The MINOS far detector is complete and taking cosmic ray data

Beam work and near detector construction at Fermilab is on schedule, first beam end 2004

Very preliminary atmospheric neutrino data

Calibration detector exposure at CERN

Five year program proposed to Fermilab, potential for beam upgrades

Off-axis detector to search for $\nu_\mu - \nu_e$ is under development
MINOS Physics goals

- **Demonstrate Oscillation Behavior**
  - Precise measurement of CC energy distribution between near and far detector.
  - “Standard” oscillations or some other explanation?
    - Can we see clear “oscillatory” behavior from the first osc. max? Rise at low energy?
    - Neutrino decay?

- **Precise Measurement of Oscillation Parameters**
  - How close to 1.0 is $\sin^2 2\theta_{23}$?
  - Measurement of $\Delta m^2$ ~ 10 times better than Super-K
MINOS Physics Goals

**Precise Determination of Flavor Participation**
- Number of CC $\nu_x$ events far/near $\sim 2\%$: Probability for $\nu_x \rightarrow \nu_x$ oscillation.
- Number of CC $\nu_e$ events far/near: Sensitive to $\nu_x \rightarrow \nu_e$ oscillation down to about $2\%$. **Discovery/first measurement of $U_{e3}$?**
- Number of NC events far/near: probability for $\nu_x \rightarrow \nu_{\text{sterile}}$ oscillation down to about $10\%$.
- $\nu_x$’s which disappear but don’t appear as $\nu_e$ or disappear to $\nu_{\text{sterile}}$ must be $\nu_x$!

**Direct Measurement of Atmospheric $\nu$ vs $\overline{\nu}$.**
- CPT Violation?
Far detector at Soudan

- Completed July 2003
- Magnet powered and running
- Half the detector has been running since mid 2002
- Detector working well, up to or better than specifications in all respects
- Taking atmospheric neutrino data, Soudan 2 exposure by the end of next year
Cosmic ray muons

- Cosmic ray muons are used for calibration (and physics!)
- 2.6ns/plane timing resolution permits direction determination
- Veto shield tags incoming muons
- Background to neutrino events
Upward muons

- Timing allows measurement of $1/\beta$
- Good separation of downward (cosmic ray) and upward (neutrino induced) muons
Atmospheric neutrino interactions have been observed.

Magnetic field gives a charge measurement, can distinguish neutrinos from anti-neutrinos.

First underground detector with this capability.

Potential to test CPT.
Sensitivity to CPT

- Measure oscillations in $\nu$ and $\bar{\nu}$
- CPT violation would produce a different value of $m^2$ in the two cases

<table>
<thead>
<tr>
<th></th>
<th>Neutrino</th>
<th>Antineutrino</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of events</td>
<td></td>
<td></td>
</tr>
<tr>
<td>in 24 kT years</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reconstructed contained vertex with muon</td>
<td>440</td>
<td>260</td>
</tr>
<tr>
<td>Reconstructed upgoing muon</td>
<td>280</td>
<td>120</td>
</tr>
</tbody>
</table>

For $m^2=0.003$ eV$^2$, $\sin^2 2\theta = 1.0$
Beam and Near Detector

- Tunneling completed
- Detector elements built
- Installation starts later this year
- First beam December 2004
A mini-version of the MINOS near and far detectors
- 1m x 1m x 3.7 m
- 60 planes x 24 strips/plane
- Readout technologies of both the near and far detectors

Being exposed to electron, pion, proton and muon beams from 0.5-10 GeV/c momentum at the CERN PS.

Aiming at a relative energy calibration of the two detectors of ±2% to make the systematic error on \( \Delta m^2 \) negligible compared to the statistical error
Particle Identification by topology

- 2 GeV particles identified by beam time-of-flight and cherenkovs.
MINOS running plan

- Draft Fermilab long-range plan
  - 4 years of physics running for MINOS starting in April 2005.
  - Goal for protons on target in first year = $2.5 \times 10^{20}$

- BUT plans are being developed for increased proton intensity.

- New MINOS Running Request (May 2003)
  - 5 years of running with a total of $25 \times 10^{20}$ protons on target in that time. Original MINOS physics sensitivity was based on $7.4 \times 10^{20}$ pot.

- There are several options for providing this number of protons. Much effort at Fermilab is directed to improving the proton intensity both for the collider program and for MINOS.

- MINOS has provided updated physics sensitivity curves based on 7.4, 16 and $25 \times 10^{20}$ total protons on target.
Sensitivity to oscillations

- Three proton intensities
  - Points with errors; ratio of measured to expected (by projection from the near detector) $\nu_{\mu}$ cc events for $\sin^22\theta=1$, $\Delta m^2=0.0025$
  - Blue line; neutrino decay hypothesis
  - Dashed line; oscillations with $\Delta m^2=0.0016$, $\sin^22\theta=1$

- 90% and 99% confidence allowed regions, compared with Super-K
• MINOS sensitivities based on varying numbers of protons on target

\[ \Delta m^2 = 0.0025 \text{ eV}^2 \]
To do better with $\bar{\nu}_e$ appearance:

- Aim at 10 times CHOOZ limit and measurement of the sign of $\Delta m^2$
- Use off-axis narrow-band beam, peaking at the first oscillation maximum $\sim 2$ GeV
- Build a new 50 kton, low $Z$, low density detector on the surface
Design of a detector using compressed wood panels as absorber and MINOS style scintillator with APD readout or RPCs as active detector is well advanced.

Simulations show that values of

\[
\frac{\text{Number of } \nu_e \text{ events}}{\text{number of background events}} > 35
\]

Can be obtained at the CHOOZ limit.

Proposal to Fermilab soon.

$100-150M$ price tag.