Recent Results from the MINOS Experiment

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Abstract. We report on recent results from the MINOS (Main Injector Neutrino Oscillation Search) experiment. A ν_μ beam, originating from the NuMI beamline at Fermilab, IL is detected by both the MINOS near detector located 1km from the target and the far detector located 735km away in Soudan, MN. MINOS has observed muon neutrino disappearance in the far detector using beam data collected from Jan, 2005 to Feb, 2006. The observed spectrum of ν_μ charged-current events at the far detector is consistent with muon neutrino oscillations where the oscillation parameters are measured to be $|\Delta m^2_{32}| = 2.74^{+0.44}_{-0.26} \times 10^{-3}$ eV^2/c^4, and $\sin^2(2\theta_{23}) > 0.87$ (68% C.L.).

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INTRODUCTION

Neutrino oscillations are currently best described by the 3×3 PMNS mixing matrix [1] which relates the observed 3 flavor eigenstates (ν_e, ν_μ, ν_τ) to the 3 mass eigenstates (ν_1, ν_2, ν_3). In this scenario, the survival probability (in vacuum) of a ν_μ with energy E (in GeV) after traversing a distance L (in km) is approximated by

$$P(\nu_\mu \to \nu_\mu) \sim 1 - \sin^2 2\theta_{23} \sin^2(1.267 \Delta m^2_{32} L/E) \tag{1}$$

where $\Delta^2 m_{32} = m_3^2 - m_2^2$ is the mass difference of the 3 and 2 mass states in eV^2, and θ_{23} is the PMNS matrix mixing angle. Equation 1 assumes $\nu_\mu \to \nu_\tau$ is the dominant contribution.

The Main Injector Neutrino Oscillation (MINOS) experiment, is a long baseline neutrino oscillation experiment based at Fermi National Accelerator Laboratory (FNAL) in Batavia, IL and the Soudan Underground Laboratory in Soudan, MN. A beam of 90% ν_μ, with a peak energy of $E = 3.1$ GeV/c^2 originating from the NuMI beamline at FNAL is detected by both the MINOS near detector (ND) located 1km from the target and the far detector (FD) located at a baseline $L = 735$km away in Soudan Lab. We report on the first results from the MINOS experiment's search for ν_μ disappearance.

THE NUMI BEAMLINE AND MINOS DETECTORS

The NuMI (Neutrinos at the Main Injector) beamline at Fermi National Accelerator laboratory utilizes 120 GeV/c protons from the FNAL main injector accelerator to generate a muon neutrino beam. The current beamline is designed to accept up to 4×10^{13} 120 GeV/c protons every 1.9 secs which corresponds to 0.4 MW average beam power. The beam is extracted in a single turn 8-10 μ sec spill and directed along a 350m beamline onto a graphite target 6.4mm wide transverse to the beam and 95.4cm in length (1.9 interaction lengths). The charged hadrons produced from the beam interactions in the target are then focused using 2 pulsed magnetic paraboloid focusing horns which preferentially select and focus π^+, k^+ in the range 0 to 15 GeV. The focused hadrons travel along an evacuated decay pipe 675m in length and 2m in diameter where they decay thereby producing a beam of 89% ν_μ, 10% $\bar{\nu_\mu}$, and 1% $\nu_e + \bar{\nu_e}$. The target is inserted 50.4cm into the first horn and the distance between the two horns is 10m. The peak beam energy in this configuration is 3.1 GeV/c^2. The distance between the target and first horn can be increased by up to 2.5m to produce higher beam energies.

The NuMI beamline began operations on January 21st, 2005 and has been operating with an overall average beam power of 160 kW. Occasionally, the line has been run with beam power as high as 265 kW. In its first year of operation (January, 2005 through February, 2006), NuMI delivered 1.39×10^{20} protons-on-target (POT) to MINOS.

The MINOS experiment comprises two magnetized iron tracking calorimeters. The near detector (ND) is 0.98 kT and is located 1km from the NuMI target at FNAL, 103m underground. The far detector (FD) is 5.4 kT and is located on the NuMI beam axis 735 km from FNAL and 705m underground in the Soudan Underground Laboratory in Minnesota. Both detectors are comprised of layers of 2.54 cm thick iron plates with scintillator strips of 4.1 cm width and 1cm thickness mounted on the plates. Scintillation light in each strip is collected using a single wavelength shifting fiber readout at both ends. Both detectors are magentized with a toroidal magnetic field. The FD is 31m in length and is comprised of 486 fully instrumented octagonal plates 8m in width. In the FD, the readout from 8 fibers are multiplexed. The ND has a "squashed" octagonal structure with 282 planes. The ND is 4.8 m in width, 3.8 m in height, and 16.6 m in length. The ND is divided into two sections: the calorimeter section, which is the first 120 planes, and the muon spectrometer section which is the last 162 planes. In the spectrometer region, only every fifth plane is instrumented and the fiber readout is four-fold multiplexed.

The FD has been fully operational since August, 2003 and has been used to perform the first direct measurment of the ratio of atmospheric ν_μ to $\bar{\nu}_\mu$ events [3].

The single particle response of the MINOS iron calorimeters to $e^\pm, \pi^\pm, p^+$ in the range 0-10 GeV has been measured using CalDet [2], a small calibration detector which duplicated the steel and scintillator structure of the MINOS detectors. We find that the MINOS MC correctly models the single particle response measured in CalDet. The hadronic energy resolution was measured to be $55\%/\sqrt{E}$ and the electromagnetic resolution was measured to be $23\%/\sqrt{E}$.

DATA SELECTION AND RESULTS

To search for ν_μ disappearance, charged current (CC) neutrino interactions in which a μ is produced are reconstructed in the ND and FD. Firstly, only events which occured within the 10μ second spill interval are selected (as tagged by the GPS timing system used in both detectors). Secondly, events which pass beam and detector quality selection critirea are further examined to preselect charged-current event candidates. Each event is required to have at least one high quality reconstructed track with a vertex contained

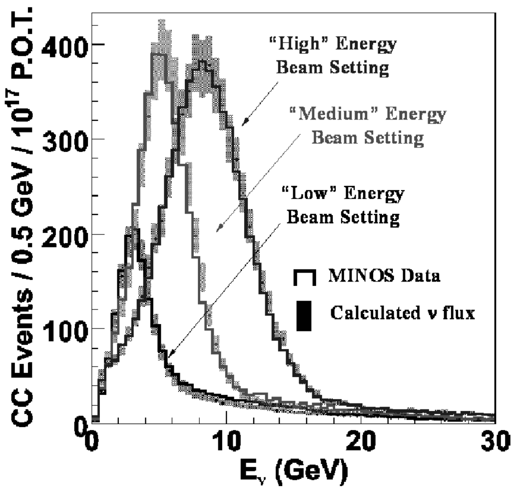

FIGURE 1. The spectrum of CC ν_μ events measured in the ND from 3 different beam tunes (solid histogram). The shaded points represent the range of the MC prediction with beam modeling uncertainties for each tune.

within the detector fiducial volumes. The fiducial volume in the ND is a 4m long cylindrical region in the calorimeter section starting 1m in from the face of the detector and with a radius of 1m centered on the ν beam. In the FD, the cylindrical fiducial volume starts 50 cm from the front and ends 50 cm from the rear of the detector with a radius of 3.7m centered on the detector axis. For the final event selection, a combination of 3 probability density functions (PDF) for charged current and neutral current (NC) interactions is used to determine the likelihood an event is CC/NC. The product of the probabilities is combined into one event classification parameter, *PID*, as follows:

$$PID = -(\sqrt{-\log(P_{CC})} - \sqrt{-\log(P_{NC})} \tag{2}$$

where P_{CC} is the probability an event is a charged current ν_μ interaction, and P_{NC} the event is a neutral current ν_x interaction. The PDFs used are the event length in number of planes (a quantity related to the momentum of the μ track), the fraction of the event pulse height in the track (a measure of the inelasticity of the CC events), and the track pulse height per plane (a quantity closely related to dE/dX of the μ track). The PID cuts in the ND and FD are selected such that the purity of the final event sample is 98%. Six different beam tunes produced by varying the position of the target from the first horn and varying the horn currents were used to constrain the MC hadroproduction model parameters and the systematic effects of the beam focusing. The distribution of selected data in the ND and tuned MC events, normalized to the number of POT for 3 different energy tunes is shown in Figure 1. We find good agreement between the near detector data and tuned MC.

A GEANT based Monte Carlo simulation of the ND is first used to correct the reconstructed ν_μ energy spectrum in the data for purity, reconstruction efficiencies and energy smearing to estimate the true ν_μ flux at the ND. A simulation of the beamline geometry is then used to transport the ν_μ flux measured at the ND to the FD, thus

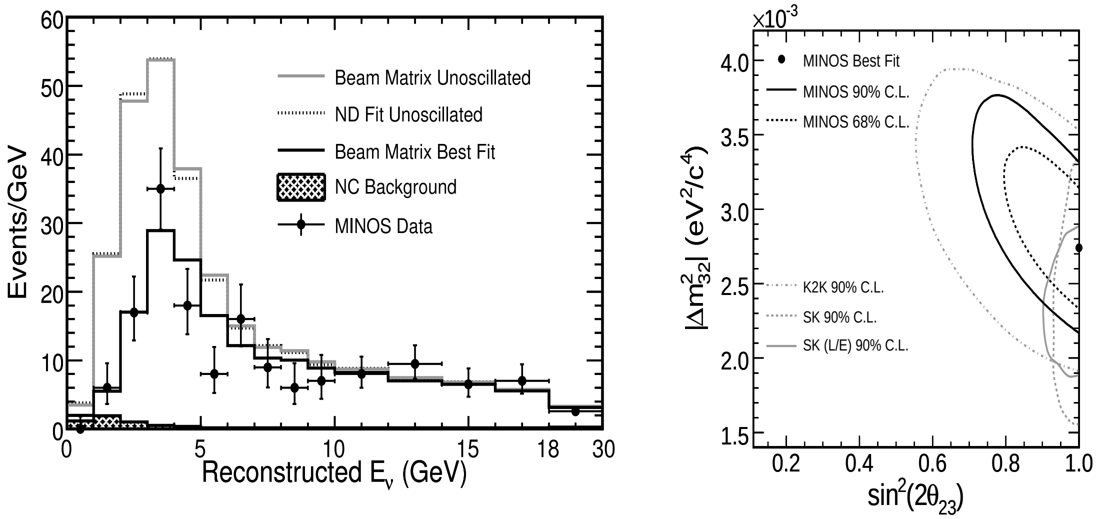

FIGURE 2. The spectrum of CC ν_μ events in the MINOS far detector and the results of the fit to the oscillation hypothesis (left). The MINOS exclusion contours (right).

producing the predicted spectrum of ν_μ unoscillated events in the FD. Using 1.27×10^{20} POT collected in the lowest energy beam tune from May, 2005 to February, 2006, the spectrum of reconstructed ν_μ events in the FD was compared with the MC prediction as shown in Figure 2 [4]. We observe a large deficit of muon neutrino events in the range 0-10 GeV/c^2. The predicted number of unoscillated ν_μ with energy < 10 GeV is $238.7 \pm 10.7(\text{syst})$, wheras the observed number of events is 122 - a defict of 6.2 standard deviations (systematic and statistical combined). A likelihood fit was performed to the observed spectrum of ν_μ in the FD using the oscillation hypothesis outlined in Equation 1. The fit results are shown overlaid with the data in Figure 2. We find $|\Delta m^2_{32}| = 2.74^{+0.44}_{-0.26} \times 10^{-3}$ eV^2/c^4, and $\sin^2(2\theta_{23}) > 0.87$ (68% C.L.) [4]. The MINOS exclusion contours overlaid with the latest results from the K2K and SuperKamiokande experiments are shown in Figure 2.

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REFERENCES

1. B. Pontecorvo, *JETP (USSR)* **34**, 247 (1958)
   Z. Maki, M. Nakagawa, and S. Sakata, *Prog. Theor. Phys.* **28**, 870 (1962).
2. P. Adamson et. al., *Nucl. Instrum. Meth. A* **556**, 119-133 (2006).
3. MINOS Collaboration (P. Adamson et. al.), *Phys. Rev. D* **37**, 072002 (2006).
4. MINOS Collaboration (D. Michael et. al.), FERMILAB-PUB-06-243, BNL-76806-2006-JA, hep-ex/0607088, submitted to Phys. Rev. Lett. (2006).