MINOS Results from the First Year of NuMI Beam Operation

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William & Mary

(for the MINOS Collaboration)

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The MINOS Experiment

A large detector at Soudan
> The “far detector” or FD

A smaller detector at Fermilab
> The “near detector” or ND

Measure the beam and neutrino energy spectrum near the source
> See how it differs far away
MINOS has been collecting data with the NuMI beam since 3/05

- Data from $1.27 \times 10^{20}$ protons on target (POT) was accumulated under nominal beam conditions
- Previous MINOS results from $0.93 \times 10^{20}$ POT

We report for the first time preliminary results from the full $1.27 \times 10^{20}$ POT sample

- These results supersede our previously reported results
MINOS Collaboration

32 institutions
175 scientists

Argonne • Athens • Benedictine • Brookhaven • Caltech • Cambridge • Campinas • Fermilab
College de France • Harvard • IIT • Indiana • ITEP-Moscow • Lebedev • Livermore
Minnesota-Twin Cities • Minnesota-Duluth • Oxford • Pittsburgh • Protvino • Rutherford
Sao Paulo • South Carolina • Stanford • Sussex • Texas A&M
Texas-Austin • Tufts • UCL • Western Washington • William & Mary • Wisconsin
MINOS physics goals

- Test the $\nu_\mu \rightarrow \nu_\tau$ oscillation hypothesis
  - Precisely measure oscillation parameters
    \[ \Delta m^2_{32} = m^2_3 - m^2_2 \text{ and } \sin^2 2\theta_{23} \]
- Search for sub-dominant $\nu_\mu \rightarrow \nu_e$ transitions
- High statistics studies of neutrino-nucleus interactions
- Search for/constrain exotic phenomena
- Atmospheric neutrino oscillations
Example of a disappearance measurement

Look for a deficit of $\nu_\mu$ events at a distance…

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta \sin^2(1.267 \Delta m^2 L / E)$$

\begin{align*}
\text{Events} \\
\text{Visible energy (GeV)} \\
\end{align*}

Monte Carlo

$\nu_\mu$ spectrum

Spectral ratio

Monte Carlo

$0.0033 \text{ eV}^2$

NC subtracted

$0.0033 \text{ eV}^2$

NC subtracted
The NuMI beam at Fermilab

Design parameters

> 120 GeV protons from the Main Injector
> Main Injector can accept up to 6 booster batches per cycle
> 1.87s minimum cycle time
> $4 \times 10^{13}$ protons/pulse
> 0.4 MW
> 10µs extraction

Averages from 10/05 to 1/06

> 170 kW
> $2.3 \times 10^{13}$ protons/pulse
> 2.2 s cycle
The NuMI beamline

Water-cooled segmented graphite target
- 47 2.0 cm segments; total length of 95.4 cm

2 parabolic horns carrying
- Up to 200 kA current provides up to 3T fields
- Target can be positioned up to 2.5m upstream of the first horn to change beam energy
The NuMI neutrino beam

Majority of running in the LE-10 configuration

- Beam composition: 98.7% $\nu_\mu + \bar{\nu}_\mu$ (5.8% $\bar{\nu}_\mu$), 1.3% $\nu_e + \bar{\nu}_e$
- Collected data in 5 other beam configurations for systematics studies (roughly 5% of the total exposure)

![Beam MC graph](image)

<table>
<thead>
<tr>
<th>Beam</th>
<th>Target - Horn Separation (cm)</th>
<th>FD Events per $10^{20}$ POT*</th>
</tr>
</thead>
<tbody>
<tr>
<td>LE-10</td>
<td>-10</td>
<td>390</td>
</tr>
<tr>
<td>pME</td>
<td>-100</td>
<td>970</td>
</tr>
<tr>
<td>pHE</td>
<td>-250</td>
<td>1340</td>
</tr>
</tbody>
</table>

* Events in fiducial volume
MINOS Detectors

**Near Detector**
- 1 kton
- $3.8 \times 4.8 \times 15 \text{ m}^3$
- 282 steel planes
- 153 scintillator planes

**Iron and Scintillator tracking calorimeters**
- 2.54 cm thick magnetized steel planes $\langle B \rangle = 1.2T$
- $1 \times 4.1 \text{ cm}^2$ scintillator strips
- Multi-anode PMT readout
- GPS time-stamping to synchronize FD data to ND/Beam
- Software triggering in DAQ PCs
- Main Injector spill times sent to the FD for a beam trigger

**Far Detector**
- 5.4 kton
- $8 \times 8 \times 30 \text{ m}^3$
- 484 planes
MINOS Calibration system

ND & FD response

> Light Injection system (PMT gain)
> Source scan (within a strip)
> Cosmic ray muons (strip to strip)
> Stopping cosmic ray muons (detector to detector)
> Overall energy scale (Test beam)

Energy scale errors

> 5.7% absolute
> 2% ND/FD relative
A blind analysis

Far detector blinding

> Unknown fraction of FD events were hidden
  • Blinded as a function of event length and energy
> The “Open” FD data used to check data quality

All near detector data was open

> Used to study beam properties, cross sections, and detector systematics

Analysis procedures defined prior to box opening
Near detector events

- High event rate in the near detector
  - Over $1 \times 10^7$ events in the fiducial volume
- Multiple interactions per main injector spill
  - 10 $\mu$s beam spills
- Events are separated by topology and 19ns timing
  - Linear response to increasing intensity

Number of events vs intensity
A 2 GeV $\nu_\mu$ event

Track Energy 2.04 GeV
Shower energy 0.20 GeV
$q/p = -0.52 \pm 0.03$

< 2 PE
0<PE < 20 PE
>20 PE

1pe PMT cross-talk
$\nu_\mu$ CC event pre-selection cuts

- At least one good track
- Fitted track with negative charge
- Track vertex within the fiducial volume
  - $\text{ND } r < 1\text{m}$ from beam center
  - $\text{FD } r < 3.7\text{m}$
Near detector rate & event vertices

- Event rate is flat as a function of time
- Horn current scans on July 29 – Aug 3
- Different tunes in Feb
- Acceptance well reproduced

Events/10^{18} POT

50000
45000
40000
35000
30000
2/06
1/06
12/05
11/05
10/05
9/05
8/05
7/05
6/05
5/05
0

Days Since May 1, 2005

X ND

Y ND

Z ND

MINOS Preliminary 1.27 \times 10^{20} POT

MINOS Preliminary

MINOS PRELIMINARY

MINOS PRELIMINARY

MINOS PRELIMINARY

MINOS PRELIMINARY
Event selection performance

Charged current events are selected using a likelihood procedure

> Combine probability density functions for 3 low level variables to differentiate CC & NC interactions

> Efficiency is reasonably flat vs visible energy over most of the energy range

> NC contamination is limited to the lowest bins (below 1.5 GeV)
Hadron production tuning

- Varying the dependence on $p_T$ and $x_F$ in FLUKA05
- Also allow small changes in
  > Cross section parameters
  > Horn focusing
  > Neutrino energy scale

Weights applied vs $p_z$ & $p_T$

- Distribution of pions producing MINOS neutrinos

**Graphs:**
- LE-10/170kA
- LE-10/185kA
- LE-10/200kA
- pME/200kA
- pHE/200kA
- Horns off

**Plots:**
- Events / 0.5 GeV / 1e20 POT
- Reconstructed $E_\nu$ (GeV)

**Colors:**
- MC
- LE-10/185kA
- MINOS Preliminary
Predicting the unoscillated FD spectrum

Start with near detector data & extrapolation to the far detector

> Use Monte Carlo to provide corrections due to energy smearing and acceptance
> Encode pion decay kinematics & the geometry of the beamline into a matrix used to transform the ND spectrum into the FD energy spectrum

This is the primary method used in our analysis
Different methods of predicting the FD spectrum

ND fit methods

> 2 types of fits made to all 6 beams
  • ND fit to $E_\nu$ distribution
  • 2D fit to ($E_\nu$, $y$) grid
> The MC is then used to produce the extrapolation FD spectrum

ND data extrapolation methods

> 2 types of fit used
  • Beam matrix
  • F/N ratio
    – Events in each ND energy bin are scaled via MC into a number of FD events in the same bin

The methods are robust to different categories of systematics
Selecting far detector beam induced events

GPS time stamping both detector sites
  > FD trigger reads out 100μs of activity around beam spills

FD neutrino events have distinctive topology
  > They point to Fermilab
  > Easily separated from cosmic muons with 60° cut around the beam axis

Backgrounds estimated from “fake” triggers
  > 2.6 million triggers
  > 0 events survived cuts
  > Upper limit of 0.5 events

MINOS Preliminary
1.27×10^{20} POT

Time of neutrino interactions from beam spill (μs)
Far detector beam data analysis

This analysis uses data collected from 20 May, 2005 to 3 March, 2006

MINOS Preliminary  $1.27 \times 10^{20}$ POT

Mean = $3.47 \pm 0.18$
A large energy dependent deficit

- Below 10 GeV the significance of the deficit is 5.9σ (stat+syst)
- Preliminary result from the 1.27×10^{20} POT sample
MINOS best-fit spectrum for $1.27 \times 10^{20}$ POT

$$|\Delta m^2_{32}| = 2.72^{+0.38}_{-0.25} \text{ (stat)} \times 10^{-3} \text{ eV}^2$$

$$\sin^2 2\theta_{23} = 1.00^{+0.38}_{-0.25} \text{ (stat)}$$

Normalization = 0.98

Measurement errors are 1 sigma, 1 DOF

$$\sum_{i=1}^{\text{nbins}} 2(e_i - o_i) + 2o_i \ln \frac{o_i}{e_i} + \frac{(1 - N)^2}{0.04}$$
FD distributions

Event Classification Parameter

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

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

Predicted no oscillations (solid)

Best fit (dashed)
\[ |\Delta m^2_{32}| = 2.72^{+0.38}_{-0.25} \text{(stat)} \times 10^{-3} \text{eV}^2 \]
\[ \sin^2 2\theta_{23} = 1.00^{+0.13}_{-0.13} \text{(stat)} \]

Constrained to \( \sin^2(2\theta_{23}) \leq 1 \)

Statistical errors
Allowed region

\[ |\Delta m_{32}^2| = 2.72^{+0.38}_{-0.25} \text{(stat)} \times 10^{-3} \text{eV}^2 \]

\[ \sin^2 2\theta_{23} = 1.00^{+0.13}_{-0.13} \text{(stat)} \]

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Statistical errors
\( |\Delta m^2_{32}| = 2.72^{+0.38}_{-0.25} \text{(stat)} \times 10^{-3} \text{ eV}^2 \)

\( \sin^2 2\theta_{23} = 1.00^{+0.00}_{-0.13} \text{(stat)} \)

Constrained to \( \sin^2(2\theta_{23}) \leq 1 \)

Statistical errors

When constrained to \( \sin^2(2\theta) = 1 \)
## Systematic errors

<table>
<thead>
<tr>
<th>Preliminary Uncertainty</th>
<th>$\Delta m^2 \ (10^{-4} \text{ eV}^2)$</th>
<th>$\sin^2 2\theta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Near/Far normalization $\pm$ 4%</td>
<td>0.03</td>
<td>0.000</td>
</tr>
<tr>
<td>Muon momentum scale $\pm$ 2%</td>
<td>0.35</td>
<td>0.003</td>
</tr>
<tr>
<td>Near/Far shower energy scale $\pm$ 2%</td>
<td>0.10</td>
<td>0.003</td>
</tr>
<tr>
<td>NC contamination $\pm$ 50%</td>
<td>0.88</td>
<td>0.038</td>
</tr>
<tr>
<td>CC cross-section uncertainties</td>
<td>0.16</td>
<td>0.004</td>
</tr>
<tr>
<td>Intranuclear re-scattering / absolute energy scale $\pm$ 6%</td>
<td>0.83</td>
<td>0.018</td>
</tr>
<tr>
<td>Reconstruction</td>
<td>0.13</td>
<td>0.005</td>
</tr>
<tr>
<td>Fit bias</td>
<td>0.10</td>
<td>0.010</td>
</tr>
<tr>
<td>Beam uncertainties</td>
<td>0.25</td>
<td>0.005</td>
</tr>
<tr>
<td>Total Systematic (summed in quadrature)</td>
<td>1.31</td>
<td>0.044</td>
</tr>
<tr>
<td>Statistical sensitivity</td>
<td>3.6</td>
<td>0.12</td>
</tr>
</tbody>
</table>
Projected sensitivity of MINOS

Input parameters

\[ |\Delta m_{32}^2| = 2.72 \times 10^{-3} \text{ eV}^2 \]

\[ \sin^2 2\theta_{23} = 1.00 \]

Statistical errors only

90% C.L.
2nd year of MINOS running in the NuMI Beam is underway

The first FD beam event in the new run

> A muon from an interaction in the cavern rock
MINOS Summary

Preliminary results from the first year of accelerator neutrino exposure

- Our exposure to date is $1.27 \times 10^{20}$ POT
- Disfavors no oscillations at 5.9 $\sigma$ (rate only)
- It is consistent with $\nu_\mu$ disappearance with the following parameters

$$\left| \Delta m_{32}^2 \right| = 2.72^{+0.38}_{-0.25} \text{ (stat)} \pm 0.13 \text{ (stat)} \times 10^{-3} \text{ eV}^2$$

$$\sin^2 2\theta_{23} = 1.00^{+0.25}_{-0.13} \text{ (stat)} \pm 0.04 \text{ (syst)}$$

- A fit constrained to the $\sin^2(2\theta)=1$ boundary yields

$$\left| \Delta m_{32}^2 \right| = 2.72^{+0.25}_{-0.25} \times 10^{-3} \text{ eV}^2$$

The systematics are under control

- Many systematics are data driven and will improve with increasing statistics and further analysis
- We should be able to make significant improvements in precision with a substantially larger dataset
Dedication

Lynn Miller
MINOS Co-Spokesman

Michael Murtagh

Julia Thompson

Doug Michael