Study of the FNAL to DUSEL Long Baseline Neutrino Oscillation Experiment with a Large Water Cherenkov Detector

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Abstract

This report summarizes studies of the BNL/FNAL long baseline neutrino experiment, using the analysis machinery developed for the Super-Kamiokande and T2KK (Tokai to Kamioka and Korea) experiments. The analysis consists of predetermined neutrino flux spectra, neutrino-nucleus cross section tables, energy response functions, and efficiency factors calculated for neutrino interactions in water using the Super-Kamiokande atmospheric neutrino Monte Carlo. The efficiency factors are based on a multi-variable likelihood calculated using simulated and fully-reconstructed Super-Kamiokande atmospheric neutrino events. For neutral current interactions, rather than energy response functions, we use flux weighting of fully reconstructed Super-K atmospheric neutrino Monte Carlo events.

Using this analysis machinery, we considered an experimental setup that has been proposed in the U.S. We assumed a wide-band, 0.5° off-axis 1MW beam with 120GeV protons, a 300 kTon water Cherenkov detector, a baseline of 1300km, 30×10^{20} POT for neutrinos and the same for anti-neutrinos, in order to compare our results with those of the BNL/FNAL Joint Study on Long Baseline Neutrinos[1].

1 Introduction

The next generation of long baseline experiments, those that run after T2K and NOνA, will have the principle goal of discovering CP violation in the leptonic sector, assuming θ_{13} is large enough. In addition, the next generation experiments may be required to determine the neutrino mass hierarchy if combined information from T2K, NOνA and reactor experiments is unable to do so unambiguously. The next generation experiments will require powerful neutrino beams in the MW class, combined with very large detectors of order Mton mass, in order to accumulate sufficient statistics to detect a different oscillation probability for neutrinos and antineutrinos.

To determine the CP violating phase δ 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)[2], using an upgraded beam following the T2K experiment.

Another approach, and the one presented in this report, is to use a wide-band energy beam, and measure electron neutrino appearance from both the first and second maxima with the same detector. Figure 1 shows the wide energy band ν_μ flux and the oscillation probability of ν_μ oscillating to ν_e for an on-axis neutrino beam from BNL or Fermilab to a large detector in the western United States. Such a detector is envisioned for the proposed Deep Underground Science and Engineering Laboratory (DUSEL), which may be located at the Homestake mine in South Dakota, the Henderson mine in Colorado, or a few other locations beings considered. In this report, we assume the beam originates at Fermilab and the detector is located at Homestake, a baseline of 1300 km. This configuration has been studied for the joint BNL/FNAL Joint Study on Long Baseline Neutrinos. We will use the analysis machinery that was developed for the T2KK

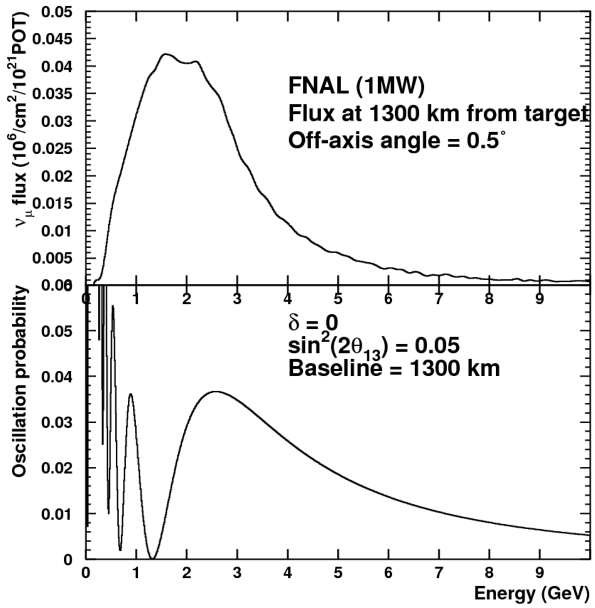


Figure 1 Neutrino flux as a function of energy for the 0.5° off-axis, 1MW beam from FNAL to Homestake, a baseline of 1300 km. For comparison, the $\nu_\mu \to \nu_e$ probability for $\Delta m^2_{(21,31)} = 7.3 \times 10^{-5}, 2.5 \times 10^{-3} eV^2$ and the other mixing angles at $\sin^2 2\theta_{(12,23)} = 0.86, 1.0$. We assumed the earth density to be constant and to be equal to 2.8 g/cm^3

studies and apply it to the wide-band beam approach to compare with the results from the FNAL/BNL working group[1].

This report consists of three major sections. Section 2 is the description of a likelihood used to separate signal from background for ν_e appearance experiments using a water-Cherenkov detector. Section 3 describes the methods that we used in order to create signal and background spectra. For the background spectra, we used the Super-Kamiokande Monte Carlo. This method differs from using software such as GLOBES in that it fully simulates the reponse of the water Cherenkov detector. Therefore our results are a good cross-check of the results obtained by the BNL/FNAL joint study group. We then show the event spectra that we obtained for one of the experimental setup presented by the BNL/FNAL joint study group, specifically, the configuration with a 0.5° off-axis 1MW beam, with 120 GeV protons, 30×10^{20} POT and a 300Kton water Cherenkov detector. Section 4 presents a χ^2 analysis testing the sensitivity to mass hierarchy and CP violation of a given experimental setup. Finally, we present our conclusions.

2 Signal / 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 $\nu_e n \to e^- p$. In the experiment considered, the appearance probability is only a few percent at most, and a small number of events is anticipated above a non-negligible background. There are three kinds of background related to this signal:

- The ν_e beam background (ν_e beam)
- The neutral current background (NC)

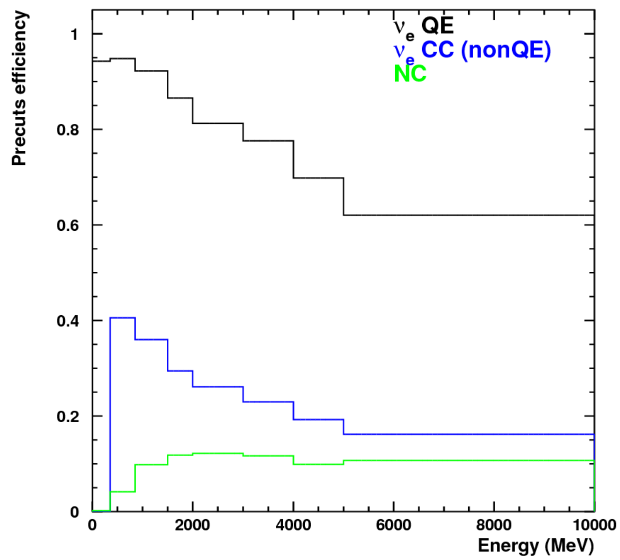


Figure 2 The precut efficiency for quasi-elastic and non-quasi-elastic ν_e interactions and NC background interactions. Misidentification of ν_μ interactions is small and is not plotted. Please refer to Tbl. 1

- The charged current ν_μ mis-identified background (ν_μ mis-ID)

The ν_e beam background is of course irreducible. The NC background mainly consists of neutral current events which are energetic enough to create a 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 π^0 can be mis-identified as a single electro-magnetic shower and therefore fake a ν_e CCQE event. 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.

Since we are interested in ν_e appearance, the events that we want to select are single-Cherenkov-ring, electron-like events with no decay electron in the fiducial volume; 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 precut efficiencies are plotted in Fig. 2 and 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-π^0 production.

After applying pre-cuts, we make the final event selection using a likelihood based on several event characteristics. The variables that are used in the likelihood can be divided in 3 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

Energy (true)	Signal			Background	
	ν_e (avg)	QE ν_e	non-QE ν_e	NC	ν_μ 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%

Table 1 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.

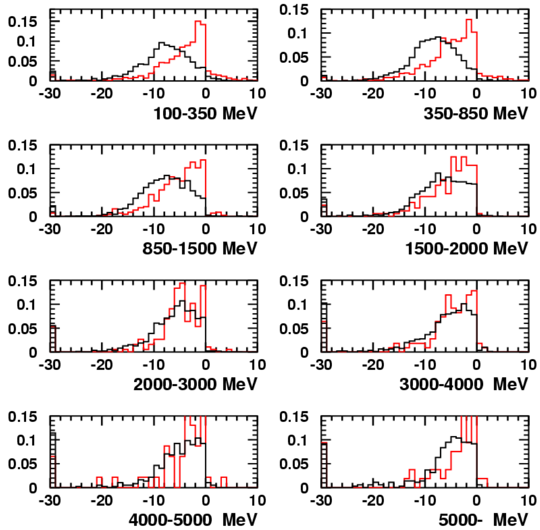
  - The energy fraction of the 2^{nd} ring

- Beam related variables:
  - The angle between the outgoing lepton and the beam direction
  - The distance between the vertex and the emitting point of Cherenkov light (Xalong)
  - The angle between vertex-pmt vector and the direction of the particle (cosopen)

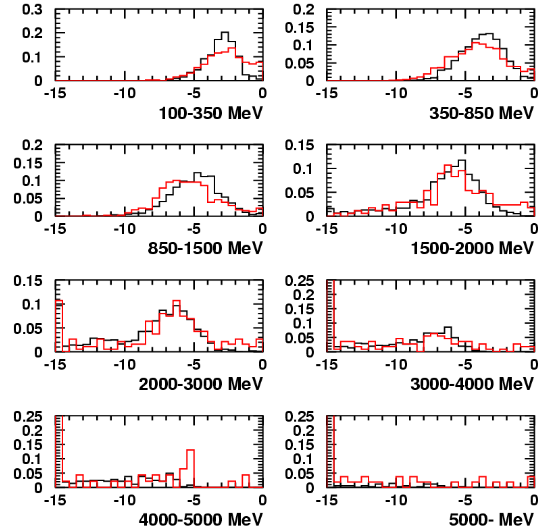
We used two standard SK variables, which we already cut on in the pre-cuts Table 1, the ring parameter and the PID parameter. Now we are using the value of that parameter as input to the likelihood. There are three variables related to a specialized fitter (POLfit for Pattern-Of-Light fitter) used to select single π^0 events[4]. 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 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. Figures 3 and 4 show the distributions of each likelihood variable for eight energy bins.

The final likelihood is presented in Fig 5. We tested two cuts on the likelihood variable. We used a cut at zero as well as a sliding cut that keeps about 40% of the signal in each energy bin. One can see that the separation between signal and background at energies higher than 3 GeV is poor, but the main energy region is between 1 and 3 GeV for FNAL wide-band beam studies. Further spectra and analysis in this document use the cut at 40% for direct comparison with the FNAL/BNL Joint Study report. Cutting this hard on the signal is an effective way of reducing the background to acceptable levels for final oscillation analysis. We have not yet studied if this fixed efficiency target is optimum.

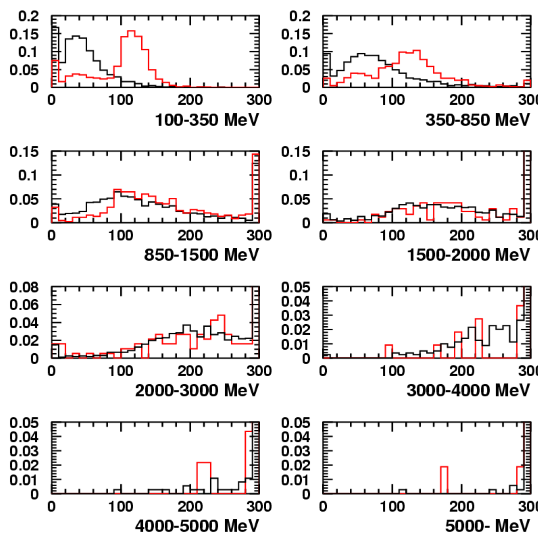
Defining the efficiency with which we can separate electrons from π^0's is a little subtle since we classify the events according to the true energy for the pre-cuts and according to the reconstructed energy for the likelihood. For ν_e events, the true and the reconstructed energy is highly correlated and we compute a single efficiency which accounts for the pre-cuts and the likelihood. This is what we use to calculate the spectrum for the ν_e signal. But for the ν_μ mis-ID and the NC background, the difference between the true and reconstructed energy is usually important and we have to divide the efficiency results between pre-cuts and likelihood. In particular, neutral current events typical "feed down" from high neutrino energy to low reconstructed energy as will be shown later. The precut efficiency is tabulated based on true neutrino energy and the likelihood efficiency is tabulated based on reconstructed neutrino energy. The efficiencies of the likelihood are in Table 2.



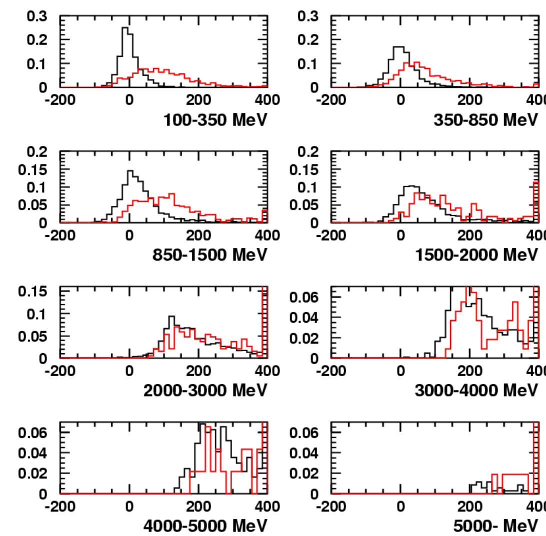
(a) Ring parameter



(b) PID parameter

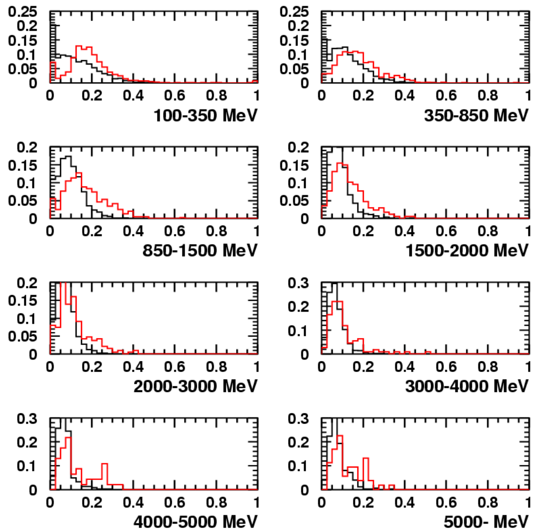


(c) π^0 mass

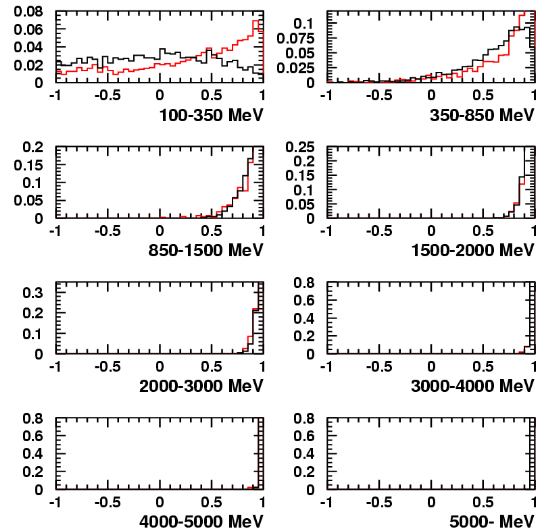


(d) π^0 Likelihood

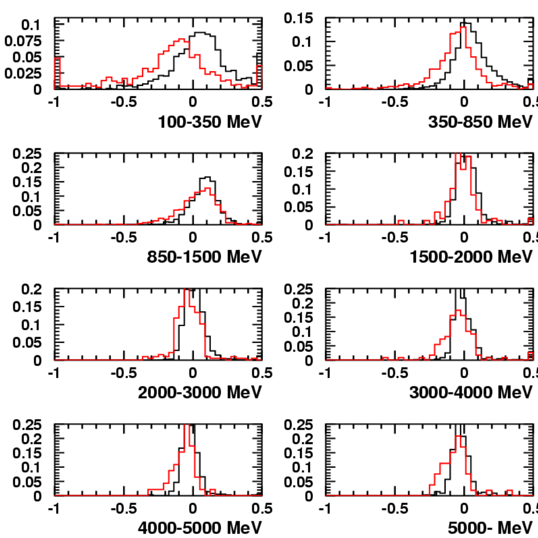
Figure 3 Likelihood variables in 8 energy bins. Black is the signal and red is the background. Events used passed the defined pre-cuts.



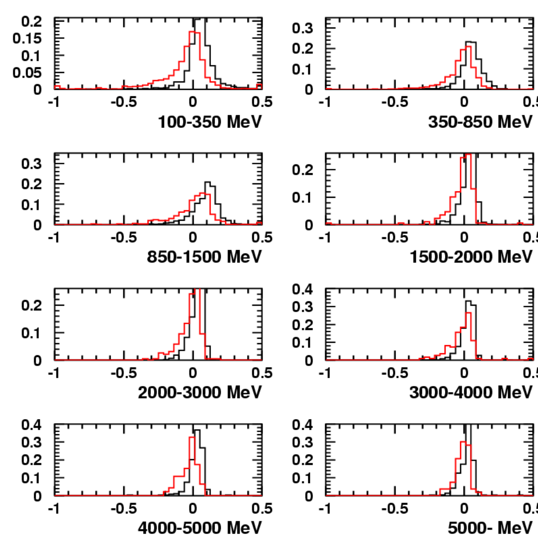
(a) Energy fraction



(b) $cos(\theta_{\nu e})$



(c) Xalong



(d) cosopen

Figure 4 Likelihood variables in 8 energy bins. Black is the signal and red is the background. Events used passed the defined pre-cuts.

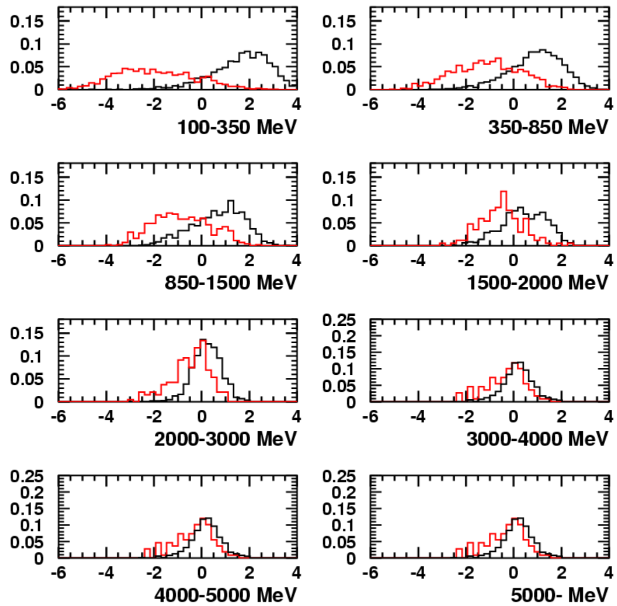


Figure 5 Likelihood results, cut was applied either at 0 or such that we keep 40% of the signal. (black = signal, red = background)

	Cut at zero			Cut keeps 40% of signal		
Energy (rec)	ν_e	NC	ν_μ mis-ID	ν_e	NC	ν_μ mis-ID
0 - 350 MeV	87.1%	10.9%	10.4%	41.4%	1.1%	0.6%
350 - 850 MeV	80.8%	22.1%	25.2%	36.8%	1.9%	2.5%
850 MeV - 1.5 GeV	78.6%	23.4%	25.6%	44.5%	4.1%	9.5%
1.5 - 2.0 GeV	72.6%	24.6%	11.1%	43.8%	5.9%	4.0%
2.0 - 3.0 GeV	73.2%	34.9%	14.6%	38.7%	10.1%	2.2%
3.0 - 4.0 GeV	69.6%	41.8%	20.0%	40.7%	9.1%	9.9%
4.0 - 5.0 GeV	78.7%	34.9%	52.9%	35.8%	15.4%	7.0%
5.0 - 10.0 GeV	83.7%	51.4%	22.2%	31.3%	20.4%	5.5%

Table 2 Efficiency for the likelihood cut, at zero and at cut position that keeps approximately 40% of the signal. These efficiencies are calculated for events which have already passed the pre-cuts, and are calculated based on reconstructed energy.

In order to trust our likelihood, we wish to 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 SK-I dataset (1489 days). 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. 6. The agreement is fairly good, but some differences appear and further study will be needed.

3 Event spectrum

In this section we will describe the method that we used to create event spectra. The spectra will be used in the χ^2 analysis of Section 4. The signal and the background have been treated differently and we explain each method in subsection 3.1 and subsection 3.2.

3.1 Signal spectrum

For every study that we conducted, the signal spectrum has been created by using the following method:

- Start with a ν_μ flux.
- Multiply the ν_μ flux by the ν_e CCQE cross-section. The cross-section for ν_e and $\overline{\nu_e}$ are shown in Fig. 7.
- Normalize the ν_μ event spectrum to the running conditions of a given experiment. This includes the volume of the detector, the power of the beam and the time length of the experiment.
- Multiply the normalized ν_μ event spectrum by the oscillation probability ($P_{\nu_e \to \nu_\mu}$) in order to have an oscillated ν_e CCQE event spectrum.
- Multiply the ν_e CCQE event spectrum by the ratio of ν_e CC Non-QE to ν_e CCQE to obtain a ν_e CC Non-QE event spectrum. This ratio was obtained using simulated Super-Kamiokande detector Monte Carlo and it is shown in Fig. 8.
- In order to simulate the energy resolution of the detector, we multiply the ν_e event spectra by a smearing matrix (E_{rec} vs. E_{true}). We used two different matrices for ν_e CCQE and ν_e CC Non-QE. We obtained those matrices using the SK atmospheric Monte Carlo as shown in Fig. 9.
- Add the ν_e CCQE and the ν_e CC Non-QE together to obtain a full ν_e event spectrum.
- Multiply the total ν_e spectrum by the global efficiency accounting for precuts and the likelihood cut.

A few assumptions were made to create the signal spectrum. We assume that the shape of the energy spectrum for the anti-neutrinos beam is identical to that of the neutrinos beam. Note that the anti-neutrinos event rate, is lower because of a lower neutrino interaction cross-section and because of a slightly lower neutrino flux.

3.2 Background

As it is described in Section 2, there are 3 kinds of background considered in this study. The ν_e beam background (ν_e beam), the neutral current background (NC) and the charged current ν_μ mis-identified background (ν_μ mis-ID). To simulate those background, 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 defined in Section 2.

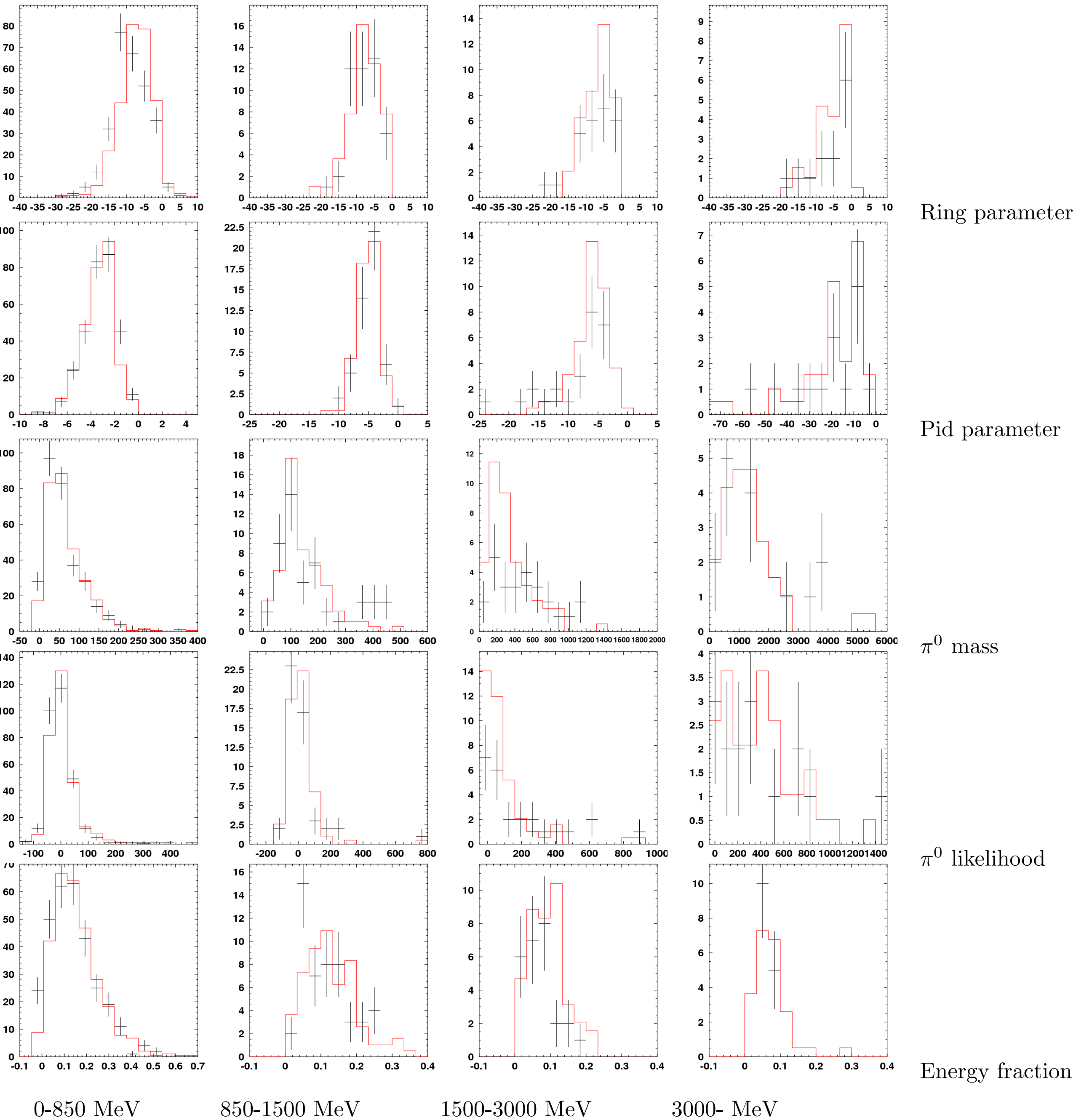


Figure 6 Comparison of data and Monte Carlo for five likelihood variables. Black = 1489 days of SK atmospheric data, Red = 9 years of SK atmospheric Monte Carlo normalized to the data livetime.

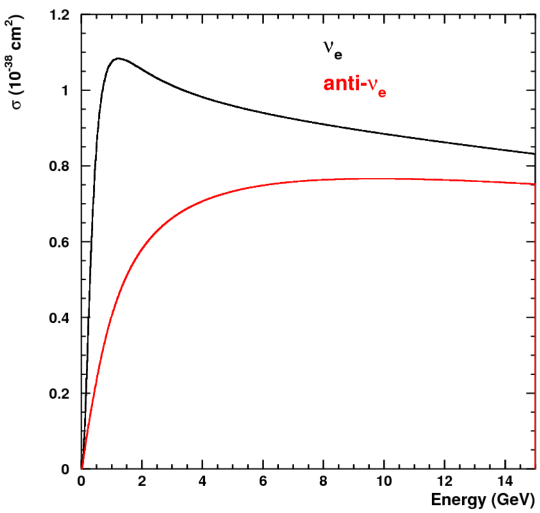


Figure 7 Cross-section for ν_e and $\bar{\nu_e}$

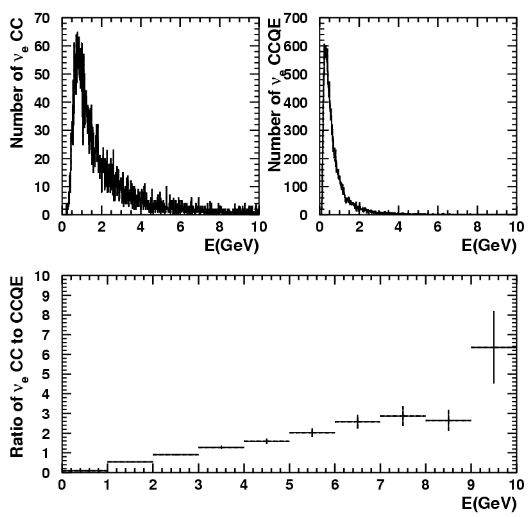


Figure 8 Top left: Number of ν_e CC Non-QE Top right: Number of ν_e CCQE Bottom: Ratio of ν_e CC Non-QE to ν_e CCQE

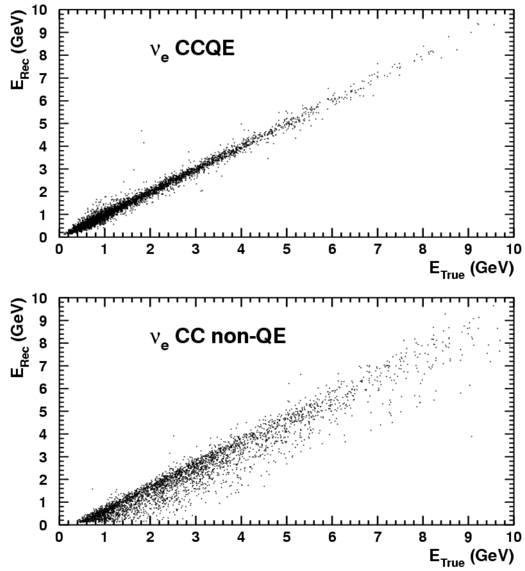


Figure 9 Top: Smearing matrix for ν_e CCQE. Bottom: Smearing matrix for ν_e CC Non-QE.

- We applied the likelihood efficiency corresponding to the right background type (ν_e, ν_μ mis-ID or NC) and using the reconstructed energy. This takes care of the likelihood efficiency, but 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.)

The Monte Carlo technique is interesting, because it is different from what has been done by the BNL/FNAL joint study group[1]. They use a purely computational method using flux, cross sections and efficiencies. This approach is also the one used by the GLoBES[3] software. We have performed some cross checks using our own version of this computational "spectrum method". We especially focused on the NC background since this is the one with a complicated detector response. Here is how we proceeded for compute the NC background with the spectrum method:

1. Multiply the ν_μ flux by the NC cross-section, and normalized 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. See Table 1.
3. Apply the NC smearing matrix (Fig. 10, left plot) to the result of the previous step to convert from true neutrino energy to reconstructed neutrino energy.
4. Finally, multiply the output of the previous step by the likelihood efficiency as a function of reconstructed neutrino energy. (Fig. 10, right plot)

The output of these steps are shown in Fig. 11. Finally we compared our two methods of creating NC background. In Fig. 12 the top histogram is the result of the "Monte Carlo method" and the bottom histogram is the result of the "spectrum method". The absolute number and the shape are in good agreement.

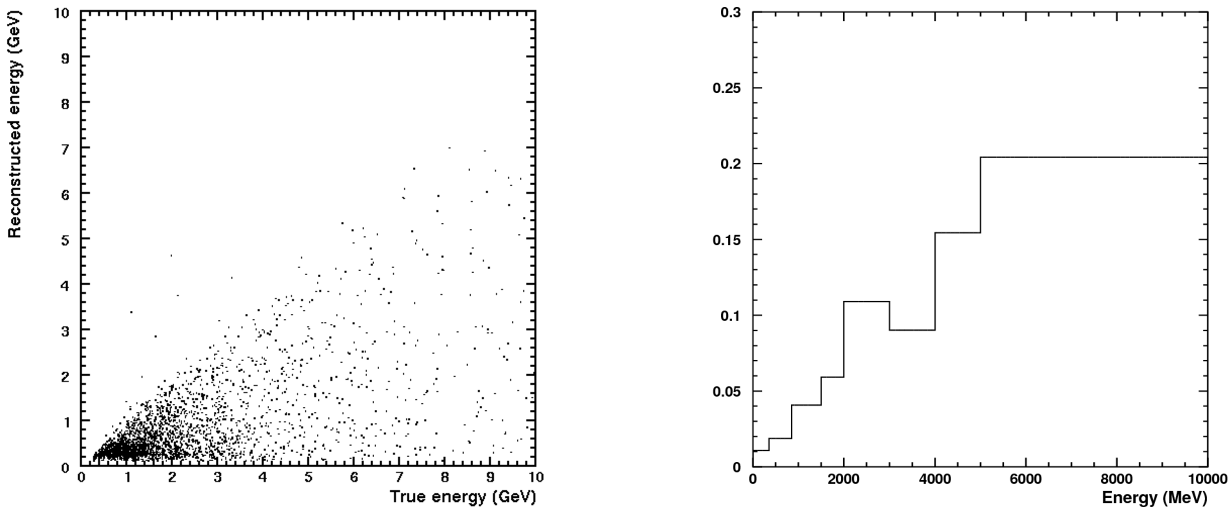


Figure 10 **Left:** Smearing matrix for NC events. **Right:** Likelihood efficiency for NC events with a cut such that we keep 40% of signal

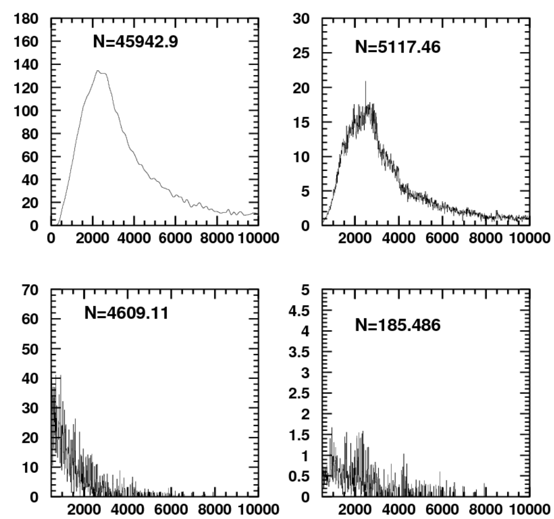


Figure 11 **Top left:** ν_μ flux multiplied by NC cross-section. **Top right:** multiplied by complete pre-cuts efficiency. **Bottom left:** multiply by the energy smearing matrix. **Bottom right:** multiply by the likelihood effciency. The plots are normalized for 30×10^{20} POT and a 300kTon detector.

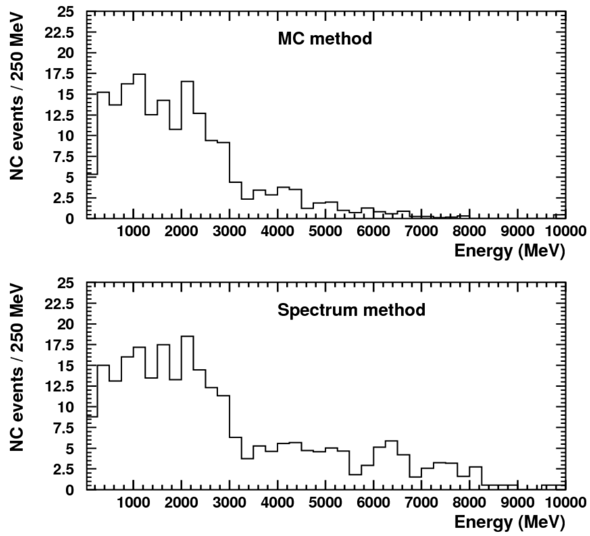


Figure 12 Comparison of methods: Top plot is the MC method, bottom plot is the spectrum method. The plots are normalized for 30×10^{20} POT and a 300kTon detector.

3.3 FNAL event spectrum

In this section, we present the event spectra that are used in the χ^2 analysis. We used the neutrino flux file provided by M. Bishai and which is shown in Fig. 1. The normalization is set for a 300 kTon detector, running with a 1 MW beam, during 5 years with neutrinos and 5 years with anti-neutrinos (where 1 year $= 1.7 \times 10^7$ seconds); this is equivalent to a 2500 Kton MW year. A 1MW beam with 120 GeV protons running for 5 years is equivalent to 30×10^{20} POT. This choice was made in order to compare our results with the one presented in [1]. The baseline is 1300 km and corresponds to a beam created at FNAL and a detector located in the Homestake mine. For the background we followed the method described in Section 3.2. The number of ν_μ interactions was 134700, the number of NC interactions was 45900, and the number beam ν_e interactions was 215.

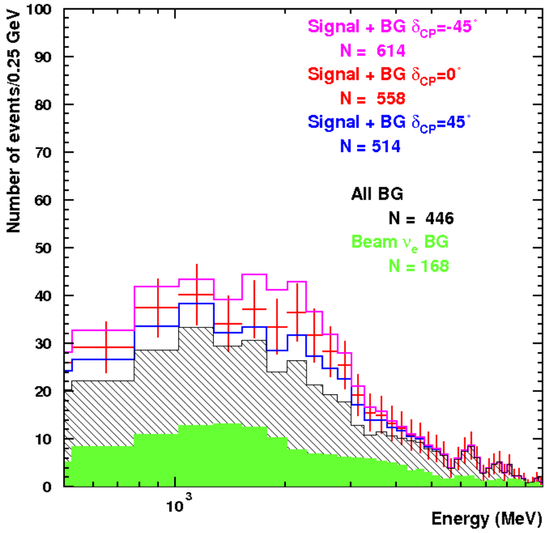
The event spectra presented in Fig. 13 and Fig. 14 are for 3 values of δ, for 2 values of $\sin^2(2\theta_{13})$, for both normal and inverted hierarchy, and for neutrinos and anti-neutrinos run. In every case, we assumed the mass splitting to be $\Delta m^2_{(21,31)} = 7.3 \times 10^{-5}, 2.5 \times 10^{-3} eV^2$ 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.

4 Oscillation analysis

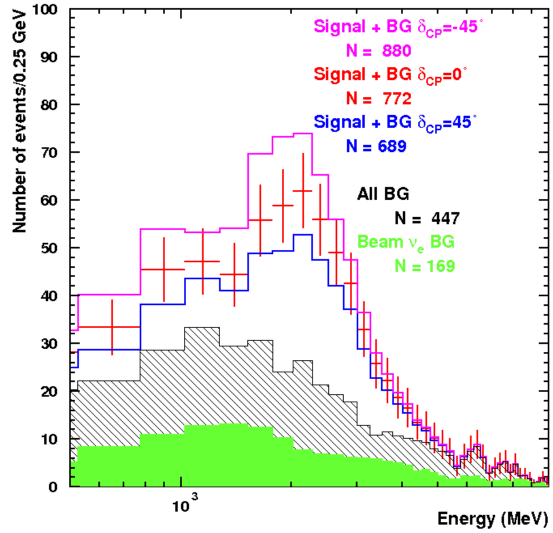
In this section, we will explain the χ^2 analysis conducted in order to evaluate the sensitivity of the FNAL-DUSEL configuration. We define the χ^2 and present the sensitivity to the mass hierarchy and CP violation. This study is highly inspired from the T2KK analysis[2].

The χ^2 definition used here is the same than the one which was used for T2KK[2, 7]:

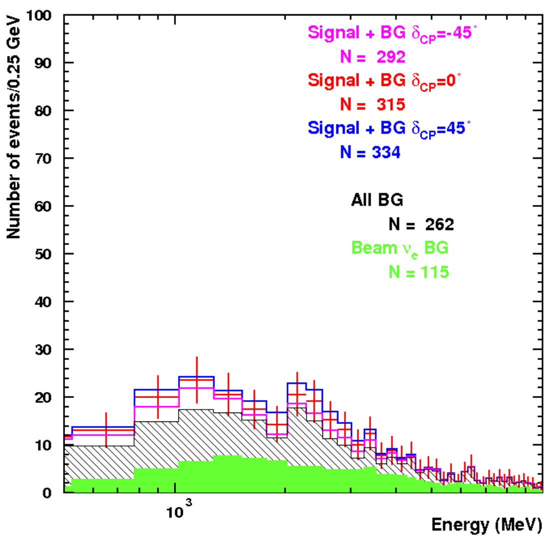
$$\chi^2 = \sum_{k=1}^{k_{exp}} \left(\sum_{i=1}^{i_{Ebin}} \frac{(N(e)_i^{obs} - N(e)_i^{exp})^2}{\sigma_i^2} \right) + \sum_{j=1}^{3} \left(\frac{\epsilon_j}{\tilde{\sigma_j}} \right)^2 \tag{1}$$



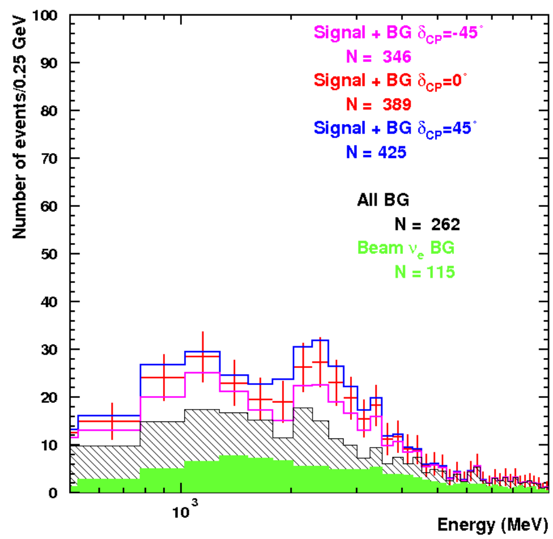
(a)neutrinos with $\sin^2(2\theta_{13})$ =0.01



(b) neutrinos with $\sin^2(2\theta_{13})$ =0.04

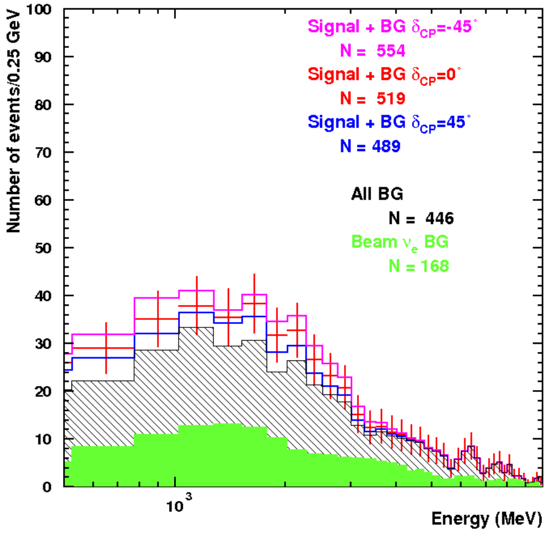


(c) anti-neutrinos with $\sin^2(2\theta_{13})$ =0.01

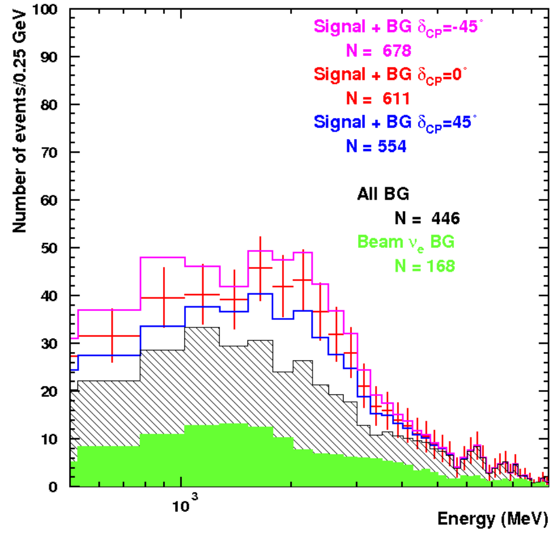


(d)anti-neutrinos with $\sin^2(2\theta_{13})$ =0.04

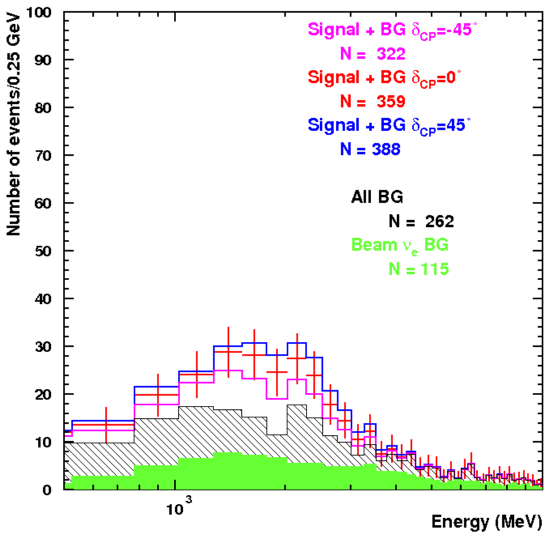
Figure 13 FNAL event spectrum with a **normal hierachy**, with 30×10^{20} POT and a 300 kton detector, baseline = 1300km, mass splitting $\Delta m^2_{(21,31)} = 7.3 \times 10^{-5}, 2.5 \times 10^{-3} eV^2$ and mixing angles $\sin^2 2\theta_{(12,23)} = 0.86, 1.0$



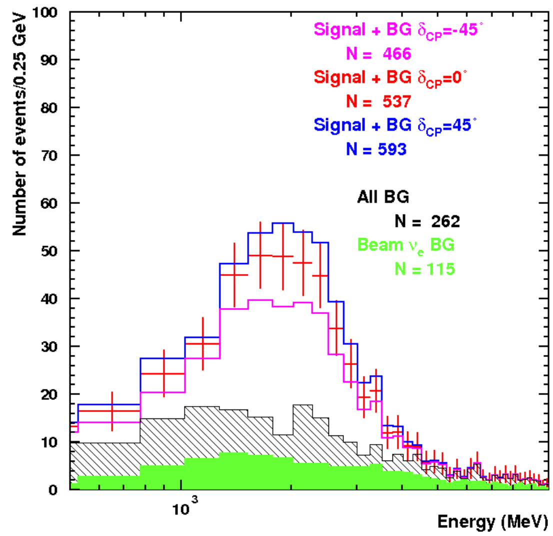
(a)neutrinos with $\sin^2(2\theta_{13})$ =0.01



(b)neutrinos with $\sin^2(2\theta_{13})$ =0.04



(c)anti-neutrinos with $\sin^2(2\theta_{13})$ =0.01



(d)anti-neutrinos with $\sin^2(2\theta_{13})$ =0.04

Figure 14 FNAL event spectrum with a **Inverted hierachy** with 30×10^{20} POT and a 300 kton detector, baseline = 1300km, mass splitting $\Delta m^2_{(21,31)} = 7.3 \times 10^{-5}, 2.5 \times 10^{-3} eV^2$ and mixing angles $\sin^2 2\theta_{(12,23)} = 0.86, 1.0$

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

where k_{exp} is the number of "experiments". For example if we have one detector and run with only neutrinos then $k_{exp} = 1$. For this analysis we had $k_{exp} = 2$ since we ran for neutrinos and anti-neutrinos and have one detector. We had 8 energy bins: 400-500 MeV, 500-600 MeV, 600-700 MeV, 700-800 MeV, 800-1200 MeV, 1200-2000 MeV, 2000-3000 MeV, and 3000-4000 MeV. The first sums are for the number of observed single-ring electron events in the i^{th} energy bin, $N(e)_i^{obs}$ is the number of events observed for the given oscillation parameters, and $N(e)_i^{exp}$ is the expected number of events, for the assumed $\sin^2(2\theta_{13})$, δ and the mass hierarchy. Both $N(e)_i^{obs}$ and $N(e)_i^{exp}$ contain background events. σ_i denotes the statistical uncertainties in the expected data. The energy resolution was taken care of by the smearing matrices as described in Section 3.1.

During the fit, the values of $N(e)_i^{exp}$ are recalculated to account for neutrinos oscillation. The systematic uncertainties in the predicted rates are accounted for. The overall background normalization is assumed to be uncertain by $\pm 5\%$, and the effect is taken into account through ϵ_1 in eq. (1). In addition, it is also assumed that the background has an energy dependent uncertainty with the functional form of $((E_\nu(rec) - 800MeV)/400MeV) \times (1 + \epsilon_2)$. The energy-dependent part is also assumed to be uncertain by 5%. The uncertainty in the detection efficiency of the electron and positron signals is assumed to be 5%. In summary, $\tilde{\sigma_j} = 0.05$ for $j = 1, 2$, and 3.

N_i^{BG} is the number of background events for the i^{th} bin. N_i^{signal} is the number of events that appeared by neutrino oscillations, and depend on $\sin^2(2\theta_{13})$, δ and the mass hierarchy. The uncertainties in N_i^{BG} and N_i^{signal} are represented by 3 parameters ϵ_j. The parameter f_j^i represents the fractional change in the predicted event rate in the i^{th} bin due to a variation of the parameter ϵ_j. The third sum in the χ^2 definition collects the contributions from variables which parametrize the systematic uncertainties in the expected number of background events. During the fit, these 3 parameters are varied to minimize χ^2 for each choice of the oscillation parameters.

To estimate the sensitivity to mass hierarchy, we scan over true values for δ and true values for $\sin^2(2\theta_{13})$ and perform a best-fit analysis using our definition of χ^2. The 2 and 3 standard deviations are defined to be $|\chi^2_{min}(wrong\ hierarchy) - \chi^2_{min}(true\ hierarchy)| > 4$ and 9 respectively. If we can uniquely determine the mass hierarchy at a given confidence level, we consider those "true" values for δ and θ_{13} to be accepted. The results are shown in Fig. 15. Roughly speaking, this experimental configuration can determine the mass hierarchy with 3σ confidence if $\sin^2 2\theta_{13}$ is greater than 10^{-2}.

We estimate the sensitivity for CP violation in a similar way. We say that there is evidence for CP violation at a chosen confidence level if $\delta = 0$ or π can be excluded. Fig. 16 shows these sensitivity curves. The 2 and 3 standard deviations are again defined to be $|\chi^2_{min}(\delta \neq 0\ or\ \pi) - \chi^2_{min}(true\ value\ of\ \delta)| > 4$ and 9 respectively.

We can also present the same results in another way. For a given value of $\sin^2(2\theta_{13})$, one can draw the region, as we did in Fig. 15 and Fig. 16, where the mass hierarchy can be resolved (or CP violation can be signaled) at 2 or 3 standard deviations. These plots can be converted to the ones in Fig. 17 and Fig. 18 by computing the fraction of the region of δ above the resolution contour at the given value of $\sin^2(2\theta_{13})$. This plot gives an alternative way of representing the sensitivity of the experiment to the mass hierarchy or CP violation, and is used for example in the proposal of the NOνA experiment [8]. The FNAL-DUSEL experimental setup can uniquely determine the mass hierarchy to 3σ significance for 25% of randomly chosen values of δ if $\sin^2\theta_{13}$ is greater than 0.01. The experiment requires somewhat larger values of $\sin^2 2\theta_{13}$ to discover CP violation at 3σ significance.

5 Summary

We studied the case of a 0.5° off-axis 1MW beam, with 120 GeV protons, 30×10^{20} POT and a 300Kton water Cherenkov detector, which is one of the cases presented by the BNL/FNAL joint study group. We

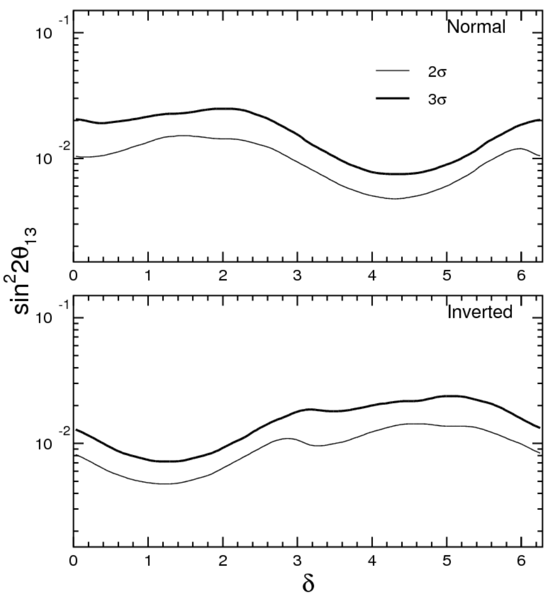


Figure 15 Sensitivity to the mass hierarchy for 30×10^{20} POT for neutrinos and 30×10^{20} POT for anti-neutrinos with a 300 kTon detector and a baseline of 1300 km.

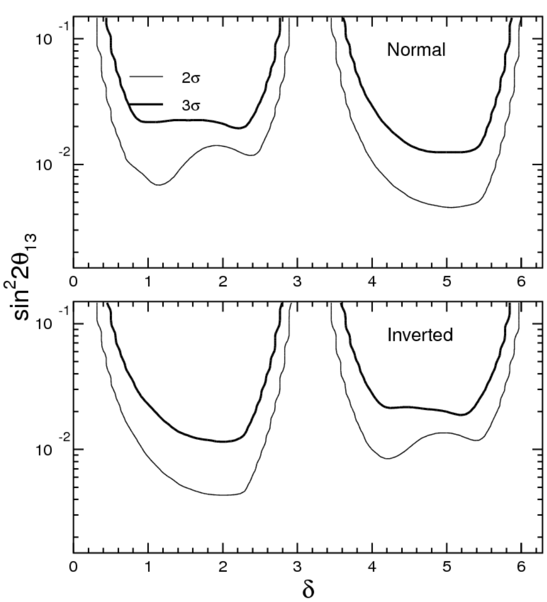


Figure 16 Sensitivity to leptonic CP violation for 30×10^{20} POT for neutrinos and 30×10^{20} POT for anti-neutrinos with a 300 kTon detector and a baseline of 1300 km.

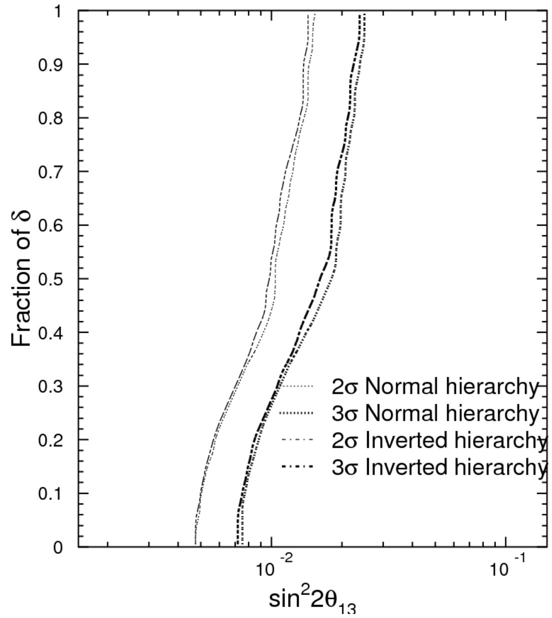


Figure 17 Sensitivity to the mass hierarchy,for 30×10^{20} POT for neutrinos and 30×10^{20} POT for anti-neutrinos with a 300 kTon detector and a baseline of 1300 km.

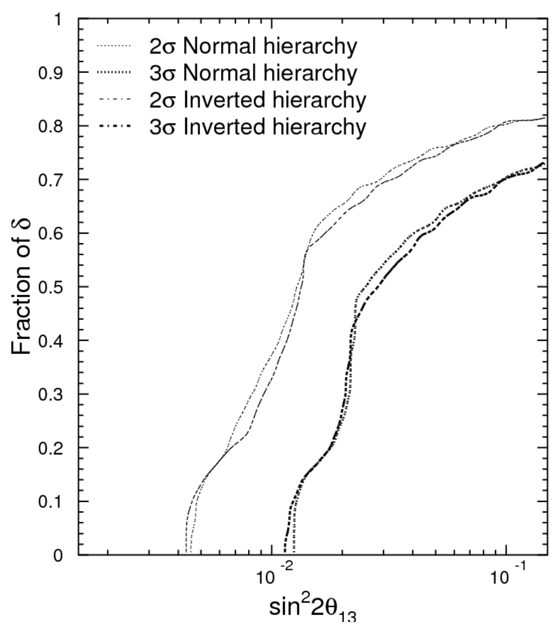


Figure 18 Sensitivity to leptonic CP violation for 30×10^{20} POT for neutrinos and 30×10^{20} POT for anti-neutrinos with a 300 kTon detector and a baseline of 1300 km.

have independently calculated a likelihood for separation of ν_e and NC background. The efficiencies are in good agreement with the similar study[9] actually used in the BNL/FNAL report. The results in Tbls. 1, 2 in this report can be compared to Tbl. VIII of the BNL/FNAL report[1].

Our NC background spectrum is calculated using the Super-Kamiokande Monte Carlo, which differs from what can be done with the GLOBES software in that it more completely accounts for underlying correlations. Nevertheless, the spectra are in basic agreement. Figures 13 and 14 of this report can be compared to Fig. 9 of the BNL/FNAL report. Differences in the shape of the event spectrum may be due to more accurate treatment of event reconstruction by the Monte Carlo method; typically the resolution of the two oscillation maxima are somewhat worse in our study. The number of events in each signal and background category is in general agreement.

The sensitivity curves for oscillation analysis of mass heirarchy and CP violation are also in good agreement. Figures 15 and 16 can be compared to Fig. 12 and Fig. 13, respectively, of the BNL/FNAL report. We also presented sensitivity curves in the style of fraction of δ.

6 Acknowledgements

We are grateful for numerous correspondences with M. Diwan and M. Bishai which were essential to understanding the assumptions and inputs of the BNL/FNAL Joint Study. We are also indebted to our Super-Kamiokande collaborators for years of work that went into developing the atmospheric neutrino Monte Carlo. Our original studies were prepared for the T2KK workshop and we received helpful comments from many. We are particularly grateful to K. Okumura for assistance with the software. The original version of this software was developed by M. Ishitsuka and coathors[2].

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