Progress of the MINOS Experiment

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International Workshop on Astroparticle and High Energy Physics

October 14 - 18, 2003, Valencia, Spain
Outline:

- Physics Goals
  - NuMI beam $\nu$’s
  - CR atmospheric $\nu$’s
- Construction Progress
- Beginning of data collection
  - CalDet
  - Cosmics
Strategy

- **Two-detector measurement**
  - high mass w/ low price / kg
  - reliable and robust technology
  - underground (shielding)
- **Use high intensity 120 GeV MI**
  - (up to) $4 \times 10^{13}$ protons/pulse
  - 0.4 MW
  - Single turn extraction (8.4 µs)
  - $\sim 4 \times 10^{20}$ protons/year
- **Flexible well-controlled beam**
  - (Hadronic hose)

Start data collection in early 2005
MINOS Collaboration

32 institutions
200 physicists
• Decisive low-systematics observation of $\nu_\mu \rightarrow \nu_\tau$
• Determine $\Delta m_{23}^2$ and $\sin^2 2\theta_{23}$ with $\sim 10\%$ accuracy
• Measure (or improve limits) on $\nu_\mu \rightarrow \nu_e$ transition
• Measure (or improve limits) on $\nu_\mu \rightarrow \nu_{\text{sterile}}$
• Test CPT in atmospheric $CC_\mu$ charge-separated interactions
• Test exotic hypotheses: decay, extra-dim, decoherence

How well we do will largely depend on the amount of flux delivered!
Energy spectra: Near to Far projections

Near versus Far
$E_{\nu}$ in $CC_{\mu}$

$\Delta m^2 = 0.002$ eV$^2$
$\Delta m^2 = 0.0035$ eV$^2$
$\Delta m^2 = 0.005$ eV$^2$

No Oscillations

~2 yrs of running
Protons for MINOS

\[ \Delta m^2 = 0.0025 \text{ eV}^2 \]
\[ \sin^2 2\theta = 1.0 \]

- Original MINOS proposal
  2 yrs@ $3.7 \times 10^{20}$ pot = $7.4 \times 10^{20}$ pot
- $2 \times 10^{20}$ pot/yr expected in 2005
- Proposals at Fermilab to upgrade the accelerator complex to reach $7.2 \times 10^{20}$ by 2009
- MINOS could integrate $25 \times 10^{20}$ for a 5 yr run
Electron appearance

- Sensitivity is determined by statistical fluctuation of the NC $\pi^0$ BG in the far detector.
- Limit on $U_{e3}^2$ will scale like $1/\sqrt{N}$ and is not limited by systematics for any realistic exposure.
- Limit can be further improved by removing high-energy tail from the NuMI beam and increased proton flux in late years.

For $\Delta m^2 = 0.0025$ eV$^2$

$\sin^2 2\theta_{13} = 0.067$
Electron appearance

MINOS sensitivities based on varying numbers of protons on target

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

120 GeV/c protons strike graphite target
Magnetic horns focus charged mesons (pions and kaons)
Pions and kaons decay giving neutrinos

Decay Pipe
\[ l = 677 \text{ m}, \ r = 1 \text{ m} \]

Hadron Absorber
MINOS Detectors

- 1 spill every 1.9 seconds
- 4e13 protons/10 μsec spill
- 3.8e20 protons/year

\[ L = 1.04 \text{ km to Near, 735 km to Far Detector} \]

NuMI Tunnel Project

677 m decay pipe
Target
Near Detector

Horn 1

Horn 2
NuMI neutrino beams

horns and target can be moved to tune to a different energy spectrum

In a later stage (> 2007 ?) running with antineutrinos is foreseen

$\nu_\mu$ CC Events/kt/year

<table>
<thead>
<tr>
<th>Low</th>
<th>Medium</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>470</td>
<td>1,270</td>
<td>2,740</td>
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</table>

$\nu_\mu$ CC Events/MINOS/2 year

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<tr>
<th>Low</th>
<th>Medium</th>
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<td>5,080</td>
<td>13,800</td>
<td>29,600</td>
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</table>

$4\times10^{20}$ protons on target/year

$4\times10^{13}$ protons/1.9 seconds
Modern tools of experimental particle physics: TBM – Tunneling Boring Machine

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TBM - front

Decay pipe is finished and encased in concrete

Tunneling: a nightmare…but it’s over
Outfitting end-game

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Beam components ready

Target from Protvino

Horn 2

Part of NuMI shielding

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Detector technology

Main Features:

- Extruded scintillator strips
  - Far in 8 modules
- Wavelength-shifting + clear fibers
- 8m octagonal 1 in thick Fe plates
  - Far in 8 pieces
- Multi-anode PMT readout
  - M16 in Far
  - M64 in Near
- 8-fold optical multiplexing in Far
- Front-ends
  - VA(IDE) for M16
  - QIE for M64
- Software trigger
Far – 735.3 km away

- 2 Supermodules
- 5.4 kT
- 485 scint. planes
- 93,120 strips (4.1 x 1.0 cm)
- 8-fold MUXed 2-ended readout
- 1551 M16s
- 722 km of WLS fiber
- 794 km of clear fiber
- $B \sim 1.5T$ (R=2m)
- HAD $\sim 55\% / E^{1/2}$
- EM $\sim 23\% / E^{1/2}$
Plane assembly

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Steel Welded and modules placed.

Crane carries plane down the hall for installation

Plane lifted to vertical

FarDet Installation by Week

6-8 Planes per week

Planes Installed

Schedule (future at 6.4 pln/wk)

Planes Installed

Milestones

AHEP-2003: Progress of the MINOS Experiment

Valencia, Spain, October 14-18, 2003
FarDet: Done

SM 1 + SM2 (248 + 237 = 485 planes)
Near – 1040 m away

- veto - target - shower - μ spectrometer
- 1 kT
- 3.8 x 4.8 “squeezed” octagon
- 12,300 scint.strips
- 1-end readout
- no-multiplexing
- 220 M64s
- QIE-based front-end
- 282 steel planes
- 153 scintillator planes
- 65 km WLS fiber
- 51 km clear fiber

Near detector will provide high event statistics for “mundane” neutrino physics
NearDet construction

Status as of October, 2003
- All planes assembled and “shelved”
- Beneficial occupancy of the Near Hall in Dec’03
- Near detector will be ready late summer 2004
The third detector - CalDet

• MINOS calibration challenge:
  • Near/Far relative calibration to 2%
  • absolute calibration of 5%

• Main ingredients:
  • cosmic ray muons
    • energy scale calibration
    • strip-to-strip response
    • muon energy unit (MEU)
  • light injection system
    • PMT gain drifts
    • PMT/electronics linearity
  • calibration detector (CalDet)
    • define MEU
    • topology and pattern recognition

2 CalDet modules being staged in T7
CalDet – it’s an experiment

- 5 tons
- 1 m x 1 m x 3.7 m
- 60 MINOS planes
- 5 modules (for moving)
- 24 strips/plane (a total of 1440 strips)
- Consecutive scintillator planes rotated 90°
- FarDet and/or NearDet readout
- Clear and green (to simulate size of far detector) ribbon cable transports light to PMTs
- No B field

- ~3,200 front-end channels
- T11 (0.5-3.5 GeV/c) & T7 (1-10GeV/c)
- full MINOS calibration scheme
- “paved the road” for commissioning of FarDet
- taking data now
CalDet: electrons

Strip vs. Plane profile, weighted by number of hits

Strip vs. Plane profile, weighted by MEU deposited

"Wings" due to PMT xtalk

Sample Event (2GeV e+)

Electron Line Shapes
CalDet – 2 GeV events

Electron

Pion

Muon

Proton

Strip

Plane

Plane

Plane
**CalDet: pions and protons**

**Sample Pion Events**

- Even Plane view
- Odd Plane view
- Relative Pulse Height

- 3.5 GeV

**Sample Proton Events**

- Even Plane view
- Odd Plane view
- Relative Pulse Height

- 3.5 GeV

- 2 GeV

- 1 GeV
Front-end electronics comparison: 
NearDet vs FarDet in CalDet

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• In order to have NearDet and FarDet respond similarly they have to be … different.

• This is due to scales of the detectors and event rates difference by \( \sim 10^5 \)

• VA + M16 (8x multiplexed)

• QIE + M64 (not multiplexed)
MINOS Observatory:
Atmospheric Neutrinos and Muons

- B field makes MINOS a unique underground observatory
  - measure charge and momentum of muons from ~0.5-70 GeV/c.
  - distinguish neutrinos from antineutrinos (for $p_\mu > \sim 1$ GeV/c)
  - measure $E_\nu$ (even w/ exiting muon): determines $L/E$

- Use timing and topology for event direction

- MINOS will directly compare atmospheric $\nu_\mu$ and $\bar{\nu}_\mu$ oscillations

- Measure contained events and upward going muons

- Start data-taking before NuMI beam

- Opportunities for young researchers

<table>
<thead>
<tr>
<th>Number of events in 24 kT years</th>
<th>Neutrino</th>
<th>Antineutrino</th>
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<tbody>
<tr>
<td>Reconstructed contained vertex with muon</td>
<td>620</td>
<td>400</td>
</tr>
<tr>
<td>Reconstructed upgoing muon</td>
<td>280</td>
<td>120</td>
</tr>
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MC Expectation with no oscillations
MINOS Observatory: CR muons

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Run 4436, Snarl 424.

β⁻¹ = -1.072889, φ = 140.578065, \( \chi^2 = 0.001683 \), Planes Hit = 47

Run 4436, Snarl 89.

β⁻¹ = 1.000265, φ = 152.045888, \( \chi^2 = 0.346579 \), Planes Hit = 23

Upward candidate

Downward candidate
Direction by timing

- Use Y direction timing and direction cosines at vertex to identify upward-going muons
- Tight $1/\beta (=c/v)$ distribution indicates good timing
- Negative $1/\beta$ values indicate upward-going muons
- Peak at $1/\beta = -1$ clearly seen

\[ \sigma = 0.056 \]
Upgoing example

$\mu^+$ with $p = 5.4$ GeV/c

Run 12849, Series 33889, Plane Hit = 92, Track length = 8.36 m
$\beta^1 = -1.086$, vertex(x,y,z) = (-3.083, -0.877, 6.529)
$\cos(\theta)_{xy} = -0.222$, $\cos(\theta)_{yz} = -0.106$
$p_{\text{hit}} = 5.397$ GeV/c, $(\Delta p)/p = 0.027$, $p_{\text{reco}} = 5.263$ GeV/c
MINOS Observatory Challenge: Finding a ν-dle in a stack of steel…

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Reconstructed “vertices” for cosmic ray events which have a track that ends inside the detector. Most are clearly downgoing stopping muons. A few mis-reconstruct for known reasons (hardware and software commissioning) which will be fixed soon.

Example of one downgoing stopping muon which appears to have a vertex just inside the nominal fiducial volume of the detector. This was due to tracking software which is not yet completely commissioned.
MINOS Observatory News:
Contained event candidate

Run 7465, Snarl 412
Vertex: (x,y,z) = (-1.9, 2.1, 6.9)
cos(zenith) = 0.42, dcosz = 0.34
Summary

• MINOS and NuMI construction progressing very well
  FarDet: 100%
  NearDet: 100% (but not underground)
  CalDet: 95% data → analysis underway

• MINOS observatory in operation
  SM 1&2 B field is on
  Collect CR data
  calibration, commissioning physics

• Developing physics analysis tools
• NearDet to be installed late summer 2004
• First protons in Dec’04
• Commissioning and start data taking early 2005
  (on schedule for the last 2 years!)
MINOS gets going on the far side

LHC Dipoles
Coils for the first octant p5

Light Sources
Proposed new facility p15

Neutrinos
Heat from the Earth p20
How to assemble a MINOS sandwich in 100 seconds

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**Protons for MINOS**

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\[ \Delta m^2 = 0.0016 \text{ eV}^2 \]

\[ \sin^2 2\theta = 1.0 \]

- Original MINOS proposal
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MINOS Observatory News:
bending muons!

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Bending Muon in BField
Run 6645, Snarl 2400

Stopping muon

\[ P_{\text{range}} = 3.86 \text{ GeV/c} \]

\[ P_{\text{curvature}} = 4.03 \text{ GeV/c} \]
MINOS Observatory News:
Upward muon candidate

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First Observed Upward Going Muon in MINOS
128 Planes, 3.5 days data
Number of Track Planes > 20, Hough Chi^2 < 100, Good Vertex and Exit Positions

Run 3381, Snail 2621

Y vs X Position

Y Position (m)
-4 -3 -2 -1 0 1 2 3 4
X Position (m)
-4 -3 -2 -1 0 1 2 3 4

Reconstructed V vs Z
Reconstructed T vs Z

cos(zenith angle) = -0.17