Recent Results from the MINOS Experiment

Costas Andreopoulos (*)

* for the MINOS collaboration

Double Beta Decay & Neutrinos 2007 (DBD07), June 11-13, Osaka, Japan
• 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
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

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

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

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

• 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?)
  - Which one? … or none (quasi-degenerate)?
  - Is $\theta_{23}$ maximal?
    (hidden symmetry?)
  - Can we measure the absolute scale?
    (not accessible with oscillations)
  - Is CP violated at the leptonic sector?
  - Dirac/Majorana?
    (not accessible with oscillations)
  - Which one? … or none (quasi-degenerate)?
Physics Goals for MINOS

- 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
How the experiment is done

A 2 detector, long-baseline neutrino experiment using an intense, accelerator-made beam
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

Outline
- v Oscillations
- MINOS Goals
- MINOS Overview
- Beamline
- Detectors
- Events

Event Id
- ND Spectra
- Tuning
- FD Prediction
- Observed spectrum
- Allowed Regions
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Summary
Why a 2 detector experiment? Reducing systematic errors

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Hadron Production Uncertainty

Why a 2 detector experiment? Reducing systematic errors

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Summary

<table>
<thead>
<tr>
<th>Spread due to models:</th>
</tr>
</thead>
<tbody>
<tr>
<td>– 8% (peak)</td>
</tr>
<tr>
<td>– 15% (tail)</td>
</tr>
</tbody>
</table>
The MINOS Collaboration

- 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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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.
**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, ...)

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**B Field**
- 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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**Operational since**
June 2003

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**Summary**
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The NEAR Detector @ Fermilab

- at Fermilab
- ~ 1 km from NuMI target
- ~ 1 kton
- 282 steel planes
- B Field ~ 1.2 T
- scintillator plane
- steel plane (magnetized)
- coil hole
- 3.8 m
- PMTs & front-end electronics
- 1-ended readout
- 64-anode PMTs (HPK M64)
- no multiplexing upstream
- 4x MUX in spectrometer
- no deadtime during spill!
- QIE electronics
- operational since November 2004

Purpose:

- Measure beam with high statistics before oscillations
- Tune neutrino & beam / hadron-production MC
- Predict Far detector spectrum
- Predicted Sensitivity
- Systematics
- Allowed Regions
- Observed spectrum
- FD Prediction
- Tuning
- ND Spectra
- Event ld
- Events

Outline
- MINOS Overview
- Detector
- Beamline
- MINOS Goals
- V Oscillations
• 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

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

$55\% / \sqrt{E}$
$23\% / \sqrt{E}$
How do neutrinos interact at few GeV?

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QEL CC

DIS CC

low multiplicity inelastic CC (RES)

LAr images, courtesy A.Currioni

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Event topologies

Monte Carlo Events

nu_mu CC

NC

nu_e CC

• long μ track
• hadronic activity at vertex

• short event
• often diffuse

• short event
• typical EM shower profile

Outline

v Oscillations

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The 1st year (1.27E+20 POT) nu_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 m of detector centre

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

At least one good reconstructed track
- With negative charge
Event Selection

Using a maximum likelihood technique with 3 input PDFs:

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Summary
Error envelopes indicates size of beam modelling, neutrino interaction modelling and calibration uncertainties (combined).

Good Data / MC agreement
Tuning

● Hadro-production (Fluka05 based beam simulation) tuning

● Even better data / MC agreement is obtained

● Applied weights as function of xF and pT

Weights applied vs p_{z} & p_{T}
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>

$\chi^2 = \sum_{i=1}^{n \text{bins}} 2(e_i - o_i) + 2o_i \ln(o_i/e_i) + \sum_{j=1}^{n \text{sys}} \Delta s_j^2 / \sigma_j^2$

See energy dependent suppression.
Δm^2_{32} = 2.74^{+0.44}_{-0.26} \text{ (stat + syst)} \times 10^{-3} \text{ eV}^2

\sin^2 \theta_{23} = 1.00^{+0.15}_{-0.13} \text{ (stat + syst)}
Computed with fake (mc) data at $\Delta m^2=0.0027\,\text{eV}^2$, $\sin^22\theta=1.0$

<table>
<thead>
<tr>
<th>Preliminary Uncertainty</th>
<th>Shift in $\Delta m^2$ ($10^{-3},\text{eV}^2$)</th>
<th>Shift in $\sin^22\theta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Near/Far normalization $\pm-4%$</td>
<td>0.050</td>
<td>0.005</td>
</tr>
<tr>
<td>Absolute hadronic energy scale $\pm-11%$</td>
<td>0.060</td>
<td>0.048</td>
</tr>
<tr>
<td>NC contamination $\pm-50%$</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)

\[ \Delta m^2 = 0.00274 \text{eV}^2, \quad \sin^2 2\theta = 1.0 \]
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)

\[
|\Delta m^2_{32}| = 2.74^{+0.44}_{-0.25} \text{ (stat + syst)} \times 10^{-3} \text{ eV}^2 \\
\sin^2 2\theta_{23} = 1.00^{+0.00}_{-0.13} \text{ (stat + syst)}
\]

Analysis of the second year's data in progress

More analyses under way (numu->nue, search for sterile nus,...)
Back-up Slides
Physics reach: $\nu_e$ appearance

Expected "exposure" by the end of the year
Muons momentum

Shower energy

Inelasticity $y$

### Shower Energy Distribution

- **Data**: Mean 6.764, RMS 6.185
- **MC**: Mean 6.383, RMS 5.795

### Muon Momentum Distribution

- **Data**: Mean 0.3951, RMS 0.2595
- **MC**: Mean 0.3968, RMS 0.2574

*MINOS PRELIMINARY*
Back-up Slide

PRD 73, 072002 (2006)
GPS synchronises two detectors

Distance known precisely: 734,298.6 ± 0.7 m

Time of Flight Measurement:
Nominal: (734298.6 ± 0.7 m distance) 2449356 ns
Measured: 2449223 ± 84 (stat) ± 164 (sys) ns 99% C.L.

Neutrino Velocity:
\( (v-c)/c = 5.4 \pm 7.5 \times 10^{-5} \) 99% C.L.
Track energy from range: 9.596 GeV
Reconstructed Shower energy: 5.108 GeV
High rates, Multiple neutrino interactions per beam spill.