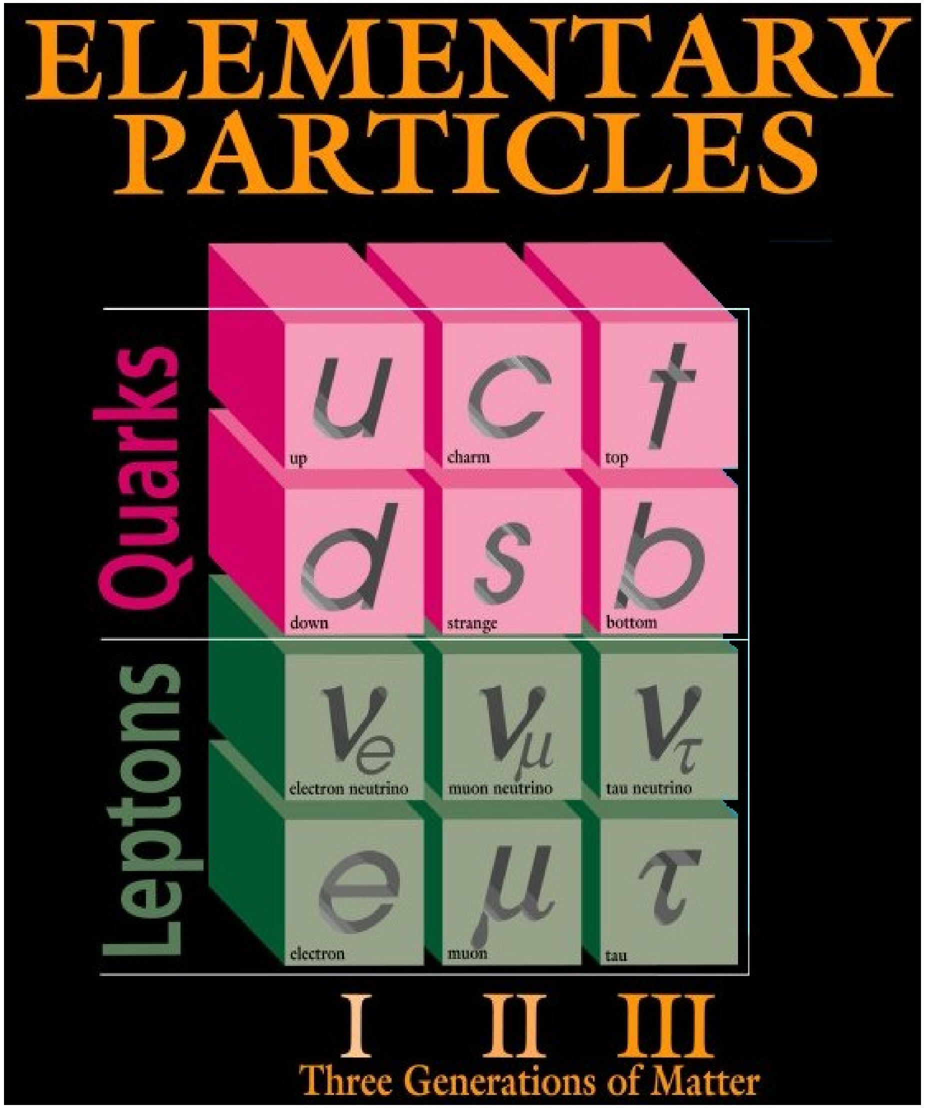
Neutrino Oscillations with MINOS – and the Search for New Physics

Gregory Pawloski

University of Minnesota

Neutrinos



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?

Probing Neutrinos

Neutrino Oscillations

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

Mixing Angles (θ_{12}, θ_{23}, θ_{13}, δ_{CP})

θ_{23}, Δm^2_{32}, θ_{13}, δ_{CP}

New Physics Searches

Take advantage of the uniqueness of neutrinos

- Unknown neutrino-matter interaction
- Superluminal neutrinos

Neutrino Oscillations

Neutrino Eigenstates

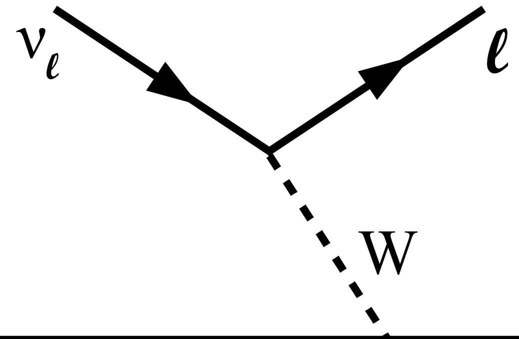
Three known types of neutrinos

Weak Eigenstates

ν_e

ν_μ

ν_τ

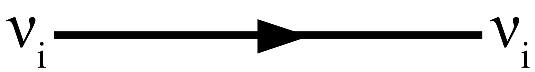


Mass Eigenstates

ν_1

ν_2

ν_3



$$E^2 = p^2 + m^2$$

$$|\nu_i(t)\rangle = e^{-iEt}\,|\nu_i\rangle$$

Neutrino Mixing

Mass eigenstates are a linear combination of weak states

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

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

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

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

PMNS (Pontecorvo-Maki-Nakagawa-Sakata) Matrix

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

Atmospheric terms **Unknown terms** **Solar terms**

$c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$

Mixing Parameters – What we know

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

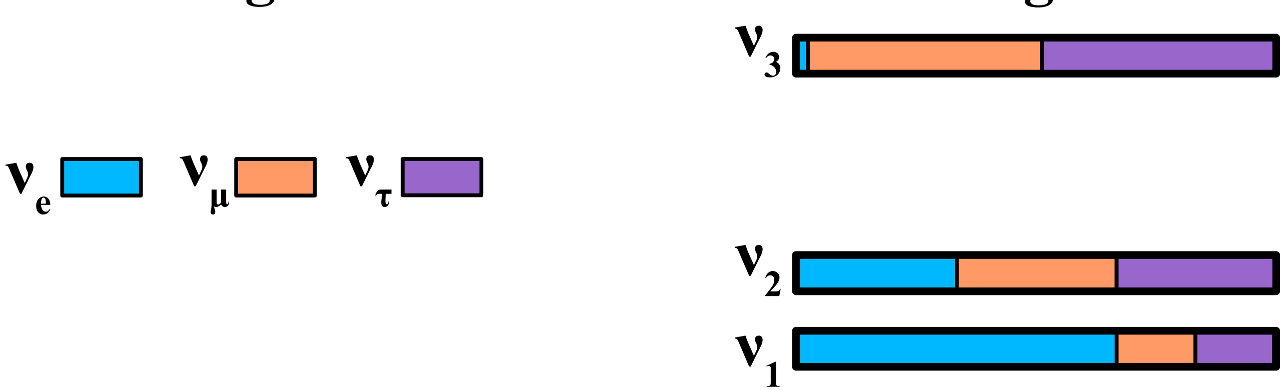
Atmospheric terms **Unknown terms** **Solar terms**

Mixing Parameters – What we know

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

Atmospheric terms **Unknown terms** **Solar terms**

Weak Eigenstates **Mass Eigenstates**

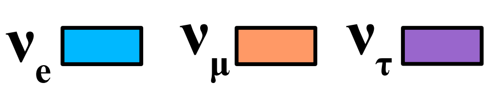


Mixing Parameters – What we know

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

Atmospheric terms **Unknown terms** **Solar terms**

Weak Eigenstates



Mass Eigenstates

From Solar and Reactor Experiments

$\sin^2\theta_{12} \approx 0.321 \pm 0.023$

$\Delta m^2_{21} \approx (7.67 \pm 0.22) \times 10^{-5}\ eV^2$

2008 Global Fits
M.C. Gonzalez-Garcia
and M. Maltoni
*Phys Rept **460** (2008)*

Mixing Parameters – What we know

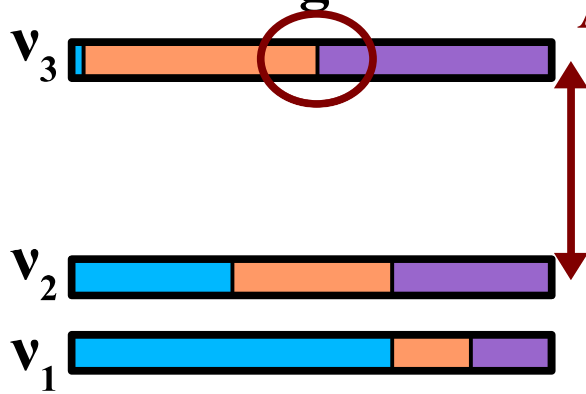
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12}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

Atmospheric terms **Unknown terms** **Solar terms**

Weak Eigenstates

ν_e ν_μ ν_τ

Mass Eigenstates



From Atmospheric and Accelerator Experiments

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

$\sin^2 2\theta_{23} > 0.9$

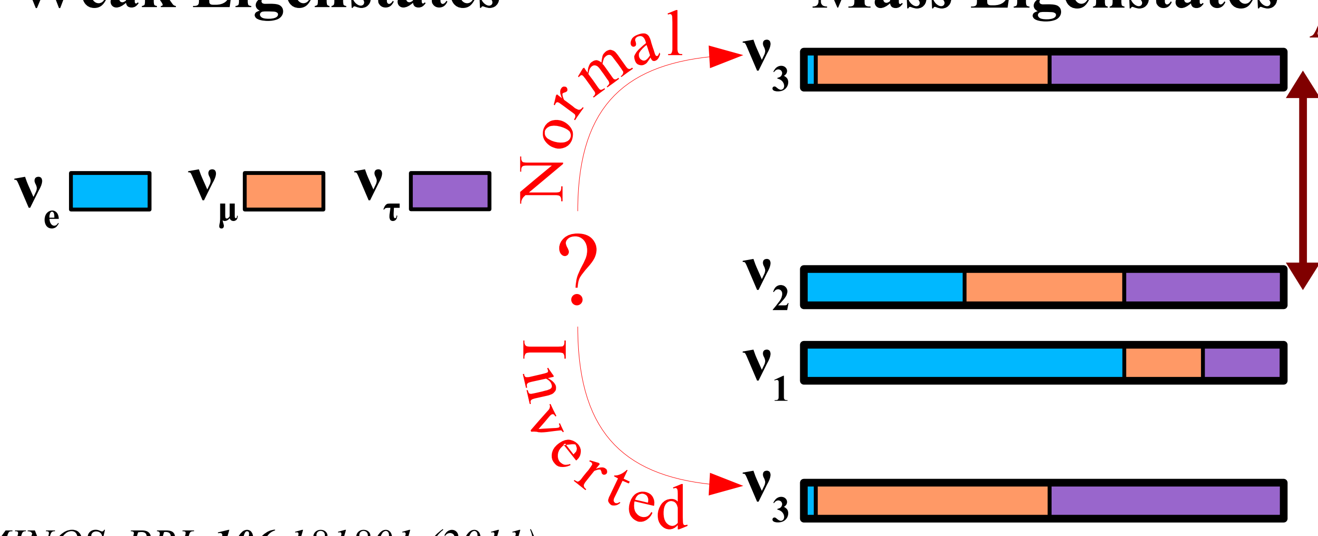
*MINOS, PRL **106** 181801 (2011)*

Mixing Parameters – What we know

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

Atmospheric terms **Unknown terms** **Solar terms**

Weak Eigenstates **Mass Eigenstates**



From Atmospheric and Accelerator Experiments

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

What is the mass hierarchy?

$\sin^2 2\theta_{23} > 0.9$

*MINOS, PRL **106** 181801 (2011)*

Mixing Parameters – What we know

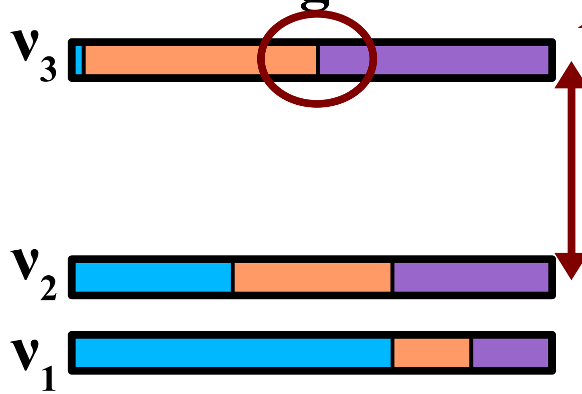
$$
\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=
\begin{pmatrix}1&0&0\\0&c_{23}&s_{23}\\0&-s_{23}&c_{23}\end{pmatrix}
\begin{pmatrix}c_{13}&0&s_{13}e^{-i\delta_{CP}}\\0&1&0\\-s_{13}e^{i\delta_{CP}}&0&c_{13}\end{pmatrix}
\begin{pmatrix}c_{12}&s_{12}&0\\-s_{12}&c_{12}&0\\0&0&1\end{pmatrix}
\begin{pmatrix}\nu_1\\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

Atmospheric terms **Unknown terms** **Solar terms**

Weak Eigenstates

ν_e ν_μ ν_τ

Mass Eigenstates



From Atmospheric and Accelerator Experiments

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

$\sin^2 2\theta_{23} > 0.9$

Is θ_{23} non-maximal?

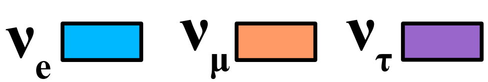
*MINOS, PRL **106** 181801 (2011)*

Mixing Parameters – What we know

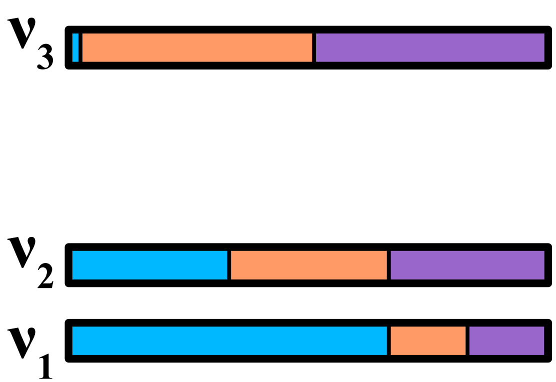
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}1&0&0\\0&c_{23}&s_{23}\\0&-s_{23}&c_{23}\end{pmatrix}\begin{pmatrix}c_{13}&0&s_{13}e^{-i\delta_{CP}}\\0&1&0\\-s_{13}e^{i\delta_{CP}}&0&c_{13}\end{pmatrix}\begin{pmatrix}c_{12}&s_{12}&0\\-s_{12}&c_{12}&0\\0&0&1\end{pmatrix}\begin{pmatrix}\nu_1\\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

Atmospheric terms **Unknown terms** **Solar terms**

Weak Eigenstates



Mass Eigenstates



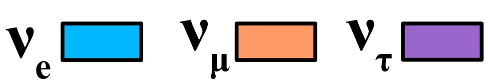
Remaining Questions

Mixing Parameters – What we know

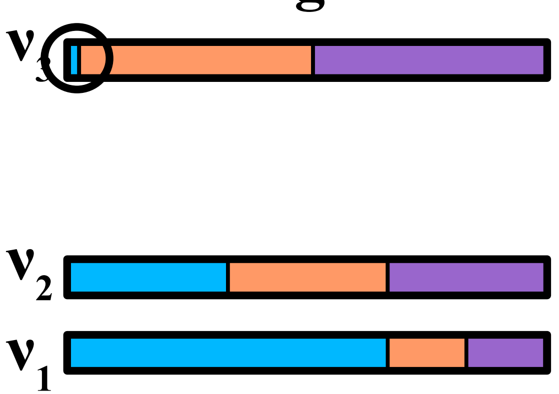
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12}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

Atmospheric terms **Unknown terms** **Solar terms**

Weak Eigenstates



Mass Eigenstates



Remaining Questions

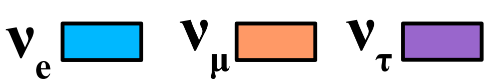
What's the value of θ_{13}?

Mixing Parameters – What we know

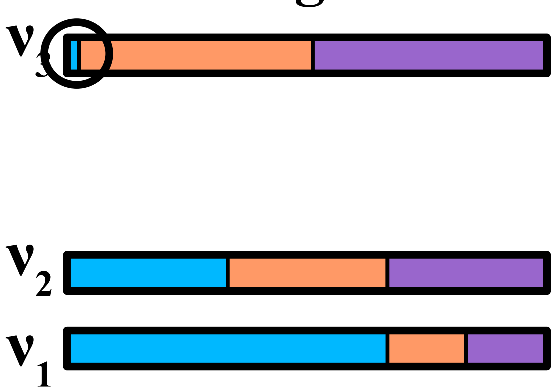
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12}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

Atmospheric terms — **Unknown terms** — **Solar terms**

Weak Eigenstates



Mass Eigenstates



Remaining Questions

What's the value of θ_{13}?

$\sin^2(2\theta_{13}) < O(10^{-1})$

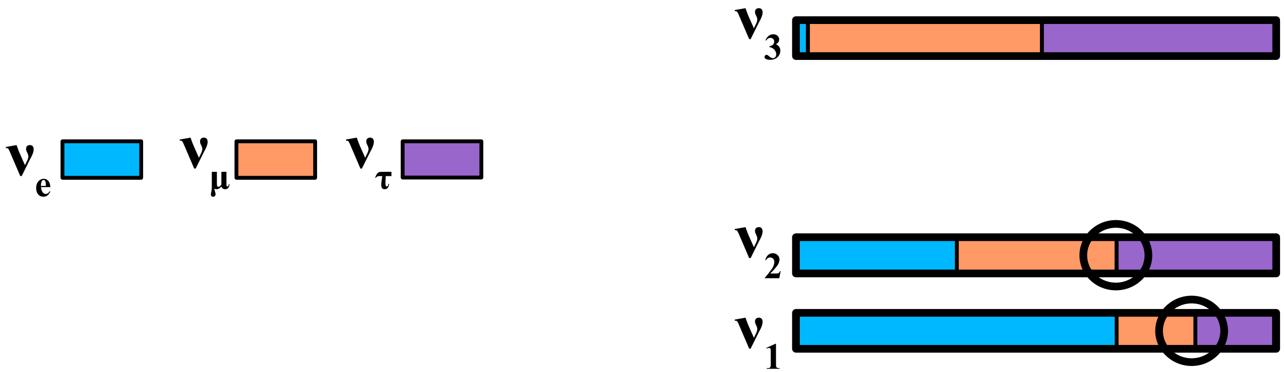
Mixing Parameters – What we know

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

Atmospheric terms **Unknown terms** **Solar terms**

Weak Eigenstates

Mass Eigenstates



Remaining Questions

What's the value of θ_{13}?

$\sin^2(2\theta_{13}) < O(10^{-1})$

What's the value of δ_{CP}?

Unknown

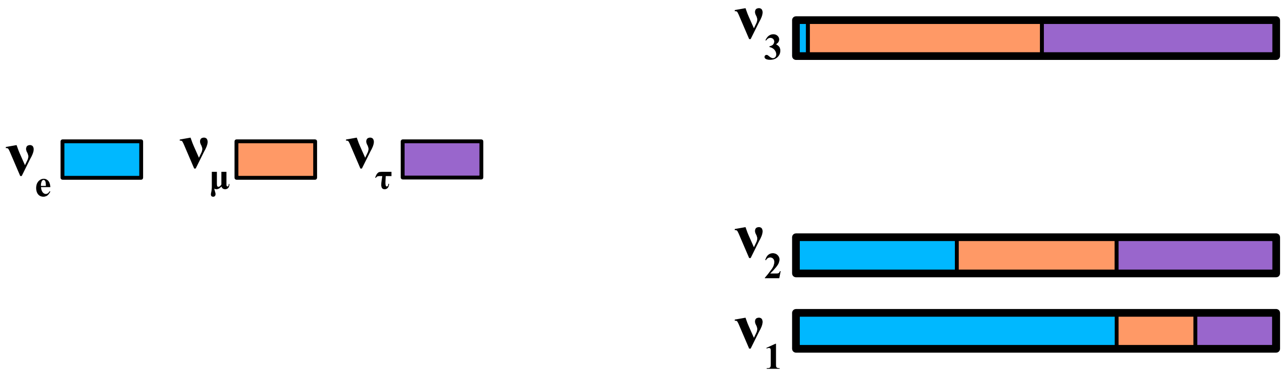
Mixing Parameters – What we know

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

Atmospheric terms **Unknown terms** **Solar terms**

Weak Eigenstates

Mass Eigenstates



Remaining Questions

What's the value of θ_{13}?

$\sin^2(2\theta_{13}) < O(10^{-1})$

What's the value of δ_{CP}?

Unknown

Is there CP violation in the lepton sector?

The Remaining Questions

1) Is there a non-maximal mixing between the ν_μ and ν_τ states?

   Is $\theta_{23} \neq 45°$?

2) What's the mass hierarchy?

   Is $\Delta m^2_{32} > 0$?

3) Is there an ν_e component to the ν_3 mass state?

   Is $\theta_{13} \neq 0$?

4) Is there CP violation in the lepton sector?

   Is $\delta_{CP} \neq 0$? (Is $\theta_{13} \neq 0$?)

The Remaining Questions

1) Is there a non-maximal mixing between the ν_μ and ν_τ states?

   Is $\theta_{23} \neq 45°$?

2) What's the mass hierarchy?

   Is $\Delta m^2_{32} > 0$?

3) Is there an ν_e component to the ν_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

The Remaining Questions

1) Is there a non-maximal mixing between the ν_μ and ν_τ states?

   Is $\theta_{23} \neq 45°$?

2) What's the mass hierarchy?

   Is $\Delta m^2_{32} > 0$?

3) Is there an ν_e component to the ν_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

ν_μ disappearance analysis can potentially address this

The Remaining Questions

1) Is there a non-maximal mixing between the ν_μ and ν_τ states?

   Is $\theta_{23} \neq 45°$?

2) What's the mass hierarchy?

   Is $\Delta m^2_{32} > 0$?

3) Is there an ν_e component to the ν_3 mass state?

   Is $\theta_{13} \neq 0$?

4) Is there CP violation in the lepton sector?

   Is $\delta_{CP} \neq 0$? (Is $\theta_{13} \neq 0$?)

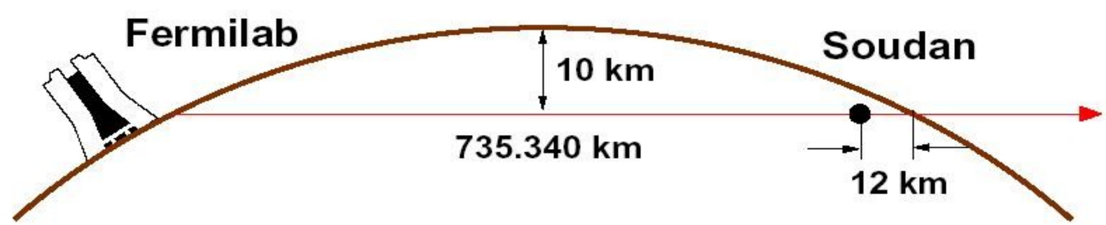
MINOS can potentially address these questions

ν_e appearance analysis can potentially address this

So how does MINOS study oscillations?

Long Baseline Accelerator Neutrinos

- ν 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

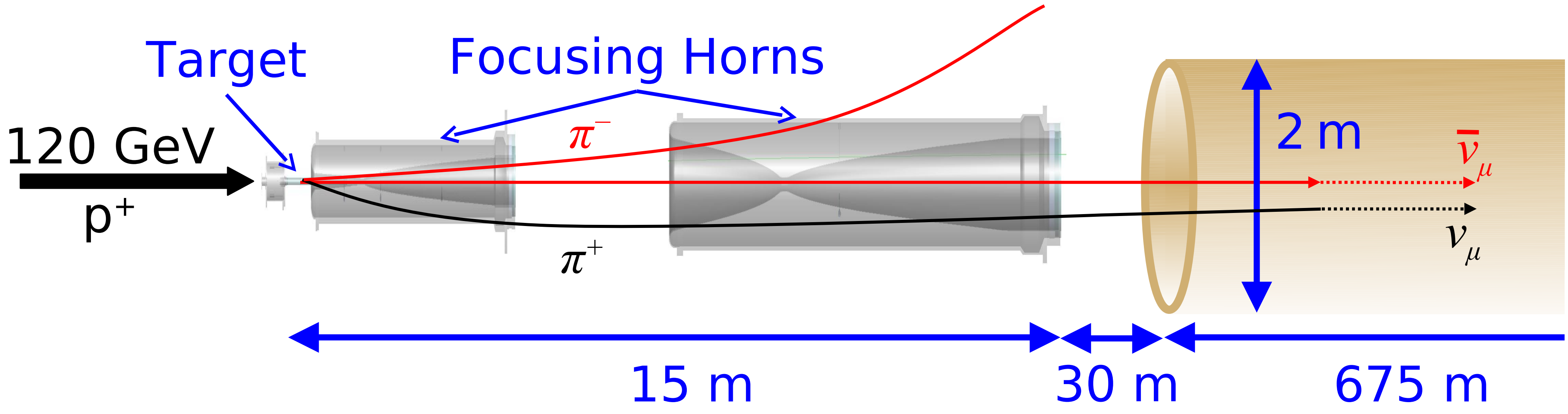


Neutrino Production

Proton collision produces hadrons

Magnetic horns focus charged hadrons

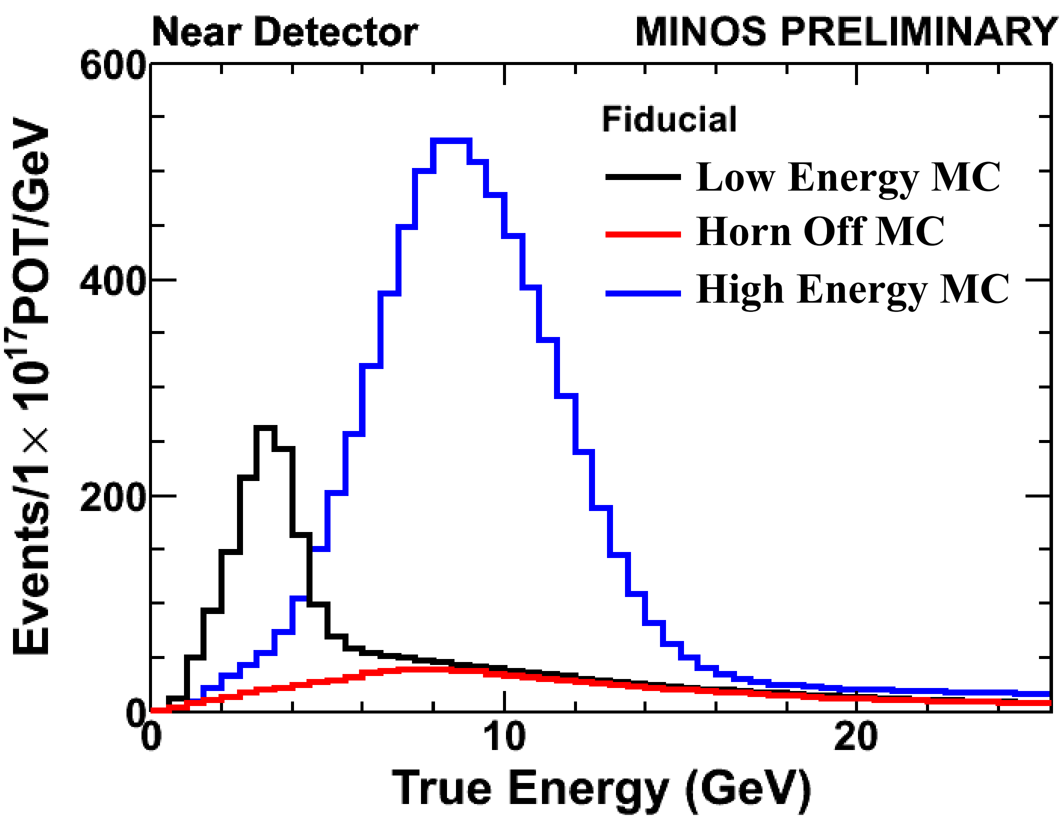
Decays produce neutrinos



NuMI Beam Composition

Control ν energy spectrum

- Target and horn positions
- Horn current



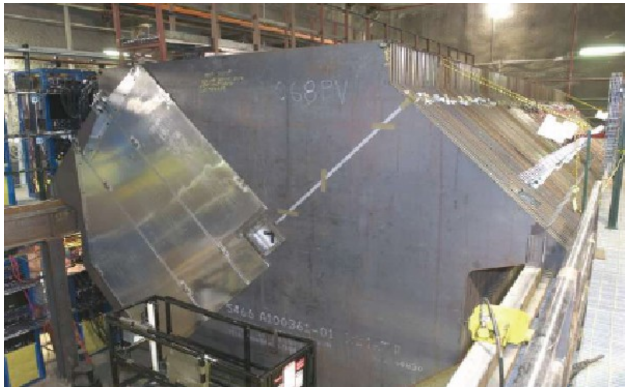
Default configuration is Low Energy

- Optimizes L/E for atmospheric Δm^2

CC interactions in the Near Detector are:

- 93% ν_μ
- 6% $\bar{\nu}_\mu$
- 1% $\nu_e + \bar{\nu}_e$

Two Detectors



Near Detector

1 kton mass (larger ν flux)

1 km from neutrino source

100 m underground

Measures beam before oscillations

Far Detector

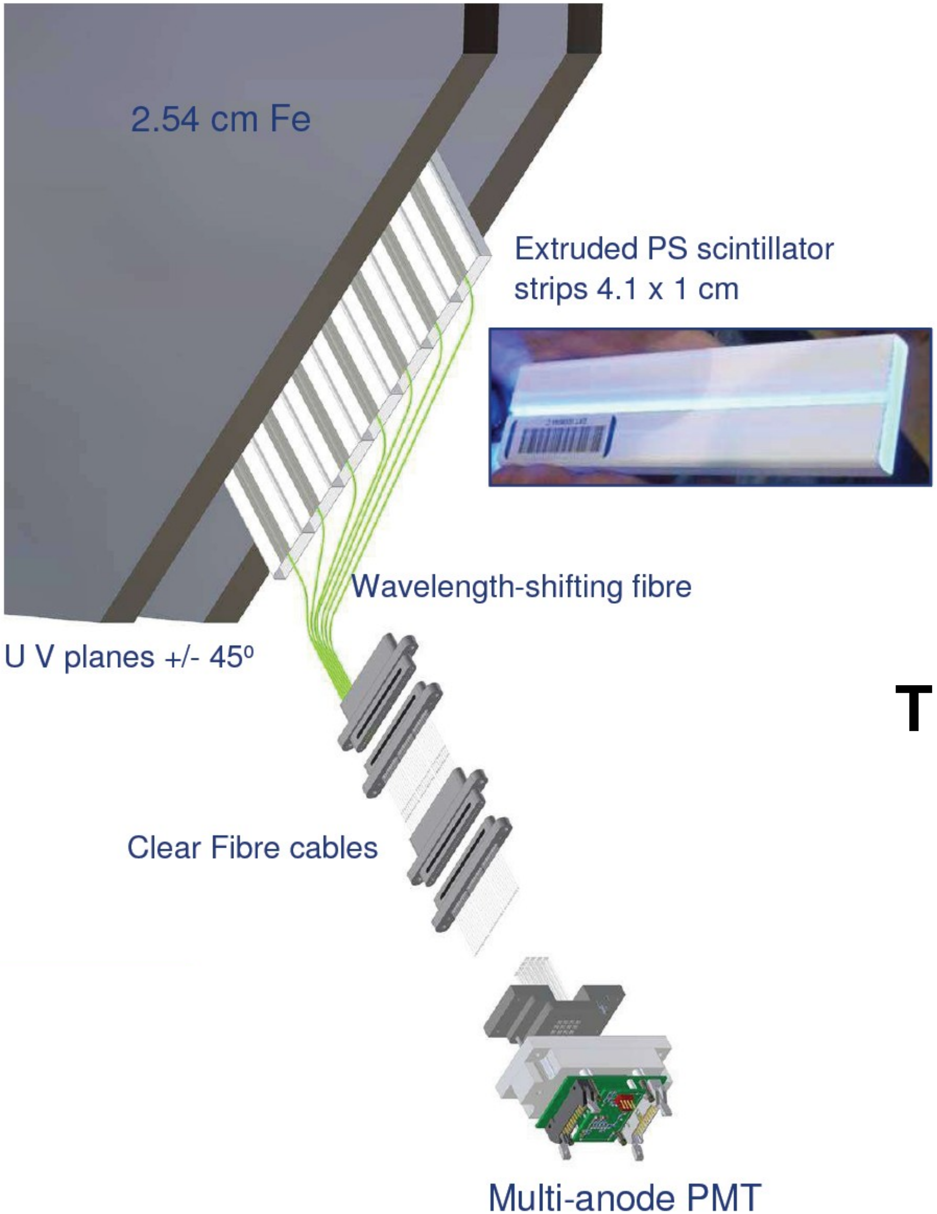
5.4 kton (smaller ν flux)

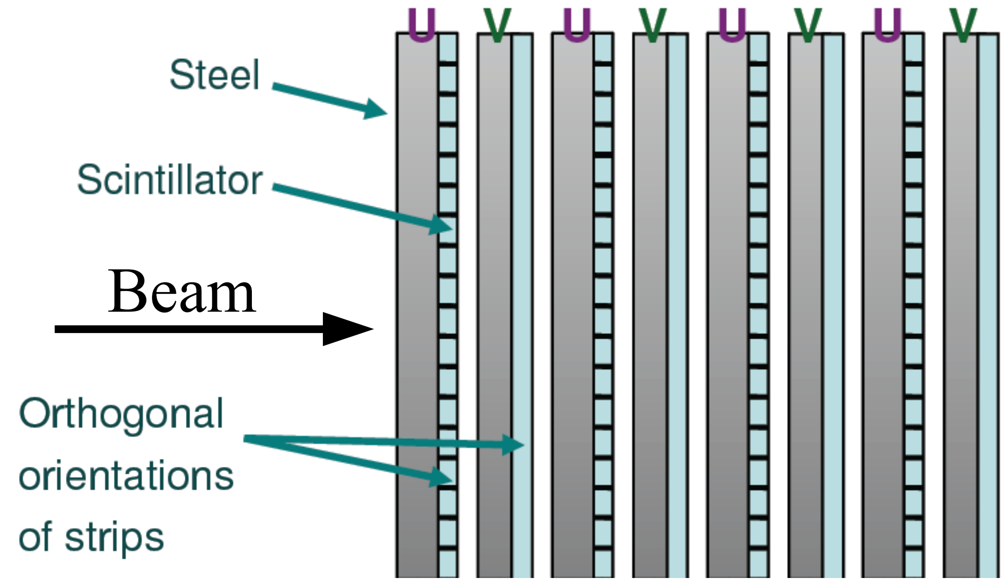
735 km from neutrino source

705m underground

Measures changes in beam relative to Near Detector

Functionally Identical Detectors



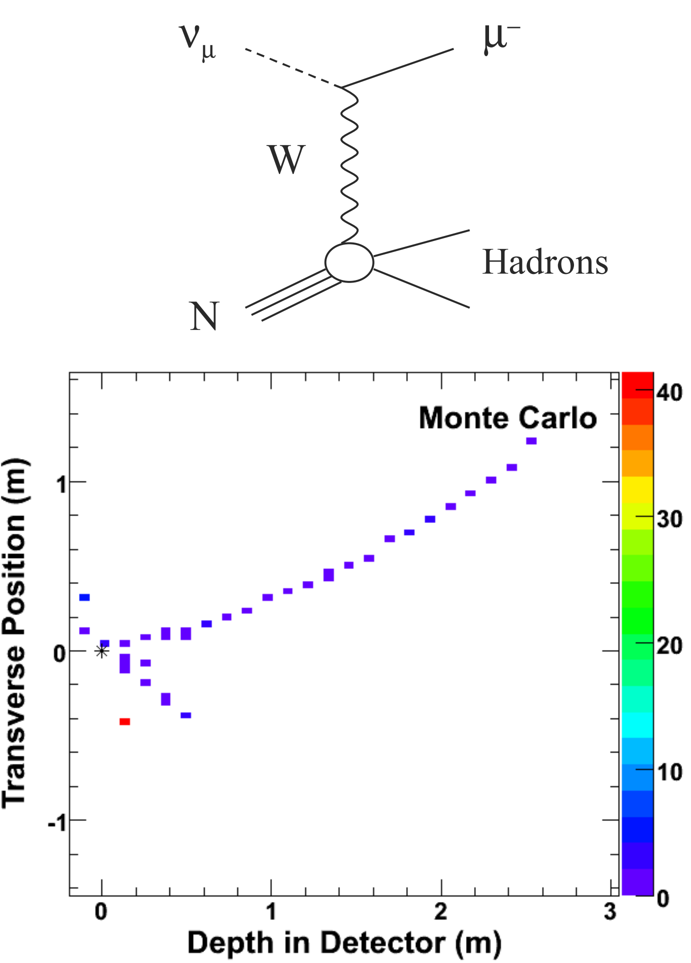


Tracking calorimeters

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

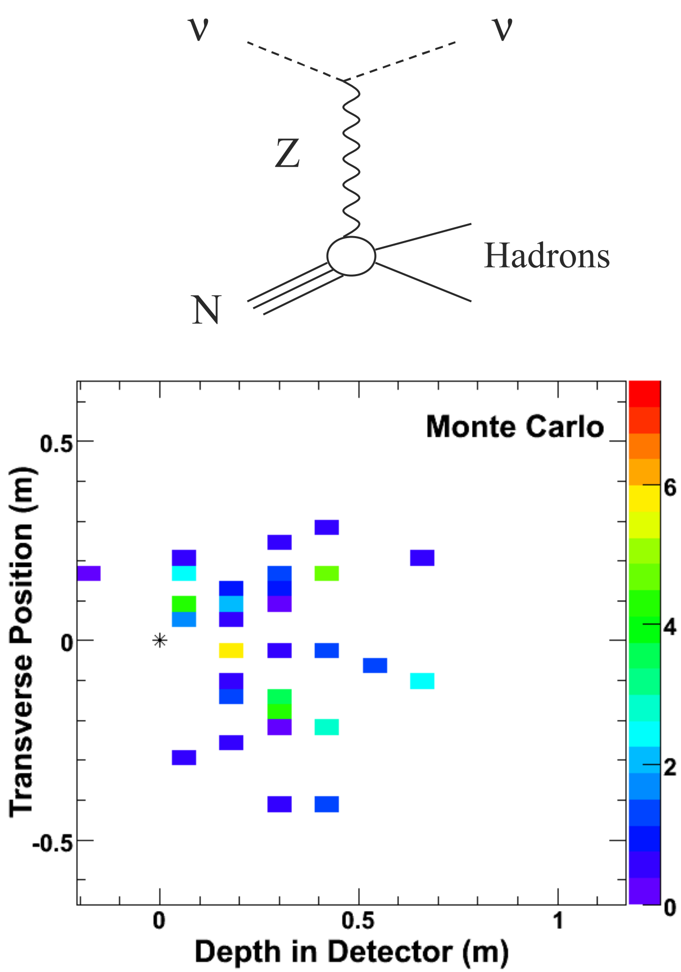
Event Topologies

ν_μ CC Event



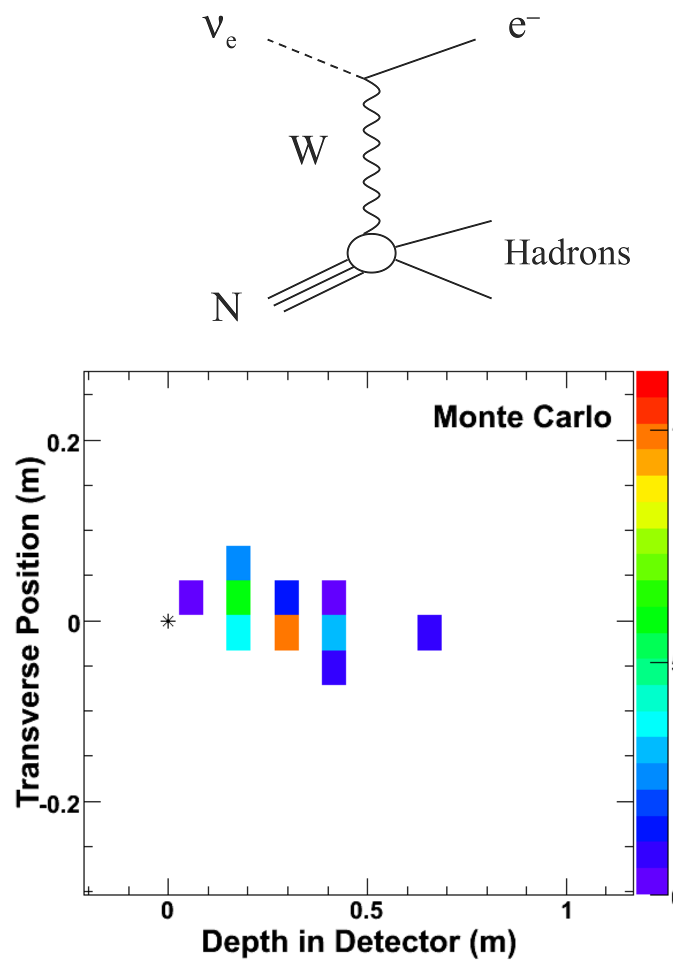
Long muon track
Hadronic activity at vertex

NC Event



Short event
Often diffuse

ν_e CC Event



Compact event
EM shower profile

MINOS Oscillation Results

ν_μ Charged Current Disappearance

ν_μ CC Disappearance

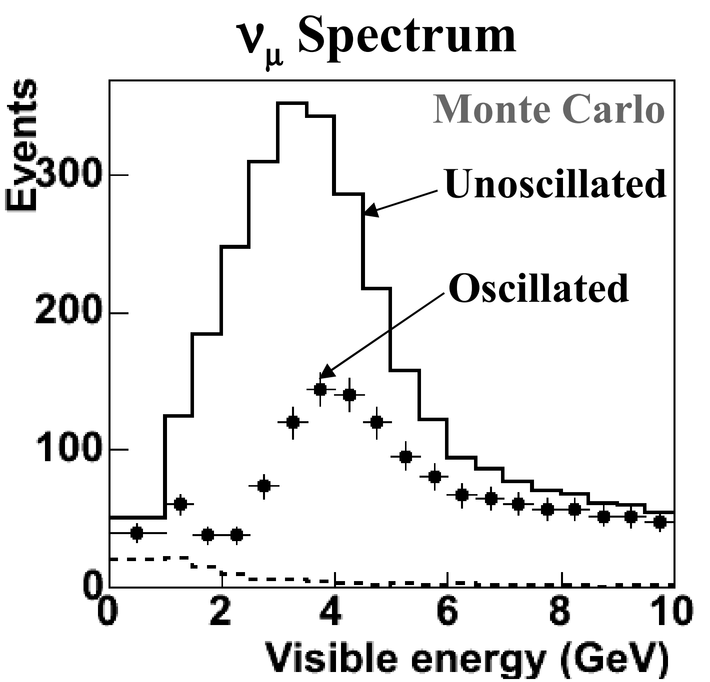
Looking for a deficit of ν_μ events in the Far Detector

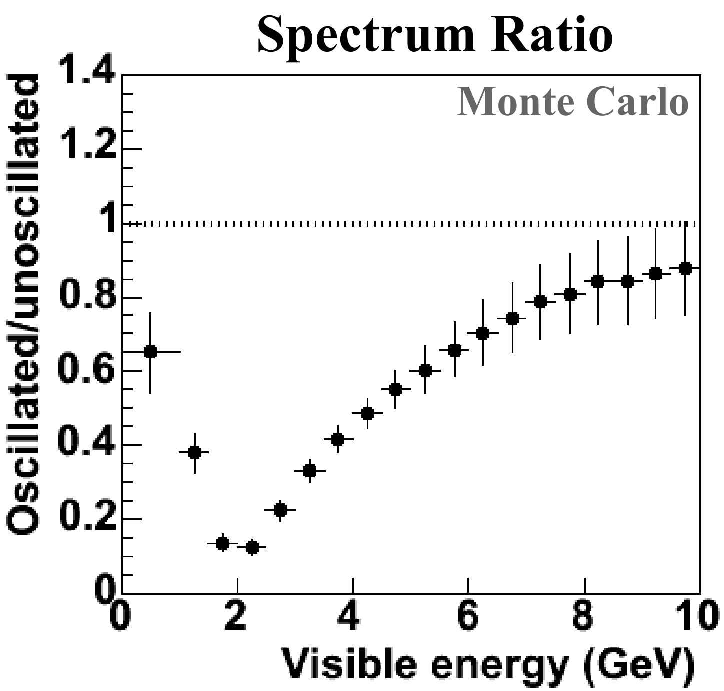
- Precision measurements of atmospheric Δm^2 and $\sin^2(2\theta)$
- Test the neutrino oscillation hypothesis

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

Example MC

Parameters set to: $\sin^2(2\theta)=1$, $\Delta m^2=3.35\times10^{-3}\,\text{eV}^2$





ν_μ CC Disappearance

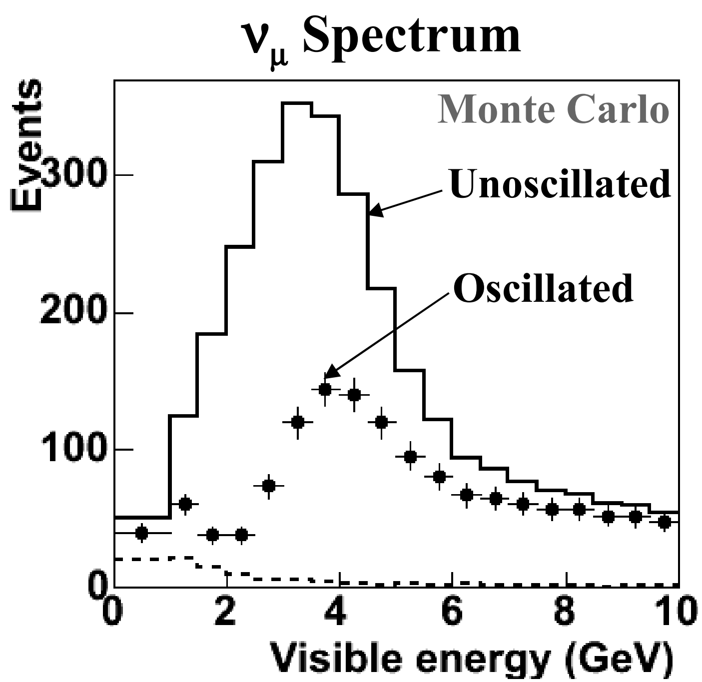
Looking for a deficit of ν_μ events in the Far Detector

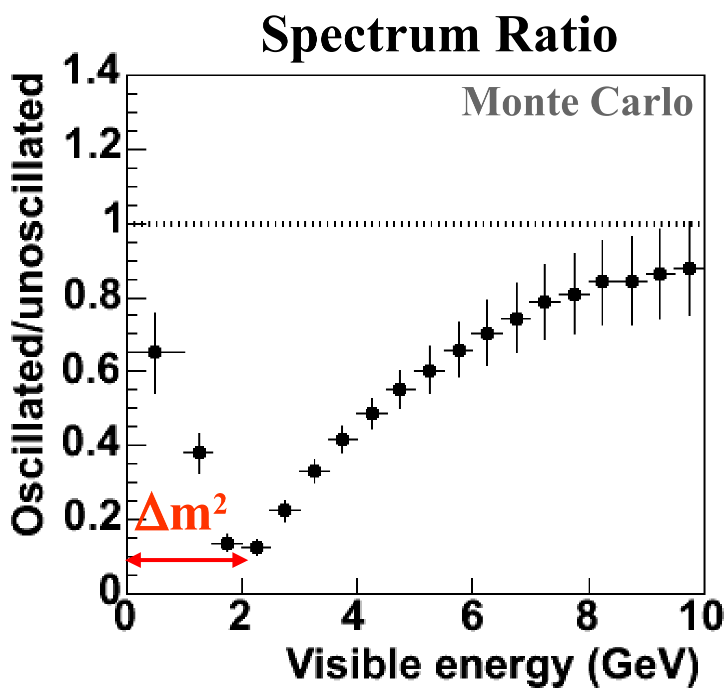
- Precision measurements of atmospheric Δm^2 and $\sin^2(2\theta)$
- Test the neutrino oscillation hypothesis

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

Example MC

Parameters set to: $\sin^2(2\theta)=1$, $\Delta m^2=3.35\times10^{-3}eV^2$





ν_μ CC Disappearance

Looking for a deficit of ν_μ events in the Far Detector

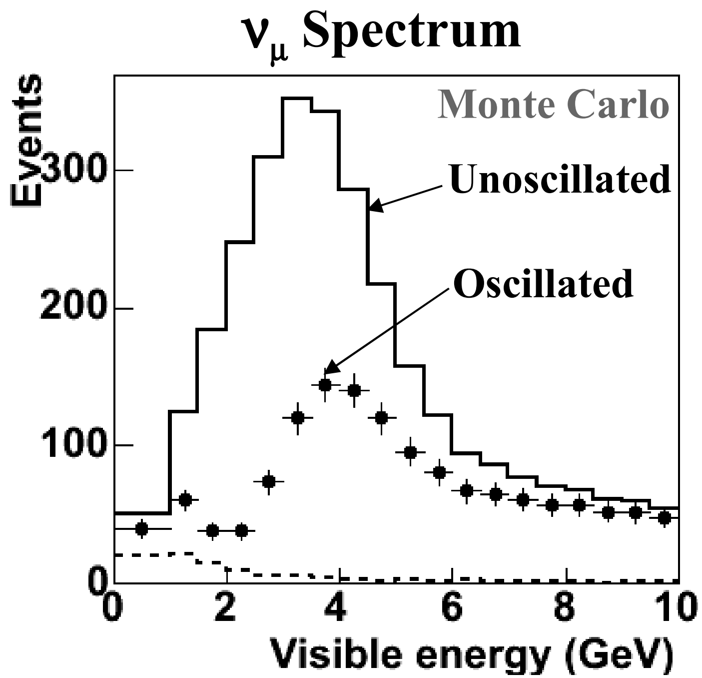
Precision measurements of atmospheric Δm^2 and $\sin^2(2\theta)$

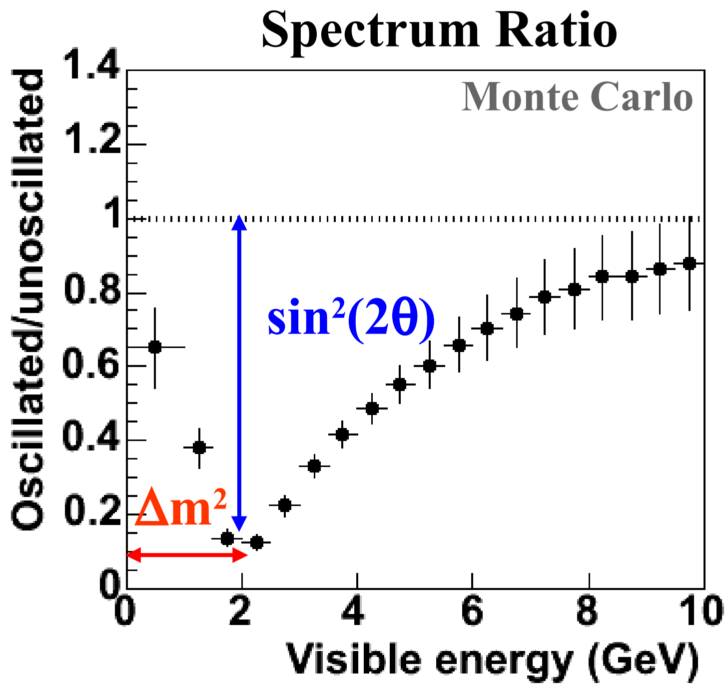
Test the neutrino oscillation hypothesis

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

Example MC

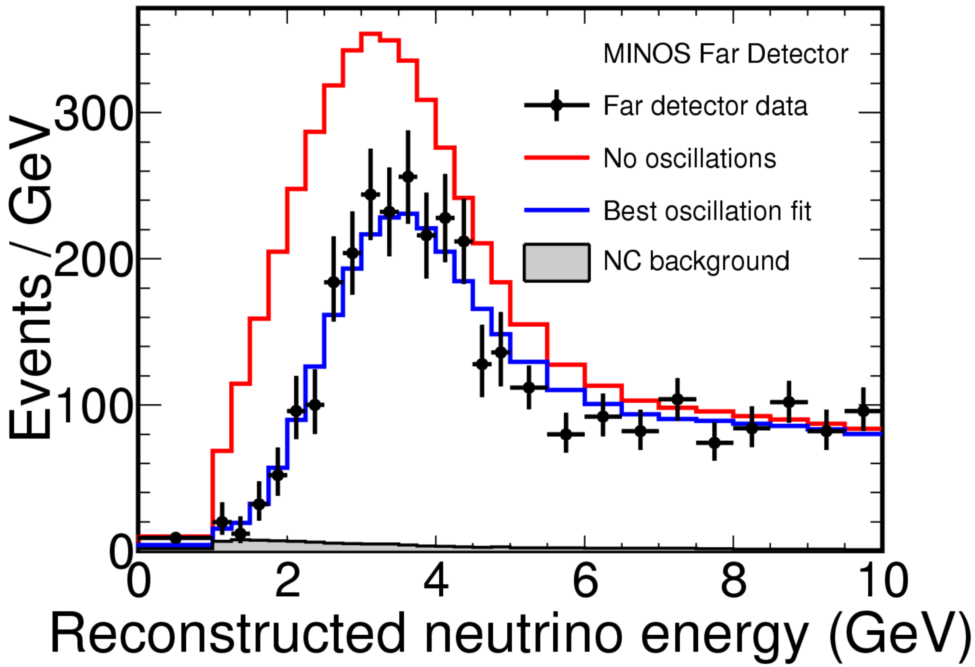
Parameters set to: $\sin^2(2\theta)=1$, $\Delta m^2=3.35\times10^{-3}\,\text{eV}^2$

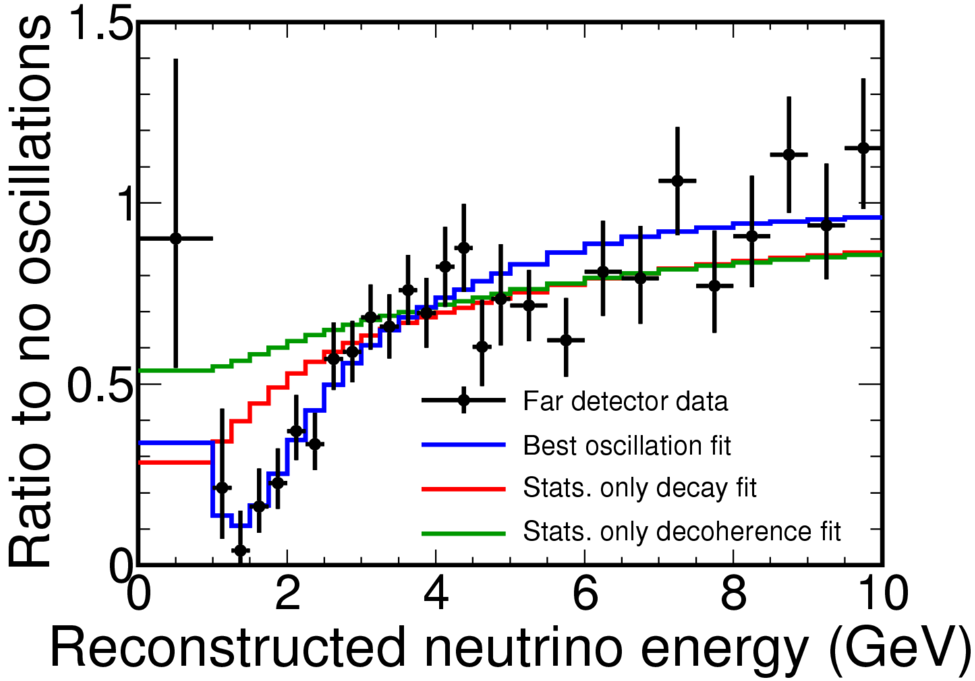




ν_μ CC Disappearance

Selected ν_μ CC events in the Far Detector





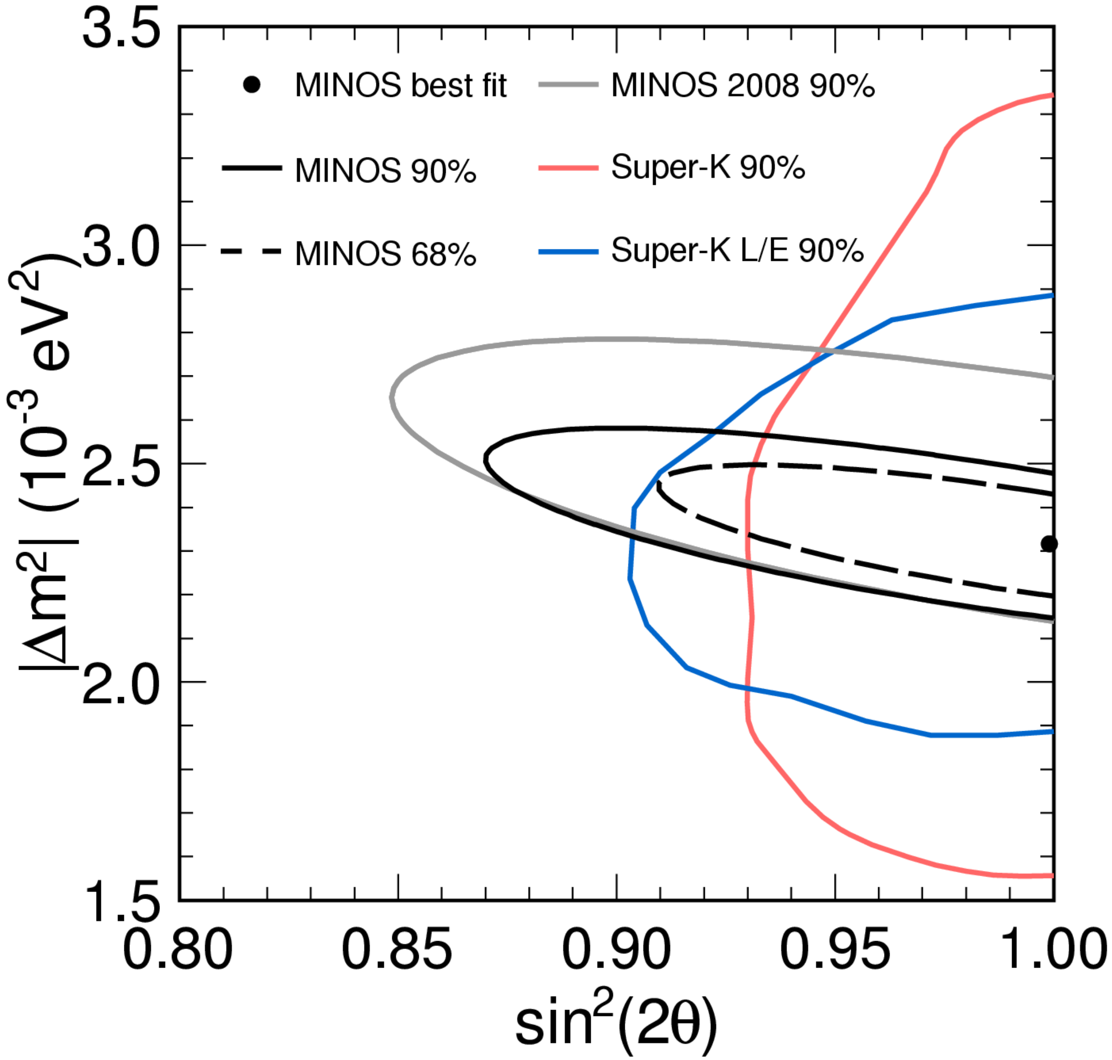
Data consistent with oscillations

Pure decoherence[1] disfavored at more than 9σ

Pure decay[2] disfavored at more than 7σ

[1]G.L. Fogli et al., PRD 67:093006 (2003)
[2]V. Barger et al.,PRL 82:2640 (1999)

Fitting Oscillation Parameters



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

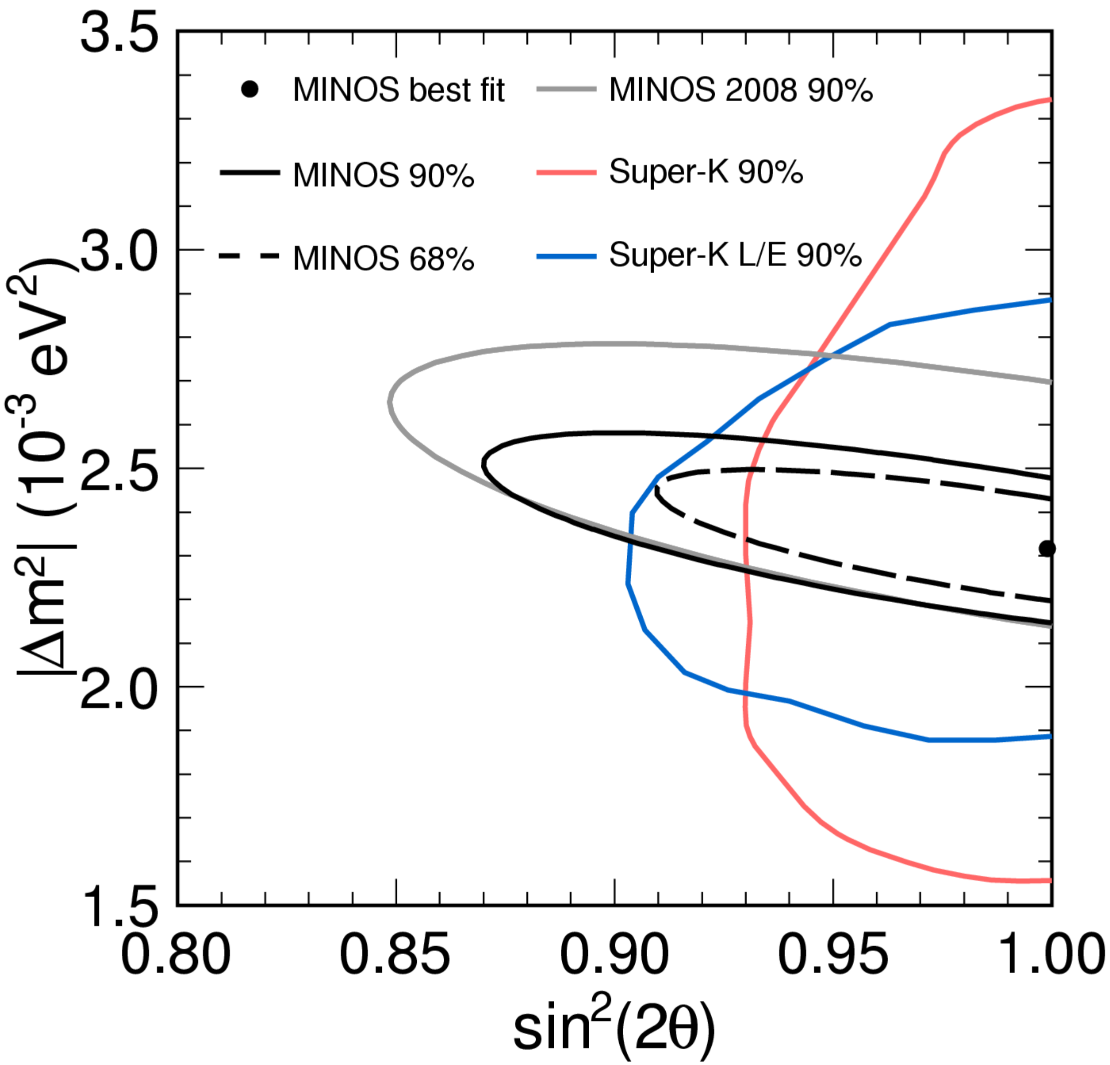
$\sin^2(2\theta) > 0.90$ (90% C.L.)

Dominant Systematics

- Normalization
- NC Background
- Shower Energy
- Track Energy

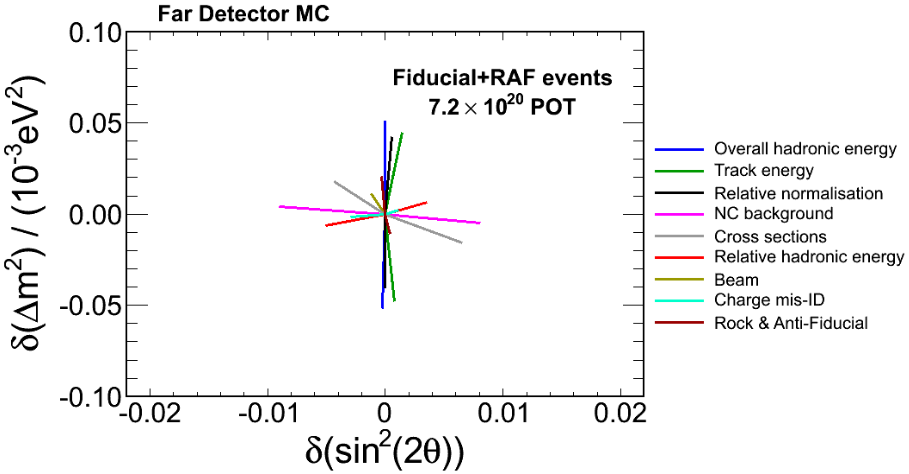
ν_μ CC Disappearance

Fitting Oscillation Parameters



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

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



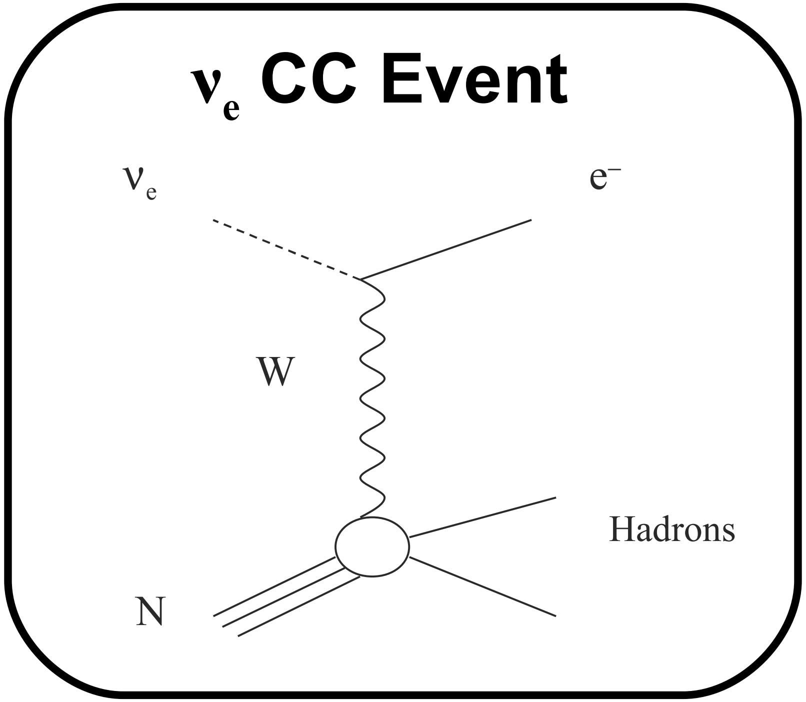
ν_e Charged Current Appearance

ν_e CC Appearance

Searching for subdominant $\nu_\mu \rightarrow \nu_e$ oscillations

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

Constrain θ_{13} by looking for an excess of ν_e-like events



ν_e CC Appearance

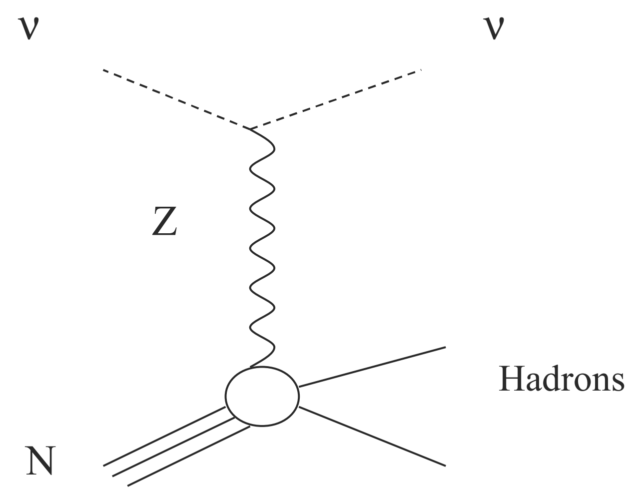
Searching for subdominant $\nu_\mu \rightarrow \nu_e$ oscillations

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

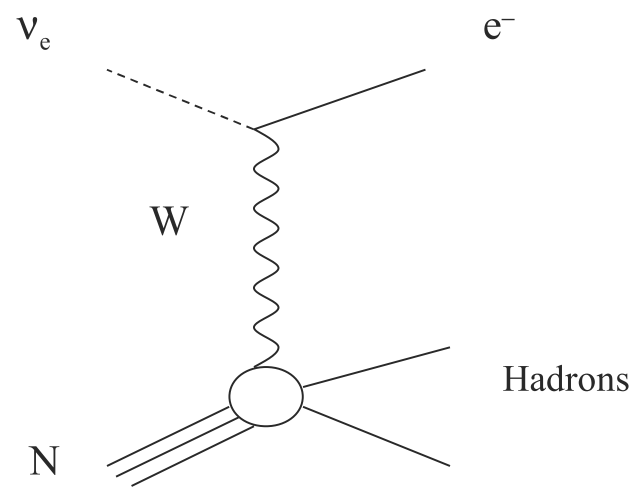
Constrain θ_{13} by looking for an excess of ν_e-like events

Need to distinguish between hadronic showers and electrons

NC Event



ν_e CC Event



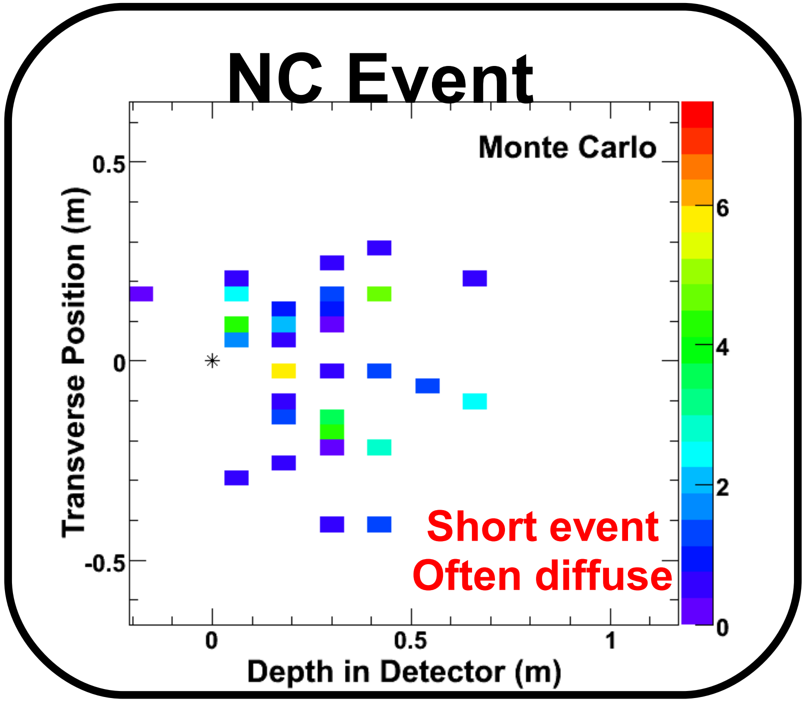
ν_e CC Appearance

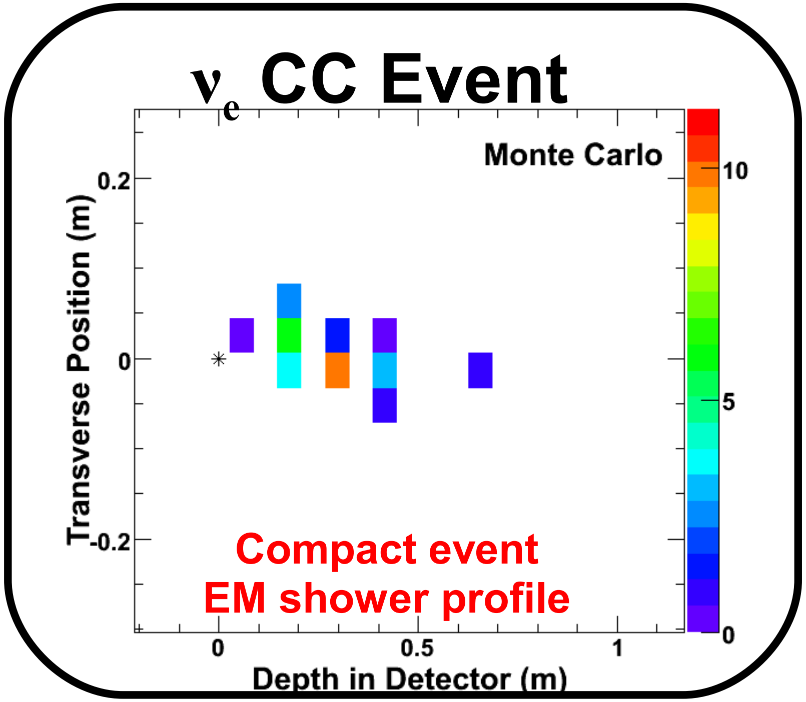
Searching for subdominant $\nu_\mu \rightarrow \nu_e$ oscillations

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

Constrain θ_{13} by looking for an excess of ν_e-like events

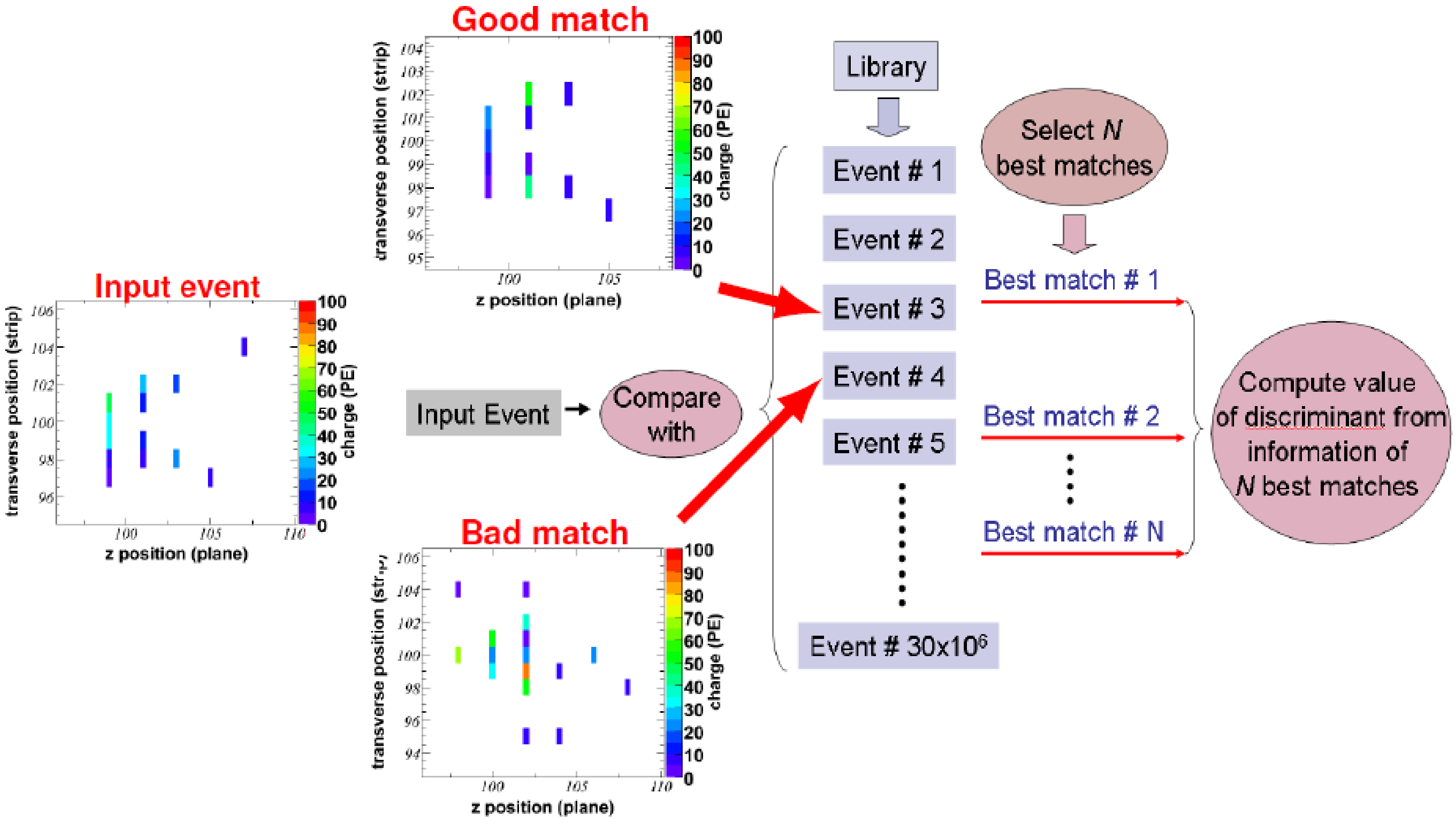
Need to distinguish between hadronic showers and electrons





Select electromagnetic shower topologies

Library Event Matching (LEM)



ν_e CC Appearance

Select electromagnetic shower topologies

Feed 3 variables from the 50 best matches and event energy into a neural network

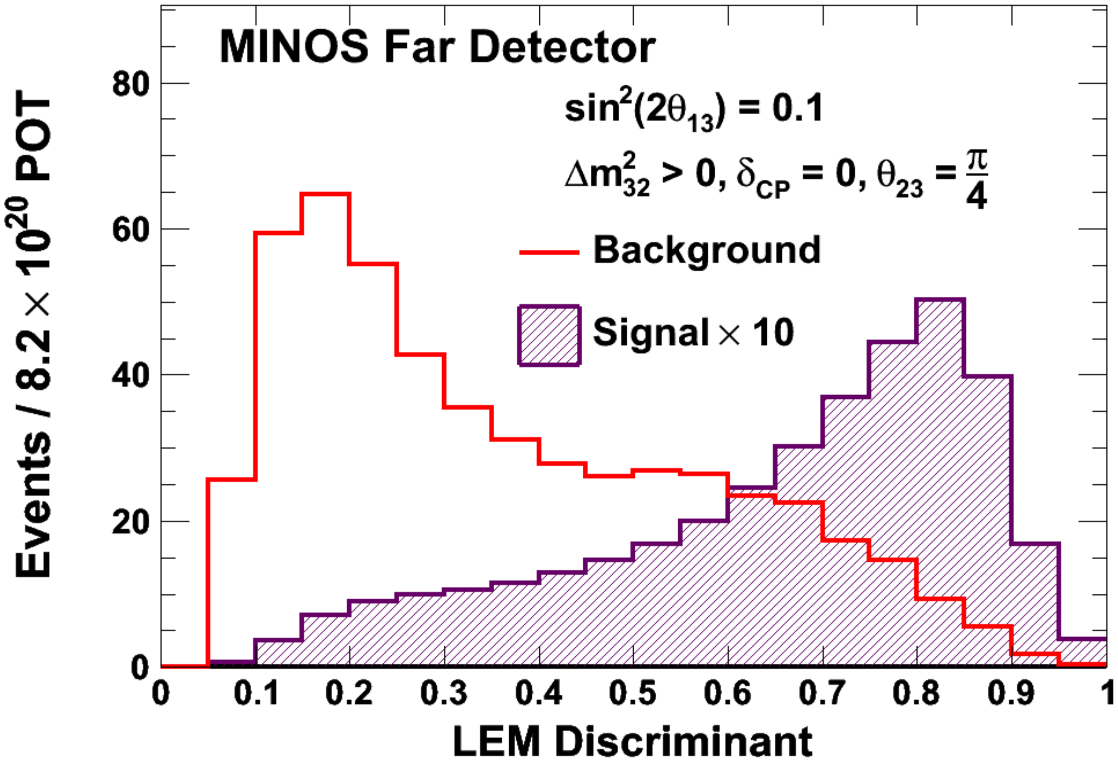
Background:

- π^0's generated via NC or deep-inelastic ν_μ-CC interactions
- τ in FD from oscillations
- Non-oscillation beam ν_e

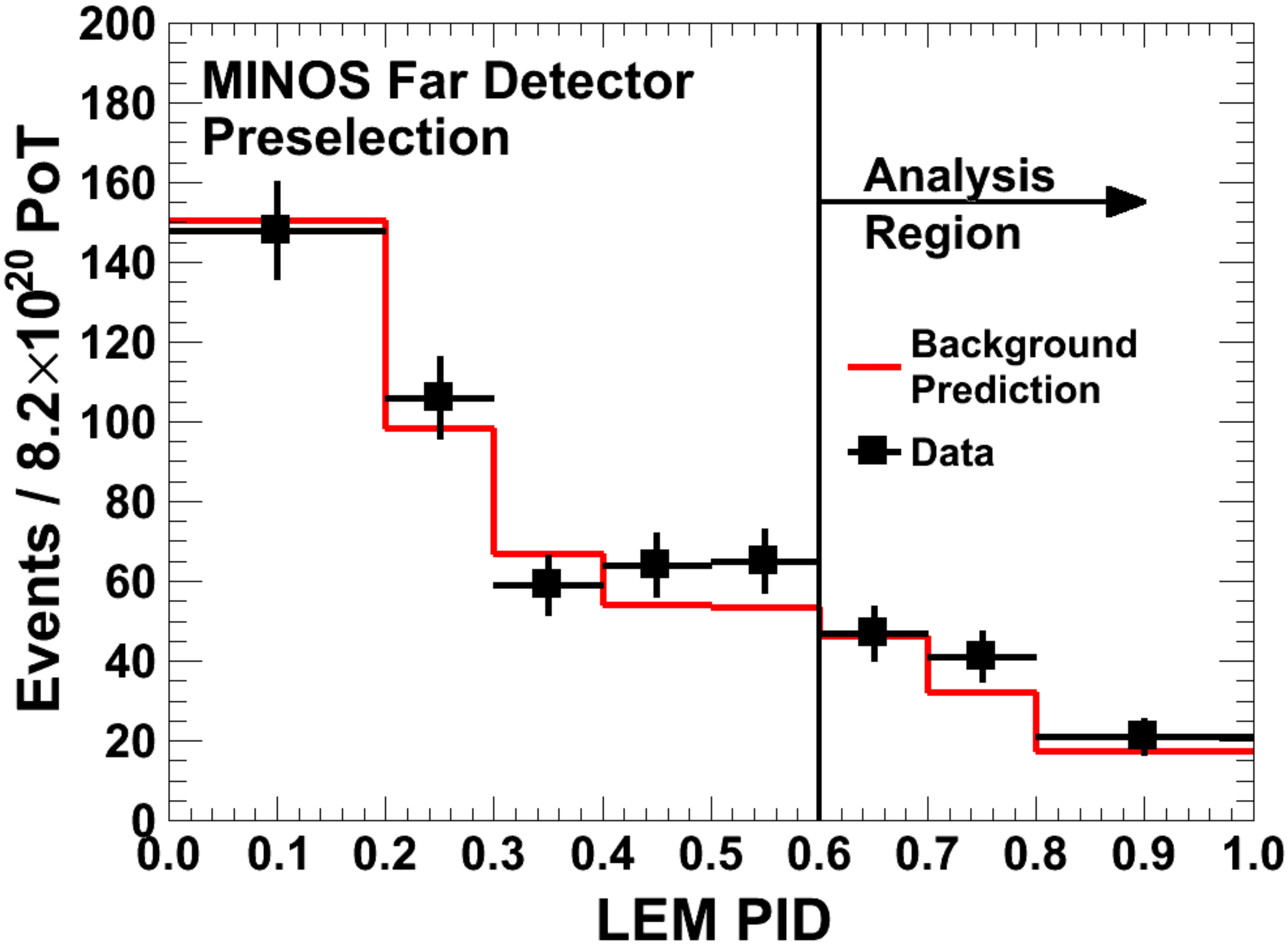
Measure background rate at Near

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

Fit prediction in bins of LEM and energy to Far Data



ν_e CC Appearance

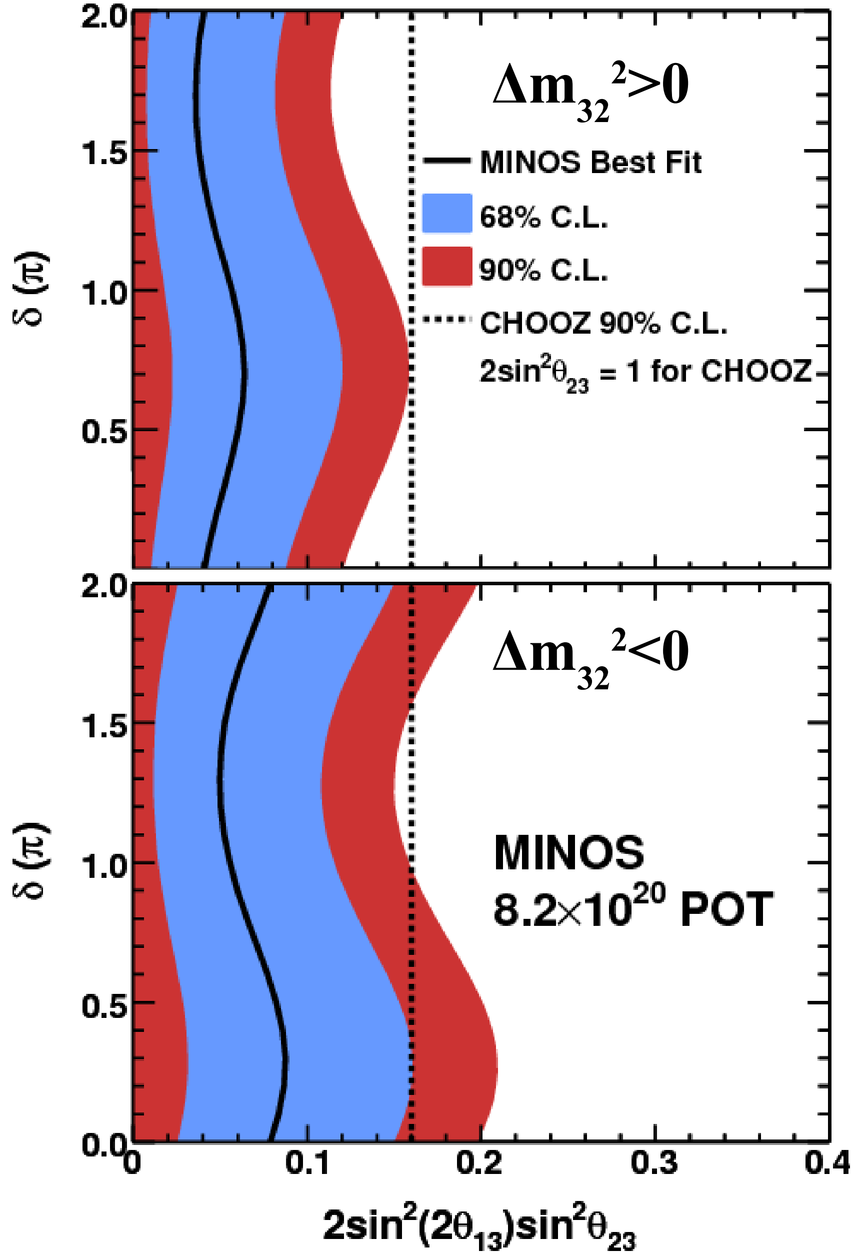


Signal Enhanced Region of LEM > 0.7

Far Detector background expectation: **49.6 ± 7.0(stat.) ± 2.7(syst.) events**

Far Detector observation: **62 events**

ν_e CC Appearance



Assuming:

$\delta_{CP}=0$, $\theta_{23} = \pi/4$

normal (inverted) hierarchy

$$\sin^2(2\theta_{13}) < 0.12\,(0.20)$$

90% CL

$$\sin^2(2\theta_{13}) = 0.04\,(0.08)$$

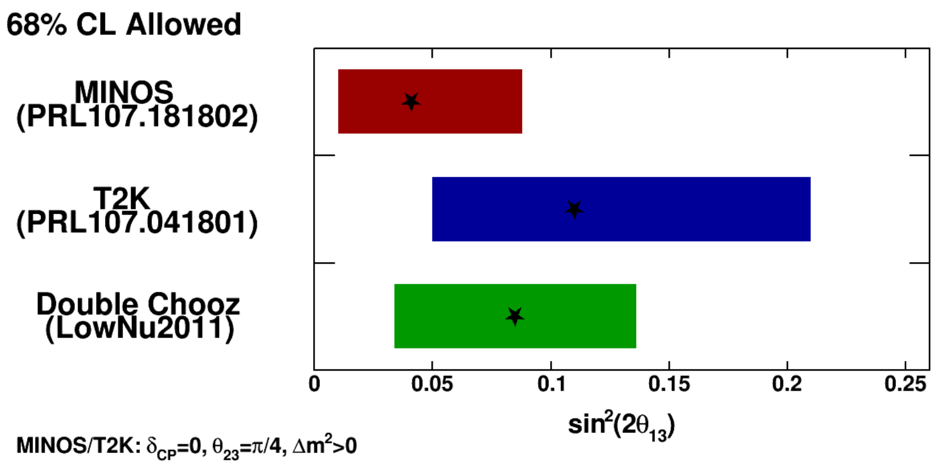
Best Fit

Exclude $\sin^2 2\theta_{13}=0$ at 89% CL

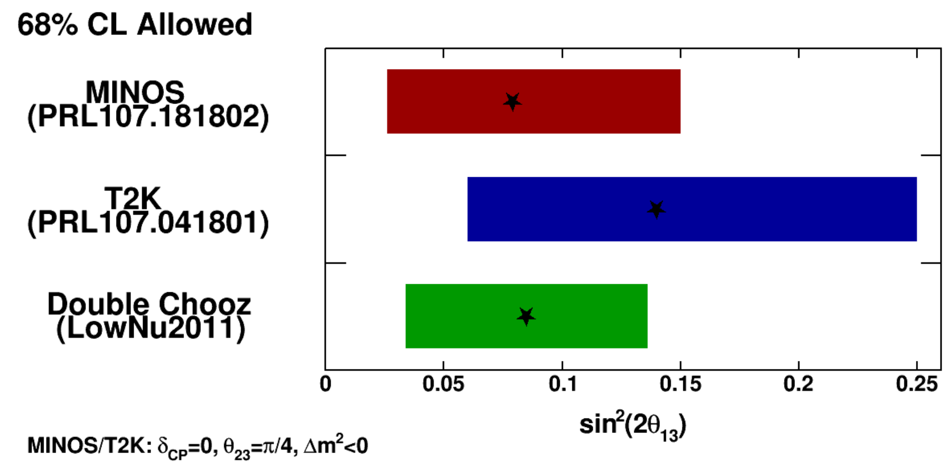
Tightest constraints on θ_{13} for a normal hierarchy

Comparison with T2K and Double Chooz

Normal Hierarchy



Inverted Hierarchy



Probing Neutrinos

Neutrino Oscillations

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

Mixing Angles (θ_{12}, θ_{23}, θ_{13}, δ_{CP})

θ_{23}, Δm^2_{32}, θ_{13}, δ_{CP}

New Physics Searches

Take advantage of the uniqueness of neutrinos

- Unknown neutrino-matter interaction
- Superluminal neutrinos

New Physics Searches

$\bar{\nu}_\mu$ Charged Current Disappearance

Search for new neutrino-matter interactions

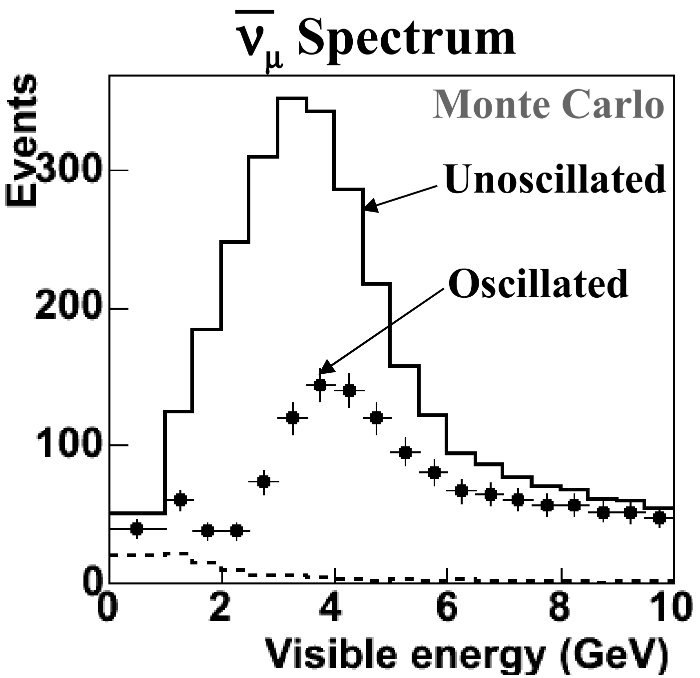
CPT Violation

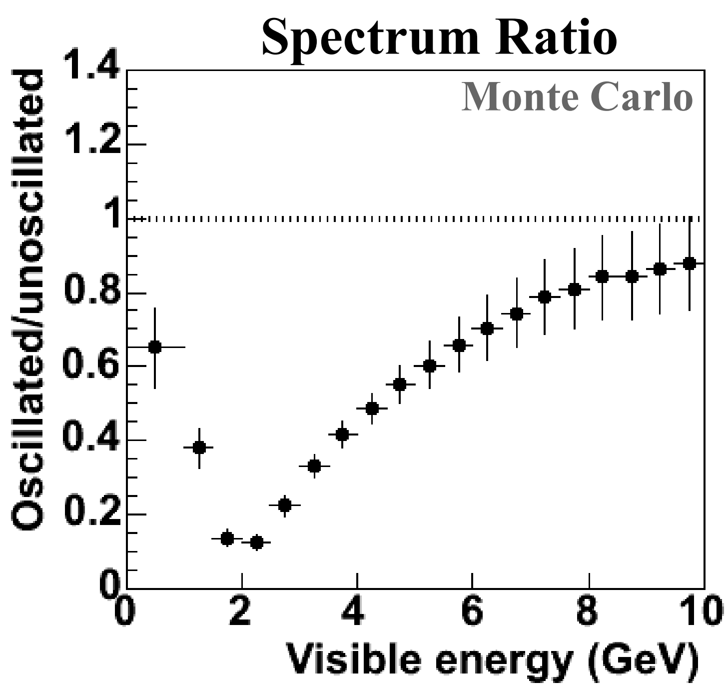
$\overline{\nu}_\mu$ CC Disappearance

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

Same as ν_μ disappearance analysis but with antineutrinos

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





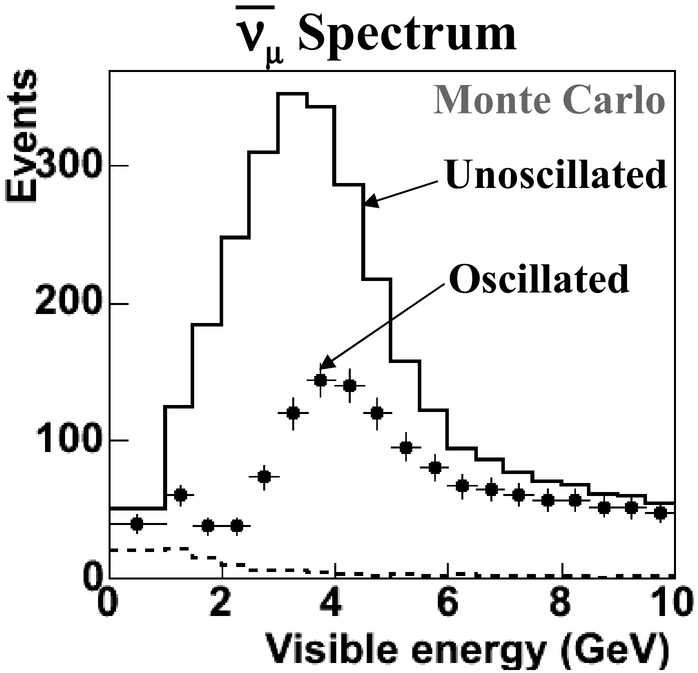
$\overline{\nu}_\mu$ CC Disappearance

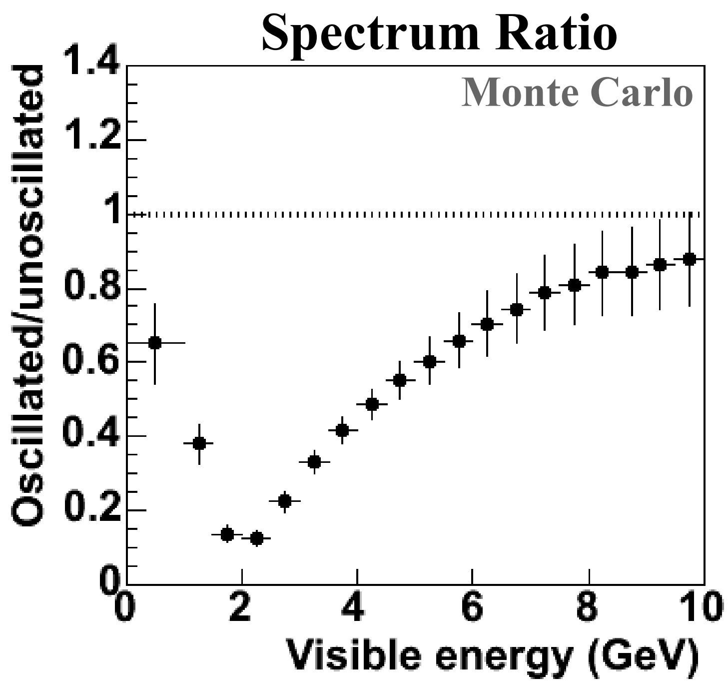
Looking for a deficit of $\overline{\nu}_\mu$ events in the Far Detector

Same as ν_μ disappearance analysis but with antineutrinos

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

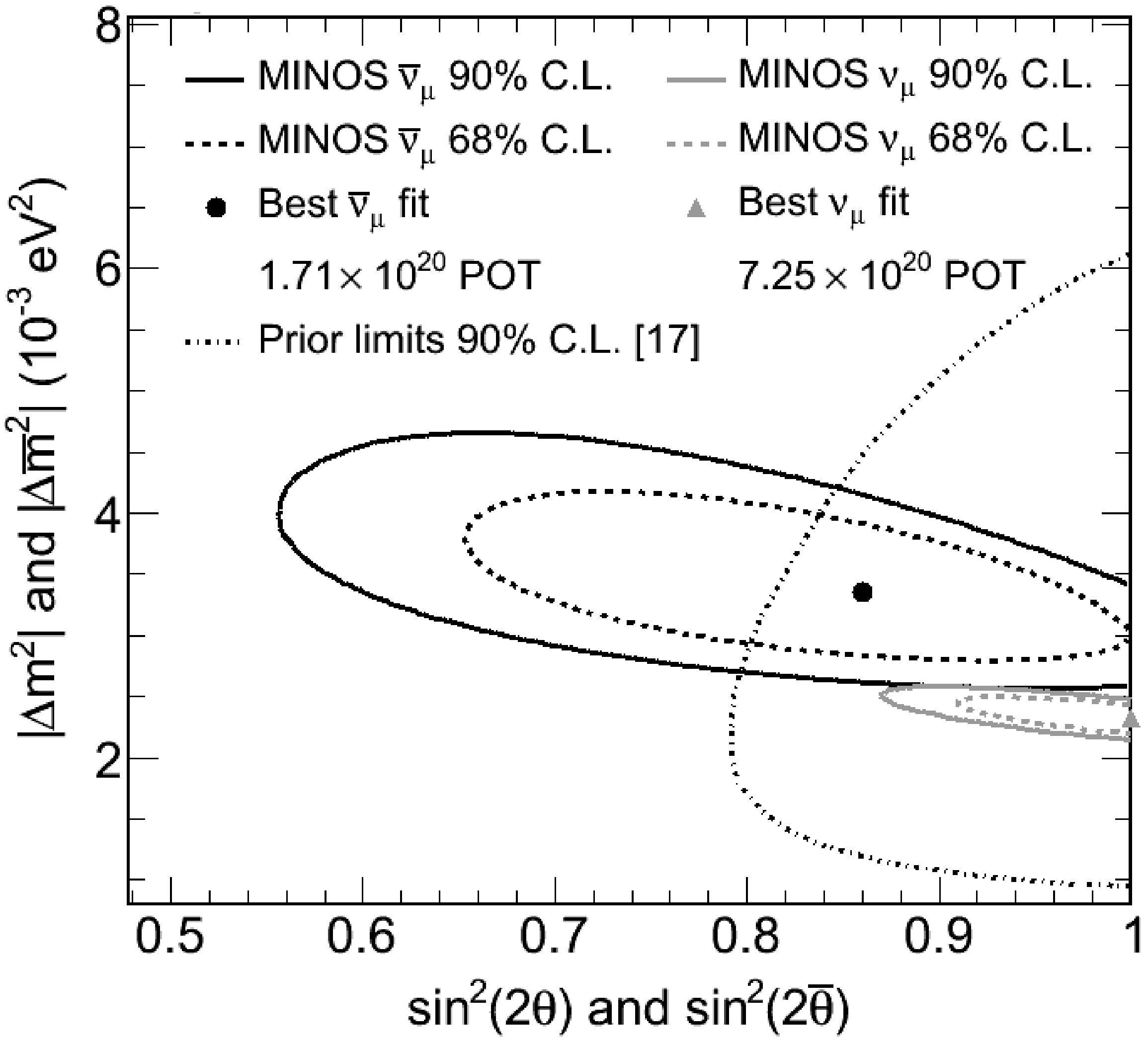
CPT conservation: $P(\overline{\nu}_\mu \rightarrow \overline{\nu}_\mu) = P(\nu_\mu \rightarrow \nu_\mu)$





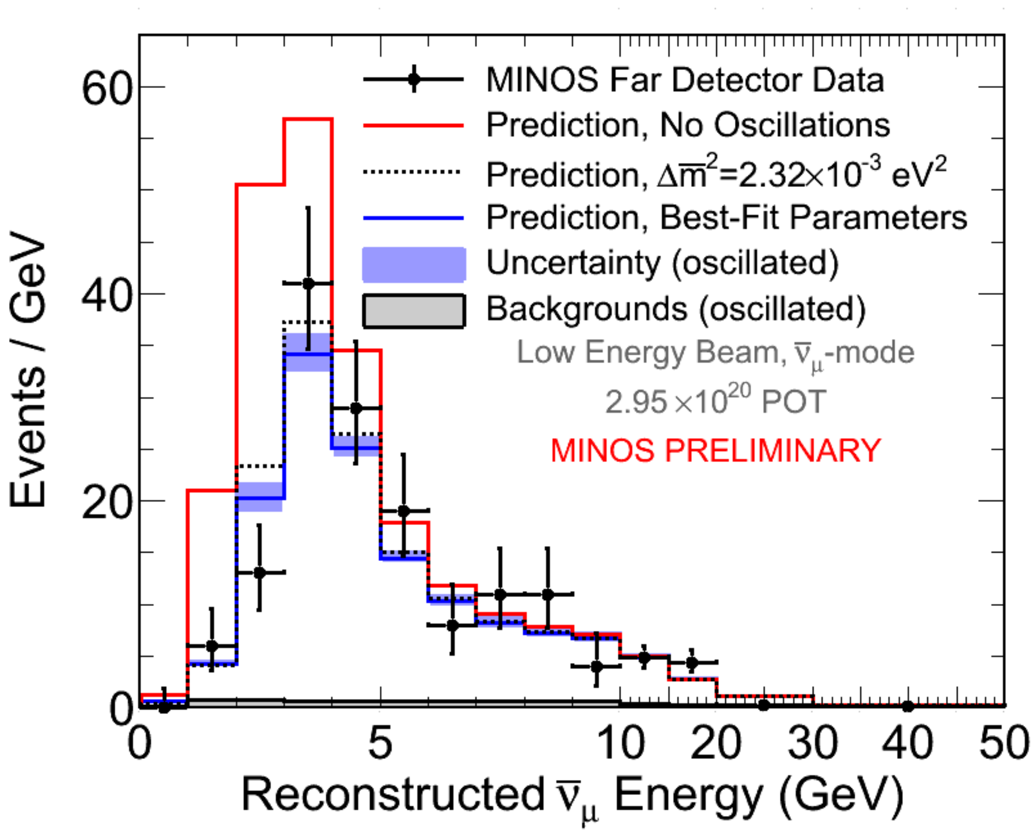
$\overline{\nu}_\mu$ CC Disappearance

Why is this study interesting – old results



$\overline{\nu}_\mu$ CC Disappearance

Selected $\overline{\nu}_\mu$ CC events in the Far Detector



Observed Events = 193

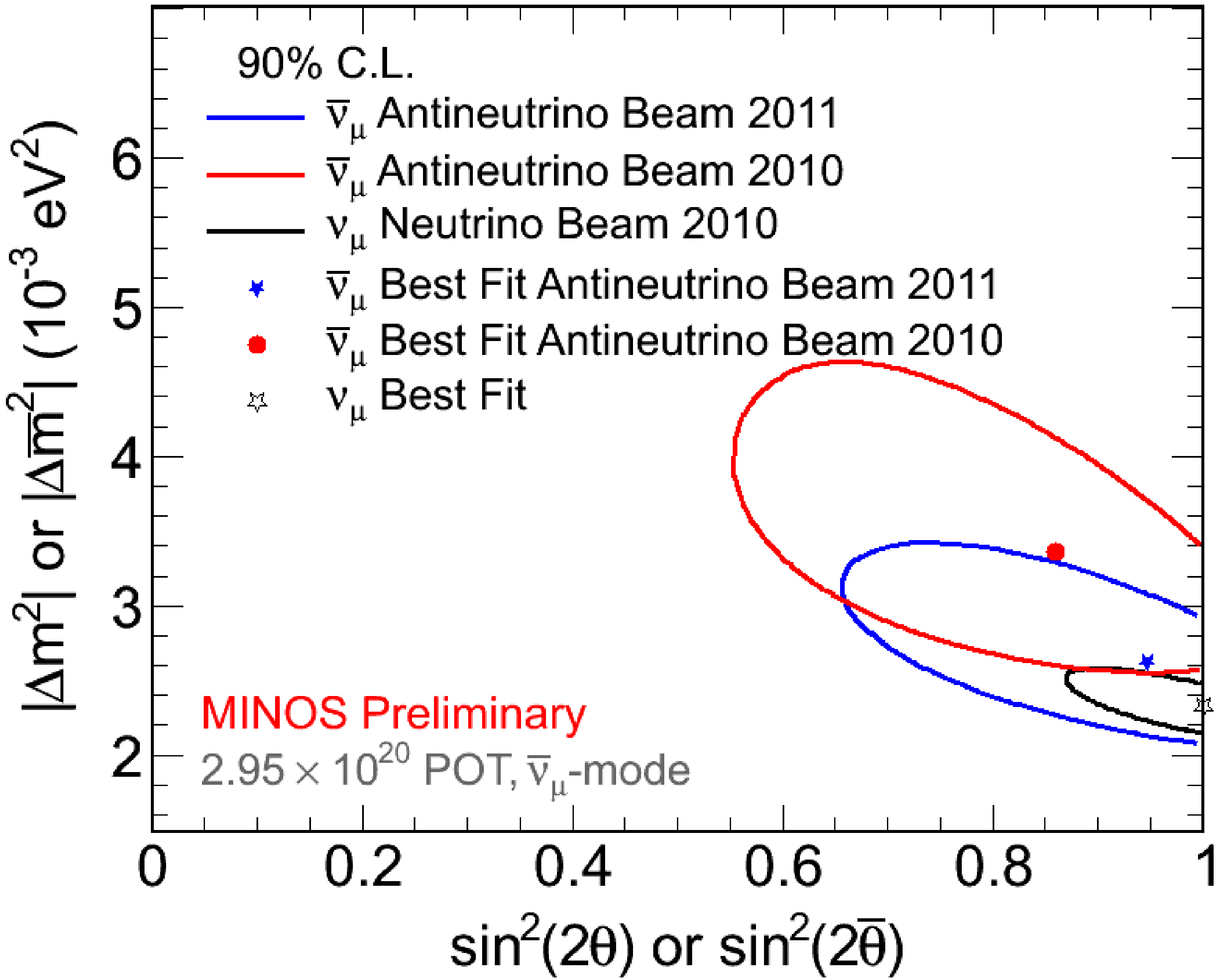
Expectation (No Osc.) = 273

No oscillations ruled out at 7.3σ

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

$\sin^2(2\overline{\theta}) = 0.86^{+0.10}_{-0.11}\text{(stat)} \pm 0.01\ \text{(sys)}$

$\overline{\nu}_\mu$ CC Disappearance



Superluminal Neutrinos????

Neutrino Velocity Measurements

Fermilab ~500m baseline experiment (1979)

Muon Neutrinos

$E > 30$ GeV

$|v-c|/c < 4 \times 10^{-5}$

Supernova 1987a

Electron Antineutrino Detection

$E \sim 10\text{-}40$ MeV

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

$|v-c|/c < 2 \times 10^{-9}$

Opera (2011)

Muon Neutrinos

$E \sim 17$ GeV

$(v-c)/c = [2.48 \pm 0.28\ (\text{stat}) \pm 0.30\ (\text{sys})] \times 10^{-5}$

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

Baseline:	
Distance[a] ND to FD, L	$734\,298.6 \pm 0.7$ m
Nominal time of flight, τ	$2\,449\,356 \pm 2$ ns
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

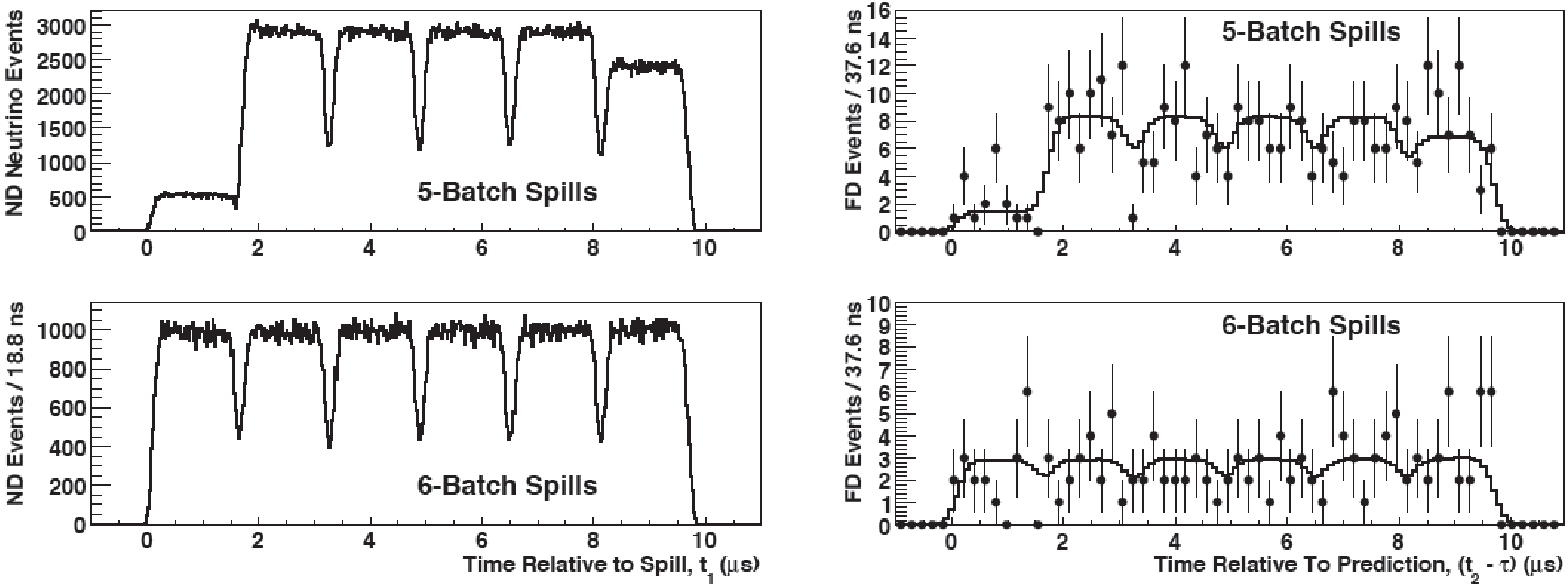
[a]Distance between front face of the ND and the center of the FD.

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

TABLE II: Sources of uncertainty in ν relative time measurement.

What does MINOS have to say about that

Difference in the time distribution between the Far and Near



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

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

1.8 σ Deviation

MINOS Plans

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.

Conclusions

These questions still remain unanswered

- Is there a non-maximal mixing between the ν_μ and ν_τ states?
  - Is $\theta_{23} \neq 45°$?
- What's the mass hierarchy?
  - Is $\Delta m^2_{32} > 0$?
- Is there an ν_e component to the ν_3 mass state?
  - Is $\theta_{13} \neq 0$?
- Is there CP violation in the lepton sector?
  - Is $\delta_{CP} \neq 0$? (Is $\theta_{13} \neq 0$?)

But we are constraining the possible solutions

- MINOS sets the tightest limits on θ_{13} assuming normal hierarchy
- MINOS sets tightest constraints on the magnitude of Δm^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...