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The NuMI off-axis long baseline experiment

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Abstract. Several different experiments have now established that neutrinos do oscillate or may have presented experimental evidence that can be explained by neutrino oscillations [1,2,3,4,5]. The purpose of future experiments is now to measure with high precision the parameters of the neutrino mixing or so-called MNS matrix. One of those experiments is planned at the powerful NuMI neutrino beam line. The experiment is especially designed to obtain a high sensitivity for electron neutrino appearance in a muon neutrino beam. This measurement is related to the mixing angle Θ_{13}, which is so far undetermined from previous measurements. This article will report on possible technology choices and the physics reach of the experiment.

1 Introduction

The NuMI neutrino beam line and the MINOS experiment [6] represent a major investment of US High Energy Physics in the area of neutrino physics. The forthcoming results could decisively establish neutrino oscillations as the underlying physics mechanism for the atmospheric ν_μ deficit and provide a precise measurement of the corresponding oscillation parameters, Δm^2_{23} and $\sin^2 2\Theta_{23}$. This, however is just the beginning of a long journey into unchartered territory. The key is the detection of $\nu_\mu \to \nu_e$ oscillation, controlled by the little known angle Θ_{13}. A precise measurement of the amplitude of theses oscillations will enable a determination of the pattern of the neutrino mass hierarchy and even the measurement of CP violation in the neutrino sector might be within reach. The full potential of the NuMI neutrino beam can be exploited by complementing the MINOS detector with a new detector, optimized for the detection of ν_e interactions at some off-axis position and collection data in parallel with MINOS [7]. The first phase of the proposed program would consist of a 50 kton detector being exposed to a beam of neutrinos and anti-neutrinos. In a five year run its sensitivity to $\nu_\mu \to \nu_e$ oscillations will be at least a factor of ten beyond our current limit for this mode. The future direction of the program will depend on the results of the first phase, but it is very likely that it will be a combination of a significant increase of the neutrino beam intensity via an upgraded proton source and an increase of the detector mass by a factor of five or so. Depending of the circumstances, the goals of Phase II may be a further increase of the sensitivity of a search for the $\nu_\mu \to \nu_e$ oscillation signal, or perhaps, a measurement of the CP violating phase δ in the lepton sector.

2 The beam

Construction of the NuMI neutrino beam is currently underway at Fermilab. This beam directs 120 GeV protons from the Main Injector toward a 96 cm long graphite target. The secondary pions and kaons produced on this target a captured and focused by two parabolic magnetic horns pulsed at 200 kA. The mesons decay in an evacuated region 675 m long and 2 m in diameter to yield a very pure beam of muon neutrinos. One of the main features of the NuMI beam line is its flexibility. It is possible to change the peak energy of the neutrino beam between 3 and 16 GeV by moving the relative position between the horns and the target. Anti-neutrino running can be achieved by inverting the horn currents. The NuMI beam line is designed for proton intensities of 4×10^{13} protons per pulse every 1.9 sec. The beam power corresponds to 0.4 MW and a total of 3.7×10^{20} are expected every year. However, the initial aim is to run the beam with 2×10^{13} protons per pulse.

It is possible to construct a nearly mono-energetic neutrino beam by viewing the NuMI beam at a location off the main beam axis. This is an implementation of a concept developed for the proposed experiment E-889 at Brookhaven [8] and will also be used by a Japan experiment which aims to send a neutrino beam from J-PARC to the Super-Kamiokande experiment [9]. Because all pions contribute neutrinos of roughly the same energy, it is possible to compensate the reduction in flux (see Fig. 1). As one can see, it is possible to increase the neutrino yield in the 1-2 GeV region by placing the detector off the beam axis, while at the same time reducing the high-energy component of the neutrino beam. This has the advantage that most of the neutrinos are in the region of the oscillation maximum and thus enhances the possible oscillation signature. However, one has to have a reasonable estimation

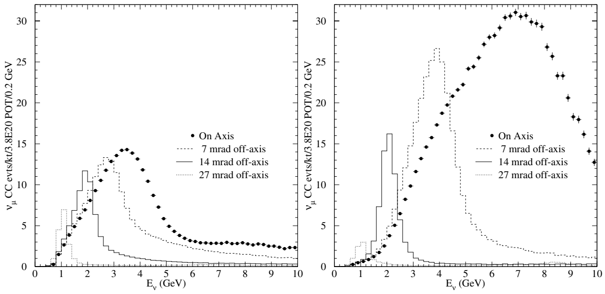

Fig. 1. Off-Axis neutrino flux at 735 km for the NuMI beam line in the low energy (*left*) and medium energy (*right*) configuration

of $\varDelta m^2$ before deciding on a location for the experiment. This low energy neutrino peak is produced almost exclusively by decays of pions and thus reducing the uncertainties related to beam predictions. The total number of events in the peak region can be predicted on the basis of the MINOS near detector with an accuracy better than 2%.

3 ν_e appearance measurement

The challenge for future experiments is to observe $\nu_\mu \rightarrow \nu_e$ oscillations down to the level of a few parts per mil. The CHOOZ experiment [10] gives a limit on the ν_e disappearance probability of about 0.1. This translates into a limit on the ν_e appearance probability of 0.05. There seems to be no theoretical guidelines on what the parameter should be, so one has to devise the most sensitive experiment possible.

Charged current ν_e interactions can be identified by the presence of an electron in the final state. The experimental backgrounds arise from, two general sources. There are genuine events with electrons resulting from the intrinsic ν_e component of the beam and additionally there are potentially mis-identified neutral current events of high y ν_μ charged current events where π^0's in the final state are mistaken for an electron.

The intrinsic ν_e component of the beam is of the order of $0.5 - 1.0\%$ and arises from μ and K_{e3} decays. However, the energy spectrum is quite different from the expected oscillation signal (see Fig. 2).

The experimental challenge is to reduce these two backgrounds as much as possible, while maintaining enough sensitivity for the ν_e oscillation signal. The background from beam ν_e's can only be reduced by good energy resolutions as they have a much higher energy than the possible oscillation signal. The Neutral Current background can be reduced by a well designed detector, which allows for a neutral current suppression down to the level of the intrinsic beam ν_e contamination.

In highly segmented detectors it is possible to separate electron showers from π^0's using several experimental methods:

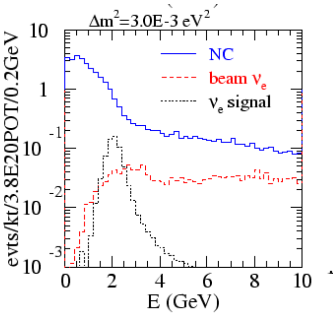

Fig. 2. Energy spectrum for events in the Off-Axis Detector

- finite separation between the vertex and the conversion points of the π^0 decay photon,
- two electromagnetic showers for π^0's versus one for electrons, and
- double pulse hight right after the photon conversion.

Success of the separation based on this criteria requires fine segmentation longitudinally as well as transversely. Besides this the detector must also distinguish electrons from hadrons.

4 Detector technology

Identification of the final state electron in a calorimetric detector requires that the sampling frequency is of the order 1/4-1/3 of the radiation length. Neutrino detectors must serve as a target and as a detector at the same time, hence their mass must be maximized. These two requirements lead to the conclusion that the absorber should be made out of a low Z material to maximize the mass of the detector while maintaining good sampling frequency. A low Z absorber will lead to a minimal number of active detector planes for a given total mass of a detector and thus will minimize the cost. Events will generally have a large spatial extend in these detectors and it will be necessary to have a fiducial cut of the order of 1 meter away from the edges of the detector. This in turn requires that the transverse size of the detector is as large as practically possible. A detector of $20 \times 20\text{m}^2$ transverse size will have a fiducial volume of around 81%.

Neutrino interaction in the region of 1-3 GeV involve very low multiplicity reactions: quasi-elastic scattering, resonance production, single pion production. In such a low multiplicity environment a low Z tracking calorimeter will provide valuable information on the topological properties of the event. Muons will show up as a minimum ionizing trail of hits, while electrons will lead to fuzzy tracks. Typical neutral current events are not very spectacular and have just a few hist from low energy final state hadrons.

Neutrino experiments do not present a significant challenge to the active detectors. The low cost and long term stability of operations are among the most important characteristics. The principle challenges of the detector will be therefore in the engineering area: how to build as large and cheap as possible a low Z calorimeter.

There are currently two major alternatives investigated. One using RPCs as active detectors while the other uses liquid scintillator as the detection medium. Both detector options use wood (particle board) as the cheapest, most readily available low Z absorber material.

Technical details, the current state of the R&D, and detector designs can be found at [7,11,12].

5 Physics reach

The total physics reach of the NuMI off-axis experiment has still some uncertainties. It will depend on the total detector mass funded and the number of protons delivered by the Fermilab Main Injector.

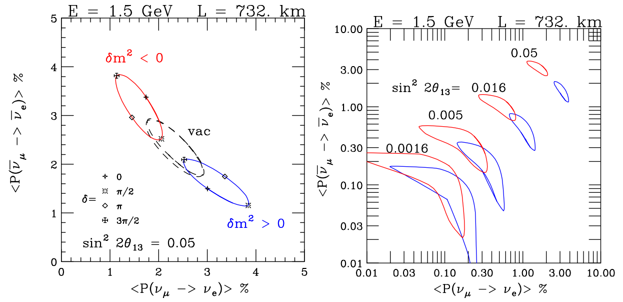

Fig. 3. Neutrino and anti-neutrino oscillation probabilities assuming a constant matter density of 3.0g/cm^3 for an L/E of 500 km/GeV. The mixing parameters are fixed to be $|\Delta m^2_{31}| = 3 \times 10^{-3}\text{eV}^2$, $\sin^2 2\theta_{23} = 1.0$, $\Delta m^2_{21} = 5 \times 10^{-5}\text{eV}^2$, $\sin^2 2\theta_{12} = 0.8$ with the labeled values of $\sin^2 2\theta_{13}$ and δ

One main feature of the experiment is that it will be able to measure the oscillation probability for neutrinos as well as for anti-neutrinos. This is important as one can see in Fig. 3. The oscillation probability simultaneously depends on Θ_{13}, the mass hierarchy and the CP violating phase δ. It will therefore be possible to restrict those parameters simultaneously, by combining neutrino and anti-neutrino running with measurements form other experiments.

The sensitivity of this experiment is indicated in Fig. 4. It shows possible 90%CL. limits for different running conditions and detector masses.

6 Summary and conclusion

The NuMI off-axis program offers a nice path to study neutrino oscillation with high statistical accuracy. It will significantly increase our knowledge of θ_{13} and may even enable us to determine the neutrino mass hierarchy and study CP violation. It will be complementary to a possible JPARC-to-Super-Kamiokande or reactor neutrino experiment and will significantly increase our understanding of neutrino oscillations.

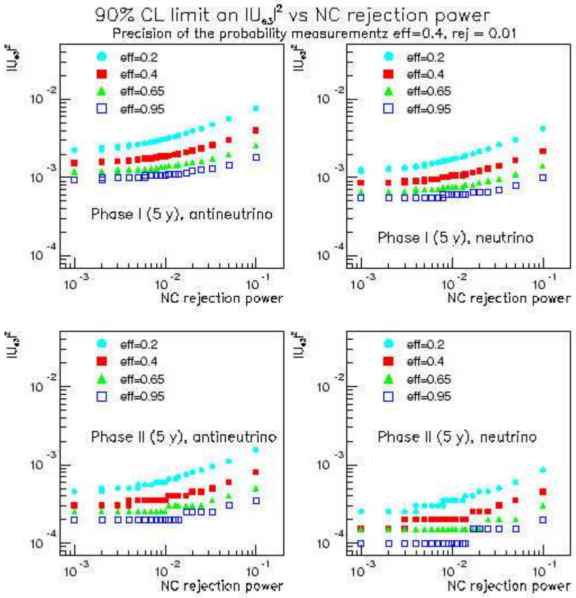

Fig. 4. Oscillation probability reach for different running options as a function of selection efficiency and neutral current rejection power. For details see [13]

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