Cosmic Rays and Neutrinos at MINOS

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The Reality of MINOS

- Intro
  - The MINOS Detector(s)

- Cosmic Ray Physics
  - Muon Charge Ratio at the surface
  - Seasonal Variations and Sudden Stratospheric Warmings
  - Atmospheric Neutrinos and Oscillations

- Neutrino Oscillations
  - Charged current oscillation parameters
  - Searching for sterile neutrinos
  - $\nu_e$ Appearance and $\theta_{13}$
MINOS has two functionally identical detectors that measure the NuMI neutrino beam from Fermilab.

Oscillation Physics Goals:
- Precision measurements of $\sin^2 2\theta_{23}$ and $\Delta m^2_{23}$
- Mixing to sterile neutrinos
- Study subdominant oscillation mode $\nu_\mu \rightarrow \nu_e$, measure/limit $\theta_{13}$

Other Studies:
- Cosmic ray physics and atmospheric neutrinos
- CPT tests
- Near Detector studies of neutrino interactions
- Lorentz violation
MINOS Collaboration

Argonne • Arkansas Tech • Athens • Benedictine • Brookhaven • Caltech • Cambridge • Campinas • Fermilab • Harvard • IIT • Indiana • Minnesota-Twin Cities • Minnesota-Duluth • Oxford • Pittsburgh • Rutherford • Sao Paulo • South Carolina • Stanford • Sussex • Texas A&M • Texas-Austin • Tufts • UCL • Warsaw • William & Mary

28 institutions, 175 scientists, funded by DOE, NSF, SFTC
The far detector is located in northern Minnesota at the Soudan Underground Mine -- 2341 ft. below surface (2070 m.w.e.).

Construction on the far detector was completed in 2003.
484 planes of steel mounted with scintillator strips totaling 5.4kT.

Strips of scintillator 4.1cm wide and up to 8m long.

Strips in successive planes rotated by 90°.

Wavelength shifting fiber used to collect scintillator light.

Double ended readout

8 strips are mapped to one PMT.
First large underground detector with a magnetic field.

Toroidal field with strength 1.3T. Separates $\mu^+$ and $\mu^-$ up to 200GeV.

Data was taken in two configurations:
Forward Field – 609.82 live days
Reversed Field – 201.75 live days
Cosmic Ray Event

Event Display for a cosmic muon event.
Timing resolution is $\sim2.3\text{ns}$. 

[Image: Cosmic Ray Event Display]
Muon Charge Ratio

Measure the ratio $R = \frac{\mu^+}{\mu^-}$

Charge Ratio changes at higher energies

- $R$ can increase with energy – increased kaon importance.
- $R$ can decrease with energy – effects from heavy elements.
- $R$ can decrease with energy – increased charm production and semileptonic decays.

Charge ratio important for modeling cosmic ray interactions and doing accurate calculations of atmospheric fluxes. It is particularly important for measuring the ratio $\nu/\bar{\nu}$.

MINOS has large statistics and can explore an energy range (1-7 TeV) where few measurements exist.

(Naumov, hep-ph/0201310)
Event Selection

Use curvature of muon track to measure energy and charge.

Muons that have crossed more planes will have a more reliable charge determination.

Important cuts

- Good Track Fit: \((q/p)/\sigma_{(q/p)} > 2.2\)
- Minimum Information Cut: Require \(N\) hits within 3.5m of coil hole.

Hard cuts are required to minimize systematic effects ~95% of our data was removed.
Systematic Errors

The forward and reverse field data sets found a different charge ratio. There still remains a systematic offset.

Use geometric mean of forward and reverse data to cancel out geometric and alignment effects.
Create two independent samples:

\( r_1 \) – geometric mean of
1\textsuperscript{st} half reversed field + forward field just before switch

\( r_2 \) – geometric mean of
2\textsuperscript{nd} half of reversed field + forward field just after switch.

\[ R = 1.374 \pm 0.004 \text{(stat.)} \pm 0.010 \text{(syst.)} \]

(Adamson \textit{et. al}, PRD 76:052003)
To find the energy at the surface:

$$E_{surface} = \left( E_{underground} + \frac{a}{b} \right) e^{bX} - \frac{a}{b}$$

- \(a\) = ionization energy loss
- \(b\) = radiative energy loss
- \(X\) = slant depth

Project the energy of each muon to the surface using \(a\) and \(b\) for rock at Soudan.

(Adamson et. al, PRD 76:052003)
Comparison with other Measurements

MINOS sees an increase in the charge in ratio comparison to other experiments.

Studies in the MINOS Near Detector are consistent with L3C showing the difference is not likely due to systematic errors.

C. Amsler et al. (Particle Data Group), Physics Letters B667, 1 (2008)

More details on the Near Detector results will be forthcoming.

What is the physics behind this rise in the charge ratio?
Qualitative Model: (Gaiser, 1990)

\[
\frac{N_{\mu^+}}{N_{\mu^-}} = \frac{f_{\pi^+}}{1 + \frac{1.1E_\mu\cos\theta}{115\text{GeV}}} + \frac{0.054f_{K^+}}{1 + \frac{1.1E_\mu\cos\theta}{850\text{GeV}}}
\]

\[
\frac{(1-f_{\pi^+})}{1 + \frac{1.1E_\mu\cos\theta}{115\text{GeV}}} + \frac{0.054(1-f_{K^+})}{1 + \frac{1.1E_\mu\cos\theta}{850\text{GeV}}}
\]

\(f_{\pi^+}/f_{K^+}\) = fraction of pions/kaons giving \(\mu^+\)

\((1-f_{\pi^+})/(1-f_{K^+})\) = fraction of pions/kaons giving a \(\mu^-\)

\(f_{\pi^+}, f_{K^+}\) independent of energy

best fit values:

\(f_{\pi^+} = 0.55\) \(f_{K^+} = 0.67\)

(Adamson et. al, PRD 76:052003)
Previous experiments (Barrett, MACRO, AMANDA) have seen the muon rate change for different seasons of the year.

As the temperature increases:

- The atmosphere expands and correspondingly decreases the density causing a higher muon flux reducing the chances for interaction.
- For low energy muons the change in the production height can be cause the muon to decay before it reaches the earth.

Measure the correlation between muon flux underground and the temperature

\[
\frac{R_\mu - \langle R_\mu \rangle}{\langle R_\mu \rangle} = \alpha_T \frac{T_{\text{eff}} - \langle T_{\text{eff}} \rangle}{\langle T_{\text{eff}} \rangle}
\]
Temperature data taken from European Centre for Medium-Range Weather Forecasts (ECMWF). Effective temperature taken by weighting according to where muons detected in MINOS originate.

Three years of data shows a high correlation between muon flux and effective temperature. From a straight line fit:

$$\alpha_T = 0.87 \pm 0.03$$
Previous experiments have seen correlations averaged over seasons. Sudden Stratospheric Warmings (SSW) cause large temperature changes over a few days. First seen in 1950 they occur ~4/decade.

Can MINOS see correlations on shorter timescales?
MINOS observes a SSW

SSW in February 2005 clearly seen by MINOS

First correlation between underground muons and meteorological phenomena in the stratosphere. Can data be used such data for future meteorological applications?
Atmospheric Neutrinos
Atmospheric Neutrinos

Contained vertex events  (Adamson et. al, PRD 73:072002 )
August 2003 to February 2005
Live time – 418 days

Upward-going muon events  (Adamson et. al, PRD 75:092003 )
August 2003 to April 2006
Live time – 854.1 days

Total Live Time up to Date: ~1200 days
Selecting Neutrino Induced Muons

Upward muons come from neutrinos not cosmic rays.

Distinguish upward from downward muons by

\[ \frac{\Delta T}{\Delta S} \rightarrow \frac{1}{\beta} = \frac{c}{v} \]

Parent Neutrino Energy

- **Monte Carlo**
  - **L**: \(1\text{GeV} < \text{Energy} < 10\text{ GeV}\)
  - **H**: \(10\text{ GeV} < \text{Energy} < 100\text{ GeV}\)
  - **U**: ???

Divide into low (L), high (H) and undefined (U) energy.
Oscillations most prominent for low energy.

A better way to do this measurement is ...
Neutrino Oscillations in MINOS
Neutrinos at the Main Injector

120 GeV protons on graphite target

Secondary hadrons are focused by magnetic horns

Tunable energy beam by changing relative positions of horns and target

Beam Composition:

\[ 92.9\% \, \nu_\mu, \ 5.8\% \, \bar{\nu}_\mu, \ 1.3\% \, \nu_e + \bar{\nu}_e \]
Total NuMI Protons to Monday, 25 August 2008

- RUN I - $1.27 \times 10^{20}$ POT
- RUN IIa - $1.23 \times 10^{20}$ POT
- RUN IIb - $0.71 \times 10^{20}$ POT
- RUN III

High Energy Runs
Measure $\nu_\mu$ spectrum at the near detector and extrapolate to the far detector. If neutrinos oscillate you expect an energy-dependent reduction at the far detector.

**Survival Probability:**

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta \sin^2 \left( 1.27 \frac{\Delta m^2 [eV^2] L [km]}{E [GeV]} \right)$$

**Why?**

- Needed for reactor $\theta_{13}$ experiments
- Is $\theta_{23} = 45^\circ$? New symmetry?
- Demonstrate that it can be done.
\( \nu_\mu \) Disappearance Results

Consistent with 2 flavor oscillations and maximal mixing.

\[(\text{hep-ex/0806.2237 , accepted by PRL})\]

\[|\Delta m^2| = 2.43 \pm 0.13 \times 10^{-3} \text{ eV}^2 \ (68\% \text{ C.L.})\]

\[\sin^2(2\theta) > 0.9 \ (90\% \text{ C.L.})\]

3.36x10\(^{20}\) protons on target
Searching for Sterile Neutrinos

Neutral current (NC) events appear as shower-like events without a track.

All active flavors participate in NC interactions. Their yield should be similar between the Near and Far Detectors.

Any deficit of NC events at the far detector could indicate mixing from $\nu_\mu$ to sterile neutrinos.

Must take into account $\nu_e$ appearance since they are hard to distinguish in our detector.
Sterile Neutrino Results

Use oscillation results from MINOS and Kamland+SNO. Look at both $\theta_{13}=0$ and $\theta_{13}$ at the CHOOZ limit.

**Rate based:**

$$ R = \frac{N_{Data} - N_{CC\, Bkg}}{N_{MC}} $$

- $R=0.99\pm0.09\pm0.07 \,(\theta_{13}=0)$
- $R=0.9\pm0.09\pm0.07 \,(\text{max } \theta_{13})$

**Spectrum Fit:**

$$ f_s = \frac{P_{\nu_{\mu}\rightarrow\nu_s}}{1 - P_{\nu_{\mu}\rightarrow\nu_{\mu}}} $$

- $f_s < 0.68 \,(90\% \text{ C.L.}) \,(\theta_{13}=0)$
- $f_s < 0.80 \,(90\% \text{ C.L.}) \,(\text{max } \theta_{13})$

*Consistent with no deficit of NC events.*

2.46x10^{20} protons on target

(hep-ex/0807.2424, submitted to PRL)
At the CHOOZ limit we expect $\sim 12 \nu_e$ signal events and $\sim 42$ background events with $3.25 \times 10^{20}$ protons. Matter effects and $\delta$ affect the sensitivity.

Results should be out by next year!
Summary and Future

• Cosmic Ray Physics
  – The muon charge ratio was measured to be for surface energies from 1-7 TeV. This significantly higher than previous experiments.
  – Correlations between the muon flux and temperature were seen.
  – Atmospheric muons have some sensitivity to oscillation parameters.
    ❑ Work on neutrino point source searches and coincidences with gamma ray bursts is making its way through the collaboration.

• Neutrino Physics
  – Precise measurements of $\sin^2 2\theta_{23}$ and $\Delta m^2_{23}$.
  – No evidence for sterile neutrinos was seen.
    ❑ Results for $\theta_{13}$ will be released soon.
The End