MINOS Experiment

Cat James
Particle Physics Division
Neutrino Department
Outline

• Introduction
  – The MINOS Experiment & Detectors, NuMI Beam
  – The MINOS collaboration & FNAL MINOS group

• MINOS & NuMI this past year
  – Performance, uptime, accumulated POT

• A Selection of Recent Physics Results
  – CC oscillation analysis
  – Cosmic Ray Charged Ratio

• Physics in the pipeline
  – NC event analysis
  – $\nu_e$ appearance analysis
Introduction – MINOS Physics Goals

- Precision studies of $\nu_\mu$ disappearance.
  - Measure $\Delta m^2_{23}$ and $\sin^2 2\theta_{23}$  \textit{PRL 97, 191801 (2006)}
  - High statistics constraints on alternative disappearance models. (e.g. neutrino decay, neutrino decoherence, sterile neutrinos ... )

- Search for sub-dominant $\nu_e$ appearance.
  - First observation or improved limit for small mixing angle $\theta_{13}$.

- Atmospheric neutrino oscillations.
  - Contained vertex $\nu_\mu$ CC interactions. \textit{PRD 73, 072002 (2006)}
  - Neutrino-induced upward-going muons. \textit{PRD 75, 092003 (2007)}

- Cosmic ray physics.
  - Muon charge ratio at TeV energies. \textit{PRD 76, no. 5, Sep 20, 2007}
Main Injector Neutrino Oscillation Search
a two detector long baseline
ν oscillation experiment.

• Accelerator beam of muon neutrinos, produced by NuMI facility at Fermilab.

• Use the Near Detector at Fermilab to measure the spectrum and composition of the neutrino beam. The measured ND spectrum is directly used to predict the Far Detector un-oscillated spectrum.

• Use the Far Detector at the Soudan mine to study neutrino disappearance in the beam. Beam production modeling and neutrino cross section uncertainties cancel out between the two Detectors.
$\nu_\mu$ Disappearance Measurement

Look for $\nu_\mu$ deficit:

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta \sin^2 \left( \frac{\Delta m^2 L}{E} \right)$$

Far Detector $\nu_\mu$ spectrum

- **Un-oscillated** (extrapolated from near detector)
- **Oscillated** (measured in far detector)

Simulation 

Spectrum ratio

Visible energy (GeV)
Neutrinos from the Main Injector - NuMI

- 120 GeV protons from Main Injector, directed onto 1λ graphite target
- 10ms spills with 2.4s cycle time
- 2.5 x 10^{13} protons per pulse
- Typical beam power ~175 kW
- Target position wrt focusing horns is moveable, making the beam energy spectrum configurable.
- Majority of running in LE configuration
Introduction – MINOS Detectors

Near Detector
1 kT mass
1 km from target
282 steel planes
153 scintillator planes
100m underground

Functionally Identical Detectors

Far Detector
5.4 kT mass
735 km from target
486 steel planes
484 scintillator planes
700m underground

steel and scintillator sandwich sampling calorimeters.
Magnetized steel ($B \sim 1.3T$).
GPS time-stamping for synchronization.
MINOS Collaboration

30 institutions  175 physicists

Argonne • Athens • Benedictine • Brookhaven • Caltech • Cambridge
Campinas • Fermilab • College de France • Harvard • IIT • Indiana
Minnesota-Twin Cities • Minnesota-Duluth • Oxford • Pittsburgh • Rutherford
Sao Paulo • South Carolina • Stanford • Sussex • Texas A&M
Texas-Austin • Tufts • UCL • William & Mary • Wisconsin

24 PhD theses from MINOS data so far – more on the way
Average since 2003 is 4 per year
FNAL MINOS Group

• 26 MINOS Collaborators in the FNAL group
  – 23 senior staff; 2 RAs; 1 Wilson Fellow
  – 13 within PPD/Neutrino Department, 2 in other PPD Depts
    • 3 are co-Convenors of Analysis Working Groups
    • Co-Spokesperson
    • Run Coordinator for the past 1.5 yrs
  – 11 within Accelerator Div
    • 6 cover NuMI Beam operations from the External Beams Dept
    • 1 in the Main Injector Dept
    • 4 in other departments
  – 2 within Computing Div
NuMI Beam Performance

Good beam delivery for most of this past running period, June 1, 2006 through July 17, 2007
- An early start to the Shutdown for the NuMI beam due to a Horn water leak, this time in Horn-2. Repairable.
- Longest downtimes were due to NuMI-specific problems

Protons on Target
- For the running period - 2.2 E20
- For Fiscal Year 2007 - 1.9 E20
- Since last December -
  - Per pulse average 2.3 e13
  - Per week average 4.8 e18
• Big improvements on the way
  - Slip-Stacking in the Main Injector works!
  - Doubles the per-pulse intensity to NuMI target, from about 2.3 e13 to ~4.0 e13 ppp
  - Works in the normal NuMI-PBar Mixed Mode
  - Only short tests during the last run, due to losses within MI. Installation of collimators in MI, proceeding now, will allow slip-stacking to be the normal running mode when we start up
MINOS – data collection

The MINOS Experiment - C. James

1.27x10^{20} POT Run I

Physics data set used for last year's results

Higher ν beam energy study data

Physics data set added in for current analysis and results

1.23x10^{20} POT Run IIa

Total NuMI protons to 00:00 Monday 16 July 2007

Uptime during beam
Far Detector > 98%
Near Detector > 95%

Accelerator shutdown

2005/05/02 2005/08/10 2005/11/19 2006/02/27 2006/06/08 2006/09/17 2006/12/26 2007/04/06 2007/07/16

0 1 2 3 4 5 6

Protons per week (E18)

3.5 3.0 2.5 2.0 1.5 1.0 0.5

Total Protons (E20)

Run IIb
Recent Results – CC oscillation analysis
Event Topologies

\( \nu_\mu \) CC Event

\( \nu_\mu \) CC Event

NC Event

\( \nu_\mu \) CC Event

\( \nu_e \) CC Event

long \( \mu \) track & hadronic activity at vertex

short event, often diffuse

short, with typical EM shower profile
Recent Results – CC oscillation analysis
New and Improved Analysis

- Improvements over 2006 analysis
  - Improved event selection
  - Improved shower modelling
  - New intra-nuclear modelling

- CC/NC interactions separated using multivariate 2D likelihood procedure combining information from
  - Track observables
  - Event length
  - Event kinematics

- Data and Monte Carlo agree well

**Improvement in selection**

~1% more CC signal.
~50% less NC background.
Recent Results – CC oscillation analysis
Hadron Production Tuning

- Parameterize Fluka 2005 hadron production model as $f(x_F, p_T)$.
- Fit to near detector data collected in different beam configurations.
  - incorporate into the fit: horn focusing current, beam misalignments, cross-sections, neutrino energy scale, neutral current background.
- Improved agreement between data and MC in all configurations.
Recent Results – CC oscillation analysis
Predicting the Far spectrum

• Directly use near detector data to extrapolate from near to far detector.
  – Use detector Monte Carlo to correct for energy smearing and detector acceptance.
  – Use a beam transfer matrix derived from the beam simulation to relate neutrino interactions in each detector via their parent hadrons.
  – Beam Matrices that correspond to different hadron production models are very similar (spread in each column determined primarily by the geometry of the beamline)
Recent Results – CC oscillation analysis
Systematic Uncertainties

- Systematic uncertainties on oscillation parameters are evaluated by fitting fake data sets generated from MC with systematic shifts applied.
- The three largest uncertainties identified from this study are included as nuisance parameters in the oscillation analysis.

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>$\Delta m^2 \times 10^{-3} \text{ eV}^2$</th>
<th>$\sin^2 2\theta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Near/far normalization (4%)</td>
<td>0.065</td>
<td>&lt;0.005</td>
</tr>
<tr>
<td>Abs. shower energy scale (10%)</td>
<td>0.075</td>
<td>&lt;0.005</td>
</tr>
<tr>
<td>NC normalization (50%)</td>
<td>0.010</td>
<td>0.008</td>
</tr>
<tr>
<td>All other systematics</td>
<td>0.040</td>
<td>&lt;0.005</td>
</tr>
<tr>
<td>Total uncertainty (quad. sum)</td>
<td>0.11</td>
<td>0.008</td>
</tr>
<tr>
<td>Statistical uncertainty</td>
<td>0.17</td>
<td>0.080</td>
</tr>
</tbody>
</table>
Recent Results - CC oscillation analysis

PRELIMINARY OSCILLATION RESULTS FOR 2.5x10^{20} POTs DATA.

### Data sample

<table>
<thead>
<tr>
<th>Data sample</th>
<th>Observed</th>
<th>Expected (no osc.)</th>
<th>Observed / Expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_\mu$ (all E)</td>
<td>563</td>
<td>$738 \pm 30$</td>
<td>$0.74 (4.4\sigma)$</td>
</tr>
<tr>
<td>$\nu_\mu$ (&lt;10 GeV)</td>
<td>310</td>
<td>$496 \pm 20$</td>
<td>$0.62 (6.2\sigma)$</td>
</tr>
<tr>
<td>$\nu_\mu$ (&lt;5 GeV)</td>
<td>198</td>
<td>$350 \pm 14$</td>
<td>$0.57 (6.5\sigma)$</td>
</tr>
</tbody>
</table>
Recent Results – CC oscillation analysis
Allowed Parameter space

Best fit values:

\[ |\Delta m^2_{32}| = 2.38 \pm 0.20 \times 10^{-3} \text{ eV}^2 \]
\[ \sin^2 2\theta_{23} = 1.00 \pm 0.08 \]
\[ \chi^2 / N_{\text{DoF}} = 41.2 / 32 \]
Recent Results – Cosmic Ray Charge Ratio

- Cosmic ray muons are produced by primaries interacting in the upper atmosphere
  - Cosmic ray primaries have positive charge – more positive pions and kaons are produced than negative
  - Charge ratio $R$ of muons will be $> 1$
- Charge ratio is important for modeling cosmic ray interactions. It also constrains atmospheric neutrino flux models and the ratio of neutrinos to anti-neutrinos
  - Increasing importance of kaons leads to increased ratio with increasing energy
  - Larger role from heavy elements leads to decreased ratio with increasing energy
  - Increase in charm production leads to decreased ratio with increasing energy

\[ R = \frac{N_{\mu^+}}{N_{\mu^-}} \]
Recent Results – Cosmic Ray Charge Ratio

- It can seem easy to pick out cosmic ray muons in the Far Detector, but it can be harder to determine the charge of the track.
  - High energy muons from cosmics don’t bend much as they pass through
  - Fiducial volume is chosen where the B field is best known and strongest
  - Selected events have to come in with some angle so as to pass through multiple planes, see more BdI

- With a set of selected events with measured charge and energy, one gets the muon charge ratio underground

- To get the charge ratio at the surface, one has to project these events back to the surface, through a column of rock, and calculate their energy loss in the rock to obtain their energy at the surface
  - Involves a knowledge of the local geology
Recent Results – Cosmic Ray Charge Ratio

Charge ratio measured by MINOS over the data’s energy range

\[ 1.371 \pm 0.003 \text{(stat)} + 0.012 - 0.010 \text{(sys)} \]

A larger value than measured by CERN L3, but also a different energy range

Make a qualitative model, using ratios of +/- pions and +/- kaons which change as a function of energy, to fit the data, shown by the line in the plot

This result was a highlight of this year’s Cosmic Ray conference in Mexico And was also featured in last week’s TAUP2007 conference in Japan

Just published this week - PRD 76 Num 5, Sep 20 2007
Results in the pipeline - NC Analysis

- Neutral current interactions are unaffected by standard oscillations, so can be used to constrain oscillations into sterile neutrinos.
- Define sterile mixing parameter $f_s$ as the fraction of disappearing muon neutrinos that oscillate into sterile neutrinos.

- Similar style of event selection to the CC analysis, but opposite emphasis
- Far detector data for this analysis currently blinded – discussion on the un-blinding process TBD at this week’s collaboration meeting.
• MINOS can constrain or measure $\theta_{13}$ near current limits, by looking for $\nu_e$ appearance.
  • Challenges are to separate signal and understand background, dominated by NC events
  • Much effort has gone into developing techniques for distinguishing between electromagnetic and hadronic showers.
• Near Detector events are extrapolated to predict the background rate in the Far Detector, and the prediction compared with the data.
• If there is a signal this will provide a measurement of $\theta_{13}$. 
The analysis group expects to “open the box” by the end of this year and have a result whose reach is comparable to the current Chooz limit.

- Plot shows $\delta_{CP}$ vs. $\sin^2 2\theta_{13}$ for both hierarchies for MINOS best fit value at $4 \times 10^{20}$ POT.
  - Plot is based on early Monte Carlo that is being superseded by a data driven sensitivity method using the latest MC version.

**MINOS Preliminary**

To be superseded soon!

Results in the Pipeline - $\nu_e$ Appearance Analysis
Summary

- **MINOS has had a successful second year of beam running.**
  - $3.6 \times 10^{20}$ PoTs have now been accumulated after two years.

- **Updated oscillation measurement based on $2.5 \times 10^{20}$ PoTs.**
  \[
  |\Delta m^2_{32}| = 2.38^{+0.20}_{-0.16} \times 10^{-3} \text{ eV}^2
  \]
  \[
  \sin^2 2\theta_{23} = 1.00^{+0.08}_{-0.08}
  \]

- **Other oscillation analyses using beam data are progressing.**
  - $\nu_e$ appearance, anti-$\nu_\mu$ disappearance, sterile neutrinos...

- **Updated atmospheric and cosmic ray results.**
  - developing combined analysis of all MINOS atmospheric neutrino data.
Backup Slides
Near Detector Events

- High event rate in near detector.
  - Multiple interactions per spill.
- Events separated based on topology and timing.
  - Timing resolution ~20 ns
  - Spatial resolution ~4 cm
- No significant bias in event rate.
Far Detector beam neutrino ID

- Beam interactions identifiable with “spill trigger”.
  - GPS spill time is sent via internet from near to far detector.
  - Events within ±50μs of spill written out by far detector DAQ.
MINOS Detector Calibration

- **Light injection system:**
  - PMT gain and linearity.

- **Cosmic ray muons:**
  - relative strip calibration.
  - intra-detector calibration.

  **Calibration Error:**
  - ND calibration: 3.1%
  - FD calibration: 2.3%
  - ND/FD calibration: 3.8%

- **Overall Energy Scale:**
  - Calibration detector at CERN measured e/μ/π/p response.

  **Energy Resolution (E in GeV):**
  - Hadrons: 56%/√E ⊕ 2%
  - Electrons: 21%/√E ⊕ 4%/E
MINOS Sensitivity as a function of Integrated POT

Monte Carlo, 90% C.L. contours, statistical errors only

Test point: $\Delta m^2 = 2.38 \times 10^{-3}$ eV$^2$, $\sin^2 2\theta = 1$

Super-K (zenith angle)
Changes from 2006 Result  (PRL 97, 191801)

Data sets:
• Pre-shutdown
• Post-shutdown

Improvements:
• reco & selection
• shower modelling
Comparison with 2006 Result  (PRL 97, 191801)

MINOS Preliminary

$|\Delta m^2_{32}|$ (eV$^2$/c$^4$)

- MINOS Best Fit
- MINOS 90% C.L.
- MINOS 90% C.L. Pre sd.
- MINOS 90% C.L. Post sd.
- MINOS 90% C.L. PRL 2006

$\sin^2(2\theta_{23})$
Selecting $\nu_\mu$ CC Interactions

Good agreement between data and Monte Carlo observed for these variables.