New Results from MINOS

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MINOS Overview

MINOS (Main Injector Neutrino Oscillation Search)

- High intensity NuMI beam produced at Fermilab
- 1kT Near Detector (ND) at Fermilab.
  - measures unoscillated spectrum.
- 5.4kT Far detector (FD) at Soudan, MN
  - measures spectrum at $L=735$ km

- Compare Far and Near rates and spectra to measure neutrino oscillations.
Measure $|\Delta m^2_{atm}|$ and $\sin^2(2\theta_{23})$ via $\nu_\mu$ disappearance.
**MINOS Physics**

- Measure $|\Delta m_{atm}^2|$ and $\sin^2(2\theta_{23})$ via $\nu_\mu$ disappearance.

- Direct measurement $|\Delta m_{atm}^2|$ and $\sin^2(2\theta_{23})$ via $\bar{\nu}_\mu$ disappearance.
  - New result based on $\sim 70\%$ more data.

- First result based on $1.71 \times 10^{20}$ PoT.

- $\nu_\mu$ and $\bar{\nu}_\mu$ parameters consistent at the $2\%$ level.
  - New Physics? (NSI, CPT symmetry violation, etc.)

**Phys. Rev. Lett. 107, 021801 (2011).**
MINOS Physics

- Measure $|\Delta m_{atm}^2|$ and $\sin^2(2\theta_{23})$ via $\nu_\mu$ disappearance.
- Direct measurement of $|\Delta \bar{m}_{atm}^2|$ and $\sin^2(2\bar{\theta}_{23})$ via $\bar{\nu}_\mu$ disappearance.
  - New result based on $\sim 70\%$ more data.
- Search for sub-dominant $\nu_\mu \rightarrow \nu_e$ oscillation via $\nu_e$ appearance.
  - New result with improved analysis technique and more statistics.

MINOS Physics

- Measure $|\Delta m_{atm}^2|$ and $\sin^2(2\theta_{23})$ via $\nu_\mu$ disappearance.

- Direct measurement of $|\Delta m_{atm}^2|$ and $\sin^2(2\theta_{23})$ via $\bar{\nu}_\mu$ disappearance.
  - New result based on $\sim 70\%$ more data.

- Search for sub-dominant $\nu_\mu \rightarrow \nu_e$ oscillation via $\nu_e$ appearance.
  - New result with improved analysis technique and more statistics.

- Searches for sterile neutrinos.

- Atmospheric $\nu$ and cosmic ray physics

- $\nu$ and $\bar{\nu}$ interaction cross sections.
NuMI Beam at Fermilab

- Movable target allows tunable beam energy (peak energies 3-10 GeV)
  - Most of MINOS data taken in Low Energy (LE) mode.
  - Other modes used to tune particle production model.
- Run in Reverse Horn Current (RHC) mode to produce a beam with a large fraction of muon antineutrinos.
MINOS Detectors

Functionally equivalent detectors: *Magnetized tracking calorimeters*

- Share same detector technology and granularity.
- Azimuthal $B$ field allows track momentum measurement and charged-sign tagging.

- 1 cm thick planes of scintillator (4.1 cm wide strips).
- Sampling every 2.54 cm of steel.
- Magnetized steel plates $\langle B \rangle = 1.3 \text{T}$

Near Detector

- 0.98 kton
- 3.8 m x 4.8 m x 15 m
- 153 active planes

Far Detector

- 5.4 kton
- 8 m x 8 m x 30 m
- 484 active planes
MINOS Event Topologies

\[ \nu_{\mu} \rightarrow \mu, W, Fe \rightarrow \text{Shower} \]

\[ \nu \rightarrow Z, \text{Shower} \]

\[ \nu_e \rightarrow e, W, Fe \rightarrow \text{Shower} \]
Antineutrino Disappearance
Survival Probability

\[ P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta_{23} \sin^2 \left( 1.27 \Delta m^2_{32} \frac{L}{E} \right) \]

- Neutrino oscillations deplete the rate and distort the energy spectrum.
Most of MINOS data is taken in this mode.

Horns focus $\pi^+, K^+$ which decay into $\nu_\mu$

Small fraction of $\bar{\nu}_\mu$ at higher energy from very forward $\pi^-$. 

<table>
<thead>
<tr>
<th>Flux $\times$ $\sigma_{CC}$ (Arbitrary Units)</th>
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<tbody>
<tr>
<td>$\nu_\mu$ Spectrum</td>
</tr>
<tr>
<td>$\nu_\mu = 91.7%$</td>
</tr>
<tr>
<td>$\nu_e + \bar{\nu}_e = 1.3%$</td>
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</table>

120 GeV $p$'s from MI

Target

Focusing Horns

$\pi^-$

$\pi^+$

$\nu_\mu$

$\bar{\nu}_\mu$

15 m

30 m

675 m
NuMI Beam $\nu_\mu$ and $\bar{\nu}_\mu$ Running

**Monte Carlo**

**Neutrino mode**
Horns focus $\pi^+, K^+$

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

**Antineutrino mode**
Horns focus $\pi, K^-$

- $\bar{\nu}_\mu = 39.9\%$
- $\nu_\mu = 58.1\%$
- $\nu_e + \bar{\nu}_e = 2.0\%$

*Diagram showing neutrino and antineutrino production and detection processes.*
Two antineutrino beam exposures

- **Run IV** \(1.71 \times 10^{20}\) PoT
- **Run VII** \(1.24 \times 10^{20}\) PoT

- **2011 \(\bar{\nu}_\mu\) Result**: Combined Runs IV+VII \((2.95 \times 10^{20}\) PoT\). 

\(\nu_e\) Appearance result

- Neutrino beam running only
  - New result \(8.2 \times 10^{20}\) PoT (previous \(7.0 \times 10^{20}\) PoT).
Antineutrino Disappearance Analysis

- Select $\bar{\nu}_\mu$-CC sample in ND and FD (FD sample is blinded until analysis is finalized).

- Select CC events with $\mu$ track
  - KNN Algorithm with 4-input variables.
- Select $\mu^+$ from track curvature.

(In signal region $E_\nu < 6$ GeV)

<table>
<thead>
<tr>
<th>Efficiency</th>
<th>ND: 53%</th>
<th>FD: 96%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Purity</td>
<td>ND: 94%</td>
<td>FD: 98%</td>
</tr>
</tbody>
</table>

- Measured ND spectrum is used to predict FD event rate and spectrum.
  - Beam flux is tuned by fitting production $x_f$ and $p_t$ distributions using several beam configurations.
  - External input from NA49 $\pi^+/\pi^-$ and $K/\pi$ ratios.
Near to Far Extrapolation

- Use measured Near Detector spectrum to predict Far Detector spectrum.

\[ E_v \sim \frac{0.43 E_{\pi}}{1 + \gamma_{\pi}^2 \theta_v} \]

- Near and Far detectors have different acceptance for neutrinos produced from \( \pi \) decay.
  - The Near detector sees a line source, while the far detector sees a point source.

- Extrapolate using **Beam transfer matrix**
  - Encodes geometry of beamline and pion decay kinematics.
  - **Matrix element** \( M_{ij} \) gives probability of obtaining a FD event of energy \( E_j \) given the observation of a ND event of energy \( E_i \).
Analysis Improvements

- Refined ND event sample.
  - More stringent track quality requirement.
- New shower energy estimator
  - ~10% improvement to sensitivity
  - Same algorithm as used for 2010 $\nu_\mu$-CC analysis.

- Reanalyzed Run IV (1.71$\times$10$^{20}$ PoT) data sample with analysis changes before opening the box on the combined sample.
  - Parameter shifts are much smaller than uncertainties.

### Run IV w/2010 analysis

$$|\Delta m^2_{\text{atm}}| = [3.36^{+0.46}_{-0.40}] \times 10^{-3} \text{ eV}^2$$

$$\sin^2(2\theta_{23}) = 0.86^{+0.11}_{-0.12}$$

### Run IV w/2011 analysis

$$|\Delta m^2_{\text{atm}}| = [3.46^{+0.47}_{-0.43}] \times 10^{-3} \text{ eV}^2$$

$$\sin^2(2\theta_{23}) = 0.82^{+0.10}_{-0.11}$$
2011 Antineutrino Oscillation Results

273 Expected (no oscillation).

193 Observed

Null-Oscillations excluded at 7.3σ

Best fit:

\[ |\Delta m^2_{\text{atm}}| = (2.62^{+0.31}_{-0.28} \text{ (stat)} \pm 0.09 \text{ (syst)}) \times 10^{-3} \text{ eV}^2 \]

\[ \sin^2(2\theta_{23}) = 0.95^{+0.10}_{-0.11} \text{ (stat)} + 0.01 \text{ (syst)} \]
Contour Comparisons

**Antineutrino Oscillation Parameters**

\[ |\Delta m_{\text{atm}}^2| = [2.62^{+0.31}_{-0.28}] \times 10^{-3} \text{ eV}^2 \]

\[ \sin^2(2\theta_{23}) > 0.75 \text{ at 90\% CL.} \]

**Neutrino Oscillation Parameters**

\[ |\Delta m_{\text{atm}}^2| = [2.32^{+0.12}_{-0.08}] \times 10^{-3} \text{ eV}^2 \]

\[ \sin^2(2\theta_{23}) > 0.90 \text{ at 90\% CL.} \]

Compatibility with Neutrino Result:

- Assuming identical underlying oscillation parameters, measurements are consistent at the 42\% CL.
- Was 2\% CL for the 2010 analysis (red curve).
Contour Comparisons

- Comparison with Super-K and T2K $\nu_\mu$ and $\bar{\nu}_\mu$ results.
- MINOS provides the best constraint on $|\Delta m^2_{\text{atm}}|$.
- MINOS is currently running in $\nu_\mu$, expect further improvement in precision.
Electron Neutrino Appearance
Electron Neutrino Appearance in MINOS

\[ P(\nu_\mu \rightarrow \nu_e) \approx \sin^2(2\theta_{13}) \sin^2 \theta_{23} \sin^2 \frac{\Delta m^2_{\text{atm}} L}{4E} + \text{smaller terms (matter effects: sign}(\Delta m^2)) \]

- Signal is small.
- Backgrounds in MINOS:
  - $\nu_e$ beam.
  - $\nu_e$-like NC interactions.
  - High-\(y\) $\nu_\mu$-CC events
\( \nu_e \) Selection and Background

**\( \nu_e \) CC-like sample selection:** NEW Library Event Matching (LEM) technique.

- Compare each candidate event to library (20M signal and 30M background events).
- Form discriminant using information from 50 best matches.
- Based on strip-level information (pattern and pulseheight).
- Gives 15% improvement in sensitivity over previous technique. (previous ANN technique used high-level reconstructed quantities (Phys. Rev. D 82, 051102 (2010)).

**Determine Far Detector backgrounds from Near Detector sample**

- Decompose Near Detector \( \nu_e \) CC-like event sample into components (NC, Beam \( \nu_e \) and \( \nu_{\mu} \)-CC).
  - Fit uses three beam configurations (LE-10, Horn-off and HE).

Extrapolate each measured background component separately to obtain FD background predictions.

\[
F_{\alpha,i} = \frac{N_{\alpha,i}}{\sum_{\beta} N_{\beta,i}} \times R_{\alpha,i}^F/N
\]

- FD prediction for component \( \alpha \) in bin \( i \)
- ND data for component \( \alpha \) in bin \( i \)
- Far/Near ratio: Ratio of selected events for component \( \alpha \) in bin \( i \) using MC
Far Detector Data

Observe 62 events

Background Prediction ($\theta_{13} = 0$)

49.6 ± 7.0 (stat) ± 2.7 (syst)

<table>
<thead>
<tr>
<th>Component</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>NC</td>
<td>34.1</td>
</tr>
<tr>
<td>$\nu_\mu$-CC</td>
<td>6.7</td>
</tr>
<tr>
<td>beam $\nu_e$-CC</td>
<td>6.4</td>
</tr>
<tr>
<td>$\nu_\tau$-CC</td>
<td>2.2</td>
</tr>
</tbody>
</table>

Best fit (for $\delta=0$, $\theta_{23} = \pi/4$, & normal hierarchy).

$$\sin^2(2\theta_{13}) = 0.041^{+0.047}_{-0.031}$$
(for $2 \sin^2 (\theta_{23}) = 1$, $\delta = 0$, and $|\Delta m_{32}^2| = 2.32 \times 10^{-3}$ eV$^2$)

90% Confidence Limits

**Normal mass hierarchy:** $\sin^2 (2\theta_{13}) < 0.12$

**Inverted mass hierarchy:** $\sin^2 (2\theta_{13}) < 0.20$

Best fit:

Normal $\sin^2 (2\theta_{13}) = 0.04$

Inverted $\sin^2 (2\theta_{13}) = 0.08$

- Most sensitive constraint on $\theta_{13}$ to date.

($arXiv$:hep-ex/1108.0015 accepted by PRL)

$\sin^2 (2\theta_{13}) = 0$ excluded at 89% CL
MINOS significantly constrains the $\theta_{13}$ range allowed by T2K.
New $\overline{\nu}_\mu$ disappearance result ($2.95 \times 10^{20}$ PoT RHC mode)

**Best fit:**

$$|\Delta m^2_{\text{atm}}| = (2.62^{+0.31}_{-0.28}(\text{stat}) \pm 0.09(\text{syst})) \times 10^{-3}\text{eV}^2$$

$$\sin^2(2\theta_{23}) = 0.95^{+0.10}_{-0.11}(\text{stat}) + 0.01(\text{syst})$$

- $\nu_\mu$ and $\overline{\nu}_\mu$ oscillation parameters are consistent at the 42% CL.
- MINOS provides the best constraint on $|\Delta m^2_{\text{atm}}|$.

New $\nu_e$ appearance result ($8.2 \times 10^{20}$ PoT FHC mode)

**90% Confidence Limits ($\delta = 0$)**

- Normal mass hierarchy: $\sin^2(2\theta_{13}) < 0.12$
- Inverted mass hierarchy: $\sin^2(2\theta_{13}) < 0.20$

- Most sensitive constraint on $\theta_{13}$ to date.
- MINOS significantly constrains the $\theta_{13}$ range allowed by T2K.

Future:

- MINOS is currently running in $\overline{\nu}_\mu$, expect further improvement in precision.
- Stay tuned: MINOS+ plans for future running in No$\nu$A era beam.
Extra Slides
\( \bar{\nu}_\mu \) Result Comparisons

Run VII only)
(Exposure 1.24E20 PoT)
\[ |\Delta m_{\text{atm}}^2| = [2.26^{+0.27}_{-0.29}] \times 10^{-3} \text{ eV}^2 \]
\[ \sin^2(2\bar{\theta}_{23}) > 0.79 \text{ (90\% CL)} \]

- 90\% CL Comparison with Run IV obtained from 2011 reanalysis.
- Results overlap at 90\% CL

Run IV only w/2011 analysis
(Exposure 1.71E20 PoT)
\[ |\Delta m_{\text{atm}}^2| = [3.46^{+0.47}_{-0.43}] \times 10^{-3} \text{ eV}^2 \]
\[ \sin^2(2\bar{\theta}_{23}) = 0.82^{+0.10}_{-0.11} \]

Combined Run IV and VII
\[ |\Delta m_{\text{atm}}^2| = [2.62^{+0.31}_{-0.28}] \times 10^{-3} \text{ eV}^2 \]
\[ \sin^2(2\bar{\theta}_{23}) = 0.95^{+0.10}_{-0.11} \]
**Neutrino vs. Antineutrino**

**$\bar{\nu}_\mu$ Oscillation Parameters**

$$|\Delta m^2_{\text{atm}}| = \left[2.62^{+0.32}_{-0.28}\right] \times 10^{-3} \text{ eV}^2$$

$$\sin^2(2\theta_{23}) > 0.75 \text{ at } 90\% \text{ CL.}$$

**$\nu_\mu$ Oscillation Parameters**

$$|\Delta m^2_{\text{atm}}| = \left[2.35^{+0.12}_{-0.08}\right] \times 10^{-3} \text{ eV}^2$$

$$\sin^2(2\theta_{23}) > 0.91 \text{ at } 90\% \text{ CL.}$$
FD Data Stability

MINOS Preliminary
Far Detector Data

$\nu_\mu$ observed at far detector$/10^{19}$ POT

Cumulative POT$/10^{20}$
Allowed Regions

\[ |\Delta m_{\text{atm}}^2| = (2.62^{+0.31}_{-0.28} \text{(stat)} \pm 0.09 \text{(syst)}) \times 10^{-3} \text{eV}^2 \]
\[ \sin^2(2\theta_{23}) = 0.95^{+0.10}_{-0.11} \text{(stat)} + 0.01 \text{(syst)} \]

- Contours are Feldman cousins corrected.
- Systematic uncertainties included in the contour.
- Effect of including systematic uncertainties is small. (dotted curves show statistics only contours).
- Result is statistics limited.
$\bar{\nu}_\mu$ Systematic Uncertainties

- $\nu_\mu$ 68% C.L.
- $\nu_\mu$ 90% C.L.

MINOS Preliminary
2.95 $\times$ 10$^{20}$ POT, $\bar{\nu}_\mu$ mode
Monte Carlo Simulation

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

$\sin^2(2\theta)$

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

$\delta(\sin^2(2\theta))$

Relative Normalisation
NC Background
WS CC Background
Overall Hadronic Energy
Relative Hadronic Energy FD
Relative Hadronic Energy ND
Track Energy
Beam
Acceptance
Cross sections
Charged-current events are selected by tracks which satisfy a multivariant topological ID that uses a k nearest-neighnor algorithm.

**kNearest-Neighbors Algorithm**

- Determine distance of “query” event to each of MC signal and bkgd. events in multivariate space
- e.g. Euclidean distance

\[
D = \left( \sum_{i=1}^{N_{\text{Var}}} |X_i^{MC} - X_i^{Q}|^2 \right)^{\frac{1}{2}}
\]

- Use the “k” MC events with smaller distances to classify “query” event:

\[
k_{\text{NN,ID}} = \frac{k_S}{k_S + k_B}
\]
NC/CC Separation (KNN Variable)

- Rejects neutral current backgrounds and high-\(y\) CC events

\[ \bar{\nu}_\mu \text{ Events} / 10^{17} \text{ POT} \]

\[ k\text{NN Separation Variable} \]

\[ \text{Background includes } \mu^- \text{-component} \]

- hadron-like
- \(\mu\)-like

require \(k\text{NN}_\text{ID} > 0.3\)
Shower Energy

Shower energy computed using the average true hadronic energy of the k nearest-neighbor MC events in 3D space.

- Total energy deposited in 1 m transverse radius around vertex.
- Sum of energy in the two largest showers.
- Length of the longest shower.

MINOS Preliminary
Beam flux is tuned by fitting $x_f$ and $p_t$ distributions with a parametric model using several beam configurations.

External input is used from NA49 $\pi^+ / \pi^-$ and $K/\pi$ ratios.

Flux model uncertainty is taken into account in predicting the FD spectrum but is among the smallest uncertainties considered.
Near Detector Coil Hole Cut

- Track fitter occasionally fails
  - Most failed tracks end near the coil hole.
  - ND coil region is difficult to model (4.2% failures in data, 6.1% in MC)
- New selection removes all tracks ending near or passing through the coil hole.
  - Selection is well modeled in MC
  - After selection only ~1% of tracks fail (both data and MC)
- ND sample is better modeled at the expense of reduced efficiency.
Near Detector Selection Efficiency

- Broad dip in efficiency due to coil hole selection
  - 53% integrated efficiency, 94% purity
- Shape and magnitude of dip are well modeled by Monte Carlo
For $2 \sin^2(\theta_{23}) = 1$, $\delta=0$, and $|\Delta m_{32}^2| = 2.43 \times 10^{-3} \text{eV}^2$

**Normal mass hierarchy:** $\sin^2(2\theta_{13}) < 0.12$

**Inverted mass hierarchy:** $\sin^2(2\theta_{13}) < 0.20$

(P. Adamson et al., Phys. Rev. D82 051102 (2010).)
What's new for 2011 analysis

- New selection criterion (LEM)
- New shape fit: 5-energy bins, 3 PID bin
- 12% Increase in sample size (1.2E20 PoT more data).

Projected 90% C.L. (Normal Hierarchy)

8.2 x 10^{20} \text{ POT}
|\Delta m_{32}^2| = 2.32 \times 10^{-3} \text{eV}^2

2\sin^2(\theta_{23})\sin^2(2\theta_{13})

MINOS PRELIMINARY

CHOOZ upper limit

Shape fit with new selection variable
Rate-only with new selection variable
2010-style analysis with new data (rate-only with old selection variable)
\( \nu_e \) Background Decomposition
LEM PID Variable

- Each event is compared to the library events (20M signal, 30M background) by calculating the likelihood that the photoelectrons came from the same energy deposition.

- Use three distributions from the best matches + reconstructed energy as input to a neural net.

- Output is LEM PID (~ 40% signal efficiency).
Antineutrinos in FHC Mode Beam

- Analyze 7% antineutrino component of neutrino beam
- Complementary information from higher energy events
- Results consistent with the other MINOS disappearance analysis

\[ |\Delta m^2_{\text{atm}}| < 3.37 \times 10^{-3} \text{eV}^2 \quad (90\% \text{ C.L.}) \]

if \( \sin^2(2\theta_{23}) = 1.0 \)

NSI Fit Run IV

- Combined fit to neutrino and antineutrino samples
- Three parameter fit to common oscillation parameters and $\epsilon_{\mu\tau}$

\[
\Delta m^2 = 2.57 \pm 0.15 \times 10^{-3} \text{eV}^2.
\sin^2(2\theta) = 0.98 \pm 0.08
\epsilon_{\mu\tau} = -0.16 \pm 0.16
\]

- Expect update from combined sample very soon.