Recent Results from the MINOS Experiment

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Introduction to the MINOS Experiment
MINOS Physics Goals

✓ Test $\nu_\mu \rightarrow \nu_\tau$ oscillation hypothesis
  ➔ Measure precisely $|\Delta m^2_{32}|$ and $\sin^2 2\theta_{23}$

✓ Search for sub-dominant $\nu_\mu \rightarrow \nu_e$ oscillations
  ➔ see talk M. Sanchez

✓ Search for or constrain exotic phenomena
  ➔ Sterile $\nu, \bar{\nu}$ decay

✓ Compare $\nu, \bar{\nu}$ oscillations
  ➔ Test of CPT violation

✓ Atmospheric neutrino oscillations

Useful Approximations:

Disappearance (2 flavors):

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta_{23} \sin^2(1.27 \Delta m^2_{32} L/E)$$

Appearance:

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 2\theta_{23} \sin^2 2\theta_{13} \sin^2(1.27 \Delta m^2_{32} L/E)$$

Units: $\Delta m^2_{32}$ (eV$^2$), L(km), E(GeV)
Long Baseline Concept

✔ Generic long baseline $\nu_\mu$ disappearance experiment
✔ Predict unoscillated charged current (CC) spectrum at Far Detector (fixed $L$)
✔ Compare with measured Energy spectrum to extract oscillation parameters

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta \sin^2 \left(1.267 \frac{\Delta m^2 L}{E}\right)$$

Inputs:
$$\sin^2 2\theta = 1.0$$
$$\Delta m^2 = 3.35 \times 10^{-3} \text{ eV}^2$$

Monte Carlo

Oscillated/Unoscillated

Neutral current (NC) background
High intensity $\nu_\mu$ beam produced by 120 GeV protons from the Main Injector at FNAL

- compare energy spectrum:
  - near detector $\rightleftharpoons$ far detector
  - 1km $\rightleftharpoons$ 735km
  - unoscillated $\rightleftharpoons$ oscillated
NuMI Beamline

✓ movable target ⇒ variable beam energy
  ➞ graphite, 47 segments, 6.4x15x20mm³

✓ 2 magnetic focusing horns ⇒ ν or ν̅ beam
  ➞ parabolic, pulsed, 200kA, 3T field

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Status of the MINOS Experiment, dpf2006
NuMI Neutrino Beam

- LE-10 configuration is most favorable for oscillation analysis and constitutes ~95% of total exposure.
  - Data in 5 other configurations for systematic studies.
- LE-10 event composition: 92.9% $\nu_\mu$, 5.8% $\bar{\nu}_\mu$, 1.3% $\nu_e$ / $\bar{\nu}_e$.

![Graph showing muon flux and target positions](image)

Expected unoscillated FD events* per $10^{20}$ pot**

- LE-10: -10 cm, 390 cm
- pME: -100 cm, 970 cm
- pHE: -250 cm, 1340 cm

*Events in fiducial volume
**pot=Protons-on-target
1\textsuperscript{st} year of NuMI Running

First neutrinos in ND

Start of LE running

Integrated $10^{20}$ POT

First Analysis Data Set (0.93x$10^{20}$ POT)

Final Analysis Data Set (1.27x$10^{20}$ POT)

Main Injector Shutdown
Detector Technology

Near and Far detector functionally identical:

- 2.54cm magnetized steel plates, $<B>=1.2\,\text{T}$ field
- 4.1x1cm$^2$ scintillator strips
- consecutive planes have orthogonal strips
- optical readout: multi-channel PMTs
- GPS timestamps
# MINOS Detectors

## NEAR DETECTOR
- Mass: 5.4 kt
- Plane size: 8x8 m²
- # steel/scint pl.: 486/484
- Front: all pl. instrumented
- Back: 1/5 pl. instrumented
- Fast QIE electronics
- Specifics: veto shield for cosmics, 8x optical multiplexing

## FAR DETECTOR

<table>
<thead>
<tr>
<th>1</th>
<th>mass (kt)</th>
<th>5.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.8x4.8</td>
<td>plane size (m²)</td>
<td>8x8</td>
</tr>
<tr>
<td>282/153</td>
<td># steel/scint pl.</td>
<td>486/484</td>
</tr>
</tbody>
</table>

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Status of the MINOS Experiment, dpf2006
Calibration

- Light injection: PMT gain
- Cosmic ray $\mu$: strip-to-strip, inter-detector
- Calibration detector: overall energy scale
  - 'mini-MINOS' at CERN test beam
  - Measured $e/\mu/\pi/p$ response

Energy resolution: $(E$ in GeV)
- Hadrons: 56% / $\sqrt{E} \oplus 2\%$
- Electrons: 21% / $\sqrt{E} \oplus 4\% / E$

- See poster J. de Jong
$\nu_\mu$ Charged Current Event Selection
Event Topologies

\[ \nu_{\mu} \text{ CC} \]

\[ \nu_{\tau} \text{ NC} \]

\[ \nu_e \text{ CC} \]

- long track (\(\mu\))
- hadronic activity near vertex

\[ E_\nu = E_{\text{shower}} + P_\mu \]

\[ \sigma(E_{\text{shower}}) : 55\%/\sqrt{E} \]

\[ \sigma(P_\mu) : 6\% \text{ range; } 13\% \text{ curvature} \]
Pre-selecting $\nu_\mu$ CC Events

✓ beam and detector monitoring quality cuts

✓ pre-selection:
  ➔ at least one good reconstructed track
  ➔ only select fitted tracks with negative charge
  ➔ fiducial volume cuts on vertex:
    × ND: $1m < z < 5m; r < 1m$ w.r.t. beam center
    × FD: $z > 50cm$ from edge, $z>2m$ from end; $r < 3.7m$
Selecting $\nu_\mu$ CC Events

Event classification parameter defined as:

$$PID = -\sqrt{-\log P_{CC}} + \sqrt{-\log P_{NC}}$$

Select CC-like events:
- $\times$ PID $>-0.2$ in FD
- $\times$ PID $>-0.1$ in ND

Monte Carlo

Input variables for PDF-based event selection

- Related to Muon momentum
  - True CC
  - True NC

- Related to event inelasticity

- Related to dE/dx
Near Detector Distributions

- event rate flat over time
- deviations due to different running conditions
- distributions well reproduced by Monte Carlo

✔ event rate flat over time
✗ deviations due to different running conditions
✔ distributions well reproduced by Monte Carlo

➔ see D. Naples talk on ND physics
Near Detector Energy Spectra

Error envelopes shown reflect uncertainties due to cross-section modelling, beam modelling and calibration uncertainties

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Status of the MINOS Experiment, dpf2006
Hadron Production Tuning

- Parametrize Fluka2005 as a function of $\nu$ parent $x_F$ and $p_T$
- Perform fit which reweights parent $x_F$ and $p_T$ to improve data/MC agreement
- Horn focusing, beam misalignments included as nuisance parameters in fits
- Small changes in x-section, neutrino energy scale, NC background also allowed

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Status of the MINOS Experiment, dpf2006
Selecting Far Detector Beam Events

✓ LE-10 data sample
  ➔ Total POT: 1.27x10^{20}
  ➔ FD live time: 98.9%

✓ Beam spill trigger reads out all activity in 100µs around spill signal (10µs)

✓ event rate constant over time

✓ event time consistent with spill

✓ additional 53° cut around beam axis to reject cosmics

✓ cosmic background estimated using sidebands outside timing cut and fake spills in anti-coincidence with beam spills: upper limit < 0.5 events
Far Detector Oscillation Analysis
Predicting unoscillated FD Spectrum

- Near and far detector see different decay angles of the neutrinos ⇒ different energy spectra

\[ E_\nu \sim 0.43 E_\pi / (1 + \gamma_\pi^2 \gamma_\nu^2) \]

- Several methods developed for extrapolation
  - Primary method is ‘matrix method’:
    - contains info of pion 2-body decay kinematics and beamline geometry
    - MC used to correct energy resolution and acceptance
  - See talk N. Saoulidou
A large energy dependent deficit
Below 10 GeV a 49% deficit is observed
Significance is 6.2 (stat+syst)

<table>
<thead>
<tr>
<th>Data sample ($\nu_\mu$ only)</th>
<th>observed</th>
<th>expected</th>
<th>ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_\nu &lt; 30$ GeV</td>
<td>215</td>
<td>336.0±14.4</td>
<td>0.64±0.05</td>
</tr>
<tr>
<td>$E_\nu &lt; 10$ GeV</td>
<td>122</td>
<td>238.7±10.7</td>
<td>0.51±0.05</td>
</tr>
<tr>
<td>$E_\nu &lt; 5$ GeV</td>
<td>76</td>
<td>168±8.8</td>
<td>0.45±0.06</td>
</tr>
</tbody>
</table>
Best-fit spectrum for $1.27 \times 10^{20}$ POT

$$|\Delta m^2_{32}| = 2.74^{+0.44}_{-0.26} \times 10^{-3} \text{ eV}^2$$

$$\sin^2 2\theta_{23} = 1.00^{+0.13}_{-0.13}$$

Normalization = 0.98

Errors are at 68% C.L. statistical + systematic
✔ Fit includes penalty terms for three main systematic uncertainties

✔ Fit is constrained to physical region: 
\[ \sin^2(2\theta_{23}) \leq 1 \]

\[ |\Delta m_{32}^2| = 2.74^{+0.44}_{-0.26} \times 10^{-3} \text{ eV}^2 \]
\[ \sin^2 2\theta_{23} = 1.00^{+0.13}_{-0.13} \]
# Systematic Uncertainties

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>$\Delta m^{2}_{32}$ ($10^{-3}$ eV$^2$)</th>
<th>$\sin^2 2\theta_{23}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>near/far normalization ±4%</td>
<td>0.050</td>
<td>0.005</td>
</tr>
<tr>
<td>abs. hadr. shower energy scale ±5%</td>
<td>0.060</td>
<td>0.048</td>
</tr>
<tr>
<td>NC contamination ±50%</td>
<td>0.090</td>
<td>0.050</td>
</tr>
<tr>
<td>all other uncertainties</td>
<td>0.040</td>
<td>0.011</td>
</tr>
<tr>
<td>total systematic uncertainty</td>
<td>0.13</td>
<td>0.07</td>
</tr>
<tr>
<td>statistical uncertainty</td>
<td>0.36</td>
<td>0.12</td>
</tr>
</tbody>
</table>

- Systematic shifts computed using MC “fake data” samples for $\Delta m^2 = 2.7 \times 10^{-3}$ eV$^2$ and $\sin^2 2\theta_{23} = 1.0$
- $\Delta m^2$ systematic is ~40% of statistical uncertainty
- Several systematic uncertainties are data driven → improve with more data and study
Far Detector Distributions

✔ Predicted no oscillations (solid)
✔ Best fit (dashed)

Event Classification Parameter

Track Vertex $r^2 \ (m^2)$

$y = \frac{E_{shw}}{E_{shw} + P_{\mu}}$

MINOS
$1.27 \times 10^{20}$ POT
Future Prospects
2nd year of NuMI Running


Integrated POT = $1.80 \times 10^{20}$

horn 1 cooling problems

scheduled shutdown
target problems

Mark Dierckxsens  Status of the MINOS Experiment, dpf2006  28
MINOS $\nu_\mu$ disappearance sensitivities for different POT

Best fit values used as input

$\Delta m^2_{32} = 2.74 \times 10^{-3} \text{ eV}^2$

$\sin^2 2\theta_{23} = 1.00$

Contours are 90% C.L. statistical errors only
Conclusions

✓ MINOS has completed a $\nu_\mu$ disappearance analysis of the first year of NuMI beam data
   ➔ Exposure used in analysis: $1.27 \times 10^{20}$ POT
   ➔ No disappearance excluded at $6.2\sigma$ from event rates only

   ➔ Results consistent with oscillation hypothesis:
     $$|\Delta m^2_{32}| = 2.74^{+0.44}_{-0.26} \times 10^{-3} \text{ eV}^2$$
     $$\sin^2 2\theta_{23} = 1.00^{+0.13}_{-0.13}$$

   ➔ Constraining $\sin^2 2\theta_{23} = 1$ yields:
     $$|\Delta m^2_{32}| = 2.74 \pm 0.28 \times 10^{-3} \text{ eV}^2$$

✓ Systematic uncertainties under control
   ➔ significant improvements expected with data driven studies & more statistics

✓ Accepted for publication in PRL (hep-ex 0607088)

✓ Second year of running underway. Stay tuned for new results
Extras
NuMI Design Parameters:
- 120 GeV protons from the Main Injector (MI)
- Single turn extraction ~10 μs spill
- MI accepts up to 6 batches from Booster
  - Either 5 or 6 for NuMI
- 1.9 second cycle time
- 4x10^{13} protons/spill
- 0.4MW

Performance Averages:
(for period: Oct 15 – Jan 31)
- 2.2 second cycle time
- 2.3x10^{13} protons/spill
- 0.17MW

Performance Records:
- 2.0 second cycle time
- 3.0x10^{13} protons/spill
- 0.29MW
Composition of Charged-Current (CC) Events:

- 92.9% $\nu_\mu$
- 5.8% $\overline{\nu}_\mu$
- 1.2% $\nu_e$
- 0.1% $\overline{\nu}_e$
Near Detector Spill

✔ Multiple events in ND per spill  
  ✗ Over 1x10^7 fiducial events collected
✔ Events separated using topology and timing  
  ✗ Color in display indicates time (blue: early, red: late)
✔ No rate effects observed  
  ✗ Linear increase in event rate with beam intensity

![Graph showing the number of events per spill vs. protons per pulse (x10^12)].

![Graph showing the earliest time (-t0) in nanoseconds with counts].
CC Event Selection

- Final selection employs a likelihood based procedure with probability density functions for three low level variables:
  - Event length
    - Related to $p_\mu$
  - Fraction of event PH in track
    - Related to inelasticity of CC events
  - Track pulse height per plane
    - Related to track $dE/dx$
ND $\nu_\mu$ CC Efficiencies/Purities

![Graph showing event classification parameter vs. number of events and efficiency/purity vs. visible energy (GeV).]