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Atmospheric neutrino contained events in MINOS

K. Ruddick, for the MINOS Collaboration.
School of Physics and Astronomy, University of Minnesota, Minneapolis, MN, USA 55455
Presenter: K. Ruddick (ruddick@physics.umn.edu), usa-ruddick-K-abs1-HE22-oral

The MINOS Far Detector has a mass of 5.4 kT and is situated at a depth of 2070 mwe. It is the first large underground detector to have a magnetic field and has been fully operational since August 2003. During that time, it has collected data on cosmic ray muons and on atmospheric neutrino interactions. We describe preliminary data on charged current muon-neutrino interactions that use the accurate timing of the detector to infer the direction of the neutrinos. We also describe the first direct separation of atmospheric muon-neutrino and muon-antineutrino, using the curvature of muons in the 1.5T magnetic field.

1. Introduction

The MINOS experiment will investigate neutrino oscillations occurring in an initially (almost) pure ν_μ beam created at Fermilab. The beam first passes through a Near Detector at Fermilab and again in a massive Far Detector after traveling a distance of 735 km. Differences in beam composition and energy spectra at the two locations will enable precise measurements of neutrino mixing parameters. The Far Detector is located 2070 mwe underground in the Soudan mine in northern Minnesota; it has a mass of 5.4 kT and has been fully operational since August 2003, studying muons and neutrinos produced by cosmic ray interactions in the atmosphere. Most recently, it has been collecting both cosmic ray and beam data. This paper is concerned solely with contained or partially-contained charged current atmospheric neutrino events in the Far Detector. The analysis utilizes the excellent timing properties of the detector to separate upward-going from downward-going events. This detector also possesses a unique property: it is the first large underground detector to have a magnetic field, allowing the charge of tracks to be identified.

The Far Detector is constructed of two “supermodules” containing a total of 486 vertical planes of 2.54 cm thick steel. Planes of 1 cm thick, 4.1 cm wide plastic scintillator strips are arranged between alternate steel planes. The steel and scintillator planes are in the form of 8-m wide octagons. There are 192 scintillator strips in each scintillator plane arranged in orthogonal u- and v- directions in alternating planes. The scintillators are read out from both ends using wavelength-shifting fibers embedded in the scintillator strips and connected to multipixel photomultiplier tubes. 8 fibers are routed to each pixel, resulting in 8-fold multiplexing. Demultiplexing of these signals to provide individual strip pulse information is achieved by comparing pulse-height and timing information from the opposite ends of strips.

A toroidal magnetic field, averaging 1.5 Tesla, is obtained by passing a 15kA current through a coil situated in a 25 cm diameter hole through the center of each supermodule and returning below the supermodule. More details of the detector construction and readout can be obtained elsewhere[1]. The ability of the detector to separate neutrino interactions from backgrounds produced by through-going muons has been considerably enhanced by the addition of an active shield that covers the top and sides of the detector.

Great care has been taken to understand the energy response of the detector. All 4.1 cm wide strips were mapped every 4 cm along their length prior to installation, using a strong radioactive source, to check for any localized anomalies. A small 1-m by 1-m calibration module was constructed and exposed to particle beams of known momenta at CERN in order to measure its response to both leptons and hadrons. Actual calibration during operation is performed using cosmic-ray muons and a dedicated LED system[2]. A minimum ionizing particle passing perpendicular through the center of an 8-m long strip produces 9 photoelectrons in the summed signal from the opposite ends of the strip. The timing resolution is 2.4 ns per hit along a muon track, so that the direction of a track can be determined even for very short tracks.

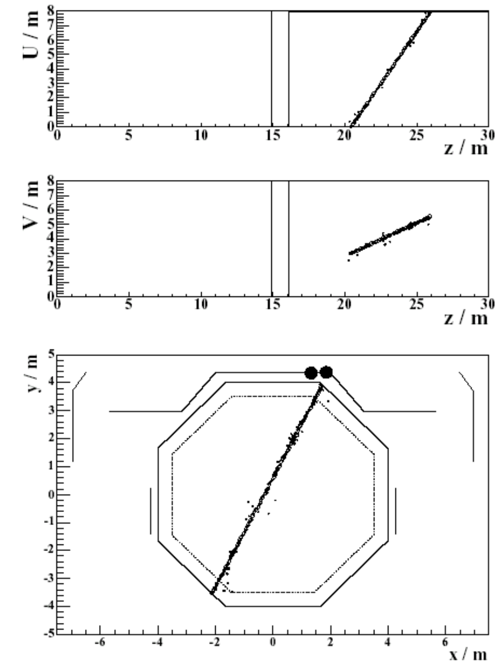

Figure 1. Cosmic ray muon. Upper two views are orthogonal u- and v-; lower is reconstructed x-y. Lines outside octagon indicate active shield placement with associated hits shown as large dark points.

2. Event Selection

The rate of ν_μ interactions in the detector is ~10^{-6} that of the cosmic-ray muons, which is 0.6 Hz. The selection procedure for identifying the contained neutrino events was optimized using a GEANT 3 simulation of the MINOS detector. For the simulation of atmospheric neutrino events, the 3D flux calculation of Barr et al[3] was used and the NEUGEN 3 program[4] was used to simulate the neutrino interactions. Hadronic interactions were modeled with the GCALOR[5] package, which gives good agreement with the low energy hadronic interactions measured in the calibration detector measurements[6].

Each plane of scintillator strips gives a 2D view of an event and these are matched to provide a 3D view of the full event. Figure 1 shows an example of a muon passing through the detector, along with the arrangement of the active shield.

Charged current ν_μ are reconstructed as muon tracks and an associated hadronic shower; the muon is required to pass through at least 8 planes of the detector, which sets an energy threshold of 0.4 GeV. The muon momentum is determined either by range, if it stops in the detector, or by bending in the magnetic field, if it leaves the detector. The momentum resolution for selected events is typically 12 to 20%, depending on the momentum. The hadronic energy resolution is $\sigma_E/E \sim 0.55\sqrt{E(\mathrm{GeV})}$.

Muon direction is determined from the timing of hits in the scintillator strips, while track curvature allows the charge to be determined. Obviously, the determination of charge depends on both track length and momentum. Figure 2 shows the distribution of charge divided by momentum Q/p divided by its error for cosmic ray muons that stop in the detector. These have momenta similar to those in the selected ν_μ sample, from ~0.8 to 10 GeV. For this momentum range, the charge is cleanly determined. This figure also illustrates the excellent agreement between actual data and the simulations.

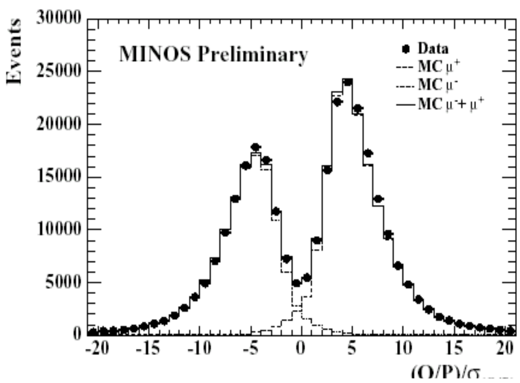

Figure 2. Reconstructed (Q/p) divided by its error.

Events are required to have a track beginning inside the fiducial volume of the detector, at least 50 cm from an outer edge and at least 5 planes from the end of either supermodule. An event is further classified either as fully contained (FC), if the track end also lies within the fiducial volume, or partially contained (PC). FC events are required to have hits in at least 8 planes and PC events are required to have a track at least 1 m long, to ensure that their direction is well determined. At this stage, the background consists of very steep cosmic ray tracks that have traveled some distance into the detector before hitting a scintillator plane, or which have been poorly reconstructed because they travel approximately parallel to the planes. These are efficiently removed by appropriate cuts along with the requirement that there be no associated veto-shield hits.

3. Preliminary Results

From the first 408 days exposure, 107 events have been selected. This is consistent with the 129±13 expected assuming no neutrino oscillations, and also with the 97±9 events assuming a nominal $\Delta m_{23}^2 = .0025 eV^2$ and $\sin^2 2\theta_{23} = 1.0$. The estimated background from cosmic ray muons in these data is 4.3±0.5. The predicted rates depend on both the cosmic ray muon flux and neutrino production and interaction rates, which have significant (~10 to 20%) uncertainties. Rather than incorporate these uncertainties, we have chosen to minimize the uncertainty in the predicted neutrino rate by normalizing our data to the rate measured in the Soudan 2 detector, which was situated at the same depth, in the same mine.

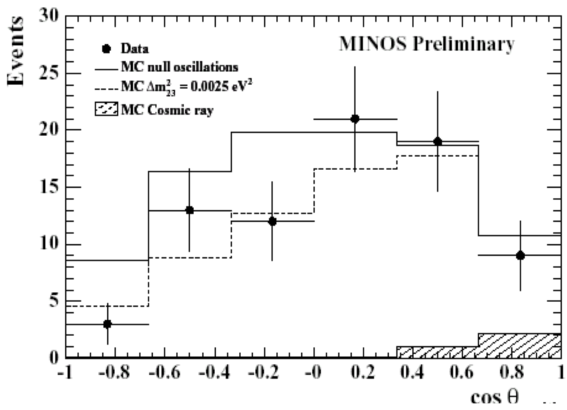

Figure 3. Reconstructed zenith angle distribution compared to Monte Carlo expectation for no oscillations and for oscillation with some nominal parameters. The shaded area is the expected cosmic ray background.

The direction, either upward or downward, of 30 of these selected events cannot be absolutely determined. These are mainly very short, low energy events and can be removed by a slightly more stringent cut. Of the remainder, 49 events are downward-going and 28 are upward-going; their zenith angle distribution is shown in Figure 3 along with expectations from the nominal oscillation parameters indicated above. The up-down ratio expected from Monte Carlo simulation is 0.92±0.03(sys.) in the absence of neutrino oscillations. The ratio of data to Monte Carlo simulation is then

$$R_{U/D}^{data} / R_{U/D}^{MC} = 0.62 \pm 0.14(\text{stat.}) \pm 0.02(\text{sys.})$$

which is 2.6 standard deviations from the expectation of no neutrino oscillations. While the data are not yet sufficient to make a significant contribution to our knowledge of atmospheric neutrino oscillations, they are sufficient to exclude the non-oscillation hypothesis at the 98% confidence level.

For the 77 events with well-determined direction, 52 events have tracks with $|Q/p| > 2\sigma_{(Q/p)}$, i.e., with well-determined charge. Of these, 34 are negative and 18 are positively charged, corresponding to a ratio

$$N^+/(N^+ + N^-) = 0.35 \pm 0.06(\text{stat.}) \pm 0.02(\text{sys.})$$

which is consistent with a wide range of oscillation parameters. Possible CPT violation scenarios can be investigated by comparing neutrino and antineutrino oscillation parameters; with 5 years of data, it will be possible to rule out certain models with significantly different Δm_{23}^2.

4. Conclusions

The first data on atmospheric ν_μ charged current interactions in the MINOS Far Detector have been presented. Preliminary analyses exclude non-oscillation at the 98% confidence level. For the first time, it has been possible to cleanly separate atmospheric ν_μ and anti-ν_μ interactions.

5. Acknowledgements

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