Neutrino Scattering Uncertainties and their Role in Long Baseline Oscillation Experiments

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ABSTRACT

The field of oscillation physics is about to make an enormous leap forward in statistical precision: first through the MINOS experiment in the coming year, and later through the NOνA and T2K experiments. Because of the relatively poor understanding of neutrino interactions in the energy ranges of these experiments, there are systematics that can arise in interpreting far detector data that can be as large as or even larger than the expected statistical uncertainties. We describe how these systematic errors arise, and how specific measurements in a dedicated neutrino scattering experiment like MINERνA can reduce the cross section systematic errors to well below the statistical errors.

1. Introduction

Over the past 5 years the field of neutrino oscillations has moved from seeing decade-old anomalies in cosmic ray [1)] and solar [2)] neutrino data to cross checks of these anomalies (SNO data [3)] and angular distributions in atmospheric neutrino data [4]) and most recently to terrestrial confirmations of the oscillation hypothesis (Kamland [5] and K2K [6]). The next steps in this field are to 1) move to the precision realm of measurements of the mass splittings and the mixing angles that have been observed, and 2) to see if any more off-diagonal elements in the neutrino mixing matrix are non-zero.

New extremely intense beamlines are being built or planned that will greatly increase the statistical reach and ultimate precision on oscillation parameters. However, with such large improvements in the statistical accuracy come new concerns about systematic uncertainties that have until now been negligible. In particular, uncertainties in neutrino cross sections and nuclear effects can produce systematic uncertainties in the extraction of mixing parameters. Although near detectors are a critical part of precision long-baseline oscillation measurements, they are not often well-suited to make all the needed cross section measurements, due to the fact that they tend to be very similar to the massive far detectors. Furthermore, a near detector can at best be a constraint on the product of the near flux, cross section and detection efficiency. Uncertainties on all of these quantities must be incorporated in ultimate near detector analyses. The studies described in this document do not address these other uncertainties, but when taken into account clearly worsen the prediction from the near detector data beyond what is described here.

This article is divided into two sections. The first section addresses the kinds of uncertainties that are most relevant for ν_μ disappearance experiments, whose aim is to precisely measure the mass splitting Δm^2_{23}, and the mixing angle which has already been determined to be large, θ_{23}. In order to achieve these goals the experiments must measure oscillation probabilities as a function of neutrino energy. Two important concerns here are uncertainties in charged current non-quasi-elastic processes, and the scale of nuclear effects. Both non-quasi-elastic channels and the nuclear environment alter the relationship between the measured and true neutrino energy. The second section addresses experiments searching for ν_e appearance, which if seen would indicate a non-zero value of θ_{13}. Because the size of the signal is unknown, the final event sample may be dominated by both signal (charged current) cross sections, or by background (neutral and charged current) processes. Either way, the experiments of the past are not precise enough to provide accurate predictions for the far detector event samples.

After discussing the ways neutrino interaction uncertainties apply to each of these measurements, a description is given of the kind of neutrino scattering measurements that are needed. As an example we give the expected precision of the MINERνA experiment, which has been proposed to run parasitically in the NuMI beamline [8].

2. ν_μ Disappearance

In order to precisely measure the mass splitting between two eigenstates one must measure the oscillation probability as a function of neutrino energy (E_ν) divided by baseline (L). The muon neutrino disappearance probability (in the standard 3-generation oscillation parameterization [7]) is expressed as

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \cos^4\theta_{13}\sin^2 2\theta_{23}\sin^2\left(\frac{1.27\Delta m^2_{23}(eV^2)L(km)}{E_\nu(GeV)}\right) - ... \quad (1)$$

where the additional terms are $\mathcal{O}(\sin^{\in}\in\theta_{\infty\ni})$ or smaller. Currently Δm^2_{23} is known to within a factor of two and $\cos^4\theta_{13}\sin^2 2\theta_{23}$ has been shown to be above 0.9, at the 90% confidence level limit [9]. Since $\sin^2 2\theta_{13}$ has been limited to below 0.1 by the CHOOZ reactor experiment[10], this means that $\sin^2 2\theta_{23}$ itself is very close to 1. The fact that θ_{23} is close to 45° has been cited as a hint of the underlying symmetry that generates neutrino mass and mixing. Precise measurements of this angle are important because the level at which the mixing deviates from maximal may again give hints to possible mechanisms for the breaking of that symmetry [11]. Furthermore, more precise measurements Δm^2_{23} are required to extract mixing angles from eventual ν_e appearance measurements.

The challenge of measuring Δm^2_{23} lies in knowing the true neutrino energy in both near and far detectors. Even if the two detectors have an identical design, any uncertainty in the "neutrino energy scale" of the signal events translates directly into an uncertainty in the extracted value of Δm^2_{23}. There are two different ways of measuring neutrino energies: either kinematic or calorimetric reconstruction. We discuss both techniques here, and then explain how uncertainties in neutrino interactions translate into energy scale uncertainties and ultimately Δm^2_{23} uncertainties.

The first experiment to provide a precision measurement of Δm^2_{23} will be the MINOS experiment [12], which will start taking data at the beginning of 2005. The MINOS experiment will use both far and near detectors, which consist of magnetized steel-scintillator calorimeters with a longitudintal steel segmentation of 2.54 cm. The transverse segmentation of the 1 cm thick scintillator planes is 4 cm. The MINOS experiment, with a baseline of 735 km, will use the NuMI beamline located at Fermilab, which can provide a variety of broad band neutrino spectra. In its lowest energy configuration, which is where MINOS expects to do most of its running, the peak neutrino energy in the ν_μ event spectrum is about 3.5 GeV.

The second experiment to use a calorimetric detector and improve the measurement of Δm^2_{23} is NOνA . Because NOνA is optimized for ν_e appearance rather than ν_μ disappearance it will use near and far calorimeters made of scintillator planes interspersed with either particle board or with other scintillator planes. The longitudinal segmentation is expected to be about a third to a sixth of a radiation length, and the transverse segmentation of the scintillator will be about 4 cm[13]. NOνA will also use the NuMI beamline, but will place its detectors between 12 and 14 mrad off the beamline axis, to get a narrow band neutrino spectrum. NOνA with a baseline of 810 km, will run with a peak neutrino energy of about 2 GeV.

Finally, the T2K experiment will use the Super-Kamiokande water Cerenkov detector for its far detector, and focus on single-ring muon-like events, for which the neutrino energy reconstruction is kinematic. T2K will use a narrow band neutrino beam from J-PARC in Tokai, whose peak is close to 700 MeV and which originates some 295 km from the far detector [14]. The near detector design has not been finalized, but at the time of this writing a water Cerenkov near detector is not forseen as part of the first phase of the experiment.

2.1. Kinematic Recontruction of Neutrino Energy

In kinematic reconstruction one assumes that the event is of a particular process (for example, quasi-elastic) and one calculates the energy assuming the kinematics of that reaction. This is the technique that is used predominantly in water Cerenkov detectors, which operate best in regimes where the quasi-elastic process dominates the cross section. In the Super-Kamiokande detector, for example, the ν_μ charged current signal sample consists of single ring muon-like events, which are then assumed to be quasi-elastic events. The energy of the incoming neutrino can in that case be calculated using only the outgoing muon momentum (p_μ) and direction (θ_μ), as follows:

$$E_\nu = \frac{m_N E\mu - m_\mu^2/2}{m_N - E_\mu + p_\mu \cos\theta_\mu} \tag{2}$$

Since the absolute energy scale for muons can be known to better than 1% through a variety of calibration techniques [15], and the ring-finding algorithms can measure ring directions extremely well, it seems plausible that the neutrino energy scale would also be determined to better than 1%. However, not all events that pass a "single muon-like ring" cut are quasi-elastic events. There are resonance and deep inelastic events where one or more pions have been absorbed in the nucleus, or which have one or more pions below the Cerenkov threshold, and those events will have a reconstructed energy which is well below the true neutrino energy, while still passing all cuts. Uncertainty in the ratio between quasi-elastic and resonance cross sections as a function of energy produces an uncertainty in the effective neutrino energy scale of the detector. Furthermore, because the ν_μ disappearance probability is large where T2K will run, the mix of quasi-elastic to non-quasi-elastic events will be very different from the mix one would expect if there were no ν_μ disappearance (which would also be the case for the mix at a near detector).

To understand how different the mix of signal processes is, consider the event spectra from the T2K beamline at the Super-Kamiokande detector, with and without oscillations. The NUANCE neutrino event generator [16] was used with fluxes from the T2K beamline simulation [14]. Figure 1 shows all of the contributions to the far detector event sample in the T2K experiment, without (left) and with (right) oscillations, after 5 years of running at the expected intensity. Note that in the case of no oscillations the event sample is predominantly quasi-elastic, but with oscillations the quasi-elastic contribution is much smaller and there are important contributions from resonant processes (single pion) and even deep inelastic scattering processes (multi-pi).

2.2. Current and Future Measurements of the Quasi-Elastic and Non-Quasi-Elastic Cross Sections

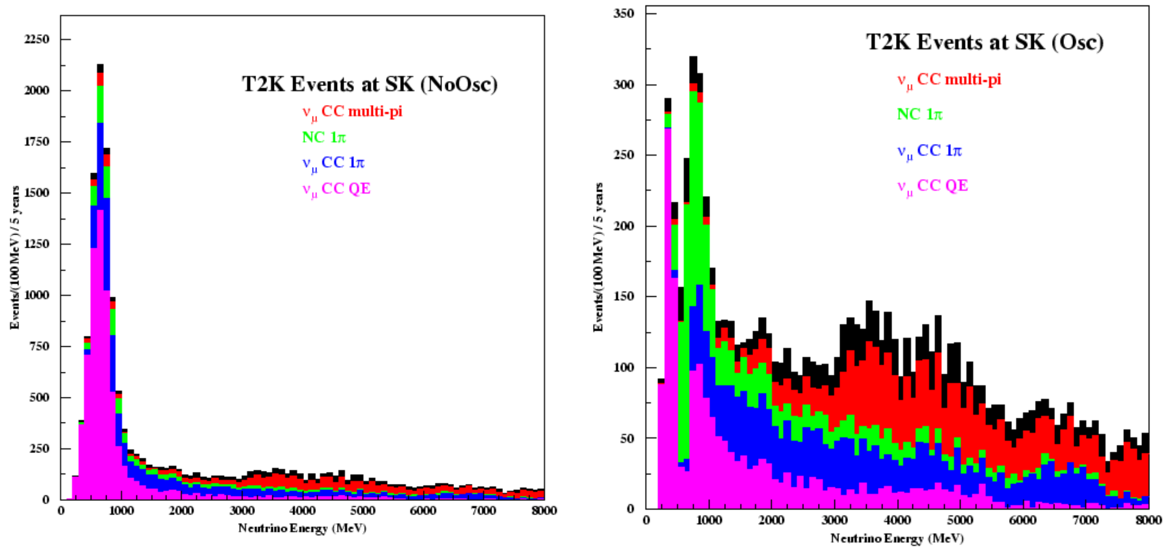

Figure 1: The neutrino energy distribution for events at T2K, broken up into various processes: quasi-elastic, single pion (Resonance), multi-pion (DIS), and neutral currents, for (left) no oscillations and (right) oscillations

As is shown in figure 2, the quasi-elastic cross sections themselves are known to at best the 10% level, and worse at energies of a few GeV [17]. Current measurements of the charged current single pion and multi pion cross sections come from experiments done in the 80's [18,19], and are known to at best the 20% level [20]. However, some of these measurements have central values which differ by much more than the total error bars, and the cross sections were measured on a variety of neutrino targets. The K2K experiment has a fine-grained near detector which can try to measure the non-quasi-elastic to quasi-elastic ratio. In reference [6] this ratio was assigned an error of 20% based on considering different cross section models which were all in agreement with their near detector data. One can see that the statistical error for the final event sample will be well above 100 events in total, so future constraints of this ratio will be extremely important.

What would best reduce this uncertainty for future experiments are precise measurements of both the differential single-pion and multipion charged current cross sections, as a function of neutrino energy. Clearly because the event samples are so different between near and far detectors, and because the water Cerenkov technology is not enough to constrain this ratio, additional measurements with fine-grained detectors are required. Ideally, there would be measurements of exclusive non-quasi-elastic final states identified with a well-modeled efficiency relative to that of quasi-elastic events. Because the reconstructed energy for these events is lower than the true neutrino energy, it is important to measure the charged current single and multi-pion (resonance) cross sections both at and above the T2K neutrino energy.

By identifying both the outgoing muon and proton in a quasi-elastic event, and by requiring there to be no other outgoing track, a fine-grained detector such as the one proposed by MINERνA can cleanly separate quasielastic events in a broad energy range, and the expected purity is above 70% [8]. In 4 years of parasitic NuMI running

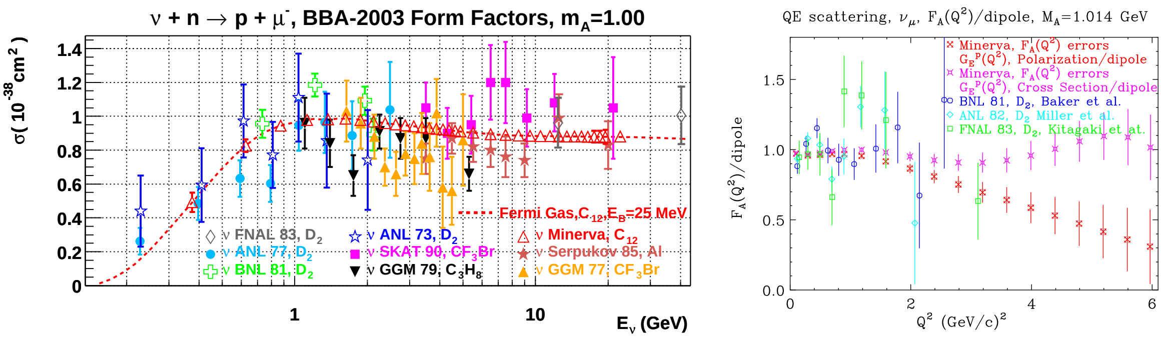

Figure 2: Current and expected MINERνA statistical sensitivity for quasi-elastic cross section (left) and form factor (right) measurements, for a 4 year parasitic MINOS run. Left: the open red triangles are in many energy bins larger than the statistical error expected in MINERνA taking into account detector acceptance and resolution.

MINERνA hopes to collect about 10^5 Quasielastic events per ton, and the expected statistical error on the cross section precision as a function of energy (after taking into account detector acceptance, backgrounds, and resolution) is shown in figure 2 (left). Figure 2 (right) shows how MINERνA would also have adequate statistics and resolution to discriminate between two different models for the Q^2 dependence of the quasi-elastic form factor, which again will have relevance for the quasi-elastic to non-quasielastic ratio. The systematic error in the energy dependence would most likely be dominated by the flux uncertainty, coming from the MIPP data on hadron production [21], but is expected to be at the 5% level at low energies.

2.3. Calorimetric Energy Reconstruction

At neutrino energies higher than 1 GeV, calorimetric energy reconstruction is a much more useful technique than kinematic reconstruction. In a calorimetric device the reconstructed or visible neutrino energy is simply the sum of all the secondary particles' energies that are visible in the event. For a ν_μ charged current event, the muon energy can be determined by first measuring its momentum using either range or curvature (if the calorimeter is magnetized), and then the remaining signal in the event is summed to be the hadron energy. Because most calorimeters have a much lower pion threshold than Cerenkov detectors, much more of the total kinetic energy is visible for multi-pion events, which dominate the cross section above a few GeV. As a result, the neutrino energy reconstruction is not as biased for non-quasi-elastic events as it is for water Cerenkov detectors.

For the MINOS detector, the absolute energy scale of the muons is set by knowing the thickness of the steel plates and by understanding the process of muon energy loss. The thickness of each of the plates has been measured to better than 0.1% and they vary with an RMS of 0.4% [22]. A muon test beam was used at CERN where a 2% absolute scale calibration was achieved [23]. The hadronic and electromagnetic energy scales have been calibrated using test beams on a prototype detector at CERN, and have been measured relative to the muon scale to better than 5% [24,25]. However, one must translate from the response from pions and muons to that of interacted neutrinos.

At neutrino energies of a few GeV and below, there are three effects that become significant in the translation between between visible energy and neutrino energy. Uncertainties in these effects must be understood and included in any precise measurement of Δm^2_{23}. One effect, which is independent of the target nucleus, is the fact that of the rest masses the secondary charged pions become important. Since MINOS cannot measure the multiplicity of final state particles, a multiplicity distribution as a function of hadron energy must be assumed. The second and third effects are due to the fact that secondary particles can either scatter in the nucleus or be completely absorbed. All three of these effects result in a reduction in the visible hadron energy in an event, which therefore results in a lower reconstructed neutrino energy. As is described in reference [26], the size of these effects can be quite large as the parent neutrino energy decreases, since there is a peak in the pion absorption cross section for pions at several hundred MeV [27].

In order to evaluate the extent to which nuclear effects will alter a Δm^2_{23} measurement in a MINOS-like detector, a crude detector simulation combined with the NEUGEN event generator [28] and NuMI fluxes at 735 km [29] was used. In this simulation the visible energy is defined simply as the sum of the kinetic energies of all the charged final state particles, plus the total energy for the neutral pions, and photons, since it is assumed they deposit all their energy in the form of electromagnetic showers.

Figure 3 shows the changes in the ratio of visible to total neutrino energy for changes in absorption and scattering separately. For the plot on the left the target is assumed to be steel, and the parameter in the event generator that describes pion absorption is set to zero or doubled. For the plot on the right all pion absorption is turned off, and the differences that remain are due to the rescattering effects between steel, carbon, and lead. Because the ν_μ disappearance probability is expected to be large, the far and near detector energy spectra will be very different, and therefore these effects will only partially cancel between the near and far detector. The extent to which they do not cancel results in a systematic error on Δm^2_{23}.

If we take the two differences described above as the uncertainties in pion absorption and rescattering, we can determine how this would compare to the MINOS statistical error. In a more complete analysis, the detector acceptance must also be taken into account. The most important cut that will reduce the size of nuclear effects comes from requiring the muon to take up a minimum energy in the event. The smaller the neutrino energy that comes from the hadron contribution, the smaller the changes which the nuclear effect uncertainties will bring to the total neutrino energy measurement. However, by requiring the muon to take up most of the neutrino energy, one will be losing precious far detector statistics. In the evaluation of the systematic errors shown here, a minimum muon energy cut of 0.5 GeV was made to try to take into account the acceptance in a real analysis. If the uncertainties on nuclear effects are assigned to be the differences shown in figure 3, then with a 0.5 GeV muon momentum cut they induce an error in Δm^2_{23} that is only slightly smaller than the statistical error expected by MINOS for 7.6×10^{20} protons on target (POT), as shown in figure 4.

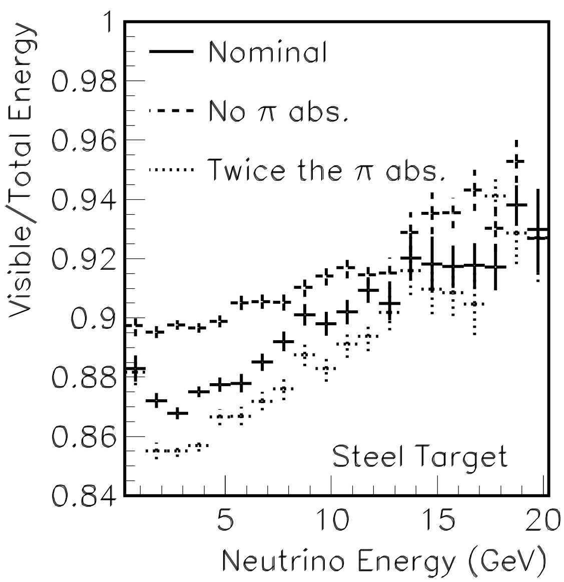

Figure 3: Ratio of visible (reconstructed) to true neutrino energy for several different models of nuclear effects. The left plot shows the ratio for steel (solid) with the nominal pion absorption, as well as the same ratio for the pion absorption turned off or doubled above what is expected. The right plot shows the differences the ratio for three different target nuclei, where the pion absorption effects are turned off to isolate the effects of pion rescattering.

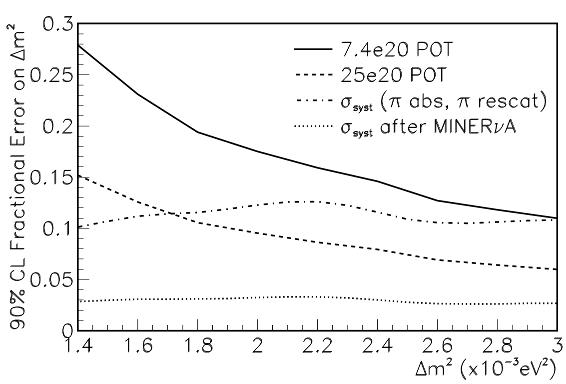

Figure 4: Fractional size of the 90% confidence level region at $\sin^2 2\theta_{23} = 1$ from statistics for the MINOS experiment. Also shown are possible systematic uncertainties due to uncertainties in nuclear effects: the dot-dashed line are those effects described in the text, and the dotted line assumes uncertainties after dedicated nuclear effect measurements where pion rescattering and absorption are measured on the target nucleus (steel). Detector acceptance is modelled by requiring muons to be above 0.5 GeV. Also shown are the statistical errors for two different integrated proton intensities.

2.4. Current and Future Measurements of Nuclear Effects in Neutrino Scattering

Evaluating the appropriate uncertainty in the size of nuclear effects in neutrino scattering is not trivial, because the only data on these effects in heavy nuclei come from charged lepton scattering [30], and one has to use theoretical models to translate the effects from the charged leptons to the neutral leptons. The only neutrino data measuring nuclear effects with neutrinos comes from pion rescattering measurements on Ne and D_2[31].

In order to make a precise measurement of nuclear effects in neutrino scattering one should measure interactions on several different target nuclei simultaneously, where one of the nuclei is the same as the far detector, and the other targets span a broad range of atomic number. A detector which can precisely identify the target nucleus event-by-event is critical. In this way the nuclear effects and their energy dependence can be measured at least in charged current interactions, and given a detector with good enough x and Q^2 resolution, these kinematic dependences can also be measured.

The MINERνA experiment has proposed a fine-grained detector which would measure neutrino interactions on steel, carbon, and lead. By running parasitically in the NuMI beamline for four years, the experiment would be able to collect about 940 k events on iron and lead, and 2.8M events on carbon within the fiducial volume of the scintillator[8]. This enormous improvement in both statistics and range of target nuclei would change our level of understanding of nuclear effects in a fundamental way, and give real constraints on neutrino interaction models. The uncertainties in Δm^2_{23} effects with this new data in hand would be small compared to the statistical error, even for higher levels of integrated protons on target, as is shown in figure 4.

3. ν_e Appearance

The goal of the next generation of neutrino oscillation experiments is to determine whether or not the last unmeasured neutrino mixing matrix element, (called $|U_{e3}|$ or $\sin\theta_{13}$) is non-zero. If θ_{13} is in fact non-zero then there is a chance that future experiments can search for CP violation in the lepton sector. If it is non-zero then the possibility of measuring the neutrino mass hierarchy also arises. For T2K and NOνA probing this matrix element is done by measuring the $\nu_\mu \to \nu_e$ oscillation probability at a "frequency" corresponding to Δm^2_{23}. The oscillation probability for $\nu_\mu \to \nu_e$ in vacuum can be expressed as [7]

$$P(\nu_\mu \to \nu_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{1.27\Delta m^2_{23}(eV^2)L(km)}{E_\nu(GeV)}\right) + ... \qquad (3)$$

where the additional terms not shown are due to effects from the non-zero solar mass splitting, Δm^2_{12}.

Looking for ν_e appearance in a ν_μ beam is quite challenging for several reasons. According to the CHOOZ limit from reactor neutrinos on $\sin^2 2\theta_{13}$[10] the appearance probability must be less than about 5% at the 90% confidence level. Also, there is an intrinsic ν_e component that can be as large as a few per cent. Finally, neutral current or high-y charged current ν_μ interactions can produce energetic neutral pions, which can in turn produce electromagnetic showers that fake a ν_e charged current event.

The T2K and NOνA experiments will reduce these backgrounds significantly below that of the current generation of long baseline experiments by using detectors optimized for electron appearance, and by placing those detectors off the beamline axis. Because of the two body decay of the charged pion, the energy spectra at small angles with respect to the beamline axis can be more peaked than the spectrum on the beamline axis. Also, at these small angles the peak energy itself is reduced. The narrowest neutrino energy spectrum occurs when the far detector is placed at an angle corresponding to 90° in the pion center of mass. In this configuration, the ν_e flux comes from the three-body decays of the muon, so the intrinsic ν_e flux at lower energies does not increase at higher angles like the ν_μ flux does. Also, the neutral current background is always a steeply falling function of visible energy because the outgoing neutrino always takes some fraction of the incoming neutrino's energy.

With this "off-axis" strategy, the NOνA and T2K experiments still expect there to be some background events after all the analysis cuts are made, even in the absence of $\nu_\mu \to \nu_e$ oscillations. The measurement of the $\nu_\mu \to \nu_e$ probability requires knowing the level of the remaining background, and the cross section and detection efficiencies for ν_e interactions.

3.1. Quantifying the effects due to cross section uncertainties

In order to understand why precise cross section measurements are needed for a ν_e appearance experiment, it is helpful to revisit how experiments will measure the $\nu_\mu \to \nu_e$ oscillation probability. The number of events in the far detector can be described as

$$N_{far} = \Phi_\mu P(\nu_\mu \to \nu_e)\sigma_e \epsilon_e M_{far} + B_{far} \tag{4}$$

where Φ_μ is the muon neutrino flux at the far detector, P is the oscillation probability, σ_e and ϵ_e are the electron neutrino cross section and efficiency, respectively, and M_{far} is the far detector mass. The background at the far detector, B_{far}, can be expressed as

$$B_{far} = \Sigma_{i=e,\mu} \Phi_i P(\nu_i \to \nu_i)\sigma_i \epsilon_i M_{far} \tag{5}$$

The notation is the same as equation 4, but ϵ_i is the efficiency for a neutrino of type i to be misreconstructed as an electron neutrino. Backgrounds come from both muon and electron neutrinos, and from several different neutrino interaction channels. Both equation 4 and 5 must be summed over those channels (quasi-elastic, resonance, etc.), as well as integrated over neutrino energy.

The error on the oscillation probability, in this simplified notation, is expressed as

$$\left(\frac{\delta P}{P}\right)^2 = \frac{N_{far}}{(\Phi_\mu \sigma_e \epsilon_e M_{far})^2} + \frac{(\delta B_{far})^2}{(\Phi_\mu \sigma_e \epsilon_e M_{far})^2} + \frac{(N_{far} - B_{far})}{\Phi_\mu \sigma_e \epsilon_e M_{far}} \left[(\frac{d\Phi_\mu}{\Phi_\mu})^2 + (\frac{\delta \sigma_e}{\sigma_e})^2 + (\frac{\delta \epsilon_e}{\epsilon_e})^2 \right] \quad (6)$$

The first term comes from the statistical error on the number of events at the far detector. The second and third terms in equation 6 suggest two regimes: in the case where the number of events in the far detector is comparable to the background prediction, the error on the probability is dominated by statistics and the uncertainty on the background. In the other regime, where the number of events is dominated by the signal events, the uncertainty on the probability is a combination of the statistics and the uncertainties on the signal channel cross sections.

Two of the three experiments described earlier in the ν_μ disappearance section are in fact optimized for ν_e appearance. Recall that T2K will use a 0.7 GeV narrow band beam and a water Cerenkov detector, and NOνA will use a 2 GeV narrow band beam and a scintillator-based calorimeter. It is extremely important that these measurements be made at more than one baseline and neutrino energy, in order to be able to probe not only the mixing angles, but also the neutrino mass hierarchy. In particular, only by running at a few GeV will one be able to use matter effects in the earth to determine whether neutrinos follow the same mass hierarchy as the charged fermions. Therefore, it is not enough to simply reduce cross section uncertainties below 1GeV where the cross section is predominantly quasi-elastic and resonance production. To get to the mass hierarchy we will need to understand neutrino interactions well above a few GeV, which means also understanding coherent and deep inelastic scattering processes.

3.2. Cross Section Uncertainties with a Near Detector

Both NOνA and T2K plan to make far detector event predictions based on measurements made in near detectors. For the case of NOνA the near detector is planned to be of a very similar design to the far detector, and can be placed in a wide range of angles with respect to the NuMI beamline. By making the near detector similar, NOνA hopes to minimize uncertainties in the detector response and efficiency. However, because the near detector will be as coarse as the far, it is not optimized for cross section measurements. For the T2K near detector suite some 280 m from the proton target, the plan is to have one near detector on axis to measure the spectrum and transverse distribution, and at least one other near detector that is off-axis which will be focused on cross section measurements. There are longer term plans to build a water Cerenkov detector at 2 km from the proton target, but even then the detector is not modular and as such the efficiencies are not expected to be identical between the near and far detectors.

To see how any uncertainties (cross section, detector acceptance, or flux) will arise in the far detector prediction based on the near detector data, it is useful to think about how the event samples are likely to change between near and far. At a near detector, the flux of muon neutrinos will have a very strong peak at a particular energy, while at the far detector that peak will have oscillated mostly to ν_τ's. At these energies, ν_τ's will not produce charged current events, only neutral current events. The neutral current event samples are likely to be similar from near to far, provided the near detector is at a similar off-axis angle. The electron neutrino events at the peak are primarily from muon decays in the beamline, which occur on average substantially farther downstream than the pion decays. Therefore, the extrapolation from the near to far detector tends to be different for all three event samples. If one cannot predict for the near event sample how many background events belong to each category (due to any of the above uncertainties), the far detector extrapolation can be wrong.

As a quantitative example of how cross section uncertainties would not completely cancel between near and far detectors, a study was done using a simulation for an early design[32)] of the NOνA detector. Although the final design of the NOνA detector will be different, the fundamental arguments will still be true: there will be a mix of contributing cross sections at the far detector that by definition cannot be the same mix as that at the near detector.

The signal and background statistics for the nominal 5 year run are given in table 1. Also given in table 1 are the fractions that each neutrino interaction process contributes to the events of that type that pass all cuts, as well as the cross section uncertainty on that process, as tabulated in reference [20)]. Without a near detector, the total error on the background prediction from cross section uncertainties, for the case that there are no ν_μ oscillations, is 16% , which is equivalent to the statistical error for that case. For the case of mixing at the level indicated in the table, the statistical error on the probability would be 8% , while the errors from cross section uncertainties alone would be 31% .

		QE	RES	COH	DIS
		Cross Section Uncertainty			
		20%	40%	100%	20%
Process	Statistics	Composition after all cuts in far detector			
Signal ν_e	175 ($\sin^2 2\theta_{13} = 0.1$)	55%	35%	n/I	10%
NC	15.4	0	50%	20%	30%
$\nu_\mu CC$	3.6	0	65%	n/I	35%
Beam ν_e	19.1	50%	40%	n/I	10%

Table 1: List of the signal and background processes than can contribute events in the NOνA far detector, for a 50 kton detector located 12 km from the NuMI axis, 820 km from Fermilab, assuming a Δm^2_{23} of $2.5 \times 10^{-3} eV^2$. Also given are the current cross section uncertainties on those processes. "n/I" indicates that the charged current coherent process was not included, since it is expected to be small compared to other charged current processes.

Figure 5 shows the fractional error on the far detector prediction as a function of the angle between the beamline and the near detector, for two different extremes:

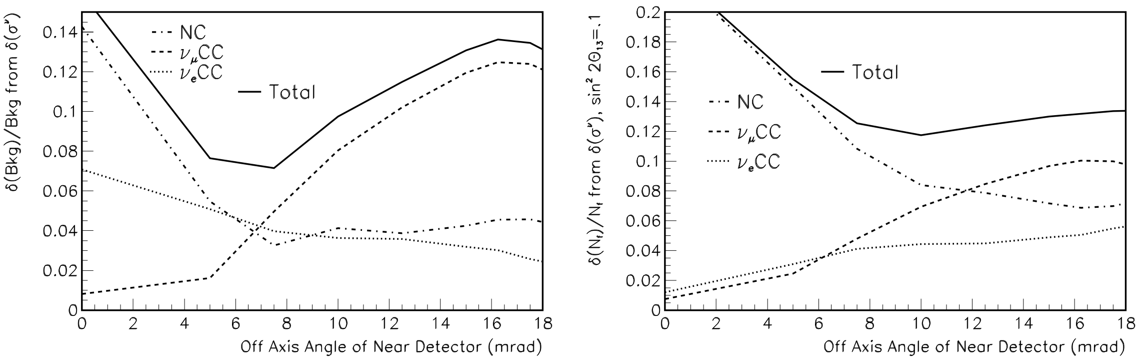

Figure 5: The fractional error in the event rates at the far detector from uncertainties in each process (Quasi-elastic, resonance, deep inelastic scattering, and neutral current coherent π^0 production), added in quadrature for each source (neutral current, ν_μ charged current, beam ν_e), plotted as a function of the angle between the near detector and the beamline axis, for (left) background-dominated experiment and (right) signal-dominated experiment.

the left plot shows the case where the $\nu_\mu \to \nu_e$ probability is zero (corresponding to the background-limited experiment), and the right plot shows the case where the probability is at about 5% (or $\sin^2 2\theta_{13} = 0.1$, corresponding to the signal-dominated experiment). For low angles the error due to the high y ν_μ charged current uncertainties is smallest. For high angles the errors due to neutral current uncertainties and low y ν_e charged current uncertainties are the smallest.

The errors for each of the three background contributions are shown, where the errors due to quasi-elastic, resonance, DIS, and coherent cross section uncertainties are added in quadrature. In the case of the background-dominated experiment, the cross section errors alone are comparable no less than half the expected statistical error of about 15% . For the signal-dominated experiment, the cross section at best a factor of two worse than the expected statistical error of 7% .

3.3. Future Measurements of Low Energy Cross Sections

Given the low statistics, discrepant data, and limited reach in target nuclei for charged and neutral current cross section measurements, there is clearly much work to be done. Section described the cross section uncertainties for quasi-elastic and resonance charged current processes, and described how MINERνA could provide an accurate quasi-elastic cross section measurement. For ν_e appearance measurements the charged current cross sections are important in case of a large signal. Regardless of signal size, however, the neutral current cross sections are important since they are very poorly known now. In some cases the best strategy will be to measure the charged current analog as a function of neutrino energy, and depend on theory combined with an average neutral current measurement to predict the neutral current cross section as a function of neutrino energy. Recent neutral current measurements have been normalized to different charged current channels: for example, the ratio of single π^0 production in neutral currents to the total ν_μ charged current cross section

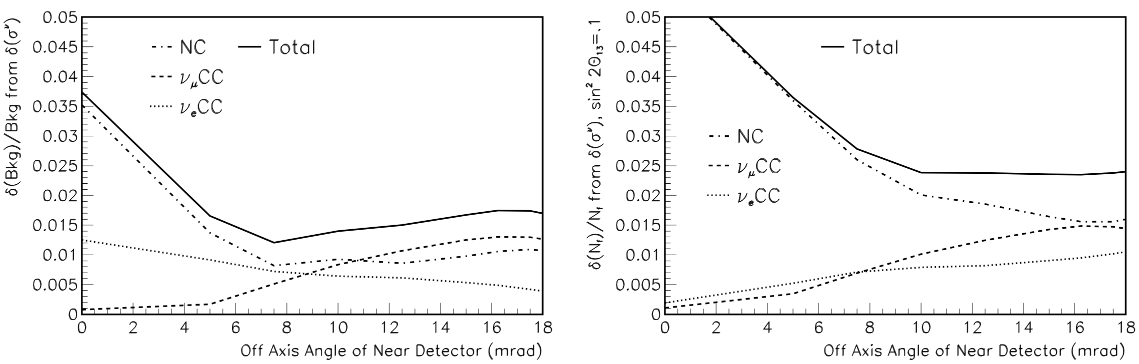

Figure 6: The fractional error in the total event rate at the far detector from post-MINERνA uncertainties in each process as a function of the angle between the near detector and the beamline axis, for the case where the $\nu_\mu \to \nu_e$ probability is 0 (left) or 5% (right).

has been measured to about 11% by the K2K collaboration [33].

With an appropriate design that would include both fine-grained fully active target surrounded by electromagnetic and hadronic calorimetry, the uncertainties on these cross sections could be improved by factors of 5 or more. As an example, the MINERνA experiment proposes to reduce the relevant cross section uncertainties for NOνA to about 5% for all of the charged current and neutral current DIS processes, 10% for the neutral current resonance processes, and 20% for the neutral current coherent π^0 processes [8]. But before describing how these measurements would be made, it is striking to see how much these measurements would reduce the systematic errors shown in figure 5.

If the uncertainties described above were achieved, then the systematic errors due to cross section uncertainties would be well below the statistical errors, as shown in figure 6. For the background-dominated experiment (left), the systematic error would be about a factor of ten less than the statistical error, and for the signal-dominated experiment (right) the systematic error would be a factor of three below the statistical error.

The remainder of this article describes strategies for isolating the resonant and coherent cross sections in the MINERνA detector, and the expected statistical precision in a four year run.

3.3.1. Resonance Cross Sections

Resonance production in neutrino scattering is extremely important for future long baseline neutrino oscillation experiments, but its cross section is only known at about the 40% level for the charged current process [34] at 2 GeV, and much worse for the neutral current process [35].

Resonance production can be studied in detail with a fine-grained experiment with good vertexing abilities and a low threshold for seeing pions. By requiring an outgoing muon, pion, and proton, MINERνA expects to fully reconstruct a large fraction of the 2×10^5 charged current resonance events that will occur in the detector, which would enable not only a precise cross section measurement as a function of energy, but also enough statistics to measure the W^2 distributions. With good neutral and charged pion identification the individual states containing both charged and neutral pions can be clearly seen, which in turn are important for ν_μ disappearance and ν_e appearance, respectively.

By measuring charged and neutral current resonance production and combining this with the energy information from the charged current resonance production, models that relate charged to neutral currents will be tested, and precise predictions for the neutral current processes will become available.

3.3.2. Coherent Cross sections

The process by which a neutrino interacts with a nucleus coherently and produces only a neutral pion (in the neutral current process) or a muon and a charged pion (in the charged current process) is perhaps the process the most poorly measured yet still seen. A handful of measurements exist at the few sigma level in both the neutral ([37]) and charged ([38]) current channels, as shown in figure 7(left). Although the cross section for this process is low, its high uncertainty and the high probability that coherent events pass ν_e analysis cuts means that this channel will contribute a significant uncertainty in the neutral current background. Furthermore, because it is an interaction that does not break up the nucleus, the nuclear effects on the cross section are important.

Coherent charged current events can be identified by looking at the energy loss of the two tracks and requiring it to be consistent with the presence of a muon and a pion, and nothing else. The background would come from incoherent processes where other particles (for example a proton) were lost. Coherent neutral current events would be identified by looking for two electromagnetic showers which reconstruct to the pion invariant mass. Backgrounds here would come again from incoherent processes, and are expected to be larger because several processes produce at least one neutral pion. The neutral current coherent sample can be separated statistically by looking at the distribution of the reconstructed angle of the neutral pion with respect to the neutrino direction and subtracting the background under the forward scattering peak.

The MINERνA experiment running in the NuMI beamline would collect over a thousand charged and neutral current coherent events in a 3-ton fiducial volume per year, resulting in a precise measurement as a function of neutrino energy for the charged current process. Figure 7 shows both the energy (left) and atomic number (right) dependence that could be measured by MINERνA in the charged current channel along with the current set of measurements. By using theory and the high statistics neutral current data one could obtain at least a factor of five improvement in the precision on the neutral current coherent background prediction.

4. Conclusions

It is clear from even these preliminary studies that dedicated neutrino scattering

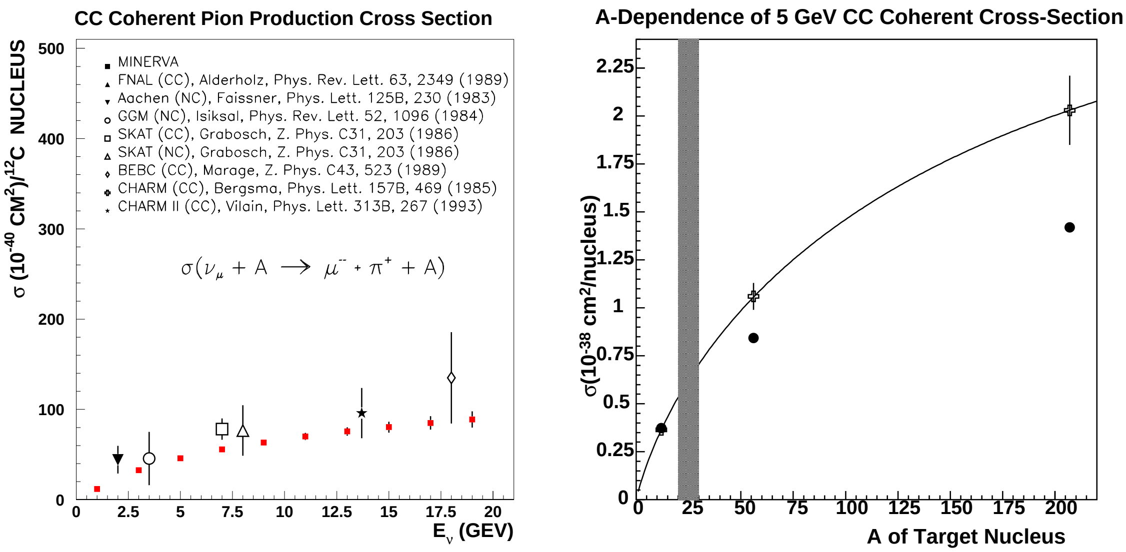

Figure 7: Expected MINERνA statistical sensitivity for the charged current coherent cross section energy (left) and A (right) dependence measurements, for a 4 year parasitic MINOS run, taking into account detector acceptance.

experiments such as MINERνA will play a very important role in helping the current and future precision oscillation experiments reach their ultimate sensitivity. In order to get the most precise values of Δm^2_{23} (which eventually is used to extract mixing angles and the CP-violating phase) this field must better understand and quantify the processes that occur between the interaction of an incoming neutrino and the measurement of the outgoing particles in the detectors. Although the issues are different depending on whether those detectors are water Cerenkov or calorimetric devices, in both cases more information is needed. Extracting the mixing parameters such as θ_{13} and ultimately the neutrino mass hierarchy and CP violation requires much better understanding of resonant cross sections. Even setting limits on these parameters will require better measurements of neutral current processes. Precise measurements of nuclear effects and exclusive cross sections will lay an important foundation for a field that is in the middle of making order of magnitude leaps in both statistics and sensivitity.

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