Recent Results from MINOS

Bob Zwaska, Fermilab
for the MINOS Collaboration

2010 Fermilab Users Meeting
June 2, 2010
Tollestrup Award

Justin Evans – University College London
Measuring $\nu_\mu$ and $\bar{\nu}_\mu$ oscillation parameters with MINOS

URA Thesis Prize

Tingjun Yang – Stanford University
Search for $\nu_\mu$ to $\nu_e$ oscillations in MINOS
The MINOS Experiment

- High-intensity neutrino beam for oscillation experiments
  - Predominantly $\nu_\mu$ beam
  - Explore and test the new standard model of neutrinos
- Operating since 2005
- Neutrino beam travels to northern Minnesota
  - 735 km baseline
  - Intense source at Fermilab
  - Oscillated source in Minnesota

Near Detector: 980 tons  Far Detector: 5400 tons
Overview

• Background of the experiment and its physics
• Description of the experiment
• Focus on the beam and our knowledge of it
• Selection of current results
• Much more from Justin and Tingjun

➤ Note: a series of new results are in preparation and will be presented on June 14 at a special W&C and at the Neutrino 2010 conference
Physics Approach

1. Measure oscillation parameters at high precision
   - Muon-neutrino disappearance

2. Search for new, unobserved transitions and measure the associated parameters
   - Electron-neutrino appearance
   - Mass hierarchy & CP violation

3. Search for alternative transitions that come from other models and study standard neutrino interactions at high precision
   - Sterile neutrino searches
   - Anti-neutrino oscillation measurements
   - Lorentz violation
   - Neutrino cross-sections
   - Rare(r) interactions

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

\[ \Delta m^2_{32} = m_3^2 - m_2^2 \]
Long Baseline $\nu$ Oscillation Exps.

- Reproduce atmospheric $\nu$ effect using accelerator beams
- $L \sim 100$’s kilometers to match oscillation frequency

**K2K** (KEK to SuperK)

$L = 250$ km  
Concluded (T2K starting)

**MINOS**

(Fermilab to Minnesota)

$L = 735$ km  
2005

Near Detector: 
980 tons

Far Detector: 
5400 tons

**CNGS** (CERN to Gran Sasso, Italy)

$L = 750$ km  
2006

**Fermilab**

$735$ km

$12$ km

$10$ km
New Players

• Neutrino physics is getting busy

• T2K: first event in far detector

• OPERA: first tau-neutrino observed
  ➢ Seminar on Friday

• Online in the next few years: Double-CHOOZ, Daya Bay, RENO, NOvA
The MINOS Detectors

- Steel / Scintillator sandwiches
- Magnetized steel
- Tracking calorimeters
  - Alternating planes of scintillator strips
  - PMT readout
- Functionally identical
- 1 and 735 km from the neutrino production target
- 980 and 5400 tons
MINOS Detectors

- Extruded plastic scintillator strips
- WLS fibers
- Multi-anode PMT

1” steel
Interaction Types

$\nu_\mu$ CC Event

$\nu_\mu$ \rightarrow $\mu^-$

$W$ \rightarrow $n, p$

NC Event

$\nu_\alpha$ \rightarrow $\nu_\alpha$

$Z$ \rightarrow $n, p$

$\nu_e$ CC Event

$\nu_e$ \rightarrow $e^-$

$W$ \rightarrow $n, p$
Event Topologies

$\nu_\mu$ CC Event

$\nu_e$ CC Event

NC Event

Monte Carlo

long $\mu$ track & hadronic activity at vertex
Event Topologies

\[ \nu_\mu \text{ CC Event} \]

**UZ**

\[ \nu_e \text{ CC Event} \]

**VZ**

**Monte Carlo**

NC Event

- long \( \mu \) track & hadronic activity at vertex
- short event, often diffuse
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
Protons as Raw Material

- High-power 120 GeV beam from the Main Injector feeds the neutrino beam
- Typical beam power is 310 kW
  - Occasional running at 400 kW
  - $10^{20}$ total protons passed on May 5
- Weekly delivery of protons has continually improved
  - Thanks to the Accelerator Division
The NuMI Beam
“Neutrinos at the Main Injector”

- 400 kW design average power
- $\sigma \sim 1$ mm
- 2 interaction length, C target
- Produces $\pi$, K mesons
- Pulsed focusing horns
- Toroidal magnetic field
- Parabolic inner conductor profile
- Focuses meson momentum band

2 m diameter
- Roughly decay length for 10 GeV $\pi^+$
- Evacuated or He-filled & cooled

Absorbs 160 kW of protons and other hadrons
- Allows high-energy muons to penetrate

Roughly decay length for 10 GeV $\pi^+$

Absorbs 160 kW of protons and other hadrons
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Muon Monitors

5 m
- 12 m
- 18 m
- 210 m

Hadron Monitor

Rock

Arrays measure distributions

Measure hadron & muon fluxes

Target

120 GeV protons
- From Main Injector

Target Hall

Decay Pipe

$\mu^+$

$\pi^+$

$\nu_\mu$

Horns #1 #2

10 m

30 m

675 m
Neutrino Beam Design

Low Energy Beam

proton

Target

Horn 1

Horn 2

MINOS Data

Pions with
$p_T=300$ MeV/c and
$p=5$ GeV/c
$p=10$ GeV/c
$p=20$ GeV/c

Vary $\nu$ beam energy by sliding the target in/out of the 1st horn

High Energy Beam

proton

Target

Horn 1

Horn 2

P$^+$
Neutrino Energy Spectrum

- Optimal beam configuration for $|\Delta m^2_{32}|$ “Low Energy”
  - Focusing positive mesons

- Beam composition in the Near Detector
  - 91.7% of $\nu_\mu$
  - 7.0% of $\nu_\mu$
  - 1.3% of $\nu_e$ and $\bar{\nu}_e$

- Significant difference in energy spectra:
  - $\nu_\mu$ peaks at 3 GeV
  - $\bar{\nu}_\mu$ peaks at 8 GeV
Precision Neutrino Beam

• Why is precision needed?
  ➢ 1000s of events in Far Detector, but 100s of millions in Near Detector
  ➢ Errors must be held to < 2% for oscillation analyses
    • Short-baseline measurements could do with much better

• Why is precision hard?
  ➢ Meson production cross sections not well known
  ➢ Neutrino interaction cross sections not well known
    • Both aggravated by nuclear effects
  ➢ Beam is produced over a large volume and mesons have numerous opportunities to reinteract
  ➢ High-power beam can damage components
    • Heating can also cause components to change position

• How do we achieve precision?
  ➢ Build everything to tight tolerances
    • Verify those tolerances
  ➢ Spend a lot of effort on simulation
  ➢ Incorporate external data
  ➢ Monitor the beam
  ➢ Use the enormous amount of Near Detector data with different beam tunes to constrain production
Achieving a Precision $\nu$ Spectrum

- Component placement affects the $\nu$ beam
  - Beam monitors detect changes in muon & hadron beams
  - Variation measured spill-to-spill
- Beam based alignment for all major components
- Horn 1 displacements affect pion focusing
Tuning MC

- Fit ND data from all beam configurations
  - Warp underlying hadron production to match neutrino data

- Simultaneously fit $\nu_\mu$ and $\bar{\nu}_\mu$ spectra
Far/Near Ratio

- Point source -> both detectors same flux
- Due to finite pion lifetime, higher energy pions decay closer to ND
- Full simulation includes acceptance effects
Muon Monitor Tuning

- Measure muon fluxes in numerous beam configurations
  - Vary target position and horn current
- Parameterization for hadron production, $f(p_T, p_z)$.
- Warp $p_T$ and $p_z$ to tune default MC to Muon Monitor data.

Data  Monte-Carlo  Tuned Monte-Carlo
Muon Monitor Flux

- Shape only measurement
  - Large uncertainty in Ionization Scale flux requires normalization to MINOS data for $E_\nu > 26\text{GeV}$.
- Error bars come from... 
  - $\pi^+/\pi^-$ ratio, $K/\pi$ ratio
  - Non-linearity
  - Backgrounds
- In situ measurement; accounts for real beamline conditions
- Independent of neutrino data

![Muon Monitor Flux Graph](image)
NuMI Target Degradation

Events Per POT v.s. Run ($E_\nu < 6$ GeV)

- Neutrino yield from the NuMI target degraded by ~5% over an exposure of ~ $6 \times 10^{20}$ protons
  - Spectral shape also changes
- Analyses must allow for a changing beam
- This experience will guide the considerations for targets in future experiments
The $\nu_\mu$ disappearance analysis:

- Run I+II (3.36 x 10\textsuperscript{20} POT)

*Phys.Rev.Lett.101:131802,2008*

- New analysis in preparation
- See Evans talk for more detail
$\nu_\mu$ disappearance

- Use both low and high energy beam
  - Blind analysis
  - Expected $1065 \pm 60$ with no osc.
  - Observed 848 events.

- Energy spectrum fit with the oscillation hypothesis

\[
P(\nu_\mu \rightarrow \nu_x) = \sin^2 (2\theta) \sin^2 \left( \frac{1.27 \Delta m^2 L}{E} \right)
\]

\[
P(\nu_\mu \rightarrow \nu_\mu) = 1 - P(\nu_\mu \rightarrow \nu_x)
\]
Allowed Parameter Space

- Analysis of 7e20 is nearing completion
- Improvements:
  - Looser cuts as systematics are better understood
  - Combine anti-neutrinos
  - Add rock muons and the edges of detector

Best fit (3.1e20 protons)

- $|\Delta m_{32}^2| = (2.43 \pm 0.13) \times 10^{-3} \text{ eV}^2$ (68% C.L.)
- $\sin^2(2\theta_{23}) > 0.95$ (68% C.L.), 0.90 (90% C.L.)
Alternative models

Two alternative disappearance models are disfavored:

[1] Decay without oscillations:
\[ \chi^2/\text{ndof} = 104/97 \]
\[ \Delta \chi^2 = 14 \]
*disfavored at 3.7\(\sigma\)*
*(5.4\(\sigma\) if combine CC & NC)*

[2] Decoherence:
\[ \chi^2/\text{ndof} = 123/97 \]
\[ \Delta \chi^2 = 33 \]
*disfavored at 5.7\(\sigma\)*

Search for active-neutrino disappearance:

- Directly test for $\nu_s$ using Neutral Current Interactions with Run I+II: $3.18 \times 10^{20}$ protons


New analysis in preparation
Neutral Current Energy Spectra

- NC selected Data and MC energy spectra for Near Detector
- Good agreement between Data and Monte Carlo
- Discrepancies smaller than systematic uncertainties
- NC events are selected with 90% efficiency and 60% purity
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- Far Detector reconstructed energy spectra for NC-like events
- Oscillation parameters are fixed. MC predictions with $\theta_{13}=0$ and $\theta_{13}$ at the CHOOZ limit are shown
  - $\nu_e$ charged current interactions selected as NC in this analysis
- Expect $377 \pm 19.4 ($stat$) \pm 18.5 ($syst$)$
  - Observe 388 events
Search for $\nu_e$ appearance:

with Run I+II+III ($7 \times 10^{20}$ POT)


- See Yang talk for more detail
Background - Near Detector Decomposition

• Use large Near Detector samples to measure backgrounds
  ➢ 3 different beams allow decomposition into background type
• Different backgrounds extrapolate differently to far detector
\( \nu_e \) Selected Far Detector Data

Background Prediction: 49.1 \( \pm \) 7.0 (stat) \( \pm \) 2.7 (sys)

Observed Data: 54

0.7 sigma excess above background
Limits

- Set limits based on total selected events

MINOS sets the tightest limits on $\theta_{13}$ assuming a normal mass hierarchy
Antineutrino Disappearance in a Neutrino Beam
with Run I+II ($3.2 \times 10^{20}$ POT)
New analysis in preparation
- See Evans talk for more detail
Antineutrinos at the Far Detector

• **Predict:**
  - Null oscillations: \(64.6 \pm 8.0 \text{ (stat.)} \pm 3.9 \text{ (syst.)}\)
  - CPT conserving oscillations: \(58.3 \pm 7.6 \text{ (stat.)} \pm 3.6 \text{ (syst.)}\)

• **Observe:**
  42 events

- Examine 7% antineutrino component
- Detector magnetic field allows charge discrimination
Dedicated Antineutrino running

- Reverse current in the NuMI focusing horns.
- Obtain a greatly enhanced antineutrino sample below 5 GeV (incl. the oscillation maximum).
- Have accumulated $1.76 \times 10^{20}$ in this mode

- Will enable a more precise measurement of the antineutrino oscillation parameters than possible with forward horn current
- Analysis is nearing completion
Selection of Additional Measurements

- **Atmospheric neutrinos**
  - New analysis in preparation
- **Lorentz Invariance**
  - New analysis in preparation
- **Neutrino cross sections**
  - Several others under preparation
- **Sudden Stratospheric Warming (Climate Physics with cosmic rays)**
- **Cosmic ray variation with season**
  - Phys.Rev.D81:012001,2010
- **Cosmic ray charge ratio**
Conclusion

• MINOS is a mature experiment
• Significant effort has resulted in a precisely understood beam
• Several of the major goals have been achieved
  ➢ Muon-neutrino disappearance verified as an oscillation phenomenon
    • Parameters precisely measured, alternatives rules out
  ➢ The neutrinos change into a type that interacts via the Neutral Current
    • Predominantly not $\nu_e$ – so we presume $\nu_\tau$
  ➢ Limits on electron-neutrino appearance have been improved
• Improvement still to be made
  ➢ Better measurements / limits (evidence?)
  ➢ Exploration of anti-neutrinos
• Wide range of additional measurements
  ➢ Neutrino fluxes / cross sections / interaction types
  ➢ Cosmic ray physics (and applied to atmospheric physics)
• Enjoy the next few talks, and come to the W&C on June 14
Recent MINOS Theses

- **Bob Armstrong** – Indiana University
  - Muon neutrino disappearance at MINOS

- **Pedro Ochoa** – California Institute of Technology
  - A search for muon neutrino to electron neutrino oscillations in the MINOS experiment

- **Steve Cavanaugh** – Harvard University
  - A Measurement of Electron Neutrino Appearance in the MINOS Experiment After Four Years of Data

- **Anna Holin** – University College London
  - Electron neutrino appearance event selection optimization in the MINIS far detector

- **David Auty** – University of Sussex
  - Analysis of numubar from the NuMI beam

- **Laura Loiacano** – University of Texas at Austin
  - Measurement of the Muon Neutrino Charged Current Inclusive Cross Section on Iron

- **Masaki Watabe** – Texas A&M University
  - Using Quasi Elastic Events to Measure Neutrino Oscillation with the MINOS detectors in the NuMI Neutrino Beam