Recent Results from the MINOS Experiment

Costas Andreopoulos (*)

* for the MINOS collaboration
• Introduction
  • Neutrino Oscillations
  • Open Questions
  • MINOS Physics Goals

• The MINOS Experiment
  • How is it done?
  • The NuMI beamline at Fermilab
  • The Detectors
    • *Detector technology*
    • *The FAR & NEAR detectors*
    • *MINOS calibration*
  • Interaction types & Event topologies

• The nu\_mu CC disappearance analysis
  • Event selection
  • NEAR Detector Energy Spectra
  • Hadron production tuning
  • Predicting the FAR Detector Energy Spectrum
  • Observed Rates & Best fit spectrum
  • Allowed Regions & Best fit parameters
  • Systematics
  • Projected Sensitivity

• Summary
Neutrino Oscillations

A quantum-mechanical interference effect

Production & Detection: Governed by electroweak hamiltonian

**Producing / detecting interaction eigenstates**
(superposition of mass eigenstates)

\[
\begin{pmatrix}
    \nu_e \\
    \nu_\mu \\
    \nu_\tau
\end{pmatrix} =
\begin{pmatrix}
    U_{e1} & U_{e2} & U_{e3} \\
    U_{\mu1} & U_{\mu2} & U_{\mu3} \\
    U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{pmatrix}
\begin{pmatrix}
    \nu_1 \\
    \nu_2 \\
    \nu_3
\end{pmatrix}
\]

PMNS (CKM-like) unitary matrix

Propagation: Governed by free hamiltonian

Each mass eigenstate propagates at different pace!

Relative mixture of mass eigenstates changes!

Flavour oscillations are possible

\[
P(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} - 4 \sum \Sigma U_{\alpha i} U_{\beta i} U_{\alpha j} U_{\beta j} \sin^2[\Delta m_{ij}^2 L / 4 E_v]
\]

Phenomenon has been observed with: **solar, atmospheric, reactor & accelerator** neutrinos!
Open Questions

Goals:
- Determine the elements of the PMNS matrix
- Determine neutrino mass (splitting)

- Impressive progress over the past decade - A 'precision measurement' era for neutrinos
- Still many open questions:
  - How close to 0 is $\theta_{13}$? (hidden symmetry?)
  - Is $\theta_{23}$ maximal? (hidden symmetry?)
  - Can we measure the absolute scale? (not accessible with oscillations)
  - Which one? … or none (quasi-degenerate)?
  - Is CP violated at the leptonic sector?
Physics Goals for MINOS

**MINOS: A precision oscillation experiment**

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

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

- Search for/constrain exotic phenomena

- Compare $\nu_\mu, \bar{\nu}_\mu$ oscillations

- Atmospheric neutrino oscillations
  - *Phys. Rev. D73, 072002 (2006)*
A 2 detector, long-baseline neutrino experiment using an intense, accelerator-made beam source $(\nu_{\mu})$ is here.

- **NearDet** measures "oscillated" flux.
- **FarDet** measures "un-oscillated" flux.

**Outline**
- Oscillations
- MINOS Goals
- MINOS Overview
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- Events
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  - ND Spectra
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**Summary**

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Reducing systematic errors

- Effect of large flux & cross-section uncertainties minimized
- Detector / reconstruction effects minimized
- 'Unoscillated' FAR spectrum extrapolated from NEAR

Monte Carlo

- Measures squared mass splitting
- Measures mixing strength

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The MINOS Collaboration

- Brazil: Campinas – Sao Paulo
- France: College de France
- Greece: Athens
- Russia: ITEP Moscow – Lebedev – Protvino
- UK: Cambridge – Oxford – RAL – Sussex - UCL

- MINOS Near Detector surface building
- v’s towards Soudan

- 6 countries
- 32 institutions
- ~175 physicists
The NuMI beamline @ Fermilab

A 'conventional' neutrino beam

- Pure / intense muon neutrino beam
- Tunable energy

First year averages:
- Intensity: 2.3E+13 POT/spill
- Cycle: 2.2 s
- Power: 170 kW

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Summary
Massive segmented iron calorimeters, with inexpensively produced plastic scintillator as active material. The scintillation light is collected by WLS fibers read out by multianode PMTs.
The FAR Detector @ Soudan mine

**Purpose:**
- Measure $\nu_{\mu}$ CC, NC — energy spectra & rates
- Search for $\nu_{e}$ appearance
- Atmospheric Neutrino physics studies (upgoing muons, contained neutrino events,...)
- Cosmic Ray physics studies (mu+/mu- charge ratio, point sources, ...)

- at Soudan mine, MN
- ~ 735 km from NuMI target
- depth: ~ 750 m
- ~ 5.4 kton
- 486 steel planes
- $B \sim 1.3 \ T$
- 2-ended readout
- 16-anode PMTs (HPK M16)
- x8 optical multiplexing
- VA electronics

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**Summary**

Operational since June 2003
The NEAR Detector @ Fermilab

**Purpose:**
- Measure beam with high statistics before oscillations
- Tune neutrino & beam / hadron-production MC
- Predict Far detector spectrum

- at Fermilab
- ~ 1 km from NuMI target
- swallow depth: ~ 100 m
- ~ 1 kton
- 282 steel planes
- B Field ~ 1.2 T
- 1-ended readout
- 64-anode PMTs *(HPK M64)*
- no multiplexing upstream
- 4x MUX in spectrometer
- Very high rates
- QIE electronics (no deadtime during spill)

operational since ~ November 2004
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**MINOS Calibration**

- Calibration detector
  - Determine overall energy scale
- Light Injection system
  - Determine/monitor PMT gains
- Cosmic ray muons
  - Equalize strip to strip response
  - Equalize detector to detector response

**Single particle energy resolution**

- 55% / $\sqrt{E}$
- 23% / $\sqrt{E}$

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

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Summary
How do neutrinos interact at few GeV?

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LAr images, courtesy A.Currioni

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Event topologies

Monte Carlo Events

- **nu_mu CC**
  - long $\mu$ track
  - hadronic activity at vertex

- **NC**
  - short event
  - often diffuse

- **nu_e CC**
  - short event
  - typical EM shower profile
The 1\textsuperscript{st} year \(1.27\times10^{20}\) POT
\textit{nu}_\textit{mu} CC
Disappearance Analysis

D.G. Michael et al, PRL 97, 191801 (2006)
Events in time with the beam

Vertex in fiducial volume

**FAR:**
- $z > 0.50 \text{ m from edge}, z > 2 \text{ m from end}$,
- within $3.7 \text{ m of detector centre}$

**NEAR:**
- $1 \text{ m} < z < 5 \text{ m from upstream end}$,
- within $1 \text{ m of the beam centre}$

At least one good reconstructed track
- With **negative charge**
Using a maximum likelihood technique with 3 input PDFs:
Error envelopes indicates size of beam modelling, neutrino interaction modelling and calibration uncertainties (combined).

Good Data / MC agreement
Hadron production tuning

- Hadro-production (Fluka05 based beam simulation) tuning
- Even better data / MC agreement is obtained
- Applied weights as function of xF and pT

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Summary
The 'Matrix' method:

- The un-oscillated FAR spectrum is determined by the NEAR spectrum
- No dead-reckoning based on MC. The MC is used only for providing corrections
- Measured NEAR spectrum is extrapolated based only on knowledge of pion decay kinematics & the beamline geometry

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

\[ \text{Flux} \propto \frac{1}{L^2} \left( \frac{1}{1 + \gamma^2 \theta^2} \right)^2 \]
• Alternative extrapolation methods give nearly identical results
• Confidence in our ability to predict the un-oscillated FAR spectrum
• Having a 2-detector experiment pays off!
### Observed rates & best-fit spectrum

<table>
<thead>
<tr>
<th>Data sample</th>
<th>observed</th>
<th>expected</th>
<th>ratio</th>
<th>significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_\mu$ only (&lt;30 GeV)</td>
<td>215</td>
<td>336.0±14.4</td>
<td>0.64±0.05</td>
<td>5.2σ</td>
</tr>
<tr>
<td>$\nu_\mu$ only (&gt;10 GeV)</td>
<td>93</td>
<td>97.3±4.2</td>
<td>0.96±0.04</td>
<td>0.4σ</td>
</tr>
<tr>
<td>$\nu_\mu$ only (&lt;10 GeV)</td>
<td>122</td>
<td>238.7±10.7</td>
<td>0.51±0.06</td>
<td>6.2σ</td>
</tr>
</tbody>
</table>

\[
\chi^2 = \sum_{i=1}^{n\text{bins}} \left[ 2(e_i - o_i) + 2o_i \ln(o_i/e_i) \right] + \sum_{j=1}^{n\text{sys}} \Delta s_j^2 / \sigma_{s_j}^2
\]

See energy dependent suppression
Allowed regions & Best fit parameters

Best fit parameters:

\[ |\Delta m^2_{32}| = 2.74^{+0.44}_{-0.26} \text{ (stat + syst)} \times 10^{-3} \text{ eV}^2 \]

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

Computed with fake (mc) data at $\Delta m^2=0.0027\,\text{eV}^2$, $\sin^2 2\theta=1.0$

<table>
<thead>
<tr>
<th>Preliminary Uncertainty</th>
<th>Shift in $\Delta m^2$ (10$^{-3}$ eV$^2$)</th>
<th>Shift in $\sin^2 2\theta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Near/Far normalization +/−4%</td>
<td>0.050</td>
<td>0.005</td>
</tr>
<tr>
<td>Absolute hadronic energy scale +/−11%</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 systematic uncertainties</td>
<td>0.044</td>
<td>0.011</td>
</tr>
<tr>
<td>Total systematic (summed in quadrature)</td>
<td>0.13</td>
<td>0.07</td>
</tr>
<tr>
<td>Statistical error (data)</td>
<td>0.36</td>
<td>0.12</td>
</tr>
</tbody>
</table>

- 3 largest uncertainties included in oscillation fit as nuisance parameters
- Size of uncertainties are obtained by doing MC studies
- Table shows shift in the oscillation parameters by fitting fake data
An updated analysis is coming soon (~2.6E+20 POT)

**MINOS Sensitivity as a function of Integrated POT**

\[ \Delta m^2 (eV^2) \]

- statistical errors only

- 90% CL

- Super-K (zenith angle)

- 1.27\( \times \)10\(^{20} \) POT
- 2.5\( \times \)10\(^{20} \) POT
- 7.4\( \times \)10\(^{20} \) POT
- 16\( \times \)10\(^{20} \) POT

**Input**: \( \Delta m^2 = 0.00274 eV^2, \sin^22\theta = 1.0 \)

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**Summary**
MINOS has completed / published a numu CC disappearance analysis of the first year's beam exposure (1.27E+20 POT)

Exclude no-oscillations at 6.2σ (rate only)

$$|\Delta m_{32}^2| = 2.74^{+0.44}_{-0.26} \text{(stat + syst)} \times 10^{-3} \text{eV}^2$$

$$\sin^2 2\theta_{23} = 1.00^{+0.13}_{-0.03} \text{(stat + syst)}$$

Analysis of the second year's data in progress

More analyses under way (numu->nue, search for sterile nus,...)
Back-up Slides
Back-up Slide
Back-up Slide

Hadron Production Uncertainty

Far Detector
- GNUMI v17 LE (-10cm, 1.85kA)
- FLUKA’05 LE (-10cm, 1.85kA)
- MARS LE (-10cm, 1.85kA)

Beam MC

Spread due to models:
- 8% (peak)
- 15% (tail)
Physics reach: $\nu_e$ appearance

90% CL Sensitivity to $\sin^2(2\theta_{13})$

- **MINOS**
  - $\Delta m^2_{23} = 2.7 \times 10^{-3}$ eV$^2$
  - $\sin^2(2\theta_{23}) = 1$
  - $4 \times 10^{20}$ pot

Expected "exposure" by the end of the year

- **CHOOZ**
  - 90% CL Excluded

**MINOS Preliminary**

- $\Delta m^2 > 0$
- $\Delta m^2 < 0$
Muons momentum  
Shower energy  
Inelasticity $y$
Atmospheric Neutrinos

PRD 73, 072002 (2006)

<table>
<thead>
<tr>
<th>Selection</th>
<th>Data</th>
<th>Expected no oscillations</th>
<th>Expected $\Delta m^2_{33} = 0.0024 \text{ eV}^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Res.</td>
<td>30</td>
<td>$37 \pm 4$</td>
<td>$28 \pm 3$</td>
</tr>
<tr>
<td>Ambig. $\nu_\mu / \overline{\nu}_\mu$</td>
<td>25</td>
<td>$26 \pm 3$</td>
<td>$20 \pm 2$</td>
</tr>
<tr>
<td>$\nu_\mu$</td>
<td>34</td>
<td>$42 \pm 4$</td>
<td>$31 \pm 3$</td>
</tr>
<tr>
<td>$\overline{\nu}_\mu$</td>
<td>18</td>
<td>$23 \pm 2$</td>
<td>$17 \pm 2$</td>
</tr>
</tbody>
</table>
**Neutrino Time Of Flight**

GPS synchronises two detectors

Distance known precisely: $734,298.6 \pm 0.7$ m

**Time of Flight Measurement:**
Nominal: $(734298.6 \pm 0.7$ m distance)
$2449356$ ns

Measured:
$2449223 \pm 84$ (stat) $\pm 164$ (sys) ns

Neutrino Velocity:
$(v-c)/c = 5.4 \pm 7.5 \times 10^{-5}$

99% C.L.
High rates, Multiple neutrino interactions per beam spill.
Track energy from range: 9.596 GeV
Reconstructed Shower energy: 5.108 GeV