure 9 we show an event with a "kink" topology classified as a charm candidate having two electromagnetic showers originating from the neutrino interaction vertex. In the 2008 GNGS run OPERA expects to see $\sim 1.2\nu_\tau$ CC interactions, and with the full statistics sample, corresponding to 2.25×10^{20} protons on target, 10.4 ± 0.76 ν_τ CC events assuming maximal mixing with a $|\Delta m^2_{32}| = 2.5 \times 10^{-3}$ eV^2.

Due to the excellent spatial resolution of the emulsion target one can distinguish e from π^0

and also reconstruct kinematic variables (momentum imbalance in the transverse plane) that can help to separate ν_e CC from NC interactions. These capabilities enable OPERA to perform a ν_e appearance study [33] with a sensitivity as shown in figure 10.

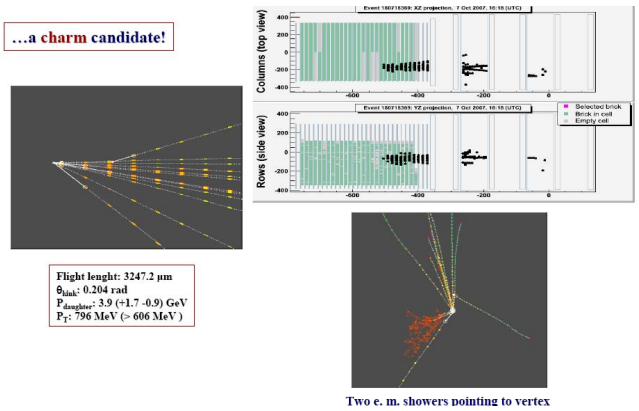

Figure 9. OPERA Charm candidate neutrino interaction. The presence of a clear "kink-topology" in one of the emulsion tracks would classify the interaction as a ν_τ candidate. However there are two electromagnetic showers originating from the interaction vertex, as clearly seen from the reconstructed emulsion information.

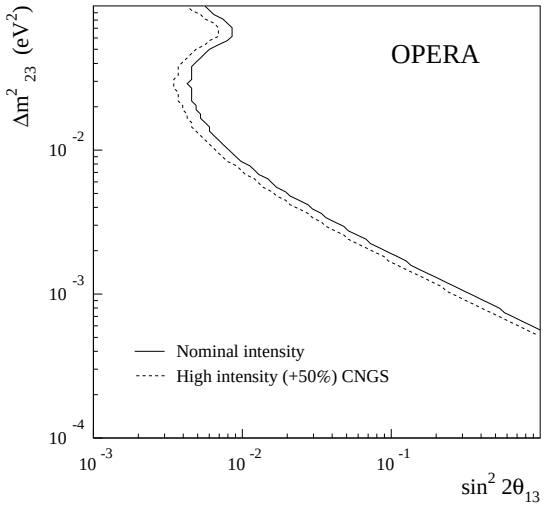

Figure 10. OPERA 90%$C.L.$ sensitivity on $\sin^2(2\theta_{13})$ as a function of Δm^2_{23}.With the full statistics sample OPERA should be able to explore the region well below the Chooz limit.

3.4. ICARUS

ICARUS [34] is a 600 Ton Liquid Argon (LAr) Time Projection Chamber (TPC) now located in the LNGS. The installation is well under way and start of operation is anticipated this calendar year (2008). This detector has excellent three dimensional imaging capabilities with spatial resolution similar to those of bubble chambers, but with electronic readout and continuous sensitivity. In figure 11 we show cosmic ray and neutrino events in the detector which clearly illustrate how powerful this detector technology is.

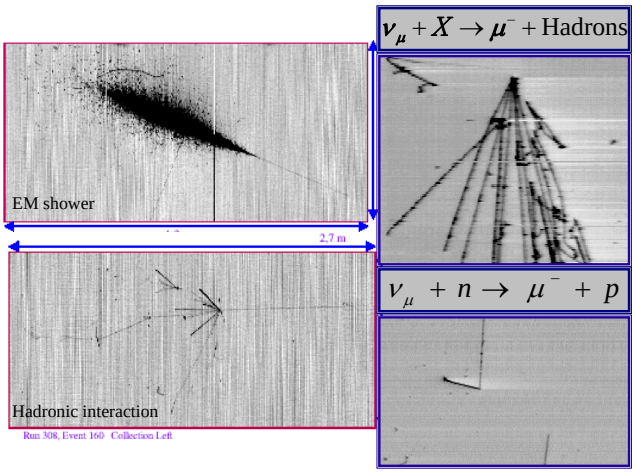

Figure 11. *Left column*: ICARUS Cosmic Ray events. *Right column*: Neutrino interactions in a small ICARUS Prototype exposed in the CERN neutrino beam. The level of detail on event characteristics, observed even by naked eye, demonstrate how powerful such a detector technology is.

Perhaps one of the most important goals of the ICARUS experiment is to prove that this detector technology can function as expected, in an underground laboratory, and for long periods of time, performing a variety of physics measurements using atmospheric, accelerator, supernova and solar neutrinos.

4. "Cross" Mixing Parameters

The main goal of the near (and longer term) future neutrino oscillation experiments is to study the "cross mixing" neutrino oscillation parameters: θ_{13}, δ_{CP} and the neutrino mass hierarchy (sign of Δm^2_{31}). We can group these experiments into two categories: near term 'Phase I" experiments with the main focus being the measurement of θ_{13}, for which only a limit currently exists from the Chooz [9] experiment, and longer term "Phase II" experiments with the main focus being the measurement of CP violation in the neutrino sector and determination of the neutrino mass hierarchy.

"Phase I" experiments can be grouped in two main categories:

Reactor experiments (Double Chooz [35] and Daya Bay [36]) : These are disappearance experiments looking for a deficit of $\overline{\nu}_e$ with respect to expectation. They have the capability of measuring θ_{13} cleanly, namely free from any possible degeneracies arising from the interplay with the other neutrino oscillation parameters, to which they have no sensitivity.

Accelerator long baseline experiments (T2K [38] and NOνA [37]) : These are appearance experiments looking for an excess, with respect to expectation, of ν_e (or $\overline{\nu}_e$)in a ν_μ (or $\overline{\nu}_\mu$) beam. They are, in principle, sensitive to more neutrino oscillation parameters than just θ_{13}.

"Phase I" experiments have an ultimate reach down to $\sin^2(2\theta_{13}) \cong 0.01$, which is larger compared to the Chooz experiment by, at least, an order of magnitude. In addition, the NOνA experiment, due to its very long baseline (810 km compared to 295 km of T2K), has the ability to determine the neutrino mass hierarchy if θ_{13} is close to the current Chooz limit.

The goals of "Phase II" experiments are:

• To extend, if possible, the θ_{13} discovery potential, in case "Phase I" experiments have only yielded more stringent limits.

• To extend the discovery potential for determining the neutrino mass hierarchy for, at least, the region of the θ_{13} discovery potential of "Phase I" experiments.

• To have a discovery potential for measuring CP violation in the neutrino sector for, at least, the region of the θ_{13} discovery potential of "Phase I" experiments. We have to note here that "Phase I" experiments do not have any significant (3σ) discovery potential for CP violation.

4.1. Double Chooz

The main goal of the Double Chooz [35] experiment is to extend the reach on θ_{13} down to a $\sin^2(2\theta_{13}) \sim 0.03$ which is a factor of ~ 5 better than the current limit. Double Chooz uses two 10.3 m^3 liquid scintillator detectors which will study $\overline{\nu}_e$'s from the two reactors at the Chooz-B nuclear power station in France. The far detector is at a distance of 1.05 km, and an identical near detector at 0.4 km were oscillations are not expected to be present. The two detector configuration is used in order to significantly reduce systematic uncertainties by cancellation. In figure 12 we see the sensitivity of the Double Chooz experiment as a function of running time. In the first phase only the far detector will be operational, and in the second phase both near and far detectors will be operational substantially increasing the θ_{13} reach due to the cancellation of systematic uncertainties. The experiment plans to start data taking in the Summer of 2009.

4.2. Daya Bay

The main goal of the Daya Bay [36] experiment is to extend the reach on θ_{13} down to a $\sin^2(2\theta_{13}) \sim 0.01$ which is a factor of ~ 15 better than the current limit. Daya Bay uses 20 ton

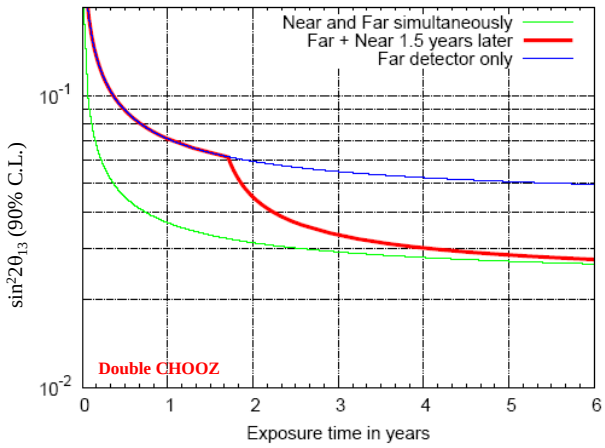

Figure 12. Double Chooz 90% C.L. limit on $\sin^2(2\theta_{13})$ as a function of running time. The blue line is the reach with the far detector alone, the green line is the reach with both near and far detectors operational from the beginning of data taking, and the red line is the realistic scenario in which the near detector becomes operational ∼2 years later than the far detector.

(target mass) liquid scintillator detectors which will study $\overline{\nu}_e$'s from the six reactors at the Daya Bay and Ling Ao nuclear power stations in China. The four identical far detectors are located at a distance of ~ 1.0 km, and a pair of two identical (with the far as well) near detectors at two different locations each at ~ 0.4 km from the reactor cores. The multiple detector configuration is used in order to significantly reduce systematic uncertainties by cancellation. In figure 13 we see the sensitivity of the Daya Bay experiment as a function of running time. The experiment plans to start data taking with all eight detectors operational at the end of 2010.

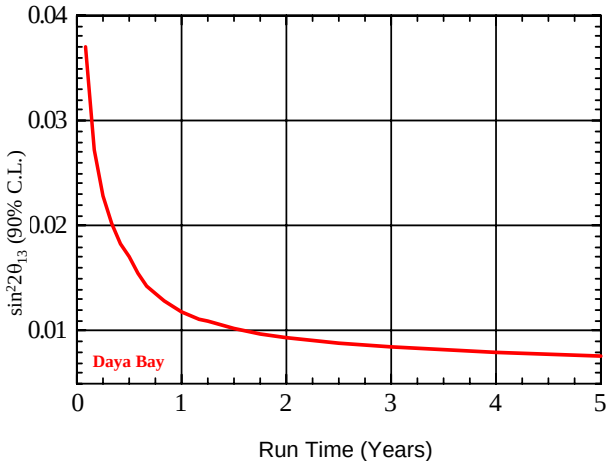

Figure 13. Daya Bay 90% C.L. limit on $\sin^2(2\theta_{13})$ as a function of running time. The ultimate reach in $sin^2(2\theta_{13})$ is ~ 0.01, a factor of three better than Double Chooz.

4.3. **T2K**

T2K [38] is a next generation long baseline accelerator neutrino oscillation experiment with a baseline $L = 295$ km and a mean neutrino energy $< E > \sim 0.6$ GeV. The far detector is the Super-Kamiokande [1] Water Cherenkov (WC) detector. The neutrino beam is an off axis (2.5^o) narrow band beam (NBB) which is currently under construction at JPARC.

The primary goal of the T2K experiment is to search for the subdominant ν_μ to ν_e oscillations with a sensitivity greater by a factor of ~ 20 with respect to the current Chooz limit. The off axis idea is used in order to highly suppress NC backgrounds to the ν_e CC signal, especially the ones with a single π^o produced in the final state. In figure 14 we show the $90\% C.L.$ sensitivity to $\sin^2(2\theta_{13})$ as a function of CP violating phase δ for the full statistics: 5 year of operation at 750 KW of beam power.

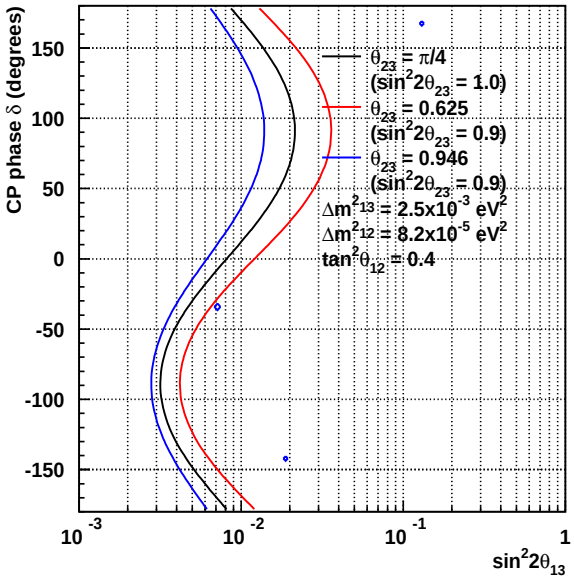

Figure 14. T2K 90%$C.L.$ discovery potential for a non-zero θ_{13} as a function of the CP violating phase δ and for three different values of $\sin^2(2\theta_{23})$. This plot assumes full statistics: 5 years of operation at 750 KW of beam power.

The T2K experiment is anticipated to start taking data in April of 2009 and have first results possibly by summer of 2010.

4.4. NOνA

NOνA [37] is a next generation long baseline experiment with a much longer baseline than T2K, $L = 810$ km, and a mean energy of $< E >\sim 2$ GeV. The NOνA detector is a fully active 15 Kton liquid scintillator detector and the neutrino beam is the NUMI off axis, at a angle of 14 mrad, NBB.

The primary goal of the NOνA experiment is to search for a non-zero θ_{13} with a similar sensitivity to that of the T2K experiment, as shown in figure 15 (left plot). In addition, due to its long baseline, NOνA has the unique capability of determining the neutrino mass hierarchy if θ_{13} is close to the current Chooz limit. In figure 15 (right plot) we show the neutrino mass hierarchy discovery potential when NOνA and T2K are combined.

NOνA is in the final design/construction phase and is expected to start taking data in 2013.

4.5. "Phase II" experiments

As we discussed previously the main goal of the "Phase II" long baseline accelerator neutrino oscillation experiments is the discovery (if present) of CP violation in the neutrino sector, and the determination of the neutrino mass hierarchy.

The measurement of the neutrino mass hierarchy requires a long baseline in order to enhance matter effects. The measurement of CP violation requires information from both the 1st and 2nd oscillation maxima of $P(\nu_\mu \to \nu_e)$ in order to break the inherent degeneracies between "genuine" CP violating and "fake" CP violation arising from matter effects.

There are two ways one can obtain information from both oscillation maxima:
(1) Create a Wide Band neutrino Beam (WBB) in order to study both of them at a fixed baseline with one detector
(2) Use Narrow Band Beams (NBB) at two different off axis angles, which involve two different baselines, and two detectors to study each one of them separately, combining the information afterwards.

Both JPARC and Fermilab have developed plans for future experiments that fulfill the above requirements.

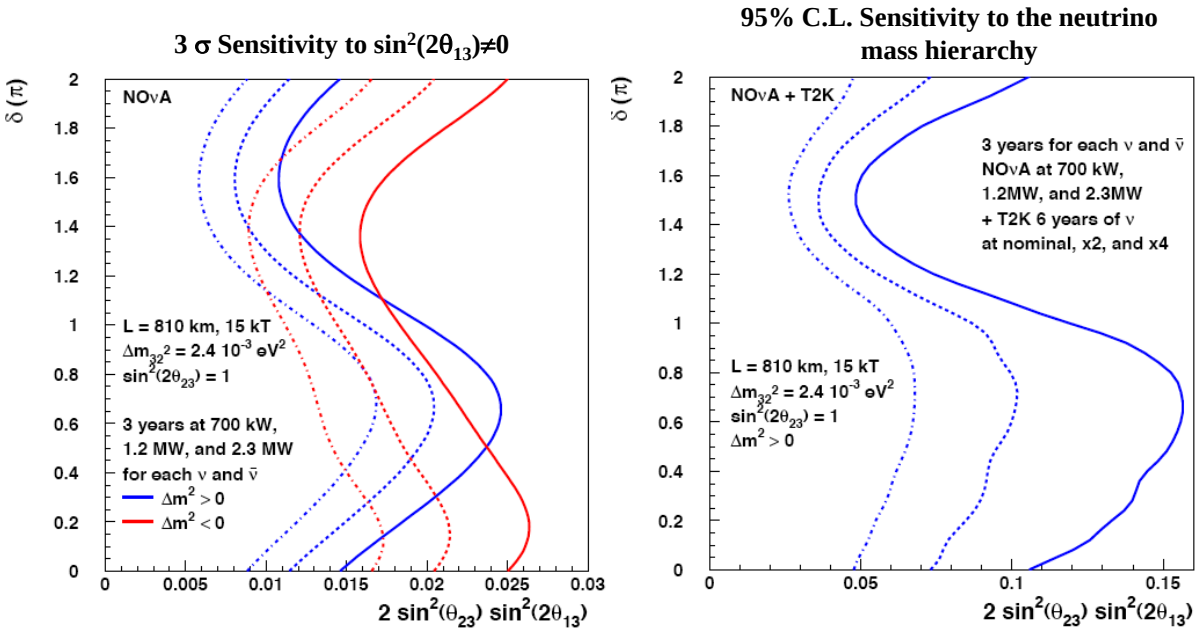

Figure 15. *Left plot*: NOνA 3σ discovery potential for a non-zero θ_{13} for normal (blue lines) and inverted (red lines) hierarchy. Running conditions: 3 years of ν and 3 years of $\overline{\nu}$ at 700 KW (continuous line), 1.2 MW (dashed line) and 2.3 MW (doted line). *Right plot*: NOνA plus T2K 95%$C.L.$ discovery potential for determining the neutrino mass hierarchy assuming normal hierarchy. Running conditions: 3 years of ν and 3 years of $\overline{\nu}$ at 700 KW (continuous line), 1.2 MW (dashed line) and 2.3 MW (doted line) of beam power for the NUMI beam and 6 years of ν running at 750 KW, 1.5 MW and 3 MW of beam power for the JPARC beam.

• **"Phase II" experiments with JPARC beams**: JPARC will be soon (2009) operating the NBB for the T2K experiment starting from a beam power of 100 KW and gradually increasing to the nominal value 750 KW. There are upgrade plans that could increase the JPARC beam power to 1.7 MW and ultimately to 4 MW.

As far as detector masses and baselines are concerned there are two options examined:
i) One 540 Kton Water Cherenkov (WC) detector at Kamioka at the 1st oscillation maximum
ii) Two 270 Kton Water Cherenkov (WC) detectors one located in Kamioka at the 1st oscillation maximum and one located in Korea, $L \sim 1000$ km, at the 2nd oscillation maximum.

The physics capabilities of this program, in terms of discovery potentials for the parameters of interest, (CP Violating phase δ, and the neutrino mass hierarchy), are illustrated in figure 16 where one clearly sees advantage of the two detector configuration covering both oscillation maxima and involving longer baselines.

• **"Phase II" experiments with Fermilab beams**: Fermilab currently operates the NUMI beam at 250 KW with an approved upgrade plan to 700 KW for the NOνA experiment. Over the course of the previous year Fermilab developed a physics plan for the next decade [40], which includes an upgrade to the accelerator complex, called "Project X". "Project X" could produce ≈ 2 MW of beam power for proton energies ranging from 60-120 GeV and resulting in very high intensity neutrino beams.

The first step of the staged program is the NOνA liquid scintillator experiment described in previous sections.

An intermediate step, with quite interesting physics capabilities, could be an upgraded

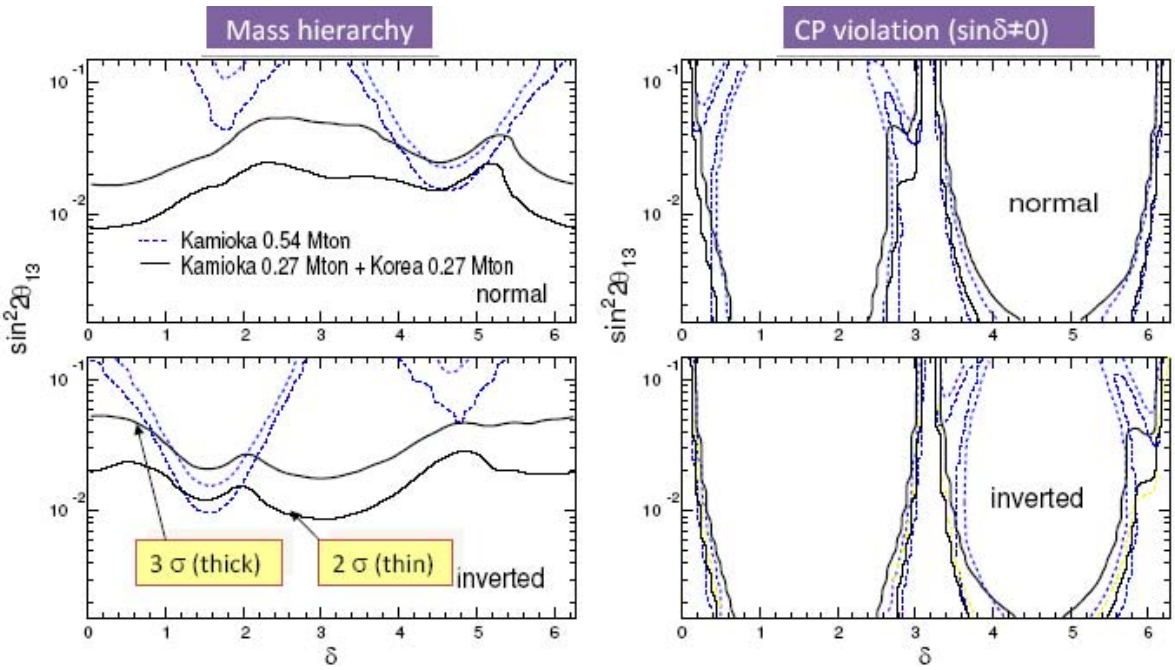

Figure 16. *Left plot*: 3σ (blue dashed line) and 2σ (gray dashed line) mass hierarchy discovery potential with 0.54 MTon Water Cherenkov detector in Kamioka with the JPARC 2.5^o off axis neutrino beam upgraded to 4 MW (nominal beam power is 750 KW). 3σ (black thick line) and 2σ (black thin line) mass hierarchy discovery potential with two 0.27 MTon Water Cherenkov detectors in Kamioka and Korea with the JPARC 2.5^o off axis neutrino beam upgraded to 4 MW (nominal beam power is 750 KW. *Right plot*: 3σ (blue dashed line) and 2σ (gray dashed line) CP violation discovery potential with 0.54 MTon Water Cherenkov detector in Kamioka with the JPARC 2.5^o off axis neutrino beam upgraded to 4 MW (nominal beam power is 750 KW). 3σ (black thick line) and 2σ (black thin line) mass hierarchy discovery potential with two 0.27 MTon Water Cherenkov detectors in Kamioka and Korea with the JPARC 2.5^o off axis neutrino beam upgraded to 4 MW (nominal beam power is 750 KW). Running conditions: 4 years of ν and 4 years of $\overline{\nu}$ running.

(technologically) detector consisting of ∼5 Kton of Liquid Argon (LAr), placed either in the NUMI beam with an $L \sim 700 - 800$ km, or at the Deep Underground Science and Engineering Laboratory (DUSEL) with an $L = 1300$ km.

The next step would be the construction, using most likely a modular approach, of massive detectors, 300 Kton of WC and/or 100Kton LAr, at DUSEL in parallel with the construction of new WBB from Fermilab to DUSEL. The initial beam power would be 700 KW.

Finally, the construction of "Project X" would increase the neutrino beam power from 700 KW to 2 MW. The physics capabilities of this staged program, in terms of discovery potentials for the parameters of interest, (θ_{13}, CP Violating phase δ, and the neutrino mass hierarchy), are illustrated in figure 17 where one clearly sees the progressive increase in the discovery potential.

5. Summary

In this talk we first presented the results and status of neutrino oscillations experiments studying the "solar" and "atmospheric" neutrino mixing parameters. These are experiments in various different phases: either in a smooth data taking and data analysis mode, or just starting or about

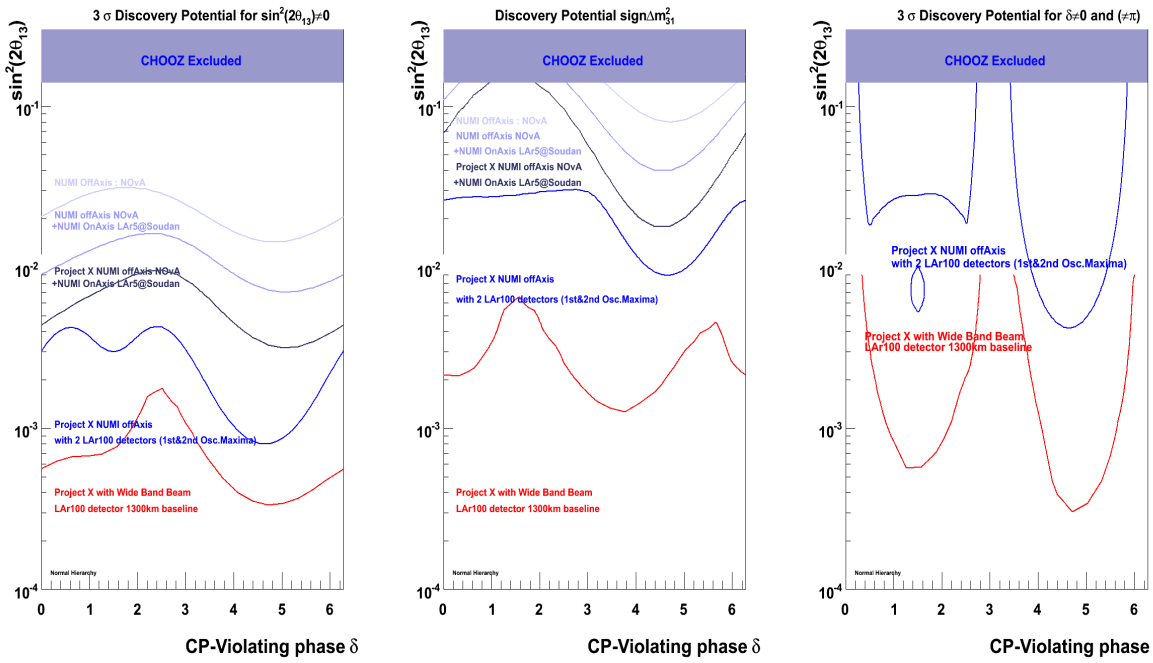

Figure 17. Fermilab Staged Plan: 3σ Discovery potentials for θ_{13}, the neutrino mass hierarchy, and CP violation. From lower to higher discovery potentials: (1) NOνA with NUMI NBB at 700 KW, (2) NOνA+5 Kton LAr with NUMI NBB+WBB at 700 KW, (3) NOνA+5 Kton LAr with NUMI NBB+WBB at 2 MW, (4) 50 Kton LAr at 1st + 50 Kton LAr at 2nd oscillation maxima with NUMI NBB at 2MW, (5) 100 Kton LAr (equivalent with $\sim$ 500 Kton of WC) at DUSEL with new WBB at 2 MW.

to start data taking. They also span a large range of neutrino sources (solar, atmospheric, accelerator, reactor), neutrino species (ν_μ,$\overline{\nu}_\mu$,ν_e,$\overline{\nu}_e$,ν_τ), neutrino energies (from a few KeV to GeV) and baselines (from a few Km to thousand of Km).

Next, we discussed the near and longer term neutrino oscillation experiments with a goal to probe the "cross" mixing neutrino parameters, which are almost entirely unknown with the exception of a θ_{13} upper limit from the Chooz [9] experiment. These experiments in general involve the use of both reactor and accelerator neutrinos from very intense neutrino beams, and the possibility of multiple massive detectors at various neutrino energies and baselines.

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