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# Measurement of the Charge-Separated Atmospheric Neutrino-Induced Muons in the MINOS Far Detector

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**Abstract:** The MINOS far detector in the Soudan mine, Minnesota, USA has found 140 neutrino-induced muons in 854.24 live days of operation. These data were tested for evidence of neutrino disappearance by computing the ratio of the number of low momentum muons to the sum of the number of high momentum and unknown momentum muons for both data and Monte Carlo expectation in the absence of neutrino oscillations. The ratio of those ratios is consistent with an oscillation signal. The data were fit for the oscillation parameters $\sin^2 2\theta_{23}$ and $\Delta m^2_{23}$ and the null oscillation hypothesis is excluded at the 94% confidence level.

## Introduction

Measurements of atmospheric neutrinos by Super-Kamiokande experiment have shown that there is a deficit of $\nu_\mu$ when compared to expectations ([1], and references therein). The hypothesis that best describes this deficit is the oscillation of $\nu_\mu(\overline{\nu}_\mu) \rightarrow \nu_\tau(\overline{\nu}_\tau)$ [2], with the oscillation probability given by $P_{\nu_\mu \rightarrow \nu_\tau} = \sin^2 2\theta_{23} \sin^2(1.27\Delta m^2_{23} L/E)$, where $\theta_{23}$ is the mixing angle, $\Delta m^2_{23} = |m^2_3 - m^2_2|$ is the mass squared difference in $\mathrm{eV}^2$ between the neutrino mass states, $L$ is the distance in km traveled by the neutrino, or its baseline, and $E$ is the energy of the $\nu_\mu$ in GeV. The Super-Kamiokande data is best fit by the oscillation hypothesis with parameters $(\sin^2 2\theta_{23}, \Delta m^2_{23}) = (1.0, 2.4 \times 10^{-3}\,\mathrm{eV}^2)$ [1]. The oscillation hypothesis for the atmospheric neutrino deficit has received strong support from the first results of the MINOS long baseline experiment [3] and the K2K long baseline experiment [4] . The analysis presented here is more fully described in [5].

## The Upward-Going Neutrino Induced Muon Sample

The MINOS far detector is a 5.4 kton steel-scintillator sampling calorimeter outfitted with magnetized steel planes. It is located at the Soudan Underground Laboratory, Minnesota, USA at a depth of 710 meters below the surface. For MINOS to find upward-going, neutrino-induced muons against the cosmic ray background, excellent timing resolution is required. The timing system was calibrated with cosmics by measuring time offsets between every channel along the track and comparing these offsets to expectation. The overall timing resolution of the detector has been determined to be $2.31 \pm 0.03$ ns.

Neutrino-induced muons are defined as events that come from below or slightly above the horizon. These events are essentially uncontaminated by the background of downward-going atmospheric muons. We first selected muon events using criteria developed for the study of cosmic ray muons with the MINOS far detector [6]. Next, cuts were designed to remove events with poor timing information and those with poorly determined values for $1/\beta$. Finally, downward-going events were separated from upward-going events by fitting a straight line to their trajectory in the detec-

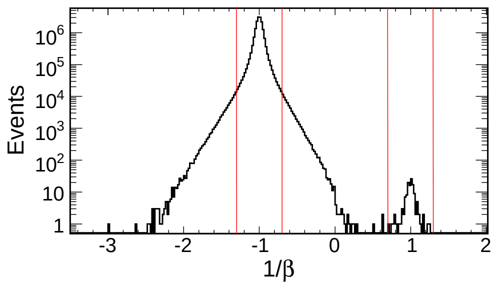


Figure 1: Distribution of $1/\beta$ for upward-going neutrino-induced muons, with a peak at 1, and downward-going cosmic ray muons, with a peak at -1. The vertical lines at 0.7 and 1.3 bracket the events included in the upward-going muon sample.

tor. Upward-going events have a positive slope, downward-going events a negative slope. Fig. 1 shows the resulting $1/\beta$ distribution for our muon sample. The vertical lines at 0.7 and 1.3 bracket the events included in the upward-going muon sample. A representative event from the upward going sample is shown in Fig. 2. The slope of the trajectory of this event is clearly positive.

## Oscillation Analysis

One way to look for evidence of neutrino oscillations in the neutrino-induced muons is to take the ratio of the number of low momentum muons, which are more likely to show an oscillation signal, to the sum of the number of high momentum and unknown momentum muons, which are less likely, and compare this ratio with its Monte Carlo expectation including backgrounds. In the data, this ratio of low to the sum of high and unknown momentum muons is given by

$$R^{data}_{L/H+U} = \sum_{L}(N_{\mu^-}+N_{\mu^+})/\sum_{H+U}(N_{\mu^-}+N_{\mu^+}), \tag{1}$$

where $N_{\mu^-}$ is the number of $\mu^-$ observed in a bin and $N_{\mu^+}$ is the number of $\mu^+$ observed in a bin. The sum over $L$ includes events in the range $1 < p_{fit} < 10$ GeV/c, and the sum over $(H+U)$ includes the remaining high momentum and unknown momentum events. Fig. 3 shows the distributions of parent neutrino energies for the low

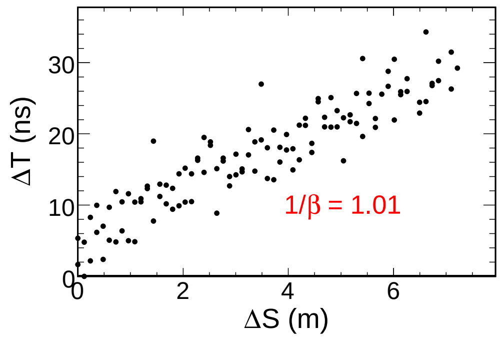


Figure 2: Distribution of $\Delta T/\Delta S$ for a typical upward-going muon, where $\Delta T$ (ns) is the time difference of each hit along the track from its upstream neighbor as a function of its distance $\Delta S$ (m) from the first hit.

momentum, high momentum, and unknown momentum muons as determined by the Monte Carlo simulation. Using the Monte Carlo simulation, a ratio similar to eq(1), $R^{MC}_{L/H+U}$, was determined. In the absence of oscillations, the ratio of these two quantities, $\mathcal{R}$, will be consistent with unity; if an oscillation signal is present, $\mathcal{R}$ will be less than unity. We find

$$\mathcal{R} = \frac{R^{data}_{L/H+U}}{R^{MC}_{L/H+U}} = 0.65^{+0.15}_{-0.12}\,(stat) \pm 0.09\,(syst). \tag{2}$$

Adding the upper statistical and systematic uncertainties in quadrature, the upper uncertainty is $+0.17$ which results in a value for $\mathcal{R}$ that differs from the no oscillation expectation of unity by $2.0\sigma$. This result is consistent with neutrino oscillations.

Figure 4 shows the fit momentum distributions for data and unoscillated Monte Carlo simulation using the combined low momentum and high momentum muon samples. The unknown momentum muons are not included in this figure. The first bin in Fig. 4 shows a deficit of events in the data relative to Monte Carlo expectation without oscillations

We used the data and Monte Carlo samples for an oscillation fit. The best fit in the physical region is found at $\sin^2 2\theta_{23} = 1$ and $\Delta m^2_{23} = 0.93 \times 10^{-3}$ eV$^2$ with $\chi^2/ndf = 5.9/7$. The results of the fit

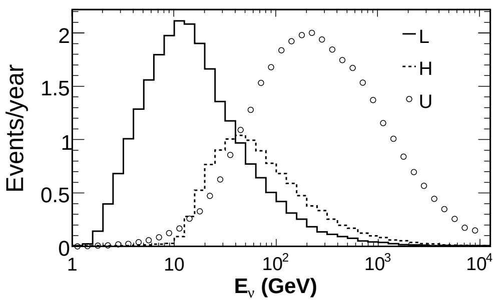


Figure 3: Distribution of energies for neutrinos producing neutrino-induced muons observed in the MINOS detector as determined by the Monte Carlo simulation. The neutrinos producing low momentum muons are shown by the solid line, those producing high momentum muons are shown by the dashed line and those producing unknown momentum muons are shown by open circles. Neutrinos producing muons detected by MINOS have energies > 2 GeV.

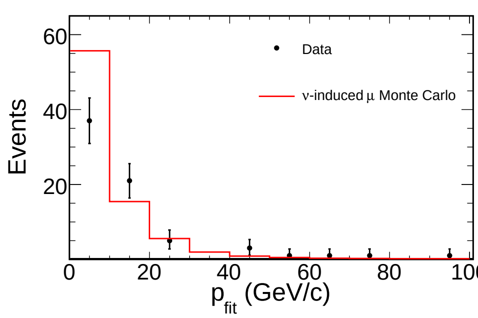


Figure 4: Distribution of fit momenta for events in the combined low momentum and high momentum data samples. The Monte Carlo expectation for no oscillations is shown by the solid line. The unknown momentum muons are not included in this figure.

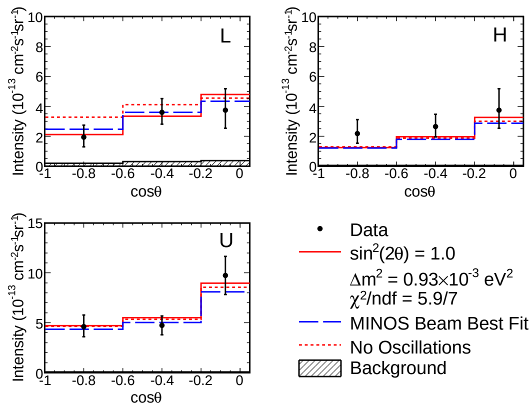


Figure 5: The intensity of neutrino-induced muons as a function of $\cos\theta$. The data are shown by the points, the best fit is shown by the solid line, and the null oscillation hypothesis is shown by the dotted line. The prediction using the MINOS result with the NuMI neutrino beam is shown by the dashed line. The top left panel shows the events with $1 < p_{fit} < 10$ GeV/c (L), the top right shows the events with $10 \leq p_{fit} < 100$ GeV/c (H) and the bottom left shows events with unknown momentum (U).

are shown in Fig. 5, where the best fit to the data in the physical region (solid line), the Monte Carlo prediction for the null oscillation hypothesis (dotted line), and the prediction derived from the MINOS result with the NuMI neutrino beam (dashed line) [3] are superposed onto the observed intensity of neutrino-induced muons.

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