# Wide Band Beam Studies for T2KK

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## Abstract

This proceedings covers four distinct topics related to an electron neutrino appearance experiment in a long baseline neutrino beam. First we present a likelihood that was created in order to distinguish charged current $\nu_e$ interactions from neutral current background. We compared the likelihood variables with the Super-K atmospheric neutrino data, when it was possible. We also optimized the cut on the likelihood variable.

Second, we present a study of the sensitivity of the T2KK experiment to CP violation and mass hierarchy as a function of the off-axis angle using the optimized likelihood cut.

Third, we present a short study which compares two methods to estimate the neutral current background. In one case we use the full Super-K atmospheric Monte Carlo, in the other case we use a matrix multiplication method similar to that used by the GLoBES software.

Finally, we compare the results achievable by the T2KK setup with the results obtained for a long baseline beam from Fermilab to DUSEL, using the same analysis framework.

## 1. Introduction

To determine the CP violating phase $\delta$ and the neutrino mass hierarchy, a powerful tool is to measure electron neutrino appearance at both the first and second oscillation maximum. Two different approaches have been considered in order to make this measurement. One approach is to have two detectors in the same beam, each of them positioned mainly at one oscillation maximum, either the first or second. This is the approach of the T2KK project (Tokai to Kamioka to Korea)[8]. Another approach, is to use a wide-band energy beam, and measure electron neutrino appearance from both the first and second maxima with the same detector[2]. This is the approach envisioned by the BNL-FNAL working group and presented in their report [3] as a model for a long baseline neutrino oscillation experiment from Fermilab to DUSEL.

In the first published T2KK article[8], the off-axis angle of the Korean detector was assumed to be 2.5°. In this proceedings, we study the sensitivity to CP violation and mass hierarchy if we choose a smaller off-axis angle for the location of the Korean detectory. 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.

The T2KK project assumes an upgraded 4MW J-PARC beam created from 40 GeV protons, running $1.12 \times 10^7$ seconds per year. This is equivalent to $28 \times 10^{21}$ POT per year. We assume 4 years of neutrino running and 4 years of anti-neutrino running. The $\nu_\mu$ flux observed at four different off-axis angles, at 1050 km from the target is presented in Fig. 1. We also assume two 0.27 Mton (fiducial volume) water

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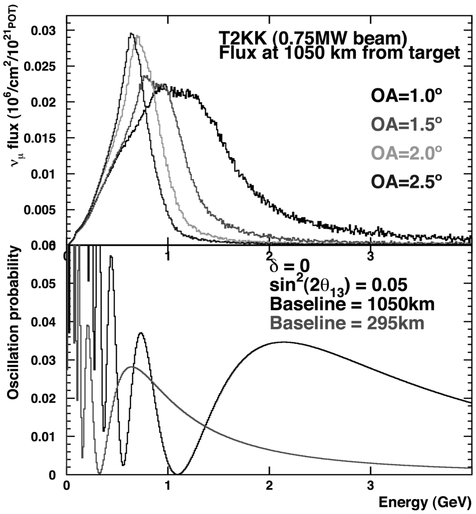

**Fig. 1** Neutrino flux as a function of energy for several off-axis angle, and a 0.75MW beam at 1050km from the target. For comparison, the $\nu_\mu \to \nu_e$ probability, for the two baseline considered in T2KK (295km and 1050km), for $\Delta m^2_{(21,31)} = 7.3 \times 10^{-5}, 2.5 \times 10^{-3} eV^2$ and the other mixing angles at $\sin^2 2\theta_{(12,23)} = 0.86, 1.0$. We assumed the earth density to be constant and to be equal to 2.8 $g/cm^3$

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°.

Our tool for these studies is the fully reconstructed atmospheric neutrino Monte Carlo sample from the Super-Kamiokande experiment[6]. In order to simulate the T2KK beam we reweight this atmospheric Monte Carlo by the ratio of the T2KK flux to the atmospheric flux.

## 2. Signal / Background likelihood Analysis

Our objective is to identify and reconstruct an excess of charged current $\nu_e$ interactions in a nearly pure $\nu_\mu$ beam. We shall be especially interested in quasi-elastic interactions such as $\nu_e n \to e^- p$. 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. This work is similar to what was done by C. Yanagisawa [4]. There are three kinds of backgrounds related to this signal:

- The $\nu_e$ beam background ($\nu_e$ beam)
- The neutral current background (NC)
- The charged current $\nu_\mu$ mis-identified background ($\nu_\mu$ mis-ID)

The $\nu_e$ beam background is of course irreducible. The NC background mainly consists of neutral current events which are energetic enough to create a $\pi^0$. The $\pi^0$ decays into two photons and if one of the photons is missed because of a very small energy or an overlapping ring, then the $\pi^0$ can be misidentified as a single electromagnetic shower and therefore fake a $\nu_e$ CCQE event. The dominant

**Table 1** Efficiency of pre-cuts as applied to neutrino interactions in the fiducial volume of the Super-Kamiokande detector simulation. The charged current $\nu_e$ 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.

| | Signal | | | Background | |
|---|---|---|---|---|---|
| True neutrino energy | $\nu_e$ (avg) | QE $\nu_e$ | non-QE $\nu_e$ | NC | $\nu_\mu$ mis-ID |
| 0 - 350 MeV | 93% | 94% | $NA$ | 0.2% | $NA$ |
| 350 - 850 MeV | 80% | 94% | 41% | 4% | 0.6% |
| 850 MeV - 1.5 GeV | 61% | 92% | 36% | 10% | 0.7% |
| 1.5 - 2.0 GeV | 46% | 86% | 29% | 11% | 0.8% |
| 2.0 - 3.0 GeV | 38% | 81% | 26% | 12% | 0.9% |
| 3.0 - 4.0 GeV | 31% | 78% | 23% | 11% | 1.0% |
| 4.0 - 5.0 GeV | 25% | 70% | 19% | 11% | 0.6% |
| 5.0 - 10.0 GeV | 20% | 62% | 16% | 10% | 1.0% |

$\pi^0$ background comes from events where one of the photon was missed because the energy was too small. The $\nu_\mu$ mis-ID background consists of charge current $\nu_\mu$ 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 $\nu_e$ appearance and especially $\nu_e$ undergoing quasi-elastic interactions, the events that we want to select are single-Cherenkov-ring, electron-like events with no decay electron; 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-cuts efficiencies are listed in Table 1. The NC efficiency is based on the total cross section for neutral current interactions which includes a large component of neutrino-nucleon elastic scattering, which are mostly unobserved in a water Cherenkov detector. The NC events that pass the pre-cuts are mostly single-$\pi^0$ production.

After applying pre-cuts, we make the final event selection using a likelihood based on several event characteristics. We reconstruct the neutrino energy assuming quasi-elastic interactions. This depends on particle masses, the reconstructed momentum/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/$\mu$-like particle identification parameter
- Light-pattern parameters used for $\pi^0$ finding:
  - The $\pi^0$ mass
  - The $\pi^0$ likelihood

  - The energy fraction of the $2^{nd}$ ring

- Beam related variables:
  - The angle between the outgoing lepton and the beam direction
  - Two more variables using the emitting point of Cherenkov light, the reconstructed vertex and the beam direction.

We already used two standard SK variables, the ring parameter and the PID parameter, as the pre-cuts (Table 1). Now we are using the value 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 $\pi^0$ events[5]. The output of this fitter includes an overall likelihood as well as the best fit mass and energy fraction of the two gammas from $\pi^0$ decay. We also use three variables that require knowledge of the beam direction, and therefore are not standard SK variables for atmospheric neutrino analysis. For those variables, 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 final likelihood is presented in Fig. 2.

In order to trust our likelihood, we check that our Monte Carlo gives an accurate representation of the data. Since we have the Super-Kamiokande atmospheric data sample, we can compare the distributions of some of the variables between Monte Carlo and data. For this study, we used 9 years of SK-I Monte Carlo and the whole (1489 day) SK-I dataset[6]. Naturally, we could not test the variables that use the beam direction since this information is not available for actual detected atmospheric neutrinos. We test the five remaining variables, and the results are shown in Fig. 3. The agreement is fairly good, but some differences appear and further study is warranted.

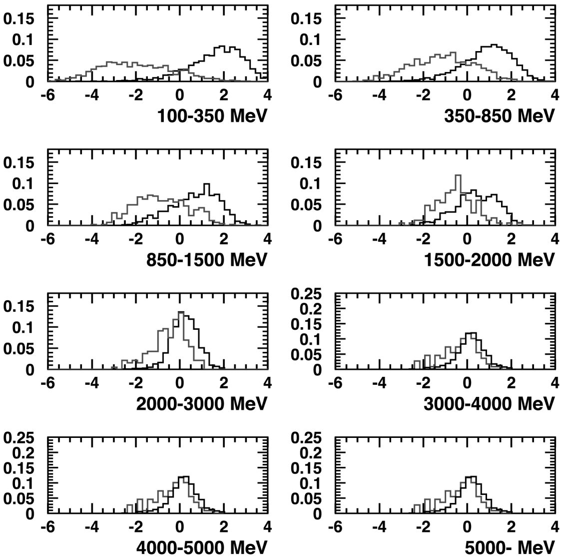

**Fig. 2** Combined likelihood distribution from 8 input variables, shown separately for 8 energy bins. Charged current $\nu_e$ signal is shown in black, and the NC background is shown in red. The events used have passed the defined pre-cuts.

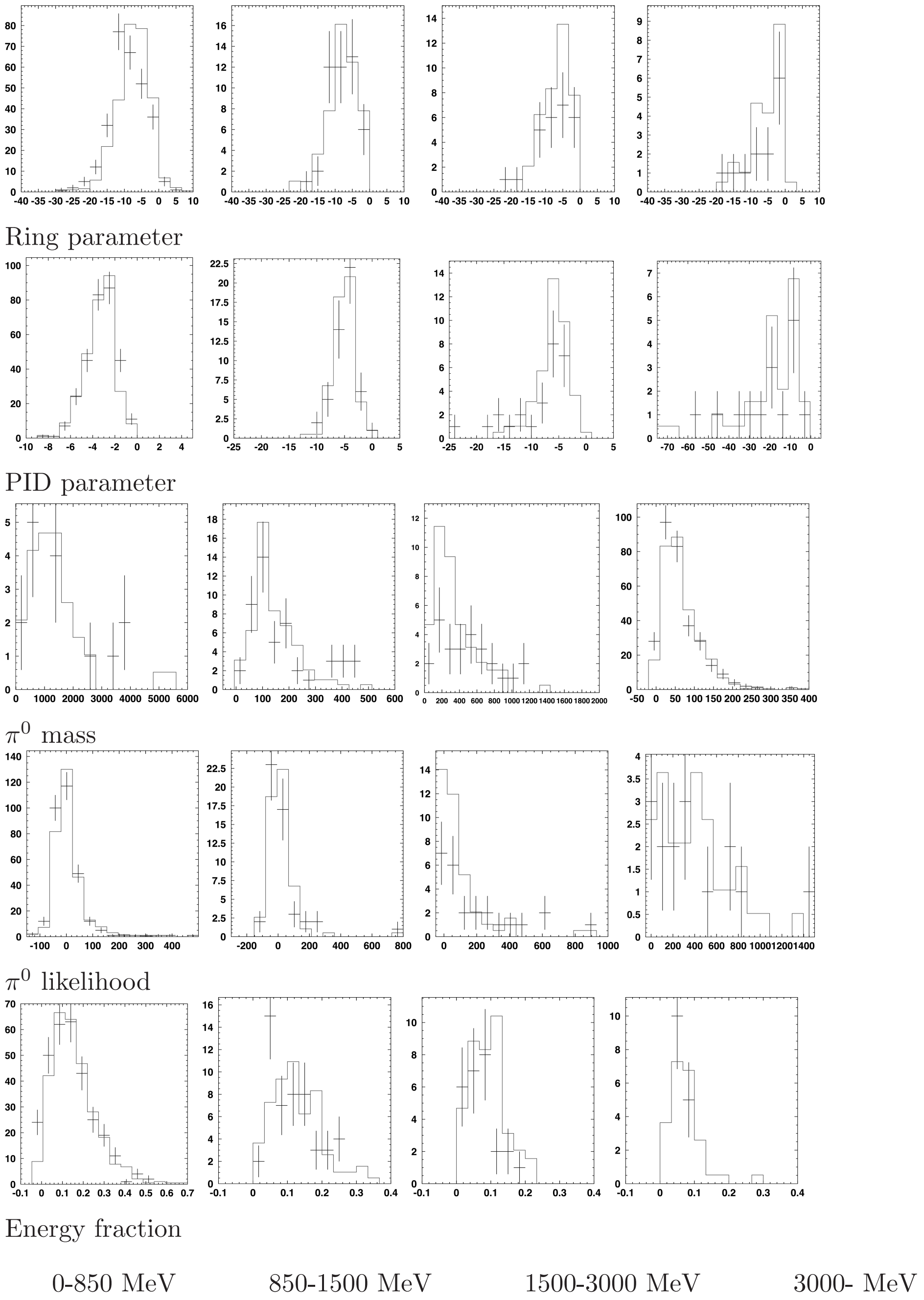

**Fig. 3** Comparison of data and Monte Carlo for five likelihood variables. Black = 1489 days of SK atmospheric data, Red = 9 years of SK atmospheric Monte Carlo normalized to the data livetime.

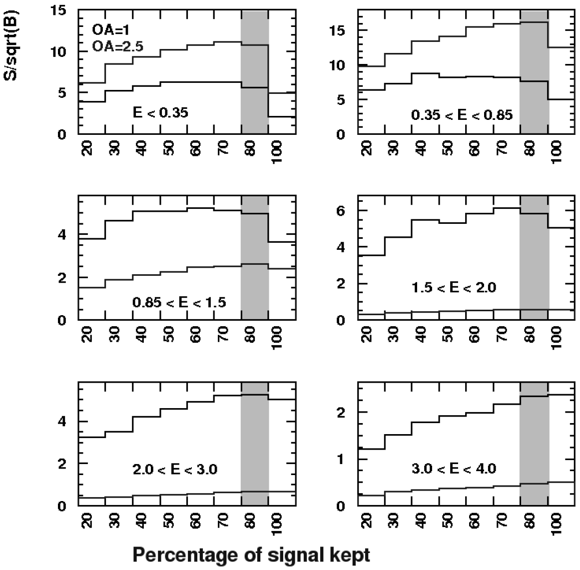

**Fig. 4** Example of $S/\sqrt{B}$ optimization for 1° and 2.5° off-axis angle. X-axis: percentage of signal kept. On average, keeping 80 % of signal gives the best $S/\sqrt{B}$ (orange band)

**Table 2** 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.

| | Cut that keeps 80% of signal | | |
|---|---|---|---|
| Energy (rec) | $\nu_e$ | NC | $\nu_\mu$ mis-ID |
| 0 - 350 MeV | 82.7% | 5.2% | 6.9% |
| 350 - 850 MeV | 84.2% | 28.0% | 25.3% |
| 850 MeV - 1.5 GeV | 83.1% | 28.2% | 30.2% |
| 1.5 - 2.0 GeV | 83.8% | 33.3% | 39.3% |
| 2.0 - 3.0 GeV | 84.5% | 27.1% | 53.2% |
| 3.0 - 4.0 GeV | 79.0% | 27.5% | 45.9% |
| 4.0 - 5.0 GeV | 75.8% | 52.3% | 41.9% |
| 5.0 - 10.0 GeV | 78.8% | 19.4% | 51.4% |

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. An example of such optimization is shown in Fig. 4 for 1° and 2.5° off-axis angle. We found that keeping a large fraction of signal (80% for example) is what generally gives the best $S/\sqrt{B}$. And we present the efficiency of such a likelihood cut in Table 2.

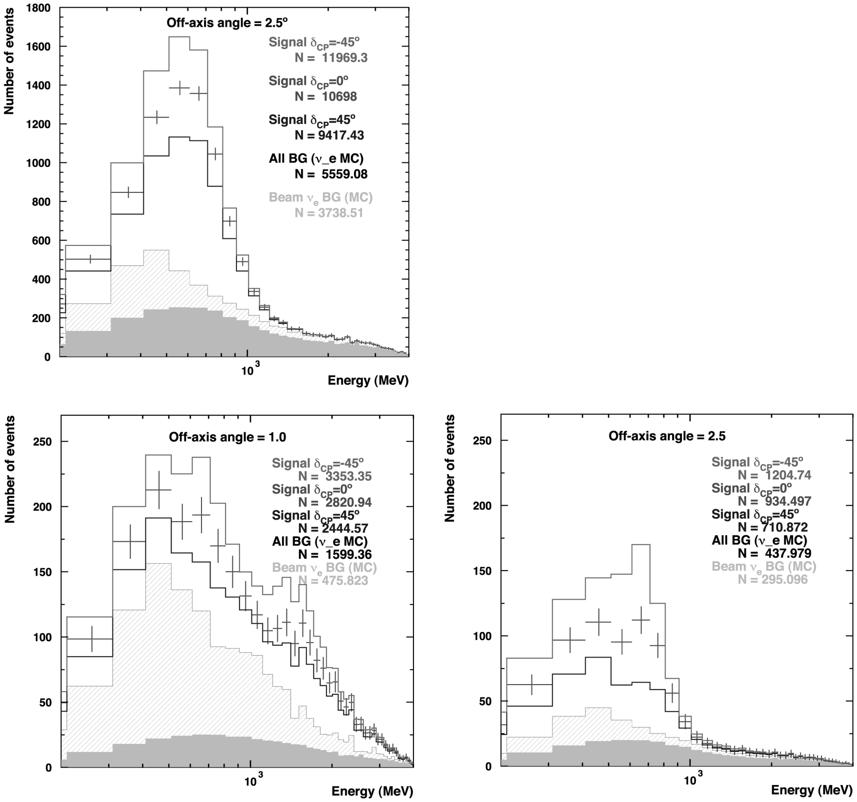

**Fig. 5** Spectrum at Kamioka (top), Korea 1.0° off-axis (bottom left) and Korea 2.5° off-axis (bottom right) for $\sin^2(2\theta_{13})$ =0.04. The remaining oscillation parameters are: $\Delta m^2_{(21,31)} = 7.3 \times 10^{-5}, 2.5 \times 10^{-3} eV^2$ and the other mixing angles: $\sin^2 2\theta_{(12,23)} = 0.86, 1.0$. We assumed the earth density to be constant and to be equal to 2.8 $g/cm^3$

## 3. Off-Axis Angle Analysis

Using the cut on the likelihood that keeps 80% of the signal, we present in Fig. 5 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 $\chi^2$ analysis used to compute the sensitivity is very similar to that presented by Ishitsuka *et al.*[8] and is defined in Eq. 2.

$$\chi^2 = \sum_{k=1}^{N_{exp}} \left( \sum_{i=1}^{N_{Ebin}} \frac{(N(e)_i^{obs} - N(e)_i^{exp})^2}{\sigma_i^2} \right) + \sum_{j=1}^{3} \left( \frac{\epsilon_j}{\tilde{\sigma_j}} \right)^2 \tag{2}$$

$$N(e)_i^{exp} = N_i^{BG} \cdot (1 + \sum_{j=1}^{2} f_j^i \cdot \epsilon_j) + N_i^{signal} \cdot (1 + f_3^i \cdot \epsilon_3) \tag{3}$$

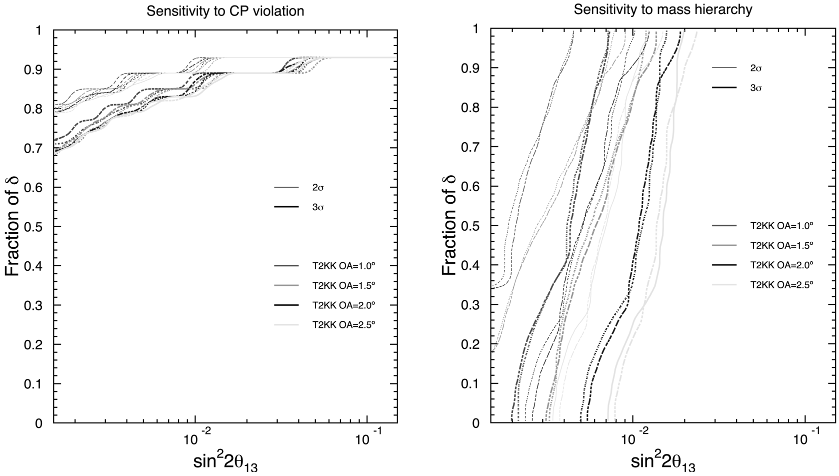

**Fig. 6** Sensitivity to CP violation (left) and mass hierarchy (right) for different values of the off-axis angle. (Other paramters: $\Delta m^2_{(21,31)} = 7.3 \times 10^{-5}, 2.5 \times 10^{-3} eV^2$ and the other mixing angles: $\sin^2 2\theta_{(12,23)} = 0.86, 1.0$. We assumed the earth density to be constant and to be equal to 2.8 $g/cm^3$)

Here, $N_{exp}$ is the number of "experiments". For example if we have two detectors (Kamioka and Korea for example) 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 2 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.

It is important to notice that several improvements have been made since the article published by Ishitsuka *et al.*[8] in 2005. Several minors bugs 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 67%, where in the same bin of Ref. [8] it was 40% (which is the T2K efficiency). In addition, the likelihood cut allows us to increase $S/\sqrt{B}$. Again for the 350-850 MeV bin, the $S/\sqrt{B}$ was increased by about 20%. The new results for the mass hierarchy and CP violation sensitivity are presented in Fig. 6 and Fig. 7. The sensitivity is now a factor of two better than what was presented in Ref. [8] for 2.5° off-axis angle. And it is found that the best sensitivity to both CP violation and mass hierarchy is achieved with the Korean detector located at 1° off-axis, which improves the sensitivity by an additional factor of four.

## 4. How to Compute the Background Spectrum

As mentioned in Section 2., there are 3 kinds of background considered in this study. The $\nu_e$ beam background ($\nu_e$ beam), the neutral current background (NC) and the charged current $\nu_\mu$ mis-identified background ($\nu_\mu$ mis-ID). To simulate those backgrounds, we used the SK atmospheric Monte Carlo as follows:

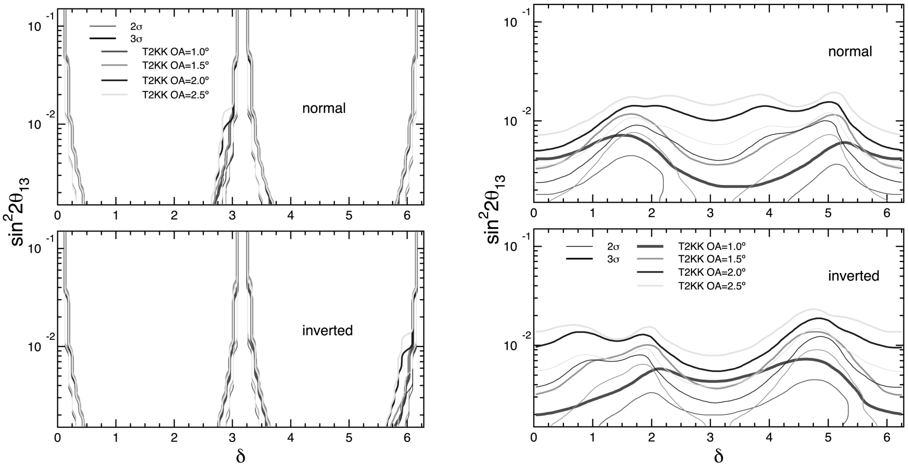

**Fig. 7** Sensitivity to CP violation (left) and mass hierarchy (right) for different values of the off-axis angle. (Other parameters: $\Delta m^2_{(21,31)} = 7.3 \times 10^{-5}, 2.5 \times 10^{-3} eV^2$ and the other mixing angles: $\sin^2 2\theta_{(12,23)} = 0.86, 1.0$. We assumed the earth density to be constant and to be equal to 2.8 $g/cm^3$)

- 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 ($\nu_e$, $\nu_\mu$ mis-ID or NC) and 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 $\nu_\mu$ 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.)

The Monte Carlo technique is different from what is being done by the GLoBES [7] software. The GLoBES software uses a purely computational method using flux, cross section and efficiency tables. As a cross check, we performed our own version of a GLoBES-like computational "smearing method". We especially focused on the NC background since this is the one with a complicated detector response. Here is how we proceeded to compute the NC background with the smearing method:

1. Multiply the $\nu_\mu$ flux by the NC cross-section, and normalize properly to account for the number of POT and the detector size. The results is an event rate which does not account for detector effects.
2. Multiply the number of NC interactions by the the pre-cuts efficiency for NC events. (Table 1)
3. Apply the NC smearing matrix (Fig. 8, left plot) to the result of the previous step to convert from true neutrino energy to reconstructed neutrino energy.

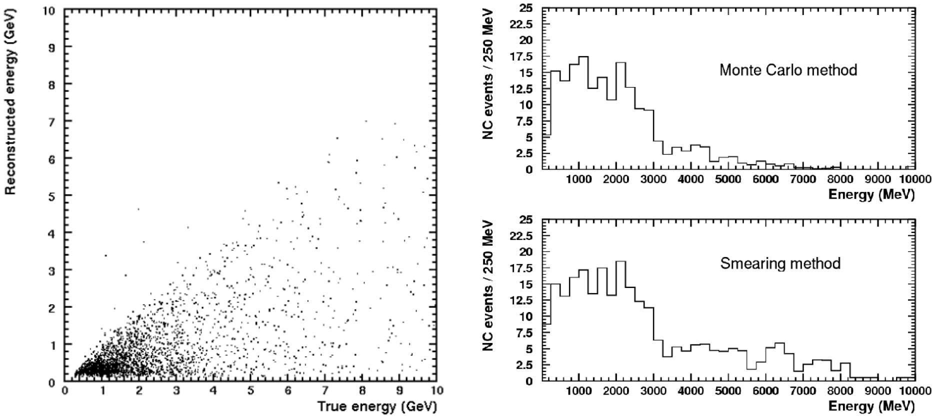

**Fig. 8** **left:** Smearing matrix for NC events, **Right:** Comparison of methods to compute NC background: Top plot is the MC method, bottom plot is the smearing method. The plots are normalized for $30 \times 10^{20}$ POT and a 300kTon detector.

4. Finally, multiply the output of the previous step by the likelihood efficiency as a function of reconstructed neutrino energy. (Table 2)

Finally we compared our two methods of creating NC background. In Fig. 8 the top histogram is the result of the "Monte Carlo method" and the bottom histogram is the result of our "Smearing method". The results are comparable but some differences can be seen at high energy.

## 5. Comparing T2KK with FNAL-DUSEL

In this section, we compare the sensitivity of the T2KK setup with the Korean detector at 1° off-axis, and the FNAL-DUSEL configuration studied in Ref. [3], using the same analysis framework. In other words, we continue to use fully reconstructed Super-K Monte Carlo and reweight by the flux used for the FNAL-DUSEL study[3]. This is quite suitable for the proposed case of a large water Cherenkov detector located at the DUSEL site, assuming it has approximately the same performance as Super-K. The $\chi^2$ definition of Eq. 2 has $N_{exp} = 2$ for neutrino and anti-neutrino running.

The FNAL-DUSEL setup assumes a 1 MW beam created from 120 GeV protons, running $1.15 \times 10^7$ seconds per year. This is equivalent to $3 \times 10^{21}$ POT per year. It assumes 5 years of neutrino running and 5 years of anti-neutrino running. It also assumes a total of 0.3 Mtons (fiducial volume) of water Cherenkov detector, at a baseline of 1300 kilometers (Homestake mine, S.D.) and at 0.5° off-axis angle. A more complete description of our analysis of this configuration is also included in Ref. [8].

An example of reconstructed neutrino spectrum for such a setup is shown in Fig. 9. This is my equivalent of Fig. 9 (top left) on page 54 of Ref. [3], and it may be compared to the lower left panel of Fig. 5 in this proceedings. The chief difference, other than the running conditions, is that the first and second oscillation maximum are at 1 and 2.3 GeV (rather than 0.7 and 1.5 GeV for the 1.0° off-axis Korean detector of T2KK).

It should be noted that the running conditions of these two setups are significantly different, the number of protons on target, in particular, differs nearly by an order of magnitude. This should be kept in mind when looking at the sensitivity

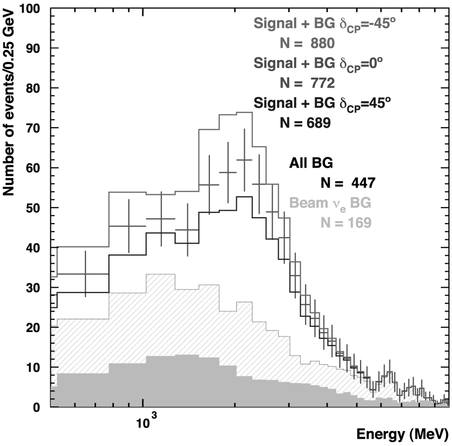

**Fig. 9** Spectrum for the FNAL-DUSEL setup at a baseline of 1300 km and 0.5° off-axis angle, for $\sin^2(2\theta_{13})$ =0.04. The remaining oscillation parameters are: $\Delta m^2_{(21,31)} = 7.3 \times 10^{-5}, 2.5 \times 10^{-3} eV^2$ and the other mixing angles: $\sin^2 2\theta_{(12,23)} = 0.86, 1.0$. We assumed the earth density to be constant and to be equal to 2.8 $g/cm^3$.

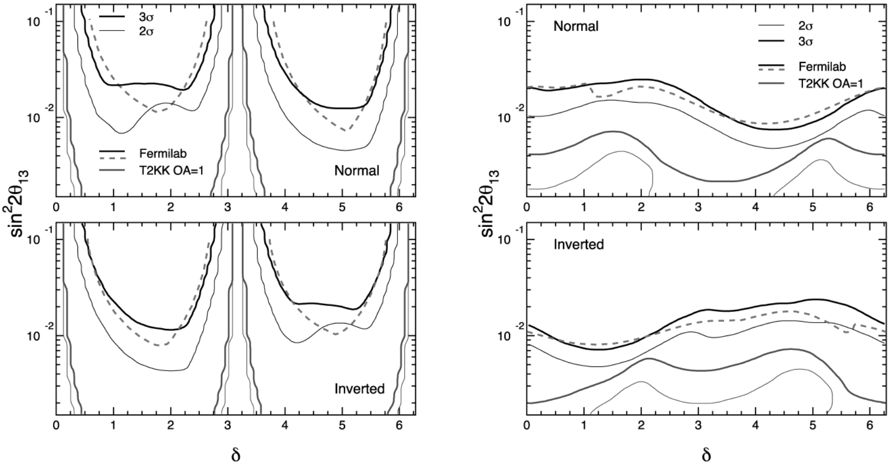

**Fig. 10** Sensitivity to CP violation (left) and mass hierarchy (right) for T2KK 1° off-axis (red). Our computations for 1 MW FNAL-DUSEL are shown in black and compared to those published in [3] (dashed blue).

plots presented in Fig. 10. In this figure, we also plotted (dashed blue lines) the results presented in Ref. [3], and we see good agreement between our results and theirs.

## 6. Conclusion

By developing a likelihood designed to reject neutral current background, we were able to increase the amount of signal that we keep from 40% up to 67%, and we were able to remove more background than what was done before. We also found that the best location for the Korean detector is at 1.0° and that allowed to improve the T2KK sensitivity by an order of magnitude compared to what was done previously.

We also checked if using a full Monte Carlo to compute the neutral current background gives similar results that using a GLoBES-like approach, and we conclude that it does.

Finally we compared the T2KK setup with the FNAL-DUSEL setup using the same analysis framework. First we found that our results for the FNAL-DUSEL setup agree very well with what is predicted by the FNAL-DUSEL working group. And second, we found that T2KK would lead to a better sensitivity in both CP violation and mass hierarchy, but we want to draw attention to the fact that the running conditions assumed for both experiments were significantly different.

We gratefully acknowledge our Super-K collaborators for the development and maintenance of the Super-K Monte Carlo and reconstruction software. We also thank T. Kajita and K. Okumura for their careful checks and their help with the software which was generously provided by the authors of Ref. [8]. We are grateful for financial support by the United States Department of Energy.

## References

[1] M. Ishitsuka, T. Kajita, H. Minakata and H. Nunokawa, “Resolving neutrino mass hierarchy and CP degeneracy by two identical detectors with different baselines,” Phys. Rev. D **72**, 033003 (2005) [arXiv:hep-ph/0504026].

[2] V. Barger, M. Dierckxsens, M. Diwan, P. Huber, C. Lewis, D. Marfatia and B. Viren, “Precision physics with a wide band super neutrino beam,” Phys. Rev. D **74**, 073004 (2006) [arXiv:hep-ph/0607177].

[3] V. Barger *et al.*, “Report of the US long baseline neutrino experiment study,” arXiv:0705.4396 [hep-ph].

[4] C. Yanagisawa, C.K. Jung, P.T. Lee, and B. Viren, Preprint submitted to The U.S. Long Baseline Neutrino Experiment Study. http://nwg.phy.bnl.gov/~diwan/nwg/fnal-bnl/docs/numunuePREBWv3.pdf

[5] T. Barszczak, PhD Thesis, U. California, Irvine. UMI-31-71221

[6] Y. Ashie *et al.* [Super-Kamiokande Collaboration], “A measurement of atmospheric neutrino oscillation parameters by Super-Kamiokande I,” Phys. Rev. D **71**, 112005 (2005) [arXiv:hep-ex/0501064].

[7] P. Huber, M. Lindner and W. Winter, “Simulation of long-baseline neutrino oscillation experiments with GLoBES,” Comput. Phys. Commun. **167**, 195 (2005) [arXiv:hep-ph/0407333].

[8] F. Dufour, E. Kearns “Study of the FNAL to DUSEL Long Baseline Neutrino Oscillation Experiment with a Large Water Cherenkov Detector” http://nwg.phy.bnl.gov/~diwan/nwg/fnal-bnl/docs/dufour_fnal_lb_study.pdf