The MINOS Experiment:
Status & Report on First Beam

Jon Urheim, Indiana University
Aspen Winter Conference,
17 February 2005

- Introduction
- MINOS Experiment Overview & Physics Reach
- Status of the MINOS Detectors & NuMI Beamline
- Report on Commissioning of NuMI Beam!
Introduction

• MINOS is reaching a milestone today !!
  – DOE review of “Critical Decision 4” criteria…
    includes:
    • observation of atmospheric neutrinos in MINOS Far Detector
    • observation of neutrinos from NuMI beam in Near Detector
    • achieve intensity of \(>1 \times 10^{12}\) protons per spill on target
    • I will talk about each of these here!
  – CD-4 marks transition to “operations” phase of expt.
    • we are quite happy about this !

• But first some background…. 
**Atmospheric Neutrinos – SuperK**

Latest new development:
- selection of events w/ good resol’n in $L/E$
- provides better sensitivity to $\Delta m^2$ !!
- can resolve characteristic dip in the $L/E$ distribution at the $\sim 3\sigma$ level.

**BEST FIT:**
- $\Delta m^2 = 2.4 \times 10^{-3} \text{ eV}^2$ (2.4)
- $\sin^2(2\Theta) = 1.0$ (1.02)

68, 90, 99% CL intervals shown

Note use of linear scale!
K2K – the 1st Long-Baseline Accelerator-based Experiment

Super-Kamiokande I

Inner detector
11146 20” PMTs
Outer detector
1885 8” PMTs

250km

12GeV PS@KEK
\( \nu \) beamline

Diagrams courtesy
Y. Hayato

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Status of MINOS
K2K – the 1st Long-Baseline Accelerator-based Experiment

Based on $0.89 \times 10^{20}$ p.o.t.

$\Delta m^2 = 2.8 \times 10^{-3} \text{ eV}^2$

$\sin^2(2\Theta) = 1.0$

107 Observed / 149.7 Expected

Plots courtesy C. Walter
The MINOS Collaboration

175 physicists from 32 institutes in 6 countries

- U.K.
- U.S.A.
- Greece
- Russia
- Brazil
- France

- Argonne
- Athens
- Benedectine
- Brookhaven
- Caltech
- Cambridge
- Campinas
- Fermilab
- College de France
- Harvard
- IIT
- Indiana
- ITEP
- Moscow
- Lebedev
- Livermore
- Minnesota
- Twin Cities
- Minnesota, Duluth
- Oxford
- Pittsburgh
- Protvino
- Rutherford
- Appleton
- Sao Paulo
- South Carolina
- Stanford
- Sussex
- Texas A&M
- Texas-Austin
- Tufts
- UCL
- Western Washington
- William & Mary
- Wisconsin

Minos collaboration members at Fermilab with the Near Detector surface bldg in the background (right)

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Status of MINOS
νμ source: (NuMI)
120 GeV protons from FNAL Main Injector
detectors: (MINOS)
1) ‘Far’ detector:
    5.4 kT magnetized iron/scintillator tracker/calorimeter in Soudan mine
2) ‘Near’ detector:
    980 T version of far detector at FNAL

3) Also:
   ‘Calibration’ detector in test beams at CERN

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Fermilab Main Injector:
- 120 GeV protons
- $2.5 \times 10^{13}$ protons/pulse
- 1.9 sec rep rate
- (~8 µsec spill)
- $\rightarrow 0.25$ MW

NuMI Beam:
- Graphite target
- Two magnetic horns
- 675 m. vac. decay pipe
- hadron absorber
- designed for $4 \times 10^{13}$ ppp

Beam Monitoring:
- muon detectors
- hadron detectors
- + Near Detector!
Soudan Underground Laboratory

- former iron mine, now a state park,
  - home of: Soudan-1 & 2, CDMS-II, and MINOS expts
Far Detector Module Layout

Shown here: 1 (of 2) super modules
- 248 planes: 8m x 8m x 15m!

Steel / Scintillator:
- 2.5 cm thick steel
- 4 cm x 1 cm polystyrene in Al cover
- 15,000 Amp-turn coil

486 Layers → 5.4 kTon!
Scintillator Detectors & PMTs

Spool of 1.2 mm WLS fiber being glued into groove

Hamamatsu M16 16-channel PMT (8 fibers per pixel)

4.1 cm x 1 cm polystyrene strips – coextruded with TiO₂ coating & groove for WLS fiber
View of Partially Constructed Far Detector

View as of April 2002. This is less than half the full detector!
Far Detector Completed !!

View as of July 2003, after energizing of SM2 coil
Calibration Detector

60-plane ‘micro - MINOS’
-- has taken data at T7 & T11
test beam lines at CERN

Detector Response

Available Energy (GeV)

Energy Resolution

MC expectation
Far Detector Live Time 10/03 - 12/04

On-Time Averages
FY04 89.3% Q1 FY05 95.4%

Rack smoke maint. + planned outage

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B. Speakman, A. Habig, B. Miller

Status of MINOS
Cosmic Ray Data in Far Detector

Upward-going muons (atmospheric neutrino-induced) based on ~ 1 yr of data.

Plots: B. Rebel

Zenith angle distribution

MC: Nuance w/ Bartol '96 flux; no-osc’n dist. normalized to data

Plotting: \[ \frac{d \delta t}{d \delta s} = \frac{1}{\beta} \] (signed by \( dy/dt \))

Note: 2.4 ns single hit timing resol’n!!
The MINOS Near Detector

1 kTon version of far det.

- 290 m d/s of hadron absorber → beam is small!
- 4 regions: ‘veto’ + ‘target’ + ‘shower’ + ‘spectrometer’ (sparse)

make as similar to far detector as possible!

Readout:

- Hamamatsu M64 pmt’s
- High instantaneous rates (≈20 ν events / 8 µsec spill) → fast front ends needed
- use FNAL QIE chips

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MINOS Near Detector

Plane construction complete in August 2004

Commissioned & calibrated w/ cosmic ray muons & light injection system

Magnet coil now installed & energized

View of Near Detector Hall nearing end of detector construction
MINOS Physics Reach

- Intense $\nu_{\mu}$ beam from FNAL
  - initially $2.5 \times 10^{20}$ p.o.t./year,
  (being commissioned now !!)

- Measure un-oscillated $E_{\nu}$ spectrum in MINOS Near Det.

- Extrapolate spectrum to Far Det. Location 735 km away…
  $\Rightarrow$ hope to use data from MIPP expt
  (FNAL E907) to enhance beam modeling capability

- Compare extrapolated spectrum with MINOS Far Det. Data
  $\Rightarrow$ measure oscillation parameters

$\nu_{\mu}$ CC Events/year
(with no oscillations)

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<thead>
<tr>
<th></th>
<th>Low</th>
<th>Medium</th>
<th>High</th>
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<tbody>
<tr>
<td>Events</td>
<td>1,600</td>
<td>4300</td>
<td>9250</td>
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**Beam spectra: M. Messier**
MINOS Physics Reach

- **MINOS Sensitivity to $\nu_\mu$ disappearance**
  (plotting ratio of yield at FarDet to expectation based on NearDet)

Assuming:
\[ \delta m^2 = 0.0025 \text{eV}^2, \sin^2 2\theta = 1.0 \]

After:
- 3yrs at nom. intensity (top)
- & w/ possible intensity upgrages (bottom)

- **Characteristic 'dip':** location & depth yield $\delta m^2$ & $\sin^2 2\theta$.
  - Will determine $\delta m^2$ to precision of $< 10\%$,
  - can also rule out exotic models of oscillations.
Sensitivity to $\nu_e$ appearance

detection of $\nu_e$ at $\Delta m^2_{\text{atm}}$
$\rightarrow$ evidence for non-zero $\theta_{13}$

For $\Delta m^2 = 0.0025 \text{ eV}^2$, $\sin^2 2\theta_{13} = 0.067$

Assuming $25 \times 10^{20}$ protons on target

Background dominated by Neutral current interactions (+ some intrinsic beam $\nu_e$'s)

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Status of MINOS
120 GeV protons extracted from MI into NuMI beam tunnel
Pitched downwards @ 160 mrad (initially) then to 58 mrad – toward Soudan
Incident on segmented graphite target
Focus charged hadrons with two magnetic horns pulsed with 200kA
675m long steel decay pipe (0.5 Torr, encased in 2-3m concrete)
Hadron absorber downstream of decay pipe
200m rock upstream of Near Detector for muon absorption
NuMI Construction - now completed!

- Horn 2 inner conductor
- NuMI 675-meter decay tunnel prior to vacuum pipe install’n
- Horn on mounting
NuMI Beam Commissioning

• December 3 - 4, 2004
  - beam transported to target hall & onto hadron absorber
    • target out -- so no neutrinos
    • small number of carefully planned pulses (to limit radiation)

• January 21 - 22, 2005
  - first beam on target !
    • horns powered
    • target at \( z = -1 \) m from nominal \( \rightarrow \) “pseudo-medium energy beam”
    • MI operating w/ single Booster batch \( (\text{nominally 5 or 6}) \)
    • 864 spills at 60-180 second intervals \( (\text{nominally 2 seconds}) \)
    • typical (max) intensity: \( 2.6e12 \) \( (4.1e12) \) protons per spill
      (note: already near initial goal for multi-batch: \( 2.5e13 \) ppp !!)

  – yes, we saw some neutrinos in the Near detector…
Final Focus to NuMI Target Hall

Installed in NuMI line

Slide courtesy S. Kopp
Beam monitoring instrumentation

Beam profiles from secondary emission monitors (SEMs) along NuMI beamline from January 21 beam test.

Transport down the entire beamline was achieved with only 12 beam pulses during the December test...

Profile from hadron monitor system, downstream from decay pipe.
Imaging the Target via Hadron & Muon Monitors

Parallel plate ionization chambers (UT Austin group)

Analysis by Texas & BNL groups
Distributions in the Near Detector

**Time distribution of energy deposited in the Near Detector:**

Beam gate open 2 $\mu$s before start of beam spill; open for 18 $\mu$s.

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For spills containing reconstructed (muon) tracks:

Angle between initial track direction and beam direction

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A. Marino

MINOS Preliminary
Event Yields

Observed 354 “Events” in 291 spills analyzed. Of these, 48 satisfy track & fiducial (containment) requirements. Both consistent w/ expectations (accounting for “rock” muons)

Total events per spill

Total events per spill satisfying track and fiducial cuts
Two separate neutrino interactions here:

1) “Rock muon” from $\nu$ interaction upstream of near detector

2) Fully-contained interaction in the near detector

Note: this is one entire $(1.6 \, \mu s)$ spill’s worth of data!

- 19 ns timing on readout allows separation of interactions

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Spill data in the Near Detector

This spill contained 4 neutrino interactions!

*Again, this is NOT a problem!*

Individual events can be easily separated according to the 19 ns time bucket in which they occur.
This spill contained 3 neutrino interactions, one with a second track!
Summary of MINOS

- **Data-taking w/ NuMI beam is “under way”**
  - Both detectors are 100% complete
    - (very stable: < 1 ns timing drifts, ~ 1% pulseheight drifts)
  - Calibration detector data analysis is complete
  - Now the main effort is to understand the beam!

- **By 2007, will have precise measurements:**
  - osc’n parameters for $\nu_\mu$ disappearance; (NC/CC ratio for mode id)
  - search for subdominant $\nu_\mu \rightarrow \nu_e$

- **Will also have ~ 24 kiloton-year exposure to atm. $\nu$’s**
  - energy, direction resol’n $\rightarrow$ Minos competitive on $\nu_\mu$ disappear.
  - 1st direct search for CPT non-cons. ($\overline{\nu}_\mu \rightarrow \overline{\nu}_\mu$ vs $\nu_\mu \rightarrow \nu_\mu$)
Introduction

- picture emerging from existing data

  - **Large effect at “atmospheric”** $\Delta m^2$
    - oscillation hypothesis very strong [Super K]
    - effect now seen at accelerator expt. [K2K]
    - dominant mode likely to be $\nu_\mu \rightarrow \nu_\tau$ [Super K]

  - **Also large effect at “solar”** $\Delta m^2$ [Davis]
    - LMA solution confirmed !! [Ga + SNO + SK + KamLAND]

- **Questions:**
  - two angles large, what about the third, $\theta_{13}$ ?
  - complex phase in MNS matrix $\rightarrow$ CPV ?
  - what about mass hierarchy ?
  - where does LSND fit ? CPT ? sterile neutrinos ?
  - Extra dimensions ?
Goals of 1\textsuperscript{st} generation of Long Baseline Experiments

Confront emerging picture with precision data

- confirm deficit of $\nu_\mu$ in accelerator-based exp’t
- confirm oscillation hypothesis:
  
  \textit{must measure/know E & L precisely to see osc’ns in L/E pin down oscillation parameters}

- demonstrate $\nu_\mu \rightarrow \nu_\tau$ is dominant mode:
  
  \textit{Tau appearance! (CNGS \rightarrow direct, MINOS \rightarrow NC/CC)}

Look for new phenomena

- evidence for non-zero $\theta_{13}$ : $\rightarrow$ detection of $\nu_e$
- test for possible CPT violation ?
- etc..
NuMI Target

Slide courtesy S. Kopp

- 47 × 2 cm graphite segments
  - 6.4 × 28 mm² profile
  - Beam is 1 mm radius
  - 1.9 interaction lengths
- Water cooled
  - 4 kW deposited beam power
- Could survive 1MW if 2mm spot size
The “Magnetic Horns”

- Toroidal Magnet $B \sim 1/r$
- $p_T$ kick of $\Delta p_T \propto B d\ell \propto r \propto p_\pi \propto E_\nu$

Slide courtesy S. Kopp
Segmented Foil SEM’s

Foil Secondary Emission Monitors
- Beam profile + halo measurement
- Very low mass (5 µm Ti)
- Reduced Beam Heating problems
- Ti signal lasts longer in the beam

Mechanical/Vacuum System
- ‘Bayonet’-style insertion is compact
- Frame is never in the path of beam
- Insertion accuracy/repeatability
- Vacuum ~10⁻⁹ Torr on 30l/s ion pump

www.hep.utexas.edu/~kopp/minos/sem/
Simulated Neutrino Interaction

\[ \nu_\mu \rightarrow \mu^- \]

\[ \nu_\mu \rightarrow \mu^- \]

'\( u' \) - view

ghost hits due to optical summing

plane #

strip #

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Status of MINOS
Beam Intensity as measured by downstream NuMI toroid

2.5e12 protons/pulse was typical. Intensity scan up to 4.1e12 ppp !

Recall CD-4 criterion: 1.0e12 ppp.

Simple extrapolation to multi-batch operations:
4.1e12 ppp $\times$ 5 = 2.1e13 ppp

c.f. intensity goal: 2.5e13 ppp

Note - this is just one of $>300$ beam instrumentation devices being read out & available for offline analysis!

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M. Bishai
Distributions of events in Near Det

Cosine zenith angle: All tracks

Azimuth angle All tracks

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N. Saoulidou

Status of MINOS
Fully contained atmospheric $\nu_\mu$ CC events in Far Detector

Energy distribution ($E_\nu = E_\mu + E_{\text{had}}$)

Zenith angle

Plots: C. Howcroft & M. Thomson