First MINOS Results from the NuMI Beam

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- On behalf of the MINOS Collaboration
- SNOW 2006, Stockholm, 2-6 May 2006
Outline

Introduction to the MINOS experiment
- Overview of MINOS physics goals
- The NuMI facility and the MINOS detectors

Near Detector and beam measurements
- Selecting CC muon neutrino events
- Near Detector distributions and comparison with Monte Carlo

Far Detector analysis
- Selecting beam neutrino candidates
- Near-Far extrapolation of the neutrino flux
- Oscillation analysis with $0.93 \times 10^{20}$ POT
The MINOS Experiment

- **Main Injector Neutrino Oscillation Search**
- Accelerator-based long-baseline neutrino experiment
- Precision experiment at the atmospheric $\Delta m^2$
- One $\nu_\mu$ beam: NuMI
  - 120 GeV protons from Fermilab Main Injector
- **Two detectors**
  - Near Detector: measure beam composition and spectrum
  - Far Detector: search for evidence of oscillations
MINOS Physics Goals

- Verify $\nu_\mu \to \nu_\tau$ mixing hypothesis
  - Make a precise ($< 10\%$) measurement of the oscillation parameters $\Delta m^2_{23}$ and $\sin^2 2\theta_{23}$

- Search for subdominant $\nu_\mu \to \nu_e$ oscillations

- Search for/rule out exotic phenomena
  - Sterile neutrinos
  - Neutrino decay

- First measurement of $\nu$ vs. $\bar{\nu}$ oscillations – CPT test
  - First large underground detector with magnetic field
  - Atmospheric neutrino oscillations:

\[
\begin{pmatrix}
  \nu_e \\
  \nu_\mu \\
  \nu_\tau
\end{pmatrix} =
\begin{pmatrix}
  U_{e1} & U_{e2} & U_{e3} \\
  U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\
  U_{\tau 1} & U_{\tau 2} & U_{\tau 3}
\end{pmatrix}
\begin{pmatrix}
  \nu_1 \\
  \nu_2 \\
  \nu_3
\end{pmatrix}
\]

$\Delta m^2_{23}$

$\sin^2 2\theta = 4U_{\mu 3}^2 (1 - U_{\mu 3}^2)$

if $\Delta m^2_{23} >> \Delta m^2_{12}$
Oscillation Measurement

Look for a deficit of $\nu_\mu$ events at Soudan...

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

Allowed regions from Super-K and K2K

Current best measurements of $\Delta m^2_{23}$ and $\sin^2 2\theta_{23}$ are provided by Super-Kamiokande (atmospheric neutrino analysis) and K2K (9x10^{19} pot)

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The NuMI Facility

Design parameters:

- 120 GeV protons from the Main Injector
- 1.9 second cycle time
- $4 \times 10^{13}$ protons/pulse
- 10 µs spill (single-turn extraction)
- 0.4 MW
The NuMI Beam

- Graphite target
- Magnetic focusing horns
- Target moveable relative to horn 1: continuously variable neutrino spectrum
The NuMI Beam

- Currently running in the LE-10 configuration
- \( \sim 1.5 \times 10^{19} \) POT in pME and pHE configurations early in the run for commissioning and systematics studies

\[ 98.5\% \mu^+ + \mu^- \left( 6.5\% \mu^- \right) \]
\[ 1.5\% e^+ + e^- \]

<table>
<thead>
<tr>
<th>Beam</th>
<th>Target z position (cm)</th>
<th>FD Events per 1e20 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 expected in fiducial volume (no osc.)
First Year of Running

Observation of neutrinos in Near Detector!

Dataset used for the oscillation analysis

2.3 \times 10^{13} \text{ protons/pulse} \text{ averaged for 15 Oct to 31 Jan (2.2 s cycle)}
The MINOS Detectors

Steel/scintillator tracking calorimeters
Functionally identical

- 1 km from target
- 1 kton
- 282 steel planes
- 153 scintillator planes

- 735 km from target
- 5.4 kton
- 484 steel/scintillator planes

Magnetised to 1.2 T
GPS time-stamping to synchronise FD data to ND/beam
Detector Technology

- 2.54 cm steel planes
- 1 cm thick, 4 cm wide plastic scintillator strips
- Orthogonal orientation on alternate planes (U, V)
- Wavelength-shifting fibre-optic readout
- Multi-anode PMTs
MINOS Calibration System

- Calibration of ND and FD response using:
  - Light Injection system (PMT gain)
  - Cosmic ray muons (strip to strip and detector to detector)
  - Calibration detector (overall energy scale)

- Energy scale calibration:
  - 1.9% absolute error in ND
  - 3.5% absolute error in FD
  - 3% relative
Event Topologies

$\nu_\mu$ CC Event

Long $\mu$ track + hadronic activity at vertex

NC Event

Short event, often diffuse

$\nu_e$ CC Event

Short, with typical EM shower profile

$E_\nu = E_{\text{shower}} + P_\mu$

55%/$\sqrt{E}$

6% range, 10% curvature
Selecting CC Events

A pure sample of $\nu_\mu$ is selected by:
1. Find events coincident in time with beam spill
2. A well-reconstructed track is found
3. Vertex is within fiducial region
4. Track curvature is consistent with negative muon
5. Cut on likelihood-based particle ID

• Three input Probability Density Functions (PDFs):
  event length, fraction of event pulse height in the reconstructed track, average track pulse height per plane

Input variables for PDF-based event selection
CC Selection Efficiencies

- Particle ID (PID) parameter:
  \[ PID = -\left(\sqrt{-\log(P_\mu)} - \sqrt{-\log(P_{NC})}\right) \]

- CC-like events: PID > -0.2 in the FD (> 0.1 in the ND)
  - NC contamination limited to bins below 1.5 GeV
  - Selection efficiency quite flat as a function of visible energy

PDF PID parameter distribution for true CC and NC events

CC selection efficiencies and purities

Monte Carlo

- Efficiency (87%)
- Purity (97%)

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Near Detector Distributions

- Very large event rates in the Near Detector (~$10^7$ events in the fiducial volume for $10^{20}$ POT)

→ High-statistics dataset:
  - Understand performance of Near Detector
  - Check level of agreement between data and Monte Carlo

Distribution of reconstructed event vertices in the x-y plane

Reconstructed track angle with respect to vertical

Beam points down 3 degrees to reach Soudan
Particle ID Variables and PID Parameter

**Event length**
- LE-10 beam
- Data: Mean 84.27, RMS 72.02
- MC: Mean 84.49, RMS 72.34

**Track pulse height per plane**
- Data: Mean 1037, RMS 608.3
- MC: Mean 1025, RMS 579.3

**Track pulse height fraction**
- Data: Mean 0.6017, RMS 0.256
- MC: Mean 0.5907, RMS 0.249

**PID parameter**
- Data: Mean 0.3565, RMS 0.4516
- MC: Mean 0.3581, RMS 0.4474

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Hadron Production Tuning

Agreement between data and Fluka05 Beam MC pretty good, but by tuning the MC by fitting to hadronic $x_F$ and $p_T$, improved agreement can be obtained.

Weights applied as a function of hadronic $x_F$ and $p_T$. LE-10/Horns off not used in the fit.
Far Detector Beam Analysis

- Oscillation analysis performed using data taken in the LE-10 configuration from 20 May to 6 Dec 2005
  - Total integrated POT: $0.93 \times 10^{20}$
  - POT-weighted FD live time: 98.9%

- Blind analysis
  - Unknown fraction of Far Detector events hidden (based on event length and total energy deposition)
  - “Open” set examined to confirm that there are no problems with FD data
  - Oscillation analyses pre-defined and validated on MC
  - When satisfied that FD data and analysis methods are OK:
    “open the box” and perform final analysis on total sample
  - No re-tuning of cuts allowed after box opening
Selecting Beam Events

- Time-stamping of the neutrino events provided by two GPS units (located at Near and Far Detector sites)
  - FD spill trigger reads out 100 $\mu$s of activity around beam spills
- Far Detector neutrino events easily separated from cosmic muons (0.5 Hz) using topology

Backgrounds were estimated by applying selection algorithm on “fake” triggers taken in anti-coincidence with beam spills.

In 2.6 million “fake” triggers, 0 events survived the selection cuts (upper limit on background in open sample is 1.7 events at 90% C.L.)
Predicting the Un-Oscillated FD Spectrum

- Directly use the Near Detector data to perform extrapolation between Near and Far
- Use Monte Carlo to provide necessary corrections due to energy smearing and acceptance
- Use our knowledge of pion decay kinematics and the geometry of our beamline to predict the FD energy spectrum from the measured ND spectrum

\[ \text{Flux} \propto \frac{1}{L^2} \left( \frac{1}{1 + \gamma^2 \theta^2} \right)^2 \]

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

Known as the Beam Matrix Method
Near to Far Extrapolation

Beam matrix holds our knowledge of two-body pion decay kinematics and geometry.
Alternative Methods to Predict FD Spectrum

- Three other methods to derive FD spectrum from ND data:
  - Extrapolation using Far/Near ratio from MC
  - Fitting to ND data → derive systematic parameters → reweight FD MC
    - Two independent methods: “NDfit” and “2d Grid Fit”

- Above methods have quite different sensitivities to systematic errors
  - Comparing results from all four provides good check of robustness of oscillation measurement
Vertex Distributions

FD box opening 4 March 2006!

- 296 selected events with a track - no evidence of background contamination
- Distribution of selected events consistent with neutrino interactions (uniform distribution of event vertices)
Physics Distributions

Muon momentum (GeV/c)

Shower energy (GeV)

\[ y = \frac{E_{\text{shw}}}{E_{\text{shw}} + P_{\mu}} \]
### Numbers of Events

<table>
<thead>
<tr>
<th>Data sample</th>
<th>observed</th>
<th>expected</th>
<th>ratio</th>
<th>significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>All CC-like events ($\nu_\mu + \bar{\nu}_\mu$)</td>
<td>204</td>
<td>298±15</td>
<td>0.69</td>
<td></td>
</tr>
<tr>
<td>$\nu_\mu$ only (&lt;30 GeV)</td>
<td>166</td>
<td>249±14</td>
<td>0.67</td>
<td>4.0$\sigma$</td>
</tr>
<tr>
<td>$\nu_\mu$ only (&lt;10 GeV)</td>
<td>92</td>
<td>177±11</td>
<td>0.52</td>
<td>5.0$\sigma$</td>
</tr>
</tbody>
</table>

- 33% deficit of events between 0 and 30 GeV with respect to no-oscillation expectation
- **Rate-only significance: 5 standard deviations**
Best-Fit Spectrum

Oscillation Results for 0.93E20 p.o.t

\[ \chi^2 (\Delta m^2, \sin^2 2\theta) = \sum_{i=1}^{\text{nbins}} 2(e_i - o_i) + 2o_i \ln(o_i / e_i) \]

- \[ \Delta m_{23}^2 = 0.00305^{+0.00060}_{-0.00055} \]
- \[ \sin^2(2\theta_{23}) = 0.88^{+0.12}_{-0.15} \]
- \[ \chi^2 / \text{n.d.f.} = 20.5/13 = 1.6 \]
- \[ 1-P(\chi^2, \text{n.d.f.}) = 8.3\% \]

- No disappearance hypothesis
  - \[ \chi^2 / \text{n.d.f.} = 70.0/15 = 4.7 \]
  - \[ 1-P(\chi^2, \text{n.d.f.}) = 4.5e-09 \]

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Ratio Data/MC

Data

Best-fit

NC subtracted

Reconstructed Neutrino Energy
Allowed Regions

\[ \chi^2 / \text{n.d.f.} = 20.5 / 13.0 = 1.6 \]

- MINOS Best Fit: Matrix Method
- MINOS Best Fit: NDfit Method
- MINOS Best Fit: F/N ratio Method
- MINOS Best Fit: 2D Grid Method
- MINOS 68% C.L.
- MINOS 90% C.L.

SuperK 90% C.L.
Super-K (L/E)
K2K 90% C.L.
## Systematic Errors

Systematic shifts in the fitted parameters computed with MC “fake data” samples for $\Delta m^2 = 0.003 \text{ eV}^2$, $\sin^2 \theta = 0.9$:

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>$\Delta m^2$ shift (eV$^2$)</th>
<th>$\sin^2 \theta$ shift</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normalisation +/- 4%</td>
<td>0.63e-4</td>
<td>0.025</td>
</tr>
<tr>
<td>Muon energy scale +/- 2%</td>
<td>0.14e-4</td>
<td>0.020</td>
</tr>
<tr>
<td>Relative Shower energy scale +/- 3%</td>
<td>0.27e-4</td>
<td>0.020</td>
</tr>
<tr>
<td>NC contamination +/- 30%</td>
<td>0.77e-4</td>
<td>0.035</td>
</tr>
<tr>
<td>CC cross-section uncertainties</td>
<td>0.50e-4</td>
<td>0.016</td>
</tr>
<tr>
<td>Beam uncertainty</td>
<td>0.13e-4</td>
<td>0.012</td>
</tr>
<tr>
<td>Intranuclear re-scattering</td>
<td>0.27e-4</td>
<td>0.030</td>
</tr>
<tr>
<td><strong>Total (sum in quadrature)</strong></td>
<td><strong>1.19e-4</strong></td>
<td><strong>0.063</strong></td>
</tr>
<tr>
<td><strong>Statistical error (data)</strong></td>
<td><strong>6.4e-4</strong></td>
<td><strong>0.15</strong></td>
</tr>
</tbody>
</table>
Projected Sensitivity

**Improve this measurement:**
Sensitivity at $16 \times 10^{20}$ POT

- Study neutrino/anti-neutrino oscillations
- Search for/rule out exotic phenomena:
  - Sterile neutrinos, neutrino decay

**Search for sub-dominant $\nu_\mu \rightarrow \nu_e$ oscillations**

$$\Delta m^2 = 0.003 \text{ eV}^2$$
Summary and Conclusions

- MINOS has performed a preliminary oscillation analysis of $0.93 \times 10^{20}$ protons on target
- No disappearance disfavoured at $5.8\sigma$ (shape + rate); $5\sigma$ (rate only)
- Consistent with $\nu$ oscillation results, with parameters:

\[
\Delta m^2_{23} = 3.05^{+0.60}_{-0.55} (\text{stat}) \pm 0.12 (\text{syst}) \times 10^{-3} \text{eV}^2 \\
\sin^2 2\theta_{23} = 0.88^{+0.12}_{-0.15} (\text{stat}) \pm 0.06 (\text{syst})
\]

- Measurement is statistically limited; systematics under control
- Significant improvements expected with more data
  - Total exposure to date: $1.4 \times 10^{20}$ POT
Backup slides
Overview of the Oscillation Measurement

- In order to perform the oscillation analysis, we need to predict the neutrino beam spectrum seen by the Far Detector in the absence of oscillations.

- Want to minimise uncertainties related to beam modelling and cross-sections (nominal values are built-in to our Monte Carlo).

- Use the Near Detector data to correct the nominal Monte Carlo:
  - Beam spectrum
  - Neutrino cross-sections
Current Knowledge of Atmospheric Neutrino Oscillations

- Current best measurements of $\Delta m^2_{23}$ and $\sin^2 2\theta_{23}$ from Super-Kamiokande (atmospheric neutrino analysis) and K2K ($9 \times 10^{19}$ pot)

- The limits (at 90% C.L.) are:
  - $\sin^2 2\theta > 0.9$
  - $1.9 < \Delta m^2 < 3.0 \times 10^{-3} \text{ eV}^2$

- This analysis is for $9.3 \times 10^{19}$ POT, and should provide a competitive measurement of the mixing parameters

Allowed regions from Super-K and K2K
Event Selection Cuts

$\nu_\mu$ CC-like events:

1. Event must contain at least one good reconstructed track
2. Reconstructed track vertex within fiducial volume of detector

Near Detector:
- $1 \text{ m} < z < 5 \text{ m}$ (from detector front),
- $R < 1 \text{ m}$ from beam centre

Far Detector:
- $z > 50 \text{ cm}$ from front face,
- $z > 2 \text{ m}$ from rear face,
- $R < 3.7 \text{ m}$ from detector centre

3. Fitted track should have negative charge (selects $\nu_\mu$)
4. Separation of CC from NC events: cut on likelihood-based Particle ID parameter
Selecting CC Events

- Events selected by likelihood-based procedure
  Three input probability density functions (PDFs):
  • Event length in planes
  • Fraction of event pulse height in the reconstructed track
  • Average track pulse height per plane

- Define $P_\mu (P_{NC})$ as the product of the three CC (NC) PDFs, at the values of these variables taken by the event

**Input variables for PDF-based event selection**

- Event length (planes)
- Track pulse height fraction
- Track pulse height per plane
Near detector rate and event vertices – LE-10 beam

- Event rate is flat as a function of time
- Horn current scans – July 29 – Aug 3
Stability of Energy Spectrum & Reconstruction with Intensity

Proton intensity ranges from $1e13$ ppp to $2.8e13$ ppp

Reconstructed energy distributions agree to within statistical uncertainties (~1-3%)

Beam is very stable and there are no significant intensity-dependent biases in event reconstruction

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Summary of ND Data/MC Agreement

- No obvious pathologies introduced by detector modelling and/or reconstruction

- Agreement between high-level quantities is within expected systematic uncertainties from cross-section modelling, beam modelling and calibration uncertainties
  - Initial agreement improved after applying beam reweighting on the xF and pT of parent hadrons in the Monte Carlo
Predicted True FD Spectrum

- Higher than nominal FD MC in high-energy tail
- Expected, given that the ND spectrum is also higher than the nominal MC in this region
Far Detector Beam Analysis

Oscillation analysis performed using data taken in the LE-10 configuration from 20 May to 6 Dec 2005

- Total integrated POT: $0.93 \times 10^{20}$
- Excluded periods of “bad data”: coil and HV trips, periods without accurate GPS timestamps
  - Effect of these cuts is small: ~0.7% of total POT
- POT-weighted live-time of the Far Detector: 98.9%
Blind Analysis

- **Blind-analysis policy for the first accelerator-neutrino results**
  - Unknown fraction of Far Detector events hidden (based on event length and total energy deposition)

- **No blinding of Near Detector data**

- **Unknown fraction of Far Detector data open**
  - Performed extensive data quality checks

- **Unblinding criteria:**
  - No problems with the Far Detector beam dataset (missing events, reconstruction problems, etc.)
  - Oscillation analysis (cuts and fitting procedures) pre-defined and validated on MC; no re-tuning of cuts allowed after box opening
Particle ID Variables (LE-10 Beam)

Event length

- Data
- MC

RMS 72.02
Mean 84.49
RMS 72.34
Mean 84.27

Track PH per plane

- Data
- MC

RMS 608.3
Mean 1025
RMS 579.3
Mean 1037

Calorimeter/spectrometer boundary

Track PH fraction

- Data
- MC

RMS 0.256
Mean 0.5907
RMS 0.249
Mean 0.6017
PID Parameter

PID cut to select CC-like events is at $-0.1$. 

- **LE-10**: Mean 0.3565, RMS 0.4516
- **pME**: Mean 0.3581, RMS 0.4474
- **pHE**: Mean 0.4093, RMS 0.5112

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Energy Spectra & Ratios (CC-like events)

Reconstructed energy (GeV)

Error envelopes shown on the plots reflect uncertainties due to cross-section modelling, beam modelling and calibration uncertainties.

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Box Opening

- Collaboration agreed on 4 March 2006 to open the box
  - Sufficient confidence in FD data
  - Analysis methods fully validated on MC datasets

Far Detector Data (full dataset)

MINOS PRELIMINARY

- Selected events
- Selected fiducial events with tracks
Track Quantities and PID Parameter

**Track length**

- **Mean**: 86.05
- **RMS**: 71.48

**Track pulse height per plane**

- **Mean**: 824.8
- **RMS**: 345.8

**Particle identification parameter**

- **Mean**: 0.3137
- **RMS**: 0.5544
Track Angles

Notice that beam is pointing 3 degrees up at Soudan!
# Breakdown of Selected Events

<table>
<thead>
<tr>
<th>Cut</th>
<th>Events</th>
<th>efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>All events in fiducial vol</td>
<td>331</td>
<td>-</td>
</tr>
<tr>
<td>Events with a track</td>
<td>296</td>
<td>89.1%</td>
</tr>
<tr>
<td>Track quality cuts</td>
<td>281</td>
<td>95.3%</td>
</tr>
<tr>
<td>PID cut (CC-like)</td>
<td>204</td>
<td>72.9%</td>
</tr>
<tr>
<td>Track charge sign cut (negative muons only)</td>
<td>186</td>
<td>91.2%</td>
</tr>
<tr>
<td>Reconstructed energy &lt; 30 GeV</td>
<td>166</td>
<td>89.2%</td>
</tr>
</tbody>
</table>