Recent results from the MINOS experiment

Mayly Sanchez
Harvard University
Outline of this talk

• The MINOS experiment
  • Physics goals
  • The hardware: the beam and the detectors
• The $\nu_\mu$ disappearance analysis
  • Results from the first year of running now published in PRL
• Progress in other MINOS Physics
  • Time-of-flight analysis
  • Neutral Current analysis
  • $\nu_e$ appearance analysis
The MINOS Collaboration

32 institutions
175 physicists

Brazil • France • Greece
Russia • UK • USA

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

Mayly Sanchez - Harvard University
MINOS physics goals

- Test for the $\nu_\mu \rightarrow \nu_\tau$ oscillation hypothesis
  - Measure precisely $|\Delta m_{23}^2|$ and $\sin^2 2\theta_{23}$
- Search for and constrain exotic phenomena
  - Sterile $\nu$, $\nu$ decay, etc.
- Search for sub-dominant $\nu_\mu \rightarrow \nu_e$ oscillations (i.e. measure $U_{e3}$)
- Atmospheric neutrino oscillations
  - Compare $\nu$ and $\bar{\nu}$ oscillations (Phys. Rev. D73, 072002 (2006))
MINOS basic idea

- Produce a high intensity beam of neutrinos at Fermilab.
- Measure the energy spectrum at a Near location (Fermilab).
- Measure the energy spectrum at a Far location, 735 km away (Soudan).
- If neutrinos oscillate, you will see evidence of the oscillation at the Far location.

Main Injector Neutrino Oscillation Search

Map showing the locations of Fermilab, Soudan, Duluth, Madison, and other nearby cities.
MINOS physics goals

Seeing $\nu_\mu$ disappearance

\[ P(\nu_\mu \rightarrow \nu_\tau) = \sin^2(2\theta) \sin^2 \left( \frac{1.27 \Delta m_{23}^2 L}{E_\nu} \right) \]

Monte Carlo

NC background

NC subtracted

0.0033 eV^2

Seeing ! disappearance
The NuMI facility

Where do we produce the neutrinos?

**April 2, 2007: ~2.6x10^{20} POT**

Doubled the data of 1st year result!

- 120 GeV protons from the Main Injector.
- Main Injector can accept up to 6 Booster batches/cycle.
- Either 5 or 6 batches for NuMI.
- ~1.9 second cycle time.
- Intensity: 4x10^{13} POT/spill.
- Single turn extraction: ~10µs spill.
- Beam power: 0.4 MW.

**Record intensity!**

4 x 10^{13} POT/Spill

- Averages (first year):
  - Cycle spacing 2.2s.
  - Intensity 2.3x10^{13} POT/spill.
  - Power 170kW.
The NuMI beamline

How do we produce the neutrinos?

- Extract protons
- Point them 3.3° downward

*120GeV* protons hit graphite target, producing pions.
*Horn pulsed at 200kA, toroidal field focuses pions.
*675m* long decay pipe, evacuated to 1.5 Torr.

Pion decay produces muons and neutrinos.

10 µs spill every 1.9s
The NuMI beamline

What neutrino energies can we produce?

- Relative positions of the target to the horns allow the energy of the beam to be tuned.

<table>
<thead>
<tr>
<th>Beam</th>
<th>Target z position (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>

We took $\sim 1.5 \times 10^{18}$ POT in pME and pHE configurations.

- Beam composition: 92.9% $\nu_\mu$, 5.8% $\bar{\nu}_\mu$, 1.3% $\nu_e + \bar{\nu}_e$

We have started running with the low energy beam, which is best for $\Delta m^2 \sim 0.0025$ eV$^2$. Position of osc. minimum for $\Delta m^2 = 0.0025$ eV$^2$. Events in Fiducial Volume
**Detector technology**

Iron/scintillator tracking calorimeter

- 2.54cm steel planes, 1.2T field.
- 4.1 x 1cm scintillator strips, up to 8m long. Extruded polystyrene (TiO$_2$ coating).
- Readout via wavelength shifting fibers (1.2mm).
- Hamamatsu multi-anode PMTs, (M16 Far and M64 Near).
- GPS timestamps to match data.
- Alternate planes (U,V) rotated 90°, for 3D hits.
MINOS Near

What is the neutrinos’ first stop?
Fermilab, IL

- ~1 kton (980 tons) total mass
- Squashed octagons (4.8 x 3.8m), since beam cross section small
- Partially instrumented (282 planes of steel, 153 planes of scintillator)
- Fast QIE electronics, continuous digitization during spill, 19ns time slices.
- Strips readout from one side only.
- Spectrometer multiplexed (x4).

Most planes are Partial, with 1 in 5 Full Full planes only, 1 in 5 instrumented, bare steel between

<table>
<thead>
<tr>
<th>Veto planes</th>
<th>Target planes</th>
<th>Hadron Shower planes</th>
<th>Muon Spectrometer planes</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 20</td>
<td>21 - 60</td>
<td>61 - 120</td>
<td>121 - 281</td>
</tr>
</tbody>
</table>
MINOS Far

Where do the neutrinos travel to?
Soudan, MN

- 2 supermodules (~15m each).
- 486 steel planes (8m octagons, 2.54cm thick) alternated with 484 scintillator planes.
- 5.4 kton total mass.
- VA electronics.
- Both sides strip readout.
- Multiplexing 8 fibers to 1 channel.
- Continuous untriggered readout of the whole detector.
MINOS calibration system

- Calibration of ND and FD response using:
  - Light Injection system (PMT gain)
  - Cosmic ray muons (strip to strip and inter-detector)
  - Calibration detector (overall energy scale)
    - mini-Minos on a CERN test beam

- Energy scale calibration:
  - 5.6% absolute error
  - ND-FD rel: 2.0%

Single particle energy resolution

- Resolution vs. available energy
  - $55\% / \sqrt{E}$
  - $23\% / \sqrt{E}$
The $\nu_\mu$ disappearance analysis
Neutrino Event topologies

What do neutrinos look like?

$\nu_\mu$ CC event

- $\mu$ track
- $+$ hadronic activity

$\nu_e$ CC event

- compact shower
- typical EM shower profile

NC event

- often diffuse
- can mimic $\nu_\mu, \nu_e$
The event selection cuts

- Events in time with the beam.
- At least one good reconstructed track.
- The fitted track should have negative charge.
- The reconstructed track vertex should be within the fiducial volume of the detector:
  - Near:
    1m < z < 5m from detector front
    r < 1m from beam center
  - Far:
    z > 50 cm from edge, z > 2m from end, r < 3.7 from detector center

Time difference of neutrino interactions from beam spill

Neutrino candidates are in ~10μs window

0.5 Hz cosmic mu rate

1.27×10²⁰ POT

Number of events vs Time relative to FD spill time prediction (μs)

Neutrino candidates are in ~10μs window
The event selection cuts

- Events selected by likelihood-based procedure, with 3 input probability functions (PDFs):

- We define the probability $P_\mu (P_{NC})$ as the product of the 3 CC (NC) PDFs at the value of these variables taken by the event.
Hadron production tuning

- Agreement between data and Fluka05 Beam MC is pretty good, but by tuning to hadronic $x_f$ and $p_t$, improved agreement can be obtained.

Weights applied as a function of hadronic $x_f$ and $p_t$
Predicting the FD spectrum

- Directly use Near Detector data to perform extrapolation between Near and Far. Have the Monte Carlo provide necessary corrections due to energy smearing and acceptance.
- Then use our knowledge of pion decay kinematics and geometry of our beamline to predict the FD energy spectrum from the measured ND spectrum.
- This method is known as the “Beam Matrix” method.
Results with all four methods are compared to check the robustness of our oscillation measurement.

- The matrix method is very powerful to extrapolate the Near detector spectrum to the Far. However we have investigated 3 other methods:
  - F/N ratio: Extrapolation using the Far/Near spectrum ratio from MC.
  - NDfit: Reweight the FD MC using systematic parameters obtained by the ND fit.
  - 2d Grid Fit: Reweight the FD MC using E vs y correction matrix and systematic parameters obtained by the ND fit.
- Results will be shown with the Beam Matrix and the NDfit.
Final Results
from $1.27 \times 10^{20}$ POT

We observe a 49% deficit between 0 and 10 GeV with respect to the no disappearance hypothesis.
The statistical significance is $6.2\sigma$ (stat+syst).

<table>
<thead>
<tr>
<th>Data sample</th>
<th>observed</th>
<th>expected</th>
<th>ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_\mu$ (≤30 GeV)</td>
<td>215</td>
<td>336.0±14.4</td>
<td>0.64±0.05</td>
</tr>
<tr>
<td>$\nu_\mu$ (≤10 GeV)</td>
<td>122</td>
<td>238.7±10.7</td>
<td>0.51±0.05</td>
</tr>
<tr>
<td>$\nu_\mu$ (≤5 GeV)</td>
<td>76</td>
<td>168.4±8.8</td>
<td>0.45±0.06</td>
</tr>
</tbody>
</table>
\[ |\Delta m^2_{32}| = 2.74^{+0.44}_{-0.26} \text{(stat + syst)} \times 10^{-3} \text{eV}^2 \]
\[ \sin^2(2\theta_{23}) = 1.00^{+0.13}_{-0.13} \text{(stat + syst)} \]
Systematic errors

Systematic shifts in the fitted parameters have been computed with MC “fake data” samples for $\Delta m^2=0.0027$ eV$^2$, $\sin^22\theta=1.0$ for the following uncertainties:

<table>
<thead>
<tr>
<th>Preliminary Uncertainties</th>
<th>$\Delta m^2$ shift ($10^{-3}$ eV$^2$)</th>
<th>$\sin^22\theta$ shift</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) N/F Normalization ± 4%</td>
<td>0.050</td>
<td>0.005</td>
</tr>
<tr>
<td>(2) Abs. hadronic energy scale ± 11%</td>
<td>0.060</td>
<td>0.048</td>
</tr>
<tr>
<td>(3) NC contamination ± 50%</td>
<td>0.090</td>
<td>0.050</td>
</tr>
<tr>
<td>(4) All other systematics</td>
<td>0.044</td>
<td>0.011</td>
</tr>
<tr>
<td>Total (sum in quadrature)</td>
<td>0.12</td>
<td>0.07</td>
</tr>
<tr>
<td>Statistical error (data)</td>
<td>0.36</td>
<td>0.12</td>
</tr>
</tbody>
</table>

The main systematic uncertainties (1), (2) and (3) are used as nuisance parameters in fitting the data.
Comparison of fit results

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

\[
\sin^2(2\theta_{23}) = 1.00_{-0.13} \text{(stat + syst)}
\]
More MINOS physics in progress
Physics reach of MINOS

\( \nu_\mu \) disappearance

- Input parameters \( |\Delta m_{32}^2| = 2.74 \times 10^{-3}\text{eV}^2, \sin^2(2\theta_{23}) = 1.00 \)

- Statistical errors only (90\% CL)

Coming soon: \( \sim 2.6 \times 10^{20}\text{ POT} \)

On track for this summer!
Neutrino time of flight

- GPS sync of the two detectors.
- We can measure the distribution times in the two detectors.
- Log likelihood fit then allows the time of flight for the neutrinos to vary.

Current PDG value: 
\(< 4 \times 10^{-5} \text{ (95\% CL)}\)

Time of Flight Measurement:
Nominal: \((734298.6 \pm 0.7 \text{ m distance})\)
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.

MINOS PRELIMINARY
The NC measurement
looking for $\nu_\mu \rightarrow \nu_s$ or $\nu$ decay

- Comparing Near/Far Neutral Current spectrum, sensitive to sterile neutrinos.
- NC events are more prone to intensity related issues, so we first study the spectra in the Near with high and low multiplicity.

Look for first results in the fall!
Physics reach of MINOS searching $\nu_e$ appearance

- We have a chance at making the first measurement of $\theta_{13}$.
  - Matter effects can change $\nu_e$ yield by as much as $\pm 20\%$
- Plot shows $\delta_{CP}$ vs. $\sin^22\theta_{13}$ for both hierarchies for MINOS best fit value at $4 \times 10^{20}$ POT
  - 10\% systematic effect included
- We can improve on current best limit (Chooz).

Expect $4 \times 10^{20}$ POT by the end of the year
We have published an oscillation analysis of the first year of beam exposure for $1.27 \times 10^{20}$ POT (PRL 97:191801, 2006).

Our result disfavours no oscillations at $6.2 \sigma$ (rate only) and using the shape the data is consistent with $\nu_\mu$ disappearance with the following parameters:

$$|\Delta m_{32}^2| = 2.74^{+0.44}_{-0.26}(\text{stat} + \text{syst}) \times 10^{-3} \text{eV}^2$$
$$\sin^2(2\theta_{23}) = 1.00_{-0.13}(\text{stat} + \text{syst})$$

A fit constrained to the $\sin^2 2\theta_{23} = 1$ boundary yields:

$$|\Delta m_{32}^2| = 2.74 \pm 0.28 \times 10^{-3} \text{eV}^2$$

The systematics uncertainties are under control and we should make significant improvements with a larger data set.

The second year of running is now done, expect results this summer.

Stay tuned for our other measurements!
The End
Backup Slides
Systematics

- Normalization: ± 4 %
  - POT counting, Near/Far selection efficiency, Fiducial mass
- Absolute shower energy scale (± 6%) / Intranuclear rescattering (± 10%): ± 11 %
- NC contamination of CC-like sample: ± 50%
  - From shape and normalization of ND PID distributions
- Relative shower energy scale: ± 2%
  - Inter-Detector calibration uncertainty
- Muon energy scale: ± 2%
  - Uncertainty in dE/dX in MC
- CC cross-section uncertainties
  - $M_A(QEL)$ and $M_A(RES)$: ± 5%
  - KNO RES-DIS scaling factor: ± 20%
- Beam uncertainty: difference between fits and weighted/unweighted MC
The diagram illustrates the ratio of far to near event spectra under different conditions. The x-axis represents the neutrino energy ($E_\nu$) in GeV, and the y-axis shows the ratio on a scale from $10^{-6}$ to 2. The graph shows three distinct regions:

- **Horn 1&2 Necks**
- **Decay Pipe**
- **Edge**

The horizontal line at 2 indicates the threshold for detection. The graph includes three different simulations:

- **Point Source**
- **Line Source**
- **Full simulation**

The point source simulation shows a significant drop-off at lower energies, while the line source simulation remains relatively flat. The full simulation combines these effects, reflecting a more complex interaction scenario.
Physics reach of MINOS

$\nu_e$ appearance

- Expected events from MC for $1.4 \times 10^{20}$ POT

<table>
<thead>
<tr>
<th></th>
<th>MC events</th>
<th>66%</th>
<th>$\sin^2 \theta_{23} = 1.0$</th>
<th>$\Delta m_{23}^2 = 0.0025 \text{ eV}^2$</th>
<th>$\sin^2 (2\theta_{13}) = 0.12$</th>
</tr>
</thead>
<tbody>
<tr>
<td>NC</td>
<td>2.80</td>
<td>(66%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CC</td>
<td>0.62</td>
<td>(15%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beam $\nu_e$</td>
<td>0.58</td>
<td>(14%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\nu_{\tau}$</td>
<td>0.23</td>
<td>(5%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total bg</td>
<td>4.23</td>
<td></td>
<td></td>
<td></td>
<td>2.8 signal events</td>
</tr>
</tbody>
</table>

- Backgrounds will be estimated from data:
  - Horn off data in ND: disentangle NC-CC
  - Beam $\nu_e$: measure $\bar{\nu}_\mu$ from $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$ in ND
  - Muon removal in CC events: estimating NC bg.