Combined Measurement of the Beam and Atmospheric ν and $\bar{\nu}$ Oscillation Parameters from the MINOS Experiment

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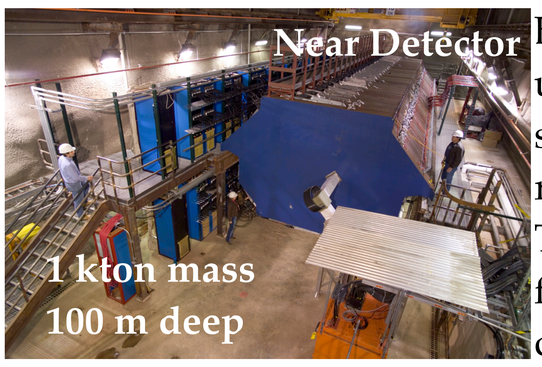
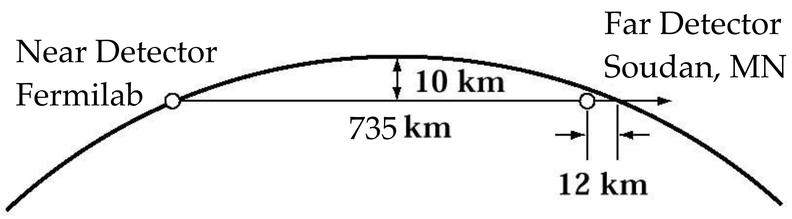
Detectors

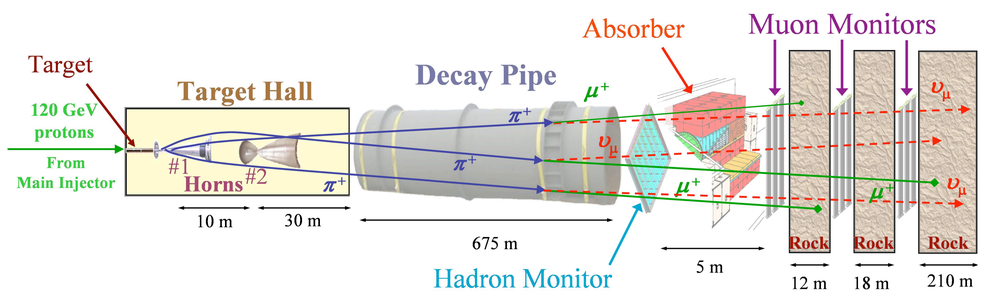


Both detectors are underground iron scintillation calorimeters with 1.3 T magnetic fields for charge discrimination.



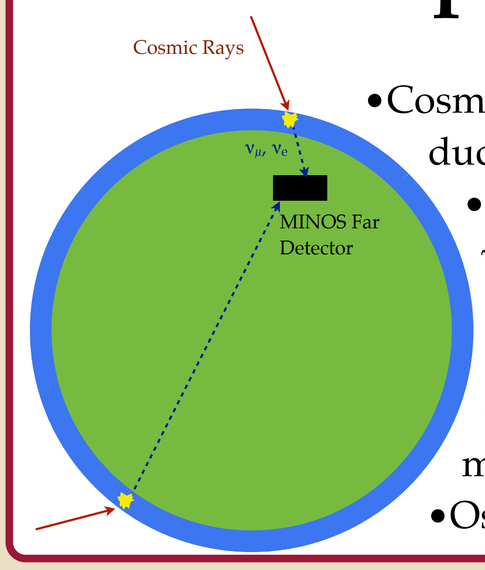
The far detector is larger and deeper but otherwise functionally identical.

Beam Neutrinos



A beam of 120 GeV protons is impinged on a graphite target. The resulting hadron beam is columnated by two magnetic horns that can operate in two polarities to produce a ν_μ-dominated or $\bar{\nu}_\mu$-enriched beam. The hadrons decay in a decay pipe. A steel absorber and rock upstream of the near detector cavern allow only neutrinos to reach the detectors.

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 $\bar{\nu}_\mu$ are detected

Beam Data

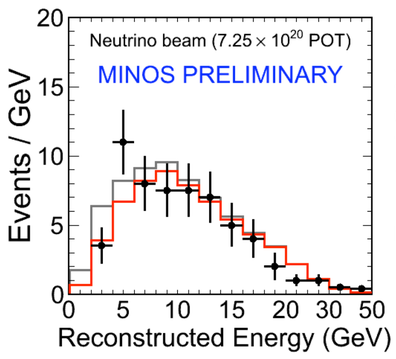
We use three sets of Beam Data.

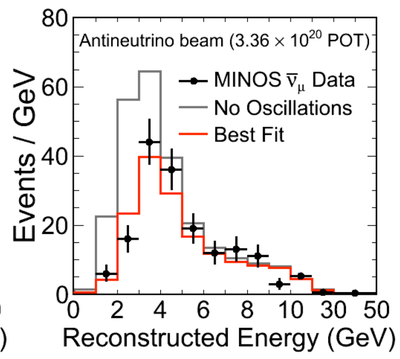
1. ν_μ from ν_μ-dominated beam: 10.71×10^{20} protons on target (POT)
2. $\bar{\nu}_\mu$ from $\bar{\nu}_\mu$-enriched beam: 3.36×10^{20} POT
3. $\bar{\nu}_\mu$ from ν_μ-dominated beam: 10.71×10^{20} POT

This analysis uses the same data quality cuts as the stand-alone analysis data set #1. We replicate the analysis procedure as closely as possible.

Atmospheric Data

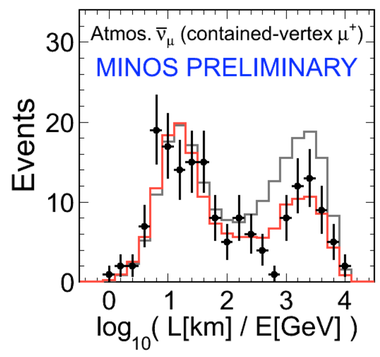
We have a data sample of 37.9 kton-years exposure of the far detector to atmospheric neutrinos. We use the same event selection as the stand-alone atmospheric oscillation analysis. The selected events are binned by reconstructed L/E and also separated into bins of resolution. The atmospheric and beam neutrino data are combined into a common analysis framework.

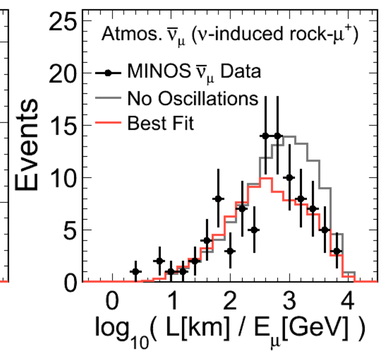




Combination Procedure

Each beam analysis and the atmospheric analysis is ported into the global fitting framework with the aim of replicating each analysis as closely as possible. We perform several cross-checks, including verifying that the results from the global fit reproduce the results from the stand alone analyses.





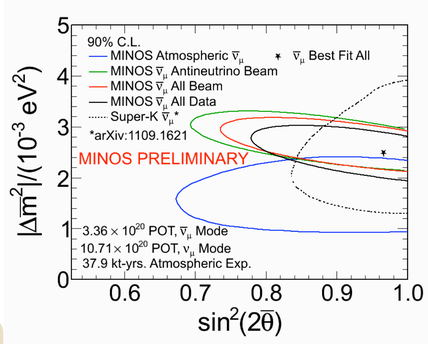
Our analyses use the approximation of two flavor oscillations ($\nu_\mu \leftrightarrow \nu_\tau$). Example energy fits are shown at left and right. In light of the recent measurements of θ_{13}, we are in the process of implementing the full three flavor for for these analysis. We incorporate all significant systematic uncertainties from the individual analyses into the combined analysis. We perform a 4-parameter fit in which we let the neutrino and anti-neutrino oscillation parameters can have different values and a 2-parameter fit in which we for neutrino and anti-neutrino parameters to be equal.

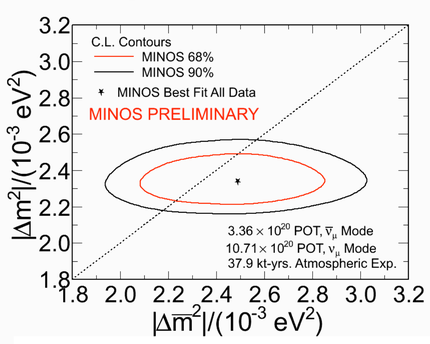
Results

$$\sin^2(2\bar{\theta}) = 0.97^{+0.03}_{-0.08} \ (> 0.83 \text{ at } 90\% \text{ C.L.})$$

$$|\Delta\bar{m}^2| = (2.49^{+0.23}_{-0.28}) \times 10^{-3}\text{eV}^2$$

From the **4-parameter** fit, we compare several data sets and the Super-K result with our full **antineutrino** oscillation parameter best fit points and contours.





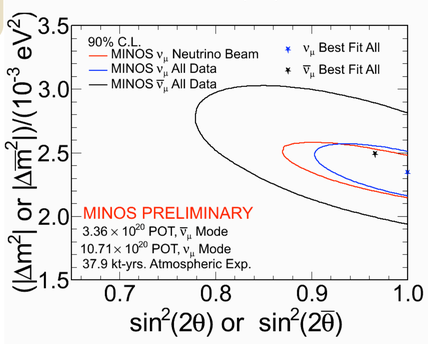
$$|\Delta\bar{m}^2| - |\Delta m^2| = (1.5^{+2.4}_{-2.9}) \times 10^{-4}\text{eV}^2$$

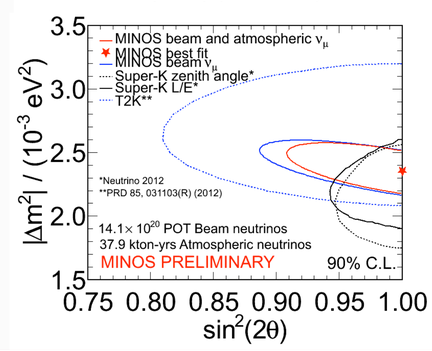
From the **4-parameter** fit, calculate the difference between our neutrino and anti-neutrino mass splitting.

$$\sin^2(2\theta) = 1.000^{+0.000}_{-0.038} \ (> 0.930 \text{ at } 90\% \text{ C.L.})$$

$$|\Delta m^2| = (2.34^{+0.09}_{-0.08}) \times 10^{-3}\text{eV}^2$$

From the **4-parameter** fit, we compare our full and beam-only antineutrino contour with our full **neutrino** oscillation parameter best fit point and contour.





$$\sin^2(2\theta) = 1.000^{+0.000}_{-0.038} \ (> 0.930 \text{ at } 90\% \text{ C.L.})$$

$$|\Delta m^2| = (2.35^{+0.10}_{-0.08}) \times 10^{-3}\text{eV}^2$$

From the **2-parameter** fit, we compare our full and beam-only oscillation parameter fit and contours with other experimental results.