Future Possibilities with Fermilab Neutrino Beams

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Abstract. We will start with a brief overview of neutrino oscillation physics with emphasis on the remaining unanswered questions. Next, after mentioning near future reactor and accelerator experiments searching for a non zero θ_{13}, we will introduce the plans for the next generation of long-baseline accelerator neutrino oscillation experiments. We will focus on experiments utilizing powerful (0.7 - 2.1 MW) Fermilab neutrino beams, either existing or in the design phase.

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 be 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.

2. "Phase I" and the Goals for "Phase II"

The main goal of all "Phase I" experiments is to measure the third neutrino mixing angle, θ_{13}. "Phase I" experiments can be grouped in two main categories:

Reactor experiments (Double CHOOZ [21] and Daya Bay [22]) : These are disappearance experiments looking for a deficit of $\bar{\nu}_e$ 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 [20] and NOvA [19]) : These are appearance experiments looking for an excess, with respect to expectation, of ν_e (or $\bar{\nu}_e$)in a ν_μ (or $\bar{\nu}_\mu$) 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 NOvA 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.

3. "Phase II" : ν Beams, Baselines and Detectors

Before we describe the requirements needed, in terms of neutrino detectors, beams and baselines, in order for "Phase II" experiments to fulfill their goals, let us read the neutrino oscillation probability for the phenomenon of interest:

$$P(\nu_\mu \longrightarrow \nu_e) \cong sin^2(2\theta_{13}) \cdot T_1 - a \cdot sin(2\theta_{13}) \cdot T_2 - a \cdot sin(2\theta_{13}) \cdot T_3 + a^2 T_4 \qquad (1)$$

where: $a = \frac{\Delta m_{21}^2}{\Delta m_{31}^2}, x = \frac{2\sqrt{2}G_F N_e E}{\Delta m_{31}^2}, \Delta = \frac{\Delta m_{31}^2 L}{4E}$ Matter effects,

$T_1 = sin^2(\theta_{23})\frac{sin^2[(1-x)\Delta]}{(1-x)^2}$

$T_2 = sin(\delta_{CP})sin(2\theta_{12})sin(2\theta_{23})sin\Delta \frac{sin(x\Delta)}{x} \frac{sin[(1-x)\Delta]}{(1-x)}$ CP Violating

$T_3 = cos(\delta_{CP})sin(2\theta_{12})sin(2\theta_{23})sin\Delta \frac{sin(x\Delta)}{x} \frac{sin[(1-x)\Delta]}{(1-x)}$ CP Conserving

$T_4 = cos^2(\theta_{23})sin^2(\theta_{12})\frac{sin^2(x\Delta)}{x^2}$

In neutrino experiments we measure the number and type of neutrino interactions as a function of energy, E, and distance, L. With this information we have to reconstruct the oscillation probability, as shown in Equation1, and determine the parameters of interest: θ_{13}, δ_{CP} and $sign(\Delta m_{31}^2)$.

This is a non trivial task especially if we take into account the fact that strong degeneracies are present between the parameters of interest, and in particular between "genuine" CP violation and "fake CP violation" arising from matter effects, as illustrated in Figure 1.

Given the above, and in order for "Phase II" experiments to achieve their goals one needs:

• High statistics since we know the effect is small. This means powerful neutrino beams (more powerful than those of "Phase I") and large detectors (larger than those of "Phase I").

• Multiple measurements as a function of L, and E in order to be able to break degeneracies.
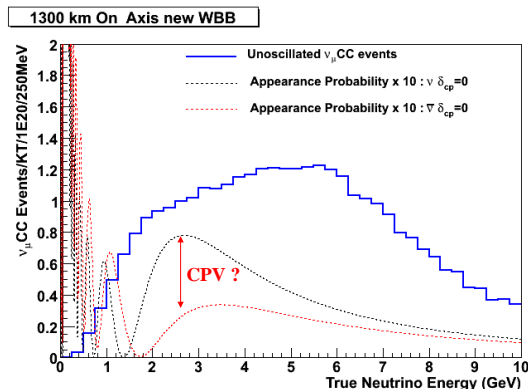
Figure 1. $P(\nu_\mu \longrightarrow \nu_e)$ for neutrinos (black dotted line) and anti-neutrinos (red dotted line) superimposed to an unoscillated ν_μ spectrum (blue histogram). The difference between the neutrino and anti-neutrino oscillation probabilities is due to matter effects and not due to CP symmetry violation. Such strong degeneracies between "genuine CP violation" and "fake CP violation" make experimental measurements challenging.

• Longer baselines (possibly longer those of "Phase I" experiments) in order to enhance matter effects increasing the discovery potential for the neutrino mass hierarchy.

3.1. Detector Options

There have been several ideas over the past years on how to construct massive neutrino detectors [10]-[17]. The two main detector technologies under consideration are Water Cherenkov (WC) and Liquid Argon (LAr). Both technologies have advantages and disadvantages : Water Cherenkov detectors are using a proven technology but have relatively low efficiency ($\sim 20\%$ on average, but with strong energy dependence) and low background rejection($\sim 1\%$ on average, but with strong energy dependence). Liquid Argon detectors are "using" a technology not proven for the mass scales of interest ($\sim$100 KT) but have high efficiency ($\sim 80\%$) and high background rejection ($< 1\%$) due to their very high spatial resolution.

3.2. Beam Options

There are two main options regarding neutrino beams, both having advantages and disadvantages.
• On Axis (or slightly Off Axis) Wide Band Beams (WBB)
The advantages of WBBs are the higher event rates and the ability to study both the first and the second oscillation maxima using one detector at a specific location. The disadvantage is the higher Neutral Current Background rate (to the ν_e signal) resulting from the high energy tail of the spectrum.
• Off Axis Narrow Band Beams (NBB)
The advantage of NBBs is the strongly suppressed rates of the Neural Current Backgrounds, since the high energy tail is significantly suppressed. The disadvantage is the lack of the ability to study both first and second oscillation maxima with one detector at one location. In this case one would need two detectors at two different locations, and given that the second oscillation maximum would require a larger off axis angle (due to the fact that it occurs at lower neutrino energies) the rates would be very strongly suppressed.

In Figure 2 we illustrate both the advantages and disadvantages discussed above, as well the importance of being able to study both the 1st and 2nd oscillation maxima : the 2nd oscillation maximum (occurring at lower neutrino energies) does not suffer, at least not to the same extend as the 1st oscillation maximum, from the degeneracies between "genuine" and "fake" CP violation discussed in the previous sections. Hence the ability to study it is very important both for the determination of δ_{CP} and the neutrino mass hierarchy.
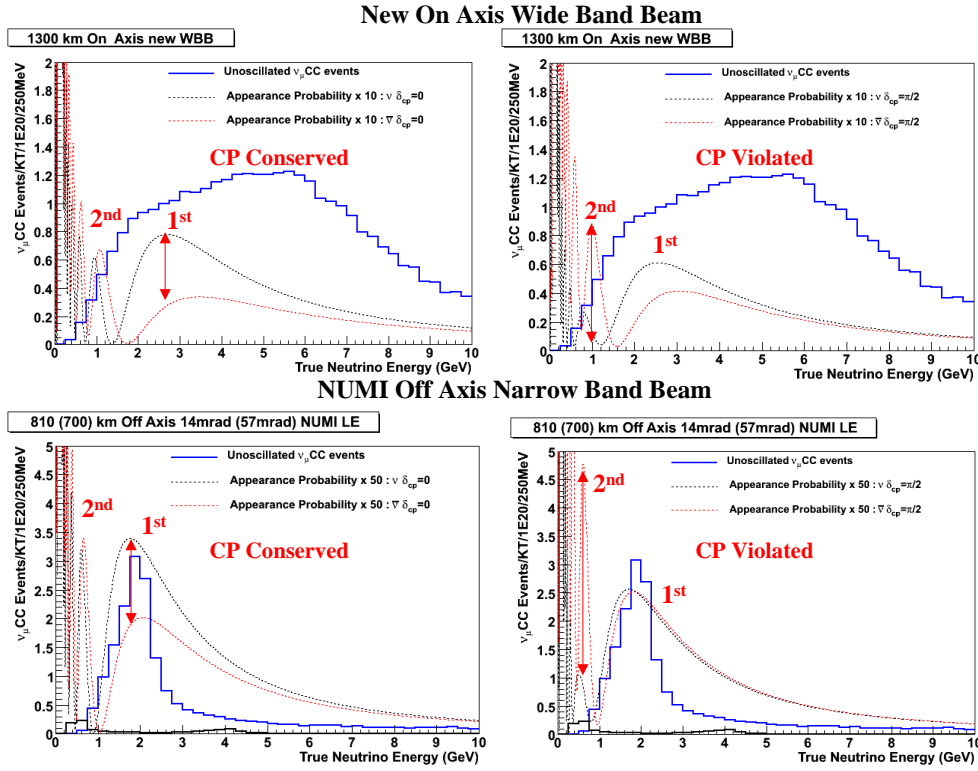
Figure 2. Top row: WBBs. Bottom row: NBBs. Left column : Conserved. Right column: CP Violatied. Blue (and black) histogram is the unoscillated ν_μ spectrum with $P(\nu_\mu \longrightarrow \nu_e)$ (black dotted line) and $P(\overline{\nu}_\mu \longrightarrow \overline{\nu}_e)$ (red dotted line) superimposed. The 2nd oscillation maximum exhibits a difference in neutrino-antineutrino oscillation probabilities only when CP is violated (matter effects do not play a significant role). Whereas the 1st oscillation maximum exhibits a difference between neutrino-antineutrino oscillation probabilities due to matter effects, even when CP is conserved. Information from both (1st and 2nd) maxima helps breaking these inherent degeneracies. In the WBB case one detector is needed to study both 1st and 2nd oscillation maxima, whereas in the NBB case two detectors at two different locations, one at 1st and one at 2nd oscillation maxima, would be necessary.

3.3. Baseline Options

Fermilab is currently operating the most intense neutrino beam world-wide (NUMI beam). This beam is currently used by the MINOS [6] experiment and in the near future by the Minerva [18](2009) and NOvA (2013) experiments. The NOvA experiment is going to use a NUMI Off Axis Narrow Band Beam at a baseline of 810 km and an off axis angle of 14 mrad.

Another possible configuration is a longer baseline of 1300 km from Fermilab to the Deep Underground Science Laboratory (Homestake Mine in South Dakota, USA) which would necessitate building a new, and preferably for reasons discussed in the previous section, WBB neutrino beam.

The two configurations along with the advantages of the longer baseline (1300 km vs 810 km) are illustrated in Figure 3: A longer baseline increases matter effects and hence increases the neutrino mass hierarchy discovery potential. In addition, 1st and 2nd oscillation maxima move to higher energies where both fluxes and cross sections are higher, and the experimental determination of type and energy of neutrino interactions is easier.
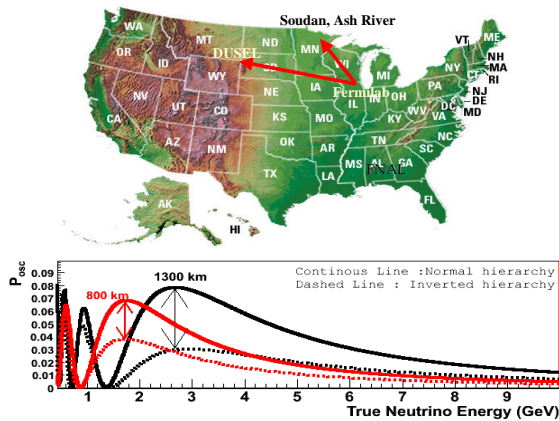
Figure 3. Top Plot: Long baseline options in the US : (A) Fermilab to Soudan (MINOS) and Ash River (NOvA) with a baseline of 735 km and 810 km respectively, using the NUMI On Axis beam (MINOS) or NUMI NBB Off Axis (NOvA). (B) Fermilab to DUSEL with a baseline of 1300 km and the possibility of a new WBB. Bottom Plot: $P(\nu_\mu \longrightarrow \nu_e)$ for the normal (continuous line) and inverted (dotted line) neutrino mass hierarchy and for two different baselines : 810 km and 1300 km.

4. Fermilab's Staged Plan

Fermilab currently operates the NUMI beam at 250 KW with an approved upgrade plan to 700 KW for the NOvA experiment. Over the course of the previous year Fermilab developed a physics plan for the next decade [23], which includes an upgrade to the accelerator complex, called "Project X". "Project X", as seen in Figure 4, could produce $\approx$ 2 MW of beam power for proton energies ranging from 60-120 GeV and resulting in very high intensity neutrino beams.
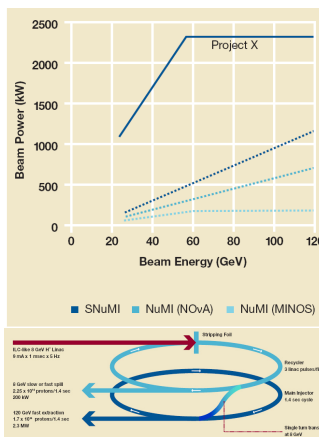

Figure 4. "Project X" beam power as a function of primary proton beam energy.

Such powerful neutrino beams (existing, or at the design phase) coupled to large detectors at long-baselines create a world-leading, staged program in neutrino physics for decades to come [23].

The first step of the staged program is the NOvA liquid scintillator experiment using the 700 KW NUMI Off Axis NBB at a baseline of 810 km.

An intermediate step, with quite interesting physics capabilities, could be an upgraded (technologically) detector consisting of ~5 KT LAr, placed either in the NUMI beam or at DUSEL. The next step will be the construction, using most likely a modular approach, of massive detectors (300 KT of WC and/or 100 KT 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" will increase the neutrino beam power from 700 KW to 2MW. The physics capabilities of this staged program, in terms of discovery potentials for the parameters of interest(θ_{13}, δ_{CP}, $sign(\Delta m_{31}^2)$), are illustrated in Figure 5. One clearly sees the progressive increase in discovery potential. The final/ultimate reach entirely fulfills the requirements of "Phase II", as described in the previous sections.
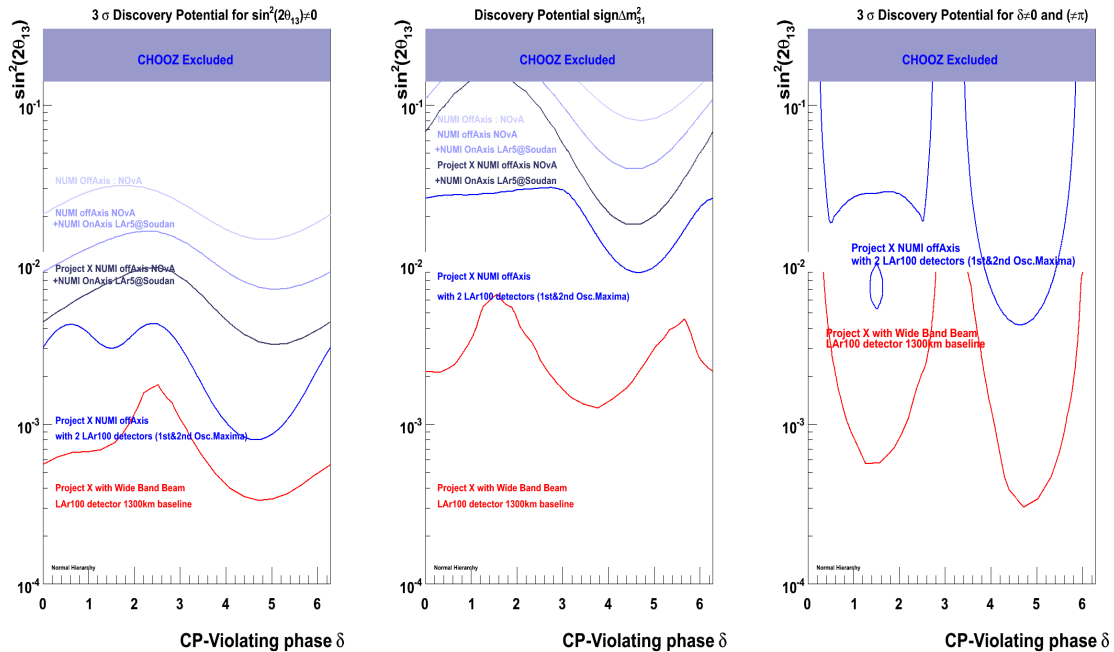
Figure 5. Fermilab Staged Plan: 3σ Discovery potentials for θ_{13}, the neutrino mass hierarchy, and CP violation. From lower to higher discovery potentials : (1) NOvA with NUMI NBB at 700 KW, (2) NOvA+5 KT LAr with NUMI NBB+WBB at 700 KW, (3) NOvA+5 KT LAr with NUMI NBB+WBB at 2 MW, (4) 50 KT LAr at 1st + 50 KT LAr at 2nd oscillation maxima with NUMI NBB at 2MW, (5) 100 KT LAr (eq. with >300 KT of WC) at DUSEL with new WBB at 2 MW.

5. Summary
In this talk we discussed the remaining open questions in neutrino oscillation physics, which determine the goals of the next generation of long baseline accelerator neutrino oscillation experiments, and a staged plan in order to address them, using existing and planned facilities at Fermilab.

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