$\bar{\nu}_\mu$ Results from the MINOS experiment

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Recontres de Blois 2010
The MINOS Experiment

Recent Results

Antineutrino Disappearance

Summary
Main Injector Neutrino Oscillation Search

Neutrinos are produced by the NuMI beam. The beams composition and energy are measured by the Near Detector. The oscillated neutrino beam is measured by the Far Detector, at a mine in Minnesota.

Measurements and limits include:
$\Delta m^2_{32}$, $\sin^2 2\theta_{32}$, $\Delta m^2_{32}$, $\sin^2 2\theta_{32}$, $\theta_{13}$, sterile neutrinos, CPT conservation, cross-sections...
Physics Goals

- With three active neutrinos there are two independent mass splittings

\[ \Delta m_{\text{atm}}^2 \approx \Delta m_{32}^2 \approx 2.4 \times 10^{-3} \text{ eV}^2 \]

\[ \Delta m_{\text{sol}}^2 \approx \Delta m_{21}^2 \approx 8.0 \times 10^{-5} \text{ eV}^2 \]

- MINOS is most sensitive to the larger of these and \( \theta_{23} \) through \( \nu_\mu \) disappearance

\[ P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta_{23}) \sin^2\left(1.27 \frac{\Delta m_{\text{atm}}^2 L}{E}\right) \]

(Monte Carlo \( \sin^22\theta = 1.0 \), \( \Delta m^2 = 3.35 \times 10^{-3} \text{ eV}^2 \))
MINOS Detectors

Both detectors are functionally equivalent, in order to reduce systematics.

**Near Detector**
- At Fermilab, IL
- 282 Planes
- 980 Ton

**Far Detector**
- At Soudan, MN
- 486 Planes
- 5400 Ton

Planes of 2.54cm Steel and 1cm Scintillator

Toroidal magnetic field allows charge sign determination

Alternating scintillator planes in perpendicular directions for 3D event reconstruction
The MINOS Experiment

Recent Results

Antineutrino Disappearance

Summary
ν_e Appearance Results

- Looking for appearance of ν_e in the ν_μ beam
- Discriminate against NC events using 11 shape variables in an Artificial Neural Network
- Find Limits:
  
  for \( \delta_{CP} = 0 \), \( \sin^2(2\theta_{23}) = 1 \),
  
  \[ |\Delta m^2_{32}| = 2.43 \times 10^{-3} \text{ eV}^2 \]

  \( \sin^2(2\theta_{13}) < 0.12 \)  normal hierarchy
  \( \sin^2(2\theta_{13}) < 0.20 \)  inverted hierarchy at 90% C.L.

arXiv:1006.0996v1 [hep-ex]
Neutral Current Results

- Neutral Current event rate should not change in standard 3 flavour oscillations
- A deficit in the Far event rate could indicate mixing to sterile neutrinos
- $\nu_e$ CC events would be included with the selected NC sample, so result depends on the possibility of $\nu_e$ appearance

Expect: 757 Events
Observe: 802 Events

No deficit of NC Events

$$f_s \equiv \frac{P_{\nu_\mu \to \nu_s}}{1 - P_{\nu_\mu \to \nu_\mu}} < 0.22 \ (0.40) \text{ at } 90\% \ C.L.$$ no (with) $\nu_e$ appearance
\( \nu_\mu \) Disappearance Results

- Last published results 2008 (PRL 101:131802, 2008)
- Additional data \( 3.4 \times 10^{20} \rightarrow 7.2 \times 10^{20} \) POT
- Many analysis improvements including:
  - Updated simulation and reconstruction
  - New selection with improved efficiency
  - Improved shower energy resolution
  - Separate data into bins of energy resolution
  - Smaller systematic uncertainties

Best fit to oscillations at:

\[
\left| \Delta m^2 \right| = 2.35^{+0.11}_{-0.08} \times 10^{-3} \text{eV}^2
\]

\[
\sin^2(2\theta) > 0.91 \text{ (90\% C.L.)}
\]
The MINOS Experiment

Recent Results

- **Antineutrino Disappearance**

Summary
Antineutrinos - Motivation

- Previously we presented an antineutrino analysis based on $3.2 \times 10^{20}$ of neutrino mode data
- World measurements of antineutrino disappearance are still limited
- MINOS magnetised detectors allow direct measurement of the charge sign of the muon
- We recently took $1.71 \times 10^{20}$ of data with NuMI in antineutrino mode
Making Antineutrinos

- With NuMI in neutrino mode only 7% of the beam is antineutrino.
- These are of a higher average energy, making it harder to measure oscillations.

\[ \nu_\mu = 91.7\% \]
\[ \bar{\nu}_\mu = 7.0\% \]
\[ \nu_e + \bar{\nu}_e = 1.3\% \]
Antineutrino Mode

**Monte Carlo Neutrino mode**

Horns focus $\pi^+, K^+$

- $\nu_\mu = 91.7\%$
- $\bar{\nu}_\mu = 7.0\%$
- $\nu_e + \bar{\nu}_e = 1.3\%$

**Monte Carlo Antineutrino mode**

Horns focus $\pi^-, K^-$

- $\bar{\nu}_\mu = 39.9\%$
- $\nu_\mu = 58.1\%$
- $\nu_e + \bar{\nu}_e = 2.0\%$

Target

Focusing Horns

120 GeV protons from MI

15 m

2 m

30 m

675 m
Selecting Antineutrinos

Basic Selection

- Events in-time with the spill
- In the fiducial volume
- At least one reconstructed track
- Positive reconstructed charge

CC/NC Separation

Using a k-Nearest-Neighbour algorithm - data is compared to monte-carlo events in four parameters:

- Track Length
- Mean energy of track hits
- Energy fluctuations along the track
- Transverse track profile
Selection Efficiency and Contamination

- High energy $\nu_\mu$ contamination does not affect the oscillation result
- Highest purity is in the oscillation region

<table>
<thead>
<tr>
<th>Energy Range</th>
<th>Signal</th>
<th>Bkgd.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-6 GeV</td>
<td>106</td>
<td>1.9</td>
</tr>
<tr>
<td>6-20 GeV</td>
<td>38</td>
<td>4.3</td>
</tr>
<tr>
<td>&gt; 20 GeV</td>
<td>8</td>
<td>3.0</td>
</tr>
</tbody>
</table>
Results: Far Detector

- No Oscillation
  Prediction: **155** Events

- Observe: **97** Events

- Disfavour no-oscillations at 6.3σ

- Best fit to oscillations:

\[
|\Delta m^2| = 3.36^{+0.45}_{-0.40} \times 10^{-3} \text{ eV}^2 \\
\sin^2(2\theta) = 0.86 \pm 0.11
\]
Comparison with $\nu_\mu$ Result

- Contours include the effects of systematic errors.
The Future

- With more antineutrino running, MINOS can quickly improve the precision by a significant amount.

- Doubling out current six-month data set would decrease the error by ~30%.
Summary

- With $7 \times 10^{20}$ POT of neutrino beam, MINOS finds:
  - Muon neutrinos disappear:
    \[ |\Delta m^2| = 2.35^{+0.11}_{-0.08} \times 10^{-3} \text{ eV}^2, \]
    \[ \sin^2(2\theta) > 0.91 \text{ (90\% C.L.)} \]
  - NC event rate is not diminished:
    \[ f_s < 0.22 \text{ (0.40) at 90\% C.L.} \]
  - Electron-neutrino appearance is limited:
    \[ \sin^2(2\theta_{13}) < 0.12 \text{ (0.20) at 90\% C.L.} \]

- With $1.71 \times 10^{20}$ POT of antineutrino beam, MINOS finds:
  - Muon antineutrinos also disappear with:
    \[ |\Delta m^2| = 3.36^{+0.45}_{-0.40} \times 10^{-3} \text{ eV}^2, \]
    \[ \sin^2(2\bar{\theta}) = 0.86 \pm 0.11 \]

- We look forward to taking more anti-neutrino data!
Backup Slides
The NuMI Beam

- **Neutrinos at the Main Injector**
- 120 GeV Protons incident on a thick, segmented graphite target produces a spray of hadrons
- Magnetic horns can focus either sign by reversing the direction of current
- Can enhance the $\nu_\mu$ flux by focusing $\pi^+ , K^+$ (or vice versa)
- Adjustable energy by moving the target relative to the horns

![Diagram](image)

120 GeV $p$'s from MI

Target

Focusing Horns

$\pi^-$

$\pi^+$

Evacuated Decay Pipe

2 m

1.5 m

3 m

675 m

Low Energy

Medium Energy

Monte Carlo
Beam Performance

Total NuMI protons to 00:00 Monday 31 May 2010

- Run I
- Run II
- Run III
- Run IV

3.21 × 10^{20} POT $\nu_\mu$ mode

Previous Analyses
Beam Performance

Total NuMI protons to 00:00 Monday 31 May 2010

Run I Run II Run III Run IV

High Energy

7.24 \times 10^{20} \text{ POT} \ \nu_\mu \text{ mode}

Current \nu_\mu \text{ Analysis}

1.71 \times 10^{20} \text{ POT} \ \bar{\nu}_\mu \text{ mode}
Previous Antineutrino Results

- Analysed $3.2 \times 10^{20}$ POT of neutrino-mode running
- Antineutrinos are on average of higher energy, moving the spectrum peak out of the expected region of oscillations
- Very poor sensitivity to oscillations
$\bar{\nu}_\mu$ Near Detector Data Spectrum

- Selected Antineutrino data energy spectrum
- Good Data/MC agreement at the Near detector
Extrapolation

- Flux and cross-section uncertainties cancel when we extrapolate from Near to Far detectors.

- Near and Far detector energy spectra are not identical:
  - Due to π/K decay kinematics, neutrino energy varies with angle - the Near detector covers a wider solid angle.
  - Higher energy π travel further and decay closer to the Near detector.

- A beam matrix encapsulates our knowledge of decay kinematics, and transports the measured Near detector spectrum to the Far detector.
Systematics

- The antineutrino analysis is statistically limited
- Studies were done to assess the effect of systematics on the fitted result
- Results contours were produced with systematic uncertainties included
Comparison with $\nu_\mu$ Result

$1.71 \times 10^{20}$ POT MINOS $\nu_\mu$ running, Far Detector

- MINOS data
- No oscillations
- $\Delta m^2 = 2.35 \times 10^{-3} \text{eV}^2$, $\sin^2(2\theta) = 1$
- Best oscillation fit
- Background

$1.71 \times 10^{20}$ POT MINOS $\nu_\mu$ running, Far Detector

- MINOS Preliminary
- Background Subtracted

$\Delta m^2 = 2.35 \times 10^{-3} \text{eV}^2$, $\sin^2(2\theta) = 1$
This shows the sensitivity to future antineutrino running, in the scenario where the new data matches the $\nu_\mu$ disappearance best fit value.
MINOS Preliminary
- Data
- Oscillated MC
- No Oscillations

Far Detector
1.71 \times 10^{20} \text{ POT}
Antineutrino Running

Events

Reconstructed Shower Energy (GeV)

CC/NC Separation Parameter

Reconstructed \mu^+ Energy (GeV)