Neutrino Oscillation Results from MINOS

Alexander Himmel
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IPMU Mini-workshop on Neutrinos, November 8th 2010
Introduction

- What is MINOS?
- Neutrino Physics
  - Oscillation Basics
  - MINOS Physics Goals
- The Experiment
  - NuMI neutrino beam
  - MINOS detectors
- The Analyses
  - Atmospheric-sector oscillations
  - Sterile Neutrinos
  - Electron Neutrino Appearance

The MINOS Collaboration

140 scientists
31 institutions

Argonne • Athens • Benedictine • Brookhaven • Caltech • Cambridge • Campinas • Fermilab • Harvard • Holy Cross • IIT Indiana • Iowa State • Lebedev • Livermore Minnesota-Twin Cities • Minnesota-Duluth • Otterbein • Oxford Pittsburgh • Rutherford • Sao Paulo • South Carolina Stanford • Sussex • Texas A&M • Texas-Austin • Tufts • UCL Warsaw • William & Mary

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What is MINOS?

- Three components:
  - **NuMI** high-intensity neutrino beam
  - **Near Detector** at Fermilab measures the initial beam composition and spectrum
  - **Far Detector** in Soudan, MN measures the oscillated spectrum

- Detectors are magnetized – unique among oscillation experiments
Neutrino Physics

- Oscillation basics
- MINOS Physics Goals
Neutrino Oscillations

• **Interact** in weak eigenstates \((e, \mu, \tau)\)
• **Propagate** in mass eigenstates \((1, 2, 3)\)
• Because the neutrinos have different masses, as they propagate they pick up **relative phases**, changing their relative amplitudes
• End up with a different weak eigenstates than we started with

\[\nu_\mu = \nu_1 \quad \quad \nu_\mu = \nu_1 \quad \quad \nu_\tau\]

Fermilab

\[10 \text{ km}\]

735 km

Soudan

\[12 \text{ km}\]
Neutrino Masses and Mixing

• Analogous to the quarks, neutrino mixing is parameterized with 3 angles and 1 complex phase

• With three active neutrinos there are two independent mass differences:
  - \( \Delta m^2_{\text{sol}} \approx \Delta m^2_{21} \approx 8.0 \times 10^{-5} \text{ eV}^2 \)
  - \( \Delta m^2_{\text{atm}} \approx \Delta m^2_{32} \approx 2.4 \times 10^{-3} \text{ eV}^2 \)

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1. Select a sample of events in the detectors
   – Which events you select defines the physics you probe
A MINOS Oscillation Analysis

1. Select a sample of events in the detectors
2. Measure the energy of those events to construct Near and Far detector spectra
A MINOS Oscillation Analysis

1. Select a sample of events in the detectors
2. Measure the energy of those events to construct Near and Far detector spectra
3. Use the Near Detector to predict the Far Detector independent of oscillations
1. Select a sample of events in the detectors

2. Measure the energy of those events to construct Near and Far detector spectra

3. Use the Near Detector to predict the Far Detector independent of oscillations

4. Compare the unoscillated prediction to the Data

\[
P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta_{23}) \sin^2 \left(1.27 \frac{\Delta m^2_{\text{atm}} L}{E} \right)
\]
A MINOS Oscillation Analysis

1. Select a sample of events in the detectors
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A MINOS Oscillation Analysis

1. Select a sample of events in the detectors
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\[ P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta_{23}) \sin^2\left(1.27 \Delta m^2_{\text{atm}} \frac{L}{E}\right) \]
MINOS Physics Goals

- Measure $\nu_\mu$ disappearance
  - Use charged currents so we can know the flavor
  - $\Delta m^2_{atm}$ and $\sin^2(2\theta_{23})$
  - Test oscillations against alternatives like decay and decoherence

- MINOS has the world’s best sensitivity to the mass splitting
MINOS Physics Goals

- Measure $\bar{\nu}_\mu$ disappearance
  - $\Delta m^2_{\text{atm}}$ and $\sin^2(2\bar{\theta}_{23})$

- Compare with $\nu_\mu$'s

- Differences from neutrinos may imply new physics in the neutrino sector

\[ \Delta m^2_{\text{atm}} \]
\[ \Delta m^2_{\text{sol}} \]
MINOS Physics Goals

- Search for $\nu_x$ disappearance
  - Neutral currents measure the combined rate of active species
  - A deficit would imply mixing with a light sterile neutrino species

$\nu_3$

$\Delta m^2_{\text{atm}}$

$\Delta m^2_{\text{sol}}$

$\nu_2$

$\nu_1$

$\nu_4$

$\nu_e$ $\nu_\mu$ $\nu_\tau$ $\nu_s$
MINOS Physics Goals

- Search for $\nu_e$ appearance
  - Measure $\theta_{13}$

- Measuring $\theta_{13}$ is the goal of the next generation of oscillation experiments
  - Measuring $\theta_{13}$ is a prerequisite for measuring CP-violation and the sign of $\Delta m^2_{\text{atm}}$
• More physics I won’t have time to discuss:
  – Atmospheric neutrinos
  – Neutrino cross-sections
  – Lorentz invariance
  – Cosmic ray physics
The Experiment

- NuMI neutrino beam
- MINOS detectors
The NuMI Beam

- 120 GeV protons incident on a thick, segmented graphite target
- Magnetic horns can focus either sign
- Enhance the $\nu_\mu$ flux by focusing $\pi^+$, $K^+$
- Adjustable peak energy
Neutrino Mode

Monte Carlo Neutrino mode
Horns focus $\pi^+$, $K^+$

$\nu_\mu = 91.7\%$
$\bar{\nu}_\mu = 7.0\%$
$\nu_e + \bar{\nu}_e = 1.3\%$

Target
Focusing Horns
Decay Pipe

120 GeV protons from MI
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$15\,\text{m}$
$30\,\text{m}$
$675\,\text{m}$
Antineutrino Mode

Monte Carlo Neutrino mode
Horns focus $\pi^+, K^+$
- $\nu_\mu = 91.7\%$
- $\bar{\nu}_\mu = 7.0\%$
- $\nu_e + \bar{\nu}_e = 1.3\%$

Monte Carlo Antineutrino mode
Horns focus $\pi^-, K^-$
- $\bar{\nu}_\mu = 39.9\%$
- $\nu_\mu = 58.1\%$
- $\nu_e + \bar{\nu}_e = 2.0\%$

Target
Focusing Horns
Decay Pipe
120 GeV protons from MI

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Antineutrino Cross-section

- x1.3 lower $\pi^-$ production
- x2.3 lower interaction cross-section

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NuMI Beam Performance

Run I
Run II
Run III
Run IV

High Energy

Previous Analyses

3.21 \times 10^{20} \text{ POT } \nu_\mu \text{ mode}

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NuMI Beam Performance

Total NuMI protons to 00:00 Monday 31 May 2010

Run I
Run II
Run III
Run IV

High Energy
Antineutrinos

7.24 \times 10^{20} \text{ POT } \nu_\mu \text{ mode }

1.71 \times 10^{20} \text{ POT } \bar{\nu}_\mu \text{ mode }

Current \nu_\mu \text{ Analysis }

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MINOS Detectors

1 in thick Steel

1 cm thick, 4.1 cm wide Plastic Scintillator

Read out on wavelength-shifting fibre to multi-anode PMTs

1.3 T toroidal magnetic field can distinguish neutrinos and antineutrinos

Strips in alternating directions allow 3D event reconstruction

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MINOS Detectors

Near Detector
- 980 tons
- 100 m depth
- 1 km from the target

Far Detector
- 5,400 tons
- 700 m in depth
- 735 km from the target
MINOS Events

**νμ CC Event**

\[ ν_μ \text{ (incoming)} \rightarrow W \rightarrow μ^- + \text{Hadrons} \]

**ν̄μ CC Event**

\[ \bar{ν}_μ \text{ (incoming)} \rightarrow W \rightarrow μ^+ + \text{Hadrons} \]

**NC Event**

\[ ν \text{ (incoming)} \rightarrow Z \rightarrow ν + \text{Hadrons} \]

Simulated Events

- Deposited charge
  - Deposited < 2.0 pe
  - Deposited > 2.0 pe
  - Deposited > 20.0 pe
Muon Antineutrinos

Measure $\Delta \tilde{m}^2_{\text{atm}}, \sin^2(2\dot{\theta}_{23})$
Why study $\nu_\mu$ and $\bar{\nu}_\mu$?

$$P(\nu_\mu \rightarrow \nu_\mu) = P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu)$$

- Antineutrino parameters are less precisely known.
  - No direct precision measurements
  - MINOS is the only oscillation experiment that can do event-by-event separation

- Differences may imply new physics in the neutrino sector manifested as a difference in the effective mass-splitting.

Selecting CC Antineutrinos

Step 1

- Preselection
  - In-time with the spill
  - In the fiducial volume
  - At least 1 reconstructed track

- Accept only positive reconstructed charge
  - Kalman filter measures q/p (~curvature) for each track
  - Eliminates the majority of the $\nu_\mu$ component of the beam
Selecting CC Antineutrinos

- CC/NC separation
  - kNN algorithm
    - Compare to Monte Carlo events

- 4-parameter comparison
  - Track length
  - Energy deposited per strip
  - Energy fluctuations along the track
  - Transverse energy profile
Selecting CC Antineutrinos

- CC/NC separation
  - kNN algorithm
    - Compare to Monte Carlo events

- 4-parameter comparison
  - Track length
  - Energy deposited per strip
  - Energy fluctuations along the track
  - Transverse energy profile

k-Nearest Neighbors “kNN”
Selecting CC Antineutrinos

- CC/NC separation
  - kNN algorithm
  - Compare to Monte Carlo events

- 4-parameter comparison
  - Track length
  - Energy deposited per strip
  - Energy fluctuations along the track
  - Transverse energy profile
Selecting CC Antineutrinos

- CC/NC separation
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- 4-parameter comparison
  - Track length
  - Energy deposited per strip
  - Energy fluctuations along the track
  - Transverse energy profile
Selecting CC Antineutrinos

- Cut applied to the output of the kNN algorithm
  - Output is the fraction of $k$ neighbors that are signal

- Started below 50% signal

- After selection:
  - Purity: 95%
  - Efficiency: 93%

<table>
<thead>
<tr>
<th>Unosc.</th>
<th>Signal</th>
<th>Bkgd.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-6 GeV</td>
<td>106</td>
<td>1.9</td>
</tr>
<tr>
<td>6-20 GeV</td>
<td>38</td>
<td>4.3</td>
</tr>
<tr>
<td>&gt; 20 GeV</td>
<td>8</td>
<td>3.0</td>
</tr>
</tbody>
</table>

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Flux and cross-section uncertainties cancel when extrapolated from Near to Far detector.
Near-to-Far Extrapolation


Step 3

\[ E_\nu \approx \frac{0.43 E_{\pi}}{1 + \gamma_{\pi}^2 \theta_\nu^2} \]

- The Near Detector and Far Detector spectra are not identical.
  - Due to $\pi/K$ decay kinematics, neutrino energy varies with angle.
  - Near Detector covers a wider solid angle
  - Effect is larger with higher energy $\pi$
    - Travel further and decay closer to the ND

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A beam matrix transports measured Near Det. spectrum to the Far Det.

Matrix encapsulates knowledge of meson decay kinematics and beamline geometry

MC used to correct for energy smearing and acceptance
Antineutrino Systematics

- Effect of uncertainties estimated by fitting systematically shifted MC
- The analysis is statistically limited.
Blind Analysis

• These results are obtained from blind analyses
  – Finalized before looking at the full Far Detector data
    • selection cuts
    • data samples
    • extrapolation techniques
    • fitting routines
    • systematic uncertainties

• No changes have been made after box opening

And so…on to the results!
155 expected without oscillations
97 observed events

Step 4
1.71 \times 10^{20} \text{ POT MINOS } \bar{\nu}_\mu \text{ running, Far Detector}

- **MINOS data**
- **No oscillations**
- **Best oscillation fit**
- **Background**

**FD Events/GeV**

**Reco. Energy (GeV)**

**Ratio to No Oscillations**

**Reco. Energy (GeV)**

**Step 4**

- 155 expected without oscillations
- 97 observed events

No-oscillations hypothesis is disfavored at 6.3\sigma
Antineutrino Contour

\[ |\Delta m^2_{\text{atm}}| = 3.36^{+0.45}_{-0.40} \times 10^{-3} \text{ eV}^2 \]
\[ \sin^2(2\theta_{23}) = 0.86 \pm 0.11 \]

- Oscillation probabilities are non-linear and there are physical boundaries
  - Simple Gaussian confidence intervals don’t work
  - Use the Feldman-Cousins technique to get correct contours and incorporate systematics
- Dot-dash line is a fit to all non-MINOS data

M.C. Gonzalez-Garcia and M. Maltoni Phys. Rept. 460, 2008

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\[ |\Delta m_{\text{atm}}^2| = 3.36^{+0.45}_{-0.40} \times 10^{-3} \text{ eV}^2 \]
\[ \sin^2(2\bar{\theta}_{23}) = 0.86 \pm 0.11 \]

- Green contours are from SuperK at Neutrino2010

- Note that SuperK cannot separate neutrinos and antineutrinos event-by-event
• More data has the potential to rapidly improve the contours
  – Doubling the data set reduces uncertainty on $\Delta m^2$ by 30%

• NuMI approved for another $2 \times 10^{20}$ POT of antineutrino running
  – Beginning ~now
Muon Neutrinos

Measure $\Delta m^2_{\text{atm}}$, $\sin^2(2\theta_{23})$
Distinguish oscillations from decay and decoherence
The Neutrino Analysis

Since our previous measurement...


- Additional data
  - $3.4 \times 10^{20}$ to $7.2 \times 10^{20}$ protons-on-target

- Analysis Improvements

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Analysis Improvements

• Updated simulation and reconstruction

• New selection improves low-energy efficiency

• New shower energy estimator
  – 30% better low-energy resolution

• No charge sign cut
  – Reclaim mis-identified neutrino events at low energy

• Split data set into resolution bins
  – Increased statistical power
Analysis Improvements

- Updated simulation and reconstruction
- **New selection improves low-energy efficiency**
- New shower energy estimator
  - 30% better low-energy resolution
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Analysis Improvements

- Updated simulation and reconstruction
- New selection improves low-energy efficiency
  - New shower energy estimator
    - 30% better low-energy resolution
- No charge sign cut
  - Reclaim mis-identified neutrino events at low energy
- Split data set into resolution bins
  - Increased statistical power

~30% better resolution below 2 GeV
Analysis Improvements

- Updated simulation and reconstruction
- New selection improves low-energy efficiency
- New shower energy estimator
  - 30% better low-energy resolution
- No charge sign cut
  - Reclaim mis-identified neutrino events at low energy
- Split data set into resolution bins
  - Increased statistical power

Positives are 30% neutrinos
Analysis Improvements
Selecting CC Neutrinos

- The selection is a logical OR between:
  - The CC/NC selector also used for antineutrinos
  - The new selector optimized for low-energy tracks

Step 1

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Neutrino Near Detector Data

- Majority of data taken in Low Energy Beam
- High Energy Beam gives us more events above the oscillation dip

Step 2
Beam Matrix Extrapolation

Step 3

- The muon neutrino analysis also uses the beam matrix extrapolation
Neutrino Systematics

- Systematics similar between neutrinos and antineutrinos
- Analysis is still statistically limited
- The 4 largest systematics are included as penalty terms in the fit.
Far Detector Neutrino Data

→ 2,451 expected without oscillations

→ 1,986 observed events
2,451 expected without oscillations

1,986 observed events

Oscillations fit the data well – 66% of fake experiments have a worse $\chi^2$
Far Detector Neutrino Data

- Can see the characteristic dip of oscillations.
- Disfavor in a statistics-only fit:
  - Pure decay† at > 6σ
  - Pure decoherence‡ at > 8σ

†V. Barger et al., PRL 82:2640 (1999)
$|\Delta m^2_{\text{atm}}| = 2.35^{+0.11}_{-0.08} \times 10^{-3} \text{ eV}^2$

$\sin^2(2\theta_{23}) = 1$

$\sin^2(2\theta_{23}) > 0.91 \text{ (90\% C.L.)}$
Neutrino Contour

MINOS Preliminary

$|\Delta m^2_{\text{atm}}| = 2.35^{+0.11}_{-0.08} \times 10^{-3} \text{ eV}^2$

$\sin^2(2\theta_{23}) = 1$

$\sin^2(2\theta_{23}) > 0.91 \text{ (90\% C.L.)}$
Neutrinos and Antineutrinos

$|\Delta m_{\text{atm}}^2| = 2.35^{+0.11}_{-0.08} \times 10^{-3} \text{ eV}^2$

$\sin^2(2\theta_{23}) > 0.91$ (90% C.L.)

$|\Delta m_{atm}^2| = 3.36^{+0.45}_{-0.40} \times 10^{-3} \text{ eV}^2$

$\sin^2(2\bar{\theta}_{23}) = 0.86 \pm 0.11$
Neutral Currents

Sterile Neutrino Search
Sterile Neutrinos

- Measurements of the $Z^0$ width at LEP limit the number of active neutrinos to 3

- A 4\textsuperscript{th} neutrino cannot couple to the $Z^0$
  - Cannot participate in weak interactions
  - Hence is must be “sterile”

- Signature is a deficit in all active flavors
  - Neutral current interaction rate is independent of neutrino flavor
  - Look for a deficit in neutral currents at the Far Detector
Selecting Neutral Currents

- Now CC (track) events are the background
  - Want to eliminate events with long tracks.

- Selection
  - Whole event must be short
    - < 47 planes
  - And either:
    - No reconstructed track
    - Track extends less than 6 planes out of the shower

Step 1
Extrapolation

- The Near and Far Detector spectra are not identical
- Again, we use the MC to account for these differences
- Far/Near ratio relates to the two detector spectra
  - Insufficient energy resolution for a beam matrix

\[
E_{\nu} \approx \frac{0.43 E_{\pi}}{1 + \gamma^2 \theta^2_{\nu}}
\]

\[
FD_{i}^{pred} = \frac{FD_{i}^{MC}}{ND_{i}^{MC}} ND_{i}^{Data}
\]

\(i\) refers to Energy bin

Step 2

Step 3
Sterile Neutrino Results

- **Expected:** 757 events
- **Observe:** 802 events
- **No deficit of NC events**

\[
R = \frac{N_{\text{Data}} - N_{\text{BG}}}{N_{\text{NC Signal}}} \pm (\text{stat}) \pm (\text{syst})
\]

\[
= 1.09 \pm 0.06 \pm 0.05 \text{ (no } \nu_e) \]

\[
= 1.01 \pm 0.06 \pm 0.05 \text{ (} \theta_{13} = 11.5^\circ) \]
Sterile Neutrino Results

- Expected: 757 events
- Observe: 802 events
- No deficit of NC events

$f_s \equiv \frac{P_{\nu_\mu \rightarrow \nu_s}}{1 - P_{\nu_\mu \rightarrow \nu_\mu}} < 0.22\ (0.40)\ at\ 90\%\ C.L.$

No (with) $\nu_e$ appearance

$f_s$ is the fraction of disappearing neutrinos that are becoming sterile neutrinos

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Electron Neutrinos

Search for $\theta_{13}$
\( P(\nu_\mu \rightarrow \nu_e) \approx \sin^2(2\theta_{13}) \sin^2(\theta_{23}) \sin^2 \left( \frac{1.27 \Delta m^2_{31}}{E} \right) + \)

\[ \sin^2(2\theta_{12}) \cos^2(\theta_{23}) \sin^2 \left( \frac{1.27 \Delta m^2_{21}}{E} \right) + \]

\[ \sin(2\theta_{13}) \sin(2\theta_{23}) \sin(2\theta_{12}) \sin \left( \frac{1.27 \Delta m^2_{31}}{E} \right) \sin \left( \frac{1.27 \Delta m^2_{21}}{E} \right) \cos \left( \frac{1.27 \Delta m^2_{32}}{E} \pm \delta_{\text{CP}} \right) \]

- If \( \theta_{13} \neq 0 \) a few percent of the disappearing \( \nu_\mu \)'s could be become \( \nu_e \)'s
- The appearance probability also depends on the complex phase \( \delta_{\text{CP}} \) and the \textbf{mass hierarchy} (via matter effects, not shown above)
• Preselection
  – Require good beam and in-time fiducial events
  – Cut events with long tracks (CC $\nu_\mu$)
  – Cut events above 8 GeV where no oscillation signal is expected
Selecting Electron Neutrinos

• Preselection
  – Require good beam and in-time fiducial events
  – Cut events with long tracks (CC $\nu_\mu$)
  – Cut events above 8 GeV where no oscillation signal is expected

• Selection
  – Distinguish a compact EM shower from a diffuse hadronic shower
  – Construct variables that parameterize shower shape
  – Use an Artificial Neural Network (ANN) based on 11 parameters

\[ E_{\text{reco}} = 7.8 \text{ GeV} \]
\[ E_{\text{reco}} = 8.0 \text{ GeV} \]
Selecting Electron Neutrinos

• Preselection
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Selecting Electron Neutrinos

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• Selection
  – Distinguish a compact EM shower from a diffuse hadronic shower
  – Construct variables that parameterize shower shape
  – Use an Artificial Neural Network (ANN) based on 11 parameters

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Extrapolation

- Near Detector consists of 3 background components:
  - Neutral Currents
  - Charged Current $\nu_\mu$
  - Beam $\nu_e$’s

- Each component extrapolates differently to the Far Detector
  - As with NC analysis, Far/Near is used

![Graphs showing data for NC, $\nu_\mu$ CC, and beam $\nu_e$ CC.]

Step 2
ND Decomposition

- Changing **horn focusing** changes the balance of the three components
- Fit three different focusing configurations
  - Low Energy (standard)
  - Horn Off
  - High Energy

![Graph showing energy distributions for different configurations.](image)

Turn off focusing horns

![Histograms comparing standard and high energy configurations.](image)
Extrapolation

- Apply decomposition to the Near Detector data
Extrapolation

- Apply decomposition to the Near Detector data
- Extrapolate each component to get a Far Detector prediction
Extrapolation

- Apply decomposition to the Near Detector data
- Extrapolate each component to get a Far Detector prediction
Systematics

- Systematic uncertainty on the prediction from:
  - Near decomposition
  - Near and far detector differences
  - Cross-section and interaction models

- Uncertainty still dominated by statistics
  - 5% syst, 15% stat
Systematics

- Systematic uncertainty on the prediction from:
  - Near decomposition
  - Near and far detector differences
  - Cross-section and interaction models

- Uncertainty still dominated by statistics
  - 5% syst, 15% stat
**ν_e Appearance Results**

- Expect: $49.1 \pm 7.0$ (stat.) $\pm 2.7$ (syst.)
\( \nu_e \) Appearance Results

- Expect: \( 49.1 \pm 7.0 \) (stat.) \( \pm 2.7 \) (syst.)
- Observe: 54 events, a 0.7\( \sigma \) excess

Step 4
\[ \nu_e \text{ Appearance Results} \]

for \( \delta_{CP} = 0, \sin^2(2\theta_{23}) = 1, \)
\[
|\Delta m^2_{32}| = 2.43 \times 10^{-3} \text{ eV}^2
\]

\( \sin^2(2\theta_{13}) < 0.12 \) normal hierarchy
\( \sin^2(2\theta_{13}) < 0.20 \) inverted hierarchy
at 90% C.L.

A new analysis is coming next year with improved sensitivity
- More data
- Significantly better background rejection
Summary

• Neutrino oscillations in the atmospheric sector
  – World’s best measurement of $\Delta m^2_{\text{atm}}$
  – Find $|\Delta m^2_{\text{atm}}| = 2.35^{+0.11}_{-0.08} \times 10^{-3} \text{ eV}^2$ and $\sin^2(2\theta_{23}) > 0.91$ (90% C.L.)

• Antineutrino oscillations in the atmospheric sector
  – First direct, precision measurement of muon antineutrino disappearance
  – Find $|\Delta \bar{m}^2_{\text{atm}}| = 3.36^{+0.45}_{-0.40} \times 10^{-3} \text{ eV}^2$ and $\sin^2(2\bar{\theta}_{23}) = 0.86 \pm 0.11$
  – New antineutrino data to address the tension with neutrinos

• Sterile neutrinos
  – No evidence of oscillations to sterile neutrinos

• The last mixing angle: $\theta_{13}$
  – A non-significant excess gives an upper limit of $\sin^2(2\theta_{13}) < 0.12$
  – An improved analysis with much better sensitivity next year
Acknowledgements

• On behalf of the MINOS Collaboration, I would like to express our gratitude to the many Fermilab groups who provided technical expertise and support in the design, construction, installation and operation of the experiment

• We also wish to thank the crew at the Soudan Underground Laboratory for keeping the Far Detector running so well

• We also gratefully acknowledge financial support from DOE, STFC(UK), NSF and thank the University of Minnesota and the Minnesota DNR for hosting us
- Dashed line shows the antineutrino prediction at the neutrino best fit point.
Atmospheric Neutrinos

\[
\frac{R_{\nu/\nu}^{\text{data}}}{R_{\nu/\nu}^{\text{MC}}} = 1.04^{+0.11}_{-0.10} \pm 0.10
\]

\[
|\Delta m^2| - |\Delta m^2| = 0.4^{+2.5}_{-1.2} \times 10^{-3} \text{ eV}^2
\]

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Neutrino and Antineutrino $y$

**Neutrinos**

**Antineutrinos**
Far Detector Data

- Good data/mc agreement in charge/momentum
- Antineutrinos focused inwards
- Neutrinos defocused outwards

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• Data shows the expected distributions of hadronic energy fraction for both neutrinos and antineutrinos
Antineutrinos in Neutrino Mode

- We’ve already presented an analysis of the antineutrino component of the neutrino beam.
- This sample has poor sensitivity to oscillations.

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MINOS Preliminary

Events / 4 GeV

Reconstructed $\bar{\nu}_\mu$ Energy (GeV)

$|\Delta m^2| (10^{-3} \text{ eV}^2)$

$\sin^2(2\theta)$

68%

90%

99.7%

MINOS Best Fit

3.2 $\times 10^{20}$ POT
\[ |\Delta m^2_{\text{atm}}| = 3.36^{+0.45}_{-0.40} \times 10^{-3} \text{ eV}^2 \]
\[
\sin^2(2\bar{\theta}_{23}) = 0.86 \pm 0.11
\]
• Increase sensitivity by improving efficiency (89% vs. 87%) at the expense of contamination (1.7% vs. 1.2%)
New Shower Energy Estimator

- Construct a three-parameter kNN using:
  - the shower energy within 1 m of the track vertex
  - the number of planes in the shower
  - the energy in the second reconstructed shower

- Estimator is the mean energy of the nearest neighbors

~30% better resolution below 2 GeV

Monte Carlo

Original Energy

New Estimator
Resolution Binning

- Improve statistical power by separating high and low resolution events.
- MC parameterization of the energy resolution
- 6 Resolution bins
  - 5 bins for events with negative reconstructed curvature
  - 1 bin for events with positive reconstructed curvature (30% true $\nu_\mu$)
Neutrino Spectrum

Far Detector Data
- Negative Curvature Resolution Bin 0
- Negative Curvature Resolution Bin 1
- Negative Curvature Resolution Bin 2

MINOS Preliminary
- Negative Curvature Resolution Bin 3
- Negative Curvature Resolution Bin 4
- Positive Curvature

Events / GeV

Reconstructed Neutrino Energy (GeV)

Prediction
- Best Fit
- Data

Alex Himmel
Removing the Charge Cut

- The positive-curvature sample is ~30% true CC neutrinos.

- If the antineutrinos are oscillated at the antineutrino best fit point, makes a change only in 3rd significant digit of the result.
Change in Systematics

Monte Carlo

Overall hadronic energy
Track energy
NC background
Relative normalisation
Relative hadronic energy
Cross sections
Charge mis-ID
Beam

Far Detector MC
MINOS PRELIMINARY
Fiducial events
$7.2 \times 10^{20}$ POT
Analysis Improvements

MINOS Preliminary

MINOS 7.2×10^{20} POT sensitivity
90% confidence level

Monte Carlo Sensitivity

$\Delta m^2 (10^{-3} \text{ eV}^2)$

$\sin^2 2\theta$

Input parameters

- 2008-like analysis
- + New shower energy estimator
- + Resolution binning

Alex Himmel
Neutrino Contour by Run

MINOS Preliminary
Peak vs. Tail

• $\nu_\mu$'s from **high-$p_t$ π's**
  - Focused by horns

• $\nu_\mu$'s from **low-$p_t$ π$^+$'s**
  - Pass through horn center

120 GeV protons from MI

Target
Focusing Horns

Decay Pipe
2 m
30 m
675 m

Monte Carlo
Focused

Monte Carlo
Unfocused

Alex Himmel
Peak vs. Tail

- $\nu_\mu$'s from low-$p_t\pi^-$'s
  - Focused by horns
- $\nu_\mu$'s from high-$p_t\pi^+$'s
  - Pass through horn center

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### Neutrino mode

Horns focus $\pi^+, K^+$

$\nu_\mu = 91.7\%$

$\bar{\nu}_\mu = 7.0\%$

$\nu_e + \bar{\nu}_e = 1.3\%$

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### Antineutrino mode

Horns focus $\pi^-, K^-$

$\bar{\nu}_\mu = 39.9\%$

$\nu_\mu = 58.1\%$

$\nu_e + \bar{\nu}_e = 2.0\%$
At the beginning of Run III, helium was added to the decay pipe to prevent failure of the upstream window.

- Our previous flux simulation could not model the helium using GFLUKA as part of GEANT3.
- Replaced it with a new flux simulation that is all FLUKA which accurately predicts the effects of helium.
Target Degradation

- Began during Run II and continued through Run III
- The exact mechanism of the decay is not known
- Missing fins at the shower max in the target model the energy-dependent effect
- Target to undergo post-mortem later this year
- Cancels between the two detector