

Intense Neutrino Beams and Leptonic CP Violation

William J. Marciano and Zohreh Parsa

Brookhaven National Laboratory¹Upton, New York 11973

E-mail: marciano@bnl.gov, parsa@bnl.gov

Abstract. Effects of the Leptonic CP violating phase, δ , on 3 generation neutrino oscillation rates and asymmetries are discussed. A figure of merit argument is used to show that our ability to measure the phase δ is rather insensitive to the value of θ_{13} (for $\sin^2 2\theta_{13} \gtrsim 0.01$) as well as the detector distance (for very long oscillation baselines). Using a study of $\nu_\mu \rightarrow \nu_e$ oscillations for BNL-Homestake (2540 km) we show that a conventional horn focused wide band neutrino beam generated by an intense 1-2 MW proton source combined with a very large water Cherenkov detector (250-500 kton) should be able to determine δ to about $\pm 15^\circ$ in 5×10^7 sec. of running. In addition, such an effort would also measure the other oscillation parameters (θ_{ij} , Δm_{ij}^2) with high precision. Similar findings apply to a Fermilab-Homestake (1280 km) baseline. We also briefly discuss features of Superbeams, Neutrino Factories and Beta-Beams.

1. Status Of 3 Generation Lepton Mixing

The known weak interaction states $|\nu_\ell\rangle$, $\ell = e, \mu, \tau$ produced in charged current interactions are related to the neutrino mass eigenstates $|\nu_i\rangle$, $i = 1, 2, 3$ with masses m_i by the 3×3 unitary matrix U .

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = U \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix} \quad (1)$$

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$$c_{ij} = \cos \theta_{ij} \quad , \quad s_{ij} = \sin \theta_{ij}$$

(Our phase convention differs in sign from the PDG, but is more consistent with V_{CKM}).

Studies of atmospheric, $K2K$ and recent MINOS $\nu_\mu \rightarrow \nu_\mu$ disappearance indicate[1]

$$\Delta m_{32}^2 = m_3^2 - m_2^2 = \pm 2.6(3) \times 10^{-3} \text{eV}^2 \quad (2a)$$

$$\sin^2 2\theta_{23} \simeq 1.0 \quad \theta_{23} \simeq 45 \pm 5^\circ \quad (2b)$$

¹ This work is supported by the U.S. Department of Energy under contract number DE-AC02-98-CH-10886.

The sign of Δm_{32}^2 is undetermined. For $m_3 > m_2$, normal ordering, neutrinoless double beta decay is highly suppressed, while for $m_2 > m_3$, inverted hierarchy, there is a chance that it could be observable in the next generation of experiments. So, determining the sign of Δm_{32}^2 is important. In the case of θ_{23} , maximal mixing, $\theta_{23} \simeq 45^\circ$ is favored. How close that angle is to 45° and whether it is less than or greater than 45° (currently only $\sin^2 2\theta_{23}$ is determined) is a key issue for model building. A very precise measurement is strongly warranted.

Solar neutrino and the Kamland reactor oscillation experiments indicate[1]

$$\Delta m_{21}^2 = m_2^2 - m_1^2 = 8 \pm 1 \times 10^{-5} \text{eV}^2 \quad (3a)$$

$$\sin^2 2\theta_{12} \simeq 0.84 \pm 0.10, \quad \theta_{12} \simeq 33^\circ \pm 4^\circ \quad (3b)$$

The angle θ_{12} is large but not maximal.

Within the 3 generation formalism, what remains to be determined are the value of θ_{13} , which is currently bounded[1]

$$0 \leq \sin^2 2\theta_{13} \lesssim 0.14, \quad (4)$$

by reactor experiments, along with the phase, δ , about which nothing is currently known

$$-180^\circ \leq \delta < 180^\circ \quad (5)$$

After those parameters are determined, one will have an intrinsic measure of leptonic CP violation via the Jarlskog invariant[2]

$$J_{CP} \equiv \frac{1}{8} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \cos \theta_{13} \sin \delta. \quad (6)$$

From the known angles ($\sin^2 2\theta_{12} \approx 0.8$, $\sin^2 2\theta_{23} \simeq 1$)

$$J_{CP} \simeq 0.23 \sin \theta_{13} \sin \delta, \quad (7)$$

which suggests it is potentially enormous in comparison with the quark CKM matrix value

$$J_{CP}^{CKM} \simeq 3 \pm 1 \times 10^{-5} \quad (8)$$

Besides determining the Δm_{ij}^2 , their signs, θ_{ij} and δ as precisely as possible, one would also like to have precision redundancy in those studies which probes deviations due to “new physics” such as sterile neutrino mixing, extra dimensions, exotic neutrino interactions, etc.

2. CP Violation

The flavor changing oscillations $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ have a very rich structure which includes CP violation. The oscillation probability is given by 3 important contributions as well as matter effects and smaller terms (which we neglect)[3, 4]

$$P(\nu_\mu \rightarrow \nu_e) = P_I(\nu_\mu \rightarrow \nu_e) + P_{II}(\nu_\mu \rightarrow \nu_e) + P_{III}(\nu_\mu \rightarrow \nu_e) + \text{matter} + \text{smaller terms} \quad (9)$$

$$P_I(\nu_\mu \rightarrow \nu_e) = \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 \left(\frac{\Delta m_{31}^2 L}{4E_\nu} \right) \quad (10)$$

$$P_{II}(\nu_\mu \rightarrow \nu_e) = \frac{1}{2} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \cos \theta_{13} \sin \left(\frac{\Delta m_{21}^2 L}{2E_\nu} \right) \times \left[\sin \delta \sin^2 \left(\frac{\Delta m_{31}^2 L}{4E_\nu} \right) + \cos \delta \sin \left(\frac{\Delta m_{31}^2 L}{4E_\nu} \right) \cos \left(\frac{\Delta m_{31}^2 L}{4E_\nu} \right) \right] \quad (11)$$

$$P_{III}(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta_{12} \cos^2 \theta_{13} \cos^2 \theta_{23} \sin^2 \left(\frac{\Delta m_{21}^2 L}{4E_\nu} \right) \quad (12)$$

while for $\bar{\nu}_\mu$, $\delta \rightarrow -\delta$ and matter effects change sign.

The rich structure of $\nu_\mu \rightarrow \nu_e$ oscillations is nicely illustrated in Figs. 1-4 for BNL-Homestake and Fermilab-Homestake distances. Matter modifies the oscillation amplitudes and peak positions (the effect is opposite for an inverted hierarchy), making it straight forward to determine the sign of Δm_{31}^2 with only a ν_μ beam. Also, the effect of δ is important even for $\delta = 0$, no CP violation. By measuring the ν_μ oscillation probability as function of a $\frac{L}{E_\nu}$ over a broad range, one can in principle measure all the parameters of neutrino oscillations with no degeneracies in δ , θ_{23} and the mass hierarchy by a fit to Eq(9). For that reason, we favor[3, 4, 5] using an on axis broad band neutrino beam for $0.5 \text{ GeV} \leq E_\nu \leq 5 \text{ GeV}$.

Do we need to know the value of θ_{13} before we embark on measuring δ ? Not really, since the degree of difficulty for measuring δ is to a large extent independent of θ_{13} (unless it is very small) and the baseline distance (for $1200 \text{ km} \lesssim L \lesssim 4000 \text{ km}$) if we use the wide band beam. To see that feature, consider the CP violation asymmetry.

$$A_{CP} \equiv \frac{P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)} \quad (13)$$

It is given to leading order in Δm_{21}^2 (assuming $\sin^2 2\theta_{13}$ is not too small) by

$$A_{CP} \simeq \frac{\cos \theta_{23} \sin 2\theta_{12} \sin \delta}{\sin \theta_{23} \sin \theta_{13}} \left(\frac{\Delta m_{21}^2 L}{4E_\nu} \right) + \text{matter effects} \quad (14)$$

For fixed E_ν , the asymmetry grows linearly with distance and increases as θ_{13} gets smaller. Of course $|A_{CP}|$ is bounded by 1; so, if it exceeds that value, e.g. if $\sin^2 2\theta_{13} \lesssim 0.003$, a breakdown in our assumption about the dominance of P_I in the denominator of eq.(13) is occurring.

The statistical figure of merit[3] is given by

$$F.O.M. = \left(\frac{\delta A_{CP}}{A_{CP}} \right)^{-2} = \frac{A_{CP}^2 N}{1 - A_{CP}^2} \quad (15)$$

where N is the total number of $\nu_\mu \rightarrow \nu_e + \bar{\nu}_\mu \rightarrow \bar{\nu}_e$ events (properly normalized). Since N falls (roughly) as $\sin^2 \theta_{13}$ and $A_{CP}^2 \sim 1/\sin^2 \theta_{13}$, we see that to a first approximation the F.O.M. is independent of $\sin \theta_{13}$. Similarly, for a given E_ν the neutrino flux and consequently N falls as $1/L^2$ but that is canceled by L^2 in A_{CP}^2 . So, to a good approximation, our ability to measure CP violation is insensitive to L (at oscillation max.) and the value of θ_{13} (if it is not too small).

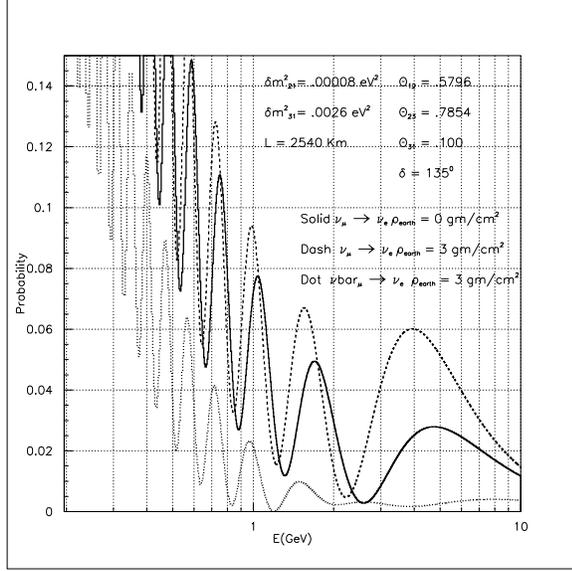


Figure 1.

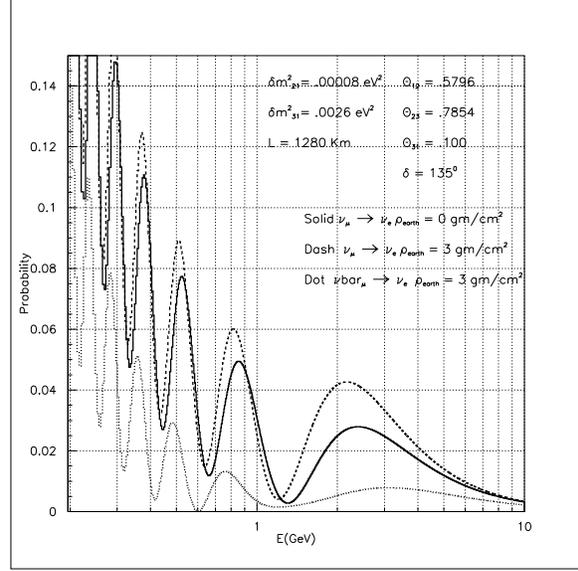


Figure 2.

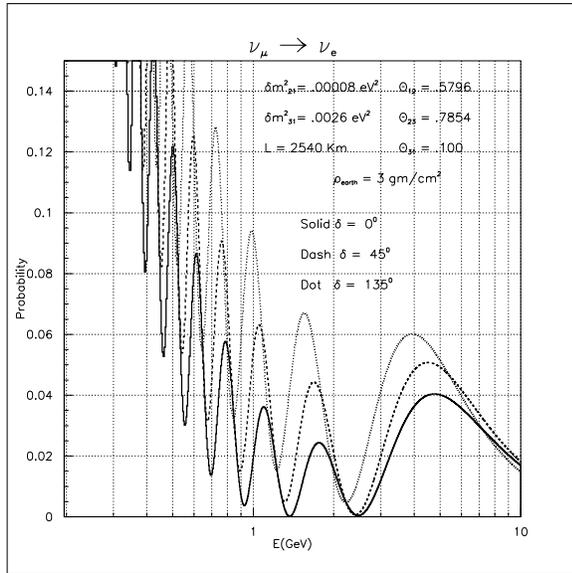


Figure 3.

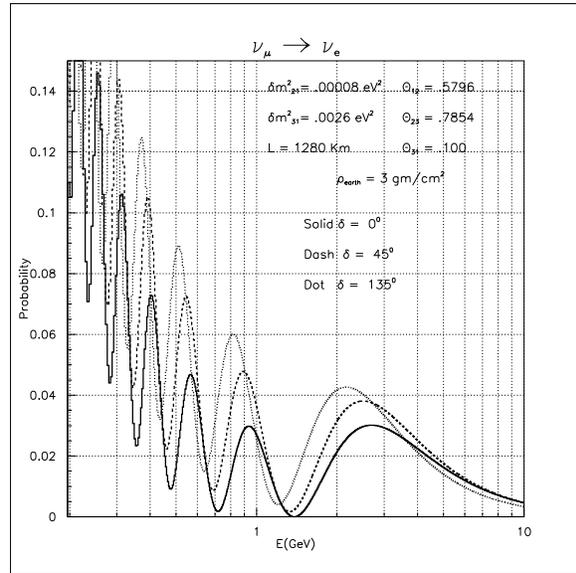


Figure 4.

Fig 1-4. Neutrino oscillations, ν_μ to ν_e , as a function of energy for (Figs. 1 & 3) BNL-Homestake (2540 km) and (Figs. 2 & 4) FNAL - Homestake (1280 km). Effects of matter for neutrinos & antineutrinos relative to neutrinos with no matter are illustrated in Figs. 1 & 2, for $\delta = 135^\circ$. A comparison of different phases $\delta = 0, 45^\circ, 135^\circ$ is given in Figs. 3 & 4. In all cases, we assume a normal mass hierarchy, $\theta_{12} = 0.5796$, $\theta_{23} = 0.7854$ & $\theta_{13} = 0.1$ radians.

Another way of seeing the insensitivity to L in determining δ is to consider the 3 terms in eqs. (10-12) separately. Each contributes to $\nu_\mu \rightarrow \nu_e$ oscillations. The number of events from P_I falls as $1/L^2$ due to flux reduction while those from P_{II} fall as $1/L$ and from P_{III} they are approximately constant (assuming $\sin \frac{\Delta m_{21}^2 L}{4E_\nu} \sim \frac{\Delta m_{21}^2 L}{4E_\nu}$). Viewing P_I and beam induced

backgrounds (which also fall as $1/L^2$) together as a total background for measuring P_{II} and P_{III} , we see that the determination of P_{II} and therefore δ relative to those backgrounds is independent of L for fixed E_ν while the P_{III} signal to background increases linearly with L . So, longer distances have some advantages for P_{III} . In addition, we see from eq. (11) that we can measure both $\sin \delta$ and $\cos \delta$ just by mapping out $\nu_\mu \rightarrow \nu_e$ oscillations (without antineutrinos) over a broad energy region. For those reasons, along with matter enhancement effects, larger E_ν high energy cross-sections, larger total neutrino flux etc. we advocate a wide band neutrino beam (on axis) $0.5 \lesssim E_\nu \lesssim 5$ GeV and a large detector at $1200 - 4000 km$ for the measurement of δ . Our study of that idea has shown many added benefits from the very long distance and broad band beam. Indeed, in principle it allows measurement of Δm_{31}^2 , Δm_{21}^2 , $sign \Delta m_{31}^2 \sin^2 2\theta_{12}$, $\sin^2 2\theta_{13}$, $\sin^2 2\theta_{23}$ and δ with outstanding to good precision in one experiment, possibly with only ν_μ running (i.e. no $\bar{\nu}_\mu$). The basic features of that proposal[6] and some of its advantages are outlined below using a BNL-Homestake baseline, but first we explain why a conventional horn focused neutrino beam is currently the only viable way to explore leptonic CP violation.

3. Other Intense Neutrino Beams[5]

3.1. Neutrino Superbeams:

By definition, a neutrino superbeam would require a 4MW or more proton driver. Such a facility would deliver 4 times as much neutrino flux as a more conventional 1MW source. However, because of heat and increased radiation loads it would require liquid targets, robotic handling and special focusing horns or solenoids. The engineering requirements for 4MW are much more demanding, requiring significant R&D to be realized[5]. The cost for such a facility would be much higher than the more conventional 1MW proton driver and horn envisioned above. Preliminary discussions of 4MW sources for neutrino superbeams and their anticipated oscillation studies are[7, 8] JPARC (Phase II) \rightarrow Hyper K (1000 kton H_2O), $L = 295 km$, CERN (Super linac) \rightarrow Frejus (1000kton H_2O), $L = 130 km$. Because of the relatively short baseline distances, those proposals would employ only low energy neutrino flux $E_\nu < 1$ GeV for their oscillation studies. That corresponds to only a fraction of the potentially available neutrino flux and the cross-section is lower. To compensate, they must employ enormous detectors (1000 Kton), a more powerful source, and long running time. We have argued that it is much more cost effective and richer in physics to use a wide band beam of higher energy neutrinos and a much longer detector baseline distance[3, 4, 5, 6].

3.2. Neutrino Factory[9]

Starting with an intense proton beam on target, the neutrino factory concept envisions capturing the μ^\pm from $\pi^\pm \rightarrow \mu^\pm \nu$ decays, cooling them and then accelerating them to 20–50 GeV. At that point they are placed in a storage ring with long straight sections where the decays $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$ or $\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$ produce clean fluxes of high energy neutrinos with $\langle E_\nu \rangle \simeq 0.7 - 0.8 E_\mu$. Neutrino factories are expected to yield about $0.03 \nu_\mu$ /proton; i.e. about $1/5$ the flux of a conventional horn focused neutrino beam. The neutrino factories advantage (if it can be utilized) is the higher energy[9]. The beam solid angle will scale as $\sim 1/E_\mu^2$ and deep-inelastic cross-sections grow as E_ν . Hence, at fixed distance one can gain $\sim E_\mu^3$ in event rate. However, in the case of oscillation studies, higher energies demand longer distance requirements for a fixed L/E and a flux fall-off by $1/L^2$. That means, for $E_\nu \simeq 20$ GeV to sit at the first oscillation peak requires a detector at 12,000 km which is not possible. Hence, neutrino factories must do their studies primarily at shorter distances ($\sim 3000 km$) where the first oscillation is only fractional. For measuring θ_{13} , the relative nearness is actually an advantage, but it is a drawback for CP violation studies which are optimized at oscillation peaks. If θ_{13} is extremely small, $\sin^2 2\theta_{13} \lesssim 0.003$, Neutrino Factories may be our best hope for measuring it. However, in that case, CP violation and the phase δ will be difficult to determine with such a facility.

3.3. Beta Beam

The interesting possibility of producing intense ν_e or $\bar{\nu}_e$ beams from nuclear beta decays was originally suggested by P. Zucchelli[10]. It is particularly well matched to CERN's radioactive beams capabilities and accelerator complex. To be competitive with other intense neutrino facilities, the radioactive nuclei must be copiously produced $\gtrsim 10^{13}/sec$, cooled, accelerated to $\gamma \simeq 100$ and kept in a large storage ring (with a long straight section) where a highly collimated ν_e or $\bar{\nu}_e$ beams is produced by the decay $N \rightarrow N'e\bar{\nu}_e$. Such a feat is extremely challenging, but the resulting beam has some very attractive features. It is absolutely clean, containing pure ν_e or $\bar{\nu}_e$ with a precisely calculable energy spectrum. Unlike the neutrino factory, it does not require a magnetized detector; so, a very large H_2O Detector can be used. The neutrino energy spectrum is relatively low but broad, which are favorable characteristics for studying CP violation and measuring δ . On the negative side, the flux is limited to $O(10^{18}\nu/yr)$ and the ν_μ appearance cross-section is small. CP violation studies lack statistics but may be marginally viable because of the potentially tiny backgrounds.

4. BNL-HOMESTAKE NEUTRINO OSCILLATION EXPERIMENT

We have written a white[6] paper and had several follow-up studies extolling the virtues of a very long baseline BNL-Homestake (2540 km) neutrino oscillation experiment. (Actually, any distance[3] from about 1200–4000 km will do.) Its basic requirements are: 1) A conventional horn focused intense ν_μ beam using an upgraded 1-2 MW AGS proton beam on a standard target. The cost and technical requirements [6] needed for the upgrade are modest in comparison with ideas for 4MW superbeam or neutrino-factory sources described above. The resulting neutrino beam (on axis at 0°) would be broad band, $0.5 \text{ GeV} \lesssim E_\nu \lesssim 5 \text{ GeV}$, peaking near 1.5 GeV. 2) The detector[11] would be about a 250– 500 kton water cherenkov detector and would likely be somewhat modular in design. This is again modest (about half the cost) in comparison with the 1000 kton behemoth detectors being considered by others. To reconstruct the neutrino energy on an event by event basis and reject π^0 background, we would primarily use quasi-elastic events $\nu_e n \rightarrow e^- p$ in the analysis. They represent less than 1/4 of all neutrino events; therefore, a detector with better resolution and acceptance such as liquid Argon or Scintillator could be smaller, in principle, of order 100–200 kton by using a larger fraction of events to do the job. 3) The run time would be about 5×10^7 sec with a ν_μ beam. Two types of oscillation measurements would be made $\nu_\mu \rightarrow \nu_\mu$ disappearance and $\nu_\mu \rightarrow \nu_e$ appearance. At a later time $\bar{\nu}_\mu$ studies might be carried out; however, they may not be necessary because the wide band beam allows sensitivity to all neutrino oscillation parameters, even δ , without actually measuring a CP violating effect such as A_{CP} directly. Instead a fit is done to the data assuming 3 generation mixing.

Because of the long distance and broad band beam, many physics studies are possible. The measurement of $\nu_\mu \rightarrow \nu_\mu$ disappearance

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta_{23} \sin^2 \left(\frac{\Delta m_{31}^2 L}{4E_\nu} \right) + \text{smaller terms} \quad (16)$$

over the range $0.5 \leq E_\nu \leq 5 \text{ GeV}$ would be sensitive to 3 or 4 oscillation cycles [6]. Such measurements would determine $\sin^2 2\theta_{23}$ and Δm_{31}^2 to better than $\pm 1\%$ statistically. Such a study will tell us if $\theta_{23} \simeq 45^\circ$ to within about $\pm 2^\circ$. Also, by comparing values of Δm_{31}^2 obtained at different E_ν , one can search for indications of “new physics”.

The study of $\nu_\mu \rightarrow \nu_e$ oscillations can be divided into three domains: 1) High Energy, $3 \text{ GeV} \leq E_\nu \lesssim 5 \text{ GeV}$, 2) Intermediate Energy, $1 \text{ GeV} \leq E_\nu \leq 3 \text{ GeV}$ and 3) Low Energy, $E_\nu \lesssim 1 \text{ GeV}$. Roughly speaking, the high energy ν_e events will be matter enhanced (suppressed) for the normal (inverted) mass hierarchy. The effect is very pronounced (see Figs. 1 & 2), making a

determination of the sign of Δm_{31}^2 relatively easy (for $\sin^2 2\theta_{13} \geq 0.01$) and allowing for a good measurement or bound on θ_{13} (via P_I) which is better than any other proposed experiment [6]. Intermediate energy events will measure both $\sin \delta$ and $\cos \delta$ via P_{II} . In that way we expect δ to be determined to within $\pm 15^\circ$ independent of its value with no ambiguity [6] (again assuming $\sin^2 2\theta_{13} \gtrsim 0.01$). That type of δ determination is more robust and statistically more powerful than A_{CP} . Note, that the energy peaks are also displaced by matter effects. Their positions can in principle be used to determine the sign of Δm_{31}^2 . (see fig. 1.) Finally, the low energy ν_e events will determine the combination $\Delta m_{21}^2 \sin 2\theta_{12}$ to about $\pm 5\%$ via P_{III} . Altogether, this single experiment will measure or constrain all parameters of 3 generation leptonic mixing with unprecedented sensitivity and without parameter degeneracies. It would put leptonic mixing on about the same level of precision as quark mixing. Specific details of detector optimization and running strategy still need to be ironed out, but the basic idea of determining all oscillation parameters via one experiment is very compelling. We also note, a Fermilab-Homestake (1280 km) and wideband beam experiment would exhibit less dramatic effects (see Fig. 2), but would have about 4 times the statistics because of the shorter distance. Overall, it would have similar discovery potential. Figs. 3 & 4 illustrate the dependence on the phase δ for BNL and Fermilab distances.

5. OUTLOOK

It appears that the combination of intense conventional wide band ν_μ beam, powered by a 1-2 MW proton accelerator, large detector and very long baseline provides an opportunity to measure Δm_{31}^2 , sign Δm_{31}^2 , Δm_{21}^2 , all θ_{ij} and δ with good to high precision. The intense proton source required for this effort is a straightforward upgrade of the AGS or Fermilab Main Injector. The large detector (= 500 kton H_2O or its equivalent) could be sited at either of the national underground lab sites being considered (Homestake or Henderson). It would also search for proton decay, supernova, atmospheric neutrinos etc. to unprecedented levels. The facility would probably be at the forefront of particle physics research for 50 years or more. Of course, proton sources at JPARC or CERN are also options for such a long baseline effort.

What remains to be done? Detector R&D to reject backgrounds such as π^0 and reduce the cost are needed. An underground lab site needs to be developed and the horn generated wide band beam flux should be optimized. After the first phase of ν_μ is completed, one might run $\bar{\nu}_\mu$ for a few years if one wants to actually observe CP violation (rather than just a determination of δ) or if an inverted mass hierarchy turns out to be correct. During that time further upgrades of the AGS or Main Injector to 2MW or more might be appropriate.

The strategy for long baseline neutrino oscillations outlined here is based on novel concepts: broad band beam, very long distance and large detector. It is bold, ambitious and doable. The opportunity is within our community's grasp and should be seized.

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