Neutrino Oscillations with MINOS – and the Search for New Physics

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Neutrinos are the oddballs of the elementary fermions

- Very tiny masses
- Neutral charge
- Rarely interact
- Only the left-handed ones interact

Still a lot we don't know about them

- Room for theoretical speculation

  Are they related to matter dominance?
  Leptogenesis?

  Are they related to Dark Matter?
  Heavy sterile neutrinos?

  Are they related to Dark Energy?
Neutrino Oscillations

Mass squared splittings ($\Delta m^2_{21}, \Delta m^2_{32} \approx \Delta m^2_{31}$)

Mixing Angles ($\theta_{12}, \theta_{23}, \theta_{13}, \delta_{CP}$)

$\theta_{23}, \Delta m^2_{32}, \theta_{13}, \delta_{CP}$

New Physics Searches

Take advantage of the uniqueness of neutrinos

- Unknown neutrino-matter interaction
- Superluminal neutrinos
Neutrino Oscillations
Three known types of neutrinos

**Weak Eigenstates**

\( \nu_e, \nu_\mu, \nu_\tau \rightarrow \nu_\ell, \ell \)

**Mass Eigenstates**

\[ E^2 = p^2 + m^2 \]

\[ |\nu_i(t)\rangle = e^{-iEt} |\nu_i\rangle \]
Mass eigenstates are a linear combination of weak states

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix}
=
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

Neutrino born in a weak flavor state is superposition of mass states will oscillate among flavor states as it propagates

\[
|\nu_f(L)\rangle \approx \sum \exp[-iL(m_j^2/2E)] U_{f,j}^* |\nu_j\rangle
\]
Neutrino Mixing Angles

3x3 Unitary Mixing Matrix

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} =
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

Can be fully described by 3 real angles and 1 complex phase for Dirac particles

PMNS (Pontecorvo-Maki-Nakagawa-Sakata) Matrix

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} =
\begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}
\begin{pmatrix}
\begin{pmatrix}
c_{13} \\
0 \\
-s_{13}
\end{pmatrix} & 0 & s_{13} e^{-i \delta_{CP}} \\
0 & 1 & 0 \\
-s_{13} e^{i \delta_{CP}} & 0 & c_{13}
\end{pmatrix}
\begin{pmatrix}
\begin{pmatrix}
c_{12} \\
-s_{12} \\
0
\end{pmatrix} & s_{12} & 0 \\
-c_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

Atmospheric terms

Unknown terms

Solar terms

\[c_{ij} = \cos \theta_{ij}, \quad s_{ij} = \sin \theta_{ij}\]
Mixing Parameters – What we know

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} =
\begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
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\end{pmatrix}
\begin{pmatrix}
c_{13} & 0 & s_{13} e^{-i\delta_{CP}} \\
0 & 1 & 0 \\
-s_{13} e^{i\delta_{CP}} & 0 & c_{13}
\end{pmatrix}
\begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
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Atmospheric terms
Unknown terms
Solar terms
Mixing Parameters – What we know

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0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

Atmospheric terms  Unknown terms  Solar terms

Weak Eigenstates

Mass Eigenstates

\(\nu_e\) \(\nu_\mu\) \(\nu_\tau\)
Mixing Parameters – What we know

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\begin{pmatrix}
\nu_e \\
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\nu_\tau
\end{pmatrix} = \begin{pmatrix}
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\nu_2 \\
\nu_3
\end{pmatrix}
\]

Atmospheric terms \quad \text{Unknown terms} \quad \text{Solar terms}

Weak Eigenstates
\[\nu_e \quad \nu_\mu \quad \nu_\tau\]

Mass Eigenstates
\[\nu_3 \quad \nu_2 \quad \nu_1\]

From Solar and Reactor Experiments
\[\sin^2\theta_{12} \approx 0.321 \pm 0.023\]
\[\Delta m^2_{21} \approx (7.67 \pm 0.22) \times 10^{-5} \text{ eV}^2\]

2008 Global Fits
M.C. Gonzalez-Garcia
and M. Maltoni
Phys Rept 460 (2008)
Mixing Parameters – What we know

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\begin{pmatrix}
\nu_e \\
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\end{pmatrix}
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c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

Atmospheric terms

Unknown terms

Solar terms

Weak Eigenstates

Mass Eigenstates

From Atmospheric and Accelerator Experiments

\[|\Delta m^2_{32}| \approx 2.32^{+0.12}_{-0.08} \times 10^{-3} \text{ eV}^2\]

\[\sin^2 2\theta_{23} > 0.9\]

MINOS, PRL 106 181801 (2011)
**Mixing Parameters – What we know**

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\nu_2 \\
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\end{pmatrix}
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- **Atmospheric terms**
- **Unknown terms**
- **Solar terms**

**Weak Eigenstates**

\[\nu_e \quad \nu_\mu \quad \nu_\tau\]

**Mass Eigenstates**

\[\nu_1 \quad \nu_2 \quad \nu_3\]

**From Atmospheric and Accelerator Experiments**

\[|\Delta m^2_{32}| \approx 2.32^{+0.12}_{-0.08} \times 10^{-3} \text{ eV}^2\]

- What is the mass hierarchy?
- \(\sin^2 \theta_{23} > 0.9\)

**MINOS, PRL 106 181801 (2011)**
Mixing Parameters – What we know

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Atmospheric terms
Unknown terms
Solar terms

Weak Eigenstates
\[\nu_e, \nu_\mu, \nu_\tau\]

Mass Eigenstates

\[|\Delta m^2_{32}| \approx 2.32 \times 10^{-3} \text{ eV}^2\]
\[\sin^2 \theta_{23} > 0.9\]

From Atmospheric and Accelerator Experiments

Is \(\theta_{23}\) non-maximal?

MINOS, PRL 106 181801 (2011)
Mixing Parameters – What we know

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\nu_3
\end{pmatrix}
\]

Atmospheric terms
Unknown terms
Solar terms

Weak Eigenstates

Mass Eigenstates

Remaining Questions

\( \nu_e \) \hspace{1cm} \( \nu_\mu \) \hspace{1cm} \( \nu_\tau \)
Mixing Parameters – What we know

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\begin{pmatrix}
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\]

Atmospheric terms  Unknown terms  Solar terms

Weak Eigenstates

\[\nu_e, \nu_\mu, \nu_\tau\]

Mass Eigenstates

\[\nu_1, \nu_2, \nu_3\]

Remaining Questions

What's the value of \(\theta_{13}\)?
Mixing Parameters – What we know

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Atmospheric terms
Unknown terms
Solar terms

Weak Eigenstates

\[\nu_e, \nu_\mu, \nu_\tau\]

Mass Eigenstates

\[\nu_1, \nu_2, \nu_3\]

Remaining Questions

What's the value of \(\theta_{13}\)?

\[\sin^2(2\theta_{13}) < O(10^{-1})\]
Mixing Parameters – What we know

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\]

Atmospheric terms
Unknown terms
Solar terms

Weak Eigenstates

\[\nu_e \quad \nu_\mu \quad \nu_\tau\]

Mass Eigenstates

\[\nu_3\]

Remaining Questions

What's the value of \(\theta_{13}\)?
\[\sin^2(2\theta_{13}) < O(10^{-1})\]

What's the value of \(\delta_{CP}\)?
Unknown
Mixing Parameters – What we know

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\begin{pmatrix}
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\begin{pmatrix}
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c_{12} & s_{12} & 0 \\
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\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

Atmospheric terms
Unknown terms
Solar terms

Weak Eigenstates
Mass Eigenstates
Remaining Questions

\[\nu_e \quad \nu_\mu \quad \nu_\tau\]

\[\nu_3\]

\[\nu_2\]

\[\nu_1\]

What's the value of \(\theta_{13}\)?
\[\sin^2(2\theta_{13}) < O(10^{-1})\]

What's the value of \(\delta_{CP}\)?
Unknown

Is there CP violation in the lepton sector?
1) Is there a non-maximal mixing between the $\nu_\mu$ and $\nu_\tau$ states? 
   Is $\theta_{23} \neq 45^\circ$?

2) What's the mass hierarchy? 
   Is $\Delta m^2_{32} > 0$?

3) Is there an $\nu_e$ component to the $\nu_3$ mass state? 
   Is $\theta_{13} \neq 0$?

4) Is there CP violation in the lepton sector? 
   Is $\delta_{CP} \neq 0$? (Is $\theta_{13} \neq 0$?)
1) Is there a non-maximal mixing between the $\nu_\mu$ and $\nu_\tau$ states? Is $\theta_{23} \neq 45^\circ$?

2) What's the mass hierarchy? Is $\Delta m^2_{32} > 0$?

3) Is there an $\nu_e$ component to the $\nu_3$ mass state? Is $\theta_{13} \neq 0$?

4) Is there CP violation in the lepton sector? Is $\delta_{CP} \neq 0$? (Is $\theta_{13} \neq 0$?)

MINOS can potentially address these questions
1) Is there a non-maximal mixing between the $\nu_\mu$ and $\nu_\tau$ states?  
Is $\theta_{23} \neq 45^\circ$?

2) What's the mass hierarchy?  
Is $\Delta m^2_{32} > 0$?

3) Is there an $\nu_e$ component to the $\nu_3$ mass state?  
Is $\theta_{13} \neq 0$?

4) Is there CP violation in the lepton sector?  
Is $\delta_{CP} \neq 0$? (Is $\theta_{13} \neq 0$?)

MINOS can potentially address these questions
$\nu_\mu$ disappearance analysis can potentially address this
1) Is there a non-maximal mixing between the $\nu_\mu$ and $\nu_\tau$ states?  
   Is $\theta_{23} \neq 45^\circ$?

2) What's the mass hierarchy?  
   Is $\Delta m_{32}^2 > 0$?

3) Is there an $\nu_e$ component to the $\nu_3$ mass state?  
   Is $\theta_{13} \neq 0$?

4) Is there CP violation in the lepton sector?  
   Is $\delta_{CP} \neq 0$? (Is $\theta_{13} \neq 0$?)

MINOS can potentially address these questions.  
$\nu_e$ appearance analysis can potentially address this.
So how does MINOS study oscillations?
$\nu$ beam produced at Fermilab

2 functionally identical detectors

**Far Detector** in Soudan Mine
- Search for evidence of oscillations

**Near Detector** at Fermilab
- Measures unoscillated beam composition
- Measures energy spectrum

Near to Far Extrapolation
- Minimize uncertainties from:
  - Cross section
  - Flux
  - Event detection
  - Event selection
Neutrino Production

Proton collision produces hadrons
Magnetic horns focus charged hadrons
Decays produce neutrinos

120 GeV
p^+ → π^−, π^+

Target → Focusing Horns → ν_μ, \overline{ν_μ}

15 m, 30 m, 675 m
Control $\nu$ energy spectrum

Target and horn positions

Horn current

Default configuration is Low Energy

Optimizes L/E for atmospheric $\Delta m^2$

CC interactions in the Near Detector are:

- 93% $\nu_\mu$
- 6% $\overline{\nu}_\mu$
- 1% $\nu_e + \overline{\nu}_e$
Two Detectors

**Near Detector**
- 1 kton mass (larger $\nu$ flux)
- 1 km from neutrino source
- 100 m underground
- Measures beam before oscillations

**Far Detector**
- 5.4 kton (smaller $\nu$ flux)
- 735 km from neutrino source
- 705m underground
- Measures changes in beam relative to Near Detector
Functionally Identical Detectors

Tracking calorimeters

- Alternating steel-scintillator layers
- Magnetized steel planes
- Scintillator planes segmented into strips
- Light read out by PMTs
**Event Topologies**

- **$\nu_\mu$ CC Event**
  - Long muon track
  - Hadronic activity at vertex

- **NC Event**
  - Short event
  - Often diffuse

- **$\nu_e$ CC Event**
  - Compact event
  - EM shower profile

---

**Monte Carlo**

- Depth in Detector (m)
- Transverse Position (m)

**Graphs**

- Long muon track
- Hadronic activity at vertex
- Short event
- Often diffuse
- Compact event
- EM shower profile
MINOS Oscillation Results
$\nu_\mu$ Charged Current Disappearance
Looking for a deficit of $\nu_\mu$ events in the Far Detector

Precision measurements of atmospheric $\Delta m^2$ and $\sin^2(2\theta)$

Test the neutrino oscillation hypothesis

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta \sin^2 \left( \frac{1.27 \Delta m^2 L}{E} \right), \quad L=735 \text{ km}$$

Example MC
Parameters set to: $\sin^2(2\theta)=1$, $\Delta m^2=3.35 \times 10^{-3} \text{eV}^2$
Looking for a deficit of $\nu_\mu$ events in the Far Detector

Precision measurements of atmospheric $\Delta m^2$ and $\sin^2(2\theta)$

Test the neutrino oscillation hypothesis

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Example MC
Parameters set to: $\sin^2(2\theta)=1$, $\Delta m^2=3.35\times10^{-3}\text{eV}^2$
Selected $\nu_\mu$ CC events in the Far Detector

Data consistent with oscillations
Pure decoherence\(^1\) disfavored at more than 9\(\sigma\)
Pure decay\(^2\) disfavored at more than 7\(\sigma\)

\(^1\)G.L. Fogli et al., PRD 67:093006 (2003)
\(^2\)V. Barger et al., PRL 82:2640 (1999)
Fitting Oscillation Parameters

$|\Delta m^2| = 2.32^{+0.12}_{-0.08} \times 10^{-3} \text{ eV}^2$

$\sin^2(2\theta) > 0.90$ (90% C.L.)

Dominant Systematics
Normalization
NC Background
Shower Energy
Track Energy
\[
|\Delta m^2| = 2.32^{+0.12}_{-0.08} \times 10^{-3} \text{ eV}^2
\]
\[
\sin^2(2\theta) > 0.90 \text{ (90\% C.L.)}
\]
$\nu_e$ Charged Current Appearance
Searching for subdominant $\nu_\mu \rightarrow \nu_e$ oscillations

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2(\theta_{23})\sin^2(2\theta_{13})\sin^2(1.27\Delta m^2 L/E) + ...$$

Constrain $\theta_{13}$ by looking for an excess of $\nu_e$-like events
Searching for subdominant $\nu_\mu \rightarrow \nu_e$ oscillations

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2(\theta_{23})\sin^2(2\theta_{13})\sin^2(1.27\Delta m^2L/E) + \ldots$$

Constrain $\theta_{13}$ by looking for an excess of $\nu_e$-like events

Need to distinguish between hadronic showers and electrons
Searching for subdominant $\nu_\mu \rightarrow \nu_e$ oscillations

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2(\theta_{23})\sin^2(2\theta_{13})\sin^2(1.27\Delta m^2 L/E) + ...$$

Constrain $\theta_{13}$ by looking for an excess of $\nu_e$-like events

Need to distinguish between hadronic showers and electrons
Select electromagnetic shower topologies

Library Event Matching (LEM)

Good match

Input event

Input Event → Compare with

Bad match

Library

Event # 1

Event # 2

Event # 3

Event # 4

Event # 5

Event # 30x10^6

Select N best matches

Best match # 1

Best match # 2

Best match # N

Compute value of discriminant from information of N best matches
Feed 3 variables from the 50 best matches and event energy into a neural network

**Background:**
- $\pi^0$'s generated via NC or deep-inelastic $\nu_\mu$-CC interactions
- $\tau$ in FD from oscillations
- Non-oscillation beam $\nu_e$

Measure background rate at Near

Extrapolate to Far by background component in bins of energy and LEM discriminant

Fit prediction in bins of LEM and energy to Far Data
**νₑ CC Appearance**

Signal Enhanced Region of LEM > 0.7

Far Detector background expectation: \(49.6 \pm 7.0\) (stat.) \(\pm 2.7\) (syst.) events

Far Detector observation: 62 events
Assuming:
\[ \delta_{CP} = 0, \ \theta_{23} = \pi/4 \]

normal (inverted) hierarchy

\[ \sin^2(2\theta_{13}) < 0.12 \pm 0.20 \]

90% CL

\[ \sin^2(2\theta_{13}) = 0.04 \pm 0.08 \]

Best Fit

Exclude \(\sin^22\theta_{13} = 0\) at 89% CL

Tightest constraints on \(\theta_{13}\) for a normal hierarchy
Comparison with T2K and Double Chooz

**Normal Hierarchy**

- **68% CL Allowed**
  - MINOS (PRL107.181802)
  - T2K (PRL107.041801)
  - Double Chooz (LowNu2011)

**Inverted Hierarchy**

- **68% CL Allowed**
  - MINOS (PRL107.181802)
  - T2K (PRL107.041801)
  - Double Chooz (LowNu2011)

\[\sin^2(2\theta_{13})\]

MINOS/T2K: \(\delta_{CP}=0, \theta_{23}=\pi/4, \Delta m^2>0\)

MINOS/T2K: \(\delta_{CP}=0, \theta_{23}=\pi/4, \Delta m^2<0\)
Neutrino Oscillations

Mass squared splittings ($\Delta m^2_{21}, \Delta m^2_{32} \approx \Delta m^2_{31}$)
Mixing Angles ($\theta_{12}, \theta_{23}, \theta_{13}, \delta_{CP}$)

$\theta_{23}, \Delta m^2_{32}, \theta_{13}, \delta_{CP}$

New Physics Searches

Take advantage of the uniqueness of neutrinos
Unknown neutrino-matter interaction
Superluminal neutrinos
New Physics Searches
\[ \bar{\nu}_\mu \text{ Charged Current Disappearance} \]

Search for new neutrino-matter interactions

CPT Violation
Looking for a deficit of $\bar{\nu}_\mu$ events in the Far Detector

Same as $\nu_\mu$ disappearance analysis but with antineutrinos

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu) = 1 - \sin^2 2\theta \sin^2 \left( \frac{1.27 \Delta m^2 L}{E} \right), \quad L=735 \text{ km}$$
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CPT conservation: $P(\bar{\nu}_\mu \rightarrow \nu_\mu) = P(\nu_\mu \rightarrow \bar{\nu}_\mu)$
Why is this study interesting – old results

\[ |\Delta m^2| \text{ and } |\Delta m^2| \ (10^{-3} \text{ eV}^2) \]

\[ \sin^2(2\theta) \text{ and } \sin^2(2\bar{\theta}) \]

- MINOS $\bar{\nu}_\mu$ 90% C.L.
- MINOS $\nu_\mu$ 90% C.L.
- MINOS $\nu_\mu$ 68% C.L.
- MINOS $\bar{\nu}_\mu$ 68% C.L.
- Best $\bar{\nu}_\mu$ fit
- Best $\nu_\mu$ fit

1.71 \times 10^{20} \text{ POT}
7.25 \times 10^{20} \text{ POT}

Prior limits 90% C.L. [17]
**Selected $\bar{\nu}_\mu$ CC events in the Far Detector**

- **Observed Events** = 193
- **Expectation (No Osc.)** = 273
- No oscillations ruled out at 7.3σ

$$|\Delta m^2| = 2.62^{+0.31}_{-0.28} \text{ (stat)} \pm 0.09 \text{ (sys)} \times 10^{-3} \text{ eV}^2$$

$$\sin^2(2\theta) = 0.86^{+0.10}_{-0.11} \text{ (stat)} \pm 0.01 \text{ (sys)}$$
\( |\Delta m^2| \) or \(|\Delta m^2| (10^{-3} \text{ eV}^2)\)

90\% C.L.
- \( \bar{\nu}_\mu \) Antineutrino Beam 2011
- \( \bar{\nu}_\mu \) Antineutrino Beam 2010
- \( \nu_\mu \) Neutrino Beam 2010
- \( \bar{\nu}_\mu \) Best Fit Antineutrino Beam 2011
- \( \bar{\nu}_\mu \) Best Fit Antineutrino Beam 2010
- \( \nu_\mu \) Best Fit

MINOS Preliminary
2.95 \times 10^{20} \text{ POT, } \bar{\nu}_\mu \text{-mode}
Superluminal Neutrinos???
**Fermilab ~500m baseline experiment (1979)**

Muon Neutrinos

E > 30 GeV

|v-c|/c < 4x10^{-5}

**Supernova 1987a**

Electron Antineutrino Detection

E ~ 10-40 MeV

Arrived hours earlier than the light (light held by dense matter)

|v-c|/c < 2x10^{-9}

**Opera (2011)**

Muon Neutrinos

E ~ 17 GeV

(v-c)/c = [2.48 ± 0.28 (stat) ± 0.30 (sys)] x 10^{-5}

Greater than 5σ measurement of superluminal velocity

**Theory says...**

Can't be flavor effect → Energy effect

High-E superluminal would radiate electron-positron pairs
What does MINOS have to say about that?

Performed measurement in 2007

Measured the difference in the time distribution between the Far and Near detector

To measure velocity you need to know **distance** and **time**

If neutrinos travel the speed of light it would take **2.45 ms** to travel from ND to FD

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**Baseline:**

<table>
<thead>
<tr>
<th>Description</th>
<th>Uncertainty (68% C.L.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A Distance between detectors</td>
<td>2 ns</td>
</tr>
<tr>
<td>B ND Antenna fiber length</td>
<td>27 ns</td>
</tr>
<tr>
<td>C ND electronics latencies</td>
<td>32 ns</td>
</tr>
<tr>
<td>D FD Antenna fiber length</td>
<td>46 ns</td>
</tr>
<tr>
<td>E FD electronics latencies</td>
<td>3 ns</td>
</tr>
<tr>
<td>F GPS and transceivers</td>
<td>12 ns</td>
</tr>
<tr>
<td>G Detector readout differences</td>
<td>9 ns</td>
</tr>
<tr>
<td><strong>Total (Sum in quadrature)</strong></td>
<td><strong>64 ns</strong></td>
</tr>
</tbody>
</table>

**MINOS Timing System:**

- **GPS Receivers:** TrueTime model XL-AK
- **Antenna fiber delay:** 1115 ns ND, 5140 ns FD
- **Single Event Time Resolution:** <40 ns
- **Random Clock Jitter:** 100 ns (typical), each site

**Main Injector Parameters:**

- **Main Injector Cycle Time:** 2.2 seconds/spill (typical)
- **Main Injector Batches/Spill:** 5 or 6
- **Spill Duration:** 9.7 μs (6 batches)
- **Batch Duration:** 1582 ns
- **Gap Between Batches:** 38 ns

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*a*Distance between front face of the ND and the center of the FD.
What does MINOS have to say about that

Difference in the time distribution between the Far and Near

\[ \delta = -126 \pm 32 \text{ (stat.)} \pm 64 \text{ (sys.) ns} \quad 68\% \text{ C.L.} \]

\[ \frac{v - c}{c} = \frac{-\delta}{\tau + \delta} = 5.1 \pm 2.9(\text{stat.} + \text{sys.}) \times 10^{-5} \quad 68\% \text{ C.L.} \]

1.8 \sigma Deviation
Short-term (6-9 months):
Analyze data sample increased by a factor of 9 with respect to the 2007 result.
Reduce major systematics.

Medium-term (1 year):
Upgrade the timing system to take all new data from now on with better timing.
(Collaborate with experts from NIST)
Analyze data taken before the NuMI shutdown. Lower statistics but more precise.

Long-term (MINOS+):
MINOS+ running in the NOvA era with upgraded timing system
Higher energy neutrinos (peak ~7 GeV)
Goal to achieve O(1ns) total systematic error.
These questions still remain unanswered
   Is there a non-maximal mixing between the $\nu_\mu$ and $\nu_\tau$ states?
      Is $\theta_{23} \neq 45^\circ$?
   What's the mass hierarchy?
      Is $\Delta m^2_{32} > 0$?
   Is there an $\nu_e$ component to the $\nu_3$ mass state?
      Is $\theta_{13} \neq 0$?
   Is there CP violation in the lepton sector?
      Is $\delta_{\text{CP}} \neq 0$? (Is $\theta_{13} \neq 0$?)

But we are constraining the possible solutions
   MINOS sets the tightest limits on $\theta_{13}$ assuming normal hierarchy
   MINOS sets tightest constraints on the magnitude of $\Delta m^2_{32}$

Search for new physics
   Less compelling motivation for new neutrino-matter interaction
   But we are compatible with superluminal neutrinos
      Confirmation or refutation to come soon...