Status of NuMI/MINOS

Mark Thomson
University of Cambridge

This talk:

• Overview
• NuMI Beam
• MINOS Far and Near Detectors
• Physics Capabilities
• First Data
  - cosmic muons
  - atmospheric $\nu$s
MINOS : Basic Idea

Measure ratio of neutrino energy spectrum in far detector (oscillated) to that in the near detector (unoscillated)

Partial cancellation of systematics

Depth of minimum

Position of minimum

Near (unosc)

Far (oscillated)
MINOS Physics Goals

**Demonstrate oscillation behaviour**
- confirm flavour oscillations describe data
- provide high statistics discrimination against alternative models: decoherence, $\nu$ decay, extra dimensions, etc.

**Precise Measurement of $\Delta m_{23}^2$**
- $\sim 10\%$

**Search for sub-dominant $\nu_\mu \rightarrow \nu_e$ oscillations**
- first measurements of $\theta_{13}$?

MINOS is the 1st large deep underground detector with a B-field
- first direct measurements of $\nu$ vs $\bar{\nu}$ oscillations from atmospheric neutrino events
The NuMI beam

- **120 GeV protons extracted from the MAIN INJECTOR in a single turn (8.7 $\mu$s)**
- **1.9 s cycle time**
- **i.e. $\nu$ beam `on' for 8.7 $\mu$s every 1.9 s**
- **2.5x$10^{13}$ protons/pulse**
- **0.3 MW on target!**
- **Initial intensity**
  
  $$2.5x10^{20} \text{ protons/year}$$
Tunable beam

- Relative positions of the neutrino horns allow beam energy to be tuned. Act like a pair of (highly achromatic lenses)
- Start with LE beam – best for $\Delta m^2 \sim 0.002$ eV$^2$

**LE BEAM:**

$\nu_\mu$ CC Events/year:

- Low 1600
- Medium 4300
- High 9250

(2.5x10$^{20}$ protons on target/year)
The NuMI $\nu$ beam: I

- Target Service Building
- Main Injector
- Carrier Tunnel
- Target Hall
- Beam Absorber
- Muon Detectors
- Minos Hall
- Minos Near Detector
- Recycler
- NuMI Extraction
- Main Injector
- To Soudan
The NuMI $\nu$ beam: II

- Protons
- Steep incline
- Carrier tunnel
- Pre-target

☆ Beam points 3.3° downwards
The NuMI $\nu$ beam: III

- Horn pulsed with 200 kA
- Toroidal Magnetic field $B \sim I/r$ between inner and outer conductors
The NuMI $\nu$ beam: IV

protons

Before shielding

Shielding Installation

Horn on mounting

0 64 128 256
METERS

Target Service Building Main Injector
Carrier Tunnel Target Hall

Beam Absorber Muon Detectors

MINOS Service Building To Soudan

Minos Hall Minos Near Detector

Neutrino 2004, June 17, Paris

Mark Thomson, Cambridge
The NuMI $\nu$ beam:

- Need long decay pipe: for a 5 GeV $\pi^+$
  $\gamma c \tau \sim 200$ m
- Evacuated to 1.5 Torr
- Steel decay pipe installed and encased in 2-3 m of concrete to protect ground water

675 m long decay pipe
Going underground

Photo by Jerry Meier

LEVEL NO. 27
2341 FEET BELOW THE SURFACE
689 FEET BELOW SEA LEVEL

2070 mwe

MINOS
Soudan 2/CDMS II

Photo by Jerry Meier
MINOS Far Detector

8m octagonal steel & scintillator tracking calorimeter

- 2 sections, 15m each
- 5.4 kton total mass
- $55\%/\sqrt{E}$ for hadrons
- $23\%/\sqrt{E}$ for electrons

Magnetized Iron ($B \sim 1.5T$)

484 planes of scintillator

One Supermodule of the Far Detector...
Two Supermodules total.
Detector Elements

- Steel-Scintillator sandwich: SAMPLING CALORIMETER
- Each plane consists of a 2.54 cm steel + 1 cm scintillator
- Each scintillator plane divided into 192 x 4 cm wide strips
- Alternate planes have orthogonal strip orientations (U and V)

- Scintillation light collected by WLS fibre glued into groove
- Readout by multi-pixel PMTs
MINOS FarDet during installation

- SM 1
- SM 2
- Optical Fibre Read out
- Electronics Racks
Far Detector fully operational since July 2003

Coil

Veto Shield
Event Information

- Two 2D views of event
- Software combination to get `3D' event

- Timing information → event direction (up/down)
- + charge deposit (PEs) → calorimetric information
- Veto shield hit
B-Field

~ 1.5 T Magnetic Field
★ Charge separation
★ Momentum measurement

Stopping muon
$P_{\text{range}} = 3.86 \text{ GeV/c}$
$P_{\text{curvature}} = 4.03 \text{ GeV/c}$

Single Hit Resolution : 2.5 ns
MINOS Near Detector

★ 1 kton total mass
★ Same basic design
   steel, scintillator, etc
★ Some differences, e.g:
   Faster electronics
   Partially instrumented:
   282 planes of steel
   153 planes of scintillator
   (Rear part of detector
    only used to track muons)
+.....

Currently being installed at Fermilab
MINOS Beam Physics (MC)

$\nu_\mu$ CC Event
- $\nu_\mu$ track
- +hadronic activity

$\nu_e$ CC Event
- compact shower
- typical EM shower profile

NC Event
- often diffuse

NC Event
- can mimic $\nu_\mu$, $\nu_e$
Test Beam

*Energy response is important – know L, need $E_\nu$*

- hadronic energy from pulse height ($\sigma_E/E \sim 55\%/E^{1/2}$)
- $E_\nu = p_\mu + E_{\text{had}}$

Response measured in CERN test beam using a MINI-MINOS

*Provides calibration information*

*Test of MC simulation of low energy hadronic interactions*
MINOS Physics Sensitivity

- Measurement of $\Delta m^2$ and $\sin^2 2\theta$

For $\Delta m^2 = 0.0025 \text{ eV}^2$, $\sin^2 2\theta = 1.0$

Large improvement in precision!

Final sensitivity depends on protons on target

- Direct measurement of $L/E$ dependence of $\nu_\mu$ flux
- Powerful test of flavour oscillations vs. alternative models
\( \nu_e \) Appearance

\[ \Delta m^2 = 0.0025 \text{ eV}^2 \]

\[ \text{MINOS 3}\sigma \text{ Discovery Limits} \]

\* 3\( \sigma \) discovery potential may significantly eat into current allowed region – exact reach depends on protons on target

\* reasonable chance of making the first measurement of \( \theta_{13} \) !
First beam in December 2004
BUT Already Have Data....
**Moon Shadow**

- **Have recorded** 10 M cosmic muons observed shadow of moon
- **Angular res. improved by selecting high momenta muons** (less multiple scattering)

![Graphs showing dN/dΩ vs. Δθ, degrees](image)

*Not to scale*
ν induced upward μ

★ Expect: 1 Event/6 Days
★ Identified on basis of timing

Earliest hits

XY view

PEs
Neutrino 2004, June 17, Paris

ν induced upward-going muons

★ Look for events coming from below horizon
★ Require clear up/down resolution from timing
  • `Good track’ > 2.0 m
  • >20 planes crossed

★ Calculate muon velocity from hit times: $\beta = \frac{v}{c}$

★ Clear separation of up/down going $\mu$s!

$\sigma_{1/\beta} \sim 0.05$

★ 48 Upward events
**NUANCE generator:**
- Bartol ’96 flux
- MC normalised to data (assuming no oscillations)

**Charge-tagging:**
- Tag $\nu/\bar{\nu}$ using muon charge
- Efficiency depends on:
  - muon momentum
  - track length
  - orientation wrt B-field
- Clean charge ID for approx. 50% of events

<table>
<thead>
<tr>
<th>Events</th>
<th>$\nu$</th>
<th>$\bar{\nu}$</th>
<th>$\nu/\bar{\nu}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>13</td>
<td>8</td>
<td>27</td>
</tr>
</tbody>
</table>

*Understanding systematics: Work in progress*
Contained Events

★ MINOS Designed for $\nu_s$ from FNAL – not atmospherics
★ Gaps between planes - potentially problematic

For Contained Atmospheric $\nu_s$:
★ use of veto shield significantly reduces background from cosmics sneaking in between plane gaps
**Contained Event Selection**

- **Signal/Noise (cosmics) = 1/200,000**
- **Veto Shield helps: efficiency ≈ 97 %**
- **Have achieved rejection factor of ≈ 1:10,000,000!**
  
  Efficiency ≈ 75 % with 98 % purity

**CC ν → μ EVENT SELECTION:**

- **Fiducial Volume:** little activity within 50cm of detector edge
- **Reconstructed muon track:** track which crosses 8 planes
- **Cosmic muon rejection:** remove steep events
- **Veto Shield:** no ‘in-time’ Veto shield hit
**MINOS Preliminary**

<table>
<thead>
<tr>
<th></th>
<th>DATA</th>
<th>MC $\nu$ no osc.*</th>
<th>MC Cosmic backgnd.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before VETO</td>
<td>88</td>
<td>39</td>
<td>63±6</td>
</tr>
<tr>
<td>VETOED</td>
<td>51</td>
<td>1</td>
<td>61±6</td>
</tr>
<tr>
<td>$\nu$ selection</td>
<td>37</td>
<td>38±8</td>
<td>2</td>
</tr>
</tbody>
</table>

* Does not include acceptance systematic uncertainties – work in progress

Measure cosmic $\mu$ bgd. from data using events solely rejected on basis of veto hit

Vetoed background agrees with MC expectation!

$\nu$ MC : Battistoni et al
Event Distributions

$E_\nu = E_\mu + E_{\text{had}}$

- MC normalised to data (no oscillations)
- Cosmic background from data - from no. of vetoed events
Charge Reconstruction

Tag $\nu/\bar{\nu}$ using muon curvature:

★ Curvature $\Rightarrow Q/p$
★ Select on basis of $(Q/p)/\sigma_{Q/p}$
★ Pure charge ID for $\sim 70\%$ of selected events

MINOS Preliminary

★ 6 $\bar{\nu}$ events
★ 17 $\nu$ events
★ 14 too short to ID $\bar{\nu}/\nu$

$\Rightarrow N\bar{\nu}/N\nu = 0.35 \pm 0.17$
(expect $0.51 \pm ?$ if $\bar{\nu}/\nu$ oscillate with same parameters)

MINOS atmos $\nu$ analysis underway!
just need more data......
Conclusions

NuMI beam installation progressing well!  
expect first protons on target December 2004!

MINOS Near Detector currently being installed/  
commissioned at FermiLab

MINOS Far Detector taking physics quality data  
since mid-2003

Atmospheric $\nu$ already being seen in the MINOS  
Far Detector

First direct observation of $\nu/\overline{\nu}$ separated  
atmospheric neutrinos

Eagerly awaiting first beam physics data, expected  
early 2005! Exciting times for MINOS.
MINOS en France