Measuring Neutrino Oscillations with the MINOS Experiment

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MINOS

- MINOS or Main Injector Neutrino Oscillation Search
- Uses Neutrinos from the NuMI beam line
- Has a peak L/E of \( \sim 250 \text{km/GeV} \)
- Leading measure of \( |\Delta m^2_{\text{atm}}| \)
MINOS Physics Goals

• The measurement of $3\nu$ oscillations via the study of the NuMI and atmospheric neutrinos

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} = U^* \begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

\[
P(\nu_\alpha \rightarrow \nu_\beta) = \left| \sum_j U^*_{\beta j} e^{-i \frac{m^2_{2j} L}{2E}} U_{\alpha j} \right|^2
\]

\[
U = \begin{pmatrix}
\begin{array}{ccc}
c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\
-s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} \\
s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13}
\end{array}
\end{pmatrix}
\]

Normal or Inverted?
NuMI Neutrino Disappearance

- Precise measurement of muon neutrino disappearance
- Direct measurement of muon antineutrino disappearance
- Far detector prediction from near detector is compared to far detector measurement
- Neutrino oscillations deplete rate and distort the energy spectrum

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

Input: \(\sin^2(2\theta)=1.0\), \(\Delta m^2=3.35 \times 10^{-3}\) eV

Monte Carlo
NuMI Neutrino Appearance

- Muons can also oscillate into electron neutrinos, giving us power to measure:
  - $\theta_{13}$
  - $\delta_{cp}$
  - $\theta_{23}$ octant
  - Mass hierarchy

\[
P(\nu_\mu \rightarrow \nu_e) \approx \sqrt{P_{atm}} e^{-i \left( \frac{\Delta m^2_{32} L}{4E} + \delta_{cp} \right)} P_{sol}^2
\]

\[
P_{atm} = \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{31} L}{4E}
\]

Solar term contributes <1% at MINOS L/E
NuMI Neutrino Appearance

• Muons can also oscillate into electron neutrinos, giving us power to measure:
  - $\theta_{13}$
  - $\delta_{CP}$
  - $\theta_{23}$ octant
  - Mass hierarchy

• Electron neutrinos experience an extra CC interaction as they pass through matter, modifying oscillation probabilities
Atmospheric Neutrino Disappearance

- Very long baselines through matter compared to NuMI disappearance analysis
- Some sensitivity to $\theta_{23}$ octant, mass hierarchy and $\delta_{cp}$
MC Event Topologies

$\nu_\mu$ Charged Current (CC)  
Neutral Current (NC)  
$\nu_e$ CC

$\nu_\mu + N \rightarrow \mu^- + X$

$\nu + N \rightarrow \nu + X$

$\nu_e + N \rightarrow e^- + X$

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DPF 2013  
15/08/13  
7/20
Electron Neutrino Appearance
Electron Neutrino Appearance

- MINOS detector granularity makes $\nu_e$ CC identification challenging
- Background estimation based on Near Detector data
- Compare candidate events to a library of MC using “Library Event Matching” (LEM)
Electron Neutrino Appearance

With the *neutrino-enhanced* beam in Signal Enhanced Region:

- If $\theta_{13} = 0$: 128.6 BG Events
- If $\sin^2(2\theta_{13}) = 0.1$: +32.5 Events
- Total Prediction: 161 Events
- Observed: 152 Events

With the *antineutrino-enhanced* beam in Signal Enhanced Region:

- If $\theta_{13} = 0$: 17.5 BG Events
- If $\sin^2(2\theta_{13}) = 0.1$: +3.7 Events
- Total Prediction: 21.2 Events
- Observed: 20 Events

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15/08/13  
10/20
Combined Electron Neutrino Appearance

Cannot distinguish between $\nu_e$ and anti-$\nu_e$ events, so we perform a combined analysis:

At $\delta_{CP} = 0$ and $\theta_{23} < \pi/4$,

- Assuming normal hierarchy:
  
  $2 \sin^2(2\theta_{13}) \sin^2(\theta_{23}) = 0.051^{+0.038}_{-0.030}$
  
  $0.01 < 2 \sin^2(2\theta_{13}) \sin^2(\theta_{23}) < 0.12$ (90% C.L.)

- Assuming inverted hierarchy:
  
  $2 \sin^2(2\theta_{13}) \sin^2(\theta_{23}) = 0.093^{+0.054}_{-0.049}$
  
  $0.03 < 2 \sin^2(2\theta_{13}) \sin^2(\theta_{23}) < 0.18$ (90% C.L.)
Muon Neutrino Disappearance
Neutrino Disappearance

- Five distinct data sets are used to study muon neutrino disappearance:
  - $10.7 \times 10^{20}$ POT in “neutrino-enhanced” NuMI beam
    - Muon neutrino charged current interactions
    - Anti muon neutrino charged current interactions
  - $3.4 \times 10^{20}$ POT in “antineutrino-enhanced” NuMI beam
    - Anti-muon neutrino charged current interactions
  - 37.9 kton-years of atmospheric neutrinos
    - Muon neutrino charged current interactions
    - Anti muon neutrino charged current interactions
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  – \textbf{37.9 kton-years of atmospheric neutrinos}
    • Muon neutrino charged current interactions
    • \textbf{Anti muon neutrino charged current interactions}
Neutrino Disappearance

MINOS PRELIMINARY
Neutrino beam (10.71 \times 10^{20} \text{ POT}), contained-vertex $\nu_\mu$
- MINOS data
- Best fit (3v)
- No oscillations
- NC background

$\nu_\mu$ $E_\nu = 1-3 \text{ GeV}$

MINOS PRELIMINARY
Atmospheric neutrinos, contained-vertex $\nu_\mu$ and $\bar{\nu}_\mu$
- MINOS data
- Best fit (3v)
- No oscillations
- NC background

$\nu_\mu$ $E_\nu = 3-10 \text{ GeV}$

$\bar{\nu}_\mu$ $E_\nu = 1-3 \text{ GeV}$

$\bar{\nu}_\mu$ $E_\nu = 3-10 \text{ GeV}$

$\bar{\nu}_\mu$ $E_\nu = 10-30 \text{ GeV}$

MINOS PRELIMINARY
Antineutrino beam (3.36 \times 10^{20} \text{ POT}), contained-vertex $\bar{\nu}_\mu$
- MINOS data
- Best fit (3v)
- No oscillations
- NC background

$\bar{\nu}_\mu$ $E_\nu = 1-3 \text{ GeV}$

$\bar{\nu}_\mu$ $E_\nu = 3-10 \text{ GeV}$

$\bar{\nu}_\mu$ $E_\nu = 10-30 \text{ GeV}$
Combined Beam and Atmospheric Neutrino Disappearance Best Fit

- Assumes identical neutrino and antineutrino mixing parameters
- Gaussian constraint based on world knowledge of $\theta_{13}$
- $\delta_{cp}$ allowed to freely float in $[0,2\pi]$ range
- Other mixing parameters set at worlds best knowledge
- 15 systematics included as nuisance parameters
Combined Muon Disappearance and Electron Neutrino Appearance
Combined Neutrino Appearance and Disappearance Best Fit

- Assumes identical neutrino and antineutrino mixing parameters
- Gaussian constraint based on world knowledge of $\theta_{13}$
- $\delta_{cp}$ allowed to freely float in $[0, 2\pi]$ range
- Other mixing parameters set at world's best knowledge
- Appearance systematics included, assumes no correlation with disappearance
Combined Neutrino Appearance and Disappearance Best Fit

- Assumes identical neutrino and antineutrino mixing parameters
- Gaussian constraint based on world knowledge of $\theta_{13}$
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Combined Neutrino Appearance and Disappearance Best Fit

- We can also marginalize over $\delta_{\text{cp}}$
- Gaussian constraint based on world knowledge of $\theta_{13}$
- Other mixing parameters set at world's best knowledge
- Appearance systematics included, assumes no correlation with disappearance
Combined Neutrino Appearance and Disappearance Best Fit

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### Combined Neutrino Appearance and Disappearance Best Fit

<table>
<thead>
<tr>
<th>Hierarchy, Octant</th>
<th>$\Delta m^2_{32} / 10^{-3} \text{eV}^2$</th>
<th>$\sin^2 \theta_{23}$</th>
<th>$\sin^2 \theta_{13}$</th>
<th>$\delta_{CP}/\pi$</th>
<th>$-2 \Delta \log(L)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal, Lower</td>
<td>+2.37</td>
<td>0.41</td>
<td>0.0242</td>
<td>0.44</td>
<td>0.23</td>
</tr>
<tr>
<td>Normal, Higher</td>
<td>+2.35</td>
<td>0.61</td>
<td>0.0238</td>
<td>0.62</td>
<td>1.74</td>
</tr>
<tr>
<td>Inverted, Lower</td>
<td>-2.41</td>
<td>0.41</td>
<td>0.0243</td>
<td>0.62</td>
<td>-</td>
</tr>
<tr>
<td>Inverted, Higher</td>
<td>-2.41</td>
<td>0.61</td>
<td>0.0241</td>
<td>0.37</td>
<td>0.09</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Best fit</th>
<th>Confidence limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal hierarchy</td>
<td></td>
<td></td>
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<tr>
<td>$</td>
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Preference for inverted hierarchy: $-2 \Delta \log L = 0.23$

Preference for lower octant: $-2 \Delta \log L = 0.09$

Exclusion of maximal mixing: $-2 \Delta \log L = 1.54$ (⇒ 79% C.L.)
Summary

MINOS has completed a combined analysis of:

- $10.7 \times 10^{20}$ POT to measure muon neutrino disappearance
- $3.4 \times 10^{20}$ POT to measure muon antineutrino disappearance
- 37.9 kton-years of atmospheric data

MINOS has completed a combined analysis of:

- $10.6 \times 10^{20}$ POT to measure electron neutrino appearance
- $3.3 \times 10^{20}$ POT to measure electron antineutrino appearance

- And now a full combination of our neutrino appearance and disappearance fits, allowing us to make our strongest comments yet on the octant degeneracy, $\delta_{cp}$, and the mass hierarchy
NuMI Neutrino Beam

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 $\pi^-, K^-$
$\bar{\nu}_\mu = 39.9\%$
$\nu_\mu = 58.1\%$
$\nu_e + \bar{\nu}_e = 2.0\%$
MINOS Detector

• Steel/Scintillator Tracking Calorimeter
  – 2.54 cm-thick steel plates
  – 1 cm-thick, 4.1 cm-wide extruded polystyrene scintillator strips
• Magnetized at $\langle B \rangle \sim 1.3T$
  – Able to distinguish between $\mu^-$ and $\mu^+$
Combined Beam and Atmospheric Neutrino Disappearance Best Fit

- 2 parameter fit assumes identical neutrino and antineutrino mixing parameters
- Gaussian constraint based on world knowledge of $\theta_{13}$
- $\delta_{cp}$ allowed to freely float in [0,2\pi] range
- Other mixing parameters set at world's best knowledge
- 15 systematics included as nuisance parameters
Combined Beam and Atmospheric Neutrino Disappearance Best Fit

- 15 largest systematics included as nuisance parameters
- Best fit systematics all have a mean value near zero and width close to unity
- Well described by gaussian distributions
- No apparent bias or pathology
Combined Neutrino Appearance and Disappearance Best Fit

- 2 parameter fit assumes identical neutrino and antineutrino mixing parameters.
- Gaussian constraint based on world knowledge of $\theta_{13}$.
- $\delta_{cp}$ allowed to freely float in $[0,2\pi]$ range.
- Other mixing parameters set at world's best knowledge.
- 15 systematics included as nuisance parameters.
Combined Neutrino Appearance and Disappearance Best Fit Inputs

- $\theta_{23}$, $|\Delta m^2_{32}|$ and $\delta_{cp}$ allowed to freely float

- Gaussian constraint based on world knowledge of $\theta_{13}$, $\sin^2 \theta_{13} = 0.0242 \pm 0.0025$. Based on a weighted average of published results from the Daya Bay, RENO and Double-Chooz reactor neutrino experiments

- The solar parameters are set to fixed values of $\Delta m^2_{21} = 7.54 \times 10^{-5} \text{ eV}^2$ and $\sin^2(\theta_{12}) = 0.307$, from the Fogli global analysis*

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Combined Electron Neutrino Appearance

Cannot distinguish between $\nu_e$ and anti-$\nu_e$ events, so we perform a combined analysis:

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  $0.01 < 2 \sin^2(2\theta_{13}) \sin^2(\theta_{23}) < 0.12$ (90% C.L.)

- Assuming inverted hierarchy:

  $2 \sin^2(2\theta_{13}) \sin^2(\theta_{23}) = 0.093^{+0.054}_{-0.049}$

  $0.03 < 2 \sin^2(2\theta_{13}) \sin^2(\theta_{23}) < 0.18$ (90% C.L.)
Electron Neutrino Appearance

- MINOS detector granularity makes $\nu_e$ CC identification challenging
- Compare candidate events to a library of MC using “Library Event Matching” (LEM)
- Compute discriminating variables based on truth information from library events that best match the candidate

Radovic (UCL) DPF 2013 15/08/13 15/22
# Combined Beam and Atmospheric Neutrino Disappearance Best Fit

<table>
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</tr>
<tr>
<td>$\sin^2 \theta_{23}$</td>
<td>0.41</td>
<td>0.62</td>
<td>0.35 - 0.68 (90% C.L.)</td>
</tr>
</tbody>
</table>

Preference for inverted hierarchy: $-2\Delta \log L = 0.25$

Preference for higher octant: $-2\Delta \log L = 0.20$

Exclusion of maximal mixing: $-2\Delta \log L = 1.79 \Rightarrow 82\% \text{ C.L.}$
MINOS: Selection I

• The actual analysis selection can be broken down into two main parts.
• The first is the selection of muon like events by using a kNN (k nearest neighbour) algorithm. This takes advantage of the way muon tracks deposit energy, specifically:
  – Track Length.
  – Mean signal in track planes.
  – Transverse track profile.
  – Signal fluctuation in the track.

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MINOS: Selection II

- The next is charge sign selection, judged by looking at the q/p of the track.
- Particularly important in the anti-neutrino analysis which aims to perform its fit with only anti-neutrinos.
- Less important for the 2 parameter analysis which includes positive sign CC events in its sample.
Near to Far Extrapolation

1. Purity correction
2. Reco to true energy conversion
3. Efficiency correction
4. Cross sections and fiducial mass

- ND reconstructed data

- FD prediction
- Oscillate
- Efficiency correction
- Beam Matrix

- Purity correction
- True to reco energy conversion
- Cross sections and fiducial mass
- Far Detector flux (true energy)
To achieve this we use the a beam matrix

This matrix describes the energy dependant differences in the neutrino flux seen at the near and far detector.

π/K/μ producing events of a given energy in the near detector produce a range of energies in the far detector, yielding the energy smearing seen.
## Selected Disappearance Events

<table>
<thead>
<tr>
<th>Data Set</th>
<th>Simulation</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No osc.</td>
<td>With osc.</td>
</tr>
<tr>
<td>$\nu_\mu$ from $\nu_\mu$ beam</td>
<td>3201</td>
<td>2543</td>
</tr>
<tr>
<td>$\bar{\nu}<em>\mu$ from $\nu</em>\mu$ beam</td>
<td>363</td>
<td>324</td>
</tr>
<tr>
<td>Non-fiducial $\mu$ from $\nu_\mu$ beam</td>
<td>3197</td>
<td>2862</td>
</tr>
<tr>
<td>$\bar{\nu}<em>\mu$ from $\bar{\nu}</em>\mu$ beam</td>
<td>313</td>
<td>227</td>
</tr>
<tr>
<td>Atm. contained-vertex $\nu_\mu + \bar{\nu}_\mu$</td>
<td>1100</td>
<td>881</td>
</tr>
<tr>
<td>Atm. non-fiducial $\mu^- + \mu^+$</td>
<td>570</td>
<td>467</td>
</tr>
<tr>
<td>Atm. showers</td>
<td>727</td>
<td>724</td>
</tr>
</tbody>
</table>
Library Event Matching (LEM)

Find best matches from a library of MC Events

Judge how signal-like an event is based on those best matches.

Matching is done using only strip info (location and charge)

No dependence on high level reconstructed quantities