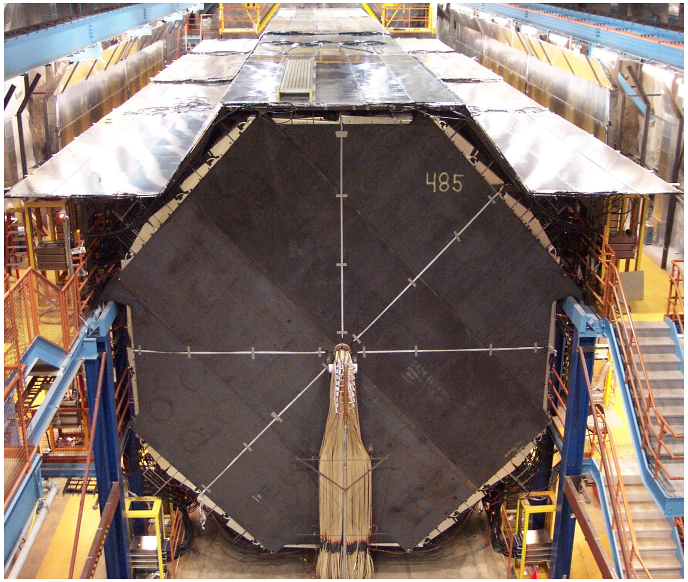


The Latest Results From The MINOS Neutrino Oscillation Experiment

Ruth Toner, for the MINOS Collaboration
University of Cambridge
March 1st, 2011

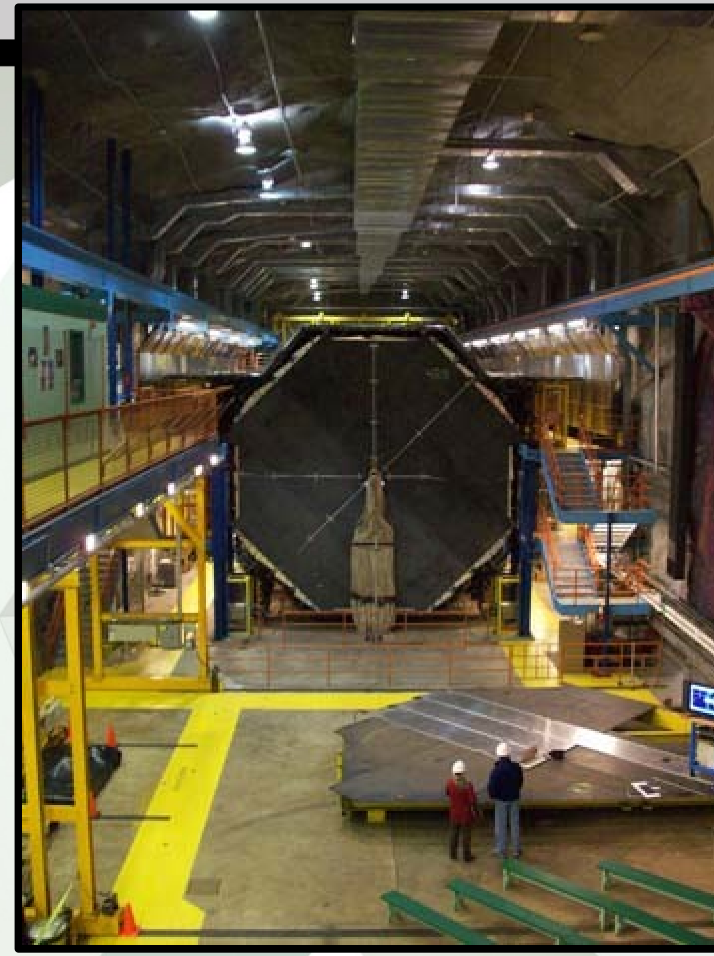
Introduction

MINOS = **M**ain **I**njector **N**eutrino **O**scillation **S**earch

- Long-baseline neutrino oscillation experiment, utilizing the Fermilab NUMI muon neutrino beam

- Use two **magnetized tracking calorimeter detectors** to study the neutrino flux from this beamline

Aim = study the oscillation of neutrinos between these two detectors



Neutrino Oscillations: Our Physics Goals

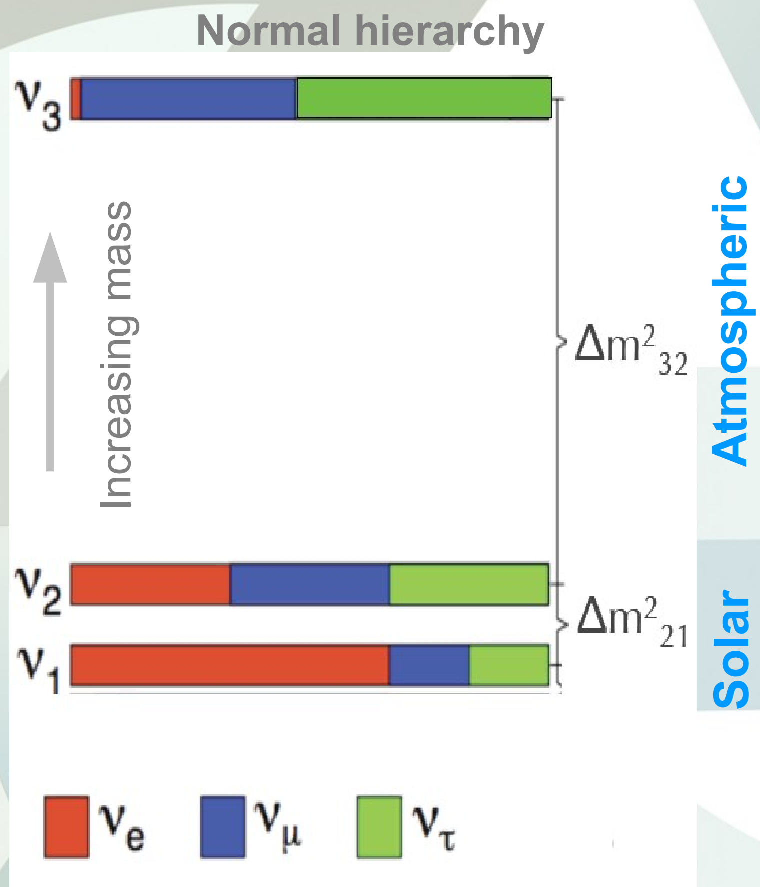
MINOS research focus:

- Neutrino oscillations in the atmospheric and accelerator regime:

$\Delta m^2_{atm} \sim 2\times10^{-3}\ \mathrm{eV}^2$

Specifically:

- Study neutrino oscillation **parameters** $\sin^2 2\theta_{23}$ and Δm^2_{32}
- Do the same study for **antineutrino oscillation** and compare behavior
- Constrain or measure $\boldsymbol{\theta_{13}}$
- Oscillations to **sterile states**?



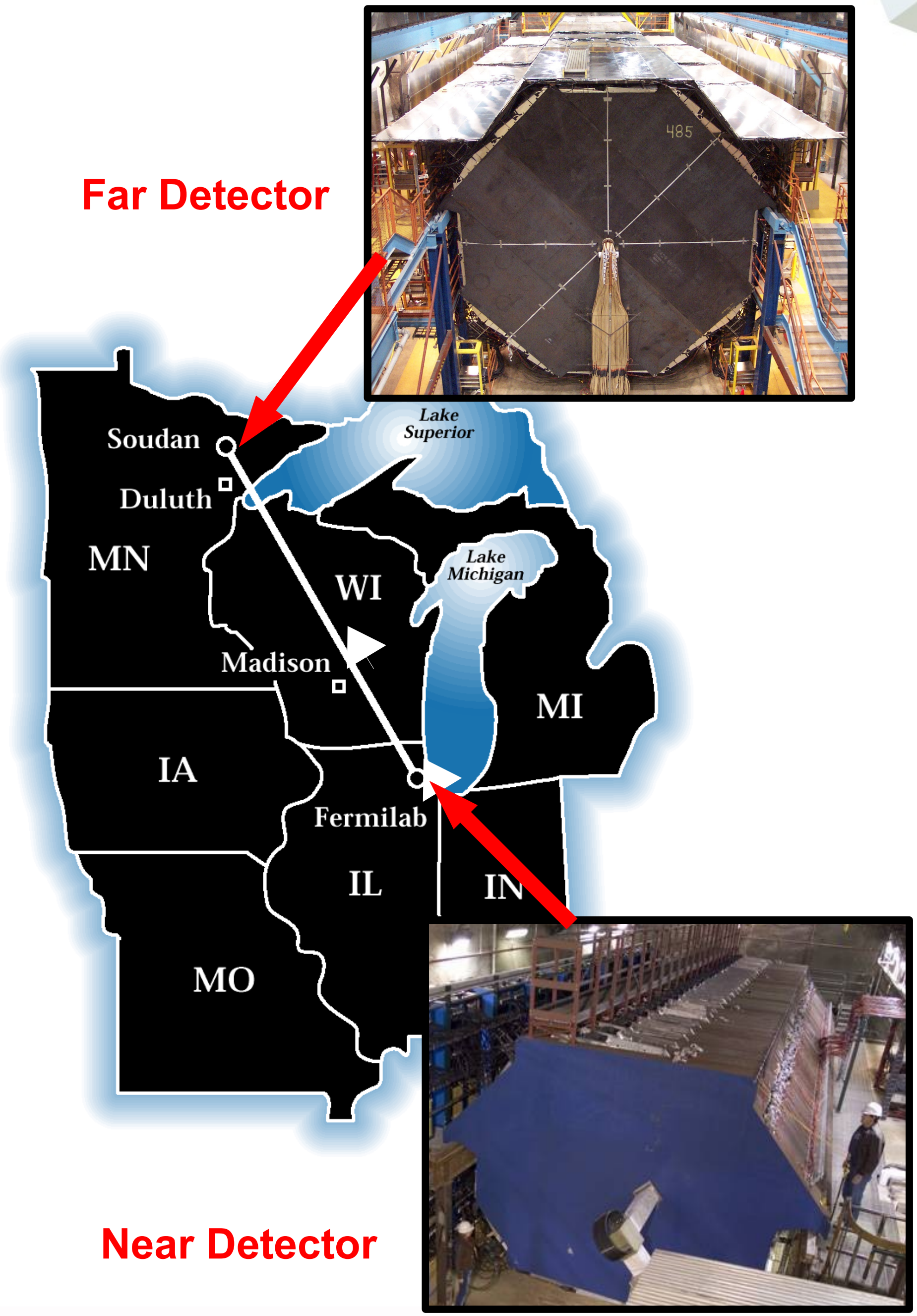
PMNS Matrix:

MINOS Measurements

Atmospheric — CP — Solar sector — Majorana Phases

$$U=\begin{pmatrix}1&0&0\\0&c_{23}&s_{23}\\0&-s_{23}&c_{23}\end{pmatrix}\times\begin{pmatrix}c_{13}&0&s_{13}e^{-i\delta}\\0&1&0\\-s_{13}e^{i\delta}&0&c_{13}\end{pmatrix}\times\begin{pmatrix}c_{12}&s_{12}&0\\-s_{12}&c_{12}&0\\0&0&1\end{pmatrix}\times\begin{pmatrix}e^{i\alpha_1/2}&0&0\\0&e^{i\alpha_2/2}&0\\0&0&1\end{pmatrix}$$

The MINOS Experiment



- Muon Neutrino Beamline (NuMI)

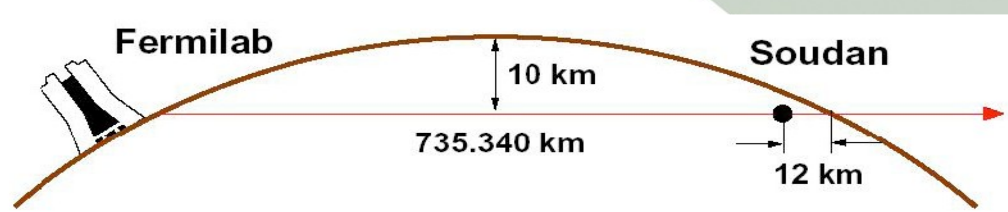
Two functionally equivalent detectors:

Near Detector: 0.029 kT fiducial mass
→ Unoscillated neutrinos

Far Detector: 4.0 kT fiducial mass at depth of 700 m (2100 mwe)
→ Oscillated neutrinos

- **Two detectors** = allows us to reduce systematic effects, such as flux mismodeling and cross-section uncertainties

- L/E ~ 500 km/GeV – atmospheric sector



The MINOS Experiment: Beamline and Detectors

The NuMI Beamline

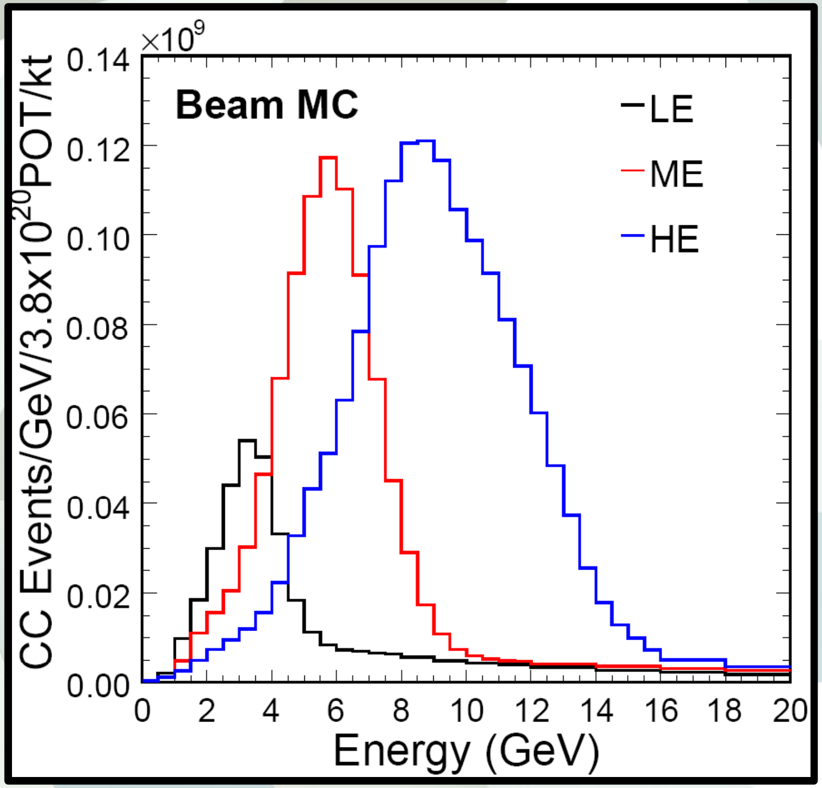
Production: 120 GeV p+ from Main Injector collides with graphite target to produce hadrons (mostly pions and kaons)

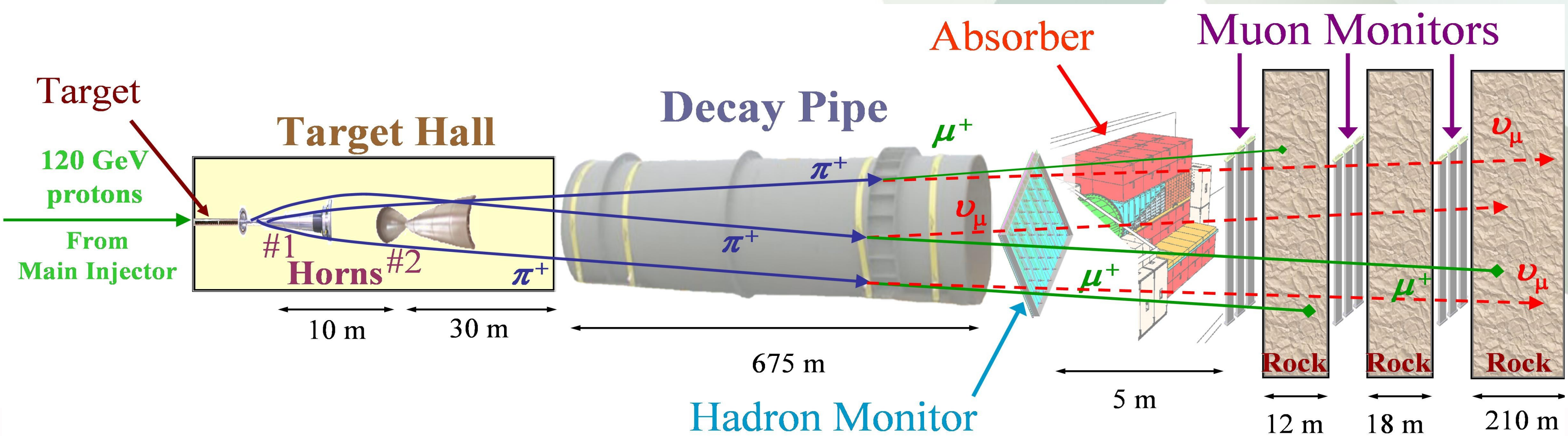
Focusing: Two magnetic focusing horns focus hadrons
- Focus pi+/K+ for neutrino beam
- Focus pi-/K- for antineutrino beam

Decay: Hadrons decay in 675 m long decay pipe

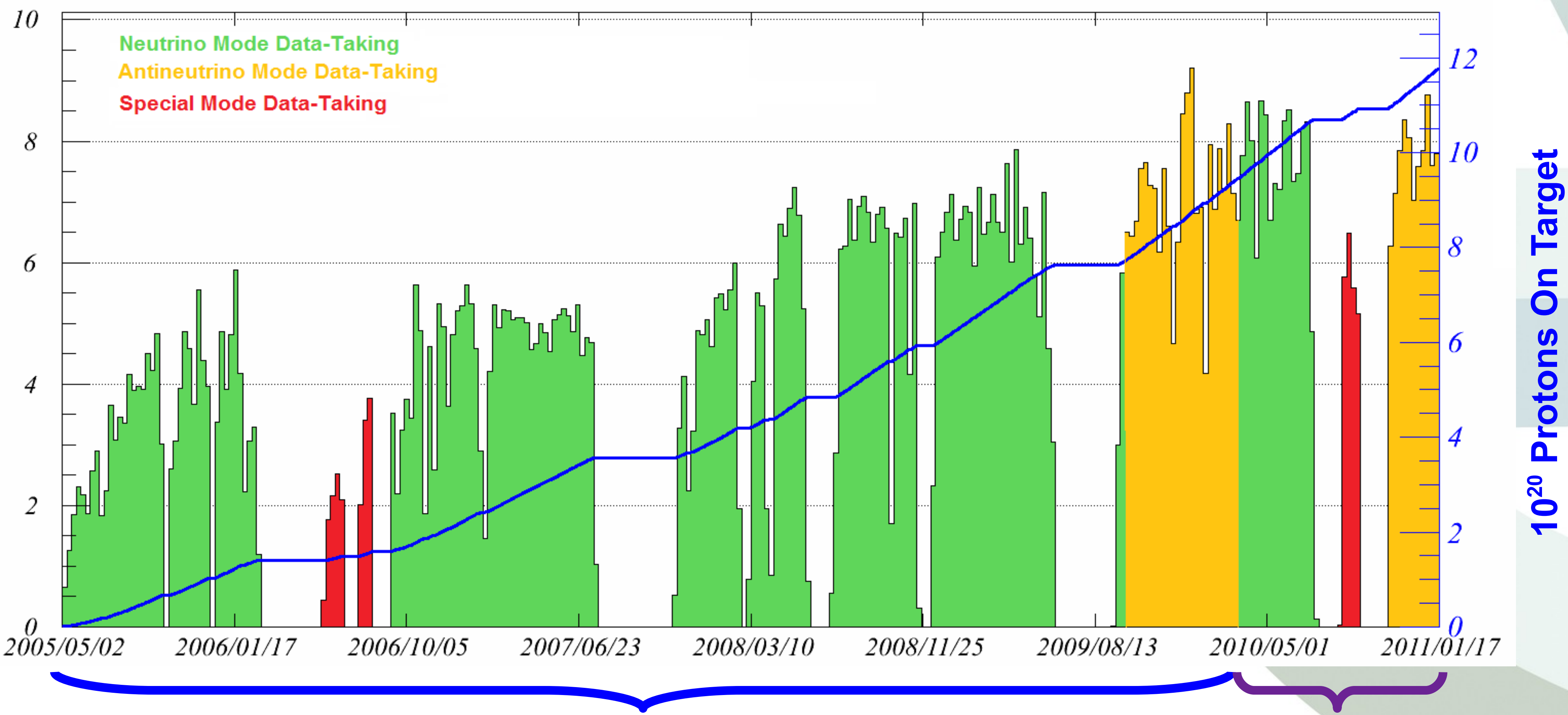
End = on-axis wide-band muon neutrino beam

- Target and horn can be adjusted to change beam peak





The NuMI Beamline



THESE ANALYSES = 7.2x10^{20}ν+ 1.75x10^{20} anti-ν)

Future Analyses

Detector Technology

Both MINOS detectors consist of a series of octagonal planes through which the neutrino beam passes and interacts

- particularly well suited for studying **μ+/μ-** tracks

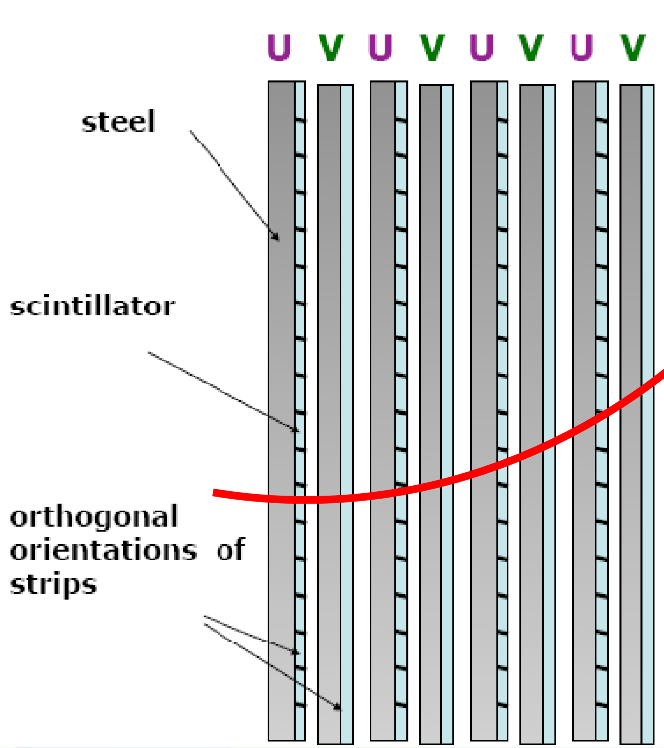
- **Each plane contains:**

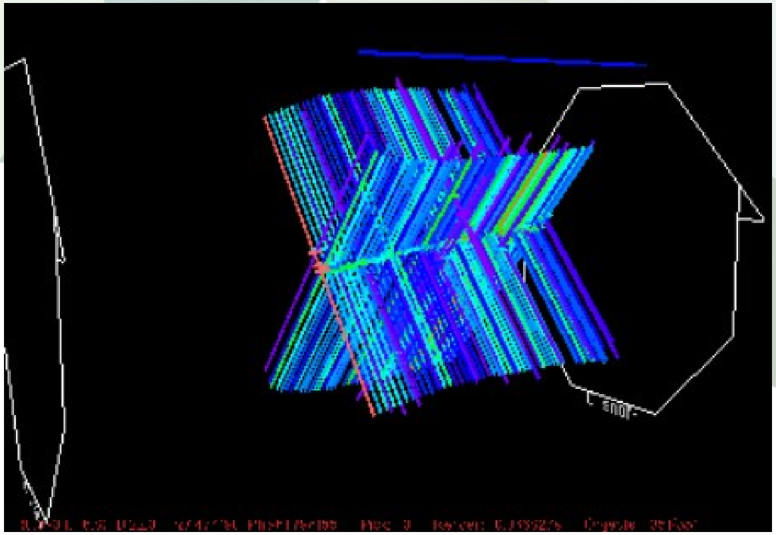
  Layer of 1” steel – **target mass**

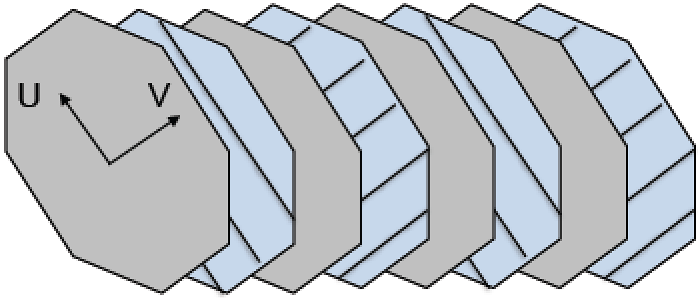
  Layer of 1 cm thick / 4.1 cm wide strips of plastic scintillator – **photons**

Detectors are magnetized (~1.3 T)

→ Muon tracks bend in field, allow you to determine charge sign: neutrino or antineutrino?



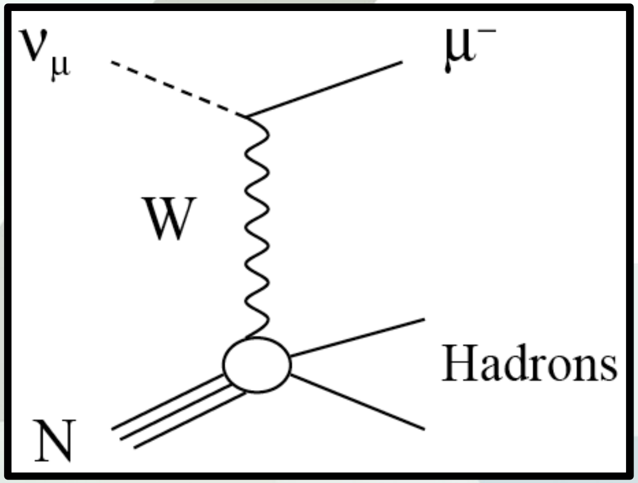


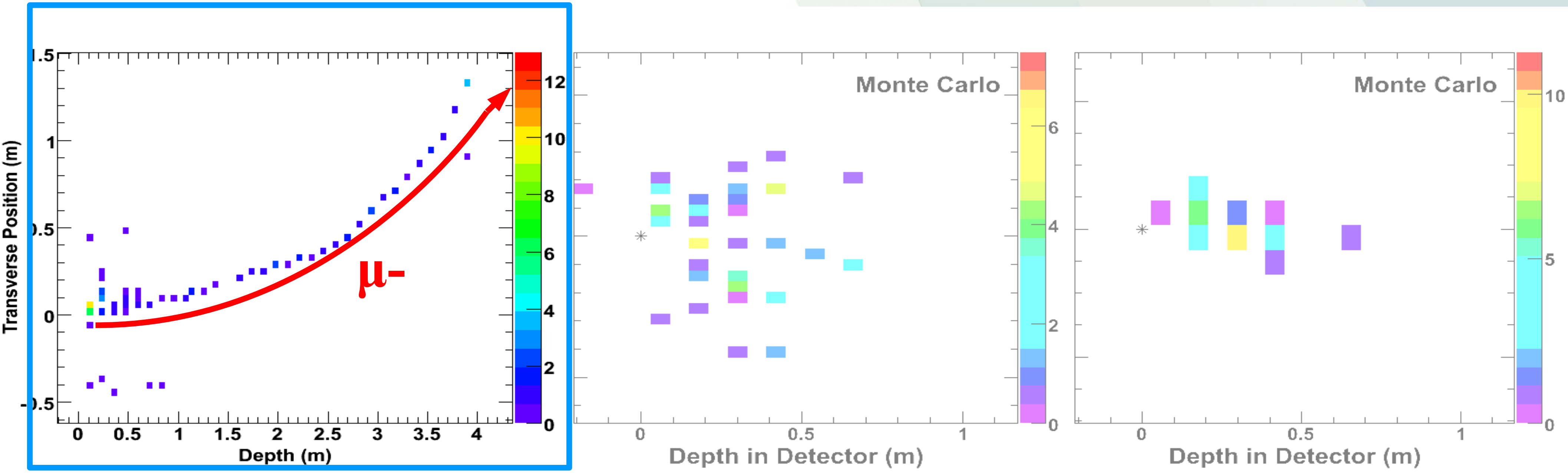


Events in the MINOS Detector

ν_μ Charged Current Events

- **Obvious signature:** hadronic shower followed by long muon track, curved in magnetic field

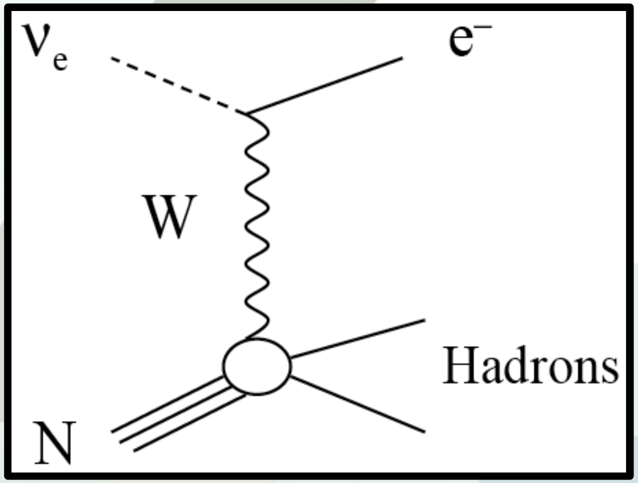


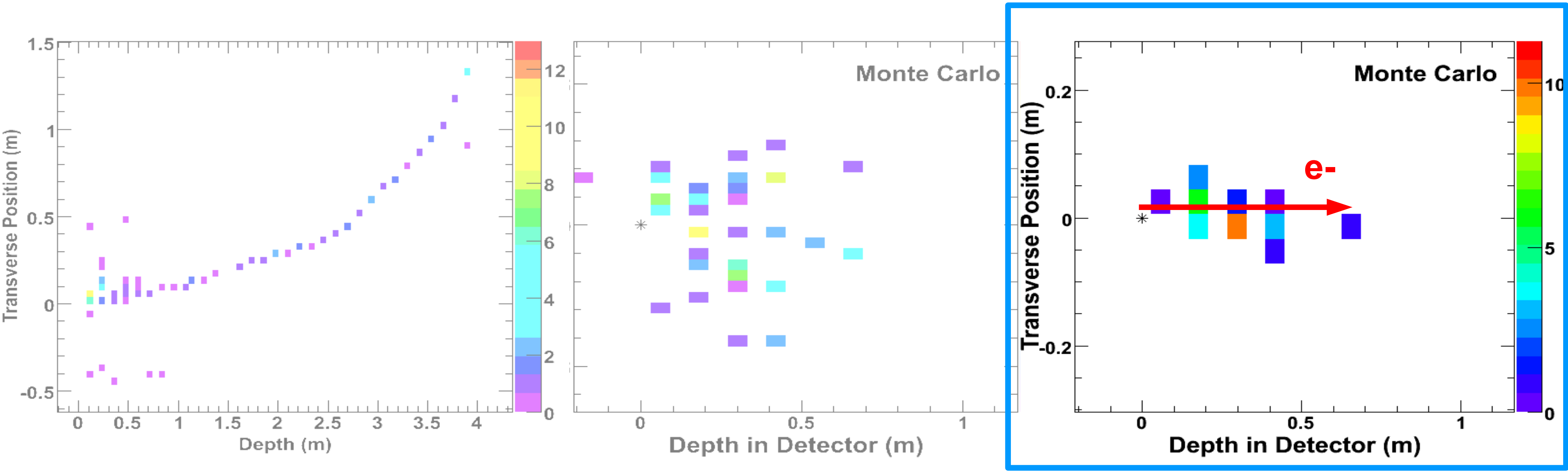


Events in the MINOS Detector

ν_e Charged Current

- electron produces electromagnetic response, resulting in a **compact shower**

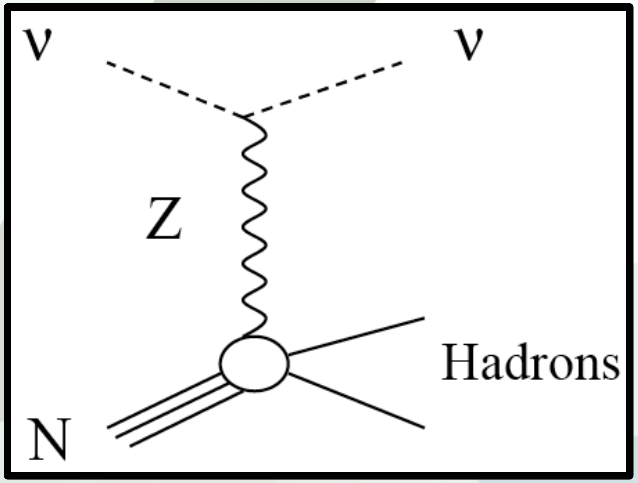


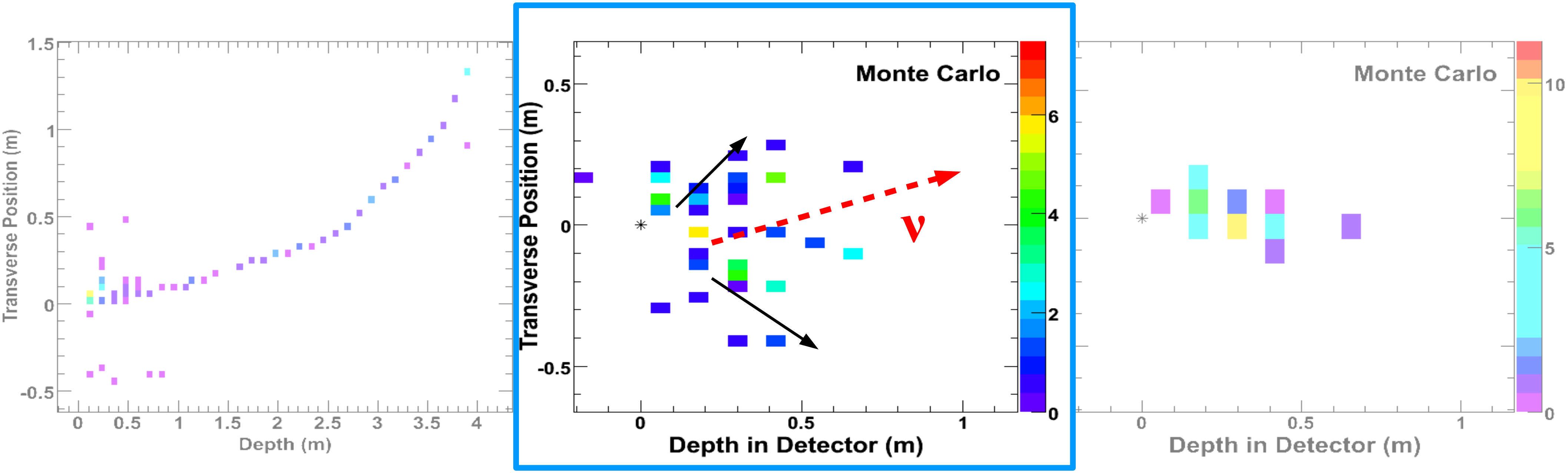


Events in the MINOS Detector

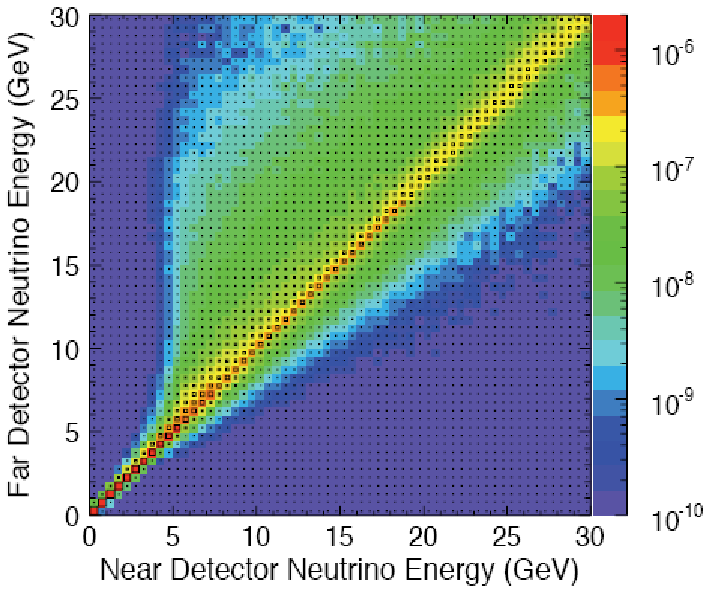
Neutral Current Events

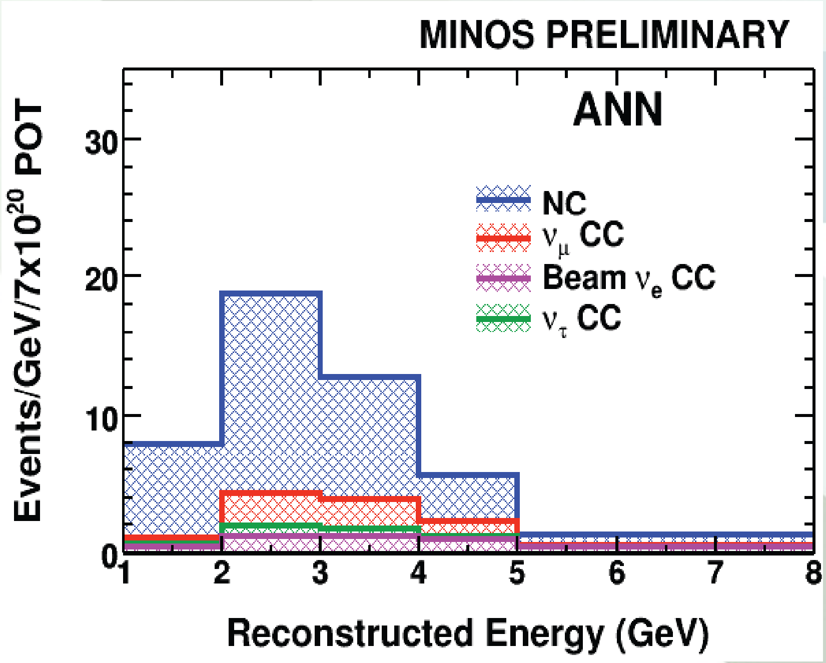
- short, diffuse hadronic shower; cannot tell what type of neutrino interacted





Scientific Analyses





ν_μ Disappearance

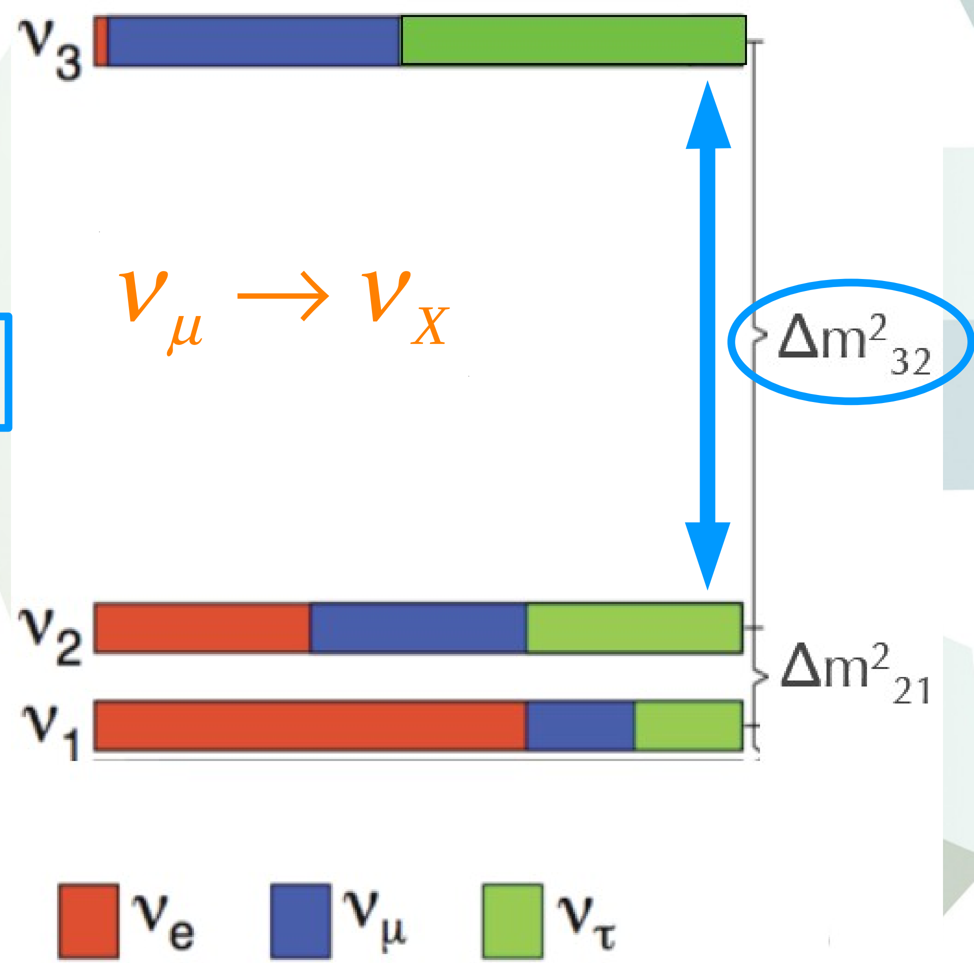
- One primary goal of MINOS is to make precision measurements of **muon neutrino disappearance**

- For oscillation, survival probability:

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta_{23})\sin^2(1.27\,\Delta m^2_{32} L/E)$$

- **An Advantage of MINOS:**
  Fixed L, and set range of E
  → Can measure **Δm^2_{32}, $\sin^2(2\theta_{23})$**

- **Presumed to be oscillating to tau neutrinos (which we do not directly observe in MINOS)**

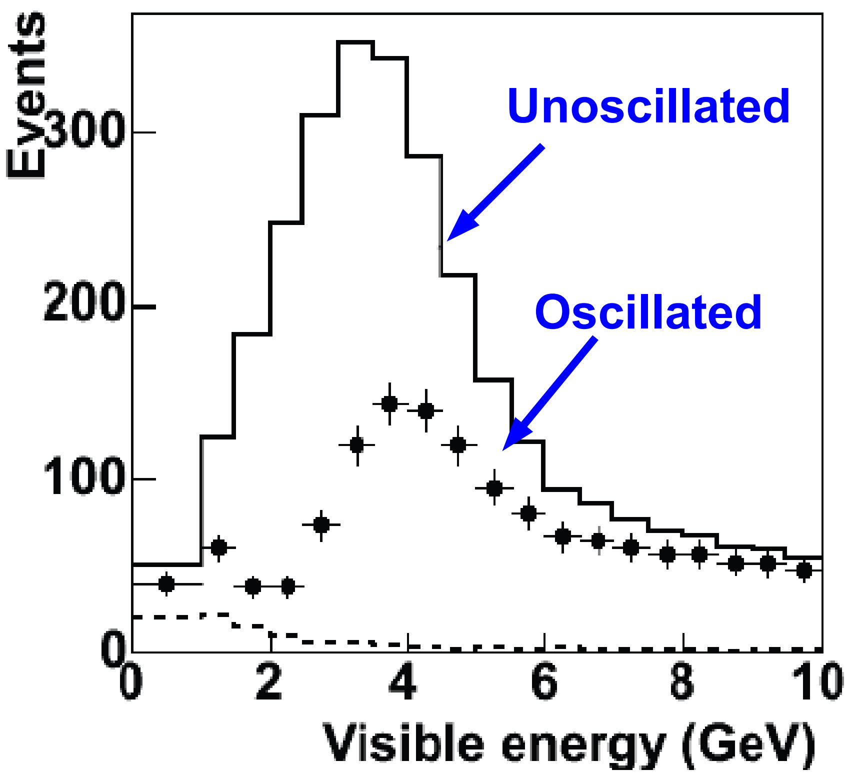


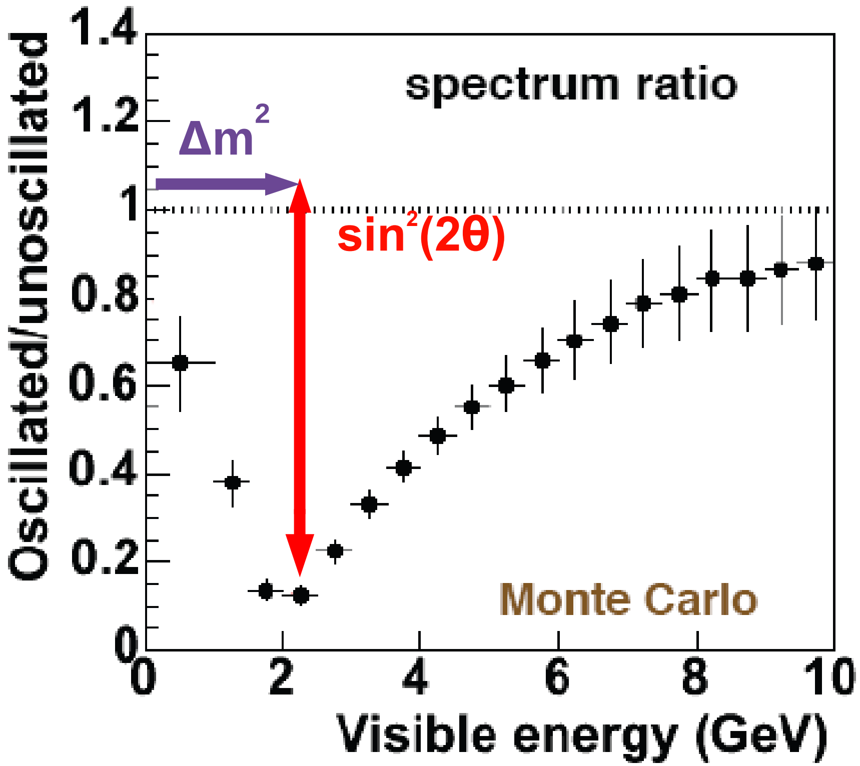
ν_μ Disappearance

Basic analysis:

- Use Near Detector to predict unoscillated spectrum at the Far Detector
- Compare **predicted unoscillated spectrum** to **(oscillated?) data**

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta)\sin^2(1.27\,\Delta m^2 L/E)$$





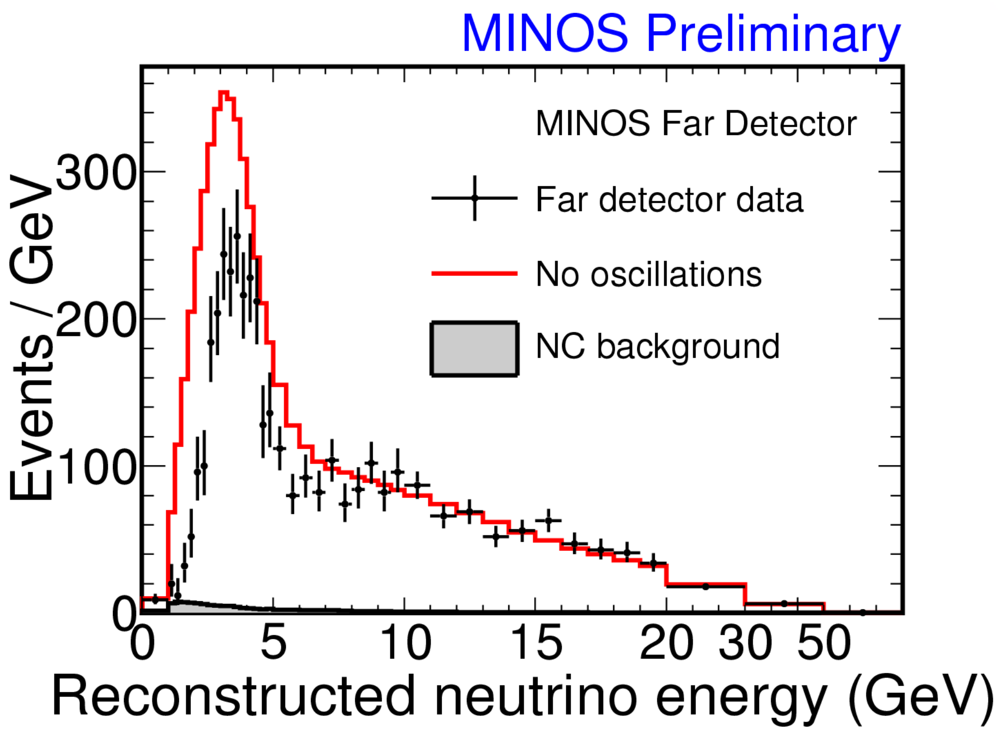
Monte Carlo

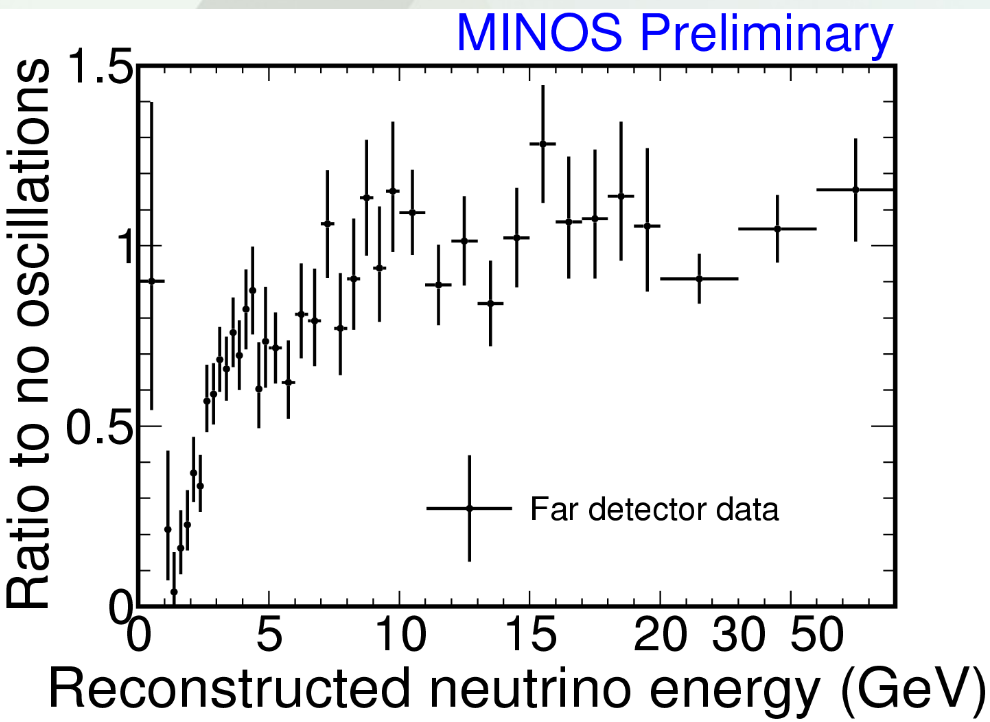
(Input parameters: $\sin^2 2\theta = 1.0$, $\Delta m^2 = 3.35\times10^{-3}\ \mathrm{eV}^2$)

Opening the Box

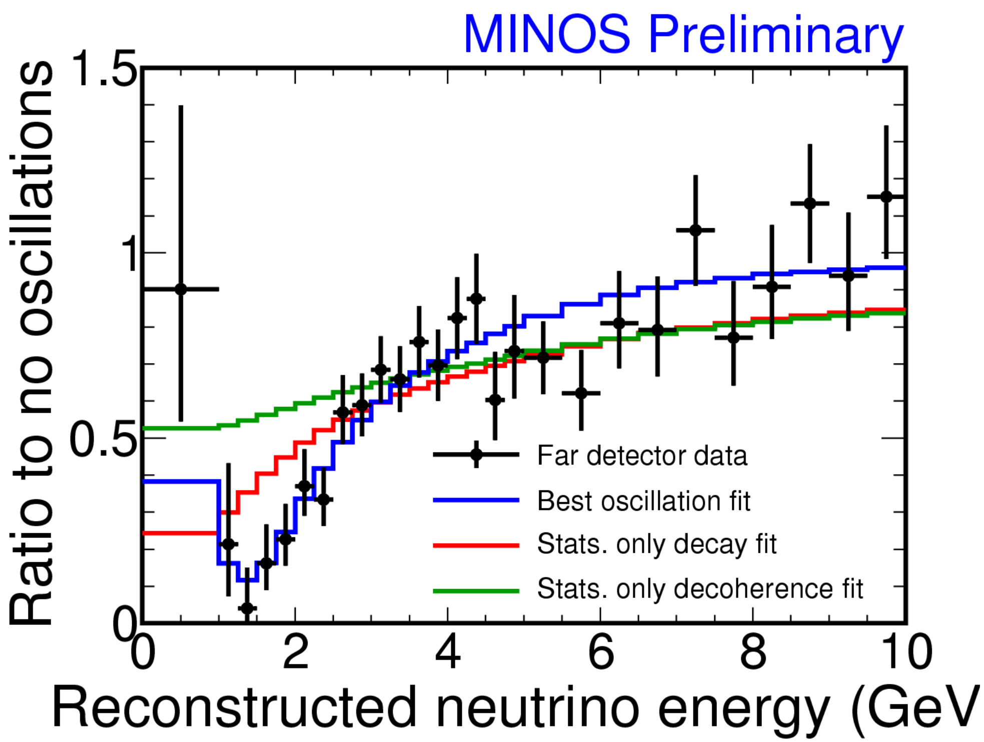
No Oscillation Prediction: **2451**

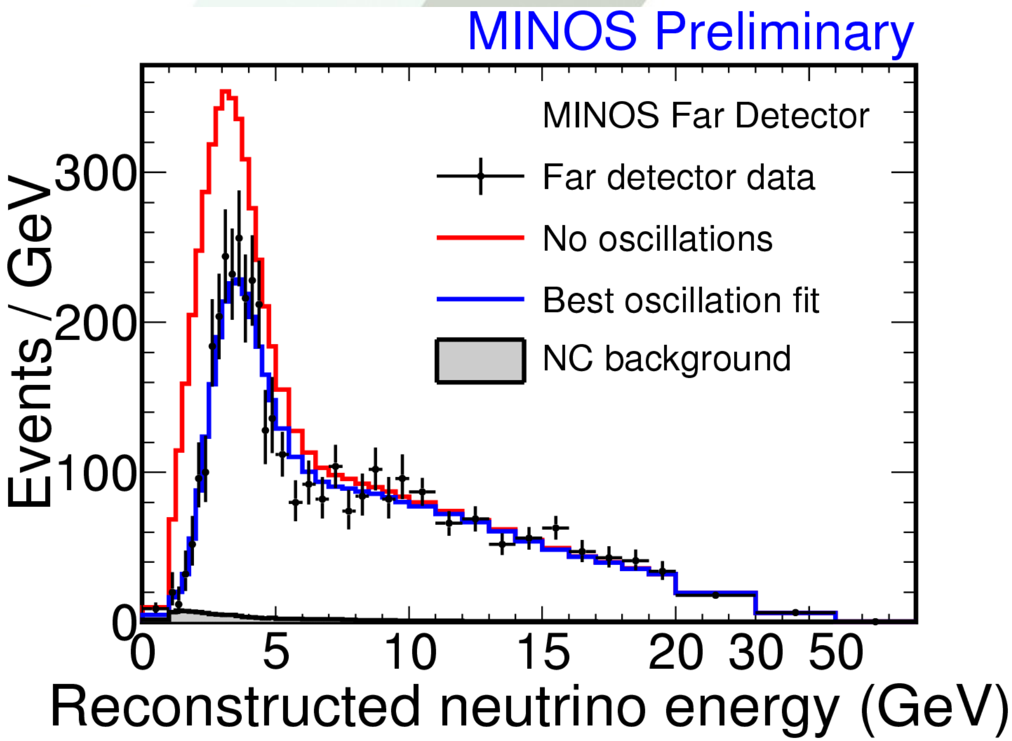
Observation: **1986**





Models of Disappearance





- $\nu_\mu \leftrightarrow \nu_\tau$ **oscillation hypothesis holds up when compared to alternate models**

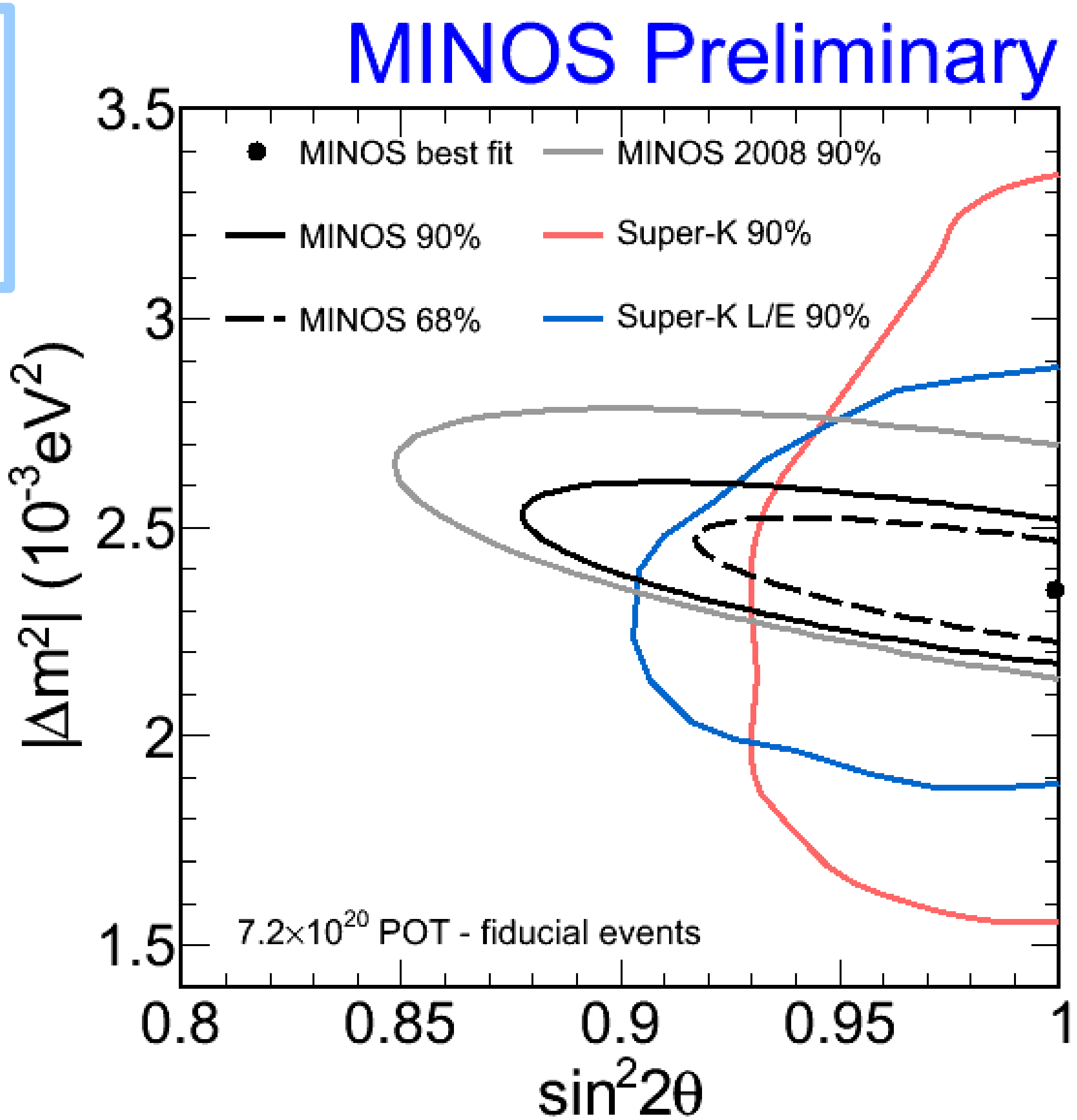
- **Pure decoherence disfavored:** **>8σ** V.D. Barger et al., Phys. Lett. B 462, 109 (1999).

- **Pure decay disfavored:** **>6σ** G.L. Fogli *et al.*, PRD67:093006 (2003)

Results

$$|\Delta m^2| = 2.35^{+0.11}_{-0.08} \times 10^{-3}\,\mathrm{eV}^2$$
$$\sin^2(2\theta) > 0.91\ (90\%\ \mathrm{C.L.})$$

- Includes systematic uncertainties from:
- Normalization
- NC background
- shower energy
- track energy



†Super-Kamiokande Collaboration (preliminary)

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

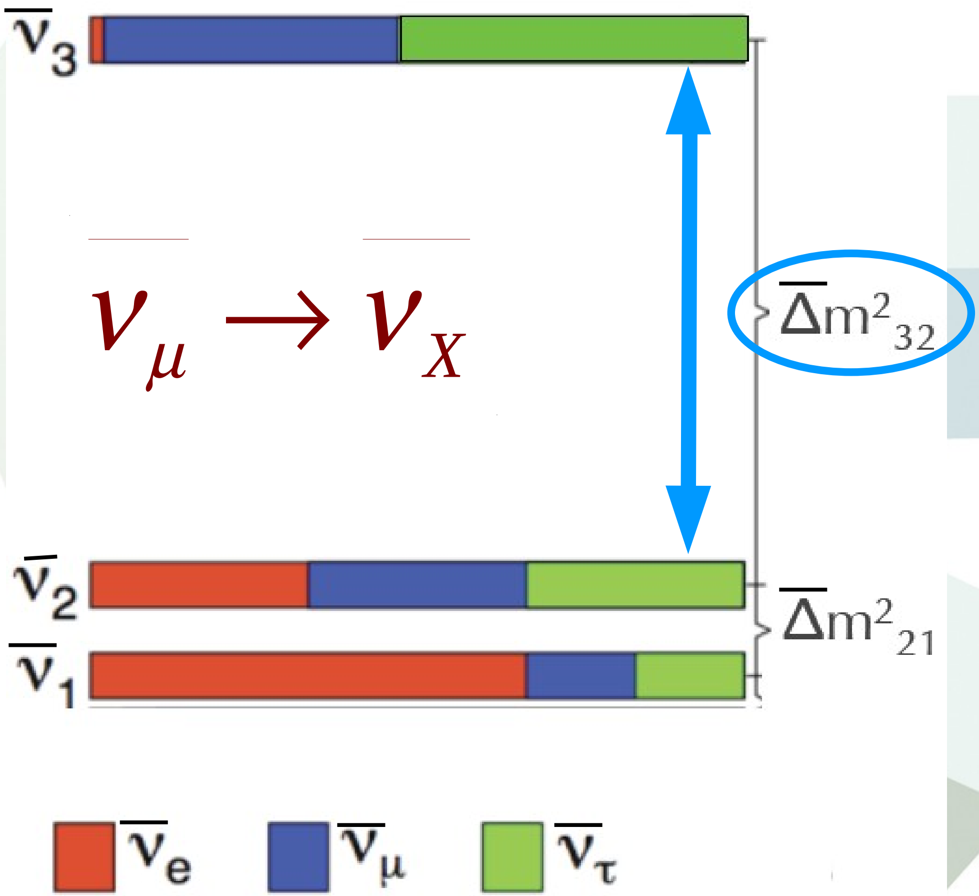
- MINOS also has the unique ability to compare neutrino and antineutrino oscillations

- We can run beam in **Antineutrino Mode**

- We can use the **curvature of muons** in the magnetic field to distinguish ν_μ and $\bar{\nu}_\mu$.

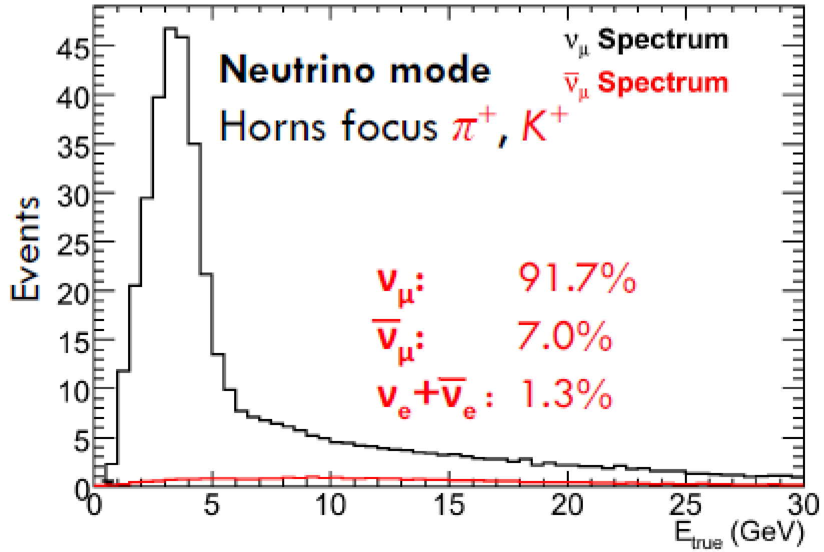
Question: Do neutrinos and anti-neutrinos behave in the same way?

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu) = 1 - \sin^2(2\bar{\theta}_{23})\sin^2(1.27\,\Delta\bar{m}^2_{23}\,L/E)$$

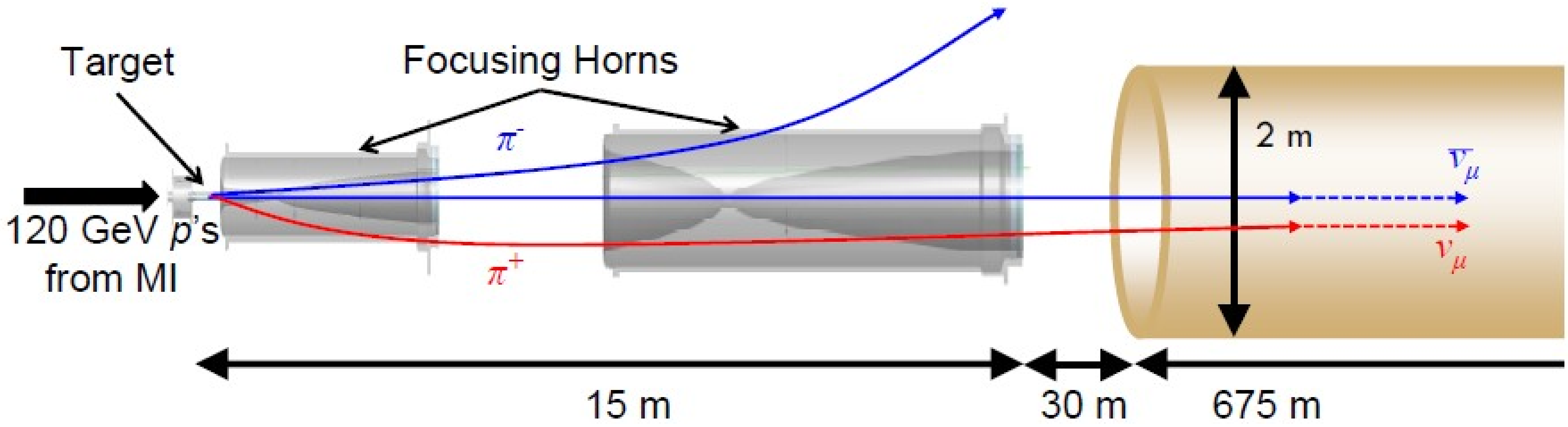


(Image: P. Vahle)

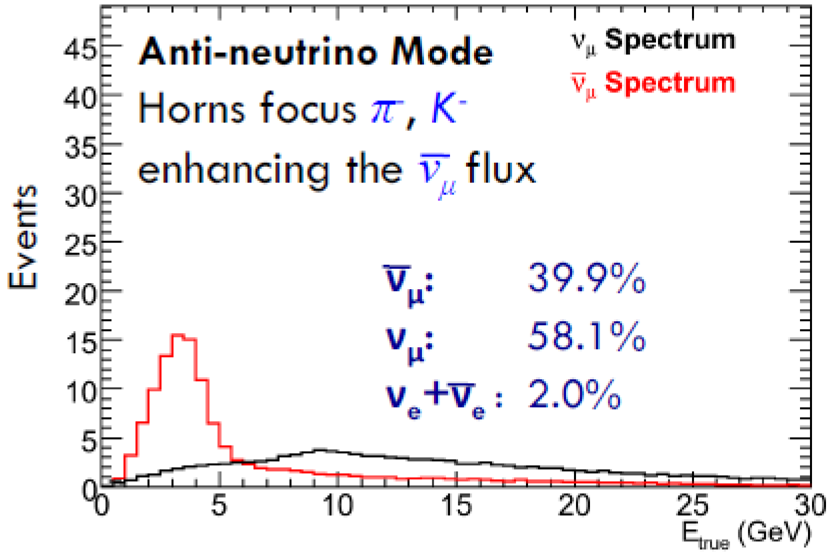
Producing an Antineutrino Beam



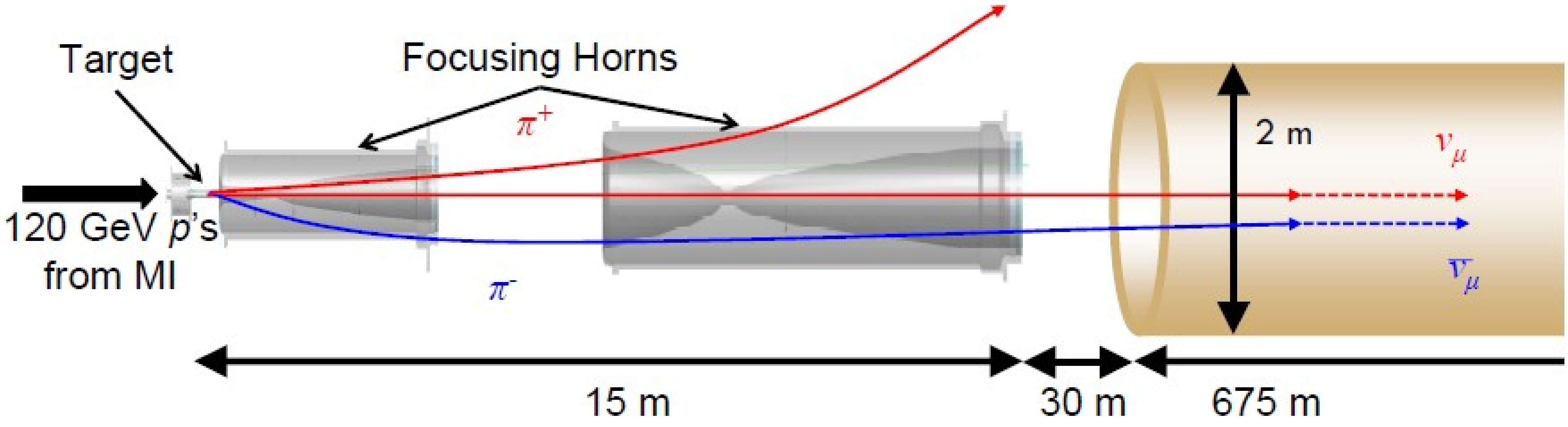
Standard Neutrino Mode



Producing an Antineutrino Beam



Antineutrino Mode



Results

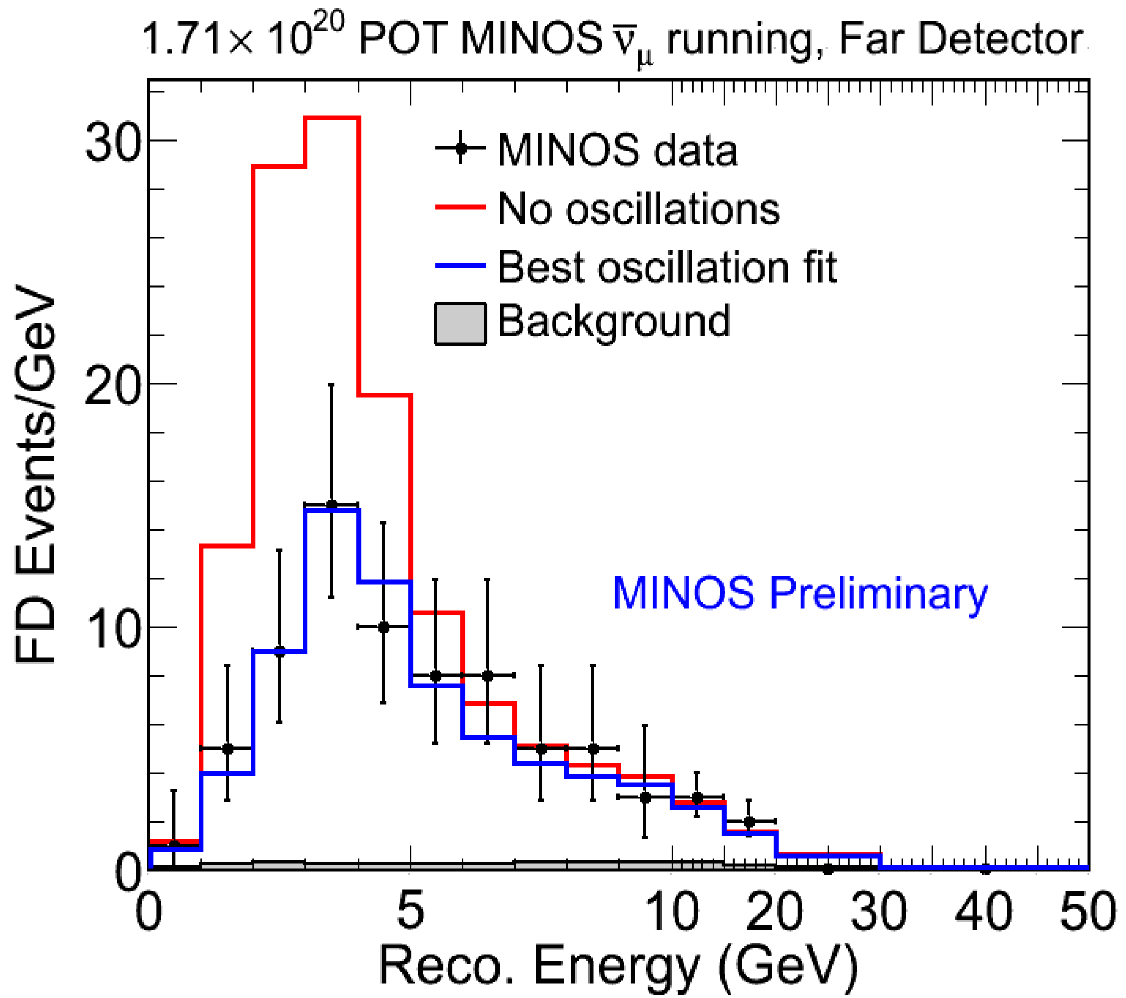
No Oscillation Prediction: **155**
Observation: **97**

- **No oscillations disfavored at 6.3σ**

- **Dominated by low statistics,** including 30% uncertainty on the ν_μ background

- Systematics less important

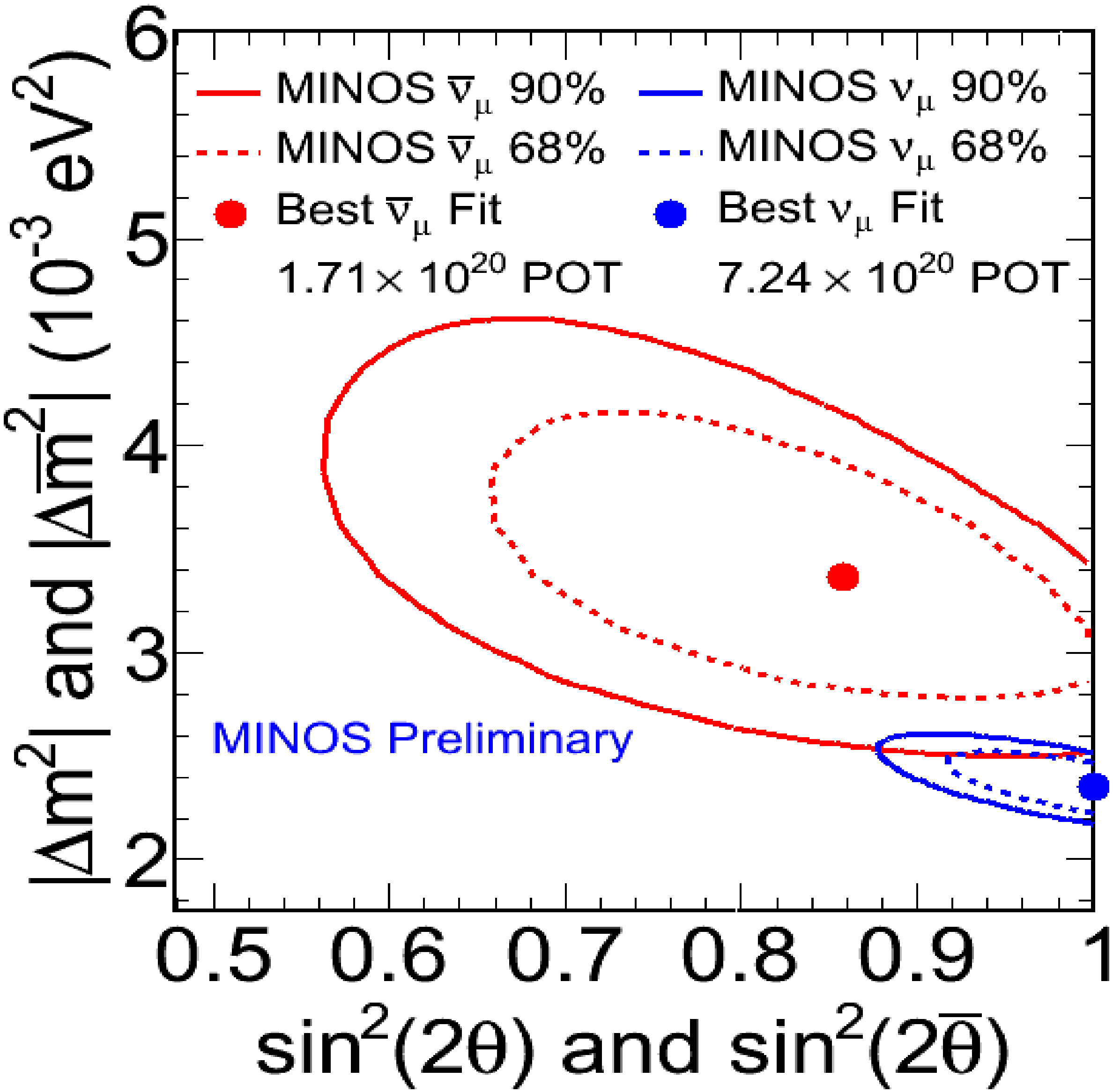
$$|\Delta \bar{m}^2| = 3.36^{+0.45}_{-0.46} \times 10^{-3}\ \mathrm{eV}^2$$
$$\sin^2(2\bar{\theta}) = 0.86 \pm 0.11$$



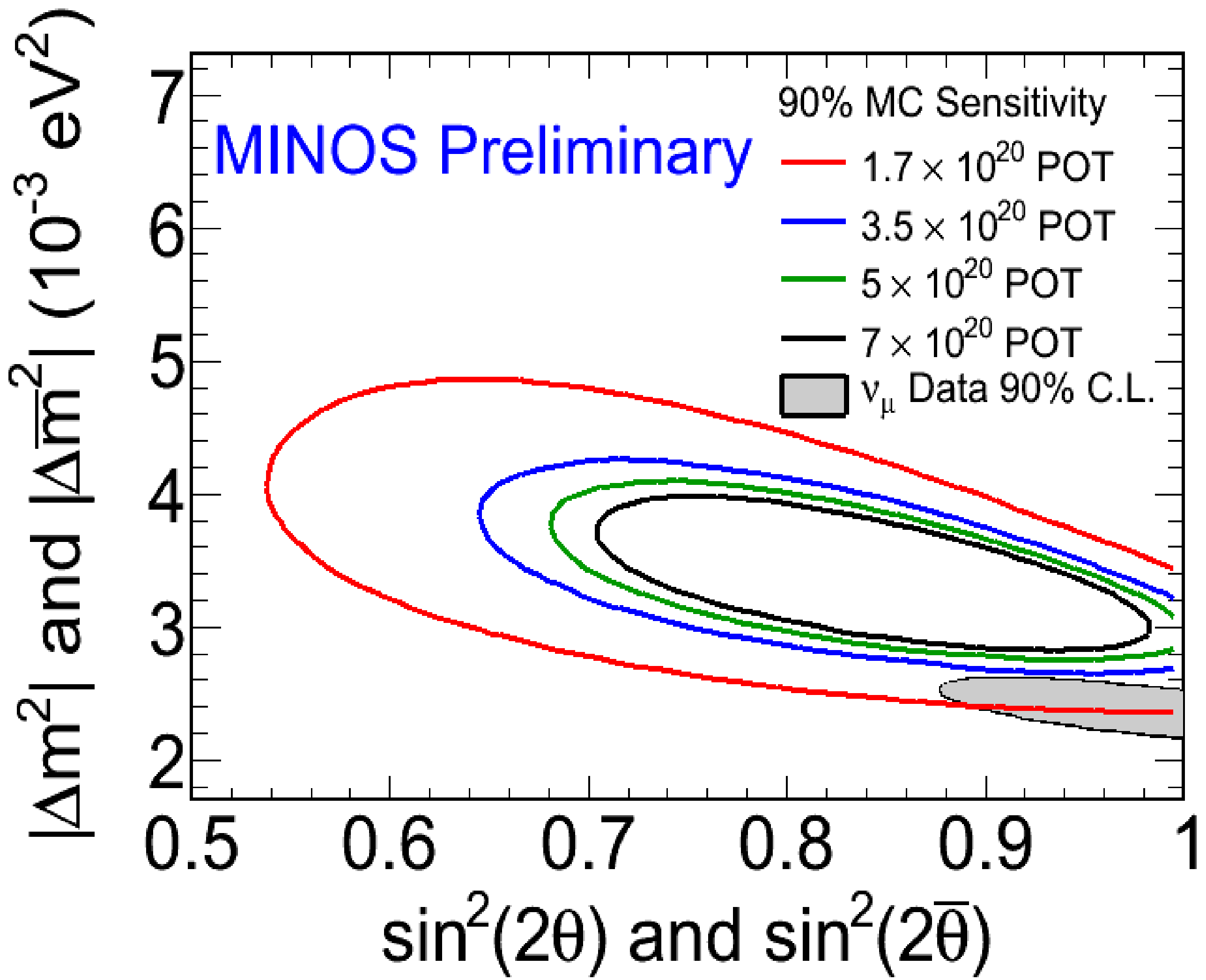
Results

- Neutrino and anti-neutrino parameters differ at ~2σ level

- We are in the process of at least doubling these statistics and doing a joint neutrino /antineutrino analysis



Future Running



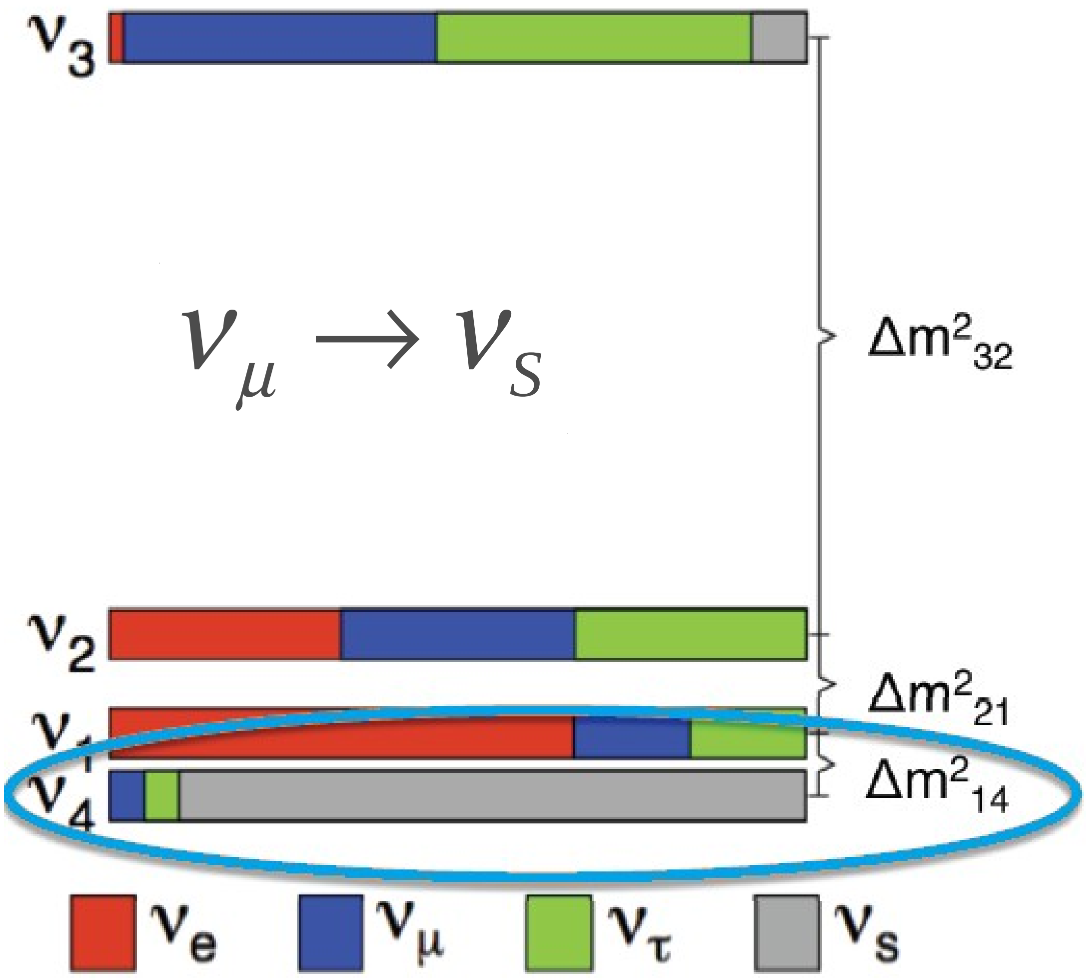
NC Event Rates

- Standard explanation for ν_μ disappearance is oscillation to ν_τ

- Another possible alternative explanation is **oscillation to a fourth, "sterile" neutrino flavor**

Rate of Neutral Current Events:
- We can predict a rate of NC events at the Far Detector
- This rate should not change for three neutrino oscillation scenario
- **A <u>deficit</u> might suggest oscillation to a fourth, "sterile" neutrino**

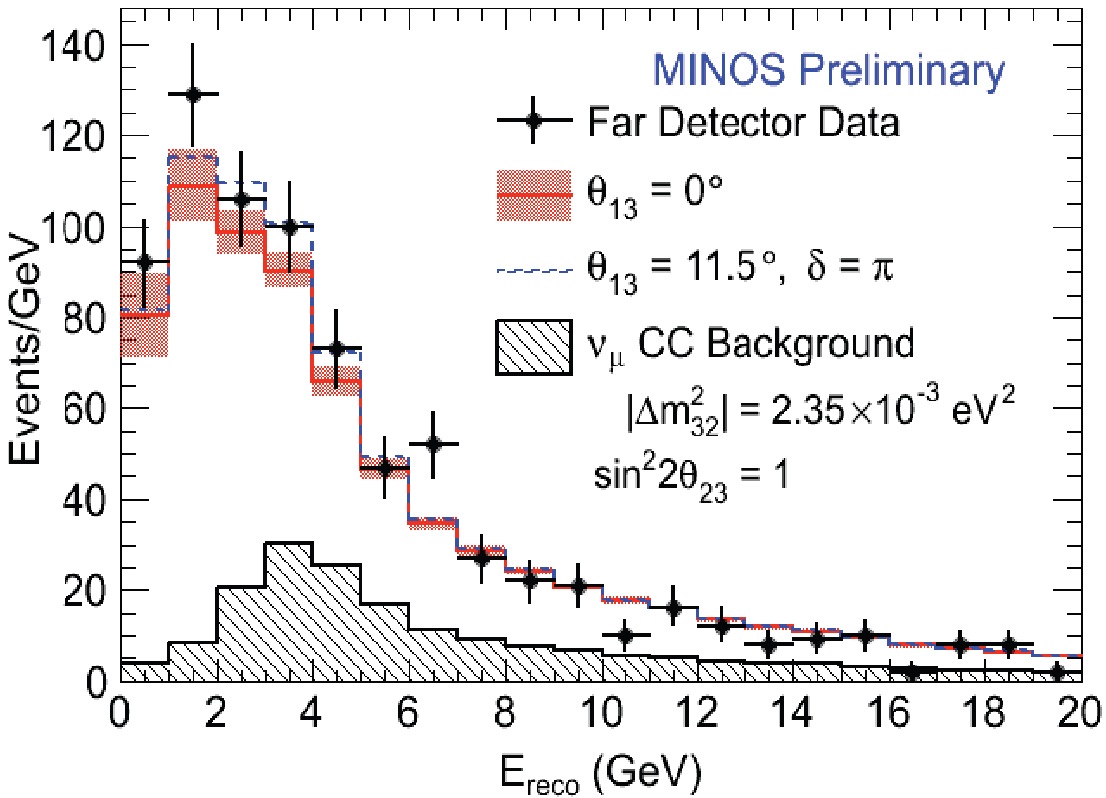
- Consider both m4 = m1 and m4 >> m3 models



$$\nu_\mu \rightarrow \nu_S$$

(Image: P. Vahle)

Neutral Current Analysis Results



Expect: 757
Observe: 802

- Results are consistent with **no significant oscillation** to sterile neutrinos

- This is also taking into account the possibility of electron neutrino appearance at the Far Detector.

The fraction of events which could be oscillating to sterile neutrinos:

$$f_s \equiv \frac{P_{\nu_\mu \to \nu_s}}{1 - P_{\nu_\mu \to \nu_\mu}}$$

$$f_s < 0.22 (0.40 \nu_e) (90\% \text{ C.L.})$$

ν_e Appearance

- MINOS is also capable of using existing detector technology to look for **ν_μ to ν_e oscillations**

- **This would allow us to better constrain or maybe even measure the as yet unmeasured mixing angle θ_{13}:**

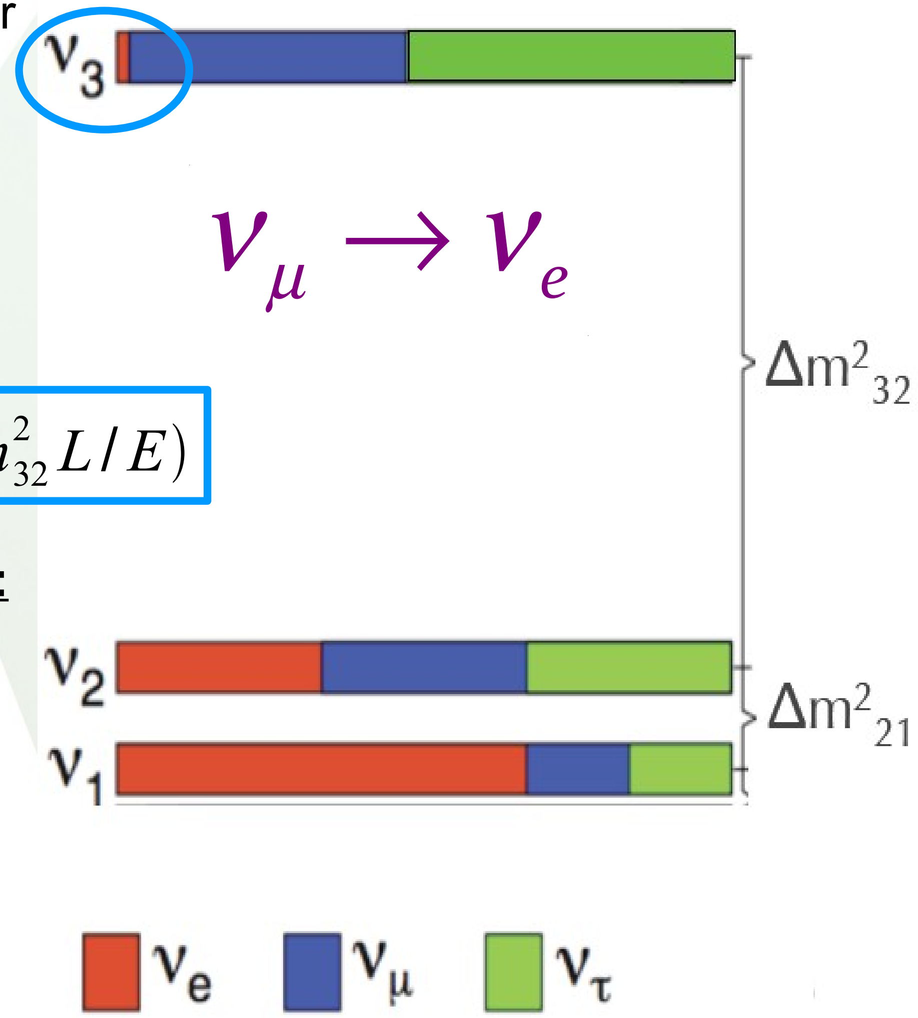
$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2(2\theta_{13}) \sin^2(\theta_{23}) \sin^2(1.27 \Delta m^2_{32} L/E)$$

<u>**Current limit from CHOOZ reactor experiment:**</u>

$\sin^2(2\theta_{13}) < 0.15$ at 90% CL

(assuming $|\Delta m^2| = 2.43 \times 10^{-3}$)

- A non-zero θ_{13} would allow for the possibility of neutrinos exhibiting CP violation



(Image: P. Vahle)

ν_e Appearance

- Unlike an experiment like CHOOZ, MINOS result would depend on $\sin^2(\theta_{23})$, CP violation phase δ, and choice of mass hierarchy (normal or inverted)

- Full equations:

Take other terms from MINOS best fits

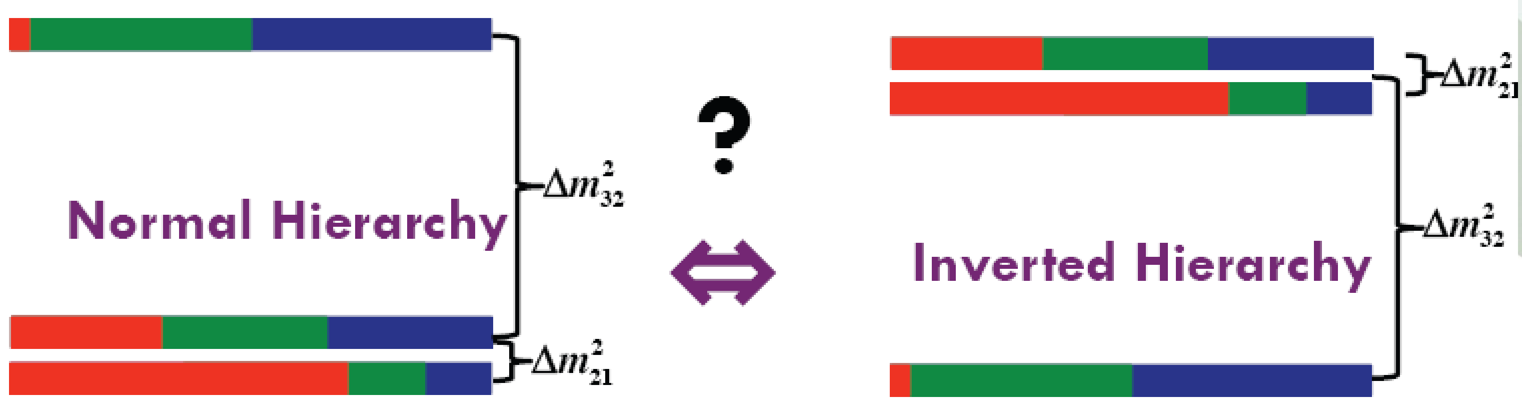
$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2(2\theta_{13})\sin^2(\theta_{23})\sin^2\left(1.27\Delta m^2_{31}\frac{L}{E}\right) +$$

$$\sin^2(2\theta_{12})\cos^2(\theta_{23})\sin^2\left(1.27\Delta m^2_{21}\frac{L}{E}\right) +$$

Small solar contribution

$$\sin(2\theta_{13})\sin(2\theta_{23})\sin(2\theta_{12})\sin\left(1.27\Delta m^2_{31}\frac{L}{E}\right)\sin\left(1.27\Delta m^2_{21}\frac{L}{E}\right)\cos\left(1.27\Delta m^2_{32}\frac{L}{E} \pm \delta_{CP}\right)$$

CP phase

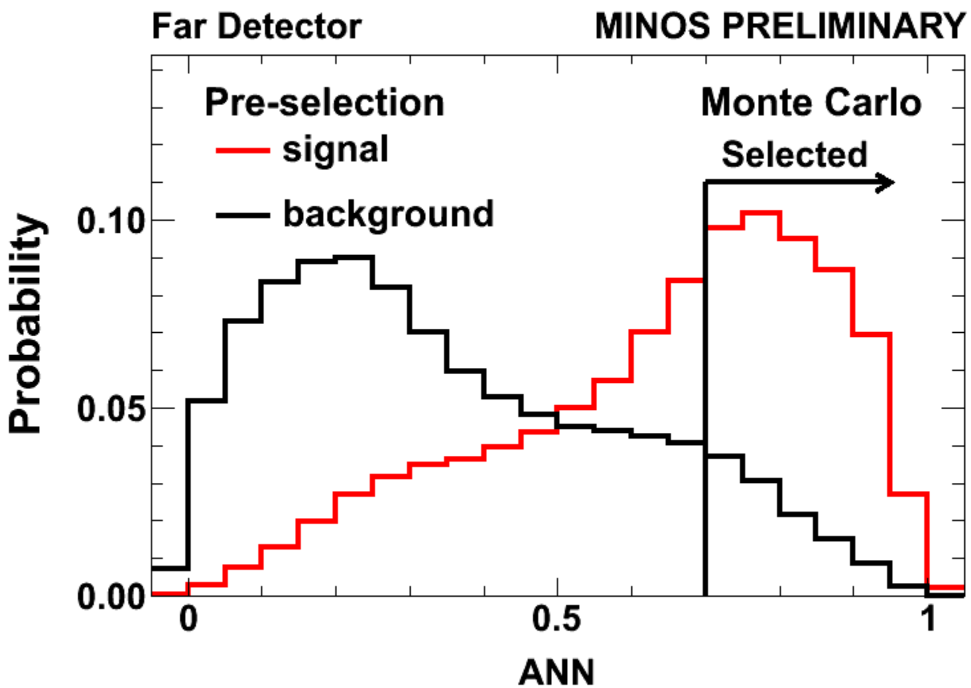


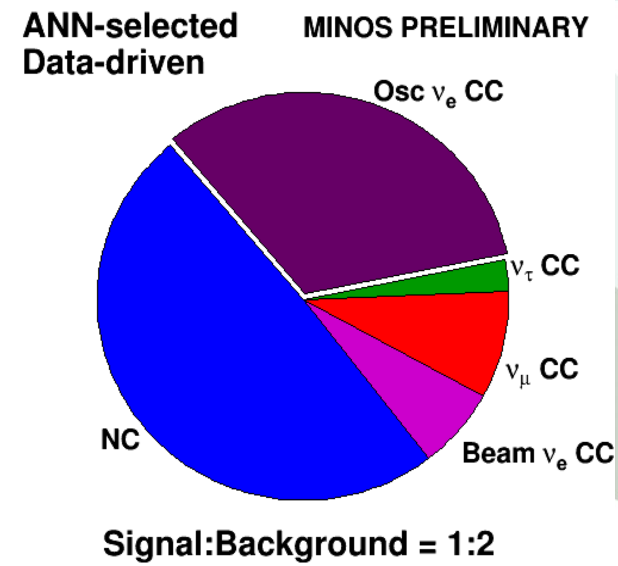
Identifying Signal and Background in the ν_e Analysis

- Main problem for ve study = small expected signal, with large background contamination (mostly Neutral Current events)

Particle Identification for ve Charged Current events: Neural net algorithm, trained on 11 separate variables quantifying event shape and energy profile
- Efficiency of 40% for ve signal events

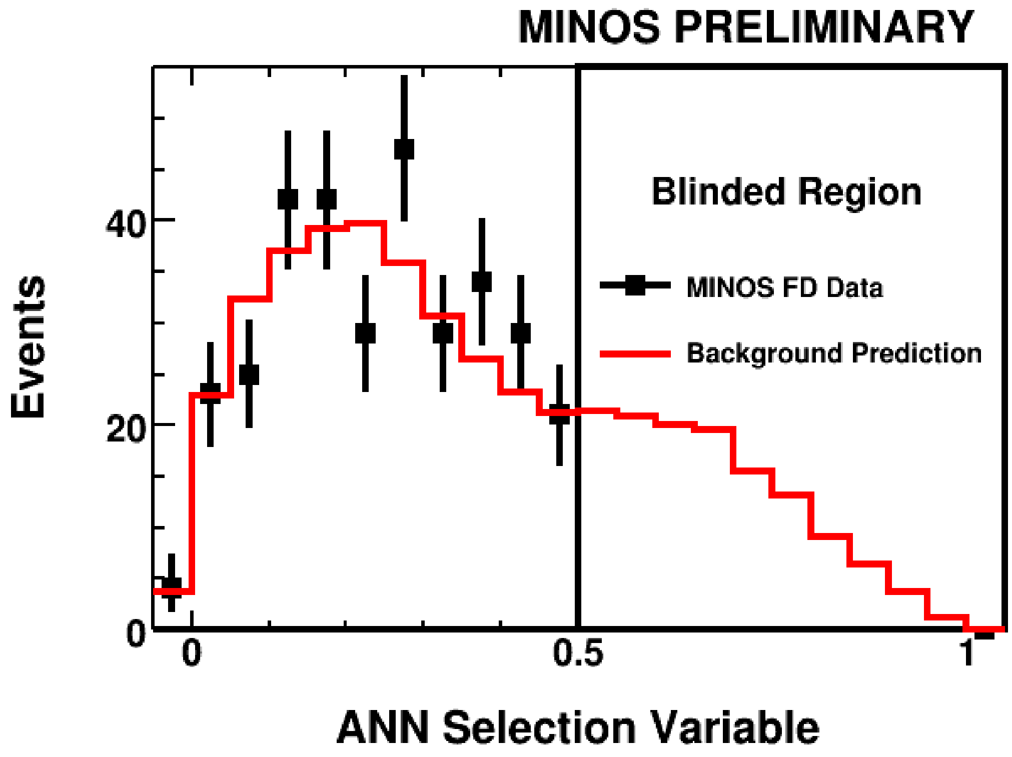
- Apply this cut to the Near Detector and use it to make a **Far Detector background prediction**

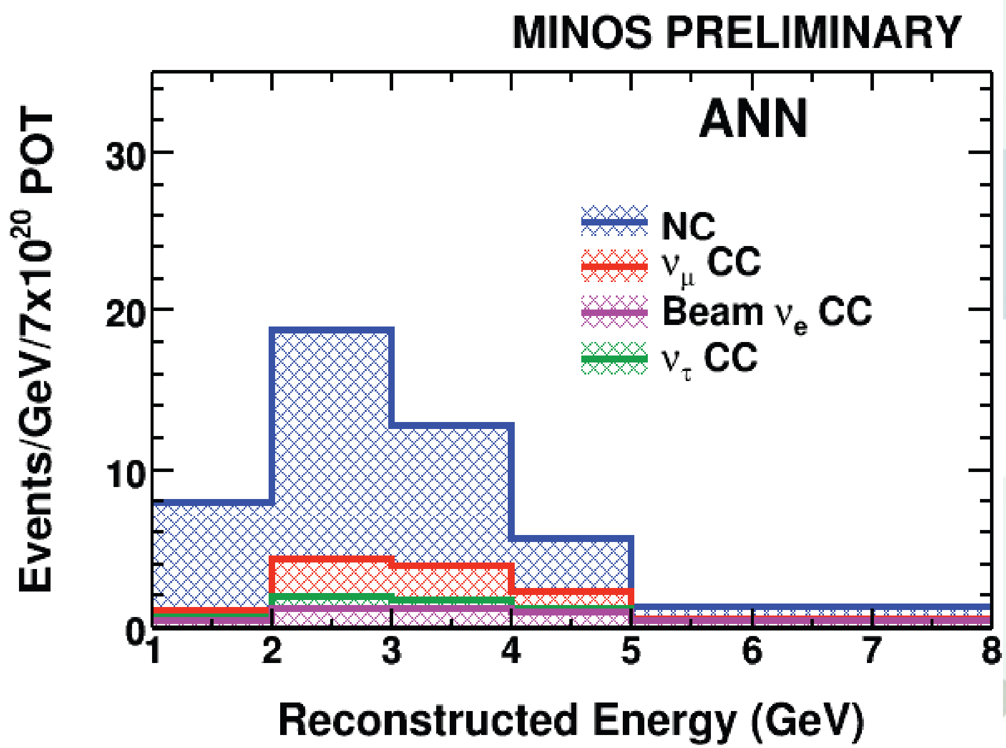




ν_e Analysis

Predicted FD background: **49.1±7(stat)±2.7(sys)**

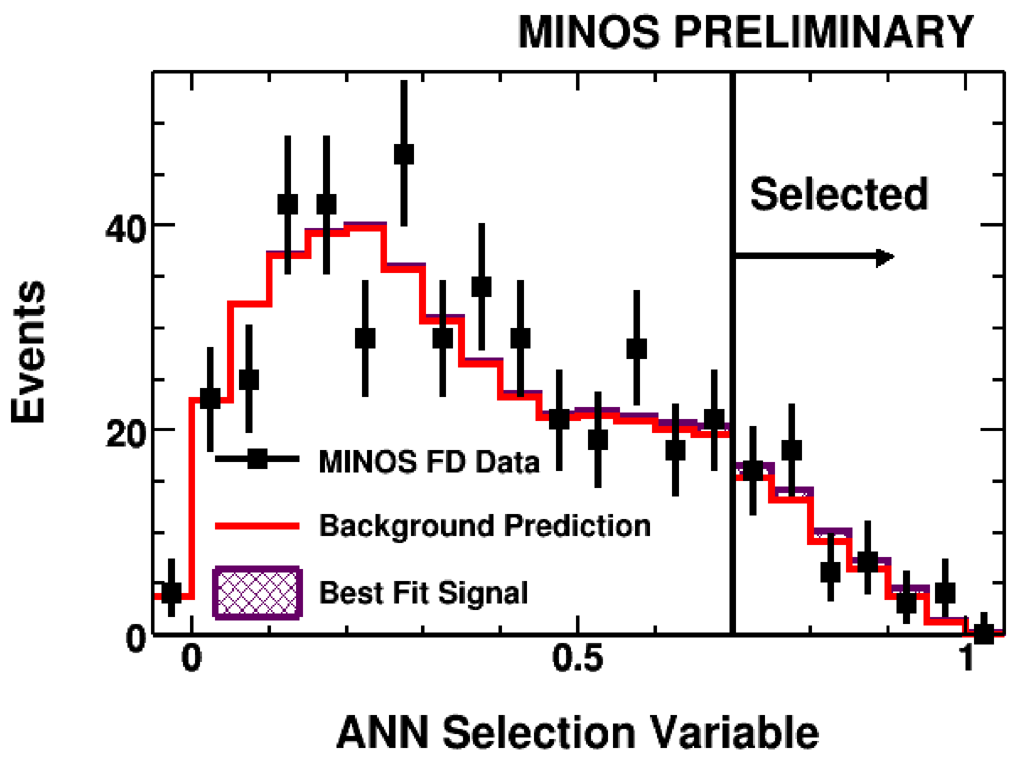


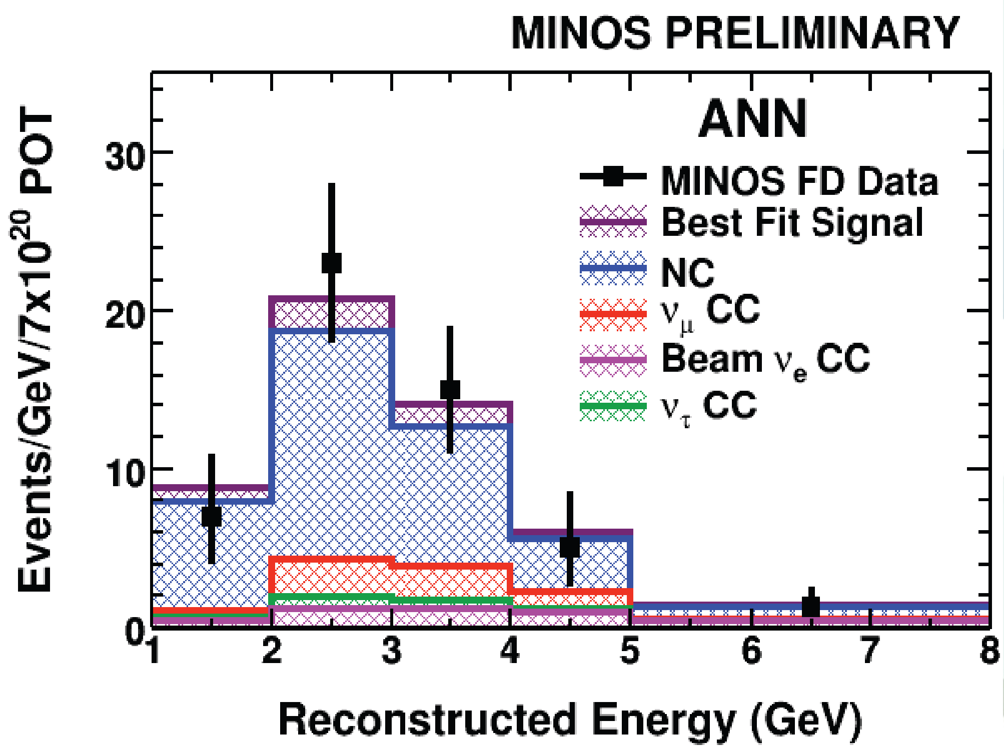


ν_e Analysis

Predicted FD background: **49.1±7(stat)±2.7(sys)**

Observed: **54 (0.7σ excess)**





Results

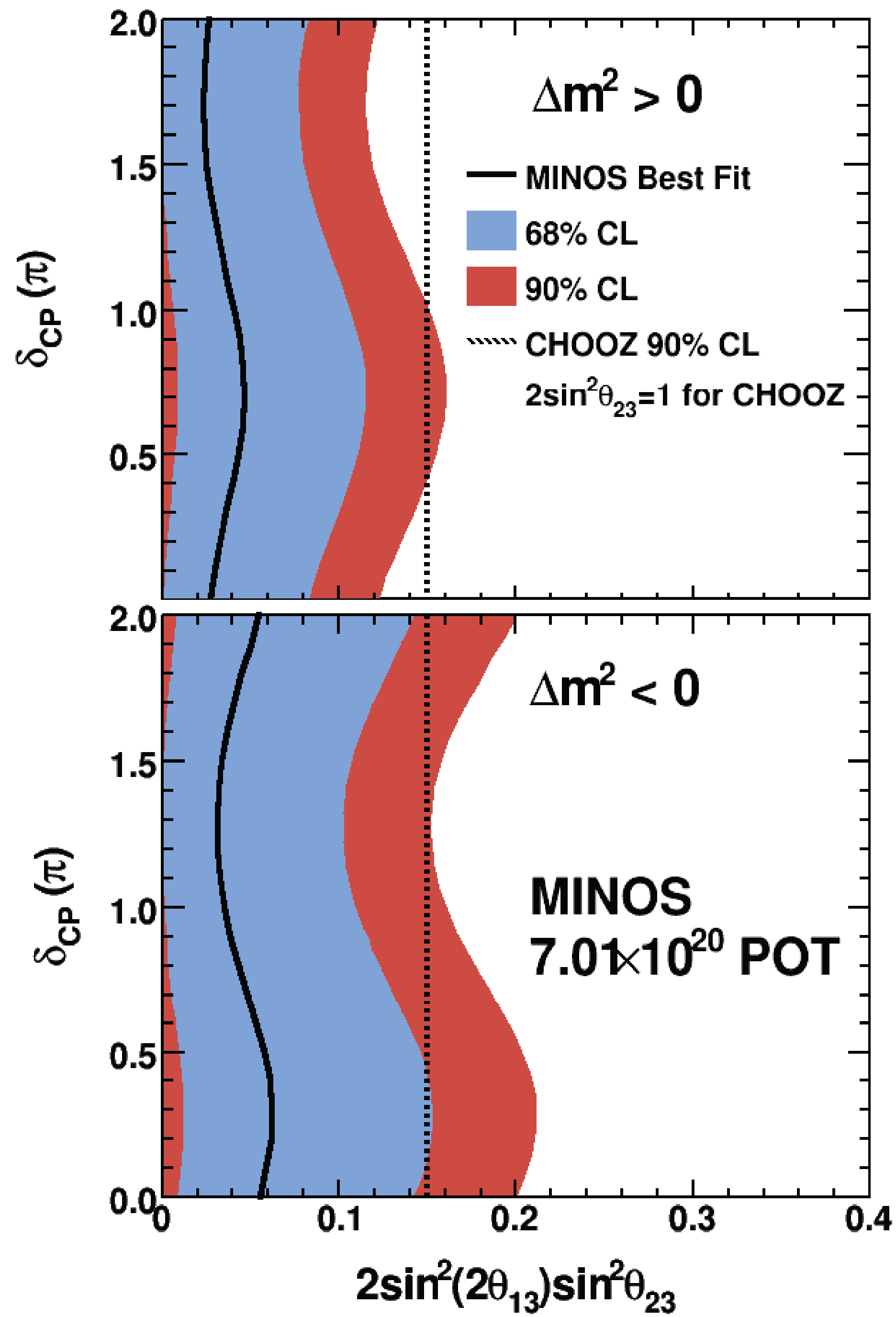
Limits: Assuming $2\sin^2(\theta_{23})=1$, CP violation phase $\delta=0$, and $|\Delta m^2| = 2.43 \times 10^{-3}$:

Normal mass hierarchy: $\sin^2(2\theta_{13})<0.12$

Inverted mass hierarchy: $\sin^2(2\theta_{13})<0.20$

- New analysis with more data and more sensitive analysis techniques will be presented later this year

Paper describing analysis
P. Adamson et al. "New constraints on muon-neutrino to electron-neutrino transitions in MINOS." Phys. Rev. D 82, 051102 (2010). arXiv:1006.0996v1 [hep-ex]



Summary

ν_μ Disappearance:
- New best fit points are consistent with standard neutrino oscillations:

$$|\Delta m^2| = 2.35^{+0.11}_{-0.08} \times 10^{-3}\,\mathrm{eV}^2$$
$$\sin^2(2\theta) > 0.91\ (90\%\ \mathrm{C.L.})$$

Sterile Neutrino Search:
- No significant evidence for reduced neutral current rate or oscillations to sterile neutrinos

$$f_s < 0.22\,(0.40\,\nu_e)\,(90\%\ \mathrm{C.L.})$$

$\bar{\nu}_\mu$ Disappearance:
- Additional data are being taken!

$$|\Delta \bar{m}^2| = 3.36^{+0.45}_{-0.46} \times 10^{-3}\,\mathrm{eV}^2$$
$$\sin^2(2\bar{\theta}) = 0.86 \pm 0.11$$

Nue Appearance:
- Non-significant (0.7 sigma) $\boldsymbol{\nu_e}$ excess seen, with new limit for θ_{13}

Normal mass hierarchy: $\sin^2(2\theta_{13}) < 0.12$

- Planning a new analysis for Spring 2011 with improved analysis and new data

It's been an exciting year for MINOS...

Stay tuned for lots more νs to come!

Backup Slides

Neutrino Oscillations

Neutrinos:

- interact weakly via **flavor eigenstates**:

$\nu_e \quad \nu_\mu \quad \nu_\tau$

- propagate as **mass eigenstates:**

$\nu_1 \quad \nu_2 \quad \nu_3$

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}|\nu_i\rangle \qquad \alpha = (e, \mu, \tau)$$

- Non-zero different masses = neutrino can **change its flavor eigenstate** as it propagates, sliding in and out of phase:

$$\begin{aligned} P(\nu_\alpha \rightarrow \nu_\beta) &= |\langle \nu_\beta | \nu_\alpha(L)\rangle|^2 \\ &= \delta_{\alpha\beta} - 4\sum_{i>j} \Re(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2[1.27\Delta m^2_{ij}L/E] \\ &\quad + 2\sum_{i>j} \Im(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2[2.54\Delta m^2_{ij}L/E] \end{aligned}$$

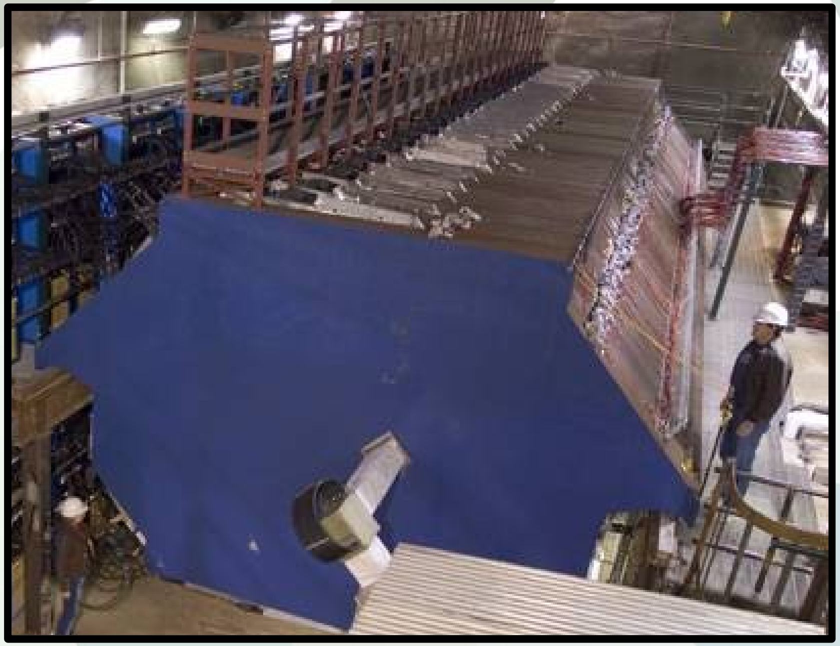
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- For the case of two neutrinos:

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2(2\theta)\sin^2(1.27\Delta m^2 L/E)$$

$$\left(1.27,\ 2.54 \text{ in units of } \frac{\text{GeV}}{\text{eV}^2\text{km}}\right)$$

Near Detector

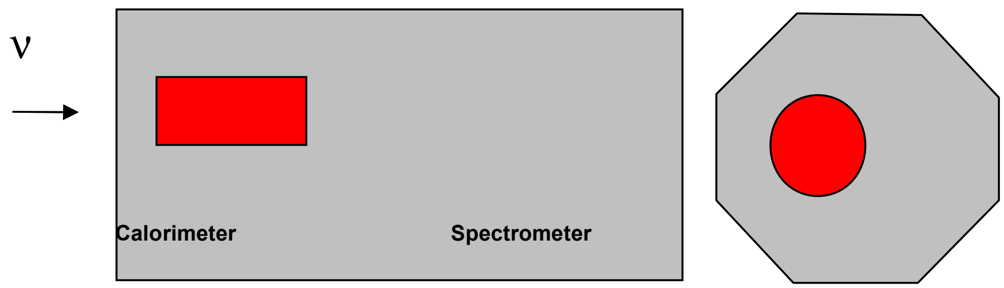


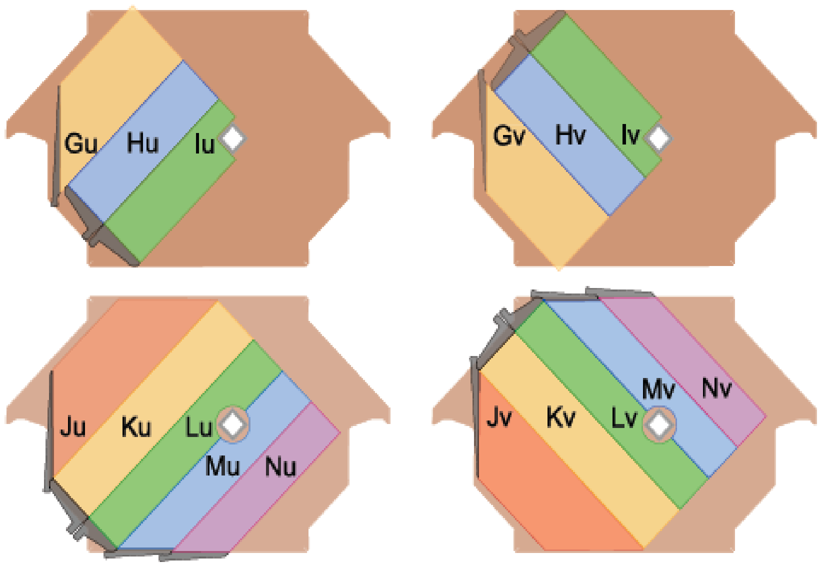
- **Measures beam before oscillations**

- 282 planes, 0.98 ktons total / 0.029 ktons fiducial

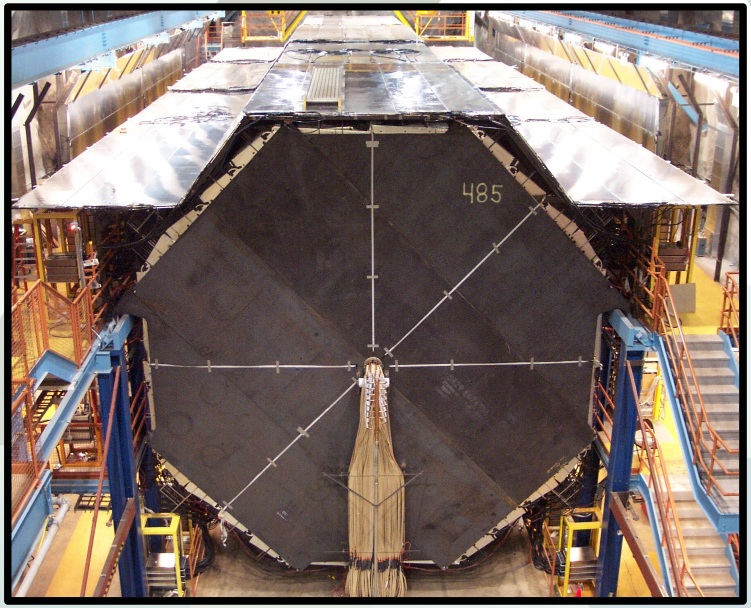
- **geometry:** 3.8x4.5 m

- **LOTS OF NEUTRINOS:** Mean of 3 ν interactions per beam spill (8 or 10 μs), as many 10
  - For a 250kW beam: 10^4 ν/day





Far Detector



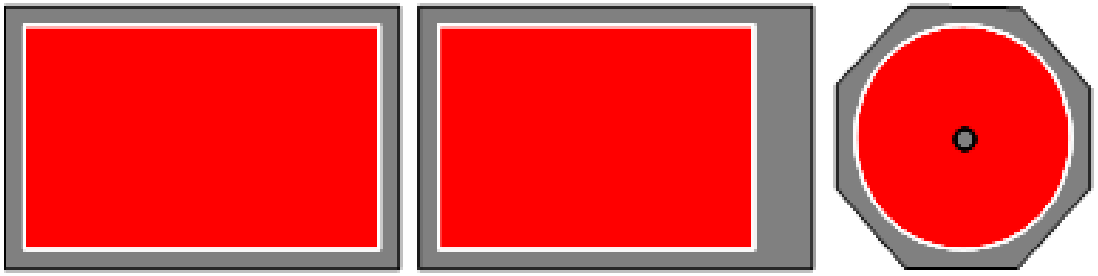
- **Look here to see if neutrinos oscillated!**

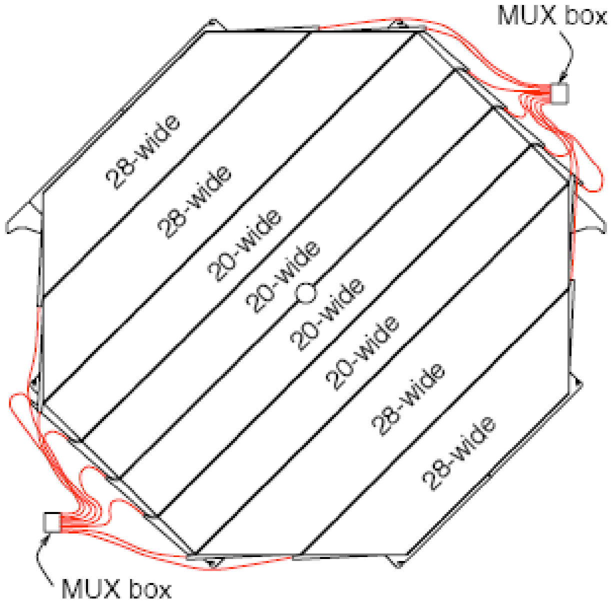
- 486 planes, 5.4 ktons total / 4.0 ktons fiducial

- **geometry:** 31 m long total, in two 15 m sections, each with 192 scintillator strips

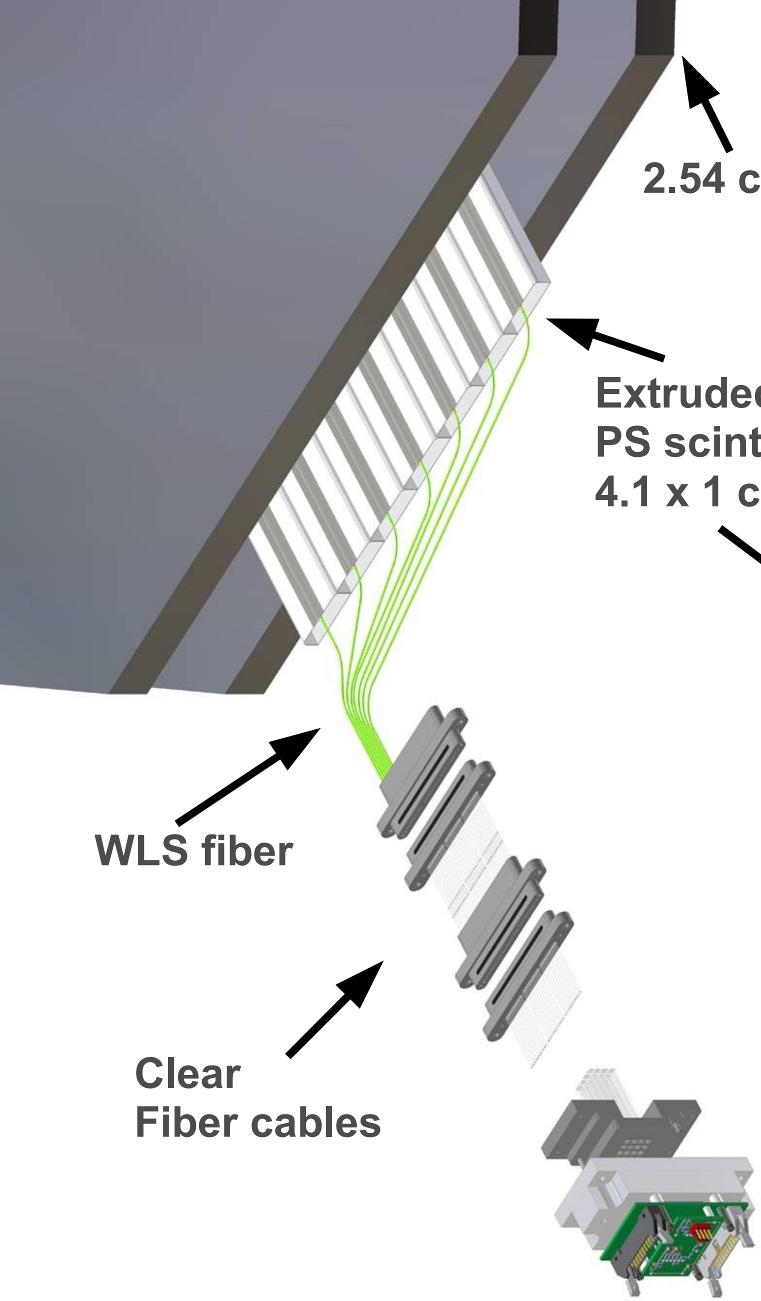
- 700 m underground to reduce cosmic ray background to negligible level

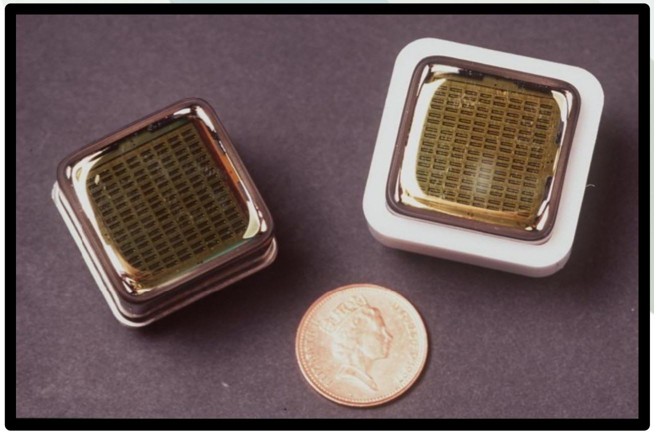
- **MUCH QUIETER:** only a few neutrino interactions per day





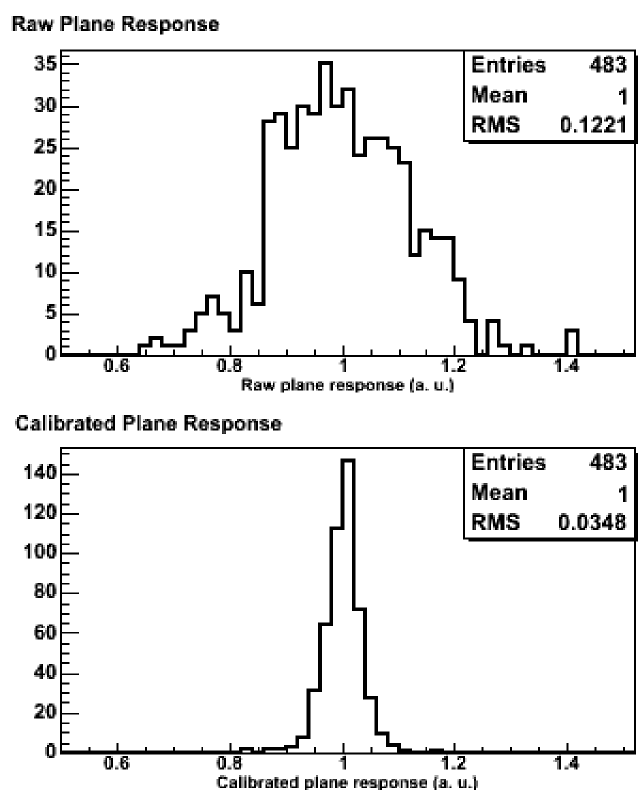
Detector Technology

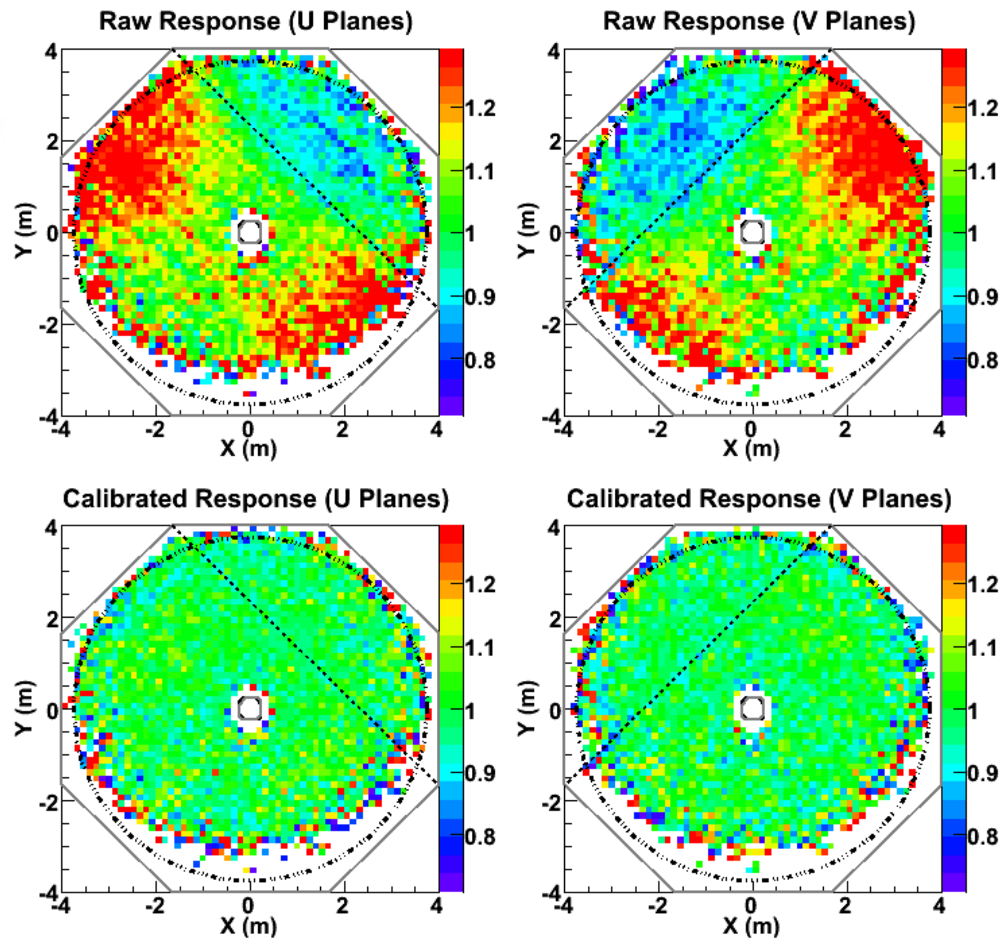




Calibrations

- Calibration of Detector response using:
  - LED-based Light Injection system (PMT gain)
  - Cosmic ray muons (strip to strip and detector to detector)
  - Calibration detector (overall energy scale)
- Energy scale calibration:
  - 1.9% absolute error in ND
  - 1.1% absolute error in FD
  - 1.6% relative





Slide: Alec Habig

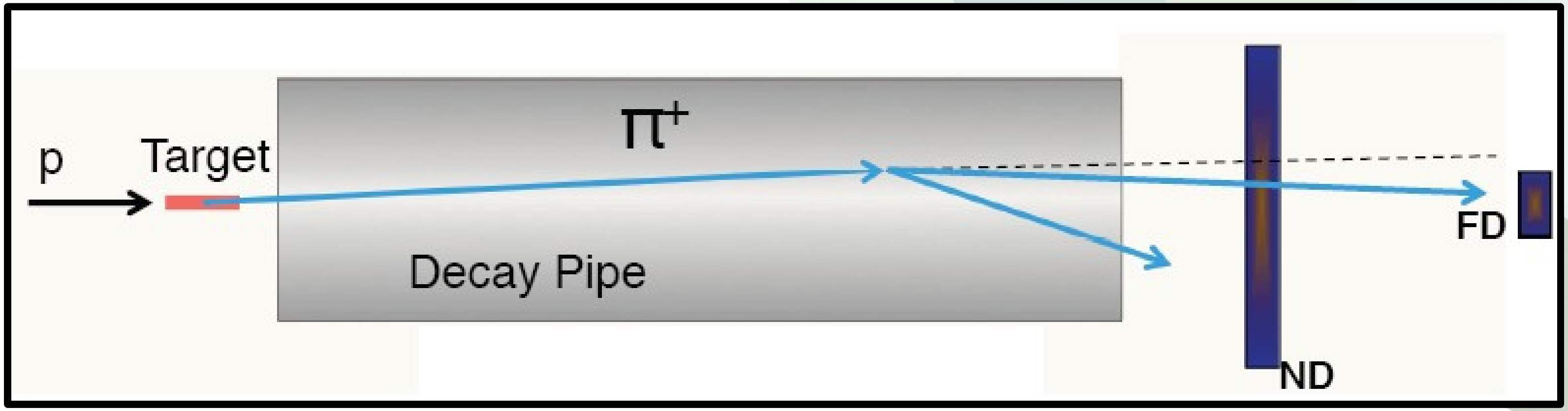
Going from Near to Far

- Far Detector Spectrum is the same as Near Detector Spectrum to first order

- **Beam spectrum:** dependent on **parent energy** and **decay angle**
    - Higher energy hadron will decay further down pipe
    - Near and Far Detectors have different angular distributions:
        Near Detector = distributed source
        Far Detector = point source

- **Monte Carlo** allows us to correct for energy smearing and acceptance

- Use knowledge of **beam geometry** and **pion decay kinematics** to predict the Far Detector spectrum from the measured Near Detector spectrum



$$Flux \propto \frac{1}{L^2}\left(\frac{1}{1+\gamma^2\theta^2}\right)^2$$

$$E_\nu \approx 0.43\frac{E_\pi}{1+\gamma^2\theta_\nu^2}$$

(Image: P. Vahle)

Neutrino Analysis Event Selection

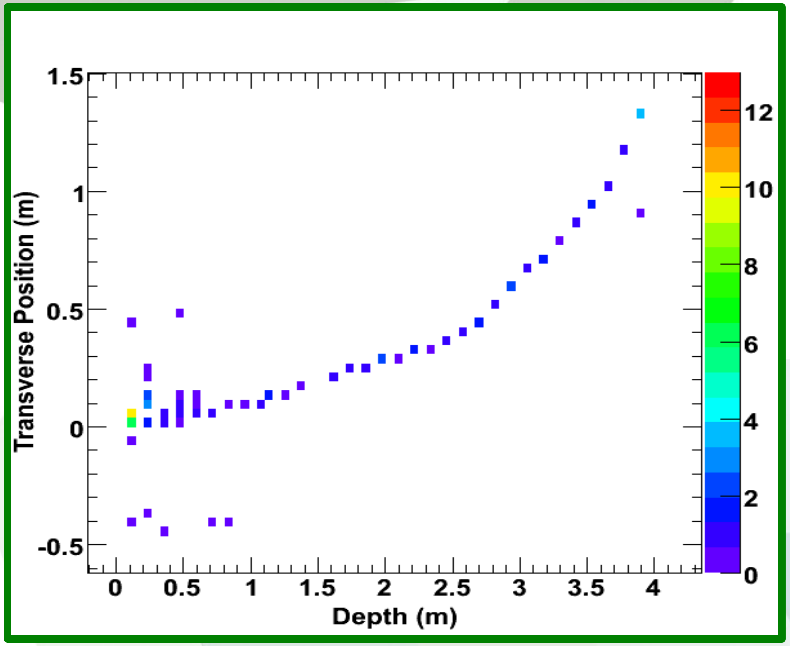
Data Selection Cuts:

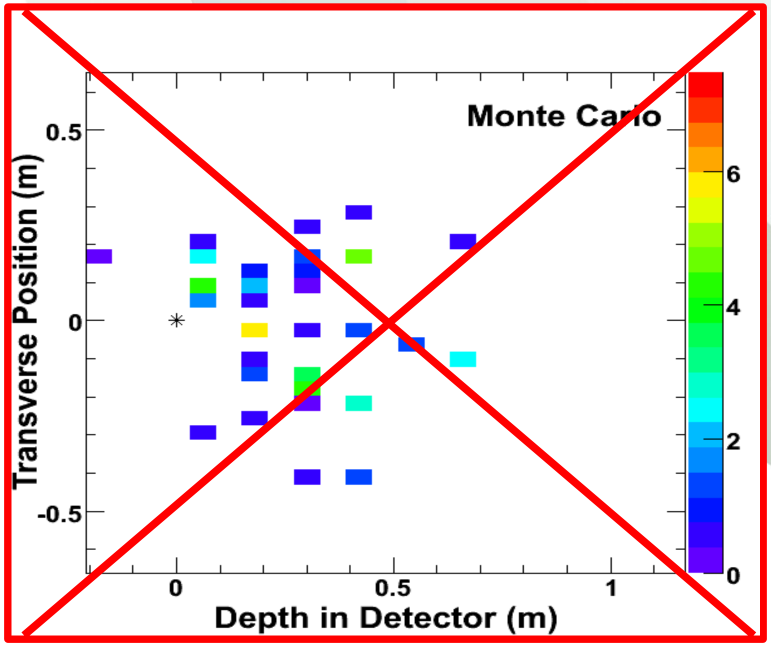
- Data Quality & Fiducial Volume

- Event must have **at least one valid reconstructed track**

- Separate out **positive and negative charge** events

- **Particle ID:** Likelihood-based parameter, separates between NuMu Charged Current and Neutral Current





Making a Far Detector Prediction

- First remove background events (NC)

- Next, must turn the Near Detector spectrum into a Far Detector prediction....

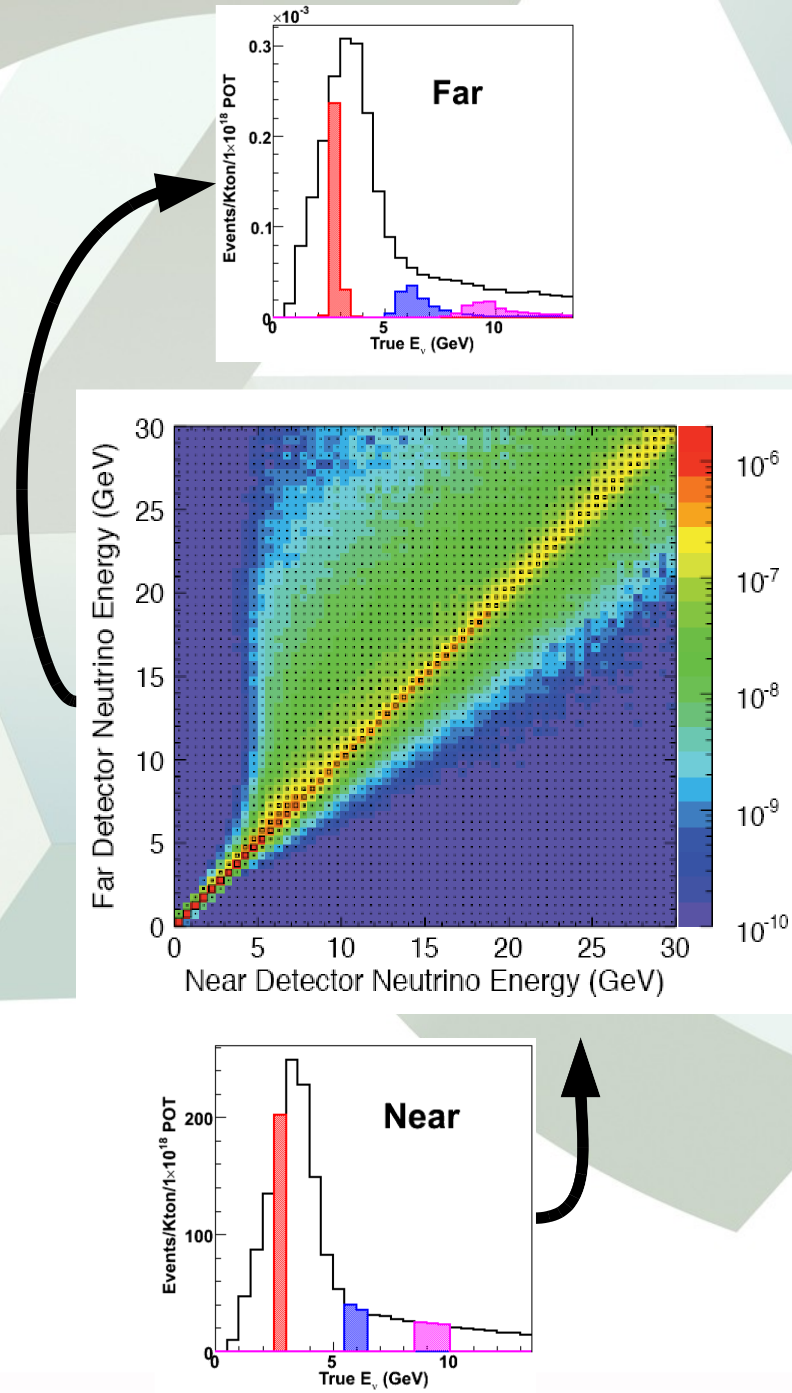
Beam matrix:

- accounts for pion 2-body decay kinematics and geometry

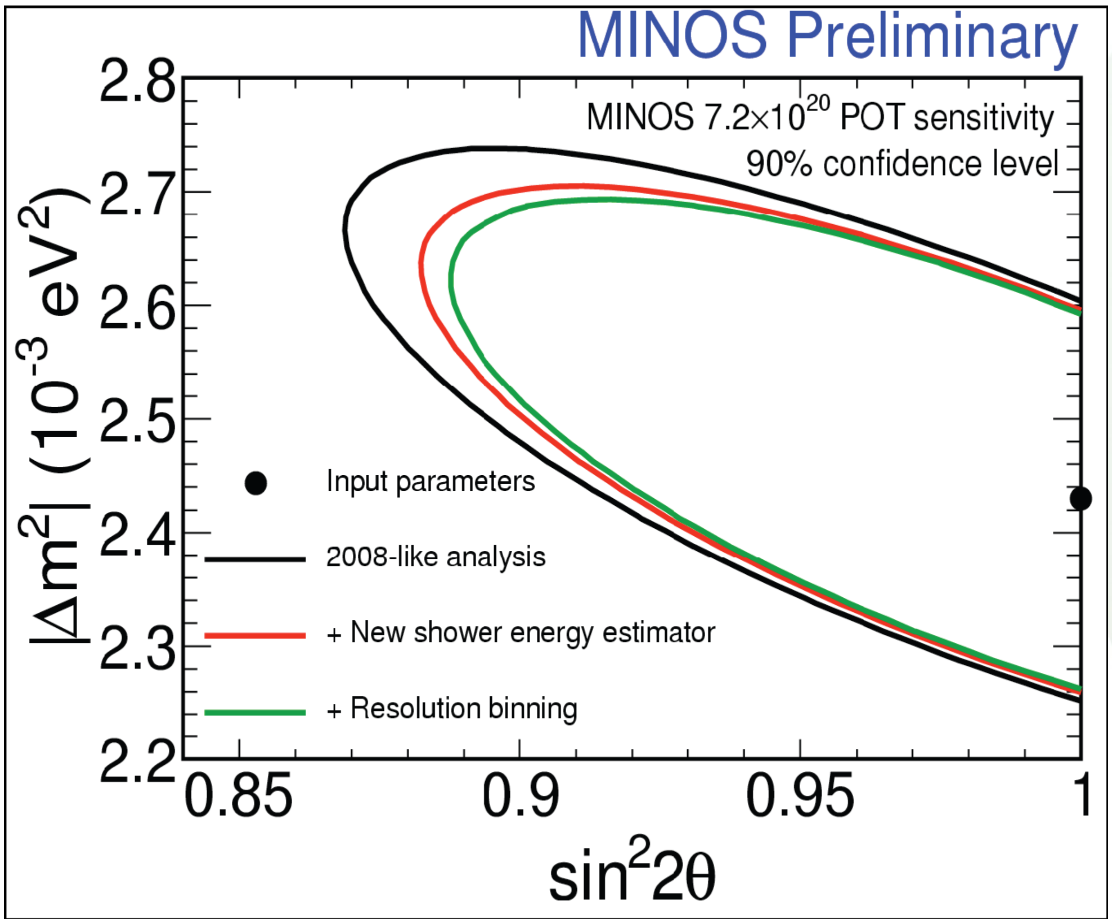
- shown: example of spread of energy bins from ND to FD.

Prediction of FD Spectrum

→ **CONDUCT A BLIND ANALYSIS**



Improvements for 2010



2008 result: arXiv:0806.2237v1 [hep-ex]

Improvements from the 2008 Analysis:

- **More Data** (3.4e20 → 7.2e20 POT!)

- Updated **reconstruction and simulation**

- New **likelihood-based selection**, with higher efficiency

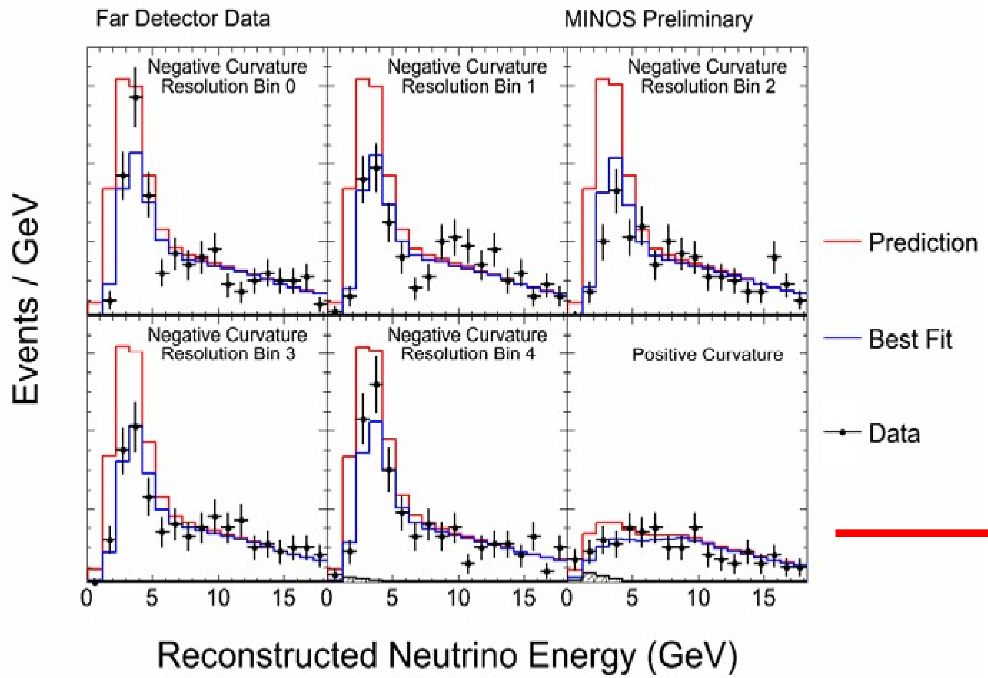
- **No charge sign cut** (recover low energy events)

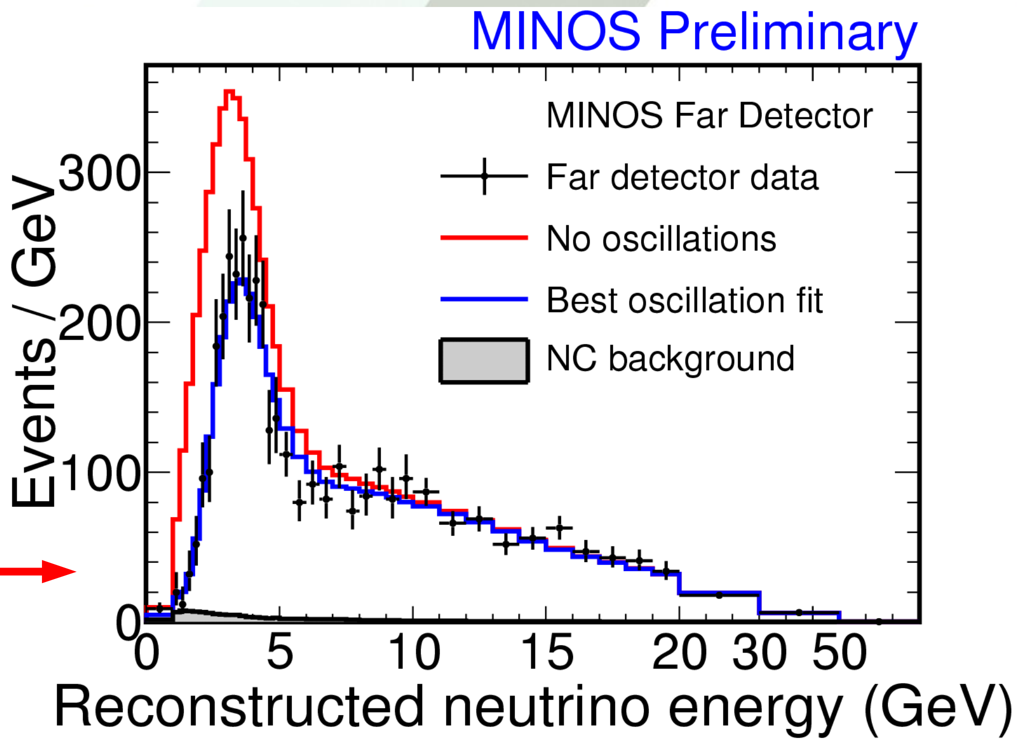
- Improved **shower energy resolution**

- Now fit in bins of **energy resolution**

- Improved systematic uncertainties

What is the Best Fit?





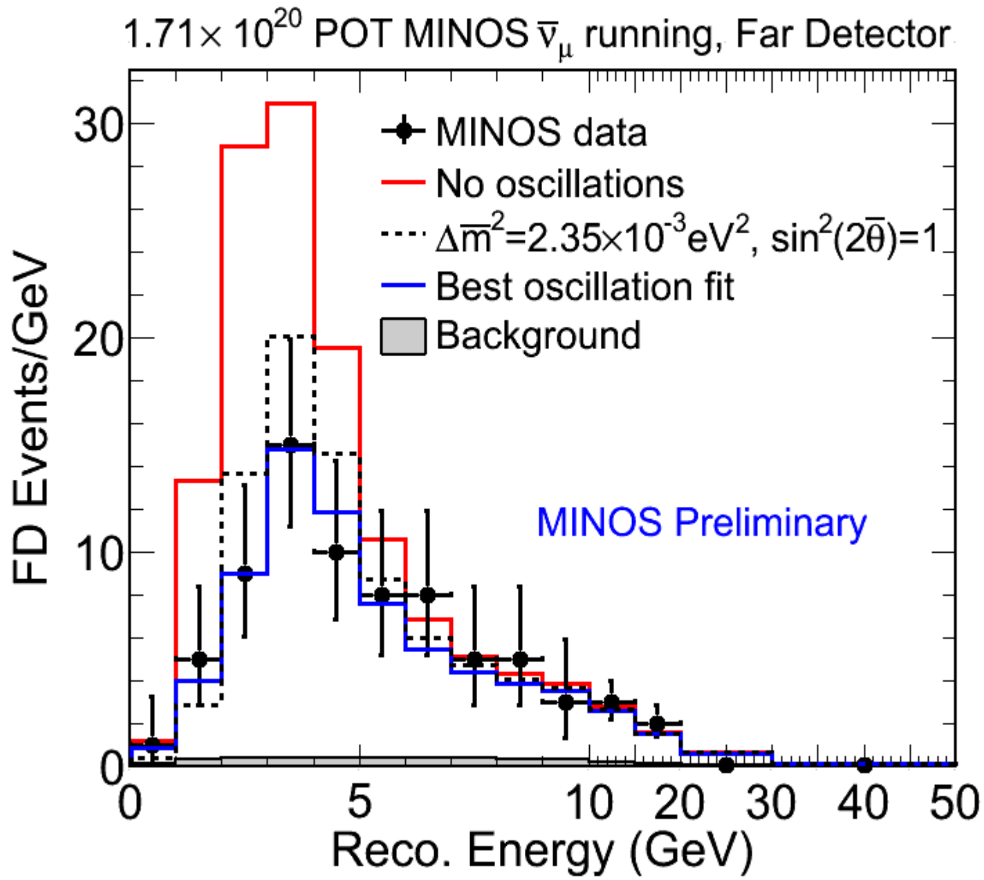
- Split up sample into **five bins by energy resolution** (plus **one wrong-sign bin**)
- this gives more weight to best-resolved events

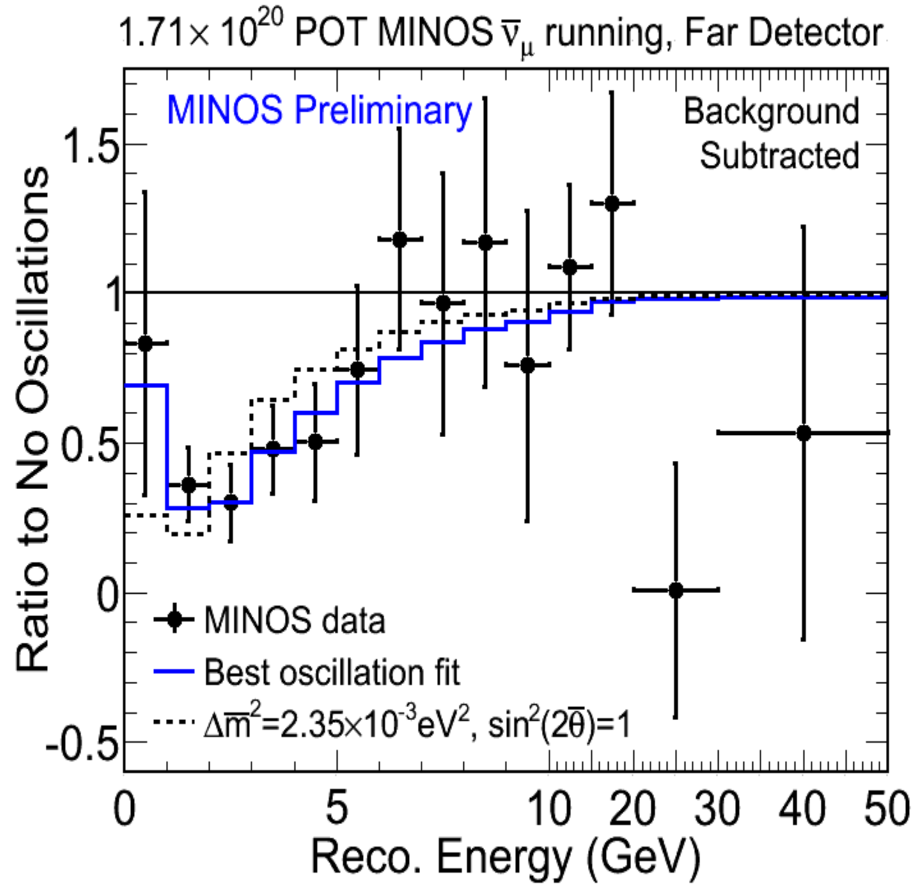
- **Do a simultaneous fit to $\nu_\mu \leftrightarrow \nu_\tau$ oscillation parameters**:

$$\left|\Delta m^2_{32}\right| = 2.35^{+0.11}_{-0.08} \times 10^{-3}\ \text{eV}^2$$

$$\sin^2 2\Theta_{23} = 1.00_{-0.05}$$

Comparison to Neutrinos





$$|\Delta m^2| = 2.35^{+0.11}_{-0.08} \times 10^{-3}\,\mathrm{eV}^2 \qquad |\Delta \overline{m}^2| = 3.36^{+0.45}_{-0.40} \times 10^{-3}\,\mathrm{eV}^2$$

$$\sin^2(2\theta) > 0.91\ (90\%\ \mathrm{C.L.}) \qquad \sin^2(2\overline{\theta}) = 0.86 \pm 0.11$$

Selecting an NC Sample

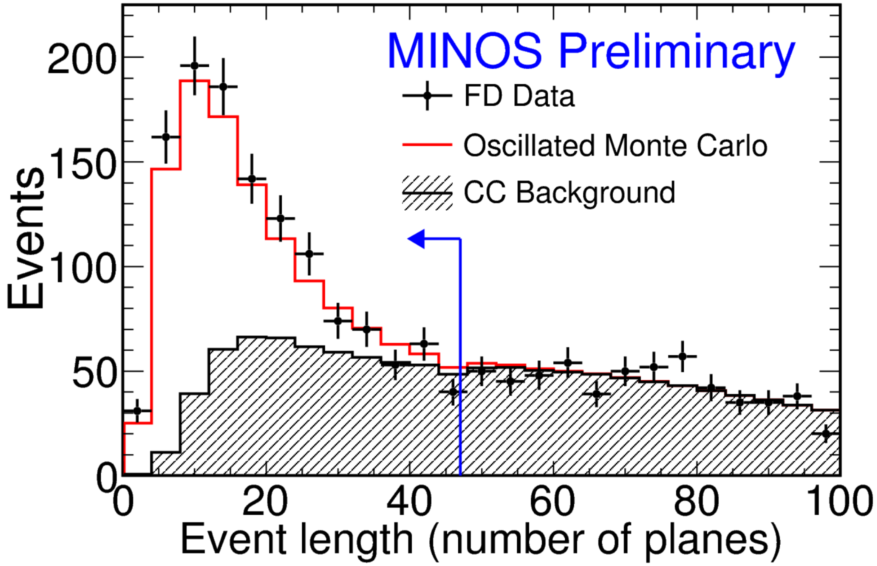
Analysis:

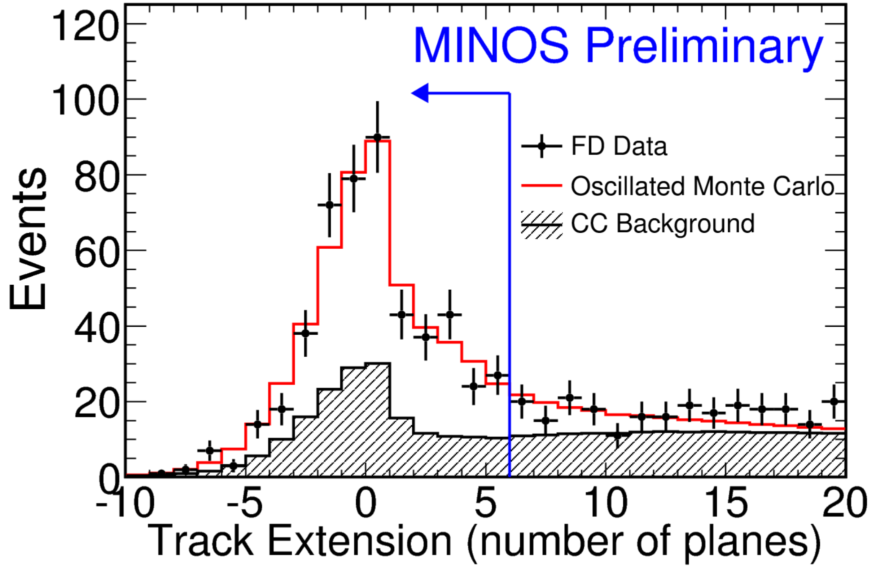
- ND Data Quality cuts remove poorly reconstructed events

-ND and FD cuts:

- <47 event planes
- track must not extend more than 6 planes from shower

- Extrapolate with Far to Near spectrum ratio for prediction





Making a ν_e Selection

EM Showers in MINOS	Detector Parameters
Radiation length in steel: 1.76 cm	Steel thickness: 2.54 cm
Molière radius: 3.7 cm	Strip width: 4.1 cm

- The MINOS detector is not optimized for studying electron neutrino appearance

Signal: ν_e Charged Current events

Background:

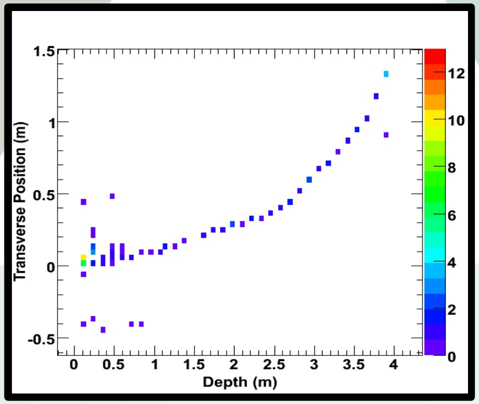
Neutral Current: hadronic shower easily mistaken for EM shower

- decay of a π^0 can make NC look particularly like a ν_e CC event

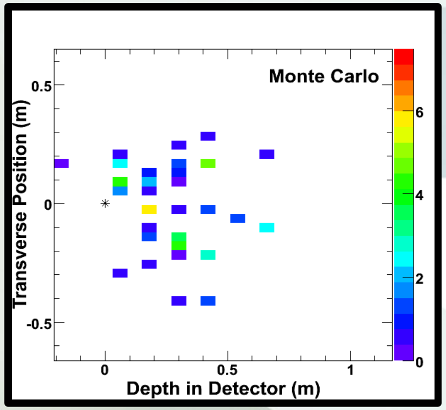
ν_μ CC: mostly easily removed by long track, but some events with short tracks are harder to eliminate

ν_e CC: must account for 1.3% contamination by non-signal beam ν_e CC events

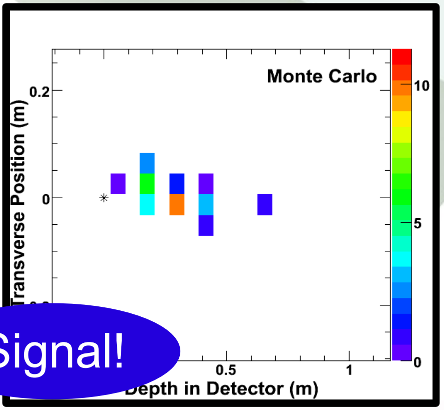
ν_μ CC



NC



ν_e CC



Signal!

Making a Far Detector Prediction

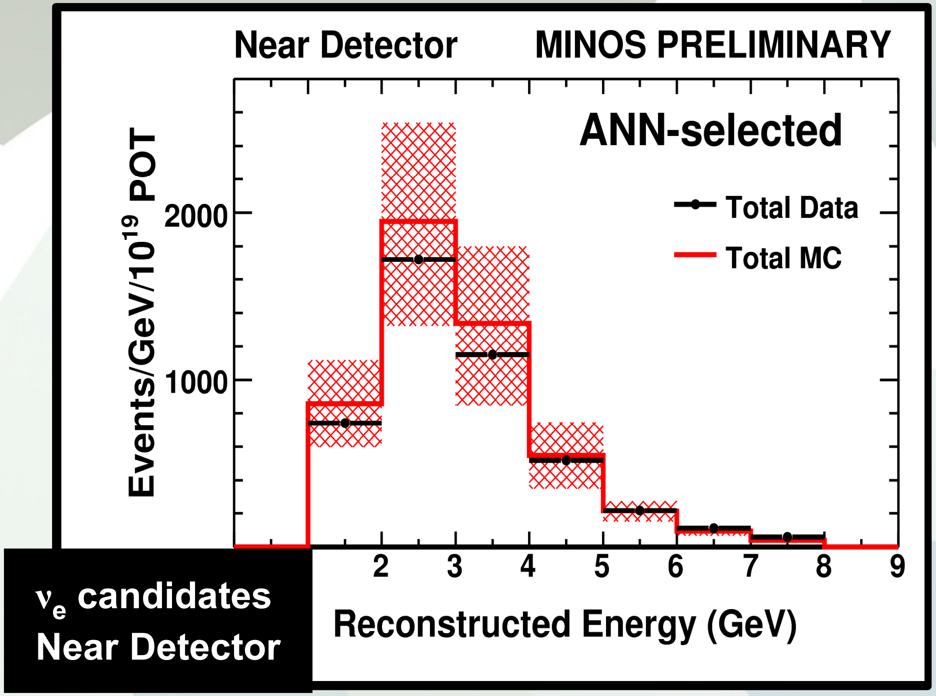
- How do we turn a Near Detector rate into a Far Detector prediction?

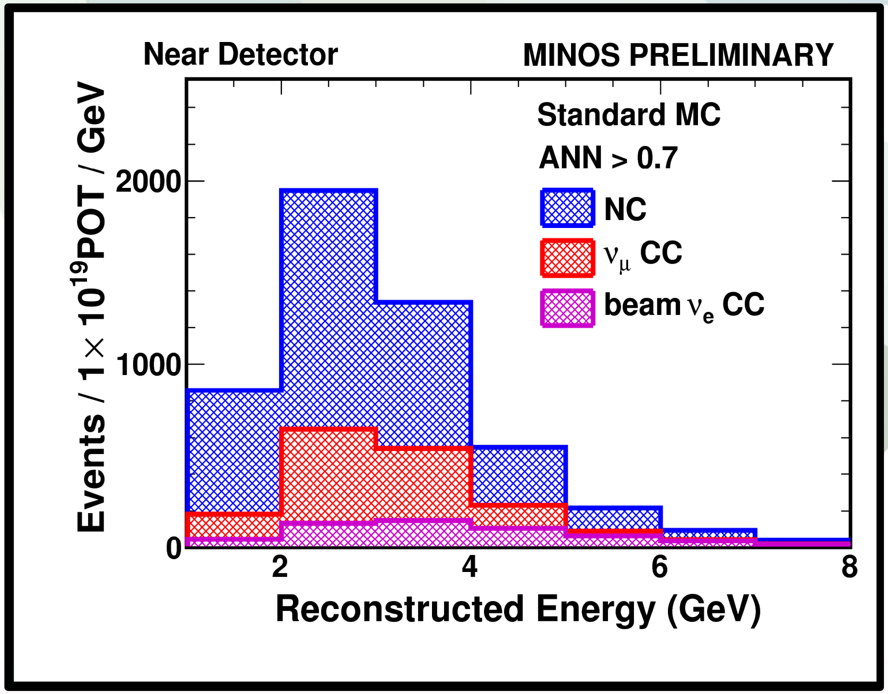
- Major Near/Far differences (beam flux, fiducial volume) are easy to correct for

- However, the separate Near Detector background components extrapolate differently to the Far Detector
  - $\nu_\mu \rightarrow \nu_x$ oscillation.

- Could use Monte Carlo to separate components, but in the Near Detector, we see **Data/MC disagreements of up to 15%**
  - Red error bands in top plot are systematic uncertainties in MC
  - most of this due to modeling of hadronic production

- We cannot rely on the MC to give us our background decomposition





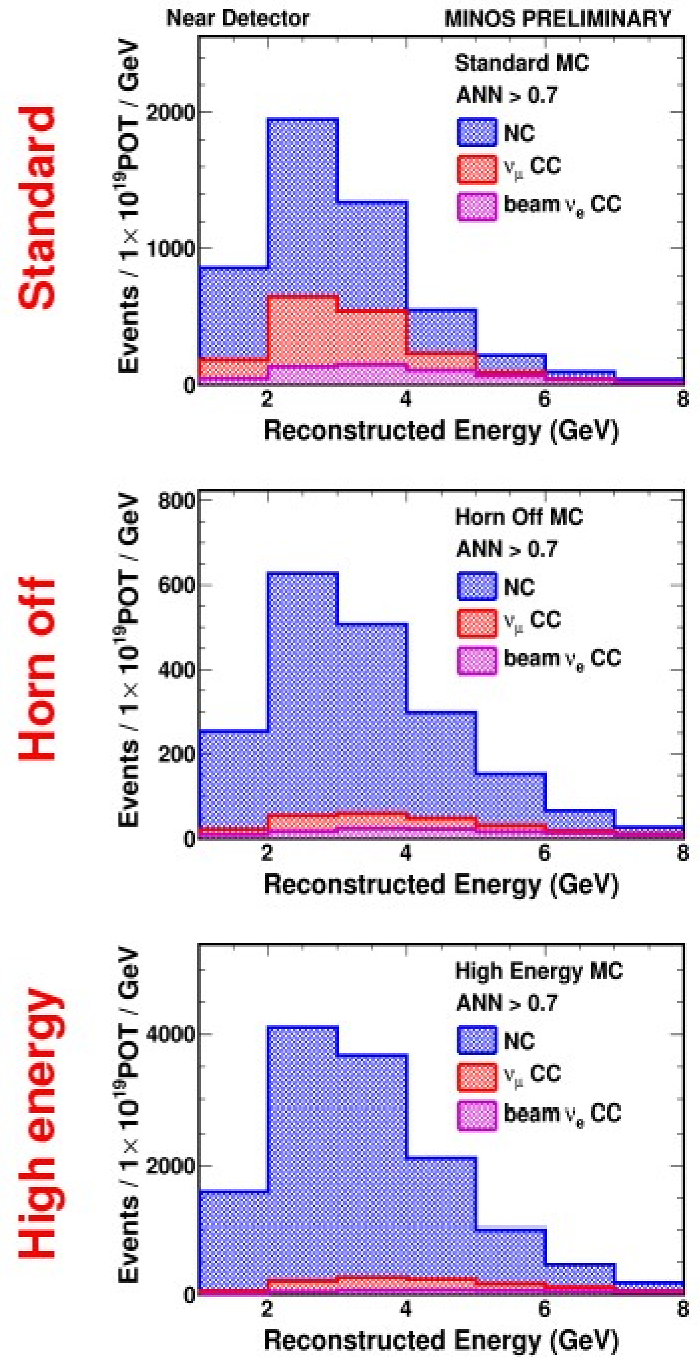
Making a Far Detector Prediction

Method:
- Adjust the NUMI beamline magnetic focusing horn and/or the position of the hadron production target to create different beam energy configurations.

1) Standard Beam: NUMI hadrons focused to create a low-energy peak at ~3 GeV.

2) Horn Off Beam: Horn is turned off so hadrons no longer focused → drastically reduces the selection of ν_μ CCs.

3) High Energy Beam: Target moved upstream from the horn, focusing higher energy pions
  -beam has a ~9 GeV peak, with similar reduction in selection of ν_μ CC events.



Background Decomposition

Near Detector Background Decomposition:

For each configuration, in the Near Detector, we have:

- **A)** the measured overall background **(Data)**
- **B)** the relative rates of each background type between configurations **(Monte Carlo)**
- **- Linear System: 3 beam configurations, 3 background components (with injected ν_e MC constraint)**
- → **Solve to get the background decomposition**

$$N^{Std} = N_{NC} + N_{\nu_\mu CC} + N_{\nu_e CC}$$

$$N^{Off} = R_{NC}^{Off/Std} N_{NC} + R_{\nu_\mu CC}^{Off/Std} N_{\nu_\mu CC} + R_{\nu_e CC}^{Off/Std} N_{\nu_e CC}$$

$$N^{HE} = R_{NC}^{HE/Std} N_{NC} + R_{\nu_\mu CC}^{HE/Std} N_{\nu_\mu CC} + R_{\nu_e CC}^{HE/Std} N_{\nu_e CC}$$

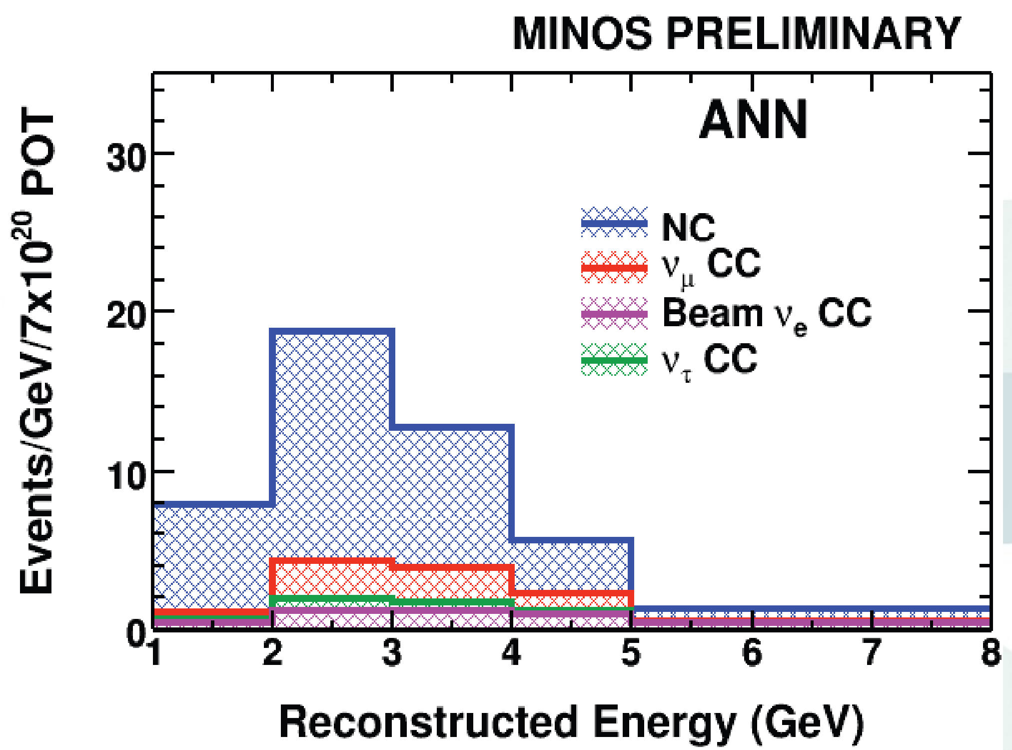
(in bins of energy)

Extrapolation

- Apply this selection to the Near Detector Data

- Adjust NuMI beamline to separate this background into its individual components.

- Can then predict background contamination at the Far Detector



Predicting the Far Detector Background:

- Extrapolate each component to the **Far Detector** in bins of energy
    - α = background component

$$Far_{\alpha}^{\text{Predicted}}(E_i) = Near_{\alpha}^{Data}(E_i)\frac{Far_{\alpha}^{MC}(E_i)}{Near_{\alpha}^{MC}(E_i)}$$

Nue Appearance Systematic Error

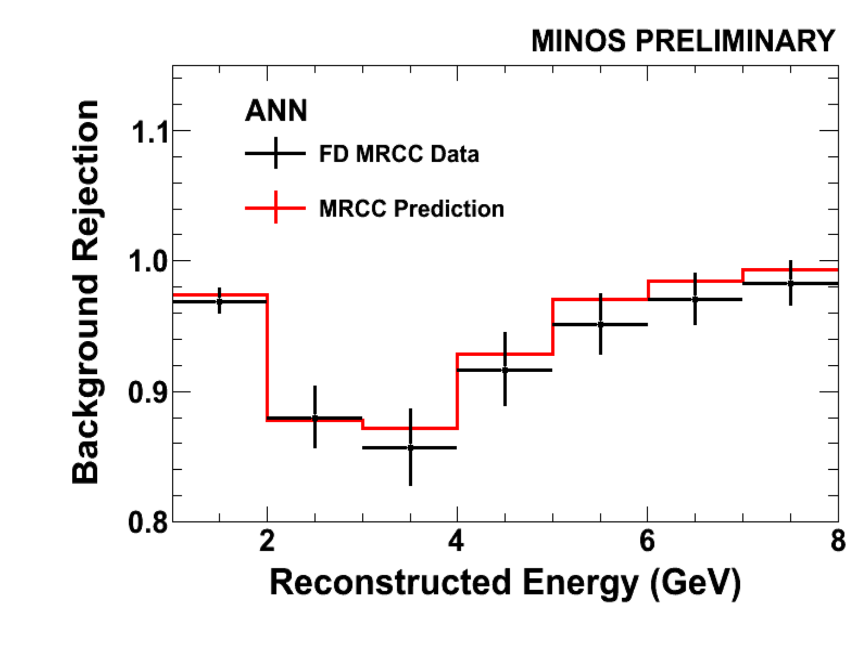
Source of Uncertainty	Effect on Background Prediction
ND Decomposition	$\pm 2.8\%$
Calibration	$+2.8\%, -2.3\%$
Far/Near Normalization	$\pm 2.4\%$
Hadronization Model	$\pm 2.3\%$
ν_τ CC component	$\pm 1.7\%$
Intranuclear Model	$+0.9\%, -1.0\%$
Beam Model	$\pm 0.5\%$
Crosstalk	$\pm 0.4\%$
Cross Section	$\pm 0.1\%$
Total Background Systematic	**$+5.6\%, -5.3\%$**

Total Statistical Uncertainty: ~14%

Blind Analysis Double Checks

1) Muon Removed Data:

- Sample of "hadronic showers" made by removing tracks from numu CC events
- Is our prediction of background rejection consistent wit the data?
- **Looks good**



2) Anti-PID Selection:

- Reverse cut: **ANN < 0.50**
- Does the analysis chain (background prediction and extrapolation) work?
- Predict 314 +/- 18 (stat) for $\theta_{13}=0$
- Observe 327
- **Looks good**