The NuMI Off-axis Beam Option : Report to NuSAG

The Off-axis Working Group

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Abstract

As part of the *Joint FNAL/BNL Future Long Baseline Study*, we investigated experimental scenarios which use off-axis neutrinos from the existing NuMI beam to continue the on-going experimental program of measuring the neutrino mass and mixing parameters. This study is directed towards understanding a Phase II experiment, meaning it would commence after the NOνA , T2K(Phase I), and currently planned reactor experiments have completed an initial period of operation and have observed a significant, non-zero result for θ_{13}.

1 Off-Axis Beams

The NuMI facility is currently providing the neutrino beam for the MINOS experiment. The NOνA experiment, which could begin operation as early as 2011, will use the NuMI beam as well. It is natural to ask to what extent the facility is suitable for use in a neutrino oscillation experiment beyond NOνA . In this paper we present the status of this work. A full discussion of this study will be available when it is completed [**?**].

Since the NuMI beam was not originally designed as a low energy beam, the geometry of the decay tunnel is not optimized for low energy neutrinos (∼1-3 GeV), which are optimum for probing the atmospheric mass scale at the nominal NuMI baseline of ∼700-800 km. However, flexibility in the positioning of the targets and horns allows the facility to be configured to a wide range of neutrino energies (∼1-15 GeV). The MINOS experiment uses a configuration, called Low Energy (LE), which gives a neutrino energy spectrum which peaks between 3 and 4 GeV, and is well matched to the MINOS ν_μ disappearance being investigated. On-axis, this configuration is the lowest possible energy configuration and there is little beam flux below 1 GeV. However, more flexibility is achievable by placing detectors off-axis, such that they intercept narrow band beams, whose peak energy is determined uniquely by the off-axis angle.

The next generation of accelerator based neutrino oscillation experiments, including NOνA , will be trying to measure the mixing angle θ_{13} by observing the appearance of ν_μ

$\rightarrow \nu_e$. The current limit on θ_{13} from the CHOOZ experiment warns us that this will be a very hard measurement, unless nature is very kind and just beyond the current limit.

There are two main reasons that off-axis neutrino beams are interesting. The first is that with the single beam one can consider a variety of sites such that the L and E of the experiment can be chosen to match a specific region of the oscillation probability. For example, the NOνA experiment will be sited at a baseline of 810 km from Fermilab, 12 km off-axis, giving a relatively narrow band beam of ∼2 GeV. This energy is approximately matched to the peak of the first oscillation maximum (for the range of Δm^2 allowed by current experiments). At the same baseline, the second maximum occurs at ∼600MeV and the position where the beam peaks at this energy is about 40 km off-axis. At this lower energy matter effects are minimal, but at the second maximum the oscillation probability is very sensitive to the CP phase δ_{CP}. In principle, a detector at the second oscillation maximum can observe the effect of the CP independent of the matter effects [**?**].

A second advantage of an off-axis beam for this type of experiment is that backgrounds from both intrinsic ν_e 's in the beam as well as feed down from higher energy neutral current events is much reduced because of the narrow energy range of the signal events. The main disadvantage is that the narrow band flux, especially at the large angles, is greatly reduced compared to the on-axis wide band neutrinos. In trying to optimize a wide band beam for low energies it has been found that the main constraint on the low energy flux was the diameter of the decay tunnel. Since it is practically impossible to widen the NuMI decay tunnel at this point, the low energy flux is the limiting factor in the off-axis technique. We note that some improvement in flux could come from from a redesign of the target and horn system. For example, to improve flux for the NOνA experiment, the NuMI beam will be reconfigured to the medium energy (ME) configuration. The main question to ask at this time is whether the advantages of reduced backgrounds out weighs the small event rates. In this study we investigated this trade-off for several experimental configurations.

At large off-axis positions the event rates are low and sensitive to the beam configuration and detector location. Also, at large angles, ν's from K decay are important, giving a peak at higher energies which will contribute to a neutral current background. Reducing the off-axis angle reduces this background. The phase space of possibilities is large but a preliminary search has shown that a second maximum experiment is best done in the NuMI LE configuration. See Figure **??**. We have considered two locations at the NOνA baseline and angles of 37 and 46 mrad, and a third at a somewhat shorter baseline than the NOνA experiment and at a slightly smaller off-axis angle than would give a peak at the second maximum, namely L = 700km and an angle of 57mrad.

2 Detector Options

Over the past several years, three potential detector technologies have been considered for a next generation experiment: liquid scintillator (similar to NOνA), water Cherenkov and a liquid argon TPC. Here, we summarize the conclusions which have been made to date in regard to the detector technology that would be best suited to the off-axis beam.

Studies of a massive liquid scintillator detector using the simulations developed for NOνA have shown that the backgrounds (mostly neutral current) would be approximately 1:1 with the signal at the second maximum and this option was not considered further.

A water cherenkov detector of the size proposed for DUSEL could give sufficient rate in the NuMI beam, though there might again be a question of background rejection. However it has been concluded that this size of detector must be sited deep underground to avoid being swamped by cosmic ray muons and there is no existing deep site available along the NuMI beam, and so we do not consider this a viable option.

A liquid argon TPC has the advantages of high efficiency and high background rejection for neutral current events, using the high spatial resolution. Thus for the same sensitivity in the same beam it can be factors of around 3 smaller than a water Cherenkov detector. For the sensitivity studies we have assumed liquid argon detector(s) with a total fiducial mass of 100 kton.

3 Event Rates

The tables below summarize the event rates in a liquid argon detector, for several of the cases which have been studied. We have generated sensitivities to θ_{13} , the mass hierarchy and δ_{CP} for each of these cases, and a total of 90×10^{20} protons on target, split between neutrinos and anti-neutrinos, in a couple of different ratios. These will be presented in the full report, and are compared to the predicted capability of the NOνA experiment. For the (810,14) case the rates are integrated from 0 to 3 GeV; for (810,37) they are integrated from 0 to 0.95 GeV; for (700,57) they are from 0 to 0.85 GeV. ν_μ are the number of ν_μ without oscillations; ν_μ (w osc) is the number remaining after oscillations; ν_e (beam) are the intrinisc ν_e 's in the beam *in the signal region*; NC are the NC in the signal region : in sensitivity calculations we assume an NC rejection based on the detector capability. For liquid argon we assume this can be as good as 99.9%. ν_e (sig) is for $\theta_{13} = 0.1$ ($\sin^2 2\theta_{13} = 0.04$).

4 On-going Work

Several independent analyses were carried out in this study, both in the area of fluxes and event rate calculations, as well as in sensitivity measurements. Results from these

Location $L(km)$, $\theta(mrad)$	NuMI tune	ν_μ	ν_μ (w osc)	ν_e (beam)	NC	ν_e (sig)
810, 14	ME	16.4	4.4	0.07	5.9	0.32
810, 37	LE	2.7	1.9	0.01	1.0	0.012
700, 57	LE	1.1	0.6	0.004	0.5	0.009

Table 1: Event rates per kiloton per 10^{20}protons on target, horns tuned for neutrinos; ν_e (signal) is for $\theta_{13} = 0.1$

Location $L(km)$, $\theta(mrad)$	NuMI tune	ν_μ	ν_μ (w osc)	ν_e (beam)	NC	ν_e (sig)
810, 14	ME	6.9	2.4	0.03	3.0	0.08
810, 37	LE	1.1	0.7	0.002	0.53	0.005
700, 57	LE	0.5	0.3	0.002	0.25	0.003

Table 2: Event rates per kiloton per 10^{20}protons on target, horns tuned for anti-neutrinos; ν_e (signal) is for $\theta_{13} = 0.1$

different analyses are presented in the detailed write-up. Satisfyingly, all analysis produced similar results ($\sim$20% agreement), and enable us to feel confident that we have the proper tools in place for carrying out these studies. We believe that we have not yet fully explored the capability of an extended NuMI off-axis program and have several more case studies being pursued. There are approximately four people working on *this* aspect of the larger study, each with only a small fraction of time available. We estimate that several more months of work (not weeks, not years) are required to complete the study. Over the past several months the NOνA collaboration has been concentrating on preparations for a CD2 review and have not been able to participate in this work as fully as they might ultimately want to. For this reason, we are not able to conclude that all numbers and sensitivities have been vetted. We hope to be able to produce a conclusive study in the near future.

References

[1] Using NuMI Off-Axis Neutrinos to Measure the Neutrino Mass and Mixing Parameters, *to be posted shortly*

[2] V. Barger, D. Marftia, K.Whisnant,"Off-axis Beams and Detector Clusters:Resolving Neutrino Parameter Degeneracies",hep-ph/0206038

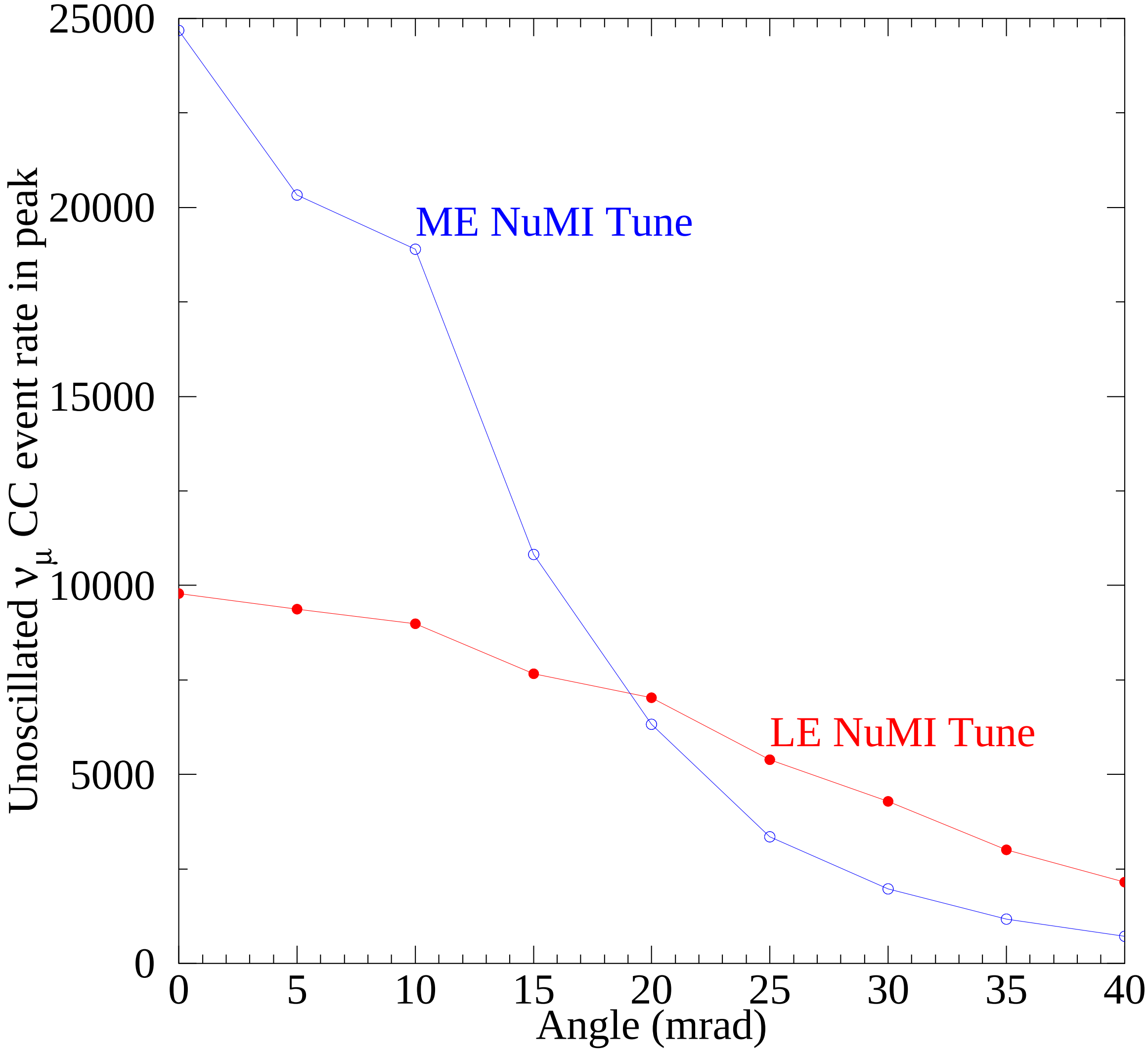

Figure 1: Relative event rates in the Off-axis beam peak as a function of angle for the NuMI ME and LE beam configurations. We see that for angles greater than 20 mrad the LE configuration improves the event rate.