Search for flavor changing non-standard interactions with the MINOS Experiment

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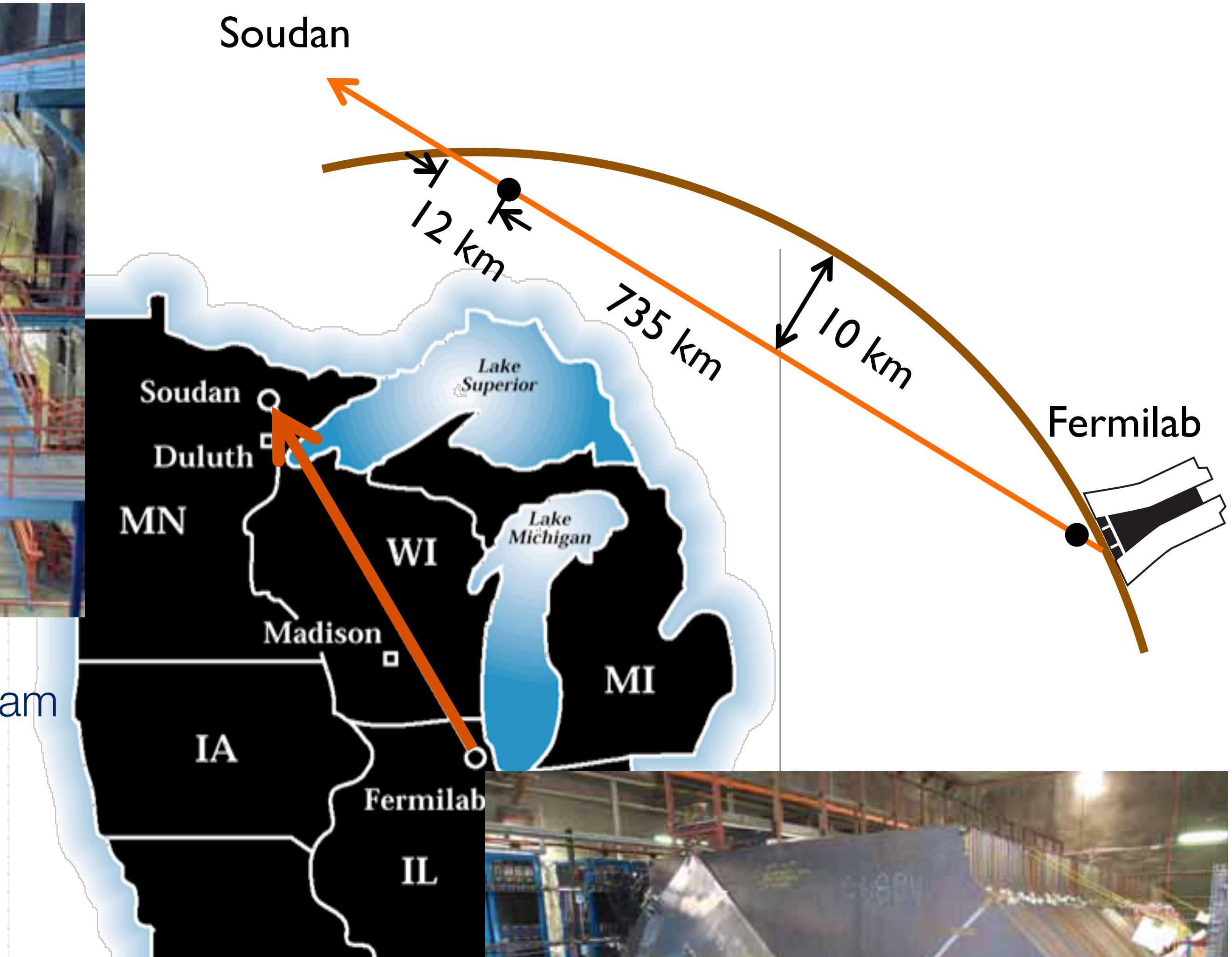
University of Pittsburgh

Tuesday, August 9, 2011

The MINOS Experiment



- **NuMI** high-intensity neutrino beam
- **Near Detector** at Fermilab
- **Far Detector** at Soudan, MN
- Look for disappearance between detectors to measure oscillations
- Magnetized detectors, ~1.3T

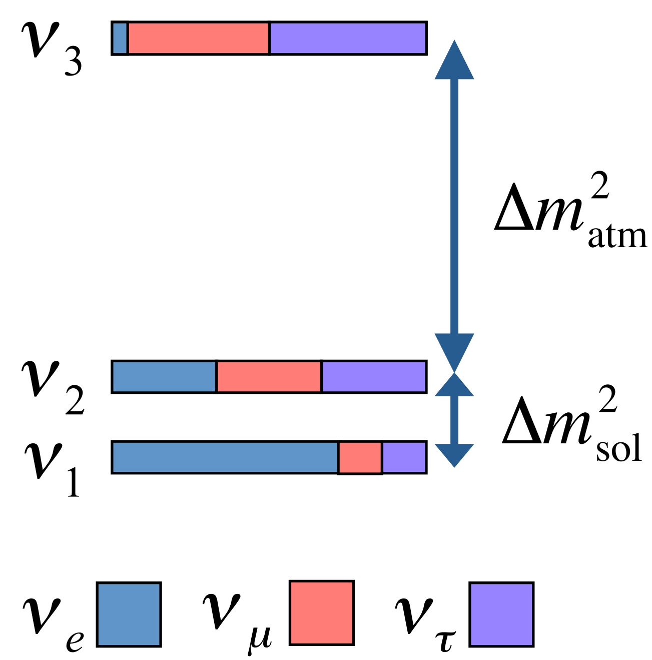
Neutrino Oscillations

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar, Reactor}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}}_{\text{Mixed Sector}} \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{Atmospheric, Accelerator}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- With three flavors there are two independent mass splittings
- MINOS is sensitive to the larger of these

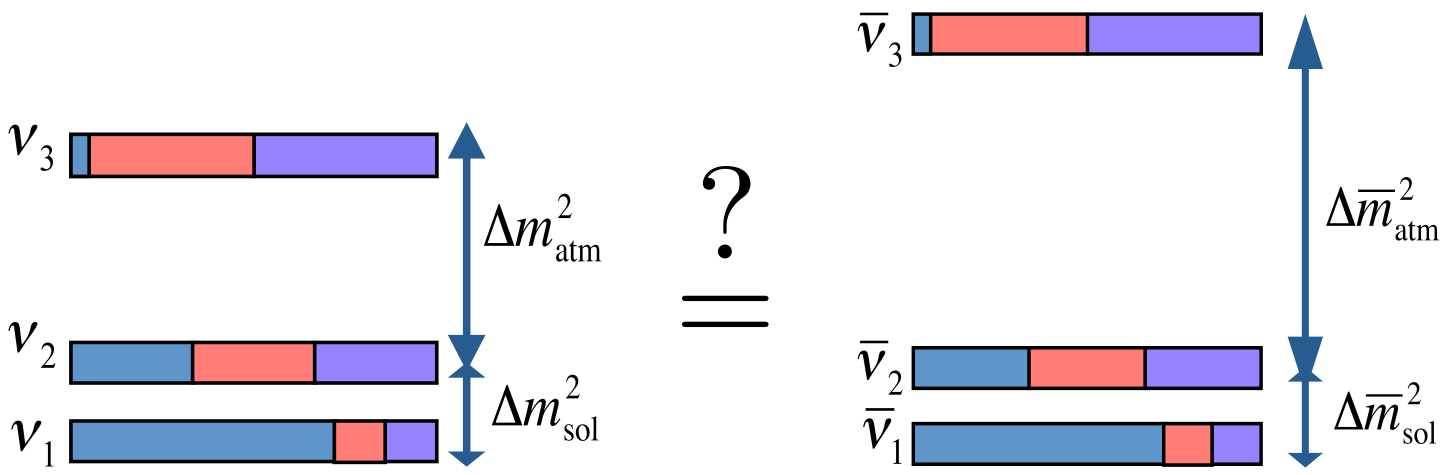
$$\Delta m^2_{\text{sol}} \approx \Delta m^2_{21} \approx 8.0 \times 10^{-5} \text{eV}^2$$

$$\Delta m^2_{\text{atm}} \approx \Delta m^2_{32} \approx 2.3 \times 10^{-3} \text{eV}^2$$



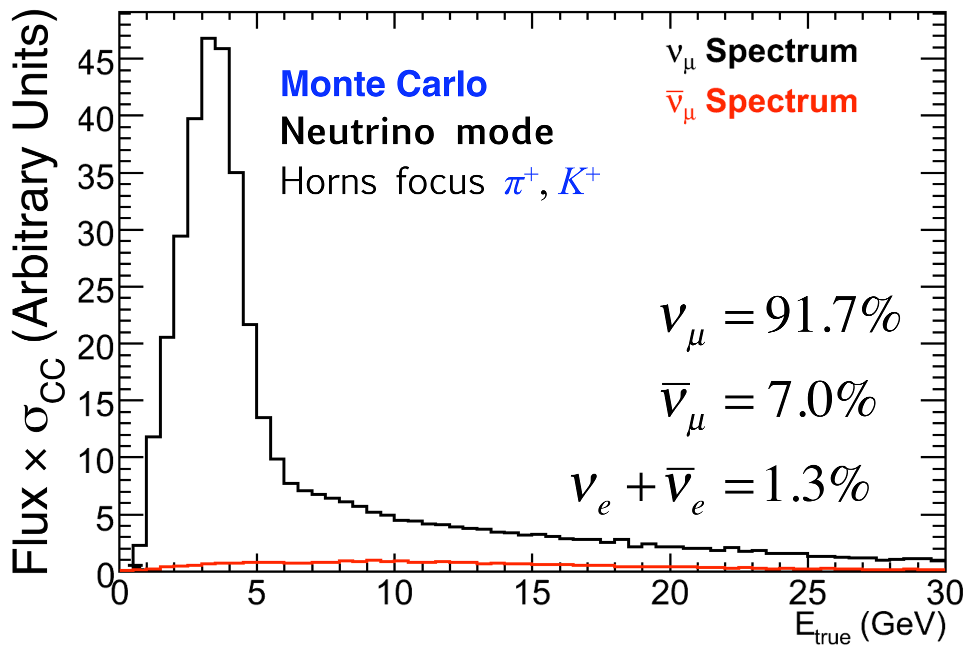
Neutrino and Antineutrino Disappearance

- **Do neutrinos and antineutrinos oscillate in the same way?**

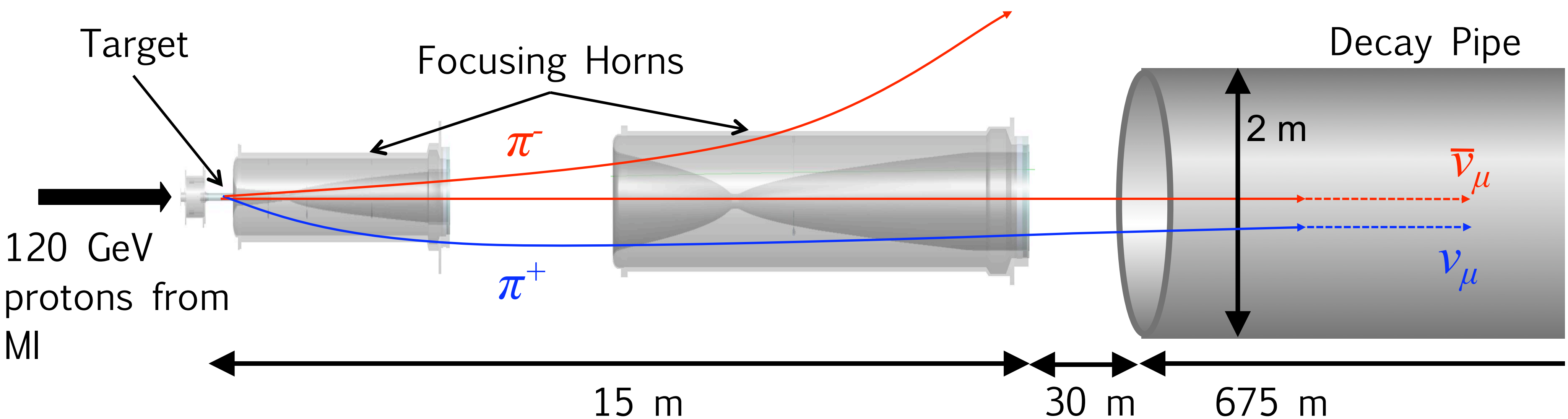


- Magnetized MINOS detectors can distiguish charge of muon: unique among oscillation experiments.
- A significant difference between effective mass splittings implies physics beyond the Standard Model, e.g. non-standard interactions.
- NuMI can be configured to generate a neutrino or an antineutrino beam.

NuMI Beam

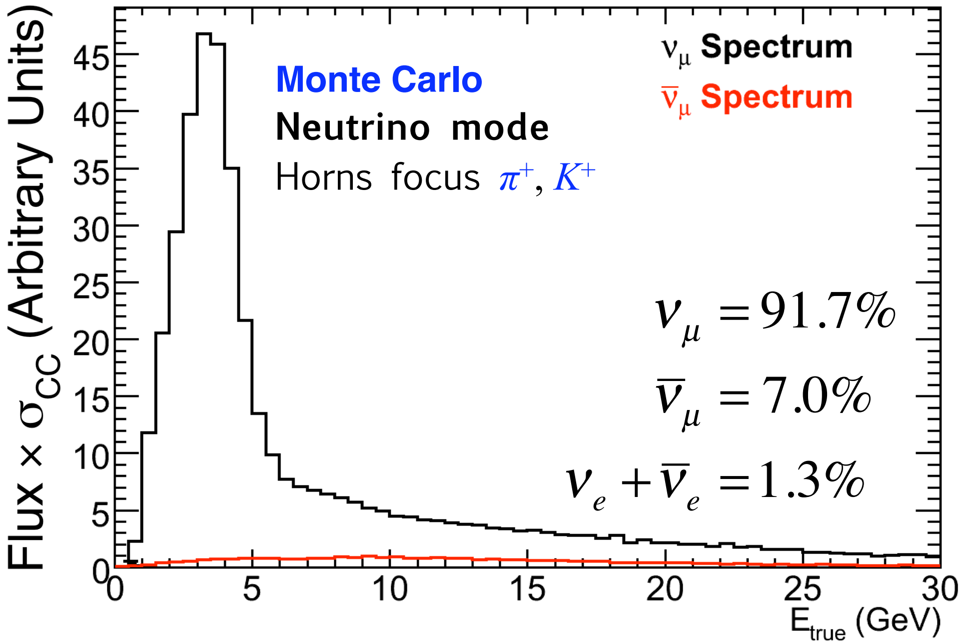


Monte Carlo
Neutrino mode
Horns focus π^+, K^+
ν_μ Spectrum
$\bar{\nu}_\mu$ Spectrum
$\nu_\mu = 91.7\%$
$\bar{\nu}_\mu = 7.0\%$
$\nu_e + \bar{\nu}_e = 1.3\%$
Flux × σ_{CC} (Arbitrary Units)
E_{true} (GeV)



Target
Focusing Horns
Decay Pipe
120 GeV protons from MI
π^-
π^+
2 m
$\bar{\nu}_\mu$
ν_μ
15 m
30 m
675 m

NuMI Beam



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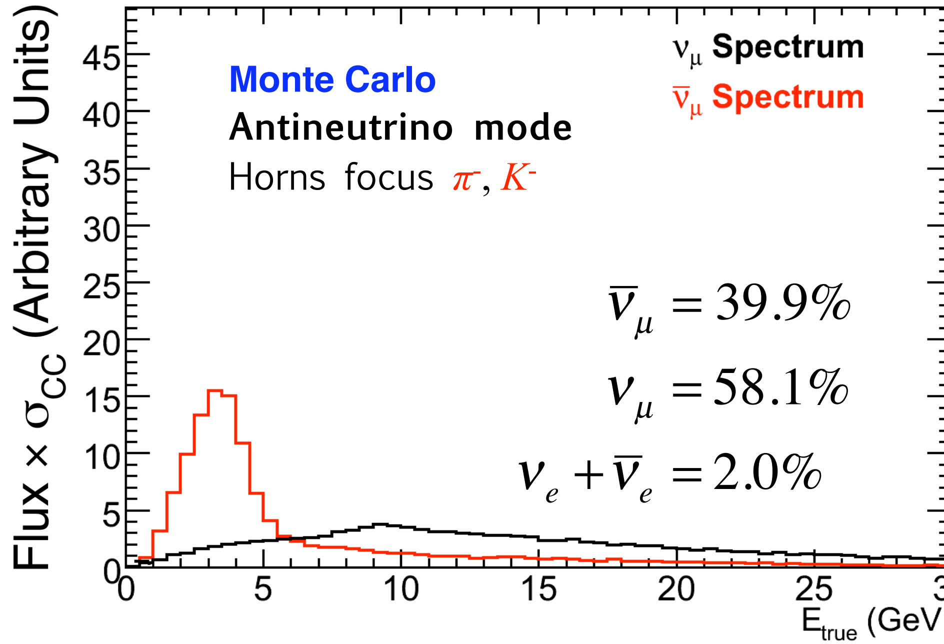
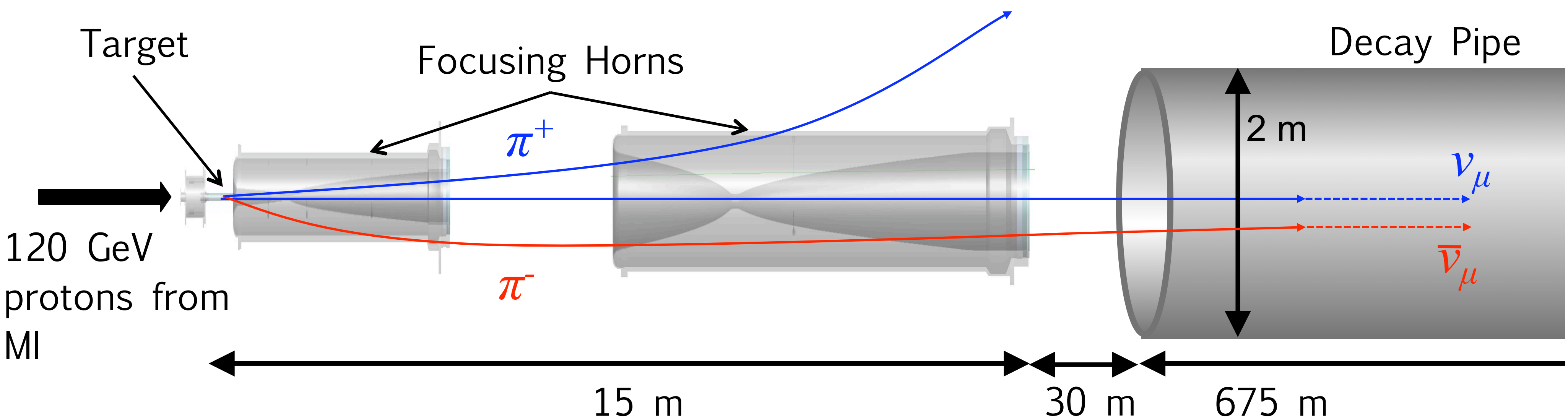


Monte Carlo
Antineutrino mode
Horns focus π^-, K^-
ν_μ Spectrum
$\bar{\nu}_\mu$ Spectrum
$\bar{\nu}_\mu = 39.9\%$
$\nu_\mu = 58.1\%$
$\nu_e + \bar{\nu}_e = 2.0\%$
Flux × σ_{CC} (Arbitrary Units)
E_{true} (GeV)



Target
Focusing Horns
Decay Pipe
π^+
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2 m
ν_μ
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120 GeV protons from MI
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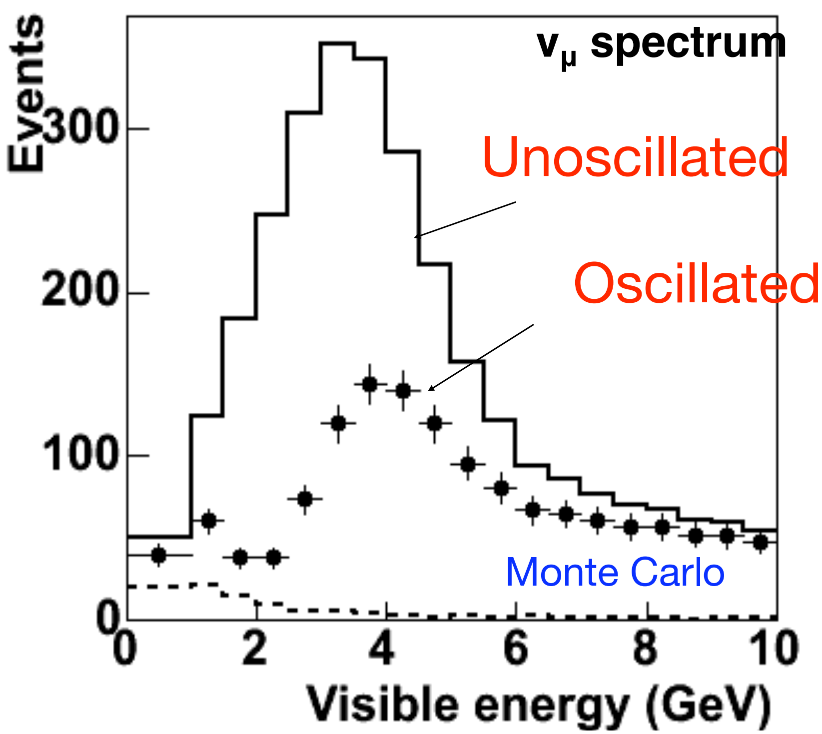
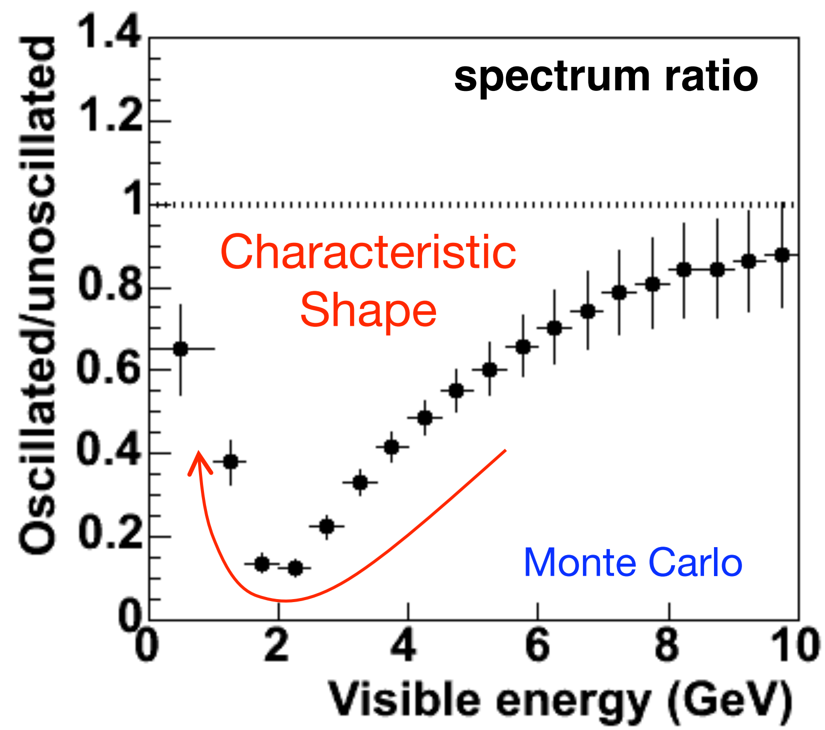
Measuring Oscillations

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2(2\theta_{23})\sin^2\left(1.27\Delta m^2_{32}\frac{L}{E}\right)$$

Monte Carlo

$\sin^2 2\theta = 1.0$, $\Delta m^2 = 3.35\text{x}10^{-3}\ \text{eV}^2$





Measuring Oscillations

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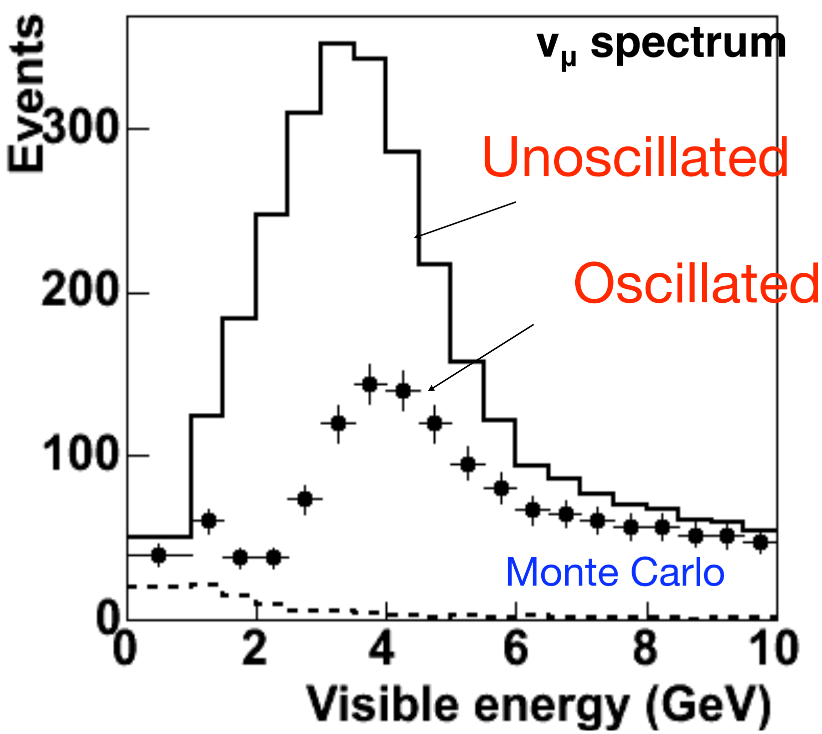

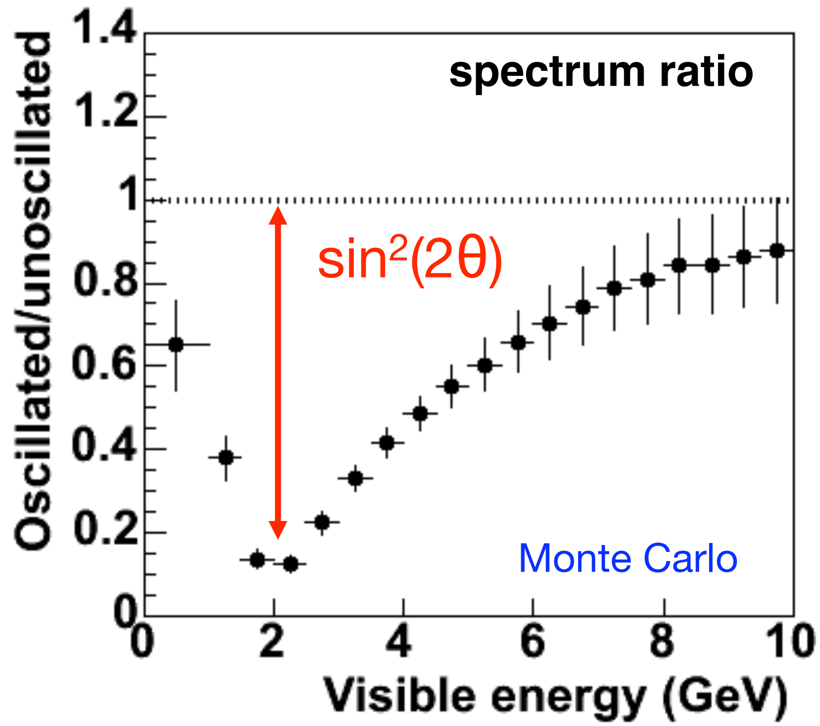

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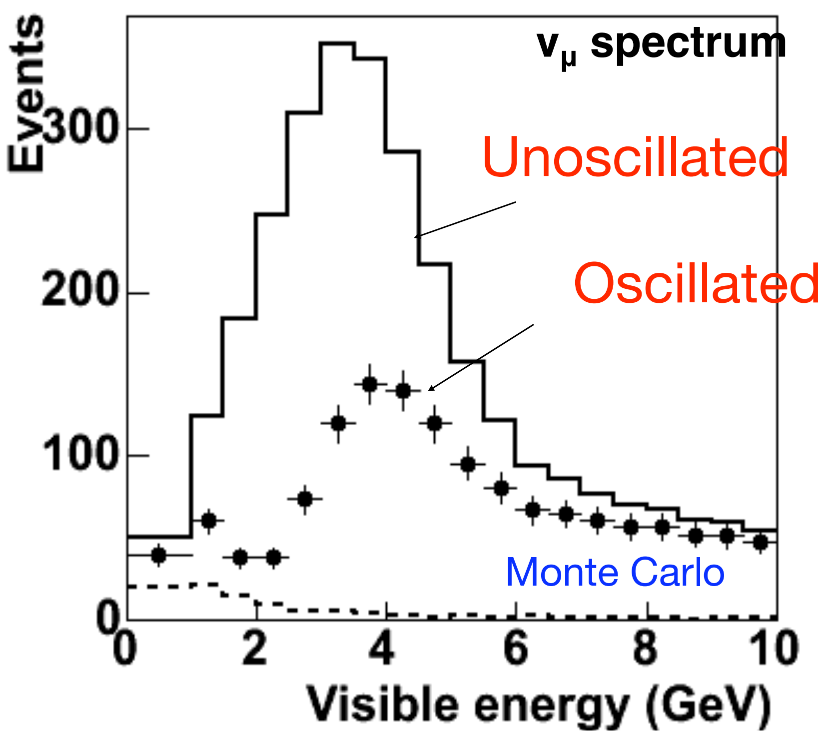
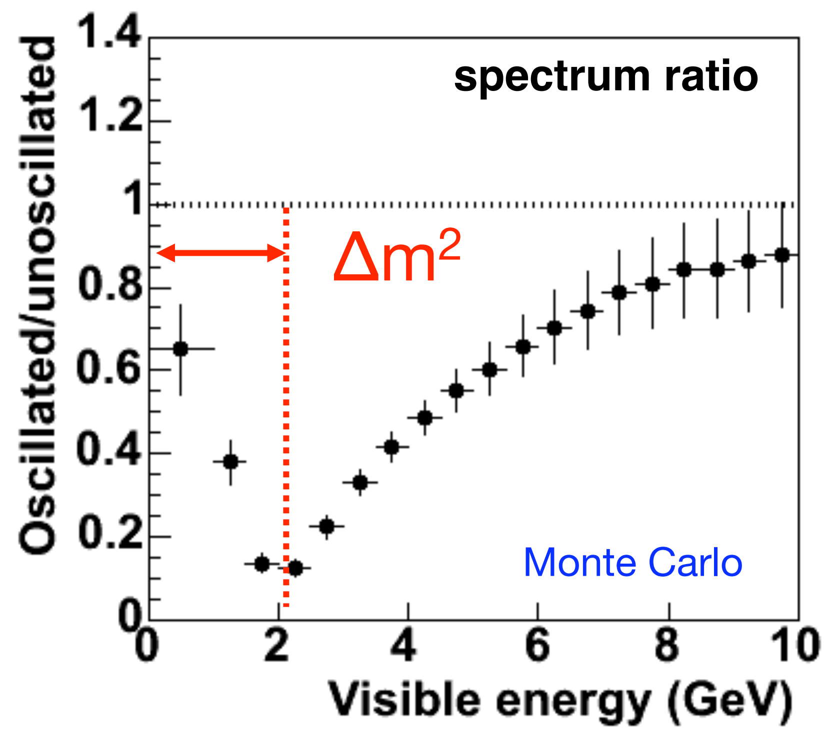
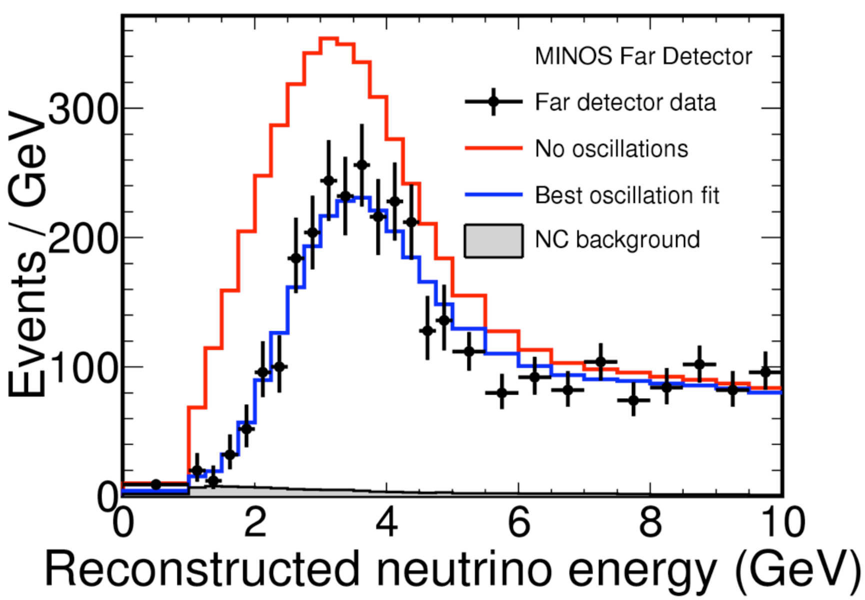
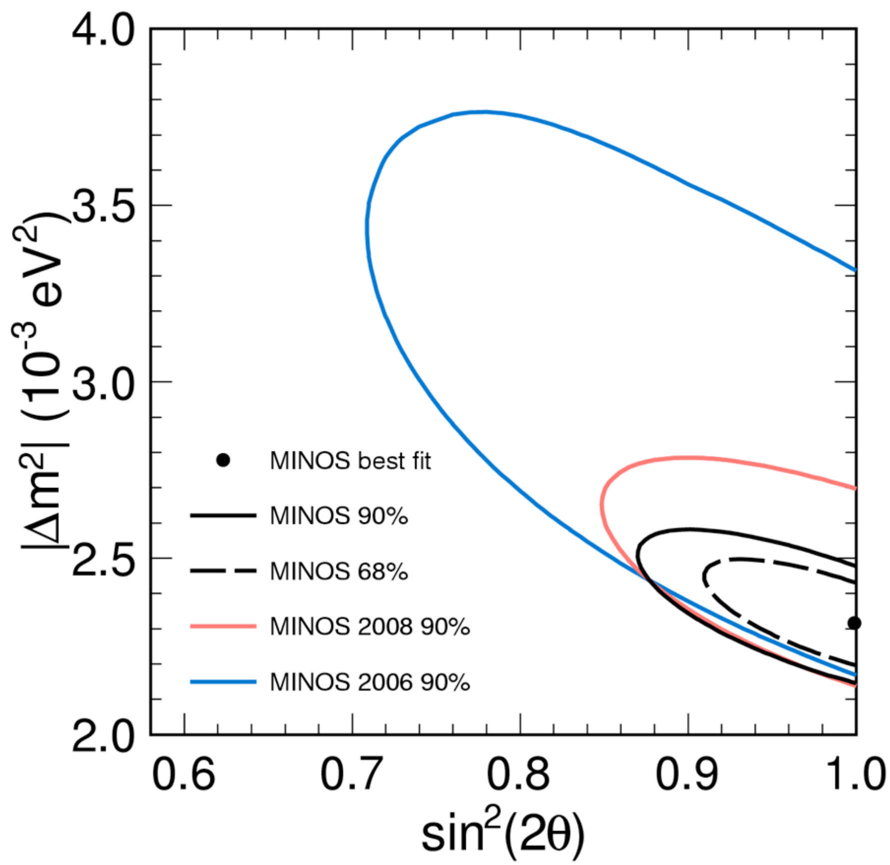
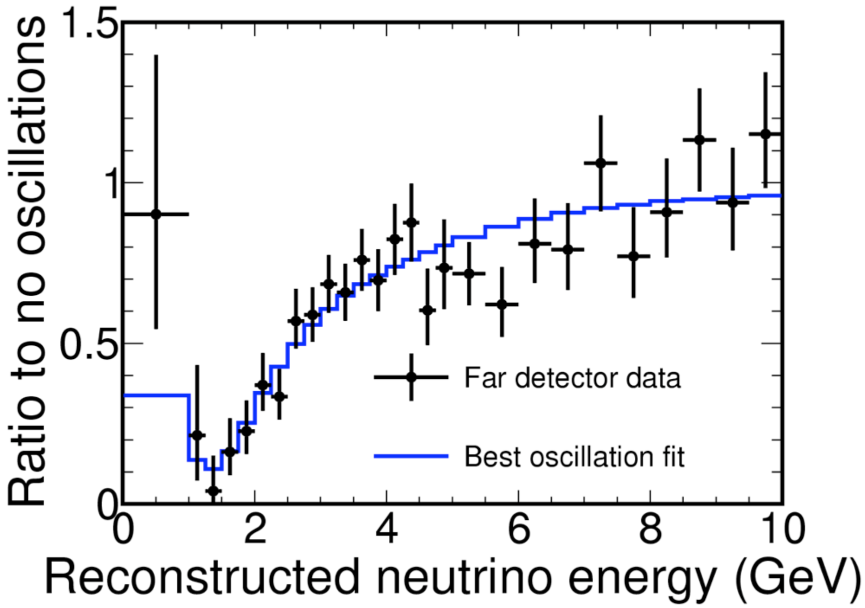




Neutrino Oscillation Results





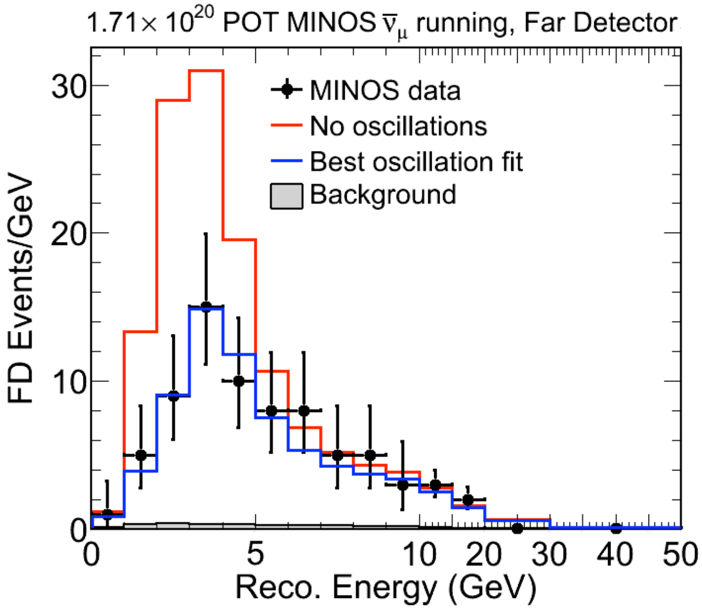


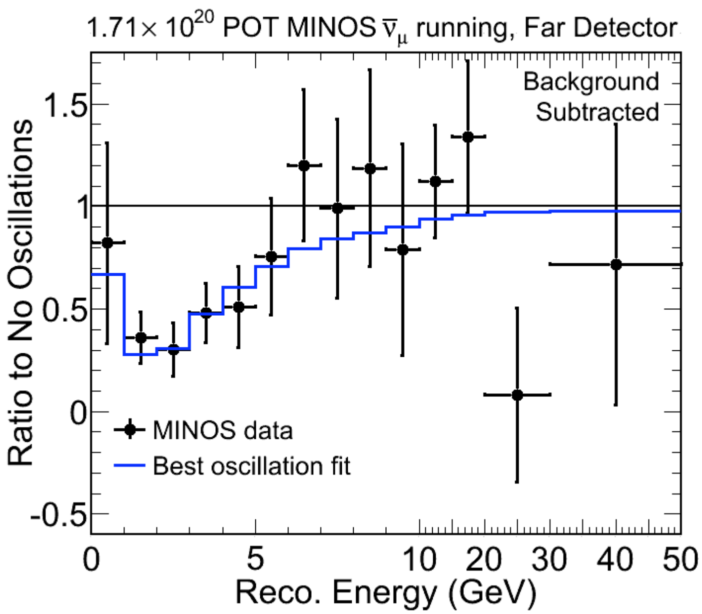
$$|\Delta m^2| = 2.32^{+0.12}_{-0.08} \times 10^{-3} \mathrm{eV}^2$$

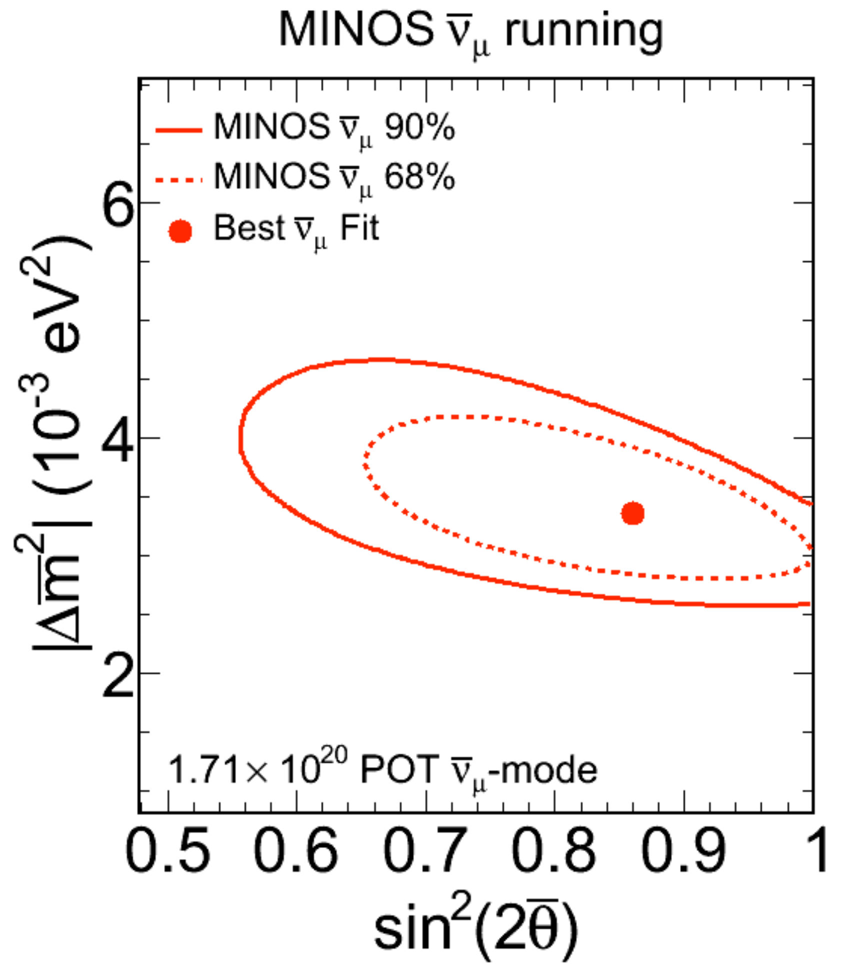
$$\sin^2(2\theta) = 1.0$$

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

Antineutrino Oscillation Results



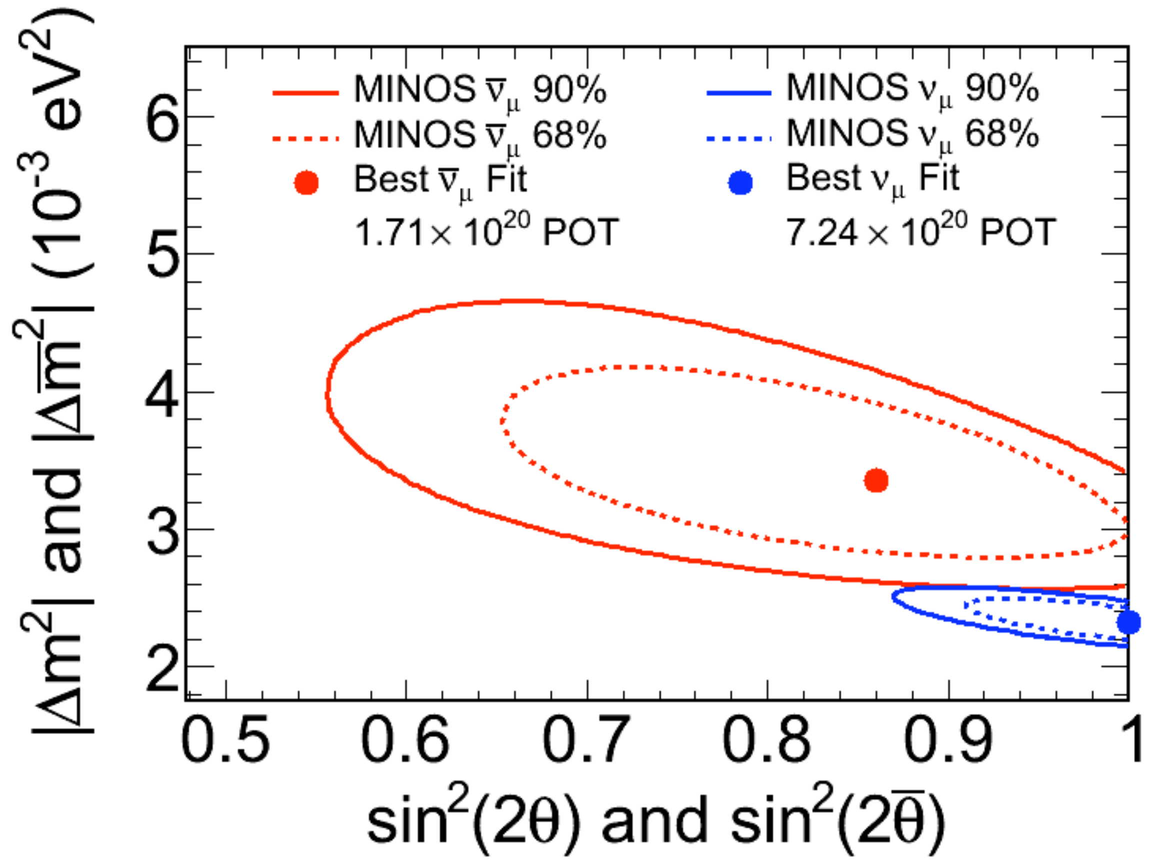




$$|\Delta\overline{m}^2| = 3.36^{+0.45}_{-0.40} \times 10^{-3}\mathrm{eV}^2$$

$$\sin^2(2\overline{\theta}) = 0.86 \pm 0.11$$

Neutrinos and Antineutrinos



- Two measurements are consistent at 2% assuming identical underlying oscillation parameters.
- Updated results with more data in two weeks!
- Motivates the search for non-standard interactions.

Flavor changing non-standard interactions

Neutrinos propogate $$i\frac{d}{dt}\overrightarrow{\nu}(t) = \hat{H}\overrightarrow{\nu}(t)$$

in vacuum, two flavors

$$H_0 = \begin{pmatrix} \sin^2\theta_{23}\frac{\Delta m^2}{2E} & \sin\theta_{23}\cos\theta_{23}\frac{\Delta m^2}{2E} \\ \sin\theta_{23}\cos\theta_{23}\frac{\Delta m^2}{2E} & \cos^2\theta_{23}\frac{\Delta m^2}{2E} \end{pmatrix}$$

through matter, analogous to MSW

$$H_{\mathrm{matter}} = \begin{pmatrix} 0 & \epsilon_{\mu\tau}V \\ \epsilon^*_{\mu\tau}V & 0 \end{pmatrix};\ H = H_0 + H_{\mathrm{matter}}$$

Real valued epsilon changes sign between neutrinos and antineutrinos

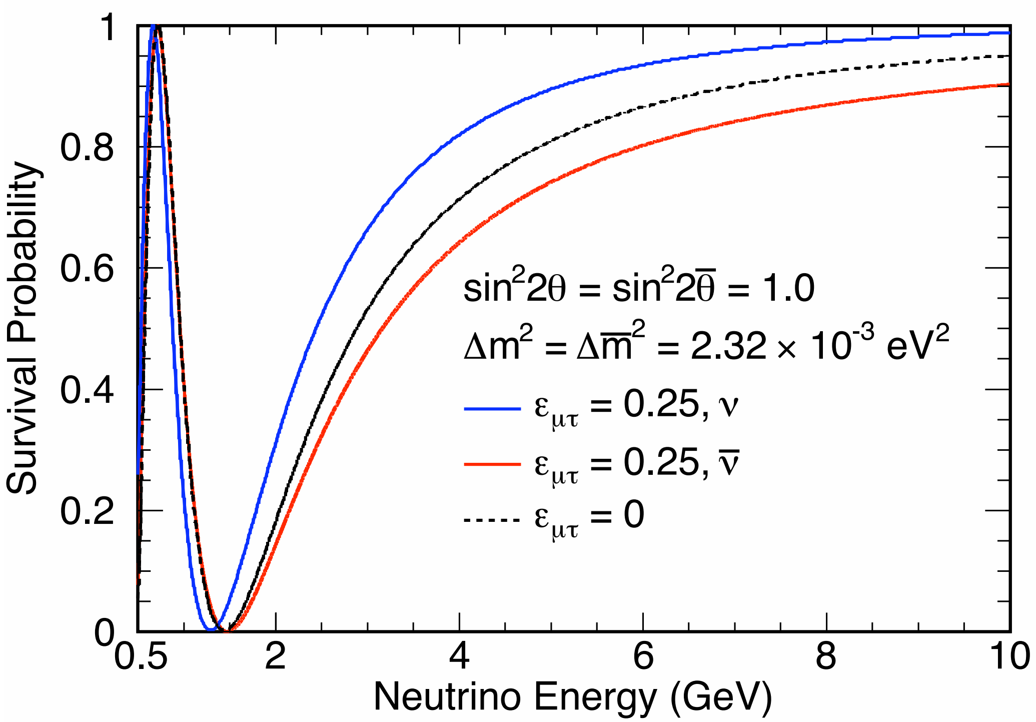
$$H = \begin{pmatrix} \sin^2\theta_{23}\frac{\Delta m^2}{2E} & \sin\theta_{23}\cos\theta_{23}\frac{\Delta m^2}{2E} \pm \epsilon_{\mu\tau}V \\ \sin\theta_{23}\cos\theta_{23}\frac{\Delta m^2}{2E} \pm \epsilon_{\mu\tau}V & \cos^2\theta_{23}\frac{\Delta m^2}{2E} \end{pmatrix}$$

Flavor changing non-standard interactions

$$P = \cos^2(F_1) + \frac{cos^2(2\theta)\sin^2(F_1)}{F_2}$$

- In units of GeV, km, eV^2

$$F_1 = \sqrt{\left(1.27\frac{\Delta m^2 L}{E}\right)^2 \pm 2\sin(2\theta)\left(1.27\frac{\Delta m^2 L}{E}\right)\epsilon V L + (\epsilon V L)^2} \qquad F_2 = 1 \pm 2\frac{\sin(2\theta)\epsilon V L}{\left(1.27\frac{\Delta m^2 L}{E}\right)} + \left(\frac{\epsilon V L}{\left(1.27\frac{\Delta m^2 L}{E}\right)}\right)^2$$



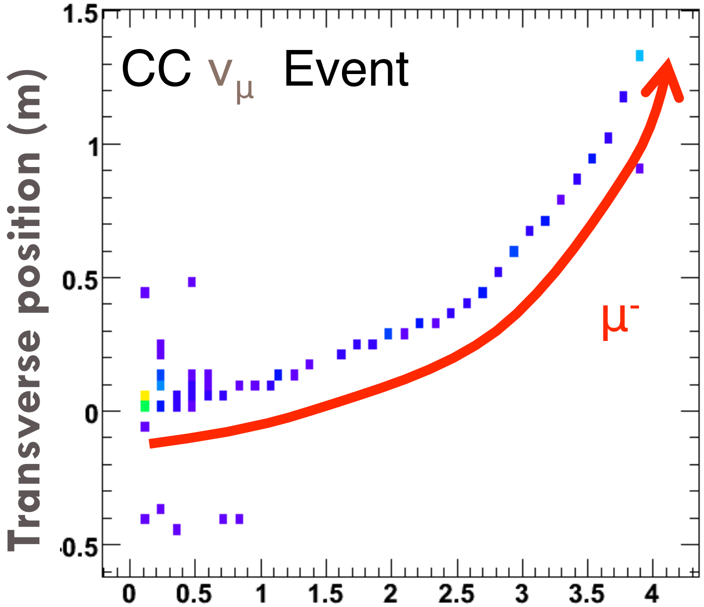
$$\text{with } \epsilon = 0;\ F_1 = \left(1.27\frac{\Delta m^2 L}{E}\right),\ F_2 = 1$$

$$P \to 1 - \sin^2(2\theta_{23})\sin^2\left(1.27\Delta m^2_{32}\frac{L}{E}\right)$$

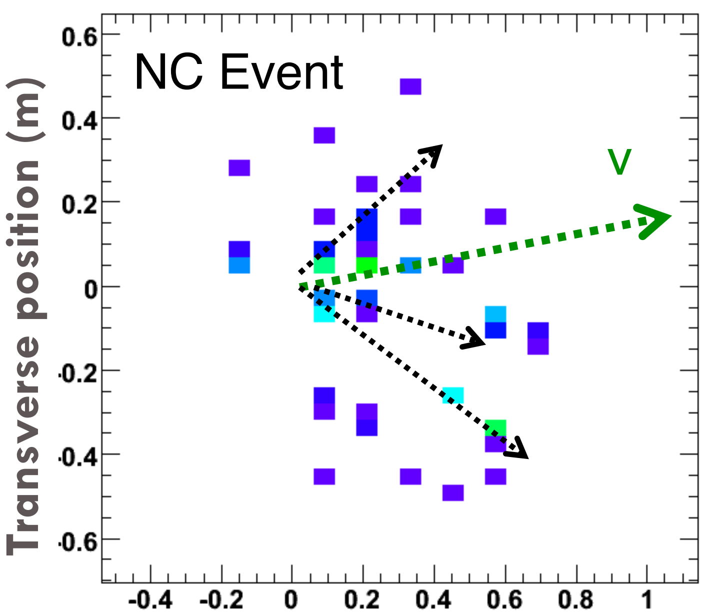
Non-standard interaction analysis

- Select (anti)neutrino events. Same event selection as above oscillation results with one exception: positive muons removed from neutrino sample.
- Measure Near and Far detector energy spectra.
- Extrapolate Near Detector data to obtain Far Detector prediction.
- Perform combined fit to neutrino and antineutrino data to measure non-standard interactions with common standard oscillation parameters.

Events at the Detectors



- **CC event (μ+, μ-): Signal**
- Long track with hadronic activity at vertex.
- Total energy = Track + Shower



- **NC event: Background**
- No track.
- Main contamination at low energy.

Neutrino Selection

CC/NC separation using a track recognition algorithm:

- 4-parameter comparison to MC events:
  - Track length,
  - mean energy of track hits,
  - energy fluctuations along the track,
  - transverse track profile.

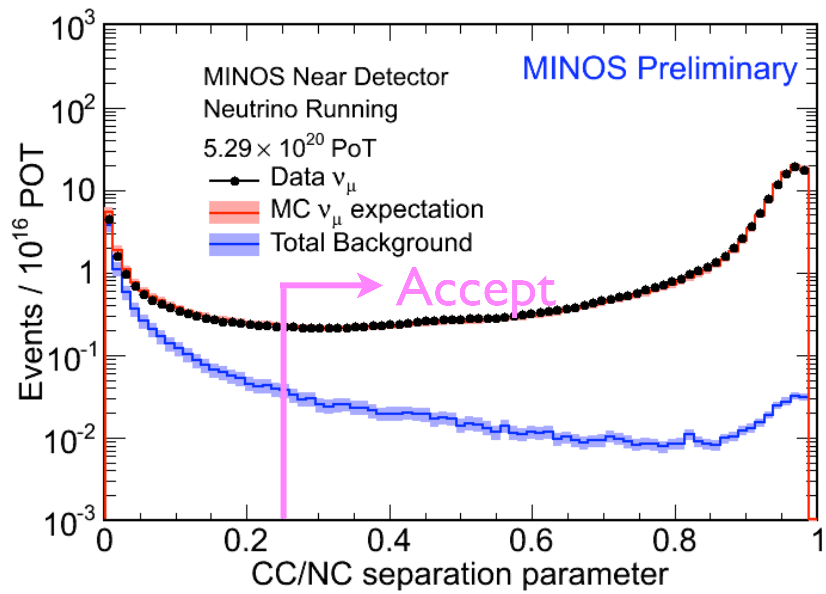
OR

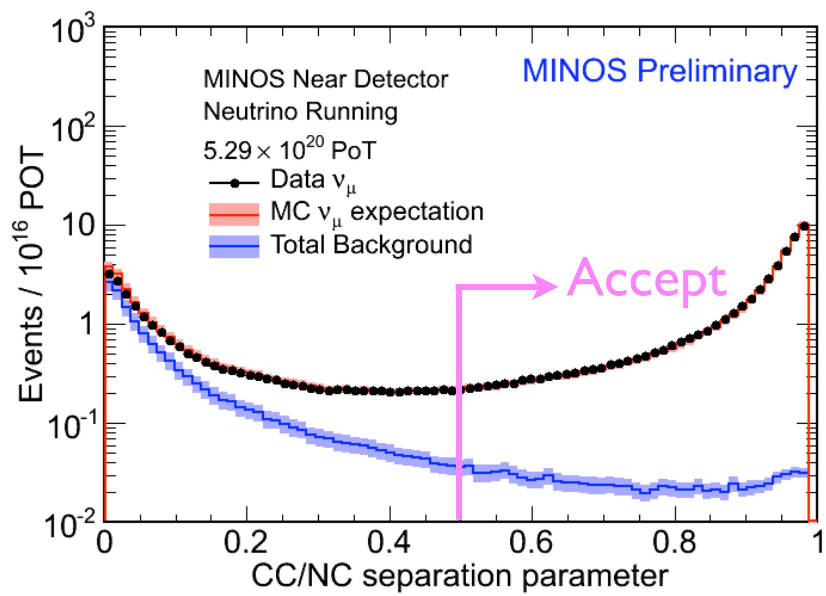
Additional algorithm to improve low energy efficiency:

  - Number of planes in track,
  - energy deposition at the end of track,
  - amount of scattering.

AND

Select on negative reconstructed charge



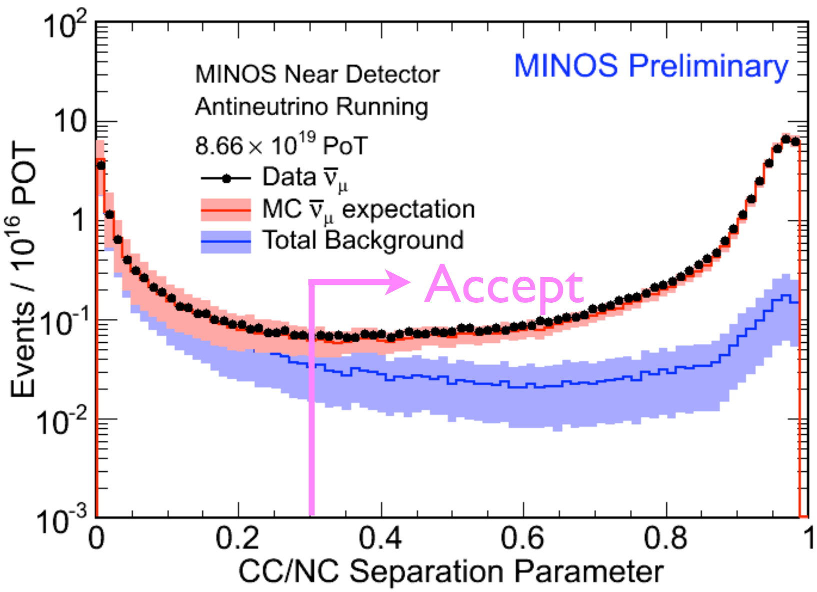


Antineutrino Selection

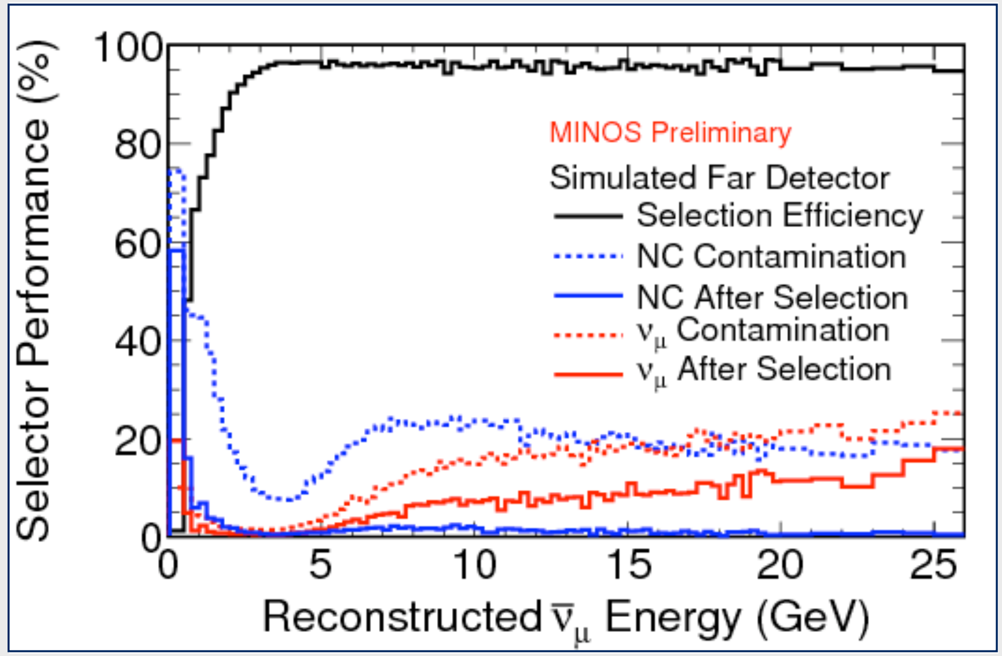
CC/NC separation using a track recognition algorithm:

AND

Select on positive reconstructed charge

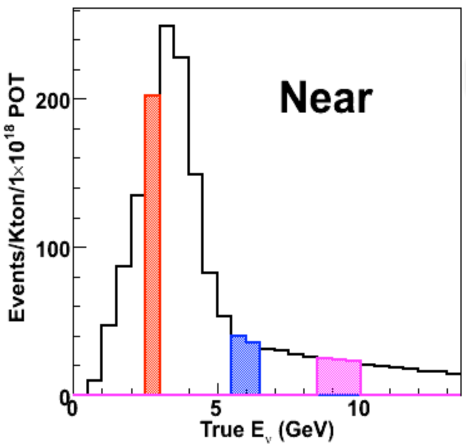


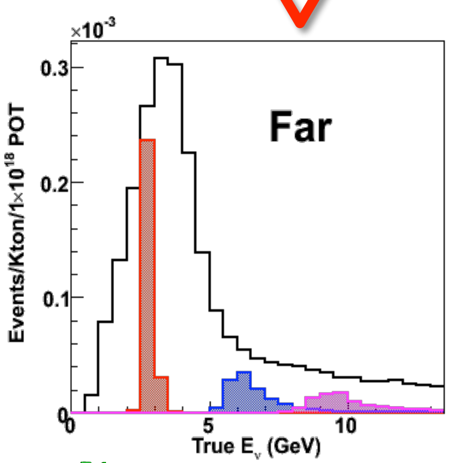
Gives an integrated efficiency of 93% and a purity of 94% at the Far Detector

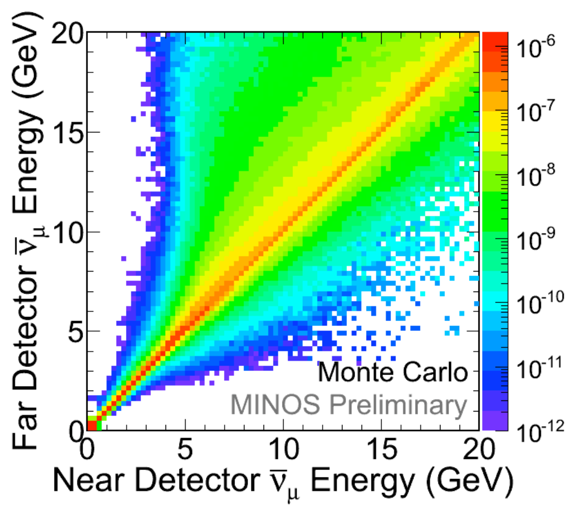


Near to Far Extrapolation

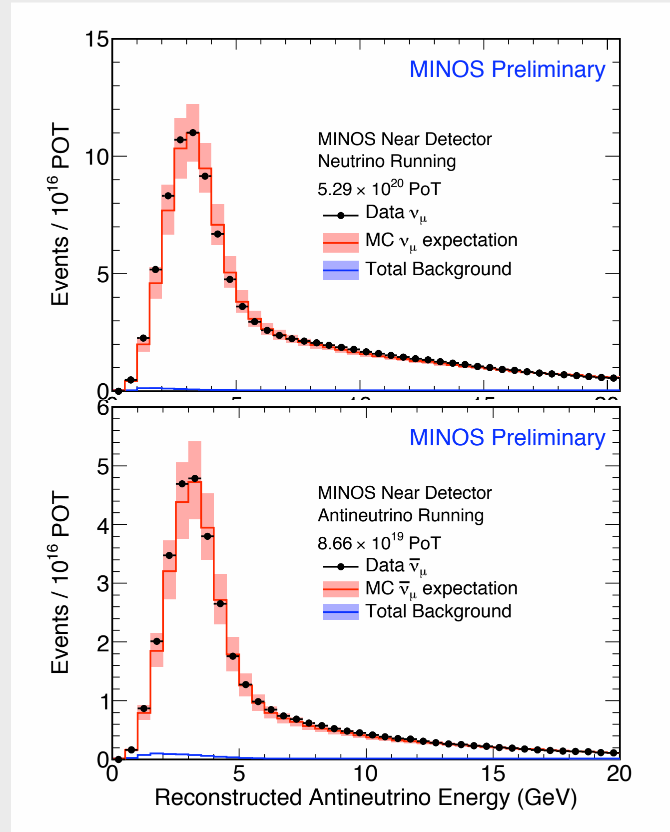
- Far Detector spectrum similar but not identical to the Near without oscillations.







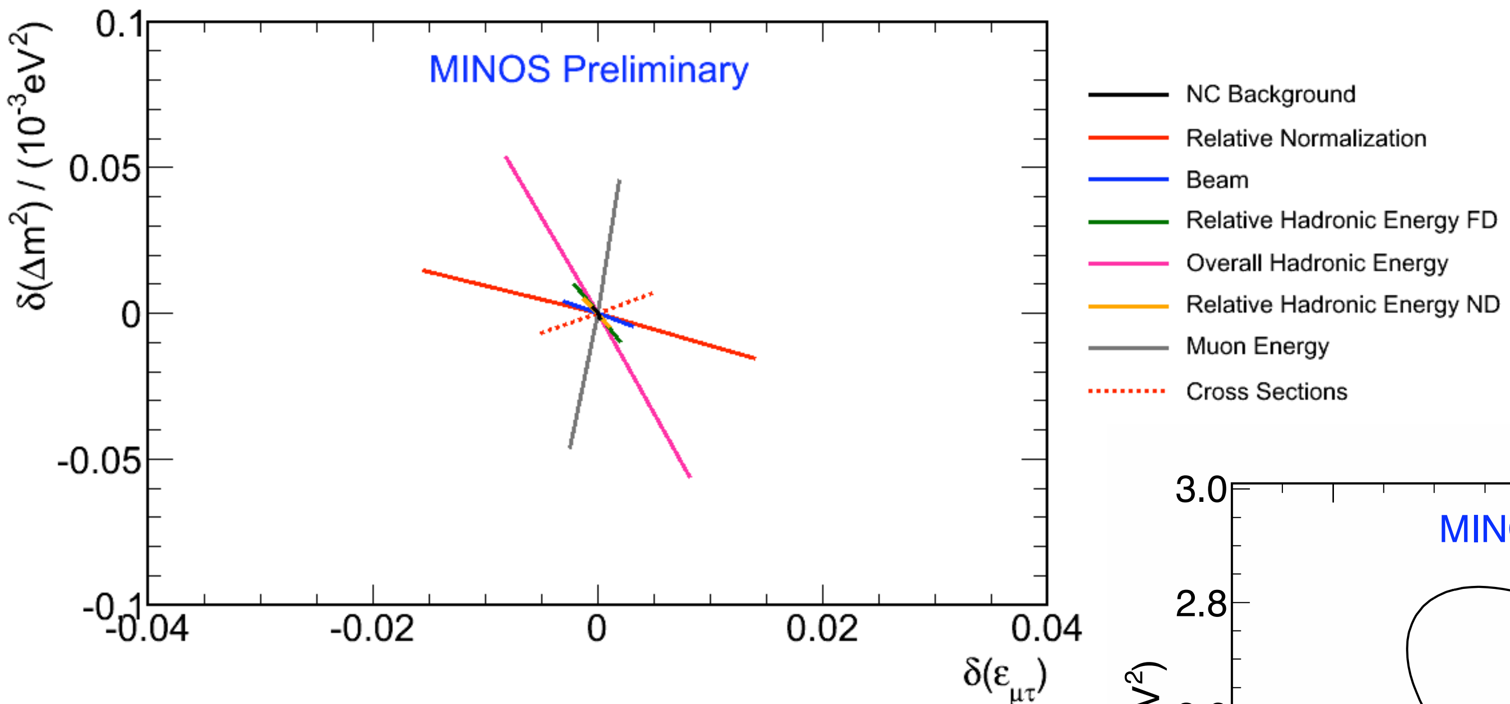
Beam Matrix: Find true ND and FD events from their parent pion.

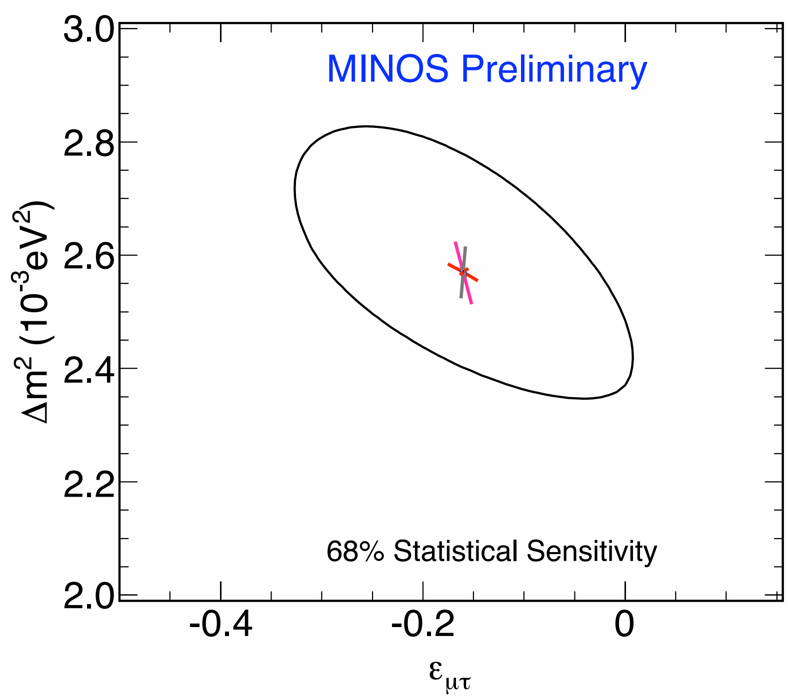


Near Detector energy spectrum shows good modeling of data by MC in both charge signs.

Far Detector prediction is obtained from this measured spectrum via the matrix extrapolation method.

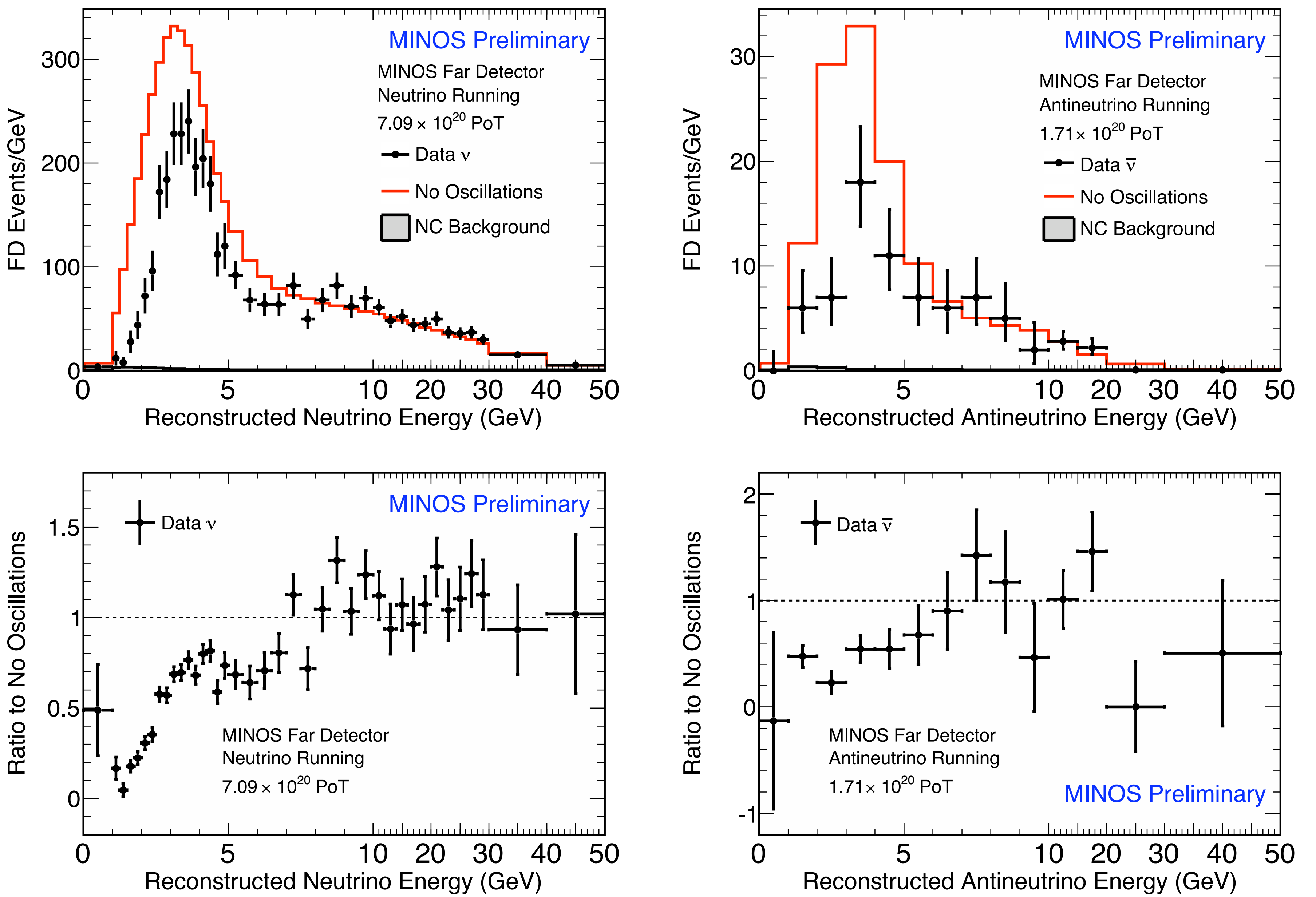
Systematic Uncertainties



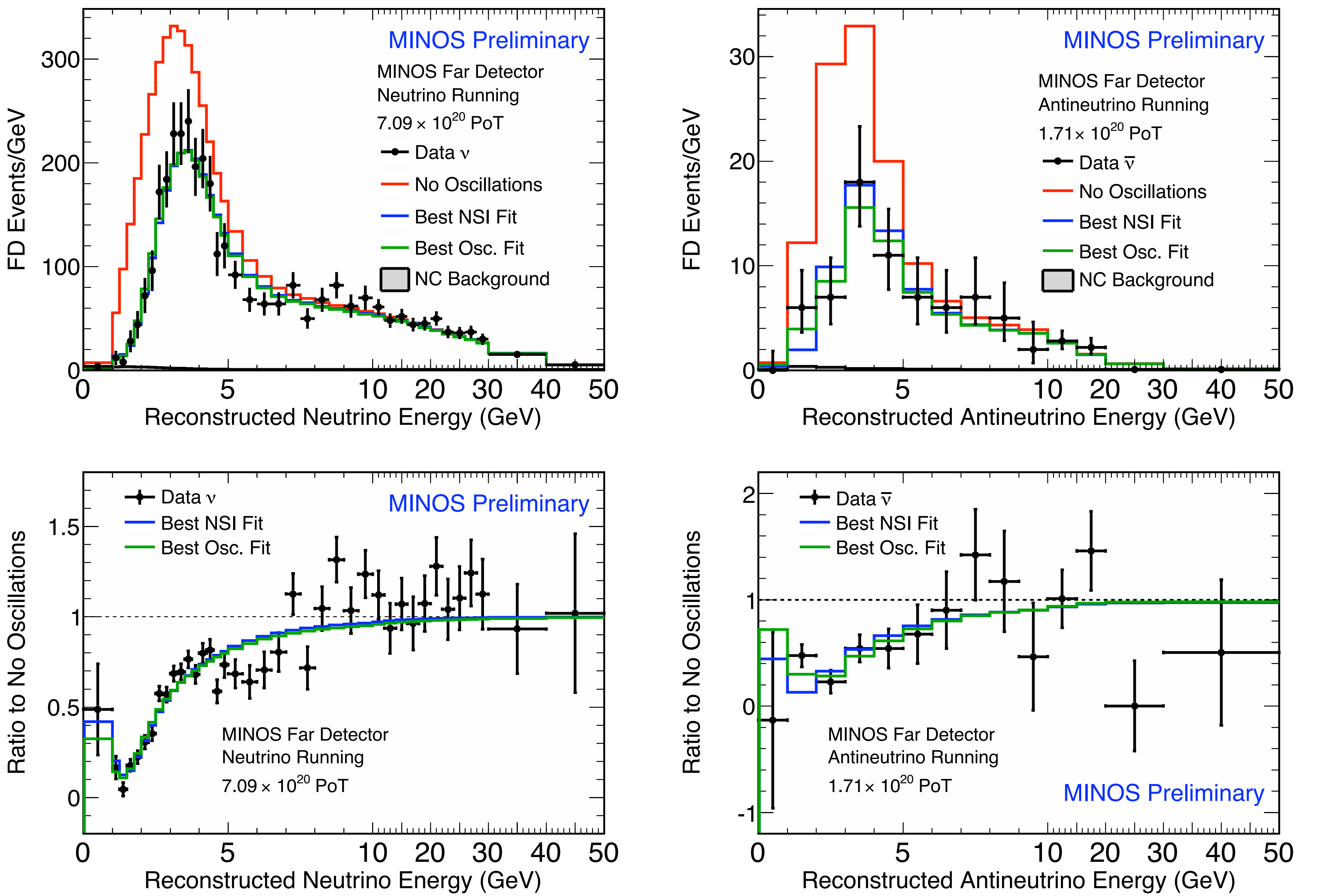


- Star plot shows effect of each systematic uncertainty on the measurement.
- Left: Size of systematics compared to statistical uncertaintly.

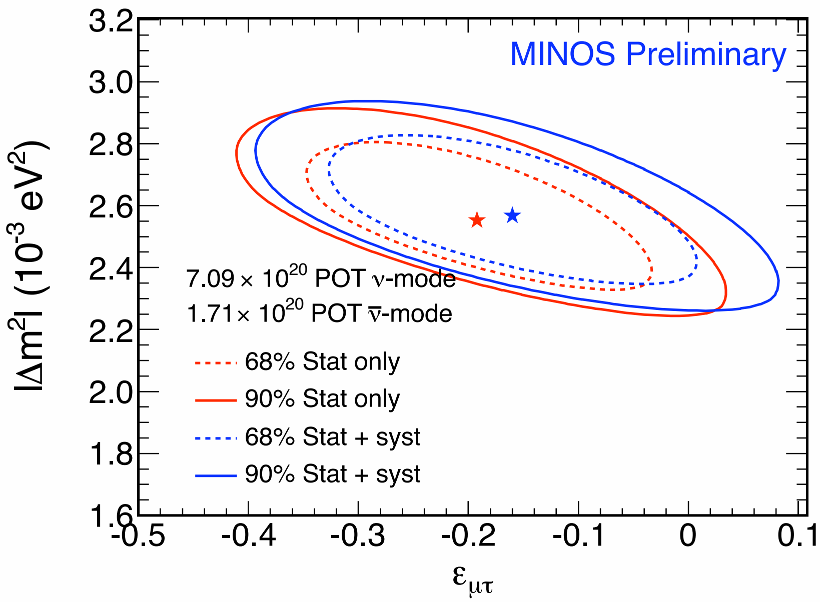
Far Detector Spectra

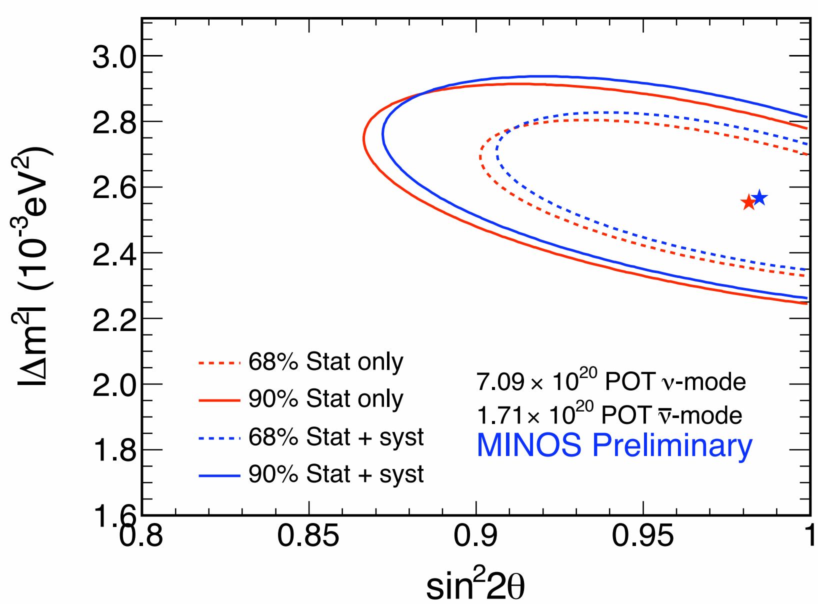


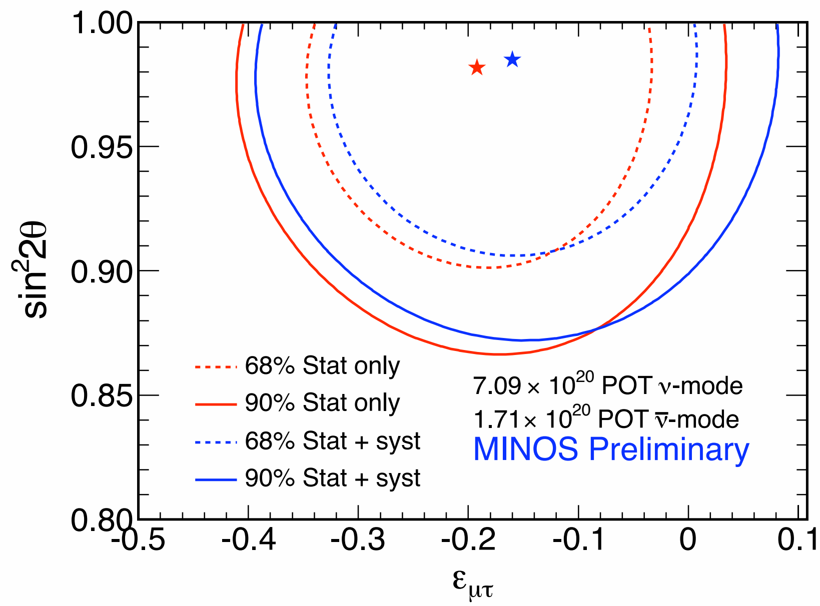
Results


MINOS Preliminary
MINOS Far Detector
Neutrino Running
7.09 × 10^20 PoT
Data ν
No Oscillations
Best NSI Fit
Best Osc. Fit
NC Background
FD Events/GeV
Reconstructed Neutrino Energy (GeV)
MINOS Far Detector
Antineutrino Running
1.71 × 10^20 PoT
Data ν̄
Reconstructed Antineutrino Energy (GeV)
Ratio to No Oscillations

Results







$$\Delta m^2 = 2.57 \pm 0.15 \times 10^{-3}\mathrm{eV}^2$$

$$\sin^2(2\theta) = 0.98 \pm 0.08$$

$$\epsilon_{\mu\tau} = -0.163 \pm 0.16$$

Summary

- MINOS performs the first direct measurement of antineutrino and the most precise measuerment of neutrino vacuum oscillation parameters.

- A fit to the non-standard interaction model to neutrino and antineutrino data gives

$$\Delta m^2 = 2.57 \pm 0.15 \times 10^{-3} \mathrm{eV}^2$$

$$\sin^2(2\theta) = 0.98 \pm 0.08$$

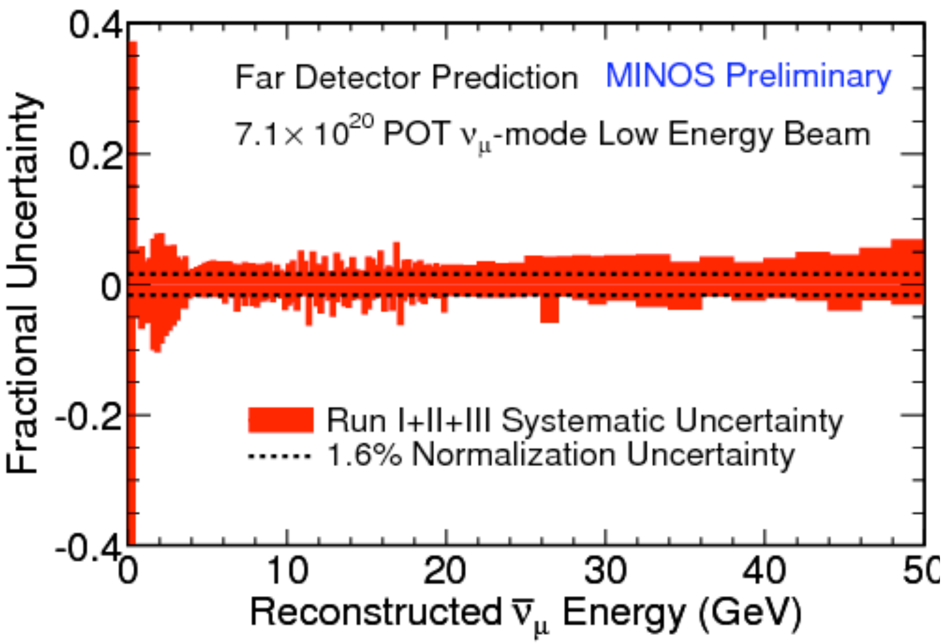
$$\epsilon_{\mu\tau} = -0.163 \pm 0.16$$

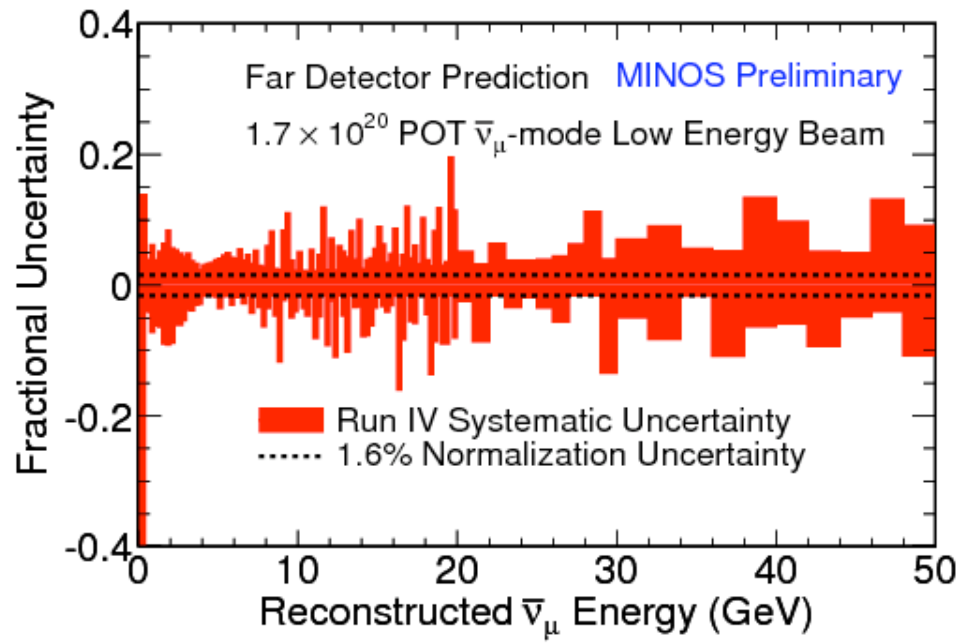
- We have an additional 1.24 x 10^{20} POT of data, non-standard and standard oscillations results very soon!

Thank you!

Systematic Uncertainties

- Bands show the effect of four most significant systematics: Muon energy scale, hadronic energy scale, normalization, neutral current background.





- Systematics <10% across all energies; preliminary conservative inclusion in the fit as a flat 10% normalization.

$$-2\ln\lambda = 2\sum_{r=1}^{4}\sum_{i=1}^{N} n_{ri}^{\mathrm{pred}} - n_{ri}^{\mathrm{data}} + n_{ri}^{\mathrm{data}} \ln \frac{n_{ri}^{\mathrm{data}}}{n_{ri}^{\mathrm{pred}}} + \left(\frac{S-1.0}{\sqrt{0.1}}\right)^2$$

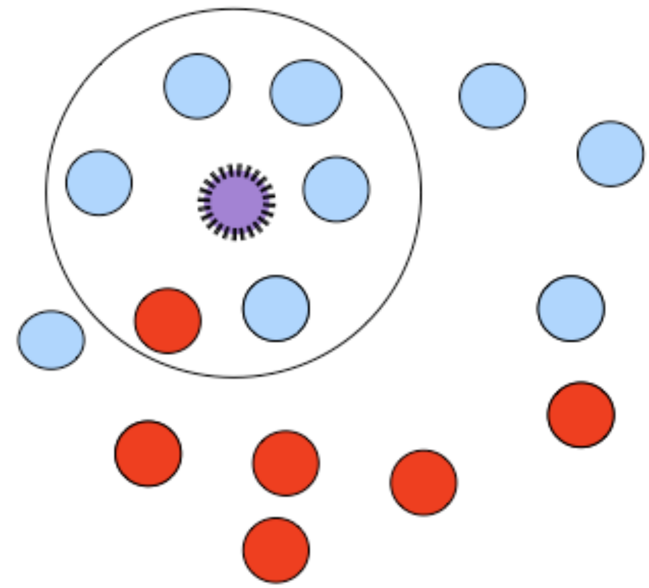
Feldman Cousins

- Gaussian contours may overestimate sensitivity in the case of low statistics and near physical boundaries.
- Felman Cousins prescription: Frequentist approach.
- Generate a large number of pseudo experiments on a ($\sin^2 2\theta$, Δm^2) grid.
- At each point find the likelihood for an X% confidence level such that X% of the experiments are below this likelihood.

CC/NC Separation Algorithm

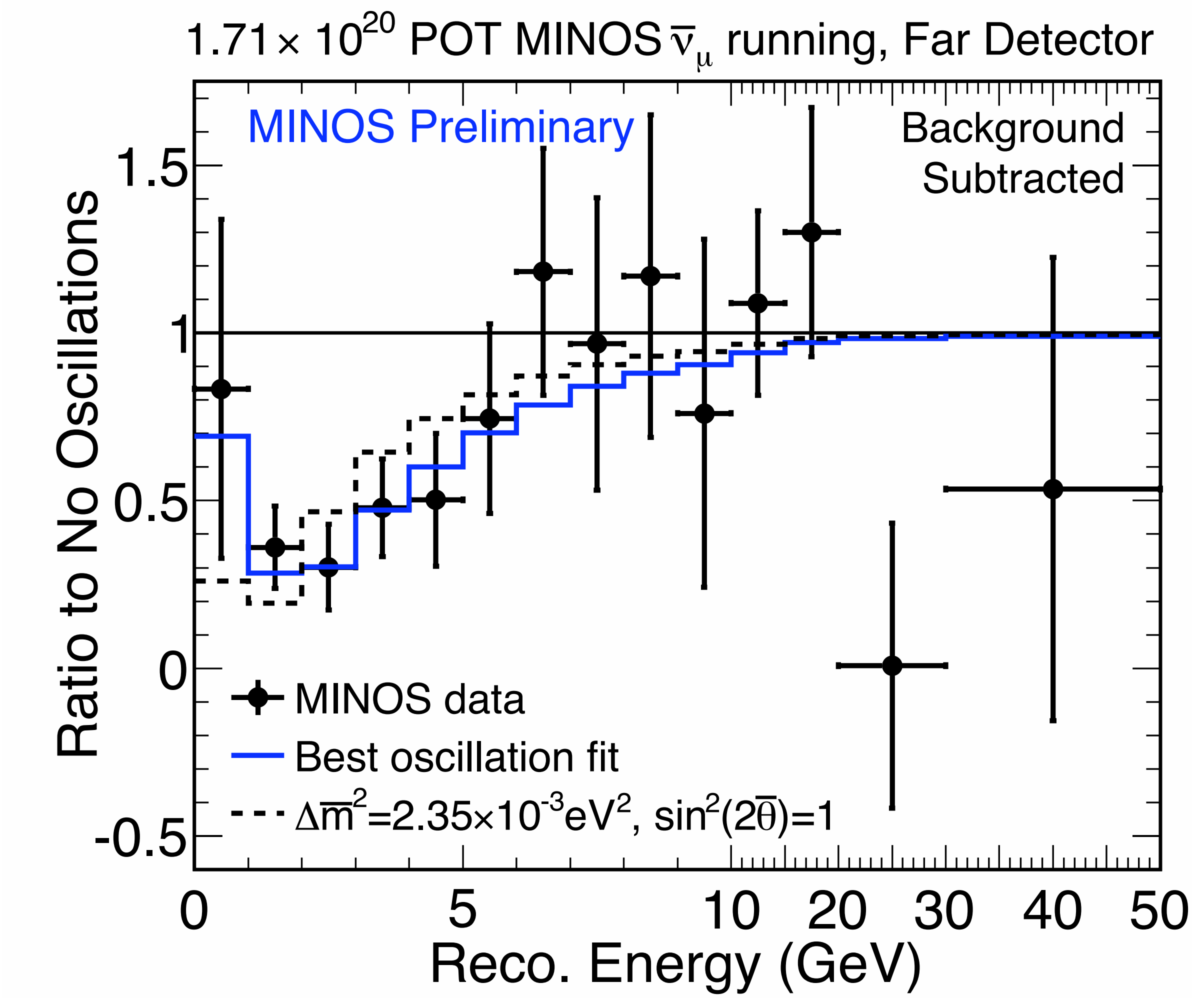
- CC/NC separation using a kNN algorithm
  - Compare to monte carlo events
- 4-parameter comparison
  - Track length
  - Mean energy of track hits
  - Energy fluctuations along the track
  - Transverse track profile
- Cartoon in 2D with k=6

k-Nearest Neighbors "kNN"

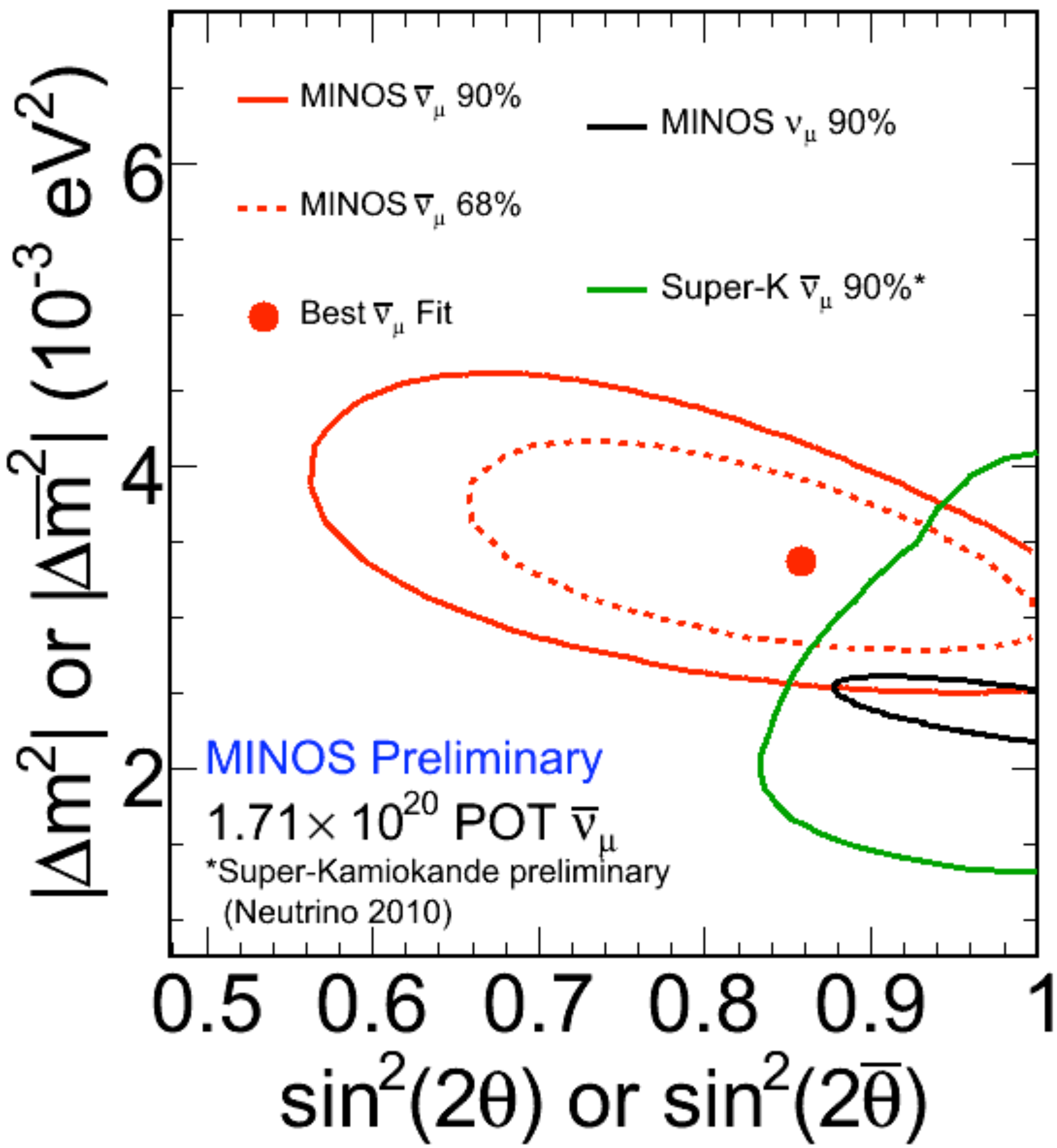


the **k**=6 **n**earest **n**eighbors contain one red and five blue
The point has a kNN of 5/6

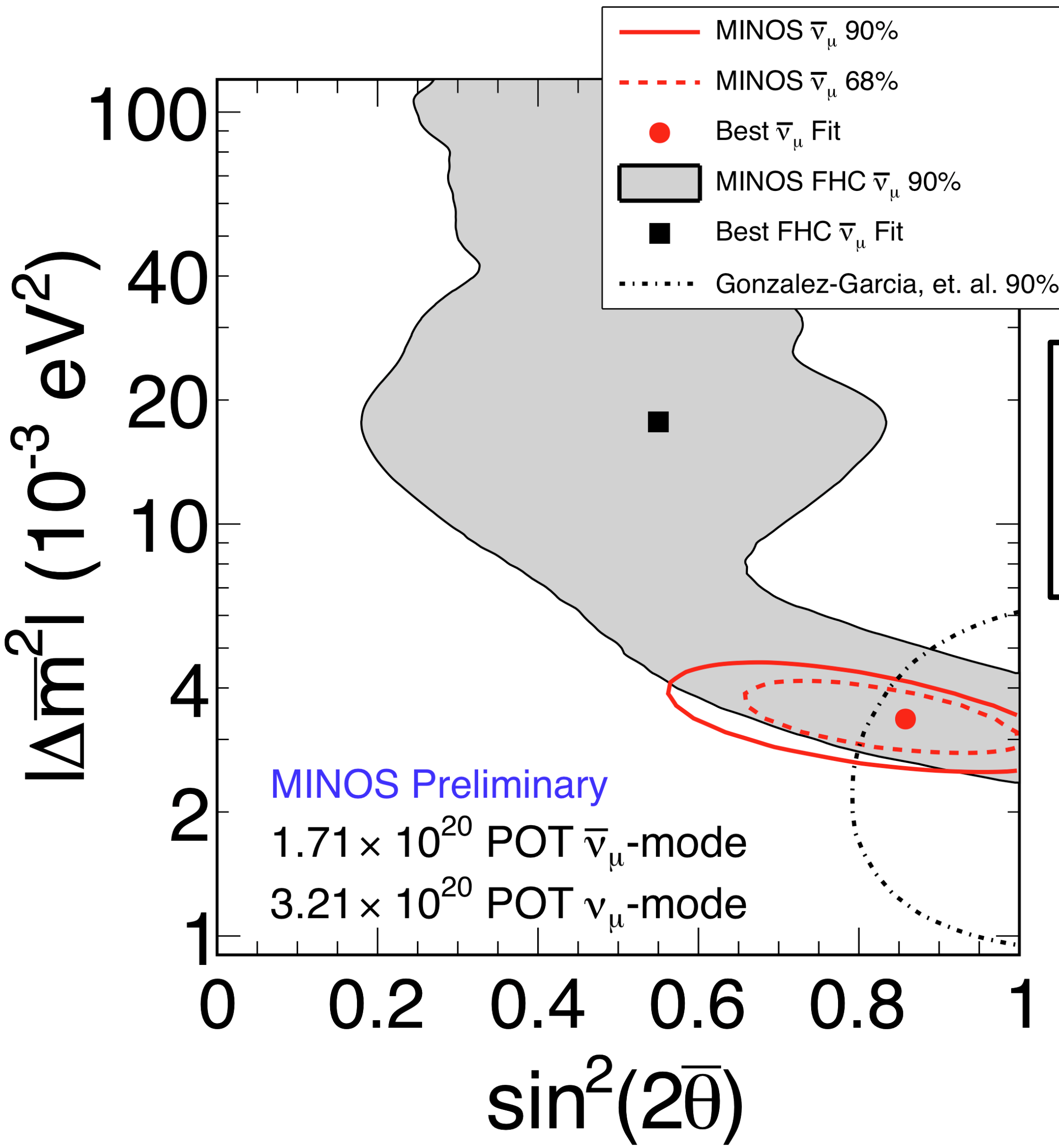
Neutrino-Antineutrino Comparison



With Super-K Antineutrino Result



Antineutrino Contour

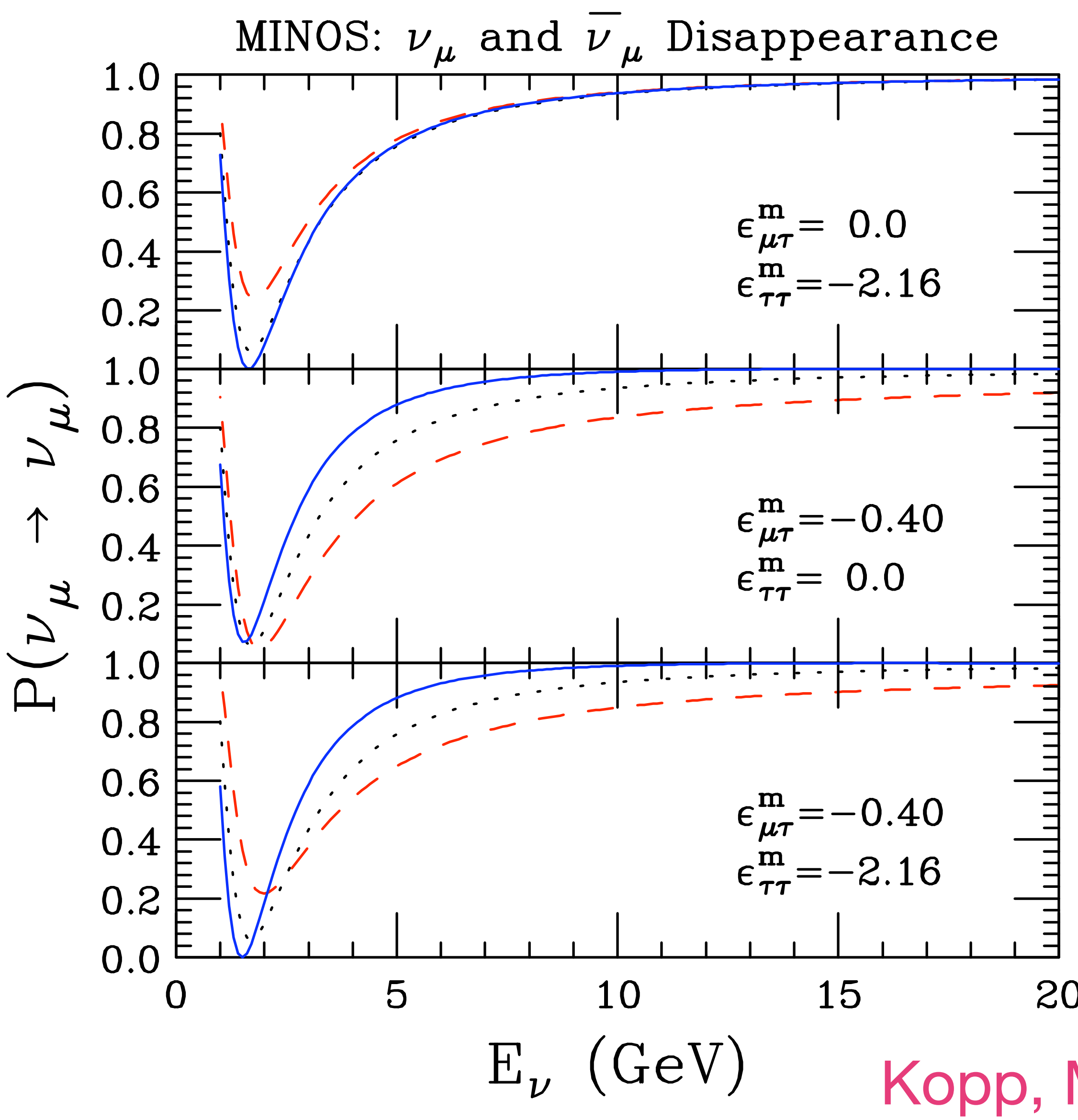


$$\left|\Delta\bar{m}^2_{atm}\right| = 3.36^{+0.45}_{-0.40} \times 10^{-3}\ \text{eV}^2$$

$$\sin^2(2\bar{\theta}_{23}) = 0.86 \pm 0.11$$

A combined analysis using all antineutrino data is planned.

Non-standard Interactions

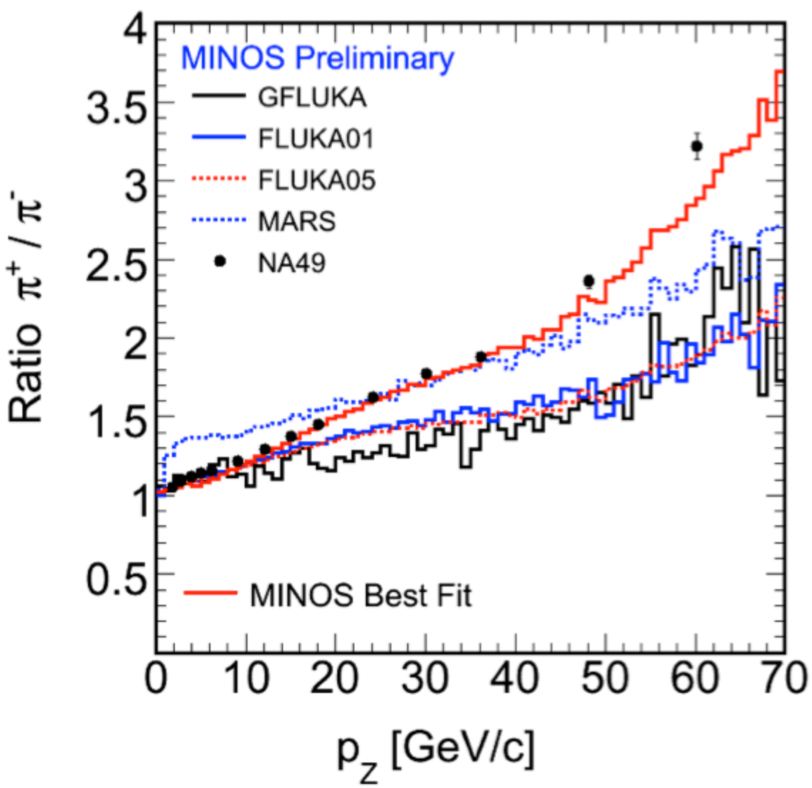


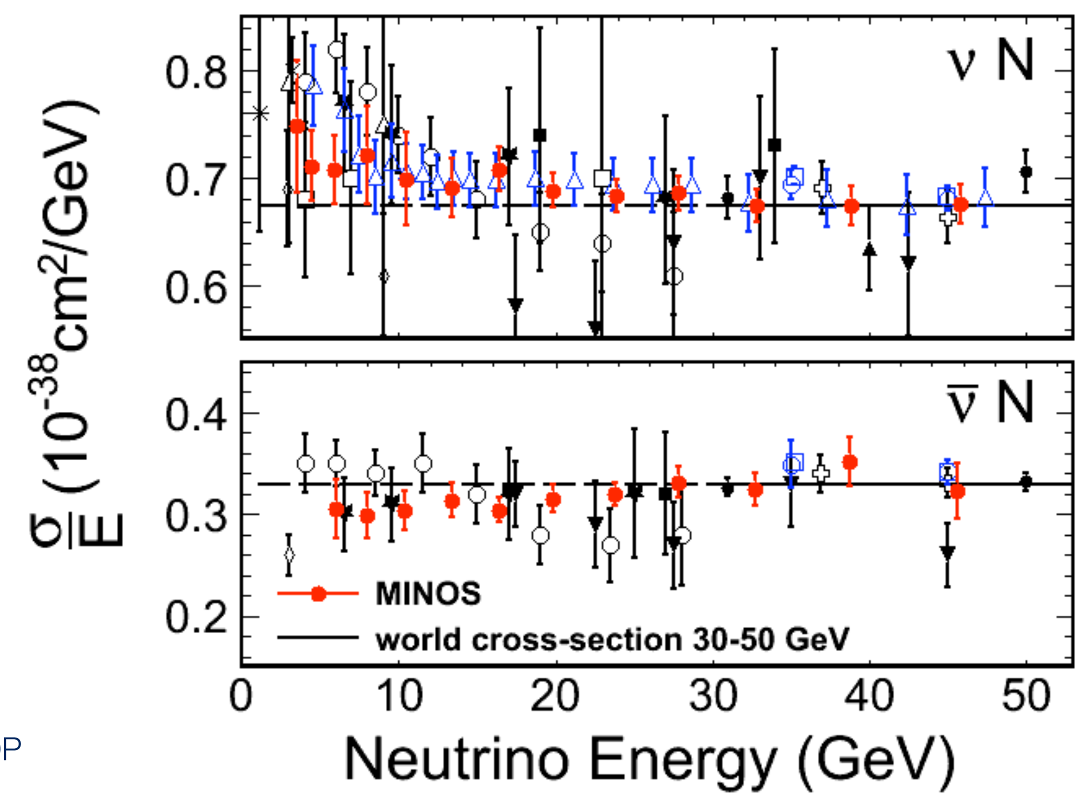
Kopp, Machado and Parke
arXiv:1009.0014v1

Making an antineutrino beam

- Hadron production and cross sections conspire to change the shape and normalization of energy spectrum

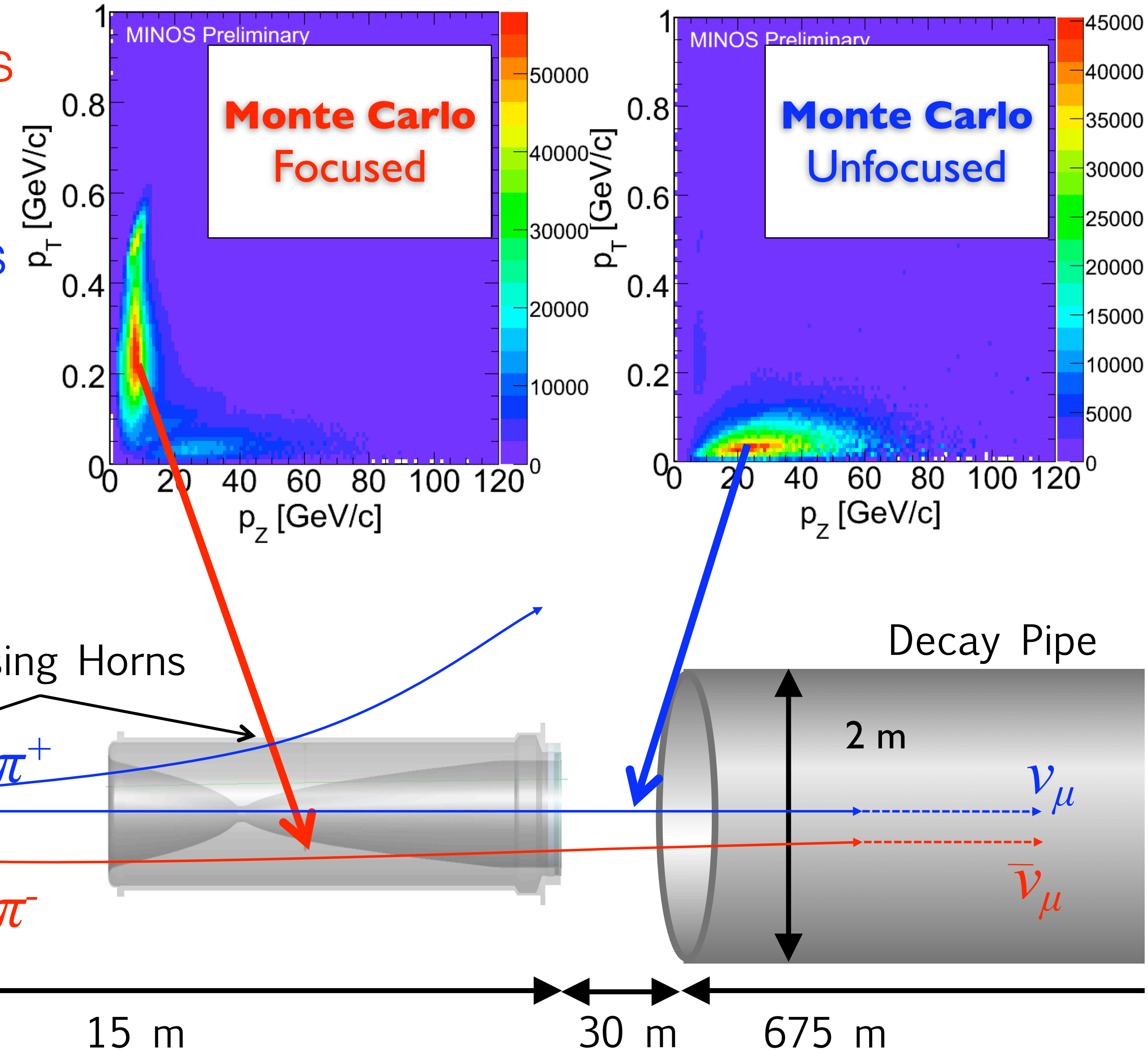
~3x fewer antineutrinos for the same exposure





Peak vs. Tail

- $\bar{\nu}_\mu$'s from **high-p_t** π^-'s
  - Focused by horns
- ν_μ's from **low-p_t** π^+'s
  - Pass through horn center



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