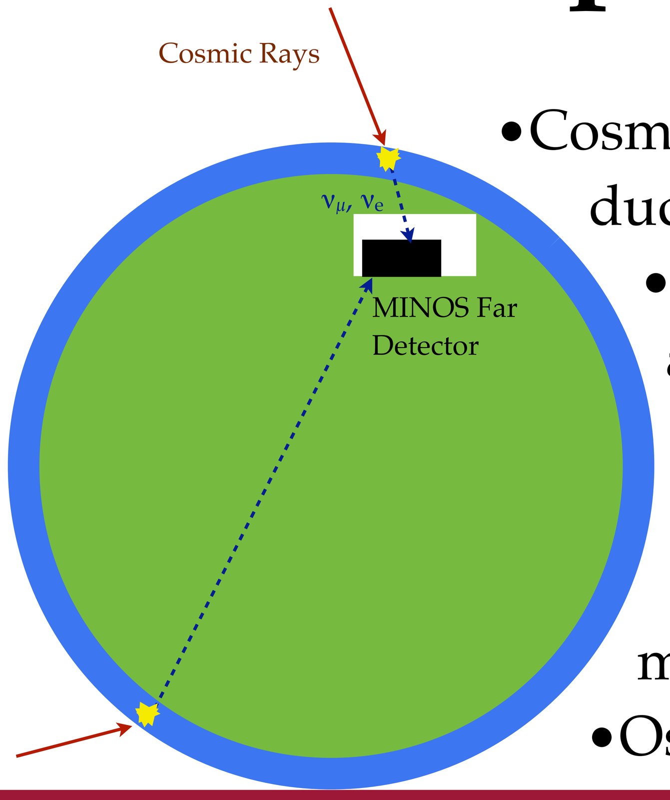
Measurements of Atmospheric Neutrinos Using the MINOS Detector

L. A. Corwin (Indiana University) for the MINOS Collaboration

Atmospheric Neutrinos



- Cosmic rays impinging on the atmosphere produce cascades of particles, including neutrinos
- Oscillation of ν_μ to other flavors appears as a ν_μ deficit for certain values of path length (L) and ν energy (E).
- L varies from ~10 to ~13000 km
- MINOS measures L/E across 4 orders of magnitude
- Oscillations in ν_μ and $\overline{\nu}_\mu$ are detected

MINOS Far Detector

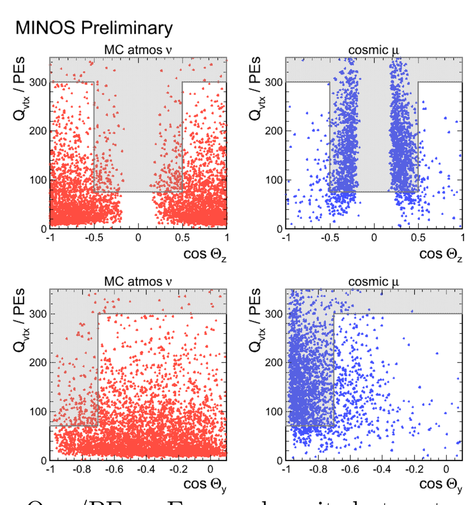
The detector is composed of 2.54 cm steel plates (total of 5.4 kton) interleaved with plastic scintillator. Its depth (700 m) provides shielding from cosmic rays. A 1.3 T magnetic field produced by a coil along the long axis allows separation of μ^+ from μ^- and thus ν_μ from $\overline{\nu}_\mu$, which is unique among underground ν detectors.

Event Selection

Data Pre-Selection

Between 1 Aug. 2003 and 1 Aug. 2008, 1657 live days (24.6 kton-Yrs) of data were collected. We select events that have clean showers (ν_e and neutral current interactions) and tracks (ν_μ charged current interactions). Our primary background source is cosmic ray events. The signatures for atmospheric ν are fully contained (FC), partially contained (PC), or upward-going events.

Two Event Categories

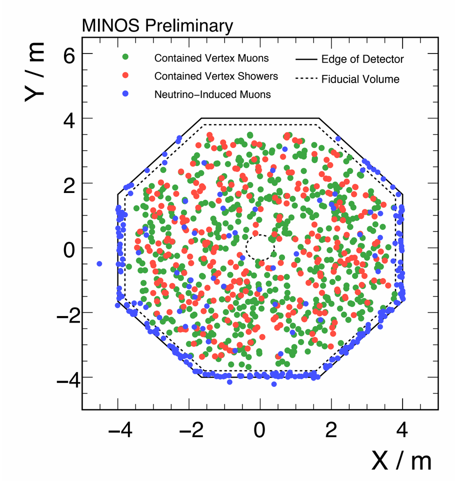


Q_{vtx}/PEs = Energy deposited at vertex
$\cos\Theta_i$ = i component of the downward direction of the track

- Upward-going tracks from interactions in the detector or rock are identified using timing data.
- FC and PC events within the detector fiducial volume are identified using containment and topology cuts applied to the top of the event and a scintillator shield to veto cosmic ray events.

Events Selected for Analysis

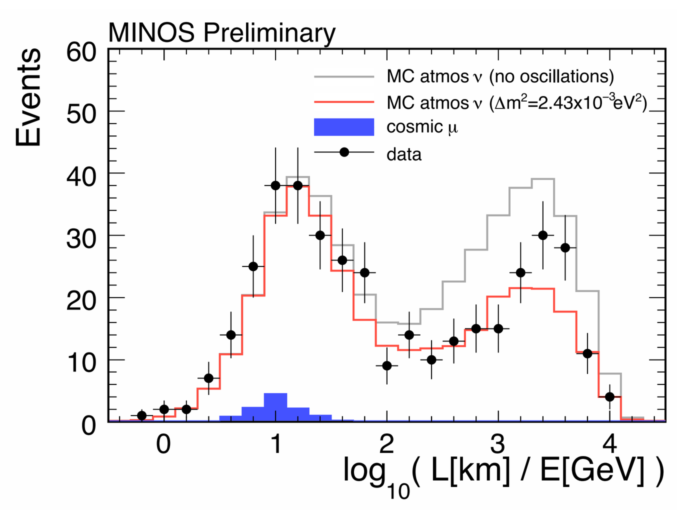
We divide data events into 3 samples:

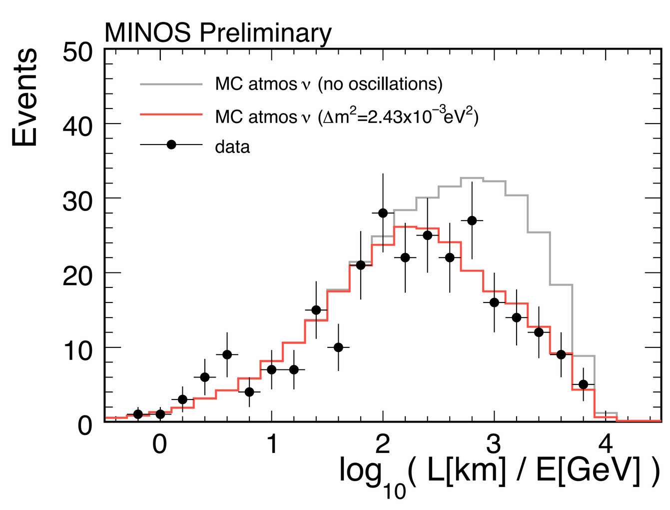


- FC or PC μ events: 572 events
- Contained Vertex Showers: 292 events
- ν Induced Rock μ: 264 events

Reconstructed vertex positions are shown above.

Oscillation Results





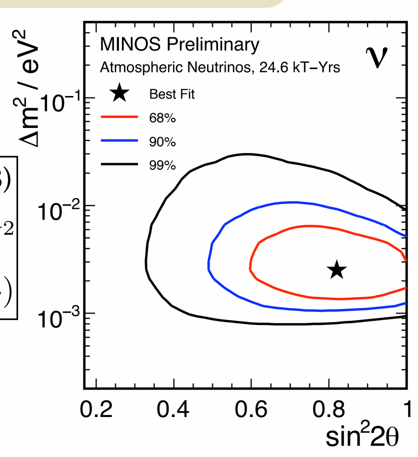
We divide the data into bins of bins of L/E resolution with 5 bins for FCPC events, 2 bins for rock μ events, and one bin for contained vertex showers. In the limit of two flavor oscillations ($\nu_\mu \leftrightarrow \nu_\tau$), we perform a maximum likelihood fit to the reconstructed L/E distributions to obtain oscillation parameters. For our ν sample, we fix the $\overline{\nu}$ parameters to the the MINOS ν best fit oscillation parameters from 2008. Then, we perform the opposite analysis for our $\overline{\nu}$ sample. Systematic uncertainties are fitted as nuisance parameters. The results of the fit are shown in the contours and values below. Limits and uncertainties are at the 90% confidence level.

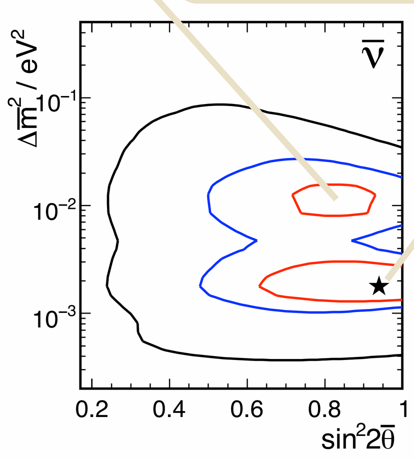
$$7 \times 10^{-3} < \frac{|\Delta \overline{m}^2_{32}|}{\mathrm{eV}^2} < 17 \times 10^{-3}$$

$$|\Delta m^2_{32}| = 2.6^{+4.4}_{-1.3} \times 10^{-3}\ \mathrm{eV}^2$$

$$|\Delta \overline{m}^2_{32}| = 1.8^{+1.5}_{-0.6} \times 10^{-3}\ \mathrm{eV}^2$$

MINOS oscillation parameters (2008)
$|\Delta m^2_{32}| = (2.43 \pm 0.13) \times 10^{-3}\mathrm{GeV}^2$
$\sin^2(2\theta_{23}) = 1.0 (> 0.9\ @\ 90\%CL)$

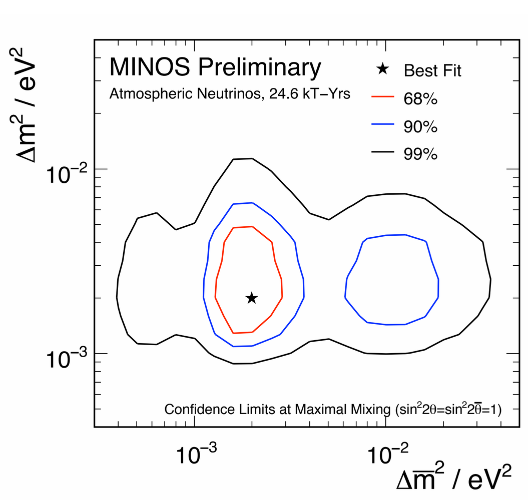




$$\sin^2(2\theta_{23}) > 0.58$$

$$\sin^2(2\overline{\theta}_{23}) > 0.60$$

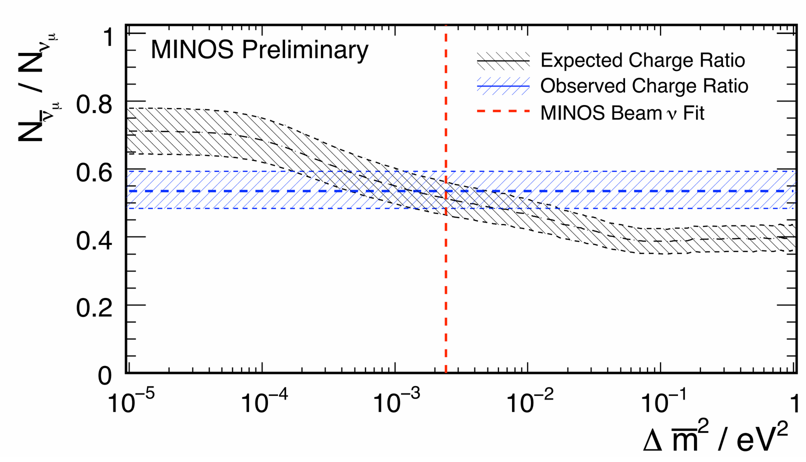
To test the consistency of the ν and $\overline{\nu}$ mass differences, we perform our fit with the mixing angles fixed to maximal mixing and the mass differences allowed to vary. The results are consistent within uncertainties, as shown at left and below.



$$|\Delta m^2_{32}| - |\Delta \overline{m}^2_{32}| = 0.4^{+2.5}_{-1.2} \times 10^{-3}\ \mathrm{eV}^2$$

$$(\text{for}\ \sin^2(2\overline{\theta}_{23}) = \sin^2(2\theta_{23}) = 1.0)$$

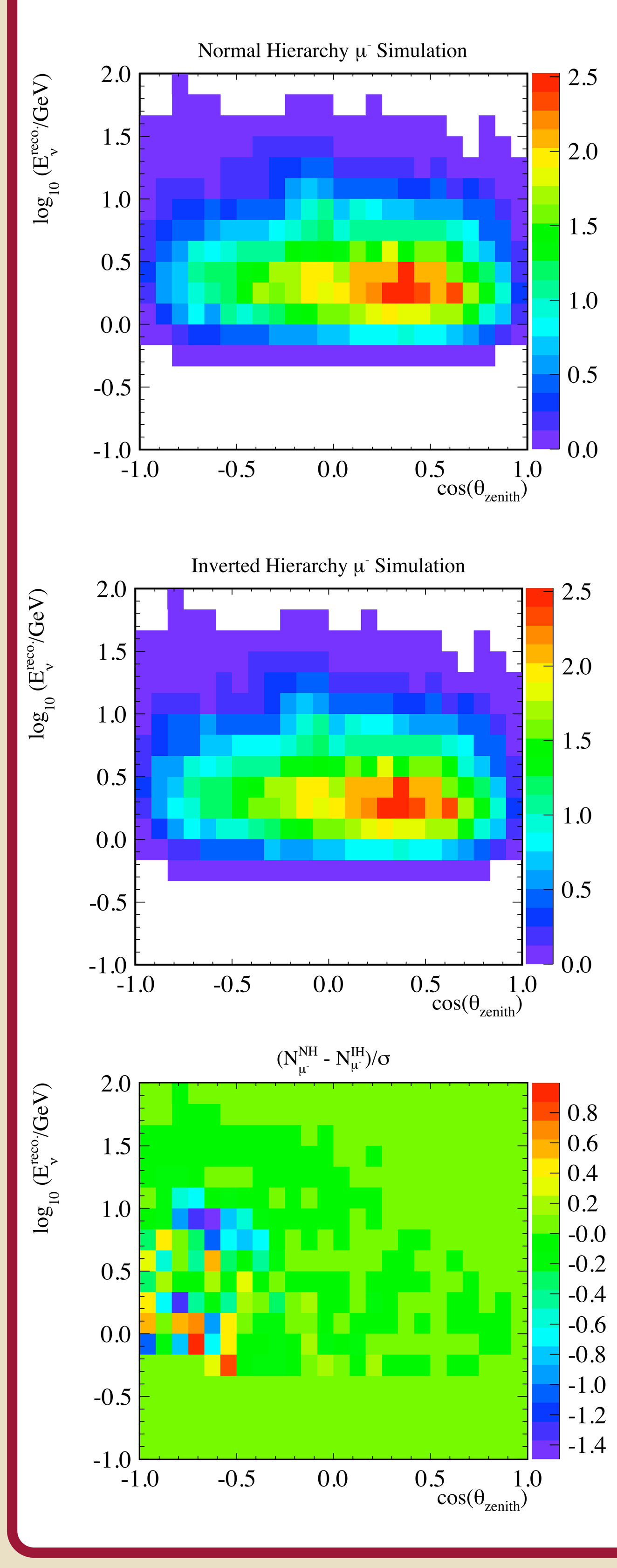
Charge Ratio Results



We use a high resolution subset of data with clean tracks and well-measured charge to calculate ratio of ν_μ to $\overline{\nu}_\mu$ events. We compare this ratio for data and MC (using the 2008 MINOS oscillation parameters) to check the consistency of ν_μ to $\overline{\nu}_\mu$ oscillations. The resulting double ratio is consistent with unity and thus with equal oscillations for ν_μ and $\overline{\nu}_\mu$.

$$\frac{R^{\mathrm{data}}_{\nu/\overline{\nu}}}{R^{\mathrm{MC}}_{\nu/\overline{\nu}}} = 1.04^{+0.11}_{-0.10} \pm 0.10$$

Future: Mass Hierarchy



The ability of MINOS to distinguish between ν and $\overline{\nu}$ allows us to search for the mass hierarchy. The number of μ^+ and μ^-, for certain values of energy and angle, depends on the mass hierarchy. The plots at left show the the events rates for μ^- calculated from simulations for MINOS for the normal (top) and inverted (middle) hierarchies. Plotted at bottom is the difference between the two rates, divided by their uncertainty.

We are currently determining how to use statistical tests (such as χ^2 or Kolmogorov – Smirnov) to compare the atmospheric data with simulations for the two hierarchies and calculate which hierarchy is more consistent with our data.

We plan to include the additional data taken since 1 Aug. 2008 in this search.