Study of Physics Sensitivity of ν_μ Disappearance in a Totally Active Version of NOνA Detector

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ABSTRACT

We describe the results of a study of potential sensitivity for $\sin^2 2\theta_{23}$ and Δm^2_{23} measurements in a totally active liquid scintillator detector placed offaxis in the NuMI beamline. We consider only events identified as quasielastic neutrino interactions. We show that one should be able to obtain sensitivities around 1 and 2-3% for $\sin^2 2\theta_{23}$ and Δm^2_{23} respectively, in a 125 kt yr exposure. Potential systematic uncertainties are considered and it is argued that they can probably be kept below this level.

Introduction.

One of the most important unresolved challenges in neutrino physics today is determining the precise value of $\sin\theta_{23}$. The most accurate information on this topic currently comes from the measurements of the zenith angle dependence of the atmospheric ν_μ in the SuperKamiokande detector, which set a 90% CL $\sin^2 2\theta_{23} > 0.90$, with the best value being close to unity [1]. This limit, however, allows a rather large range of possible values of $\sin^2\theta_{23}$, more specifically $0.35 < \sin^2\theta_{23} < 0.65$. Determining how close $\sin^2 2\theta_{23}$ is actually to unity is important because of possible clues it could give us about neutrino mass mixing matrix and/or any possible but so far unknown $\mu - \tau$ symmetry .

Obtaining significantly better precision for this quantity from disappearance measurements requires good statistics in the region of the oscillation maximum dip, knowledge of neutrino flux, excellent neutrino energy resolution and good control of systematics. The NOνA experiment in its totally active version (TASD) offers a possibility of satisfying all of the above requirements [2].

In this note we discuss various issues that affect the quality of these measurements and summarize first results from the Monte Carlo investigation of this channel, using a rather simple parametrization of the relevant quantities, which allows rapid exploration of multi dimension phase space. More specifically, we investigate the dependence of sensitivity on central energy of the beam with respect to oscillation maximum, number of events, and energy resolution. W also discuss potential systematic errors that could be introduced by underestimating (or overestimating) energy resolution and by the presence of various backgrounds. In those latter two cases we also try to see to what extent the data themselves can suggest presence of such effects.

General Procedure.

We start out with an *ansatz* that our sensitivity will be optimized if we use as our data sample only totally contained quasielastic events, ie those events where the geometrical pattern of energy deposition is consistent with the presence only of an energetic muon and a possible recoil proton[3].

We use in our investigation several neutrino spectra corresponding to different values of the detector transverse distance away from the beam axis. To obtain these spectra, we start out with GNuMI generated fluxes at these transverse distances [4] and use the best available cross section data to obtain corresponding spectra of observed quasielastic events [5]. The total neutrino interaction rates, without and with oscillations, for 4 transverse distances, 8, 10, 12 and 14 km are displayed in Fig 1.

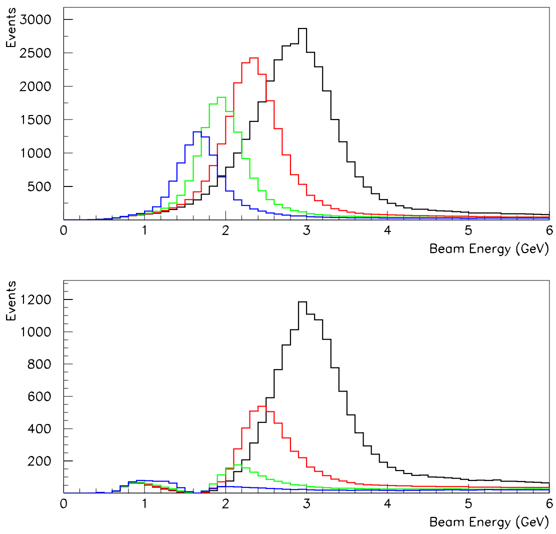

Fig.1 The total neutrino interaction rates for 4 transverse distances (from right to left) 8,10,12 and 14 km.

The data for energy dependence of both total and quasielastic cross sections, used to obtain our prediction for rates of quasielastic events, are shown in Fig.2. We parametrize then these spectra by Gaussian distributions and use in the analysis only the events

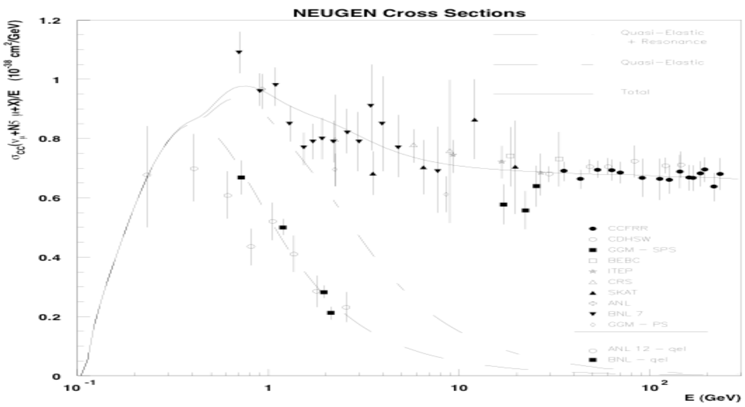

Fig.2 . Cross sections divided by energy for neutrino interactions

within +-2σ of the central energy value. We use $\Delta m^2_{23} = 2.5 \times 10^{-3}$ eV^2 and L = 820 km to obtain the disappearance probability but clearly our results will not be very dependent on the precise values of these parameters. The parameters for the calculated rates at three distances are displayed in Table I. We perform then our studies at several values of $\sin^2 2\theta_{23}$ in the currently allowed range of that parameter.

Transverse distance	No of events at the peak (no oscillations)	Total number of events (with oscillations)	Central energy	Full width at half maximum	Sigma
10 km	340	549	2.32 GeV	0.70 GeV	0.30GeV
12 km	304	160	1.92 GeV	0.58 GeV	0.25GeV
14 km	252	95	1.68 GeV	0.55 GeV	0.23GeV

Table I. Properties of the spectra used at the 3 distances studied. The number of events at the peak corresponds to the number of quasielastic events per 100 MeV for an exposure of 125 kt-yrs. To get the number of events with oscillations, we assume $\sin^2 2\theta_{23} = 0.98$.

We generate then a sample of events at each energy whose number corresponds to the expected observed number, ie with oscillations included. The energy of each event is then smeared using a Gaussian function with a width corresponding to the assumed error on the energy which is taken to be constant for all events. We then perform a maximum likelihood fit to both Δm^2_{23} and $\sin^2 2\theta_{23}$ on this generated event sample using the ROOT MINUIT Maximum Likelihood routine and limiting the range of the fit to +-2.0σ of the central energy value. The observation probability is taken to be the product of event rate times oscillation function, smeared by the energy resolution. We investigate several different bin widths of the same order as the assumed energy resolution. For value of $\sin^2 2\theta_{23} = 1$ we have also used the full Feldman-Cousins[6] prescription but the results were not significantly different from the simpler procedure.

Energy Resolution.

Minimizing and understanding energy resolution is the key to optimization of this analysis. Here we make several general comments which appear to indicate that it should be possible to keep the potential problems under control. There is no question, however, that further studies are needed in this general area.

Overall considerations. Almost all of the final state energy should be visible, the exception being boiloff neutrons from the struck nucleus. The typical Fermi momentum is about 250 MeV/c, corresponding to a kinetic energy of the nucleon of about 33 MeV. This roughly sets the scale on potential energy uncertainty due to this source as around 2% of the neutrino energy. The relative calibration of different scintillator cells can be determined from the cosmic ray muons which, in the same way as the proposed method for MINOS. Since their trajectories are determined rather precisely, one should be able to determine on the average quite well the pathlength through each cell and hence the expected energy deposition. We now consider several effects in more detail.

Muon range (total energy deposition by muons). This is by far the dominant energy contribution for the events of interest. The typical muon straggling in this energy range is about 2% but the main source of that variation are the Landau fluctuations in the energy loss along the muon path. Since we propose to measure all the energy loss, this effect should not contribute in our case. As argued above, we should be able to achieve accuracy in calibration of individual cells to the few percent level, and since a typical muon will traverse 100-200 cells, the overall statistical error should be less than 1%. There appears no fundamental reason why the systematic error on the overall scale should be worse that this. The data from MINOS CalDet detector should be able to provide some confirmatory evidence for the above statements even though one cannot attain there comparable precision due to the sampling nature of that detector.

The statistical fluctuation in number of detected photoelectrons should be of the same order. We expect typically 35-200 pe's in each cell, depending on the proximity to the readout end. For 100-200 cells that will give a statistical error of about +-1%.

The other fluctuation will be due to passage through inert material,ie PVC walls of the extrusions. Approximately 15% of the energy will be deposited in the PVC; the statistical fluctuation on this will be of the order of straggling fluctuation, about 2-3% of 15%. In addition there will be nonstatistical fluctuation due to different amount of inert material traversed, which will depend on muon position and angle, both of which will be measured precisely. Thus this fluctuation can be taken out to first order.

Saturation effects in scintillator. The recoil and boiloff protons will give energy deposition at a rate many times the minimum and thus one can have significant local energy saturation resulting in a decrease of the fraction of deposited energy carried off by the photons. These effects are relatively well understood, Birks' law [7], and can be parametrized by a constant k_B, which is a property of the scintillator material and is typically 0.01-0.015 $(\mathrm{MeV/g})^{-1}$. Specifically the actual luminescence L is given by:

$$L_{actual} = L_o \ (dE/dx / (1 + k_B \, dE/dx)$$

Thus the effect is significant only at high dE/dx, ie low β or low kinetic energy. As an example a 10 MeV proton will have its light output decreased by about a factor of 2 due to this saturation effect. Thus the effect is relatively small and can be corrected with a reasonably good accuracy. The main uncertainty is due to possible multiple protons in the same cell, or presence of a proton in the cell also traversed by the muon, since that would affect the correction. However this is mainly a geometrical effect that also depends on typical proton multiplicity. Both of these can be studied experimentally (in the data) and theoretically. Since the scale of total energy deposition by low energy, and thus highly ionizing, protons is of the order of tens of MeV, it should not be very difficult to reduce the error contribution from this source to 10 MeV or less.

<u>Energy deposition in inert material by protons.</u> As stated above the only significant inert material in the detector will be PVC walls of the extrusions, about 15% of the total mass. The dead channels should contribute much smaller fraction and they can be readily identified and appropriate cuts imposed on the data so that they do not compromise the analysis. We have already discussed the effect of PVC on muon energy loss; here we discuss the energy loss of protons in the extrusion material.

The most significant effect can occur in the cell extrusion boundaries between two successive planes where one has a 0.4 g/cm^2 thick layer of inert material (compared to 4 g/cm^2 of scintillator in each plane. This would correspond to 20 MeV loss for a forward proton for the worst case of 100% containment in the PVC. Clearly, for protons emitted at an angle, the energy loss can be greater. Very roughly, this would imply that about 10% of the events would have invisible energy loss due to this source of the order of 1-2%. A distribution of this expected energy loss can be computed on the basis of theoretical estimates using the actual geometry of the cells adopted and fine tuned by the experimental data itself. This distribution would then form an additional, rather small, component of the observation probability used in the maximum likelihood fit.

<u>Neutrons</u>. Neutrons from the breakup of the nucleus can provide a source of lost energy since they can travel a long distance before depositing their kinetic energy in a visible form. The magnitude of this energy loss, from the considerations above would be of the order of few tens of MeV. The quasielastic nature of the events might suppress this somewhat . The effect should be calculable to the required level of accuracy and accountable to first order by also including this contribution, in the analysis.

<u>Nuclear excitation.</u> A small fraction of neutrino inrteractions results in an excited nucleus which then decays via gamma, beta or nucleon emission sufficiently later so that the energy emitted in the decay would not be included. The studies done to date on these processes[8] indicate that the fractional rates are small and energy released in the few MeV range. Thus this would give a contribution less than 1%.

<u>Reabsorption and rescattering in the nucleus.</u> One can have significant visible energy loss for individual events by production of pions which get subsequently reabsorbed in the nucleus. The nucleus would have to get rid of this energy subsequently, typically by boiling off some neutrons and protons. The neutrons could give visible signatures far enough away from the main core so that overall cuts adopted might not include this energy in the total sum. The magnitude of this effect has not been carefully estimated at

this time but we believe it to be small. Its measurement is one of the goals of the proposed MINERνA experiment[5] at Fermilab. We show below some results which set the scale on how large an effect one could tolerate without compromising the analysis.

Another similar effect is scattering of the proton in the nucleus with the possibility of transferring some of the energy to other nucleons which can then leave the nucleus carrying off some energy. This effect is also probably not large but should be amenable to reasonably precise calculation. Furthermore, multiple protons will give some experimental information of how large is this effect.

Summary of resolution considerations. There are a number of physics effects which affect the total visible energy measurement, all of them of the order of a percent or so. Several of them involve more detailed understanding of nuclear effects and they need to be studied in more detail. We believe that total energy resolution in the range of 1-4% can be achieved and the results presented assume this range of values.

Absolute Energy Scale - Δm^2_{23} Measurement

A related issue is the question of absolute energy calibration. Our simulation results, discussed below, show that the statistical limitation on the precision of Δm^2_{23} measurement is of the order of 1%. Thus one would want to achieve a comparable or smaller uncertainty on the knowledge of the absolute energy scale.

The major part of the total energy deposition is the ionization energy loss of the muon. This phenomenon is understood very well theoretically through the Bethe-Block formula and there is no major theoretical uncertainty due to that source. The ultimate limitation will probably reside in lack of sufficient understanding of energy carried off by the neutrons and gammas from the excitation or breakup of the target nucleon. The other potential source is imperfect calibration of the energy response of individual cells but we see no fundamental limitation here even though significant effort will be required to assure adequate accuracy. The absolute energy scale can be determined by the use of stopping muons, in a similar way as is planned for the MINOS experiment.

The total energy observed will be somewhat smaller than the incident energy because some of it has to go into “liberating” the recoil proton from the nucleus. The size of this effect has been estimated based on observed missing energy in quasielastic electron nuclear scattering and incorporated in NEUGEN [9]. The distribution of missing energy, as calculated by this program is shown in Fig.3. The program at present does not include the pion reabsorption effects.

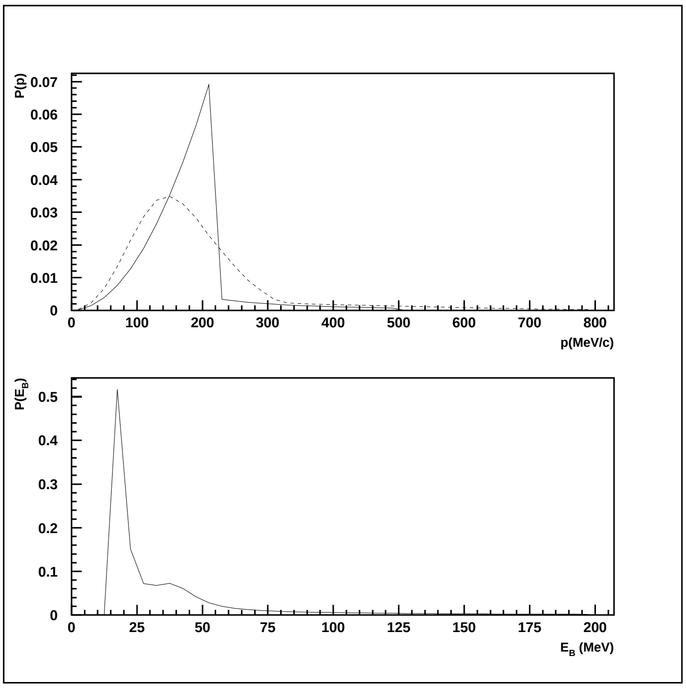

Fig. 3 The distribution of missing energy calculated by NEUGEN

Experimentally, the highly constrained events, with a sufficiently long proton track so its direction can be measured, can provide some check on our understanding of energy carried off by the neutrons. A 1.5-2.0 GeV muon track can be measured in the proposed geometry with an accuracy of about 10-15 mr, relatively independently of length since the multiple coulomb scattering begins to dominate after about 1.5 m. This translates into an error on transverse momentum of 20-30 MeV/c. For the direction of the proton to be measurable, it must give signals in at least two cells in each projection requiring a minimum momentum of about 500 MeV/c. The uncertainty in its energy measurement, due mainly to possible energy loss in the inert material, and uncertainty in its direction, will give a momentum uncertainty of about 50-100 MeV/c. Thus this contribution will dominate our uncertainty on transverse momentum balance. Without any lost neutrons, the transverse momentum balance distribution will have a width characteristic of Fermi momentum. Thus we should be sensitive to any significant contribution due to emitted neutrons, which in turn would allow setting potential limits on total energy uncertainty due to this source. Clearly, a detail MC calculation is needed of this issue.

Results of Simulations

In this section we present results on the simulations performed to date. We present first the results on the study of dependence of the sensitivity on the transverse location of the detector, ie the beam spectrum. Locations nearer to the beam axis give higher fluxes but at the expense of moving away from the oscillation maximum. We assume +-2% energy resolution for this study. The results are presented in Table II, where we show both Δm^2_{23} and $\sin^2 2\theta_{23}$ sensitivity for a 125 kt-yr exposure for 3 assumed values of $\sin^2 2\theta_{23}$: 0.95, 0.98, and 1.00.

Transverse distance	10km			12km			14km		
$\sin^2 2\theta_{23}$ inputted	0.95	0.98	1.00	0.95	0.98	1.00	0.95	0.98	1.00
$\sin^2 2\theta_{23}$ fitted	1.0±0.2	1.0±0.2	1.0±0.2	0.946±0.018	0.967±0.013	0.998±0.004	0.960±0.015	0.985±0.008	1.000±0.002
Δm^2_{23} fitted (10^{-3}eV^2)	2.43±0.06	2.49±0.06	2.53±0.07	2.57±0.07	2.50±0.07	2.52±0.05	2.60±0.05	2.52±0.03	2.48±0.02

Table II. Δm^2_{23} and $\sin^2 2\theta_{23}$ sensitivity for a 125 kt-yr exposure

As can be seen, the precision on $\sin^2 2\theta_{23}$ determination improves slightly as we go further off axis. In the subsequent calculations we shall use 12km distance which probably represents the best compromise between the precision of $\sin^2 2\theta_{23}$ measurement and the sensitivity to $\sin\theta_{13}$.

In Fig.4 we show 1σ and 2σ CL contours for these three values of $\sin^2 2\theta_{23}$ at a location of 12 km for the detector. In Table III we show the sensitivities at that location assuming 1%, 2% and 4% energy resolution, for $\sin^2 2\theta_{23} = 0.98$ and a 125 kt-yr exposure. In Table IV we show the sensitivities as a function of the bin width used in the maximum likelihood calculation. We can see that the results are not sensitive either to the bin width or to the energy resolution within the range of the values studied. Furthermore, the precision improves as the value of $\sin^2 2\theta_{23}$ approaches unity. Thus the sensitivity to the detection of deviation from unity does not have a strong dependence on how close to one is the actual value of $\sin^2 2\theta_{23}$.

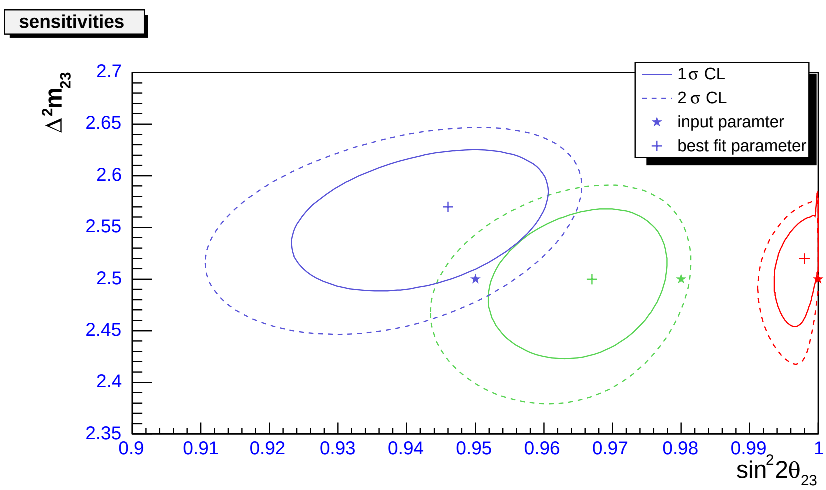

Fig.4 1σ and 2σ CL contours for three values of $\sin^2 2\theta_{23}$ 0.95, 0.98 and 1.00 at a location of 12 km

Energy resolution	1%	2%	4%
$\sin^2 2\theta_{23}$	0.970±0.011	0.967±0.013	0.965±0.015
Δm^2_{23} ($10^{-3}eV^2$)	2.51±0.06	2.50±0.07	2.53±0.07

Table III. $\sin^2 2\theta_{23}$ and Δm^2_{23} sensitivity for different energy resolutions (input parameters are $\sin^2 2\theta_{23} = 0.98$ and $\Delta m^2_{23} = 2.5\times10^{-3}eV^2$)

Bin sizes	9.6MeV	19.2MeV	38.5MeV	77MeV
$\sin^2 2\theta_{23}$	0.967±0.012	0.967±0.013	0.967±0.013	0.967±0.013
Δm^2_{23} ($10^{-3}eV^2$)	2.50±0.07	2.50±0.07	2.50±0.07	2.49±0.07

Table IV. $\sin^2 2\theta_{23}$ and Δm^2_{23} sensitivity for different bin sizes (input parameters are $\sin^2 2\theta_{23} = 0.98$ and $\Delta m^2_{23} = 2.5\times10^{-3}eV^2$)

Finally, in Figs. 5 and 6 we show the results from our initial study of potential systematics and backgrounds. Fig 5 shows contour plots for the situation where data is generated with energy resolution of +-4% but the analysis assumes that the energy resolution is +-2%. This simulated situation is probably much worse than one could expect in real life. An important complementary information is the goodness of fit, which in a real situation would give an indication that something is amiss.

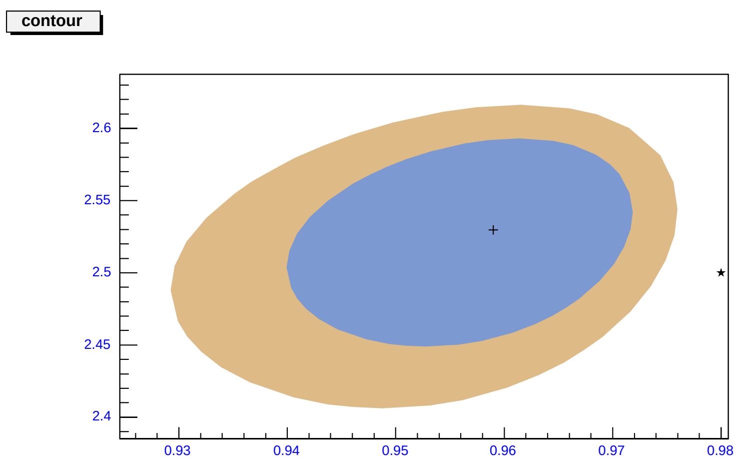

Fig. 5 Contour plots for the analysis assuming that the energy resolution is 2% while data were generated with energy resolution of ±4%

In Fig.6 we show the results when we add a 25% integrated probability that besides the Gaussian distribution with a 2% width we could also have a low energy tail on measured energy that has an exponential shape with a "decay" width of 40 MeV. Such an addition might be a reasonable approximation to potential energy loss due to escaping neutrons and/or inert matter effects. Fig.6a assumes that the knowledge of this effect is perfectly understood and the extra probability is also incorporated in the analysis. Fig. 6b displays equivalent contours when this effect is included in the data generation but not in the analysis.

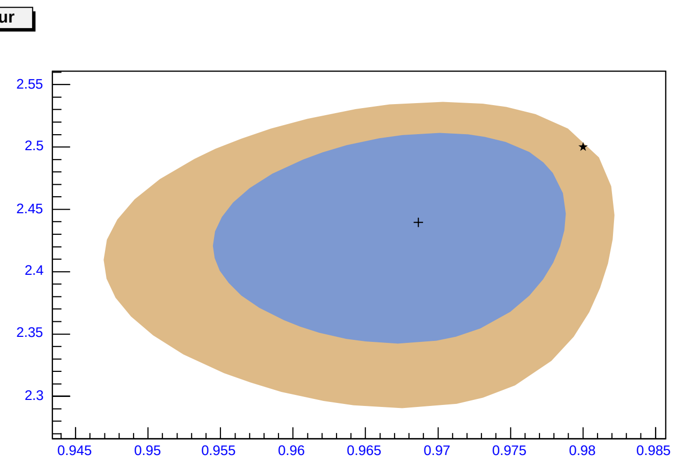

Fig. 6a Energy loss effect is included in both the data generation and the analysis.

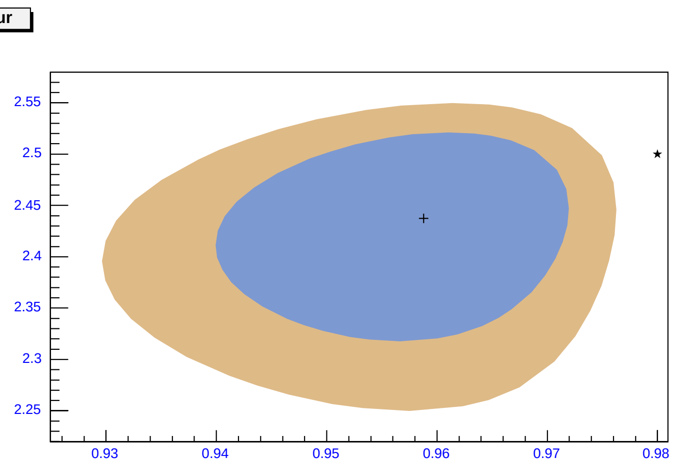

Fig. 6b Energy loss effect is included in the data generation but not in the analysis.

Such a parametrization might also be appropriate for energy loss due to pion reabsorption. To study its possible effect we have varied both the size and shape of this additional contribution to the overall energy spectrum. The results of these calculations are listed in Table V.

Energy loss	"Decay width"	Energy loss effect not included in the analysis	Energy loss effect included in the analysis
20MeV	50MeV	$\sin^2 2\theta_{23}$=0.959±0.015 Δm^2_{23}=2.44±0.10	$\sin^2 2\theta_{23}$=0.970±0.012 Δm^2_{23}=2.44±0.08
20MeV	80MeV	$\sin^2 2\theta_{23}$=0.960±0.015 Δm^2_{23}=2.43±0.09	$\sin^2 2\theta_{23}$=0.970±0.012 Δm^2_{23}=2.44±0.08
40MeV	50MeV	$\sin^2 2\theta_{23}$=0.947±0.020 Δm^2_{23}=2.37±0.15	$\sin^2 2\theta_{23}$=0.969±0.012 Δm^2_{23}=2.39±0.10
40MeV	80MeV	$\sin^2 2\theta_{23}$=0.943±0.022 Δm^2_{23}=2.34±0.16	$\sin^2 2\theta_{23}$=0.968±0.012 Δm^2_{23}=2.38±0.10

Table V. Energy loss effects on the $\sin^2 2\theta_{23}$ and Δm^2_{23} sensitivity, Δm^2_{23} in the unit of 10^{-3}eV^2 (input parameters are $\sin^2 2\theta_{23}$ = 0.98 and $\Delta m^2_{23} = 2.5\times10^{-3}$eV^2)

Summary

We have performed an initial study of the sensitivity of the NovA experiment[10] with a totally active detector to precise measurement of both $\sin^2 2\theta_{23}$ and Δm^2_{23}. We have shown that significant improvement appears to be possible over the current values. Furthermore, one should be able to understand the energy scale for Δm^2_{23} measurement at the level comparable to statistical error, ie about 2-4%.

Even though our study did not involve a full detector simulation, it is not clear that such a more detailed contamination will bring much more insight. The biggest uncertainty is connected with nuclear physics issues and thus an effort in that area, both experimental and theoretical, would be quite valuable in ascertaining the validity of our conclusions.

Acknowledgements

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