Further study of neutrino oscillation with two detectors in Kamioka and Korea

F. Dufour,[1,2] T. Kajita,[3,4] E. Kearns,[1,4] and K. Okumura[3]
[1]*Department of Physics, Boston University, Boston, MA 02215, USA*
[2]*Section de Physique, Université de Genève, 1205 Genève, Switzerland*
[3]*Research Center for Cosmic Neutrinos, Institute for Cosmic Ray Research (ICRR), University of Tokyo, Kashiwa, Chiba 277-8582, Japan*
[4]*Institute for the Physics and Mathematics of the Universe (IPMU), University of Tokyo, Kashiwa, Chiba 277-8582, Japan*
(Dated: November 10, 2009)

This paper updates and improves the study of electron neutrino appearance in the framework of two far detectors at different oscillation maxima, specifically, Tokai-To-Kamioka-to-Korea. We used a likelihood based on reconstructed quantities to distinguish charged current ν_e interactions from neutral current background. We studied the efficiency of the likelihood for a 20% photo-coverage in comparison of a 40% photo-coverage. We used a detailed neutrino event simulation to estimate the neutral current background. With these analysis tools we studied the sensitivity of the proposed experiment to CP violation and mass hierarchy as a function of the off-axis angle.

PACS numbers: PACS numbers: 14.60.Pq, 11.30.Er

I. INTRODUCTION

The θ_{13} angle, the hierarchy of the largest mass splitting, and the CP violating phase are remaining undetermined quantities in the PMNS matrix formulation of neutrino masses and mixing [1, 2]. CP violation in the lepton sector and its relation to the matter anti-matter asymmetry of the universe is especially interesting. To determine the CP violating phase δ and the neutrino mass hierarchy, a powerful approach is to measure electron neutrino appearance at both the first and second oscillation maximum in a long baseline neutrino beam. Two different approaches have been considered in order to make this comparative measurement. One approach is to have two detectors at two different baselines of the same beam, one positioned for optimum response at the first oscillation maximum and the other positioned for optimum response at the second oscillation maximum. The optimum response is achieved using the off-axis technique [3] to achieve a narrow energy band. This is the approach of the Tokai to Kamioka to Korea [4], henceforth referred to by the unofficial acronym T2KK. Another approach is to use an on-axis wide-band beam, and measure electron neutrino appearance from both the first and second maxima with a single detector [5]. This is the approach employed by the BNL-FNAL working group [6] as a model for a long baseline neutrino oscillation experiment in the United States.

In the first published T2KK article [4], the off-axis angle of the Korean detector was assumed to be fixed at 2.5°. In this article, we study the sensitivity to CP violation and mass hierarchy if we choose a smaller off-axis angle for the location of the Korean detector, which blends the two approaches described above. As one can see in Fig. 1, the off-axis angle of 1.0° results in a fairly wide band beam, and we anticipate seeing electron neutrino appearance at both the first and second maximum in the Korean detector. The detector at the Kamioka location would remain at 2.5° off-axis, and be mainly sensitive to the first oscillation maximum.

For this study, we assume an upgraded 1.66 MW J-PARC beam created from 40 GeV protons, running 10^7 seconds per year. This is equivalent to 2.59×10^{21} protons-on-target (POT) per year. We assume 5 years of neutrino running and 5 years of anti-neutrino running. The ν_μ flux observed at four different off-axis angles, at 1050 km from the target, is shown in Fig. 1. We also assume two 0.27 Mton (fiducial volume) water Cherenkov detectors with 40% photo-coverage. One of them would be located at Kamioka, at a baseline of 295 km and at 2.5° off-axis angle from the beam. The second detector would be located in Korea at distances ranging from 1000 to 1200 kilometers and off-axis angles ranging from 1° to 2.5°. The beam intensity assumed for this article is a factor of 2.4 lower than the beam assumed previously [4]. This more conservative beam power is being considered for benchmark studies [7]. In addition we assumed that a year of running is 10^7 seconds instead of 1.12×10^7, so combining the change in beam intensity and running time, the number of POT per year is a factor of 2.7 lower than in previous studies.

Our tool for these studies is the fully reconstructed atmospheric neutrino Monte Carlo sample from the Super-Kamiokande experiment [8], whereas the earlier paper used event rates calculated for the T2K experiment scaled for distance. In order to simulate the T2KK beam, we re-weight events in the Super-K atmospheric neutrino Monte Carlo sample by the ratio of the T2KK flux to the atmospheric flux.

II. SIGNAL VS. BACKGROUND LIKELIHOOD ANALYSIS

Our objective is to identify and reconstruct an excess of charged current ν_e interactions in a nearly pure ν_μ beam. We shall be especially interested in quasi-elastic interactions such as $\nu_e n \rightarrow e^- p$. In the experiment considered, the appearance probability is a few percent at most, and only a small number of events are anticipated above a non-negligible background. There are three categories of background:

- ν_e beam: The irreducible background from electron neutrinos in the beam flux regardless of neutrino oscillation. These come mainly from muon decay and K_{e3}.
- Neutral current (NC): Background where the hadronic

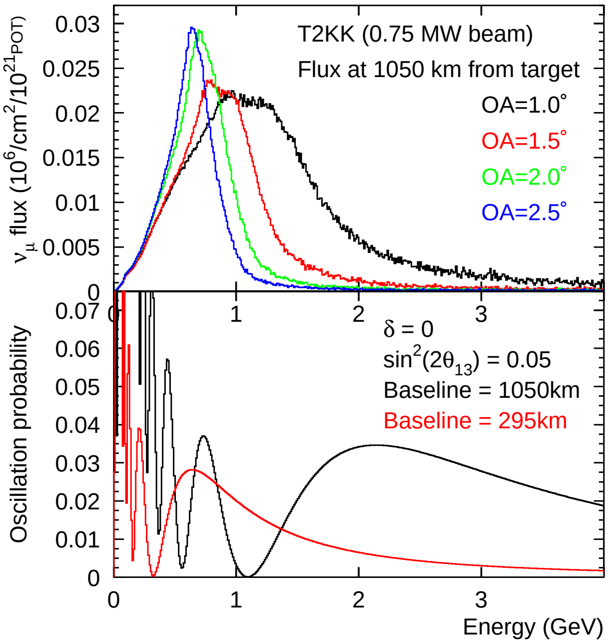

FIG. 1: (Color online) Neutrino flux as a function of energy for several off-axis angle, and a 0.75MW beam at 1050km from the target. For comparison, the $\nu_\mu \rightarrow \nu_e$ probability, for two baselines considered for T2KK (295km and 1050km). Neutrino mixing parameters are: normal hierarchy, $\Delta m^2_{(21,31)} = 8.0 \times 10^{-5}, 2.5 \times 10^{-3} eV^2$, and $\sin^2 2\theta_{(12,23)} = 0.86, 1.0$. We take the earth density to be constant and equal to 2.8 g/cm^3.

recoil of neutral current interactions are misidentified as electron showers.

- ν_μ mis-ID: Background due to muons mis-identified as electron showers.

The irreducible ν_e beam background is estimated from the details of hadron production and muon decay in the beam Monte Carlo. We take as input the calculated flux from a beam simulation assuming a graphite cylinder target, 30 mm in diameter and 900 mm in length and a 130 m decay tunnel. These are the parameters of the T2K experiment. The neutral current background mainly consists of hadronic recoils with a single π^0. The π^0 decays into two photons and if one of the photons is missed because of a very small energy or an overlapping ring, then the event can be misidentified as a single electromagnetic shower and therefore fake a ν_e CCQE event. The dominant case is when one of the photons was missed because the energy was too small. The ν_μ mis-ID background consists of charge current ν_μ events where the Cherenkov ring from the outgoing muon is mis-identified as an electron by the reconstruction algorithm. This is the smallest source of background.

Since we are interested in ν_e appearance and especially ν_e undergoing quasi-elastic interactions, the events that we want to select are fully contained inside the fiducial volume, have a single Cherenkov ring identified as electron-like, and with no decay electron present (which would signal missed π^+ in a multipion final state). These are referred to as pre-cuts. Before building the likelihood, we applied these pre-cuts, in order to remove a significant part of the background.

The pre-cut efficiencies are listed in Table I. The NC efficiency is based on the total cross section for neutral current interactions which includes a large component of neutrino-nucleon elastic scattering. These are mostly unobserved in a water Cherenkov detector. The NC background events that pass the pre-cuts are mostly single-π^0 production.

	Signal			Background	
True ν energy	ν_e (avg)	QE ν_e	non-QE ν_e	NC	ν_μ mis-ID
0 - 0.35 GeV	93%	93%	55%	*NA*	*NA*
0.35 - 0.85 GeV	85%	95%	41%	4%	0.3%
0.85 GeV - 1.5 GeV	63%	92%	39%	8%	0.3%
1.5 - 2.0 GeV	48%	85%	31%	10%	0.7%
2.0 - 3.0 GeV	41%	83%	29%	11%	0.8%
3.0 - 4.0 GeV	34%	76%	24%	12%	0.9%
4.0 - 5.0 GeV	32%	71%	27%	11%	0.4%
5.0 - 10.0 GeV	25%	67%	21%	7%	1.6%

TABLE I: Efficiency of pre-cuts as applied to neutrino interactions in the fiducial volume of the Super-Kamiokande detector simulation. The charged current ν_e interactions are broken down separately for quasi-elastic and non-quasi-elastic samples. The NC sample includes elastic scattering in the denominator of the efficiency calculation.

After applying pre-cuts, we make the final event selection using a likelihood based on several event characteristics and using the ROOT package TMVA [9]. This is a similar approach to one previously studied by others [10]. We reconstruct the neutrino energy assuming quasi-elastic interactions. This depends on particle masses, the reconstructed momentum and energy of the outgoing lepton, and the angle between the outgoing lepton direction and the known neutrino beam direction ($\theta_{\nu e}$):

$$E_{rec} = \frac{m_n E_e - m_e^2/2}{m_n - E_e + (P_e \cos\theta_{\nu e})}. \tag{1}$$

The variables that are used in the likelihood can be divided into three categories:

- Basic Super-Kamiokande event parameters:
  - The ring-finding parameter used to count rings
  - The *e*-like/μ-like particle identification parameter
- Light-pattern parameters used for π^0 finding:
  - The π^0 mass
  - The π^0 likelihood
  - The energy fraction of the 2^{nd} ring
- Beam related variable:
  - The angle between the outgoing lepton and the beam direction

We already cut on the ring parameter and the PID parameter in the set of pre-cuts (Table I). Here we used the continuous distribution of these parameters as input to the likelihood. There are three variables related to a specialized fitter (`POLfit` for Pattern-Of-Light fitter) used to select single π^0 events [11]. The output of this fitter includes an overall likelihood as well as the best fit mass and energy fraction of the two gammas from π^0 decay. We also use one variable that requires knowledge of the beam direction, and therefore is not a standard SK variable for atmospheric neutrino analysis. For that variable, we had to use the MC truth information about the neutrino direction in the simulated atmospheric neutrino Monte Carlo sample. Unlike the accelerator-based experiment, these events are simulated over a wide-range of incident angles. However, the Super-K detector has uniform response. The distributions of the combined likelihood for each energy bin is shown in Fig 2. The separation between signal and background is striking at low energies but becomes worse at higher energies.

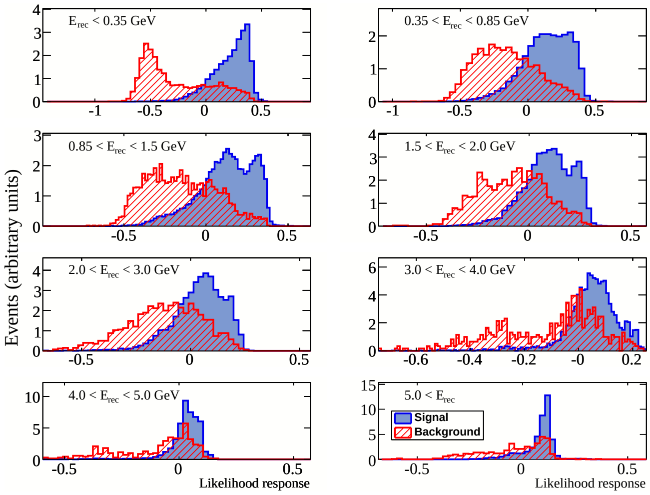

FIG. 2: (Color online) Combined likelihood distribution from 6 input variables, shown separately for 8 energy bins. Charged current ν_e signal is shown in blue (filled), and the background is red (hatched). The events used have passed the defined pre-cuts.

To choose where to cut on the likelihood variable, we compute the signal over square root of background, $S/\sqrt{B}$ for several positions of the cut. We tested cuts that range from keeping 10% of signal to keeping 100% of the signal (at the expense of increasing background). We also varied the off-axis angle and considered separate energy bins. We found that keeping a large fraction of signal, 80%, maximizes $S/\sqrt{B}$. The energy dependent efficiencies for an 80% likelihood cut is given in Table II.

A. Photo coverage

Due to the accident that happened in November 2001, where about half of the Super-Kamiokande phototubes were destroyed, Super-K has run with both 40% and 20% photo-coverage, and has atmospheric neutrino Monte Carlo samples for both conditions. It was therefore easy to repeat our studies for a detector with a 20% photo-coverage. Overall we found that both the pre-cuts and the likelihood are nearly as efficient in a detector with 20% coverage as they are in a detector with 40% coverage. The comparison of the pre-cuts is presented in Table III and the comparison of the likelihood is presented in Table IV.

	Cut that keeps 80% of signal		
Energy (rec)	ν_e	NC	ν_μ mis-ID
0 - 350 MeV	80%	15%	15%
350 - 850 MeV	80%	25%	40%
850 MeV - 1.5 GeV	80%	28%	30%
1.5 - 2.0 GeV	80%	30%	32%
2.0 - 3.0 GeV	80%	40%	18%
3.0 - 4.0 GeV	80%	50%	28%
4.0 - 5.0 GeV	80%	65%	55%
5.0 - 10.0 GeV	80%	45%	18%

TABLE II: Efficiency for the likelihood cut that keeps 80% of the signal. These efficiencies are calculated for events which have already passed the pre-cuts, and are calculated based on reconstructed energy.

	ν_e		NC		ν_μ	
	Photo-cov.		Photo-cov.		Photo-cov.	
Energy (true)	40%	20%	40%	20%	40%	20%
0 - 350 MeV	93%	92%	*NA*	*NA*	*NA*	*NA*
350 - 850 MeV	85%	84%	4%	3%	0.3%	0.6%
850 MeV - 1.5 GeV	63%	65%	8%	9%	0.3%	0.6%
1.5 - 2.0 GeV	48%	53%	10%	11%	0.7%	0.7%
2.0 - 3.0 GeV	41%	47%	11%	12%	0.8%	0.9%
3.0 - 4.0 GeV	34%	42%	12%	13%	0.9%	0.9%
4.0 - 5.0 GeV	32%	39%	11%	12%	0.4%	1.0%
5.0 - 10.0 GeV	25%	29%	7%	10%	1.6%	1.6%

TABLE III: Pre-cut efficiency for two photo-coverage: 40% (SK-I) and 20% (SK-II). The NC sample includes elastic scattering in the denominator of the efficiency calculation.

III. HOW TO COMPUTE THE BACKGROUND SPECTRUM

As mentioned in Section II, there are three categories of background: ν_e beam background (ν_e beam), neutral current background (NC), and charged current ν_μ mis-identified background (ν_μ mis-ID). To simulate the background in the long baseline beam experiment, we used the SK atmospheric Monte Carlo as follows:

- We ran over the atmospheric SK Monte Carlo, and kept events which passed all the pre-cuts.
- We applied the likelihood efficiency corresponding to the right background type (ν_e, ν_μ mis-ID or NC) and

	ν_e		NC	
	Photo-coverage		Photo-coverage	
Energy (rec)	40%	20%	40%	20%
0 - 350 MeV	80%	80%	15%	15%
350 - 850 MeV	80%	80%	25%	24%
850 MeV - 1.5 GeV	80%	80%	28%	25%
1.5 - 2.0 GeV	80%	80%	30%	35%
2.0 - 3.0 GeV	80%	80%	40%	40%
3.0 - 4.0 GeV	80%	80%	50%	42%
4.0 - 5.0 GeV	80%	80%	65%	50%
5.0 - 10.0 GeV	80%	80%	45%	45%

TABLE IV: Likelihood efficiency for two photo-coverages: 40% (SK-I) and 20% (SK-II). The likelihood cut keeps 80% of signal.

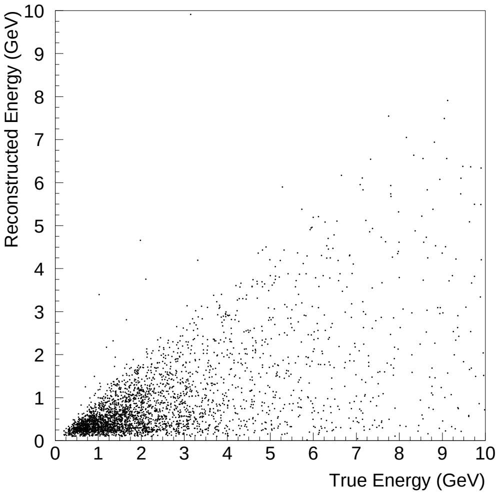

FIG. 3: Smearing matrix for neutral current events: the result of energy reconstructed using Eqn. 1 versus true neutrino energy.

using the reconstructed energy. This takes care of the likelihood efficiency, and also the energy resolution of the detector since we use reconstructed energy.

- We re-weighted this background spectrum by the ratio of the beam ν_μ flux to the atmospheric flux.
- We normalized the final background spectrum in order to account for the running conditions of the experiment: volume of detector, beam power, etc.

It is important to consider the neutral current background properly since its energy response is very uncorrelated, as can be seen in Fig. 3.

IV. OFF-AXIS ANGLE ANALYSIS

Using the cut on the likelihood that keeps 80% of the signal, we present in Fig. 4 spectra at the Kamioka location and at the Korean location for 1° off-axis angle and 2.5° off-axis angle. We also present the sensitivity to mass hierarchy and CP violation, for four different values of the off-axis angle position of the Korean detector. The χ^2 analysis used to compute the sensitivity is similar to that previously used [4] and is defined as:

$$\chi^2 = \sum_{k=1}^{N_{exp}} \left(\sum_{i=1}^{N_{Ebin}} \frac{(N(e)_i^{obs} - N(e)_i^{exp})^2}{\sigma_i^2} \right) + \sum_{j=1}^{15} \left(\frac{\varepsilon_j}{\tilde{\sigma}_j} \right)^2, \quad (2)$$

where

$$\begin{aligned} N(e)_i^{exp} &= N_i^{BG} \cdot (1 + \sum_{j=1}^{7} f_j^i \cdot \varepsilon_j) + N_i^{signal} \cdot (1 + \sum_{j=8}^{13} f_j^i \cdot \varepsilon_j) \\ &+ N_i^{\Delta E\ scale} \cdot (1 + \sum_{j=14}^{15} f_j^i \cdot \varepsilon_j) \quad (3) \end{aligned}$$

Here, N_{exp} is the number of "experiments". For example if we have two detectors (Kamioka and Korea) and run with only neutrinos then $N_{exp} = 2$. If we have two detectors but run with neutrinos and anti-neutrinos then $N_{exp} = 4$. Compared to the publication of Ishitsuka *et al.*, we added two energy bins and use events up to 3 GeV, which is relevant when the Korean detector is located at small off-axis angles. So for this analysis, we have $N_{exp} = 4$ since we ran for neutrinos and anti-neutrinos and have two detectors. We have 7 energy bins (N_{Ebin}): 400-500 MeV, 500-600 MeV, 600-700 MeV, 700-800 MeV, 800-1200 MeV, 1200-2000 MeV, 2000-3000 MeV. The sum over j in Eq. 2 is the sum over the systematic errors. We consider fifteen systematic errors $\tilde{\sigma_j}$ in this study. They are presented in Table. V and they are split into three groups. The first seven errors are on the background, the next six on the signal, and the last two on the energy scale. The largest systematic uncertainty comes from the signal normalization above 1.2 GeV, and this is due to the uncertainty on the number of rings for Multi-GeV electron-like events [12]. The systematic uncertainties were estimated using work by the Super-Kamiokande collaboration [8, 12, 13].

The results for the mass hierarchy and CP violation sensitivity are presented in Fig. 5 and Fig. 6. We find that the best sensitivity to both CP violation and mass hierarchy is achieved with the Korean detector located at 1° off-axis. The improvement in sensitivity to CP violation is rather minimal, however the sensitivity to mass hierarchy is improved by a factor of three compared to the original configuration with the Korean detector located at 2.5° off axis. This is due to the information gained by including the first oscillation maximum, with higher energy neutrinos, in the Korean far detector.

We note that several improvements have been made since the T2KK article published in 2005 [4]. Several minor problems were fixed and the cut on the likelihood variable was added. This allowed us to gain a significant number of signal events. For example in the 350-850 MeV bin, the combined efficiency (pre-cuts and likelihood) is 68%, where in the same bin of Ref. [4] it was 40%. In addition, the likelihood cut allows us to increase $S/\sqrt{B}$. Again for the 350-850 MeV bin,

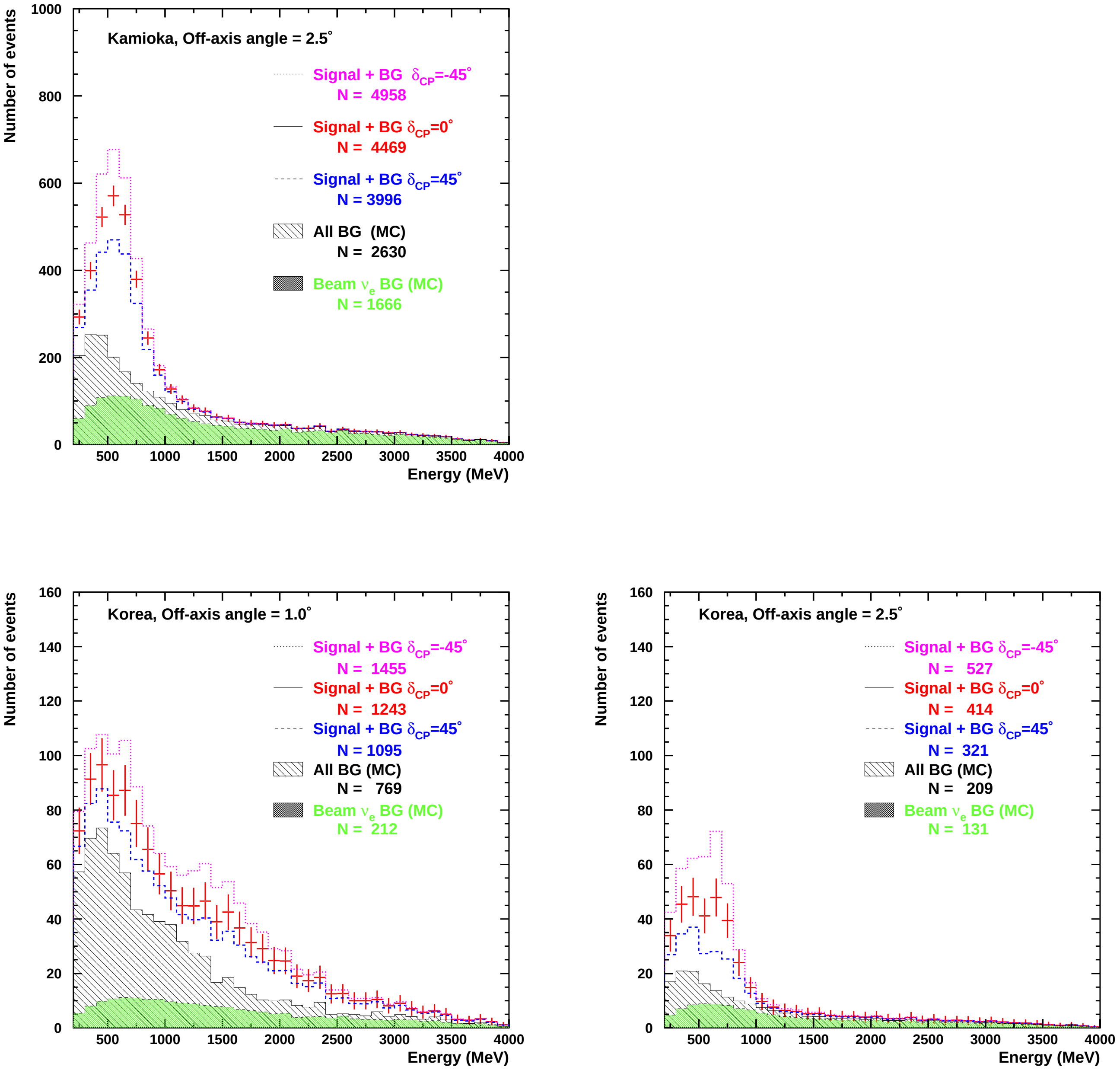

FIG. 4: (Color online) Reconstructed energy spectra at Kamioka (top), Korea 1.0° off-axis (bottom left) and Korea 2.5° off-axis (bottom right) for $\sin^2(2\theta_{13})$ =0.04 and normal hierarchy. The remaining oscillation parameters are: $\Delta m^2_{(21,31)} = 8.0\times10^{-5}, 2.5\times10^{-3} eV^2$ and $\sin^2 2\theta_{(12,23)} = 0.86, 1.0$. Each plot is normalized to 5 years of running with neutrino, a 1.66 MW beam with 40 GeV protons and in a 0.27 Mton (FV) detector (i.e. $5\times2.59\times10^{21}$ POT).

the $S/\sqrt{B}$ was increased by about 20%. If we had run with the same number of protons-on-target as the authors of the 2005 paper, the sensitivity would be a factor of two better than what we are reporting for 2.5° off-axis angle. Conversely, with the conservative benchmark beam power of 1.66 MW instead of 4MW, our sensitivity with the Korean detector located at 2.5° off-axis is roughly equivalent to that of the 2005 paper.

V. CONCLUSIONS

We have presented an updated and improved study of long baseline neutrino oscillation with a detector in Kamioka and a

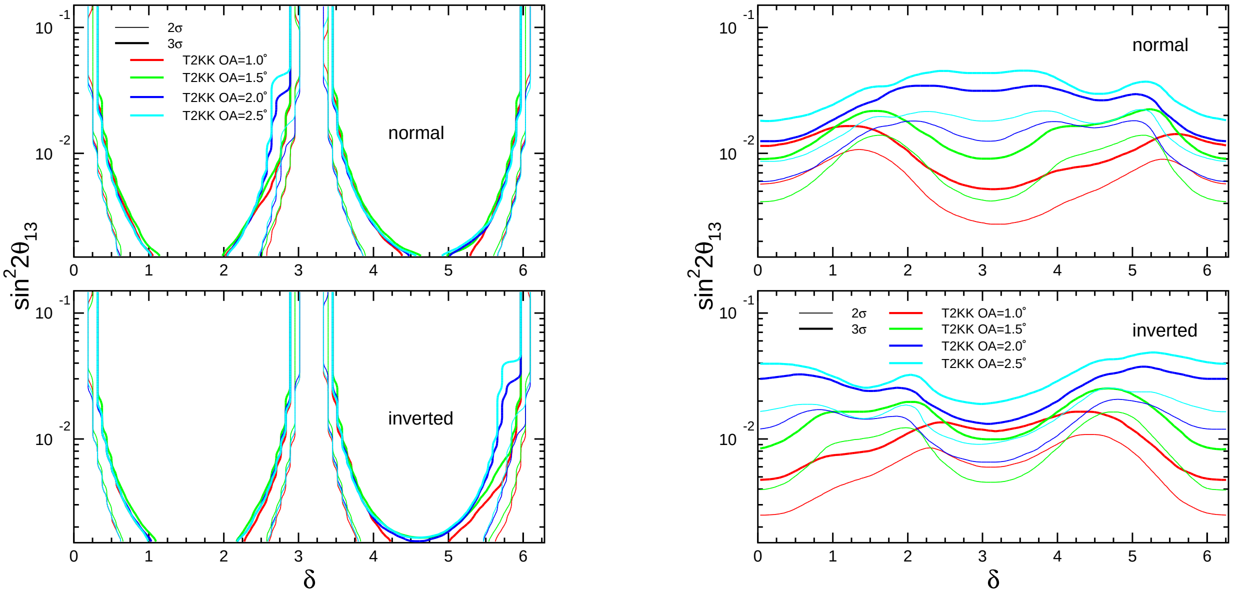

FIG. 5: Sensitivity to CP violation (left) and mass hierarchy (right) for different values of the off-axis angle. Other mixing parameters are the same as used in previous figures. Each plot considers 5 years of running with neutrinos and 5 years with anti-neutrinos, a 1.66 MW beam with 40 GeV protons and in a 0.27 Mton (FV) detector, i.e. $10 \times 2.59 \times 10^{21}$ POT. The parameter region above the curve is the region where we can determine CP violation or mass hierarchy to either 2 or 3 σ.

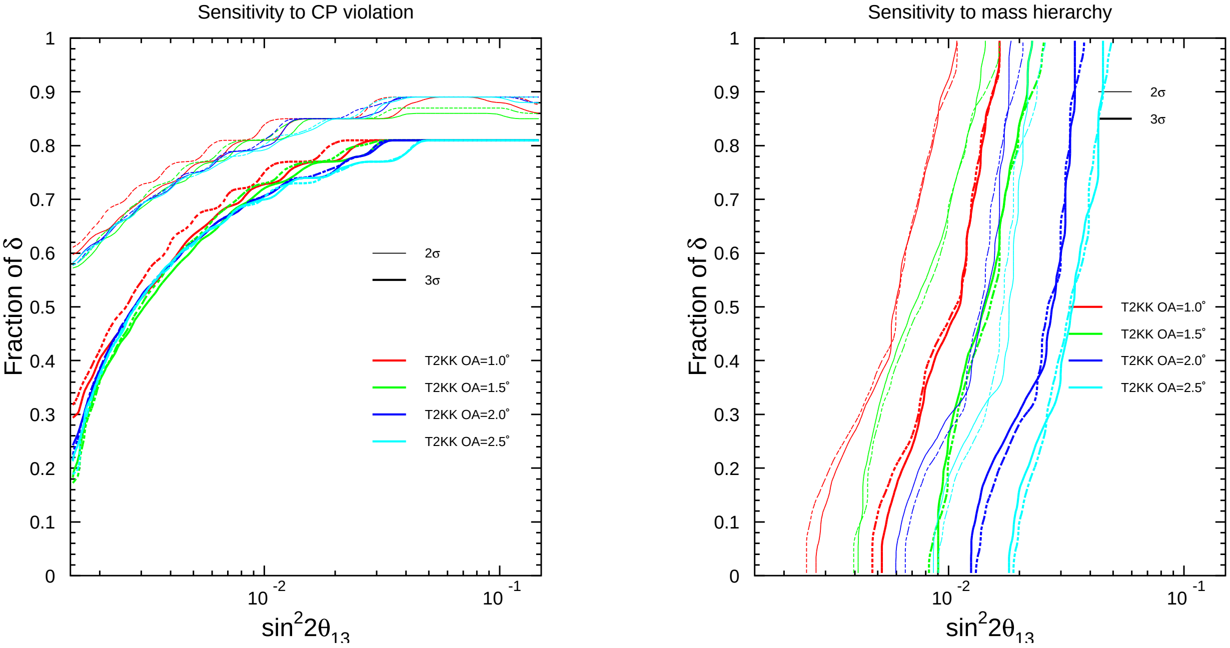

FIG. 6: Sensitivity to CP violation (left) and mass hierarchy (right) for different values of the off-axis angle. Other mixing parameters and the beam exposure are the same as used in previous figures. These plots show for what fraction of possible values of the CP phase δ we will be able to determine CP violation or mass hierarchy. The plain lines are for normal hierarchy while the dotted lines are for inverted hierarchy. If θ_{13} is large enough the mass hierarchy can always be determined whatever the value of δ; this is not the case for establishing CP violation when δ approaches 0, π, or 2π.

Index	Systematic uncertainty	Value
1	BG normalization below 1.2 GeV (for Kamioka)	5%
2	BG normalization above 1.2 GeV (for Kamioka)	5%
3	BG normalization below 1.2 GeV (for Korea)	5%
4	BG normalization above 1.2 GeV (for Korea)	5%
5	BG normalization between ν_e and $\bar{\nu}_e$ below 1.2 GeV	5%
6	BG normalization between ν_e and $\bar{\nu}_e$ above 1.2 GeV	5%
7	BG spectrum (common for Kamioka and Korea)	5%
8	Signal normalization below 1.2 GeV $\sigma(\nu_\mu)/\sigma(\nu_e)$	5%
9	Signal normalization above 1.2 GeV $\sigma(\nu_\mu)/\sigma(\nu_e)$	20%
10	$[\sigma(\nu_\mu)/\sigma(\nu_e)]/[\sigma(\bar{\nu}_\mu)/\sigma(\bar{\nu}_e)]$ below 1.2 GeV	5%
11	$[\sigma(\nu_\mu)/\sigma(\nu_e)]/[\sigma(\bar{\nu}_\mu)/\sigma(\bar{\nu}_e)]$ above 1.2 GeV	5%
12	Efficiency difference between Kamioka and Korea detector below 1.2 GeV	1%
13	Efficiency difference between Kamioka and Korea detector above 1.2 GeV	1%
14	Energy scale difference between Kamioka and Korea detector	1%
15	Energy scale difference between near and (Kamioka/Korea) detector	1%

TABLE V: List of systematic uncertainties and their assumed values.

second in Korea. Using precuts and a likelihood designed to reject neutral current background while keeping charged current quasi-elastic events, we were able to increase the amount of signal that we keep in the main signal bin (350-850 MeV) from about 40% to 68%, and we were able to remove more background than what was done before. We found that the effectiveness of the cuts and likelihood was relatively undiminished when applied to a detector with 20% rather than 40% photocoverage. We found that the best location among the possibilites we explored for the Korean detector is 1.0°, which is more on-axis than previously considered, and allows a somewhat wider band neutrino energy spectrum. This improved the T2KK sensitivity by a factor of two compared to what was published previously, even after taking a more conservative number of POT per year to be a factor of three lower. With an experiment configured at 1.0°, and a benchmark beam power of 1.66 MW, the neutrino mass hierarchy should be revealed if $\sin^2 2\theta_{13}$ is larger than 10^{-2} for a wide range of δ. CP violation would be detected at 3σ significance for 70% of possible values of δ.

The authors gratefully acknowledge the work of the Super-Kamiokande collaboration in developing the tools used for this analysis, however the results and their interpretation are the responsibility of the authors of this paper. We are thankful to the authors of Ref. [4] who generously provided their software. We are grateful for financial support by the United States Department of Energy and the Grant-in-Aid Scientific Research by the Japan Society for the Promotion of Science.

---

[1] Z. Maki, M. Nakagawa, and S. Sakata, Prog. Theor. Phys. **28**, 870 (1962).
[2] B. Pontecorvo, Sov. Phys. JETP **26**, 984 (1968).
[3] D. Beavis et al., Tech. Rep. BNL-32459, Brookhaven National Laboratory (1995).
[4] M. Ishitsuka, T. Kajita, H. Minakata, and H. Nunokawa, Phys. Rev. **D72**, 033003 (2005), hep-ph/0504026.
[5] V. Barger et al., Phys. Rev. **D74**, 073004 (2006), hep-ph/0607177.
[6] V. Barger et al. (2007), hep-ph/0705.4396.
[7] URL `http://j-parc.jp/NP08/`.
[8] Y. Ashie et al. (Super-Kamiokande), Phys. Rev. **D71**, 112005 (2005), hep-ex/0501064.
[9] A. Hocker, P. Speckmayer, J. Stelzer, F. Tegenfeldt, and H. Voss, Tech. Rep. CERN-2008-001, CERN (2007).
[10] C. Yanagisawa, C. K. Jung, P. T. Le, and B. Viren, AIP Conf. Proc. **944**, 92 (2007).
[11] T. Barszczak, Ph.D. thesis, University of California, Irvine (2005).
[12] Y. Takenaga, Ph.D. thesis, University of Tokyo (2008).
[13] M. Fechner, Ph.D. thesis, Paris U., VI-VII (2006).