PROCEEDINGS OF SCIENCE

How to do a nue->numu measurement in a MINOS-like Detector

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Magnetized steel-scintillator tracking calorimeter detector has been considered as a candidate of detectors to study $\nu_e \to \nu_\mu$ oscillation ("*golden*") channel in a Neutrino Factory. The MINOS detector is based on the technology and has been observing atmospheric neutrinos since 2003, as well as beam neutrinos since 2005. The performance of muon neutrino detection by the MINOS detector is discussed in this paper putting the focus on the prospects for the $\nu_e \to \nu_\mu$ oscillation study.

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1. Introduction

Flavor transition of neutrinos has been confirmed by neutrino experiments using various sources and detection technologies [1]. This phenomenon is explained by neutrino oscillations as a consequence of finite mass and a rotation of mass and flavor eigenstates of neutrinos. Long baseline accelerator and reactor neutrino experiments are currently running or under construction targeting to measure the remaining unknown mixing angle θ_{13}. Measurement of θ_{13} is essential to search for CP-violation in neutrino sector, which is considered as the key to understand the origin of the baryon asymmetry in the universe. One of the approaches to measure the CP-vilation phase δ for wide range of θ_{13} and also resolve the mass ordering in neutrino sector is a Neutrino Factory. Neutrino Factory uses electron and muon neutrino beam created from muon decays: $\mu^+ \to e^+ + \nu_e + \overline{\nu_\mu}$ or $\mu^- \to e^- + \overline{\nu_e} + \nu_\mu$ in their storage ring. Among various neutrino oscillation modes expected in a Neutrino Factory, $\nu_e \to \nu_\mu$(and $\overline{\nu_e} \to \overline{\nu_\mu}$) oscillations as a consequence of non-zero θ_{13} is one of the sensitive channels to the CP-violating phase δ and mass ordering in neutrino sector.

In case of μ^+ running, ν_μ appearance signal in this *golden* channel needs to be distinguished from $\overline{\nu_\mu}$ in neutrino beam (and vice versa in μ^- running) based on the charge sign identification of outgoing muons from their charged-current (CC) interactions: $\nu_\mu + N \to \mu^- + X$ (signal from $\nu_e \to \nu_\mu$ oscillations) and $\overline{\nu_\mu} + N \to \mu^+ + X$ (backgrounds). Therefore, a detector for this purpose is required to have a capability of muon charge sign identification, in addition to a detection of ν_μ CC interactions. Magnetized tracking calorimeter detector, which is currently employed in the MINOS experiment, is a candidate which could satisfy those requirements with possible improvements. The status of the MINOS experiment and the performance of the detector is described in the following sections.

2. MINOS Experiment

Primary physics goal of the Main Injector Neutrino Oscillation Search (MINOS) experiment is a precise measurements of Δm^2_{23} and $\sin^2 2\theta_{23}$ in $\nu_\mu \to \nu_\tau$ oscillations. An almost pure muon neutrino beam is created from a 120 GeV proton beam from the Main Injector accelerator at the NuMI facility. The typical neutrino energy is set at 3 GeV ("*low energy configuration*") and is optimized to measure the parameters region expected from atmospheric neutrino observation [2]. The neutrino beam is composed of 92.9 % ν_μ, 5.8 % $\overline{\nu_\mu}$ and 1.3 % $\nu_e + \overline{\nu_e}$. The MINOS experiment has been taking data from the NuMI beam since 2005, and has accumulated more than 5×10^{20} POT by September 2008. The results of $\nu_\mu \to \nu_\tau$ oscillation measurements based on 3.36×10^{20} POT NuMI beam data was report [3].

The MINOS experiment employs two detectors method to reduce the systematic errors on the neutrino oscillation parameters measurement associated with the uncertainties on neutrino beam flux, interaction cross-section and detector response. The far detector is located in the Soudan Underground Laboratory 735 km away from the NuMI target. The detector is a magnetized steel-scintillator tracking calorimeter optimized to detect ν_μ CC interactions from the NuMI beam. The detector is also capable to measure ν_e CC and neutral-current (NC) interactions. The installation of the MINOS far detector was completed in 2003, and it has been taking atmospheric neutrino data since then, as well as the data from NuMI beam since 2005. The picture of the MINOS far detector

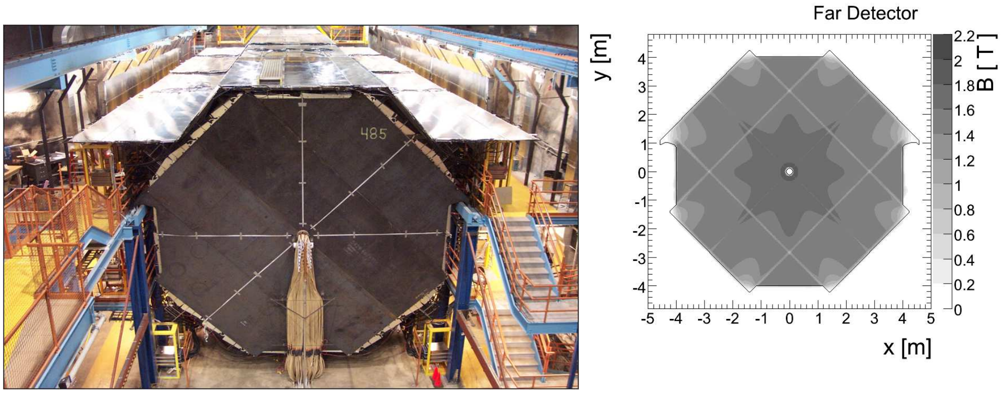

Figure 1: Left: A picture of the MINOS far detector. Right: Magnetic field map for a typical far detector plane [4]

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is in Figure 1. The near detector is based on the same technology as the far detector, and located at 1km away from the NuMI target.

3. MINOS Detectors

The MINOS detectors are magnetized steel-scintillator tracking calorimeter. Active medium of the detector consists of 4.1 cm wide, 1.0 cm thick plastic scintillator strips. Photons emitted in the scintillator are transferred by wavelength shifting fiber to multi-anode PMT, and converted to a electric signal. Scintillator strips are arranged to form a plane, and the detector is made of a series of scintillator and 2.5 cm thick steel planes. The orientations of alternating scintillator planes are rotated by $\pm 90^\circ$ in order to reconstruct three dimensional topology of particles. The steel planes are magnetized by 1.3 T using a magnet coil. The magnetic field across the plane is calculated as shown in Figure 1. Total mass of the far detector is 5.4 kton, consists of 486 planes, while near detector is 1.0 kton with 282 planes. Following ideas are adopted in the MINOS detectors to save the number of PMT and readout channels and the cost for construction. (1) Signals from eight scintillator strips are collected and fed into one PMT pixel in the far detector. The combination of eight scintillator strips are different between both ends, so that the hit strip can be identified by comparing them. (2) Downstream part of the near detector has only every fifth plane instrumented with scintillator, and is used to measure the momenta of energetic muons.

4. Detection of ν_μ in MINOS detector

Figure 2 shows the typical ν_μ CC and NC events in the MINOS detector. ν_μ CC interactions are distinguished from NC interactions with a long track from muon. ν_μ CC interaction candidates are selected by an algorithm based on a multi-variables likelihood method using the reconstructed track topology. Figure 3 shows the ν_μ CC selection efficiency and NC contamination as a function of the reconstructed neutrino energy. Efficiency to collect ν_μ CC interactions is 81.5 % including

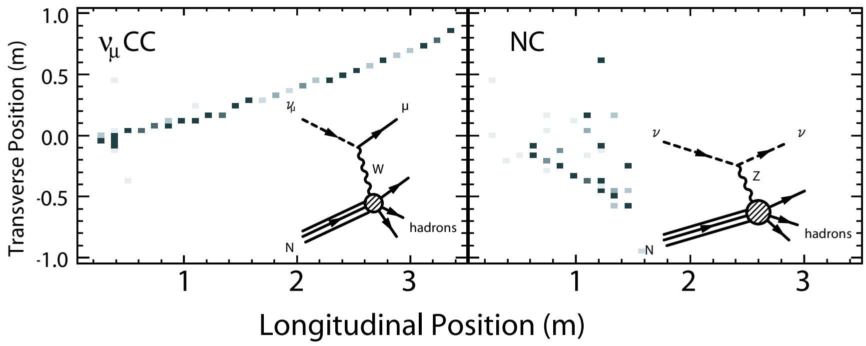

Figure 2: ν_μ CC (left) and NC (right) events in the MINOS detector. Shaded rectangles represent the scintillator hits. Neutrino beam comes from left in the figures. One of two orthogonal views is shown.

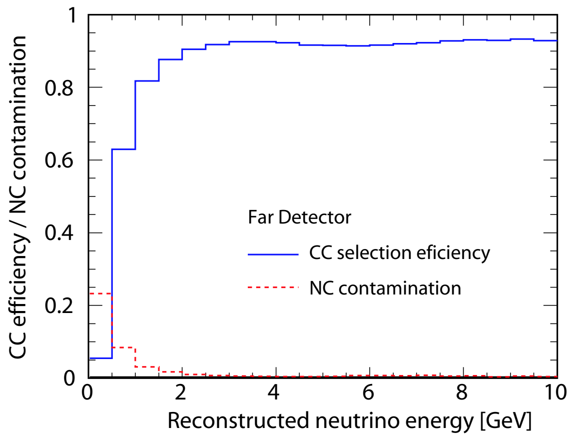

Figure 3: ν_μ CC selection efficiency (solid) and NC contamination (dashed) as a function of the reconstructed neutrino energy. Track finding efficiency is not included.

track finding and NC background reduction, while the NC contamination in the ν_μ CC candidates is 0.6 %.

Neutrino energy for ν_μ CC candidates are reconstructed as a sum of the muon energy and the hadronic shower energy around the vertex. Momentum of muon is determined by the curvature of the track, while the range of the track provides better estimation if the entire track is contained in the detector. Momentum resolutions for muons are approximately 5 % for range measurements and 10 % for curvature measurements. Shower energy is calibrated by test beam measurements using a scaled down version of the MINOS detectors in the CERN PS East Hall [5]. Resolution of the shower energy reconstruction is 59 % at 1 GeV (32 % at 3 GeV).

Curvature of the tracks in the magnetic field also provides charge sign identification for the muons, which is equivalent to identification of ν_μ and $\overline{\nu_\mu}$ in case of CC interactions. The performance of the charge sign separation was studied in the atmospheric upward muon analysis [6]. Figure 4 left-hand plot shows the χ^2_{line}/ndf by a fit to the scintillator hit distribution assuming

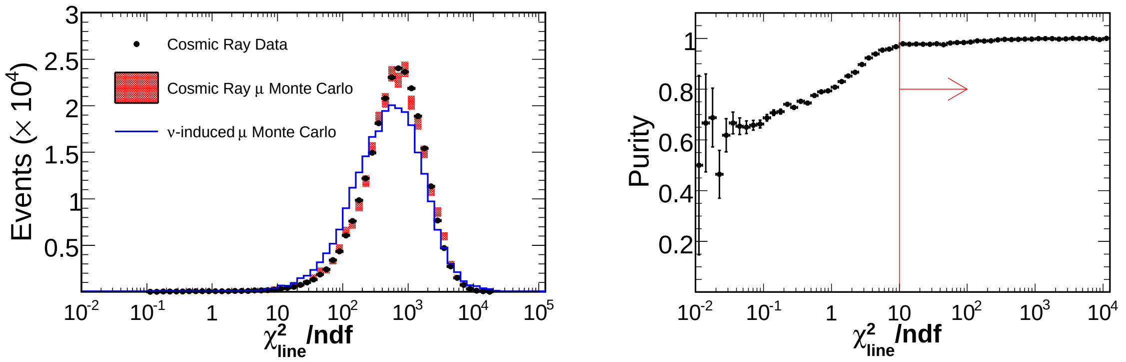

Figure 4: Left: χ^2 over number of degrees of freedom (ndf) for a fit to scintillator hit distribution assuming straight line track. Points show the data for cosmic ray muons and boxes show the Monte Carlo simulation. Solid line shows the prediction of the neutrino induced muons. Right: Purity of charge sign identification as a function of χ^2_{line}/ndf for the neutrino induced muons from Monte Carlo simulation [6].

straight line (left), which must be large in case of muons with curvature. The right-hand plot shows the purity of muon charge sign identification as a function of the cut value for χ^2_{line}/ndf. The purity is approximately 97 % at $\chi^2_{line}/ndf = 10$ and rises to over 99 % increasing χ^2_{line}/ndf values. Study of $\overline{\nu_\mu}$ oscillations including a test to CPT violation, which is done by comparing it with ν_μ oscillatons, is planned in the MINOS experiment. The performance of muon charge sign identification for the beam neutrinos will be shown in the analysis.

5. Summary

Neutrino oscillation phenomenon has been established by neutrino experiments using various sources. The targets of current and the next generation neutrino experiments are to measure the remaining unknown mixing angle θ_{13} and to study CP-violation and mass hierarchy in neutrino sector, as well as the precise measurement of other neutrino oscillation parameters. Those studies are expected in Neutrino Factory using electron and muon neutrino beamd. To study for $\nu_e \to \nu_\mu$ oscillations, detection of ν_μ CC interactions and the separations of ν_μ and $\overline{\nu_\mu}$ are required. Magnetized tracking calorimeter detector employed in the MINOS experiment provides those functions. The results of ν_μ disappearance analyses from the MINOS experiment were successful and encouraging to realize a Neutrino Factory.

References

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