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MINOS atmospheric neutrino contained events

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Abstract: The Main Injector Neutrino Oscillation Search (MINOS) experiment has continued to collect atmospheric neutrino events while doing a precision measurement of NuMI beam ν_μ disappearance oscillations. The 5.4 kton iron calorimeter is magnetized to provide the unique capability of discriminating between ν_μ and $\bar{\nu}_\mu$ interactions on an event-by-event basis and has been collecting atmospheric neutrino data since July 2003. An analysis of the neutrino events with interaction vertices contained inside the detector will be presented.

Introduction

The MINOS experiment uses two similar iron/scintillator calorimeters to measure the properties of the NuMI neutrino beam over a long baseline, and has precisely measured the neutrino flavor oscillations [1] previously seen in atmospheric neutrinos [2]. The 5400 ton Far Detector is located 700 m (2070 mwe) deep in the Soudan Mine Underground Lab in northern Minnesota [3]. The rock overburden reduces the rate of cosmic ray muons reaching the Lab by a factor of 10^5, allowing the detection of atmospheric ν via their charged-current production of leptons. These interactions can occur in the detector itself ("contained vertex interactions") or in the rock surrounding it ("upward-going muons"). This paper expands on the previously published MINOS contained vertex analysis [4] by a factor of two more data (12.23 ktyr), adds a search for showers from ν_e and NC interactions, and uses a Bayesian, bin-free fit for the oscillation parameters. The MINOS detector is unique among experiments sensitive to atmospheric neutrinos, as it is magnetized with a toroidal field of $\sim 1.5\,\mathrm{T}$, allowing the determination of momentum and charge on an event-by-event basis via the curvature of the muon track. Muon momentum provides information on the energy of the parent neutrino, and muon charge tags the parent neutrino as a ν_μ or $\bar{\nu}_\mu$. Shower-like events come from both ν_e and neutral current interactions. Since ν_μ disappear into ν_τ while ν_e do not participate in the observed atmospheric oscillations [5], showers represent a normalization of the absolute flux to calibrate the degree of ν_μ disappearance.

The Data and Analysis

To separate the neutrino-induced interactions (once or twice a week) from the much larger rate ($\sim$ 2 Hz) of cosmic ray muons which penetrate the overburden, a series of topological and timing cuts is applied to the data. "Track-like" muon events can pass this selection either by being upward-going or by the highest end of the track being contained in the MINOS Far Detector's fiducial volume. Upward-going events are neutrino-induced as the Earth screens out charged particles, and events originating inside the detector are likewise attributed to neutrinos since charged particles would be observed entering the detector. The selected events fall into one of four classes: Fully-Contained (FC), which both start and stop inside the detector; Partially-Contained Downward-Going (PCDN) originating in the detector but escaping through the bottom; the converse Partially-Contained Upward-Going (PCUP); and Upward Muons (UPMU) originating in the rock and entering the detector from below. The latter are analyzed separately [6] and discussed in detail elsewhere in this session [7]. Shower-like electron events are also selected by a separate analysis chain, and are normalized to the track-like events resulting from that same alternate analysis chain. Events in time with the NuMI beam are flagged by a very efficient (99%) GPS timestamp and removed from this analysis of atmospheric neutrinos.

Initial data and track quality selection cuts are applied to the track-like events and the data is kept based on either timing or topological information. Timing uncertainty for each flash of scintillation light is $\sigma_t = 2.4\,\mathrm{ns}$ [6], sufficient to establish the direction of travel for a muon given a physical fit for the track. Stringent track quality cuts eliminate poorly fit tracks masquerading as neutrino interactions, leaving only upward-going events.

Tracks whose highest part is contained inside the fiducial volume are also neutrino-induced. The fiducial volume is a 7.6 m octagonal region within the 8.0 m octagonal steel detector, with a 0.4 m radius cylinder around the central magnetic coil removed, and without the four steel planes at each end of the two detector modules. The planar structure of the detector allows cosmic muons to enter the detector between the planes and appear contained. These events tend to travel nearly parallel to the planes or to contain large energy deposits around the track vertex. A series of track topology cuts are applied to separate the signal and background. To eliminate cosmic rays sneaking along gaps in the detector, the axial component of the projection of the track back to the edge of the detector must pass through 0.15 m of detector, and there must be no detector activity before the highest end of the track. An additional scintillator layer placed on the top and sides of the MINOS Far Detector serves as a veto shield and aids in the rejection of entering cosmic rays. This 97% efficient shield is especially important in the selection of shower-like events for the ν_e analysis, where lack of a track prevents the precise examination of possible cosmic ray muon entry paths. Requiring a quiet veto shield eliminates 2% of the real neutrino events via accidental coincidence. In total, 277 track-like neutrino events were seen, compared to a no-oscillation expectation of 354 ± 47.

A sub-sample of events is defined which have especially well-determined tracks: those at least 1.0 m long; crossing at least 10 planes; and those for which both up/down timing fits differ by more than 0.1 m. These "high resolution" tracks offer the best window into the parent neutrino baseline and energy, the important L/E parameter that drives neutrino flavor oscillations. Additionally, the curvature of the track in the detector's magnetic field allows the separation of μ^- from μ^+, which are produced by ν_μ and $\bar{\nu}_\mu$ respectively. These data are summarized in Table 1.

The dataset analyzed for shower-like events was a 4.51 ktyr subset of that used in the track-like analysis. This analysis independently selected nearly the same track-like events as the first analysis. The comparison of the showers caused by ν_e and NC interactions (insensitive to oscillations) and the tracks caused by the ν_μ involved in oscillations is useful. 89 showers and 112 tracks were found, compared to expectations of 88.8 ± 0.9 and 149.8 ± 0.9. Complete details of this process can be found in [8], and a spectrum of these events compared to expectations is shown in Fig. 1. To test the effect of oscillations, a double ratio of track to showers in data and unoscillated Monte Carlo is formed: $\mathcal{R} = (\#tracks/\#showers)_{(\mathrm{Data/MC})}$. In the absence of oscillations, this ratio would be unity. Given the observed numbers, $\mathcal{R} = 0.75^{+0.12}_{-0.10}(stat) \pm 0.04(syst)$ rules out no oscillations at the 98.0% level. Another way to suppress the number of tracks (but not showers) is if the absolute flux normalization changes. A second result of the track to shower ratio is the best fit flux normalization. Using the flux model of Barr [9, 10] (which has a 20% quoted uncertainty [11]) this analysis finds the best fit neutrino flux to be a factor of $S_{atm} = 1.07 \pm 0.12_{stat} \pm 0.09_{syst}$ times the expected flux, a measurement consistent with theory.

Upward going neutrinos have traveled further than downward going ones, giving them more of a chance to disappear. A similar double ratio can be formed from the high-resolution track-like data in Table 1, $\mathcal{R} = (\#UP/\#DOWN)_{(\mathrm{Data/MC})}$. In the absence of oscillations, this ratio would be also be unity. The data show $\mathcal{R} = 0.72^{+0.13}_{-0.11}(stat) \pm 0.04(syst)$, a significant deficit. The L/E for these events is plotted directly in Fig. 2.

Classification	Data	Monte Carlo Expectation (no oscillations)				
		Cosmic μ^+/μ^-	$\nu_\mu/\bar{\nu}_\mu$ CC	$\nu_e/\bar{\nu}_e$ CC/NC	Upward μ^+/μ^-	Neutrons
UP ν_μ	52	-	69.9 ± 10.5	0.4 ± 0.1	1.2 ± 0.2	-
UP $\bar{\nu}_\mu$	22	-	35.7 ± 5.4	0.7 ± 0.1	0.7 ± 0.2	-
UP ?	3	-	9.0 ± 1.4	0.3 ± 0.0	0.3 ± 0.0	-
DOWN ν_μ	60	3.3 ± 0.7	64.7 ± 9.7	0.3 ± 0.0	0.1 ± 0.0	-
DOWN $\bar{\nu}_\mu$	33	3.7 ± 0.7	32.8 ± 4.9	0.6 ± 0.1	0.05 ± 0.0	-
DOWN ?	12	0.1 ± 0.1	10.2 ± 1.5	0.3 ± 0.0	0.05 ± 0.0	-
UNCERTAIN	95	4.2 ± 0.7	92.2 ± 13.8	23.6 ± 3.5	0.4 ± 0.1	0.3 ± 0.2

Table 1: A summary of the track-like atmospheric neutrino data. The "high resolution" track data is listed as up-going or down-going, and broken into charge identified sub-samples for events with clear curvature. Uncertain events are those which are not high-resolution. The data errors are statistical, the Monte Carlo from normalization uncertainties.

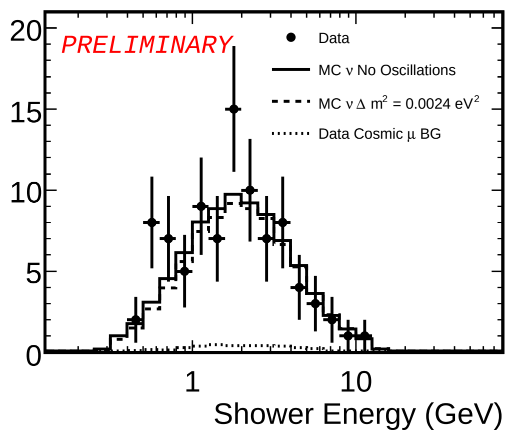

Figure 1: The spectrum of observed shower-like interactions compared to Monte Carlo expectations. Showers are primarily due to ν_e CC and any NC interactions, which are not sensitive to the ν_μ oscillations seen in the atmospheric sector.

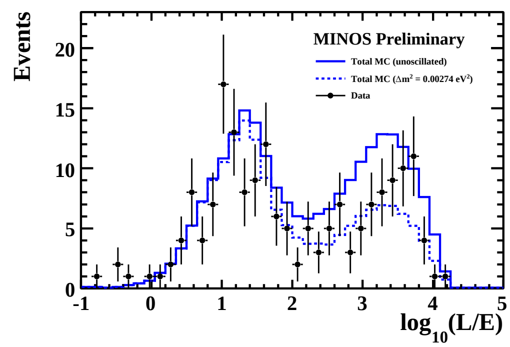

Figure 2: The high resolution data sample (dots with statistical error bars) plotted as a function of $log_{10}(L/E)$. The Monte Carlo expectations (solid line) show agreement at low L/E and disagreement at higher values. If the oscillation parameters $\Delta m^2 = 0.00274, \sin^2 2\theta = 1.0$ are applied to the MC, the dashed line results and describes the data well.

A Bayesian approach is used to estimate the oscillation parameters which best describe the data. In this method, Monte Carlo data is used to find distributions of possible parent neutrinos for each observed event in the high resolution sample of atmospheric neutrinos. These distributions are then used to form a Probability Density Function (PDF) in L/E, representing the probability that the parent neutrino came from a given L/E (see [12] for complete details of this procedure). The product of the PDFs for all the data are compared to that of the MC using a log-likelihood calculation, and the resulting allowed region in oscillation parameter space is is consistent with both previous atmospheric [2, 4] and beam [1] neutrino results, although with smaller statistics and correspondingly less certainty.

Lastly, MINOS' unique feature of a neutrino experiment with magnetic field can be used to see if ν_μ oscillate differently than $\bar{\nu}_\mu$. No such unexpected effect is seen when fitting the two samples separately. This is most concisely expressed as another double ratio of data to MC, $\mathcal{R} = (\nu_\mu/\bar{\nu}_\mu)_{(\mathrm{Data/MC})}$. In the presence of different oscillation parameters for the two sorts of neutrinos, this ratio would diverge from unity. The observed $\mathcal{R} = 0.93^{+0.19}_{-0.15}(stat) \pm 0.12(syst)$, shows no such deviation.

Conclusions

An atmospheric neutrino sample of 12.23 ktyr of tracks and 4.51 ktyr of showers seen in the MINOS Far Detector has been analyzed. Double-ratios of showers to tracks, up-going to down-going events, and ν_μ to $\bar{\nu}_\mu$ have been measured. These data are consistent with the $\nu_\mu \leftrightarrow \nu_\tau$ disappearance oscillations seen in detail in the NuMI beam [1] and with no difference in the oscillation properties of neutrinos and anti-neutrinos. A Bayesian analysis of the L/E from ν_μ induced tracks produces an allowed region in Δm^2, $\sin^2 2\theta$ space consistent with other measurements of this oscillation phenomenon. This work also produces a measurement of the absolute normalization of the neutrino flux of $S_{atm} = 1.07 \pm 0.12_{stat} \pm 0.09_{syst}$ times that predicted by Barr [9]. The MINOS detector continues to accumulate atmospheric neutrino data, with a livetime fraction of $> 98\%$. Future analysis will include the tracks, showers, and upmus in a unified analysis, further refining the above results.

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