Probing neutrino oscillations jointly in long and very long baseline experiments Postprint

Authors: H2B-4,VSG, Wang,Y, Whisnant,K, Xiong,Z, Yang,JM, Young,B

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Abstract

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Full Text

Preamble

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Probing neutrino oscillations jointly in long and very long baseline experiments

Y. F. Wang^{a}, K. Whisnant^{b}, Zhaohua Xiong^{c}, Jin Min Yang^{c}, Bing-Lin Young^{b}

^{a} Institute of High Energy Physics, Academia Sinica, Beijing 100039, China
^{b} Department of Physics and Astronomy, Iowa State University, Ames, Iowa 50011, USA
^{c} Institute of Theoretical Physics, Academia Sinica, Beijing 100080, China

ABSTRACT

We examine the prospects for joint analysis of neutrino oscillations at two baselines using neutrino superbeams. Assuming narrow-band superbeams and a 100 kt water Cherenkov calorimeter, we calculate event rates and sensitivities to the matter effect, the signs of the neutrino mass differences, the CP phase, and the mixing angle . Taking into account all possible experimental errors under general consideration, we explore optimal narrow-band beam configurations for

measuring matter effects and CP violation effects at baselines up to 3000 km. We then focus on two specific baselines—a long baseline of 300 km and a very long baseline of 2100 km—and analyze their joint capabilities. We find that the joint analysis can provide additional leverage to resolve some ambiguities associated with measurements at a single baseline.

Introduction

Although existing data from the Super-Kamiokande experiment [1] and various other corroborating experiments offer very strong indications of neutrino oscillations, appearance experiments—those demonstrating the emergence of a neutrino flavor different from the original—have not yet been convincingly performed. If neutrinos indeed oscillate, the oscillation parameters, including the leptonic CP phase, must be determined with sufficient accuracy. Furthermore, the well-known MSW matter effect [2] must be tested experimentally.

Despite various ongoing and planned neutrino oscillation experiments, additional experiments with very long baselines are needed, at least for testing the matter effect. The recently approved superbeam facility [3], which will become available toward the later part of this decade, offers the possibility of a very long baseline (VLBL) experiment that, in conjunction with other oscillation experiments, can thoroughly test all properties of neutrino oscillations.

Among all neutrino oscillation experiments, long baseline (LBL) experiments are particularly attractive. Since neutrino beams are produced in an accelerator according to definite physics criteria with the detector site chosen accordingly, these experiments can be conducted in a more controlled fashion to maximize physics output. Hence, LBL experiments will allow detailed analyses of oscillation parameters to provide a complete picture of neutrino oscillation physics. As one example of such experiments, a project called H2B is under discussion [4, 5, 6]. The neutrino superbeam for H2B would originate from the newly approved high-intensity 50 GeV proton synchrotron in Japan called HIPA [3], and the detector, tentatively called the Beijing Astrophysics and Neutrino Detector (BAND), is envisioned to be a 100 kt water Cherenkov calorimeter (WCC) with resistive plate chambers (RPC) [7] located in Beijing, China. The distance from HIPA to Beijing is approximately 2100 km. Such a very long baseline experiment would be complementary to the recently proposed J2K experiment [8], which will also use the neutrino beam from HIPA but with the Super-Kamiokande detector or its upgrade. The distance from HIPA to Super-Kamiokande is about 300 km.

In this article, we examine the prospects for investigating neutrino oscillations at H2B in conjunction with J2K, so that joint data from the two widely different baselines can be used complementarily to provide strong leverage for eliminating some ambiguities in determining oscillation parameters. The joint analysis can expand the capability of parameter searches that are not attainable by either experiment alone. The two baselines can operate in their respective favorable energy ranges. The present work demonstrates this possibility, though we have not searched for the optimal narrow beam energies for the two baselines. Assuming a narrow-band meson beam and the aforementioned 100 kt WCC with RPC, we simulate event rates for five years of operation and explore the sensitivity of these event rates to various oscillation parameters. This work can be regarded partly as a continuation of the H2B study in Refs. [4, 5, 6] and an initial exploration of the idea of joint analyses using two detectors, which we believe is appropriate for oscillation physics.

In Section 2, we discuss fundamentals of neutrino oscillation and LBL experiments. In Section 3, we present numerical results. We present joint analyses of data from two detectors in Section 4. Finally, in Section 5, we present our conclusions.

2 Fundamentals of Neutrino Oscillation and LBL Experiments

If we accept all current data, there are three distinctive mass scales provided by five categories of experiments: long baseline, short baseline accelerator experiments such as LSND, atmospheric, solar, and reactor experiments. If the LSND data are excluded, the three Standard Model neutrino flavors are sufficient and no extension beyond the Standard Model is necessary. In view of the uncertainty in the LSND data, our discussion will be restricted to the three-flavor scenario.

The oscillation of three-flavor neutrinos is a system with a limited number of degrees of freedom. The system consists of two mass-squared differences (MSD), three mixing angles, and one measurable CP phase. These parameters, together with the matter effect, determine the various survival and appearance probabilities [9]. The unitary mixing matrix in vacuum is generally parameterized as:

```
c13s12 c12c13 -c23s12 - c12^s13s23
c12c23 - s12^s13s23 s12s23 - c12c23^s13
-c12s23 - c23s12^s13 c13s23 c13c23
```

where s_{jk} = sin(_{jk}), c_{jk} = cos(_{jk}), and ^s_{jk} = sin(_{jk})e^{i }, _{jk} defined for j < k is the mixing angle of mass eigenstates _j and _k, and is the CP phase angle. The three mass eigenvalues are denoted as m , m , and m . The two independent MSD are:

```
2 - m2 32   m2 1 and  m2
```

```
21   m2
```

In LBL experiments, the neutrino beam must traverse matter, giving rise to the well-known MSW effect [2]. A widely used model for the Earth, called the Preliminary Reference Earth Model (PREM), is given in [10], and the Earth density profile can be found in [11]. Since for a VLBL experiment the matter density can vary significantly along the neutrino beam path, we perform numerical integration of the Schrödinger equation in our calculations to treat the distance-dependent matter density realistically.

The detection of a given neutrino flavor occurs through its accompanying charged lepton produced by the charge-current interaction of the neutrino with nucleons in the detector mass. For a neutrino energy E_ that is small compared to the mass of the W and Z bosons but large enough that quasi-elastic effects are negligible, the charge-current cross sections are given by _{ N} = 0.67×10 ³ cm² E_ (GeV) for electron and muon neutrinos, and _{⁻ N} = 0.34 × 10 ³ cm² E_ (GeV) for electron and muon anti-neutrinos.

For the tau neutrino, the above expression is subject to threshold suppression. The threshold for tau production is E_T = m_ + m² = 3.46 GeV. A fit of the _ to _ cross section as a function of neutrino energy in terms of the ratio of two quadratic polynomials can be found in Ref. [4].

The signal events of flavor —that is, the number of charged leptons of flavor — from a neutrino beam of flavor to be observed at baseline L is given by:

N_{ → } = *{E_min}^{E_max} Φ(E_ , L) (E_) P{ → }*(E_ , L) dE_

where Φ(E_ , L) is the total neutrino flux spectrum including detector size and running time period, P_{ → }(E_ , L) is the oscillation probability, (E_) is the neutrino charge-current cross section, and E_max and E_min are the maximum and minimum energies of the beam.

In a narrow-band beam, the neutrino flux is distributed below a given energy E_peak. The intensity peaks at E_peak and decreases rapidly below it. A wide-band beam contains neutrinos with energy spread across a significant range. In our calculations, we use realistic beam energies and profiles provided in [5, 12]. Some narrow-band beams together with the wide beam are plotted in Fig. 1 [Figure 1: see original paper]. Here dN_{cc}/dE_ Φ(E_ , L) (E_) is the energy distribution of charged-current events N_{cc} for one year of operation of a 100 kt detector at L = 2100 km.

Since statistics are generally not large in oscillation experiments, particularly in electron neutrino appearance cases, error analysis is an important factor in physics extraction. We use the approach of Ref. [6] to estimate possible statistical and systematic errors and to gauge the goodness of fit. For electron counting experiments, errors and uncertainties arise from three sources: (i) statistical error in measuring charged leptons of flavor , which is √(N_s + N_b), where N_b is the number of measured background events and can be expressed as N_b = f_ _{E_min}^{E_max} Φ(E_ , L) (E_) dE_ ; (ii) systematic uncertainty in calculating background events, denoted as r_ N_b; and (iii) systematic uncertainty in beam flux and cross section, denoted as g_ N_s. The total error is the quadrature sum of all uncertainties. In our calculations, we take r_ = 0.1, g_ = 0.05, and f_ = 0.01.

3 Numerical Results for Individual Baselines

Presently, there are sizable errors in all oscillation parameters. However, we envisage that by the H2B era, Δm^2 , , and will be fairly accurately determined, so we do not assign specific errors to them. We focus our investigations on the following parameters and effects: matter effects, MSD sign, CP violation, and .

3.1 Inputs

We present numerical results for five years of operation with a water Cherenkov detector. The detector size is assumed to be 100 kt for all baselines; other sizes will be explicitly noted when used.

The inputs for mixing angles and MSDs come from solar, atmospheric, and CHOOZ experiments. For definiteness, we take $\sin^2(2\ ) = 0.8$ and $\sin^2(2\ ) = 1.0$. In most results, we use $\sin^2(2\ ) = 0.05$ for illustration, though effects of larger and smaller values of (0.01 $\sin^2(2\ )$ 0.1) will be investigated. The MSD inputs Δm^2_sol and Δm^2_atm are respectively given by Δm^2_sol = 5×10 eV^2 and Δm^2_atm = 3×10^{3} eV^2.

Presently, the signs of the MSDs are unknown, giving four possibilities:

[The four sign combinations would be listed here]

After showing the effects of all four sign combinations on electron event numbers, we will choose sign I for illustration.

3.2 Matter Effects

Tables 1 and 2 show _ $\rightarrow$ _e event rates with and without matter effects for a narrow-band beam with E_peak = 4 GeV at both baselines. It is clear that for both narrow-band and wide-band beams, the matter effect is significant for electron event numbers at L = 2100 km but negligible at L = 300 km. As expected, _ and _ events show very little matter effect at either distance. Event rates at both baselines can be increased by using different narrow-band beams; for example, at L = 2100 km, the E_peak = 6 GeV beam has twice as many electron events as the E_peak = 4 GeV beam.

To find the optimal beam energy for measuring matter effects at a given baseline, we examine the ratio:

R_matter = |N_e|_with matter - N_e|_without matter| / ΔN_e

where ΔN_e is the total error of the electron event number (as discussed at the end of Section 2) without matter effects. This ratio approximates the statistical significance of the matter effect and is referred to in Ref. [6] as the figure of merit. Figure 2 [Figure 2: see original paper] shows R_matter versus baseline up to 3000 km for several narrow-band beams for the four MSD sign combinations. We see that for L = 2100 km, the optimal narrow-band beams for matter effects have peak energies in the range of 4-6 GeV. For example, as shown in Fig. 2 for MSD sign I, the optimal narrow-band beam has peak energy around E_peak = 4 GeV. For L = 300 km, as expected, there is very little statistical sensitivity to matter effects at all available energies.

For a narrow-band beam with E_peak = 4 GeV at L = 2100 km and E_peak = 0.7 GeV at L = 300 km, Fig. 3 [Figure 3: see original paper] shows electron event rates versus CP phase with and without matter effects. We see that for a fixed value or small range of uncertainties in , the matter effect is experimentally measurable at L = 2100 km but hardly observable at L = 300 km. However, in the currently fully allowed range of (sin²(2) 0.1), it becomes difficult even for the 2100 km baseline to distinguish matter effects from vacuum oscillations for the following reason: since electron event rates are proportional to sin²(2), the rates for sin²(2) = 0.03 with matter effects and for sin²(2) = 0.1 in vacuum are identical, as can be inferred from Fig. 3. This ambiguity is reinforced when errors are not negligible.

3.3 MSD Sign Effects

The sensitivity of event rates to MSD signs for sin²(2) = 0.05 is shown in Tables 1 and 2 for E_peak = 4 GeV and = 0 at both baselines, and in Fig. 4 [Figure 4: see original paper] for different energies at the two baselines as functions of CP phase. Tables 1 and 2 show that electron event rates are sensitive to the MSD sign at the 2100 km baseline. It is also interesting to note that for L = 300 km, there is sensitivity in distinguishing signs I and IV (where both MSDs are positive or negative) from signs II and III (where one is positive and the other negative). This general feature holds for other values of once it is determined.

Figure 4, which uses sin²(2) = 0.05, clearly shows that for L = 2100 km, signs I and II are well separated from III and IV for all CP phase values. Hence, the sign of Δm² should be readily determined with a moderate amount of electron neutrino appearance data. However, the separation of I from II depends on the CP phase value. The sign of Δm² can be determined in regions of small, intermediate, and large CP phase, but around = 130° and = 280°, signs I and II are not distinguishable. Signs III and IV are almost inseparable across the entire region, making the sign of Δm² very difficult to determine if Δm² < 0. An anti-neutrino beam would then be needed for determination. For L = 300 km, Fig. 4 shows that distinguishing I, II, III, and IV is difficult except at very specific CP phase values.

Unfortunately, the above result holds only if is already known. Similar to the situation discussed in the preceding subsection, significant uncertainty in sin²(2) muddies the waters. As sin²(2) decreases, electron event rates are reduced, making it difficult to distinguish signs I and II with small from signs III and IV with larger . We demonstrate this decrease in lepton event rate with sin²(2) in Fig. 4. Hence, when the full range of current uncertainty in is included (i.e., sin²(2) < 0.1), sensitivity to distinguish MSD signs is lost for both baselines.

3.4 CP Violation Effects

Figures 3 and 4 show electron event numbers versus CP phase, modulo matter effects. Typical total errors are also shown; the dominant error is statistical, from source (i) described at the end of Section 2. Although event rates vary significantly with CP phase, the fact that the electron event rate is not a single-valued function of CP phase makes determination of   ambiguous, even for a fixed   value. The uncertainty in   discussed in the two previous subsections exacerbates this ambiguity further.

The sensitivity of electron event rates to CP phase depends on beam energy, as shown in Fig. 5 [Figure 5: see original paper]. At some beam energies (e.g., 2 and 10 GeV for L = 2100 km and 0.7 GeV for L = 300 km), the curves are quite flat, indicating poor sensitivity to CP phase at those energies. Furthermore, at almost no energy can a unique CP phase be determined from electron event numbers at either 300 km or 2100 km.

To investigate sensitivity, we define two ratios involving the CP-conserving phases   = 0° and   = 180°:

R_CP^{(0°)}( )   [N_e( ) - N_e(0°)] / ΔN_e(0°)

R_CP^{(180°)}( )   [N_e( ) - N_e(180°)] / ΔN_e(180°)

where N_e( ), N_e(0°), and N_e(180°) are electron event numbers for CP phases , 0°, and 180°, respectively, and ΔN_e(0°) and ΔN_e(180°) are total errors at   = 0° and   = 180°. We define the figure of merit [6]—the goodness of fit for CP violation measurement—as the smaller magnitude of the two ratios:

F_CP   min(R_CP^{(0°)}( ), R_CP^{(180°)}( ))

Figure 6 [Figure 6: see original paper] plots F_CP( ) versus peak energy of the narrow-band beam separately for L = 2100 km and 300 km, showing six   values: 0°, 30°, 60°, 90°, 120°, and 150°. The curves satisfy approximately the relation F_CP(180° +)   -F_CP( ). Hence, curves for   = 180°, 210°, 240°, 270°, 300°, and 330° can be inferred as negatives of the corresponding curves for   < 180°. The left panel shows results for a 100 kt detector, while the right panel shows results for a 1000 kt detector. For the 100 kt detector at both baselines, effects of finite CP phases are within 1 of each other, including the CP-conserving case. If we increase the detector size to 1000 kt, CP violation effects can reach the 2 level for beams around E_peak   3–4 GeV and 6–7 GeV for   = 60°–120° and 240°–300° at L = 2100 km, and around E_peak   0.7 GeV for similar   ranges at L = 300 km.

3.5 Effects of sin²(2) Uncertainty

All results above use sin²(2) = 0.05. Since _ → _e is proportional to sin²(2), this parameter strongly influences electron event numbers. Accordingly, counting experiments for electron events may provide good measurements of $\sin^2(2\ \ )$.

Figure 7 [Figure 7: see original paper] presents electron event numbers versus CP phase for different $\sin^2(2\ \ )$ values. Error bars indicate estimated total errors. From these errors, we see how precisely $\sin^2(2\ \ )$ can be measured. For example, at L = 2100 km, the curve for $\sin^2(2\ \ ) = 0.08$ (0.06) lies about 1.5 (3) away from that for $\sin^2(2\ \ ) = 0.1$, making it difficult to distinguish 0.1 from 0.08 along the curves. Furthermore, without knowing the CP phase, it may be difficult to distinguish $\sin^2(2\ \ ) = 0.1$ at one CP phase from $\sin^2(2\ \ ) = 0.6$ at another CP phase. This ambiguity is even more serious for L = 300 km because there is greater variation in event numbers as a function of CP phase.

4 Joint Analysis of Baselines at 2100 km and 300 km

We anticipate that major efforts in very long baseline experiments such as H2B will focus on confirming matter effects, determining MSD signs, measuring the CP phase, and determining . However, as demonstrated in the preceding section, finding unique solutions for these parameters from measured electron event rates presents difficulties. We have repeatedly discussed ambiguities caused by the currently wide range of uncertainty in . Additional ambiguities arise from the multi-valued nature of oscillation probabilities as functions of oscillation parameters and the possibility of overlapping parameter regions.

To illustrate the latter ambiguity, consider Fig. 4. For simplicity, ignore any possible errors. Suppose a measurement at 300 km baseline with a narrow-band beam of peak energy 0.7 GeV yields an electron event rate of 60. Then the CP phase could be either around 0° or 150° for $\sin^2(2\ \ ) = 0.05$. Similarly, suppose a measurement at 2100 km baseline gives an electron event rate of 40 at 4 GeV. Then the CP phase could be either 150° or 300° for $\sin^2(2\ \ ) = 0.05$. Furthermore, since $\sin^2(2\ \ )$ is unknown, we in fact obtain a curve in the - $\sin^2(2\ \ )$ plane for a given electron event number, as shown in Fig. 8 [Figure 8: see original paper]. Hence, measurement from only one experiment—either at L = 300 km or L = 2100 km—is insufficient to determine the CP phase or $\sin^2(2\ \ )$ value.

To illustrate the advantage of joint analysis at two widely different baselines, we plot in Fig. 8 $\sin^2(2\ \ )$ versus for measured electron event rates at both 300 km and 2100 km baselines—60 and 40 events respectively—for MSD sign I. In the absence of errors, the intersection of the curves gives unique values for both $\sin^2(2\ \ )$ and . In reality, the situation is more complicated due to measurement errors, so the intersection covers a sizable area in the $\sin^2(2\ \ )$ versus plane. However, this example demonstrates the additional leverage gained with two different baselines.

In this section, we present analyses of such joint measurements, taking advantage of superbeams like HIPA that can offer multiple narrow-band beams of different energies. We use different energies at the two baselines and plot 2100 km baseline versus 300 km baseline by simultaneously examining two different parameters.

4.1 sin²(2) and the CP Phase

Figure 9 [Figure 9: see original paper] shows electron event numbers at L = 2100 km versus those at L = 300 km for fixed MSD sign I. Each curve has a fixed sin²(2) value with CP phase varying across its full range from 0° to 360°. The = 0° point is marked by a solid dot and = 180° by a cross; the direction of increasing is indicated by arrows on the curves. The curves are generally ellipses, with eccentricity determined by the specific beam energies at the two baselines.

We fix E_peak = 0.7 GeV for the 300 km baseline and allow the energy at 2100 km to vary. The upper diagram of Fig. 9 uses 4 GeV for 2100 km. As sin²(2) increases, the ellipse moves toward the upper right, increasing electron event rates for both baselines, as expected from the proportionality of _ → _e oscillation probability to sin²(2). Since ellipses for neighboring sin²(2) values overlap significantly, and sin²(2) cannot be uniquely determined, reflecting again the ambiguities discussed previously. However, there are energies where ellipse overlap is minimized. The lower diagram of Fig. 9 shows that ellipses of constant collapse into lines when the beam energy at 2100 km baseline is 6.3 GeV. In principle, joint measurements allow us to narrow down the allowed range of sin²(2). For the lines, each measurement still allows two values, but the two values that coincide on the line segment will be separated when the line becomes an ellipse. Thus, measurements at both 6.3 GeV and 4 GeV offer better possibilities for simultaneously determining sin²(2) and .

Table 3 presents, for MSD sign I, some E_peak values (in GeV) of narrow-band beams where ellipses of N_e(300) versus N_e(2100) collapse into lines as CP phase varies from 0° to 360°. At these energies, curves for MSD sign II are ellipses of high eccentricity that approximate lines. For MSD signs III and IV, and in the absence of matter effects, the curves are ellipses of very high eccentricity. For these energies, combined measurements of electron events at L = 2100 km and L = 300 km can provide better measurements of sin²(2).

4.2 MSD Sign and the CP Phase

Figure 10 [Figure 10: see original paper] presents similar results but for different MSD signs with fixed sin²(2) = 0.05. Results without matter effects are also plotted, with dotted curves denoting MSD signs II or III and dashed curves I or IV. In the absence of matter effects, MSD signs I and IV give identical results, as do signs II and III, as already shown in Tables 1 and 2. For the almost overlapped curves of MSD signs III and IV with matter effects, solid curves denote III and dotted curves denote IV.

It is clear from Fig. 10 that in the lower diagram (6.3 GeV for the 2100 km baseline), it is quite easy to differentiate MSD signs I and II from III and IV, and from the case without matter effects. For better measurements, it is again advantageous to take measurements with both line and ellipse configurations.

5 Conclusion

In our study of event rates and sensitivity to various oscillation parameters, we found: (a) At L = 2100 km, a narrow-band beam with peak energy of about 6 GeV is optimal for measuring CP violation effects, and about 5 GeV for measuring matter effects. (b) To measure CP violation effects at shorter distances such as L = 300 km, a narrow-band beam with lower peak energy (0.7 GeV) is preferable, though matter effects are hardly observable at such short baselines. (c) The two baselines, 300 km and 2100 km, are complementary. Through joint analysis of both baselines, some ambiguities associated with measurements at either baseline alone may be resolved.

With optimal narrow-band beams, a five-year operation of a 100 kt water Cherenkov detector at a very long distance such as L = 2100 km has the following physics prospects: (1) Matter effects can be observed. (2) The sign of Δm^2 may be determined. (3) The sign of Δm^2 may be determined only in favorable situations. (4) Evidence exceeding 2 for a CP-violating phase may be seen in favorable cases for a detector size of 1000 kt or with much longer running time. (5) Combined with analyses at L = 300 km, the parameter $\sin^2(2\ \ )$ may be measured and matter effects more clearly determined.

In this article, we have focused exclusively on _ → _e. Investigation of appearance and inclusion of the $\bar{}$_ beam option in the analysis, which is needed for MSD signs III and IV ($\Delta m^2 < 0$), will be undertaken in future work. There we will also perform a more complete search for optimal energies at the two baselines for various parameters.

We finally note that statistics are generally low in all cases discussed. Running with higher-energy narrow-band beams will increase statistics, though this may be disfavored by the figure of merit (signal-to-error ratio). Another approach is increasing detector mass. However, it has been pointed out that there is a saturation problem [13] caused by systematic errors of types (ii) and (iii) discussed at the end of Section 2. These errors increase linearly with the number of events rather than as the square root of the number of events as statistical errors do. Hence, when detector mass is increased sufficiently that the number of events becomes large, systematic errors dominate, and further increasing detector size may no longer be beneficial.

Figure 11 [Figure 11: see original paper] shows the ratio ΔN_e/N_e as a function of detector mass. According to our general error estimates, the best achievable ΔN_e/N_e ratio is 6%. When the detector reaches 1000 kt, the benefit of further increasing detector size is no longer significant.

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Table 1 : Event rates for 5-year operation with (without) matter effects for different MSD sign choices for a narrow-band beam of E_peak = 4 GeV. The CP phase is taken to be zero.

L = 2100 km	I	II	III	IV
electron #	34 (10)	46 (16)	3 (16)	3 (10)
muon #	430 (435)	405 (415)	413 (415)	427 (435)
tau #	10 (11)	11 (11)	12 (11)	11 (11)

L = 300 km	I	II	III	IV
electron #	159 (157)	119 (116)	114 (116)	154 (157)
muon #	39408 (39407)	39535 (39535)	39535 (39535)	39408 (39407)
tau #	72 (72)	71 (71)	71 (71)	72 (72)

Table 2 : Same as Table 1, but for a wide-band beam.

L = 2100 km	I	II	III	IV
electron #	151 (96)	151 (90)	39 (90)	49 (96)
muon #	2313 (2311)	2326 (2333)	2335 (2333)	2308 (2311)
tau #	448 (453)	443 (449)	454 (449)	458 (453)

L = 300 km	I	II	III	IV
electron #	453 (443)	359 (348)	337 (348)	431 (443)
muon #	271536 (271535)	271842 (271842)	271843 (271842)	271535 (271535)
tau #	731 (731)	718 (718)	718 (718)	731 (731)

Table 3: Some E_peak values (GeV) of narrow-band beams where ellipses of N_e(300) versus N_e(2100) collapse into line segments as CP phase varies from 0° to 360°. The MSD sign is assumed to be case I.

E_peak(300)	E_peak(2100)

Figure 1 [Figure 1: see original paper]: The energy E_ distribution of charged-current events N_cc for one year operation of a 100 kt detector.

Figure 2 [Figure 2: see original paper]: R_matter (Eq. (5)) versus baseline for several narrow-band beams. The CP phase is taken to be zero and $\sin^2(2\ )$ = 0.05.

Figure 3 [Figure 3: see original paper]: The electron event number versus CP phase with and without matter effects. sin^2(2) is assumed to be 0.05 except for the dotted curve which is for sin^2(2) = 0.03 to show the effect of varying . Representative total errors are also shown. The MSD sign is assumed to be I.

Figure 4 [Figure 4: see original paper]: Same as Fig. 3, but for different MSD signs with matter effect.

Figure 5 [Figure 5: see original paper]: The electron event rate versus CP phase for different narrow-band beams. The MSD sign is assumed to be I.

Figure 6 [Figure 6: see original paper]: F_CP( ) (Eq. (8)) versus peak energy of narrow-band beams. The MSD sign is assumed to be I. With the approximate relation F_CP(180° +) = -F_CP( ), curves for = 180°, 210°, 240°, 270°, 300°, and 330° can be inferred.

Figure 7 [Figure 7: see original paper]: The electron event number versus CP phase for different sin^2(2) values. The MSD sign is assumed to be I. Total errors at some points are also shown.

Figure 8 [Figure 8: see original paper]: CP phase versus sin^2(2) for a given electron event number N_e. The solid (dashed) curve is for N_e = 60 (40) at L = 300 km (2100 km) with narrow-band beam E_peak = 0.7 GeV (4 GeV). The MSD sign is assumed to be I.

Figure 9 [Figure 9: see original paper]: Electron event number at L = 2100 km versus L = 300 km for different sin^2(2) values. CP phase increases from 0° (solid bullets) to 180° (crosses) then to 360° according to the direction indicated by arrows. The MSD is assumed to have sign I. In the lower diagram for E_peak(300) = 0.7 GeV and E_peak(2100) = 6.3 GeV, the ellipses collapse into line segments. Typical total errors are also shown.

Figure 10 [Figure 10: see original paper]: Similar to Fig. 9 for different MSD signs with fixed sin^2(2) = 0.05. Results without matter effects are also plotted.

Figure 11 [Figure 11: see original paper]: The relative error ΔN_e/N_e versus detector size for a 4 GeV narrow-band beam.

Note: Figure translations are in progress. See original paper for figures.