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

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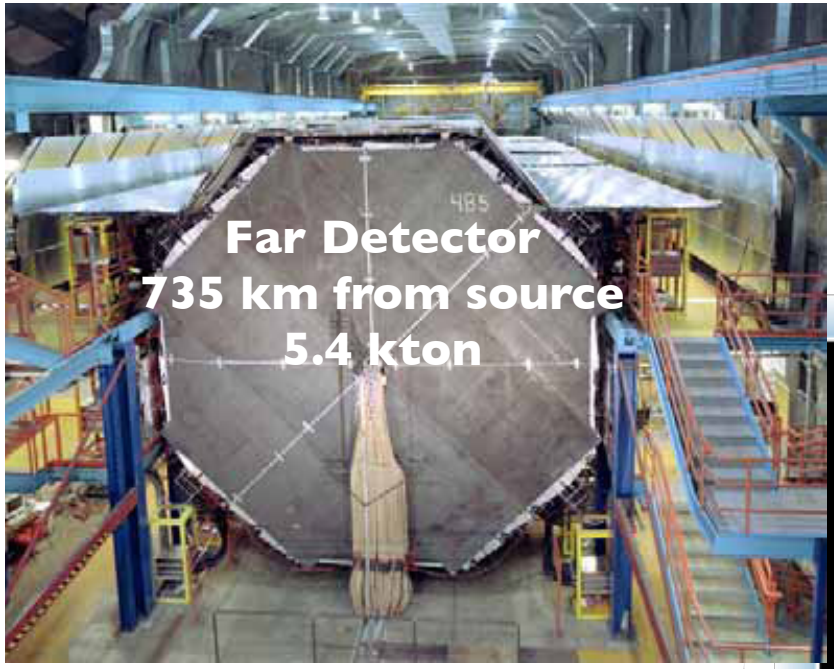
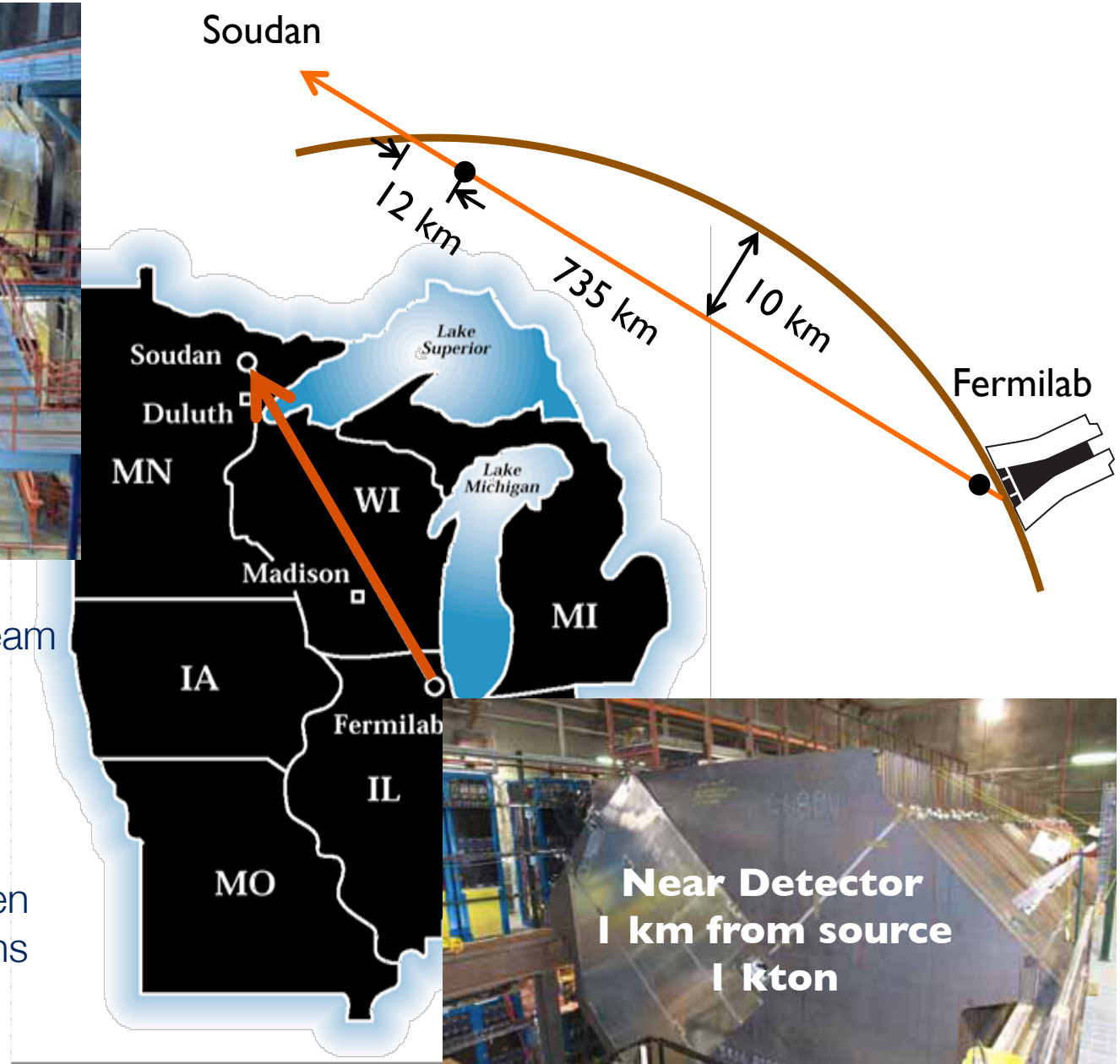
Outline

- MINOS and NuMI
- Neutrino oscillations
- Non-standard Interactions (NSI) analysis
- Results
- Future

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

MINOS Physics Goals

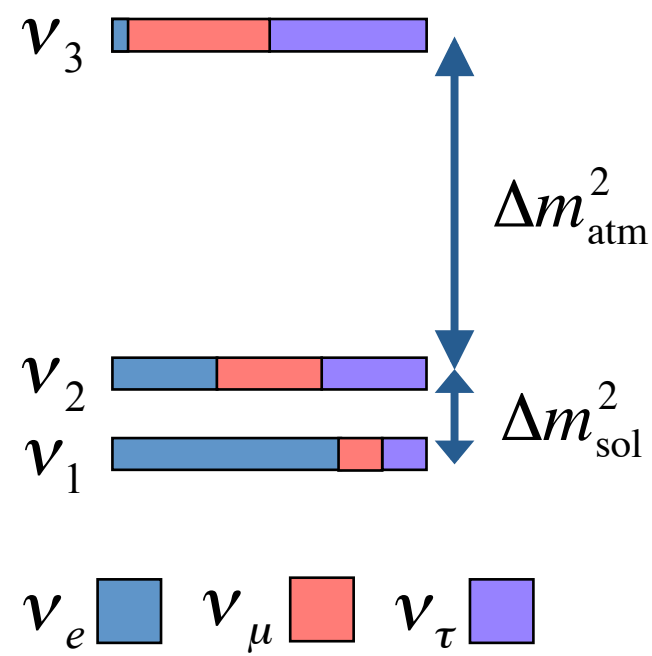
- Measure ν_μ and $\bar{\nu}_\mu$ disappearance as a function of energy
  - Vacuum oscillations: $\sin^2 2\theta_{23}$, Δm^2_{32}, $\sin^2 2\bar{\theta}_{23}$, $\Delta \bar{m}^2_{32}$
- **Are neutrino and antineutrino oscillations the same?**
  - **Search for non-standard neutrino-matter interactions as neutrinos propagate: $\sin^2 2\theta_{23}$, Δm^2_{32}, ϵ (NSI parameter)**
- Other physics goals: Mixing to sterile neutrinos, $\nu_\mu \rightarrow \nu_e$ mixing (measure θ_{13}), atmospheric neutrinos, cross section measurements, Lorentz violation, cosmic rays

Neutrino Oscillations

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

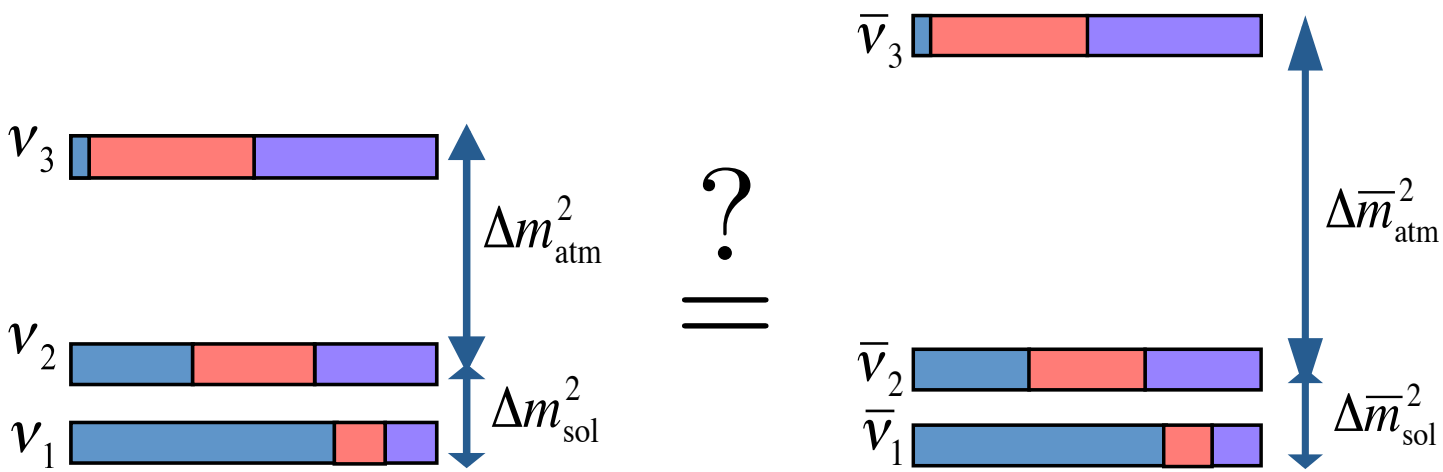
- With three flavors there are two independent mass splittings
- MINOS is sensitive to the larger of these

$$\Delta m^2_{\text{sol}} \approx \Delta m^2_{21} \approx 8.0 \times 10^{-5}\text{eV}^2$$
$$\Delta m^2_{\text{atm}} \approx \Delta m^2_{32} \approx 2.3 \times 10^{-3}\text{eV}^2$$



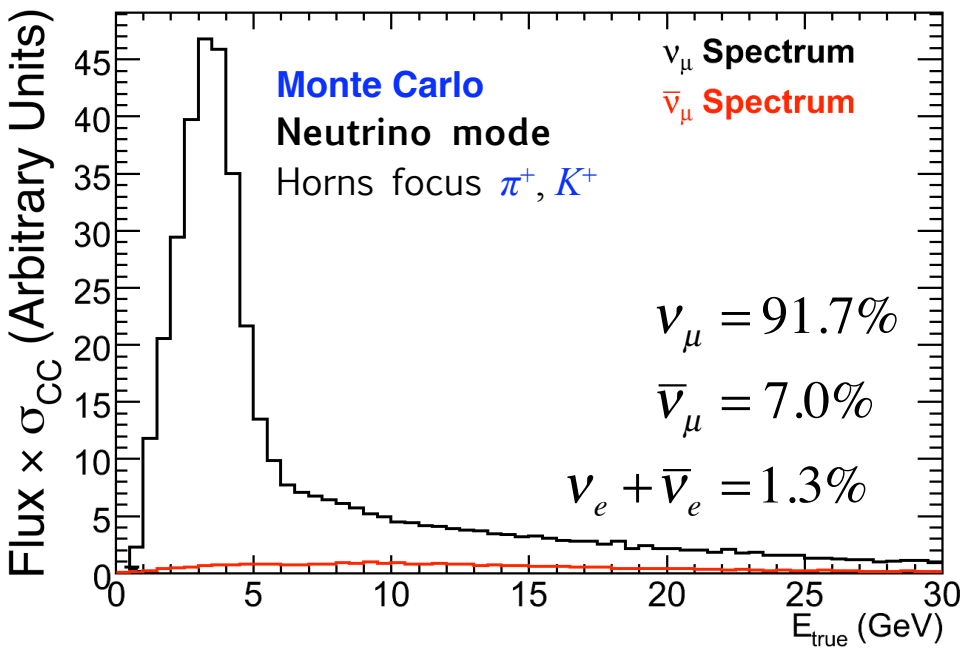
Neutrino and Antineutrino Disappearance

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

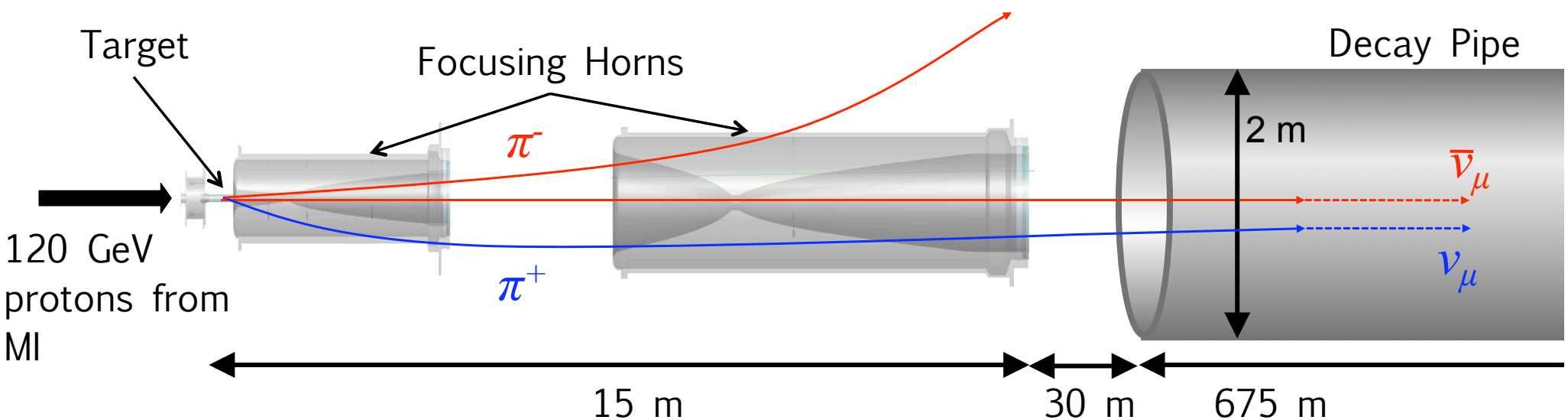


- Magnetized MINOS detectors can distiguish charge of muon: unique among oscillation experiments.
- A significant difference between effective mass splittings implies physics beyond the Standard Model, e.g. non-standard interactions.
- NuMI can be configured to generate a neutrino or an antineutrino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

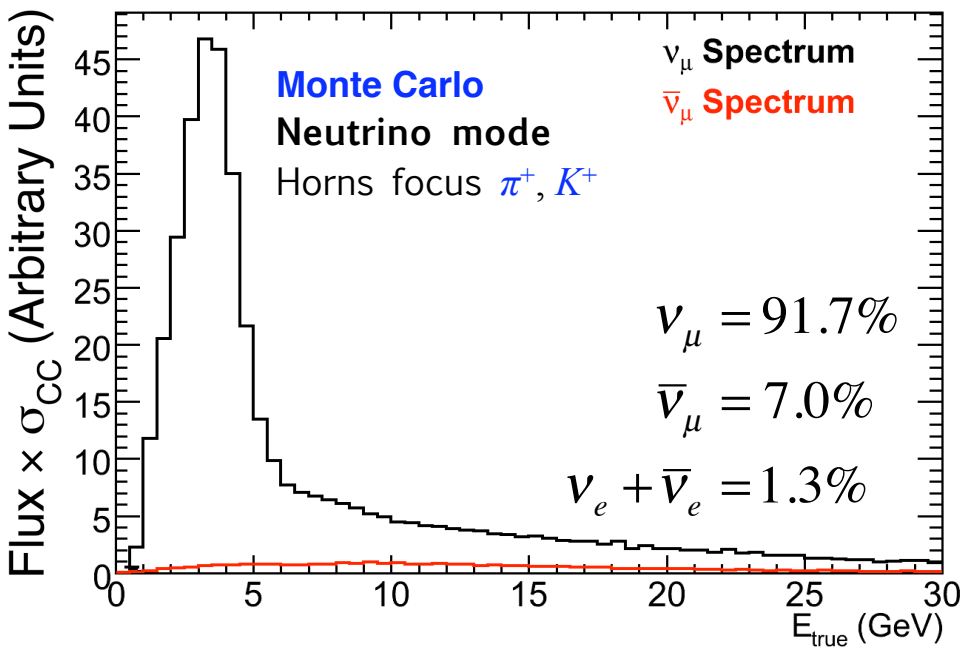
NuMI Neutrino Beam

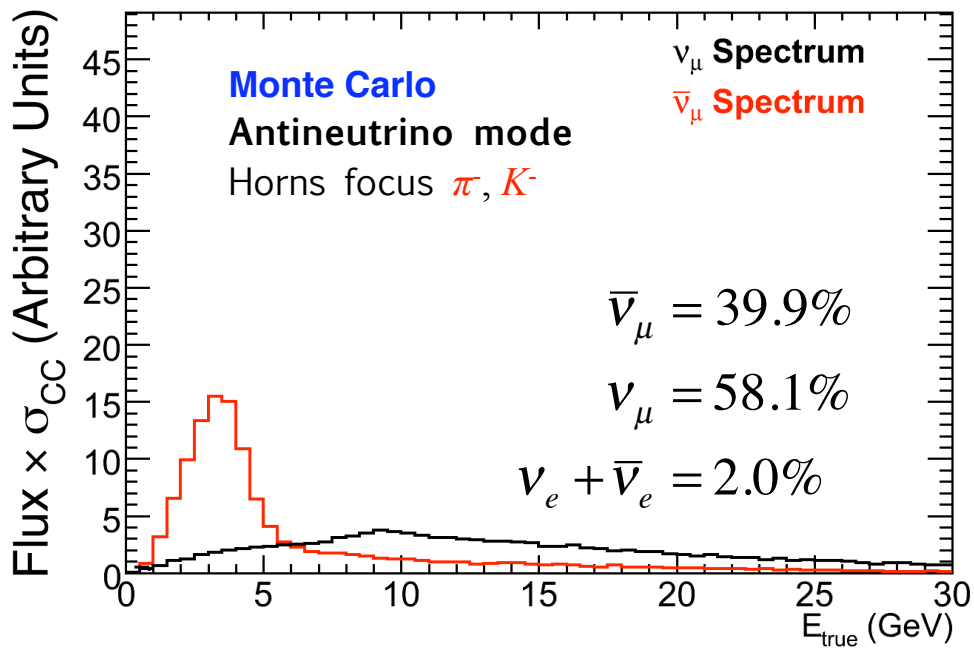


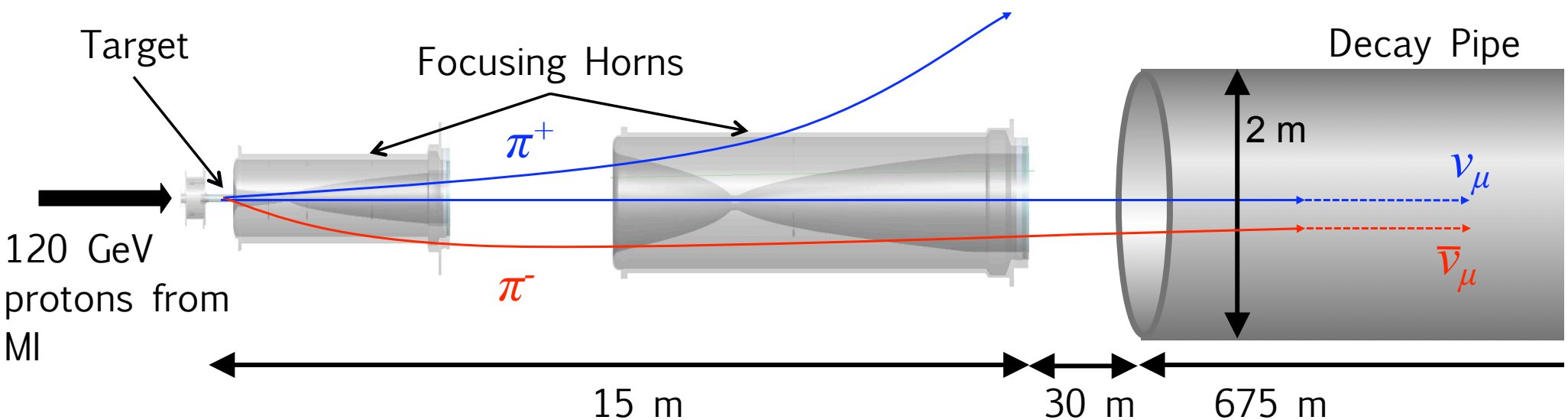
- Bombard graphite target with 120 GeV protons from the Main Injector: Produce pions and kaons
- Hadrons focused by two magnetic focusing horns
- Decay: 2m diameter pipe filled with He
- Wide-band beam, peak energy adjusted by target/horn position



NuMI Antineutrino Beam





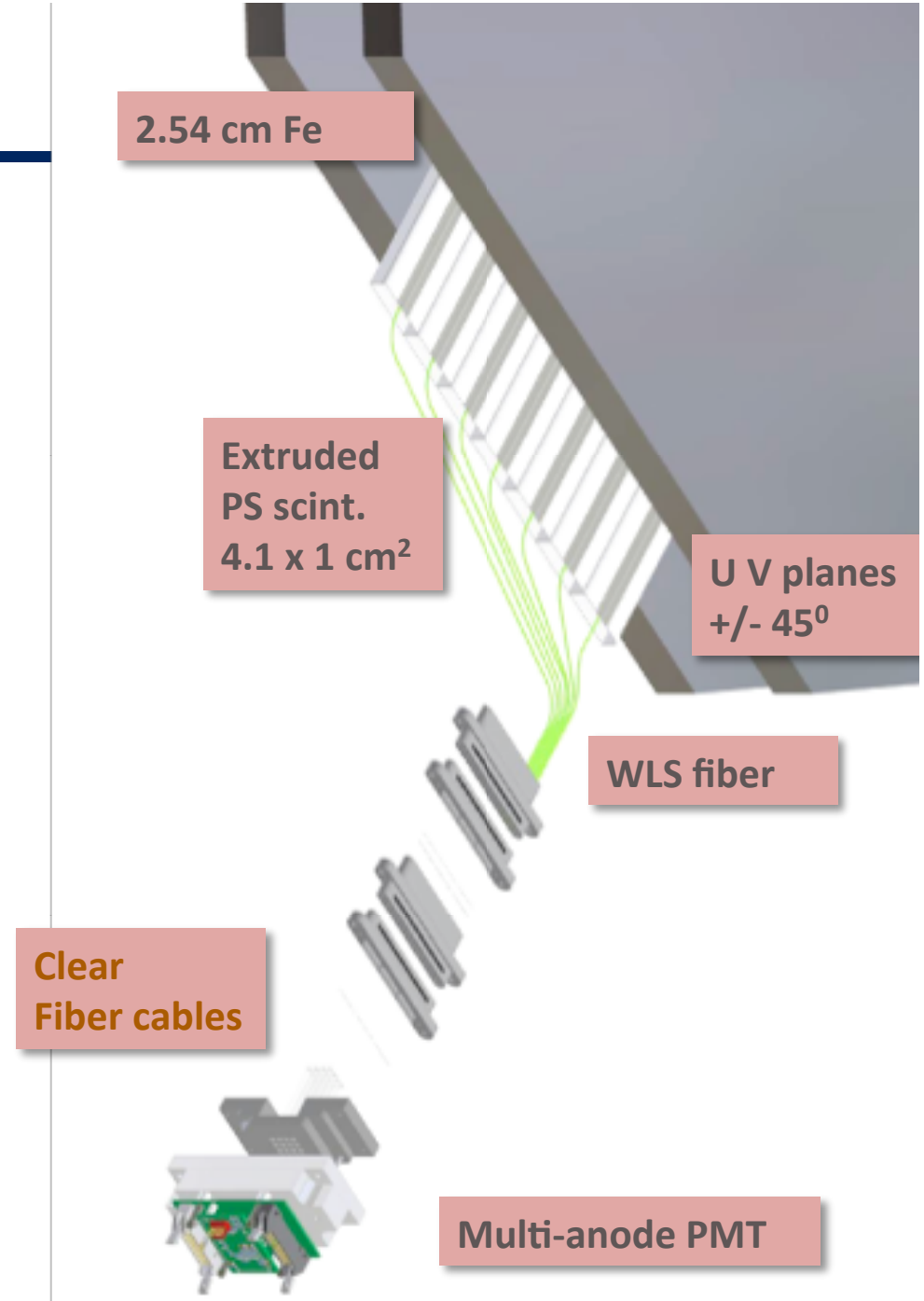


The Detectors

Magnetized, tracking calorimeters

Detector Technology

- Tracking sampling calorimeters
  - steel absorber 2.54 cm thick
  - scintillator strips 4.1 cm wide
  - 1 GeV muons penetrate 28 layers
- Magnetized
  - muon energy from range/curvature
  - distinguish μ^+ from μ^-
  - detector field adjustable to focus dominant particle in both beam modes
- Functionally equivalent
  - same segmentation
  - same materials
  - same mean B field (1.3 T)

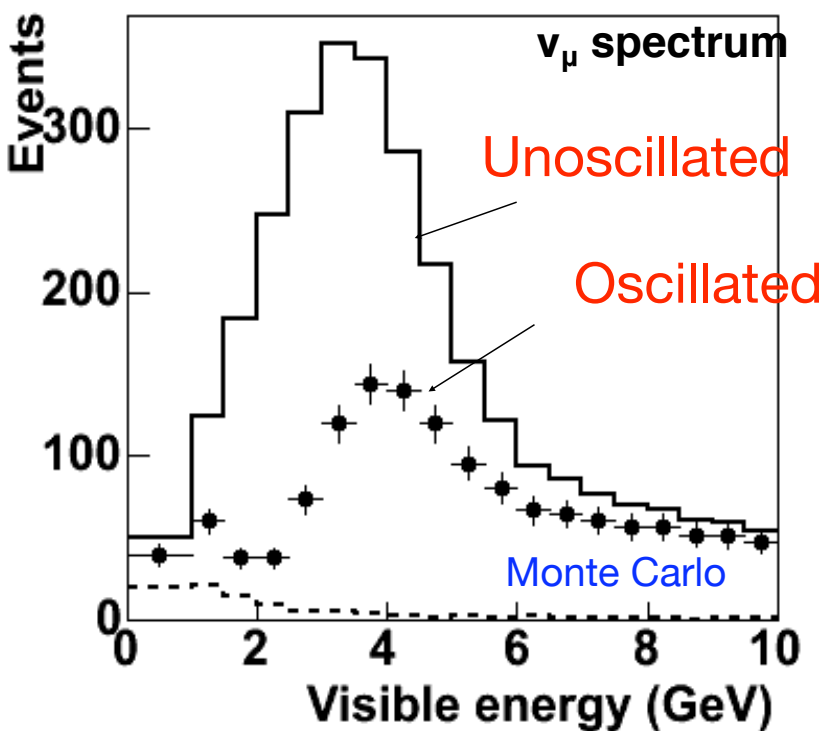


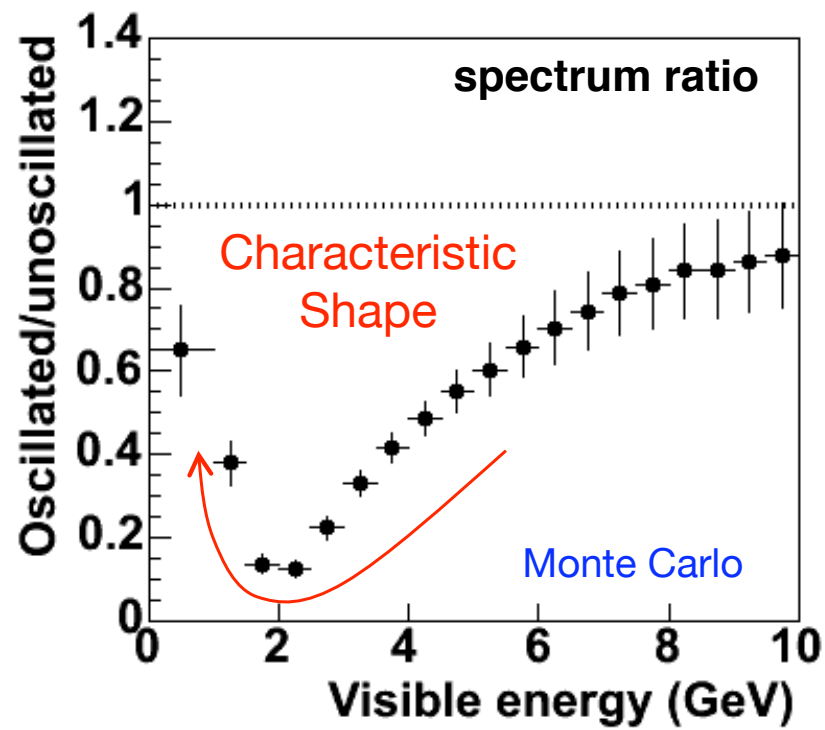
Measuring Oscillations

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

Monte Carlo

$\sin^2 2\theta = 1.0$, $\Delta m^2 = 3.35\times10^{-3}\ eV^2$





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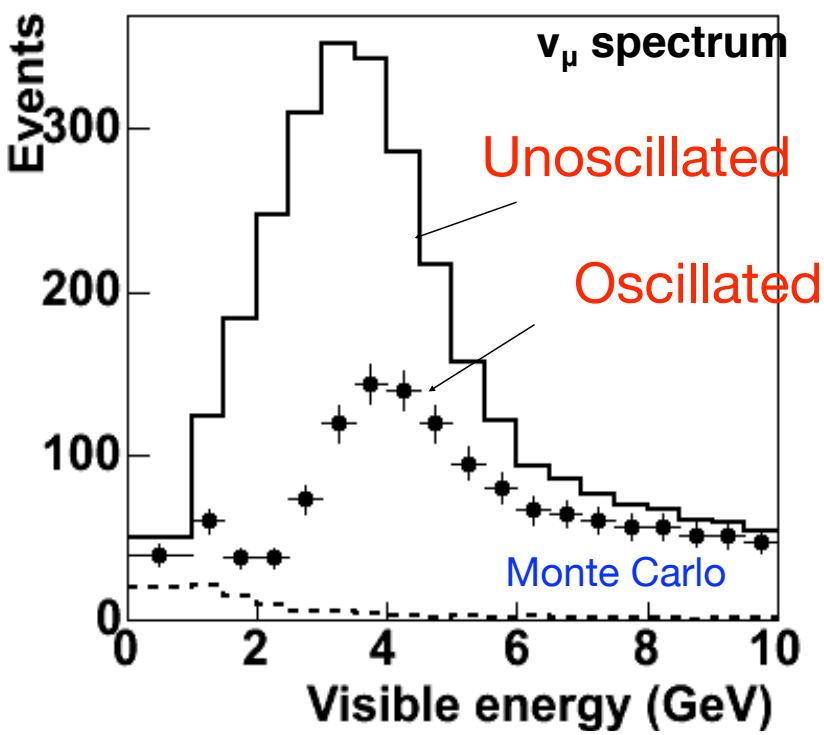

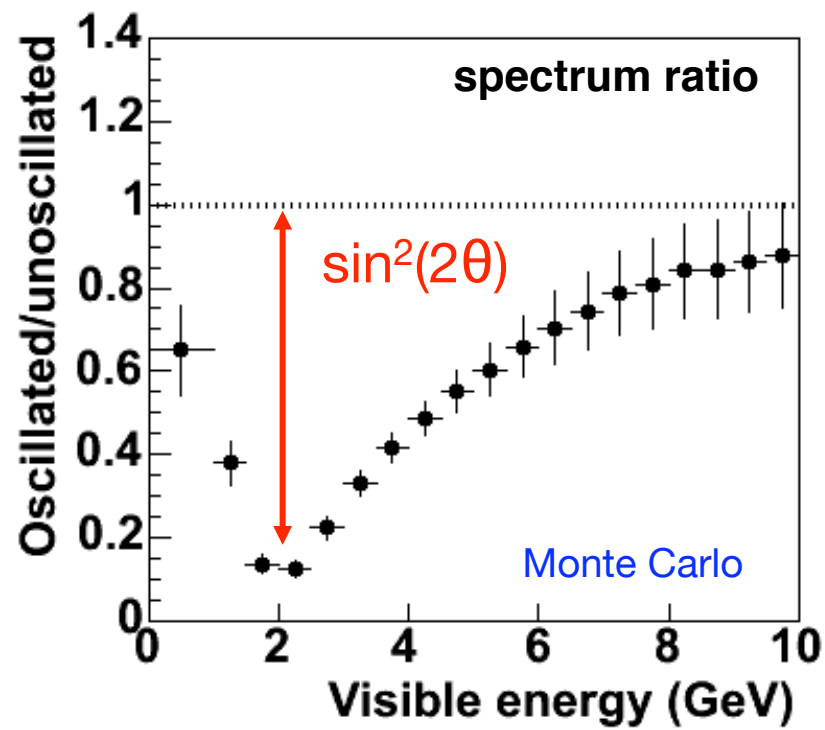

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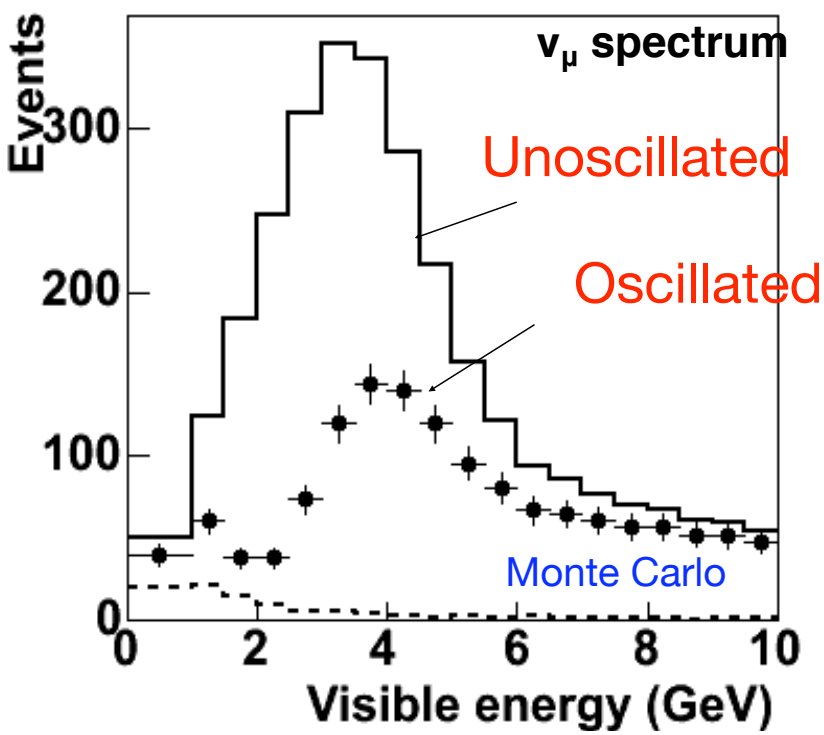
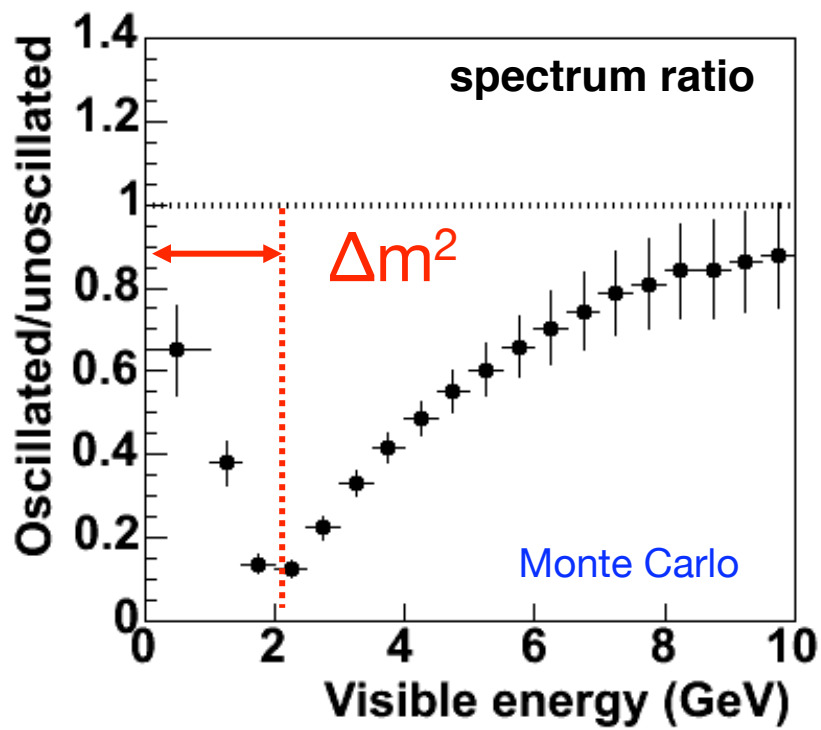
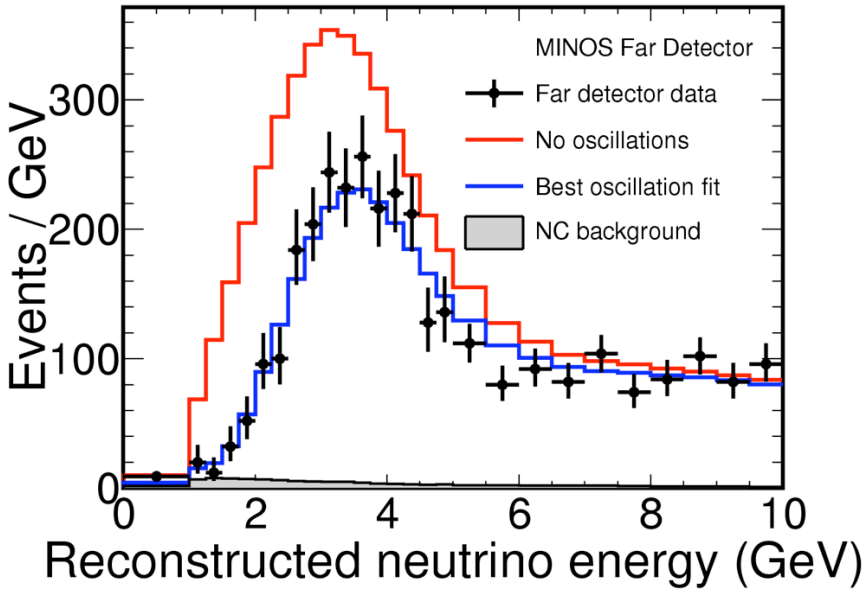
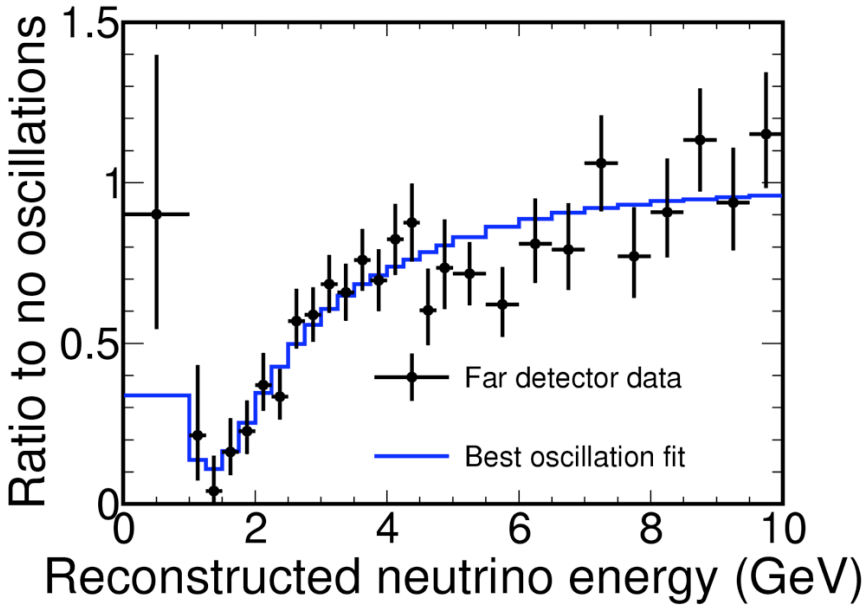


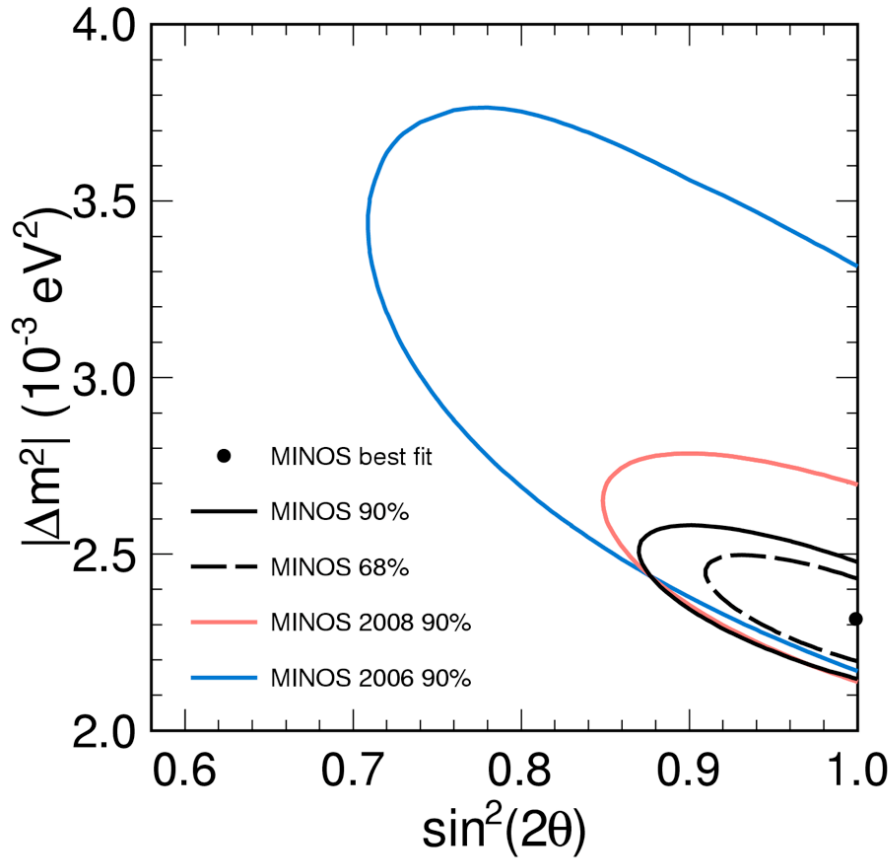


Neutrino Oscillation Results

Phys.Rev.Lett.106:181801,2011
arXiv:1103.0340v1 [hep-ex]







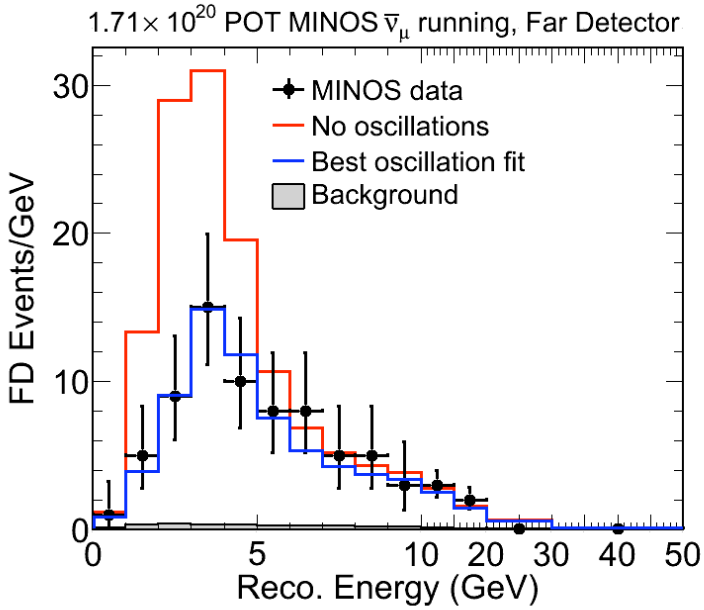
$$|\Delta m^2| = 2.32^{+0.12}_{-0.08} \times 10^{-3}\mathrm{eV}^2$$

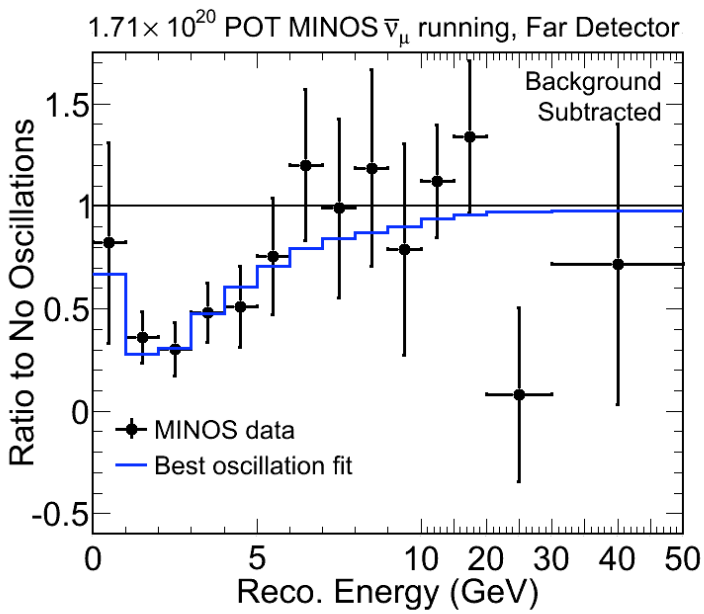
$$\sin^2(2\theta) = 1.0$$

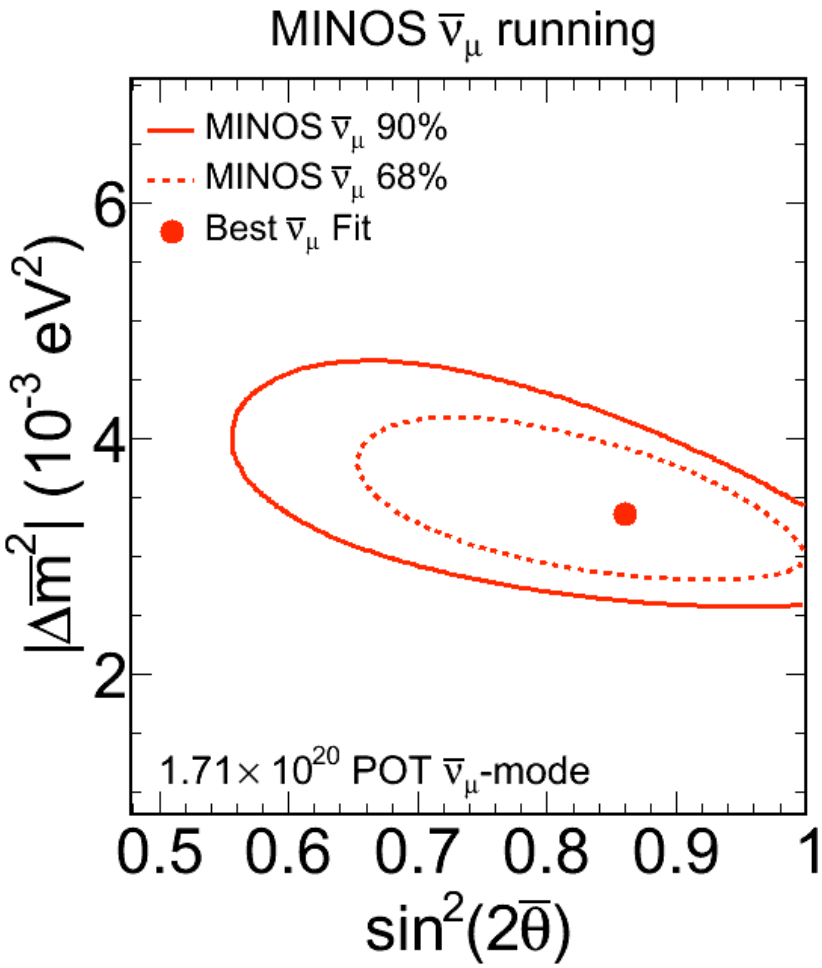
$$\sin^2(2\theta) > 0.90\ (90\%\mathrm{C.L.})$$

First Antineutrino Oscillation Results

Phys.Rev.Lett.107:021801,2011
arXiv:1104.0344v3 [hep-ex]



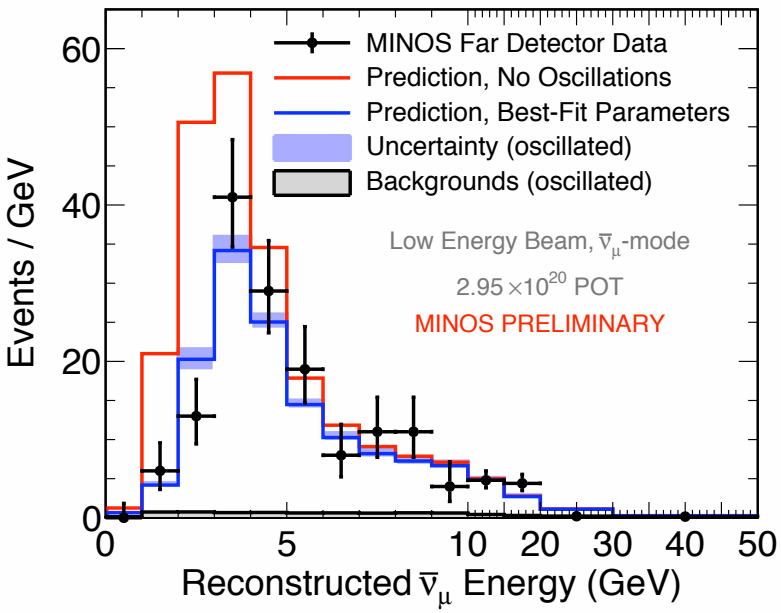


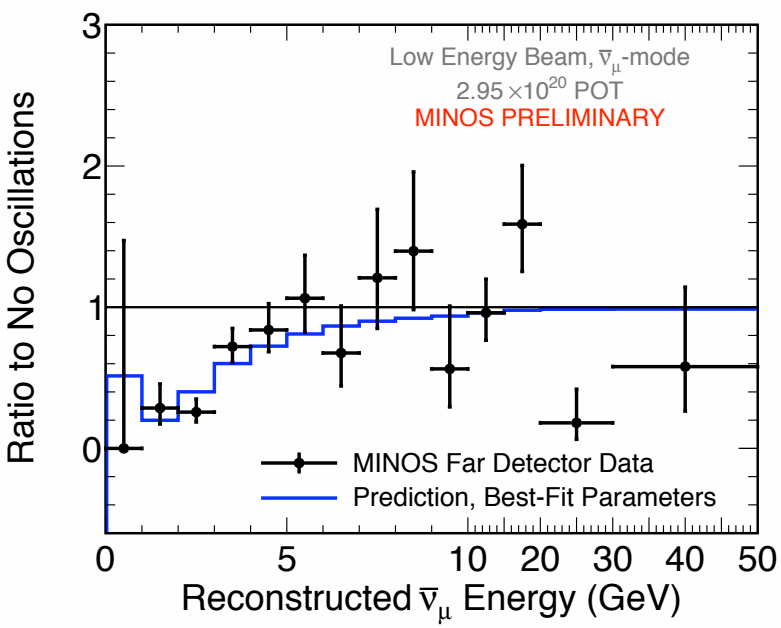


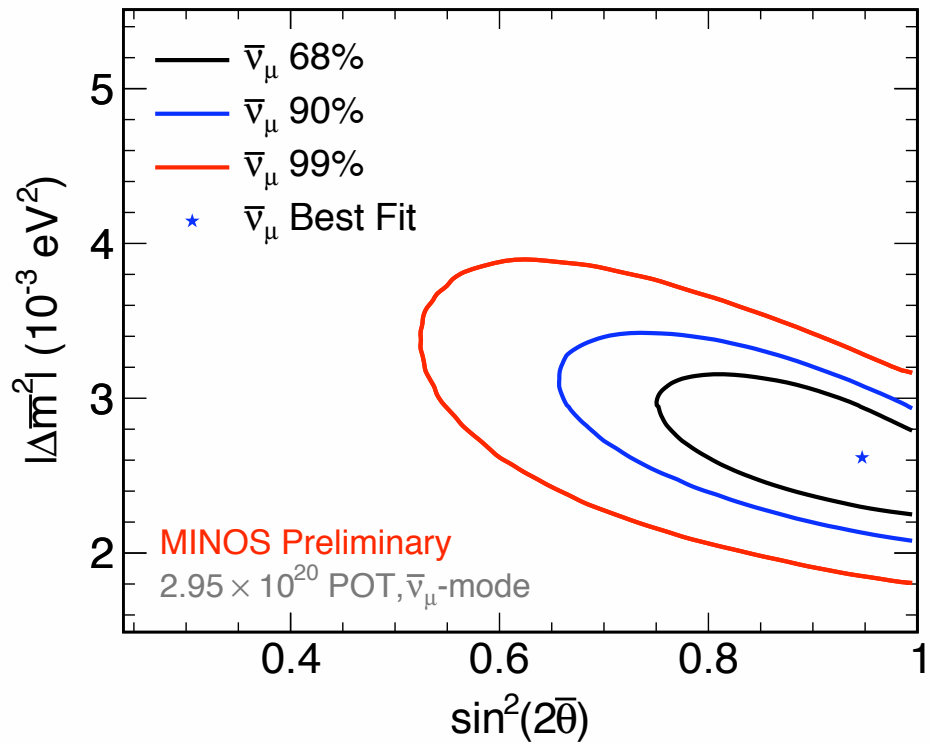
$$|\Delta\overline{m}^2| = 3.36^{+0.45}_{-0.40} \times 10^{-3}\mathrm{eV}^2$$

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

Latest Antineutrino Oscillation Results



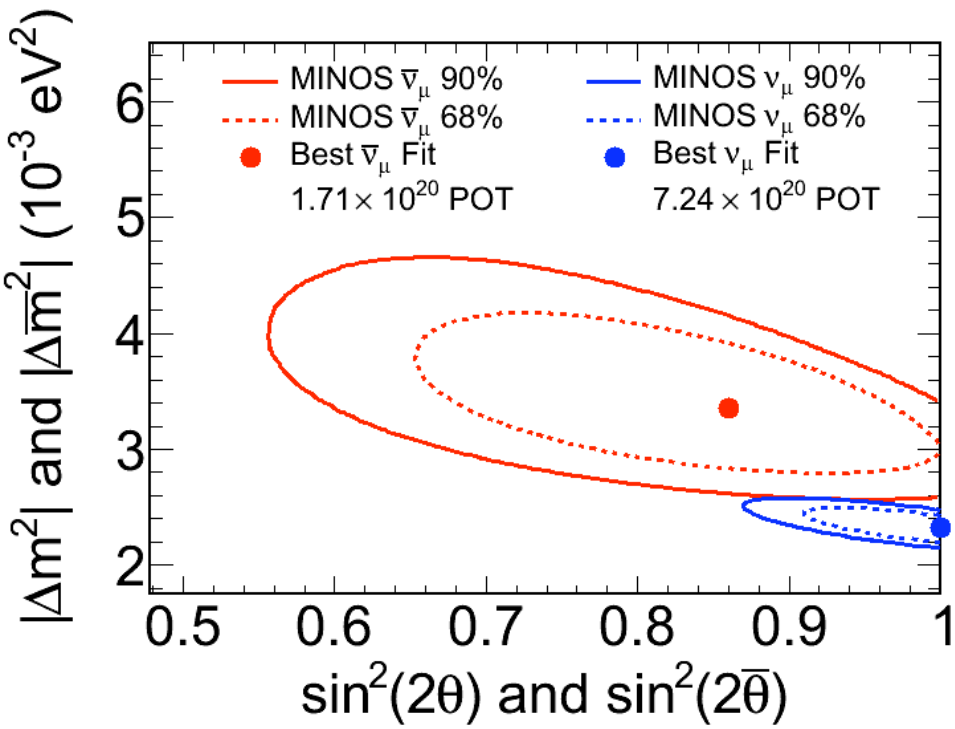


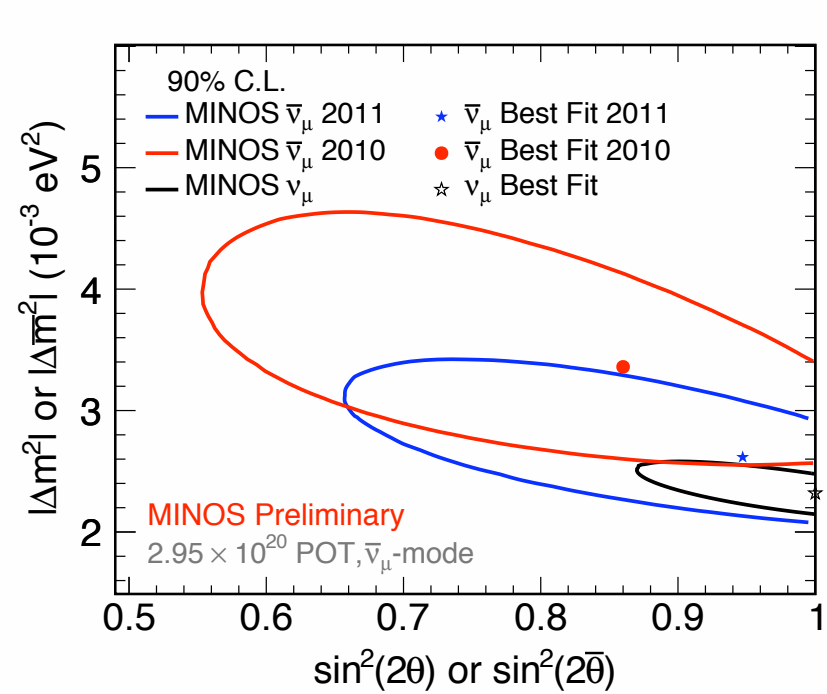


Prediction, No Oscillations: **273 events**
Observed: **193 events**
Null-oscillations excluded at **7.3σ**

$$|\Delta\bar{m}^2_{atm}| = [2.62^{+0.31}_{-0.28}(\text{stat}) \pm 0.09(\text{syst})] \times 10^{-3}\text{eV}^2$$
$$\sin^2(2\bar{\theta}_{23}) = 0.95^{+0.10}_{-0.11}(\text{stat}) \pm 0.01(\text{syst})$$

Neutrinos and Antineutrinos





- Two measurements are consistent at 2% assuming identical underlying oscillation parameters.
- Motivates the search for non-standard interactions.

- Two measurements are consistent at 42% assuming identical underlying oscillation parameters.
- Less room for large NSI but tighter limits with more data.

Non-standard interactions

- Coherent forward scattering of neutrinos via interactions with matter as they propogate.

$$H_{\text{matter}} = V \begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau} \end{pmatrix}$$

$$V = \sqrt{2} G_F N_e$$

- Flavor conserving or flavor changing; only focus on flavor changing here.
- Real valued epsilon: CP violating imaginary part does not distinguish neutrinos and antineutrinos.
- Two-flavor NSI for MINOS.

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

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

Real valued epsilon changes sign between neutrinos and antineutrinos

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

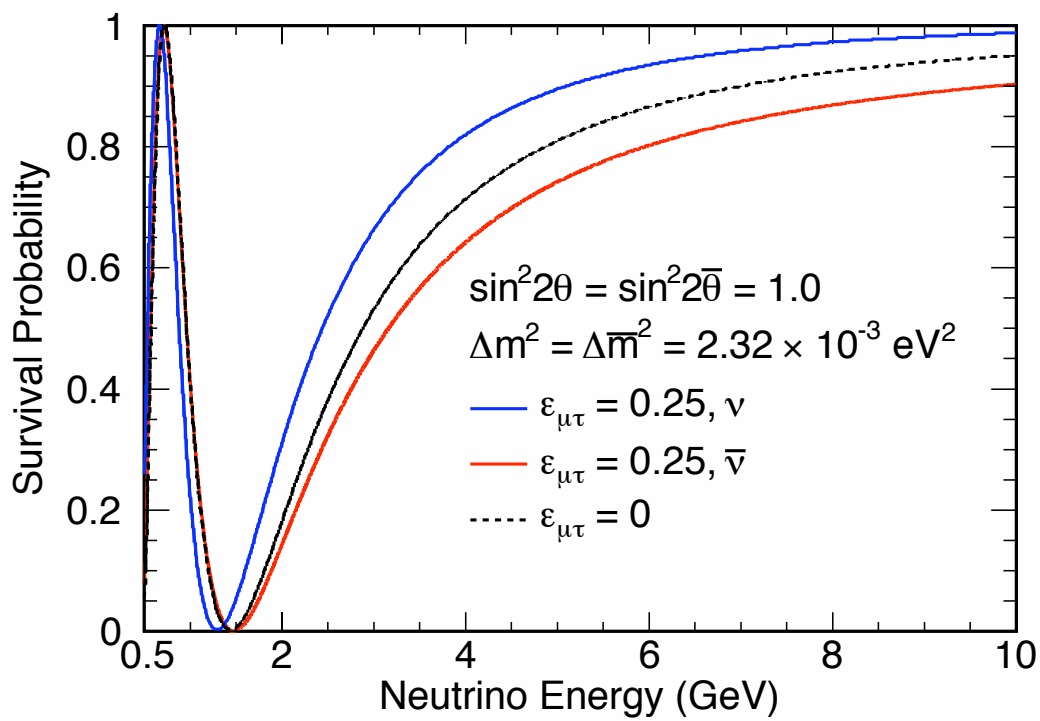
Flavor changing non-standard interactions

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

- In units of GeV, km, eV^2

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

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



$$V = \sqrt{2}G_F N_e$$

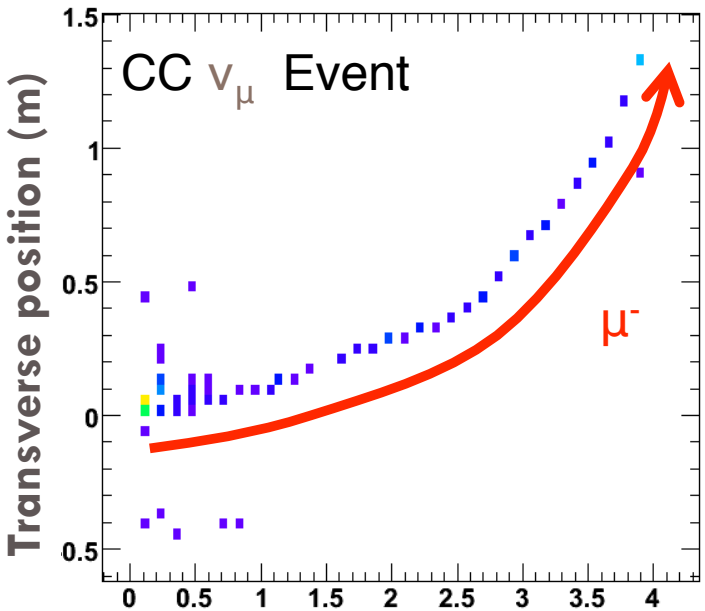
$$\text{with } \epsilon = 0;\ F_1 = \left(1.27\frac{\Delta m^2 L}{E}\right),\ F_2 = 1$$

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

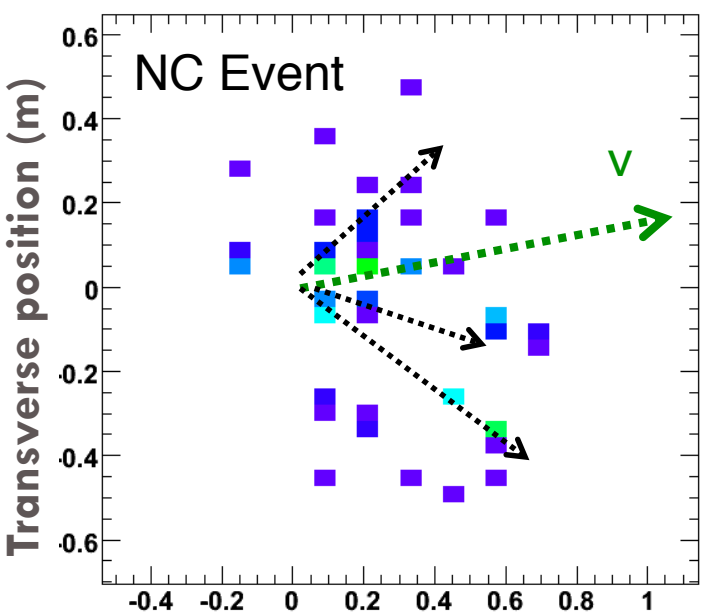
Non-standard interaction analysis

- 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.
- Blind analysis.
- Analysis with antineutrino data from Run IV only presented first.

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.

Event Selection

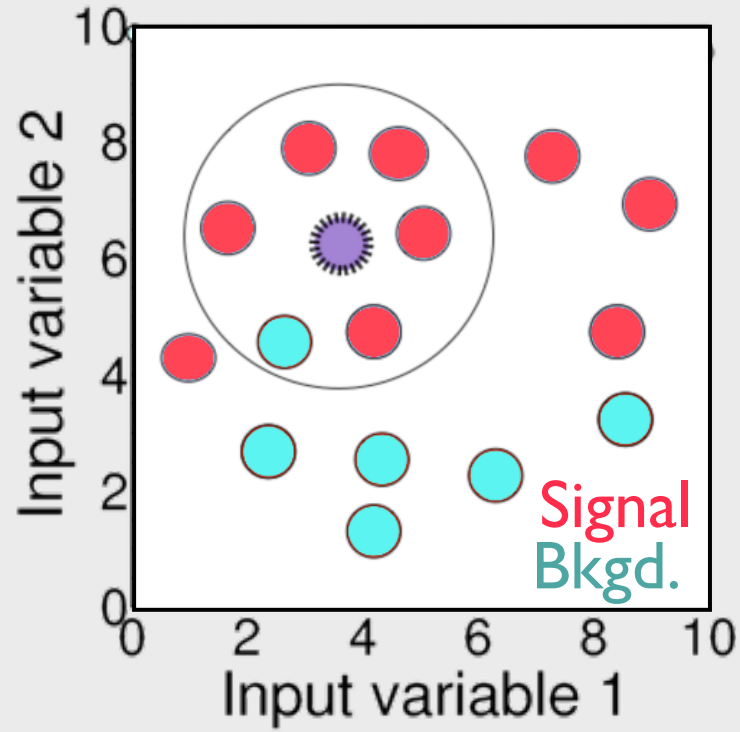
- CC/NC separation using a kNN algorithm
  - Compare to Monte Carlo events
  - Determine the distance of query event to each MC signal and background event in N-dimensional space of track-related variables

$$D = \left(\sum_{i=1}^{N_{\mathrm{Var}}} |X_i^{MC} - X_i^Q|^2 \right)^{\frac{1}{2}}$$

- Use the k nearest neighbors to classify query event:

$$\mathrm{kNN_{ID}} = \frac{k_S}{k_S + k_B}$$

- MINOS kNN: 4 variables, k=80



k-Nearest Neighbors (kNN) example 2 variables

The k = 6 nearest neighbors contain one red and five blue
This point has a kNN of 5/6

k=6, k_S=5, k_B=1 ⇒ $\mathrm{kNN_{ID}}$=5/6

Neutrino Selection

CC/NC separation using a k-Nearest Neighbors track recognition algorithm:

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

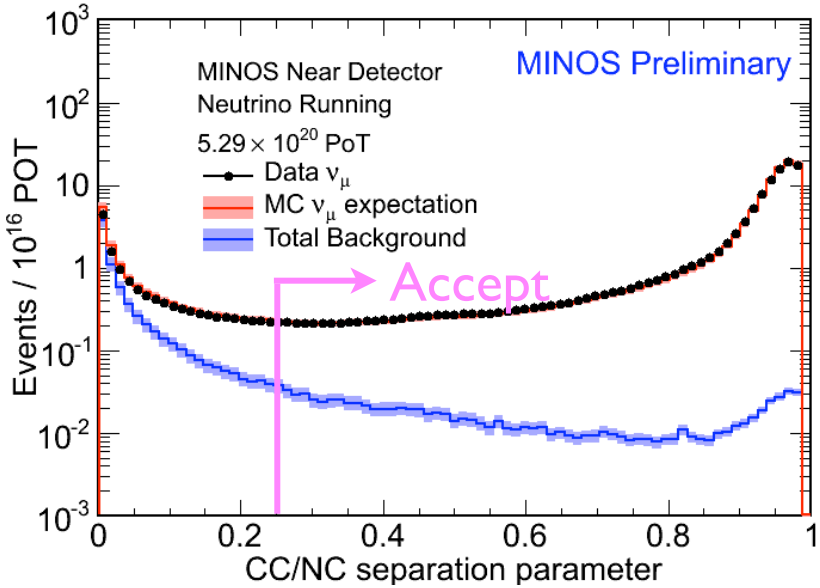
OR

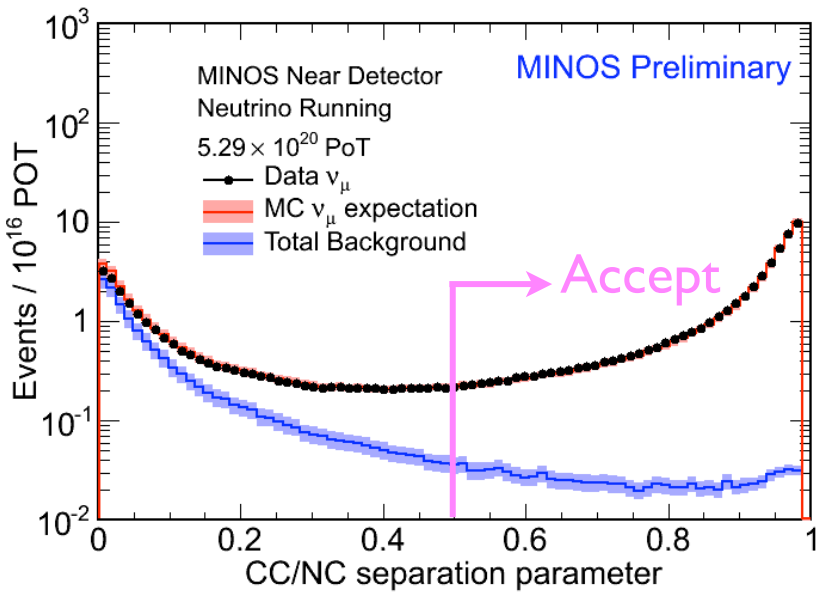
Additional algorithm to improve low energy efficiency:

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

AND

Select on negative reconstructed charge



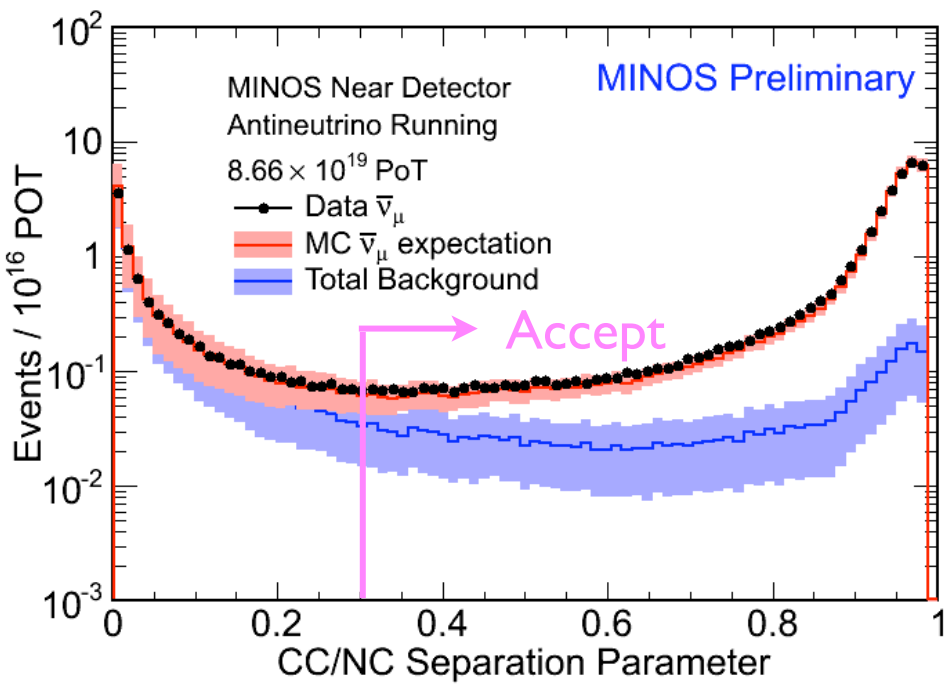


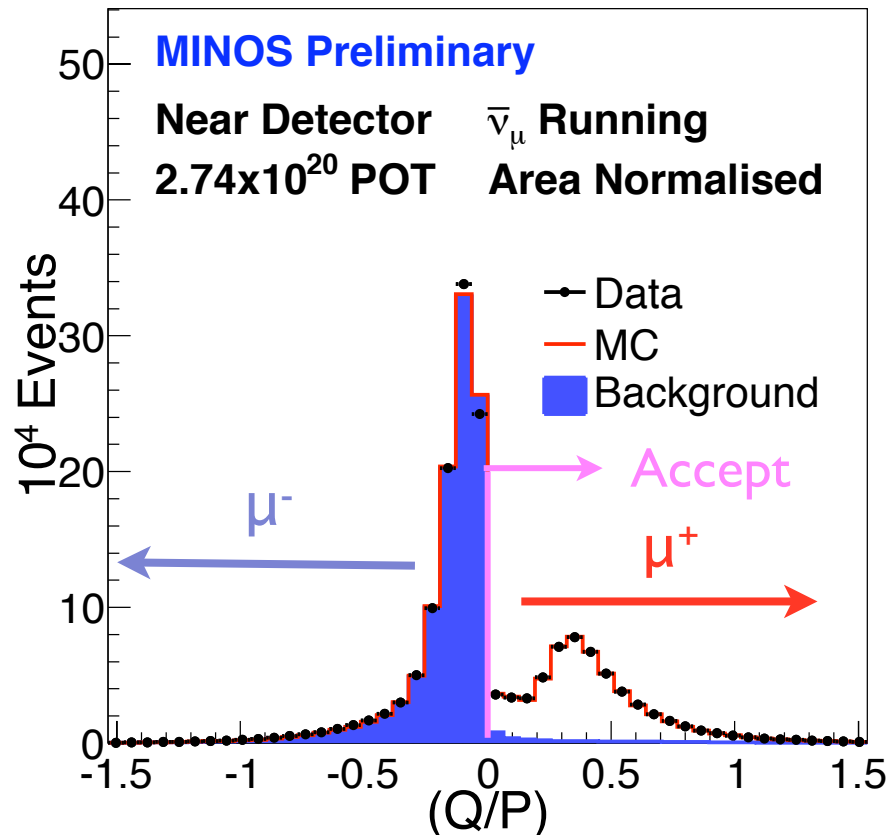
Antineutrino Selection

CC/NC separation using the primary track recognition algorithm:

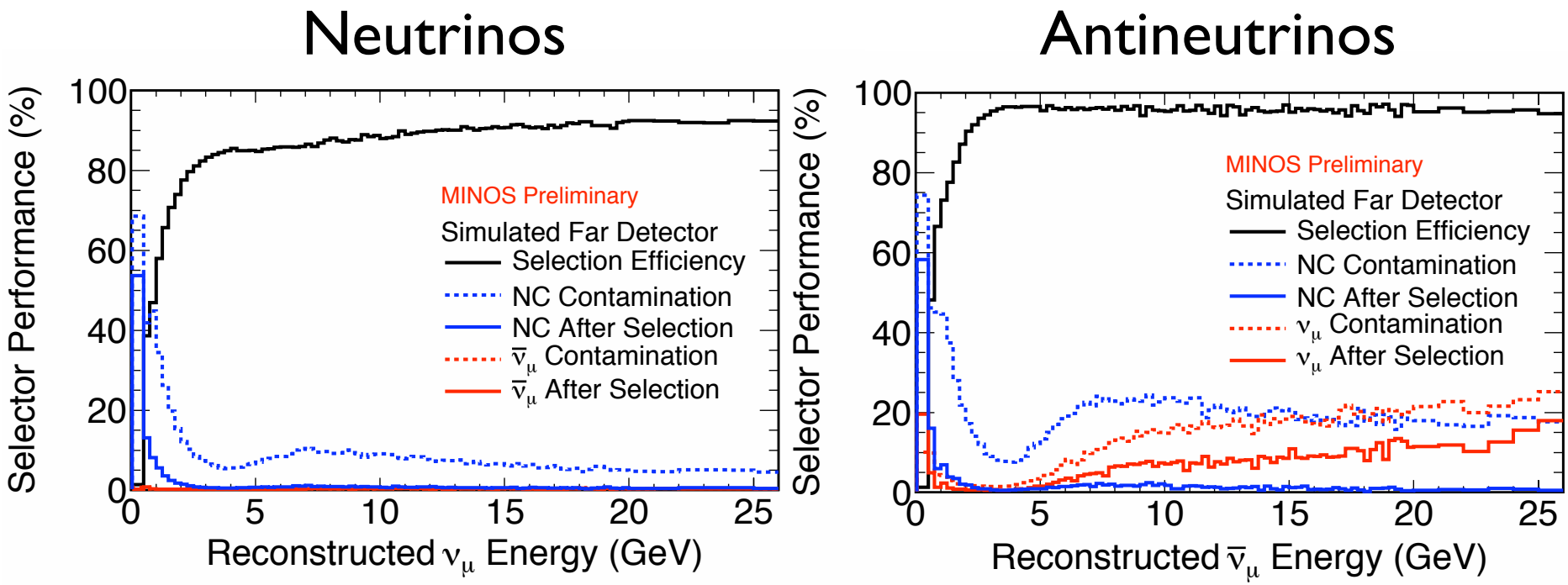
AND

Select on positive reconstructed charge





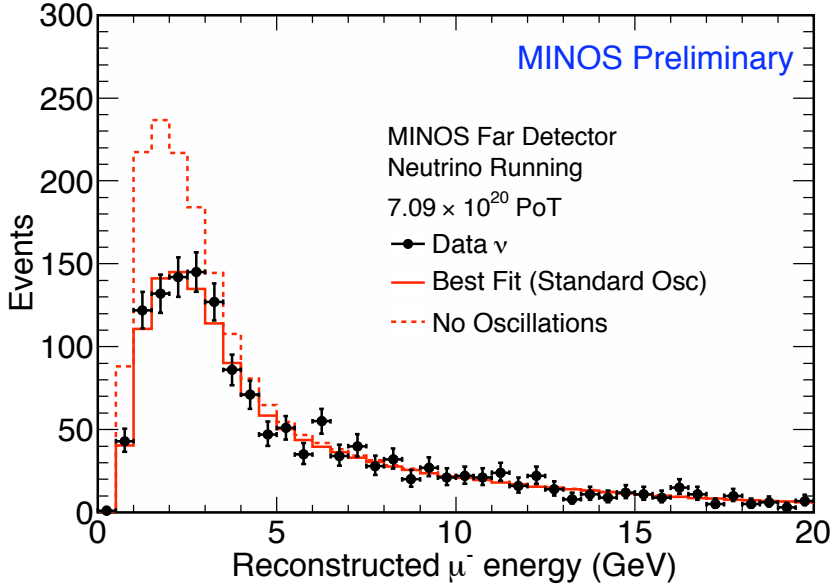
Selection Efficiency

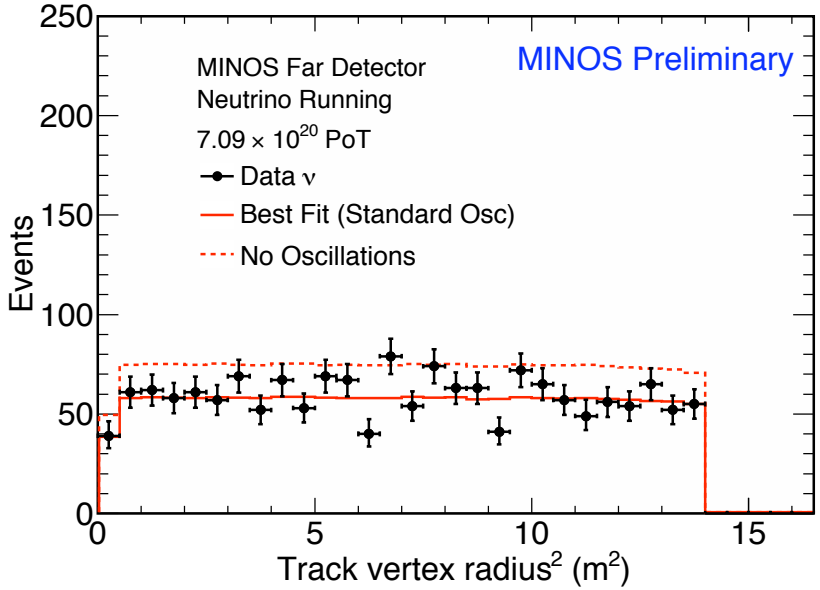


- Additional low energy kNN improves efficiency of the neutrino sample at low energy.
- Wrong sign component minimized as robustly as possible in both samples: Essential for this analysis.

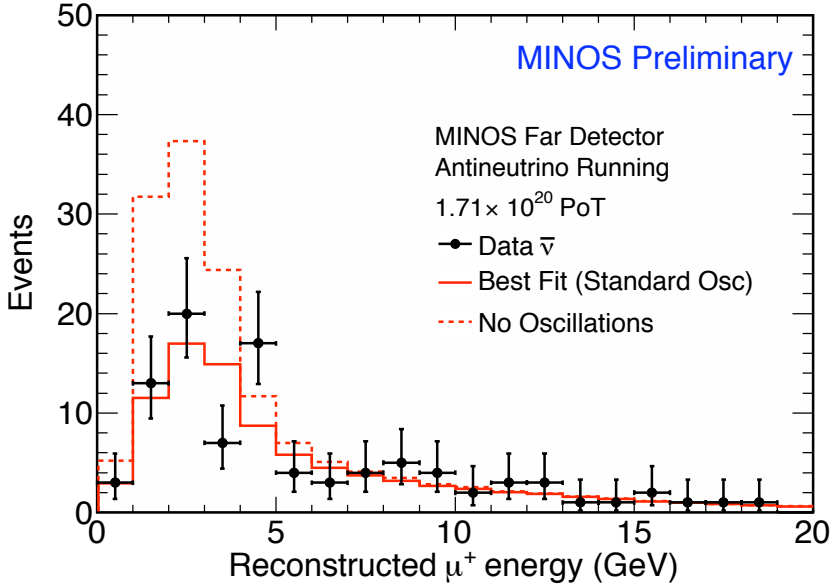
Far Detector Data/MC

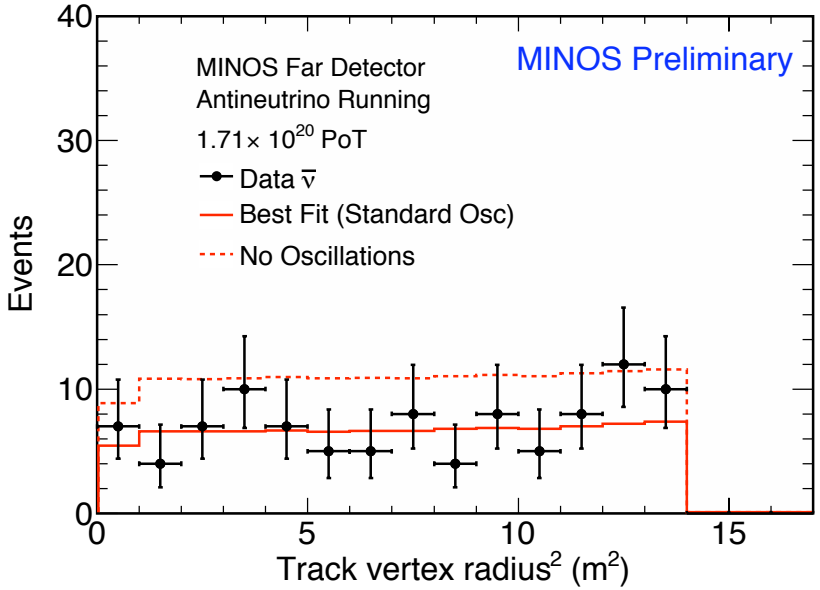
Neutrinos





Antineutrinos



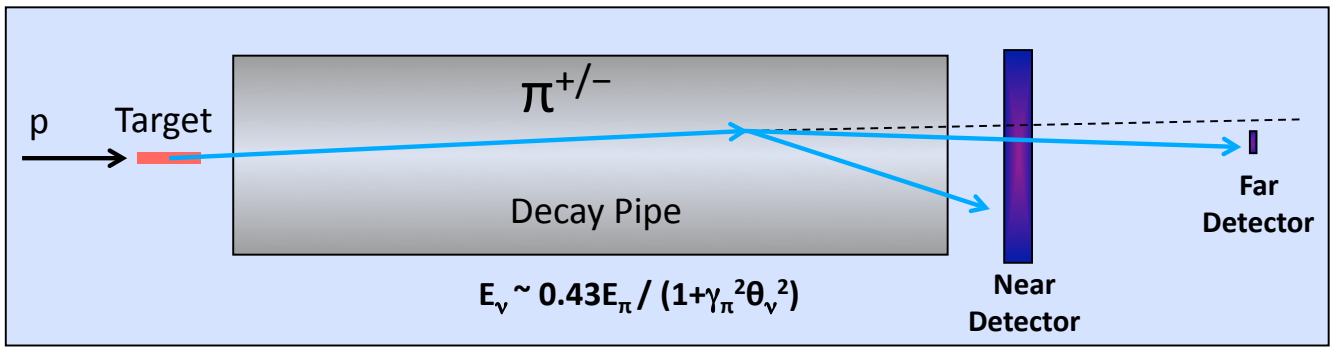


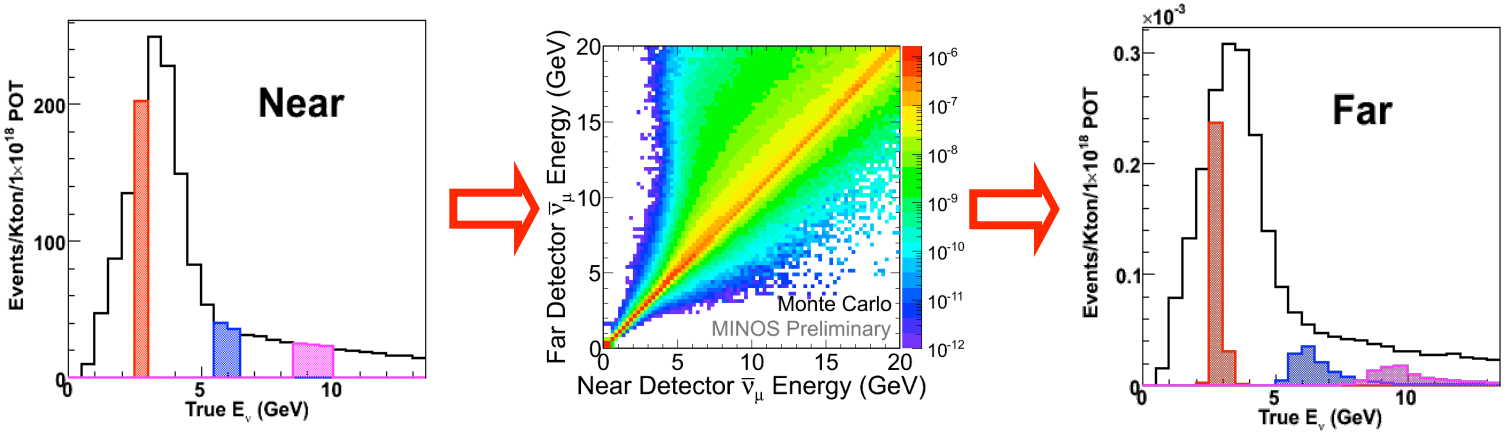
Near to Far Extrapolation

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

- Neutrino energy depends on angle wrt original pion direction and parent energy

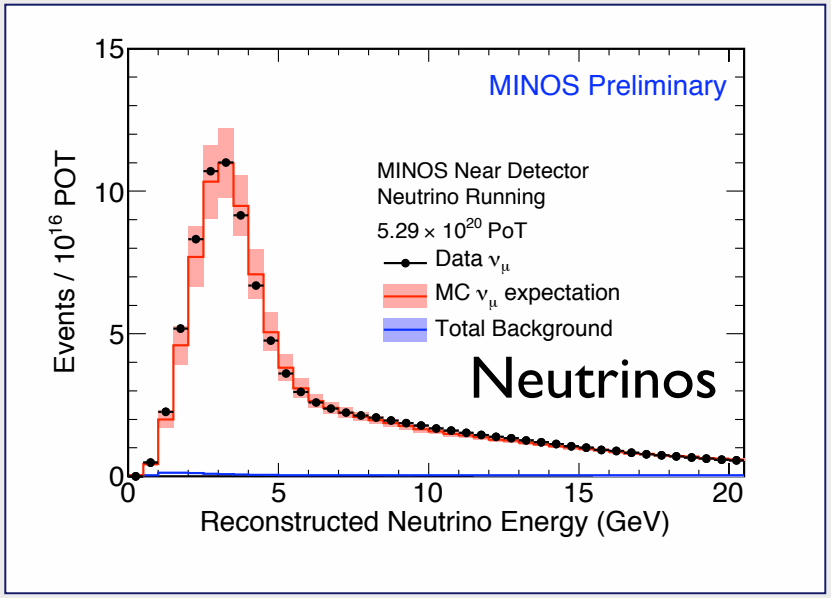
- higher energy pions decay further along decay pipe
- angular distributions of pions and neutrinos are different between Near and Far

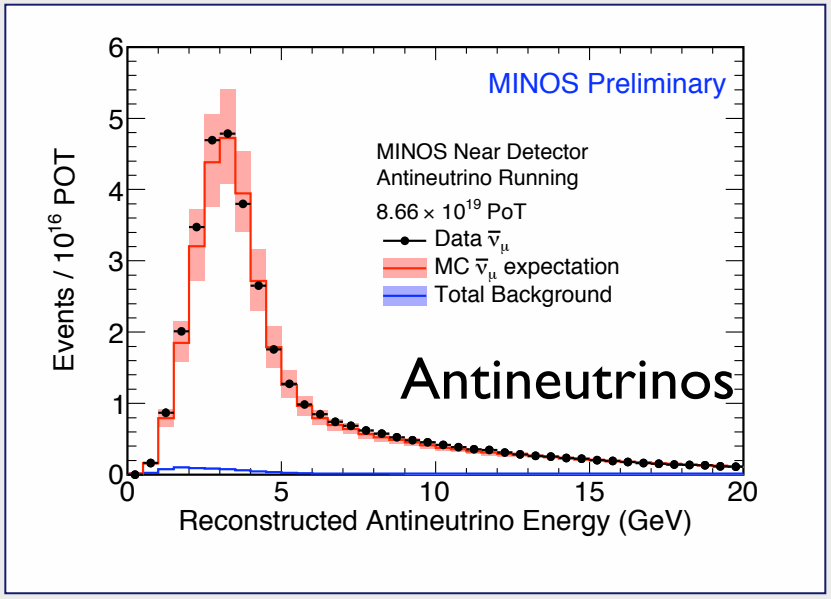




Beam Matrix: Find true ND and FD events from their parent pion.

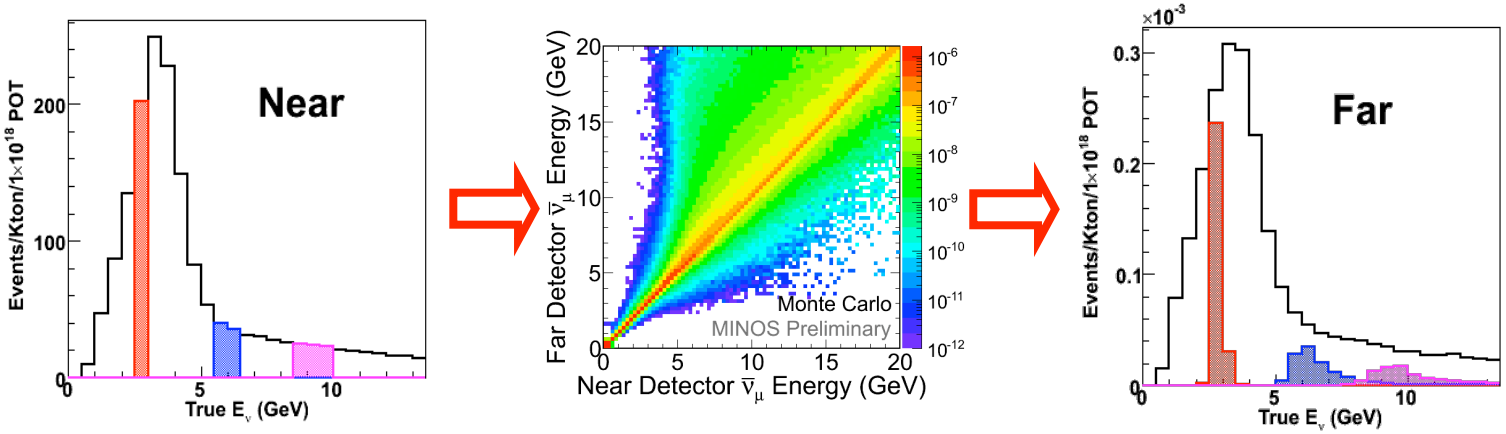
Near to Far Extrapolation





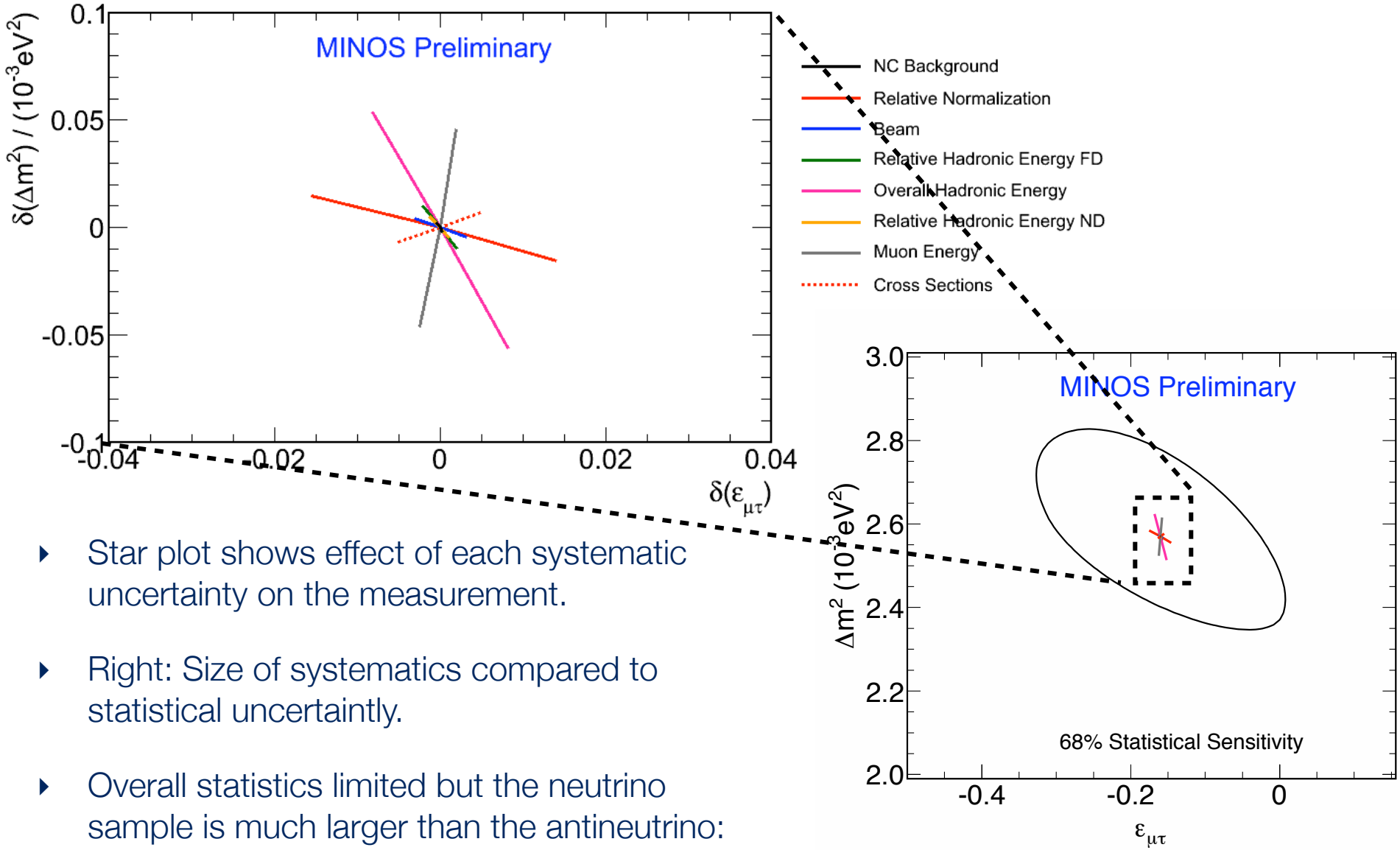
Near Detector energy spectrum shows good modeling of data by MC in both charge signs.

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



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

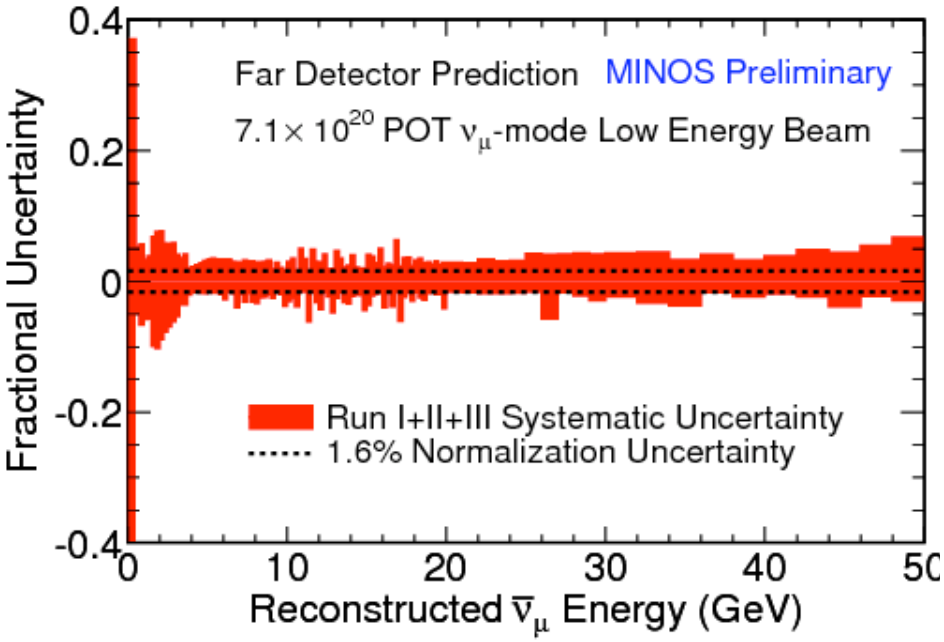
Systematic Uncertainties

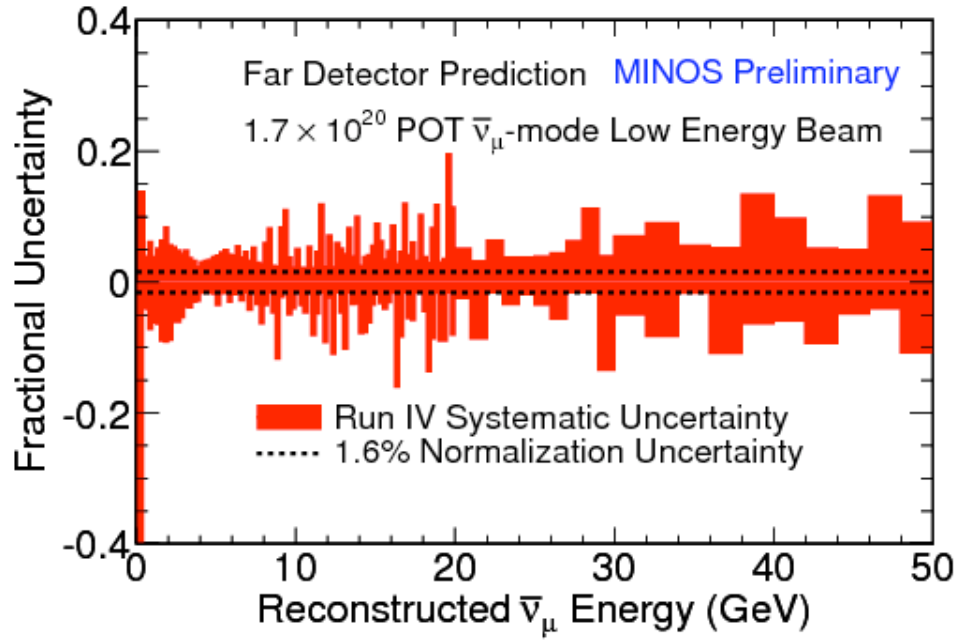


- Star plot shows effect of each systematic uncertainty on the measurement.
- Right: Size of systematics compared to statistical uncertaintly.
- Overall statistics limited but the neutrino sample is much larger than the antineutrino: Account for systematics in the fit

Systematic Uncertainties

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



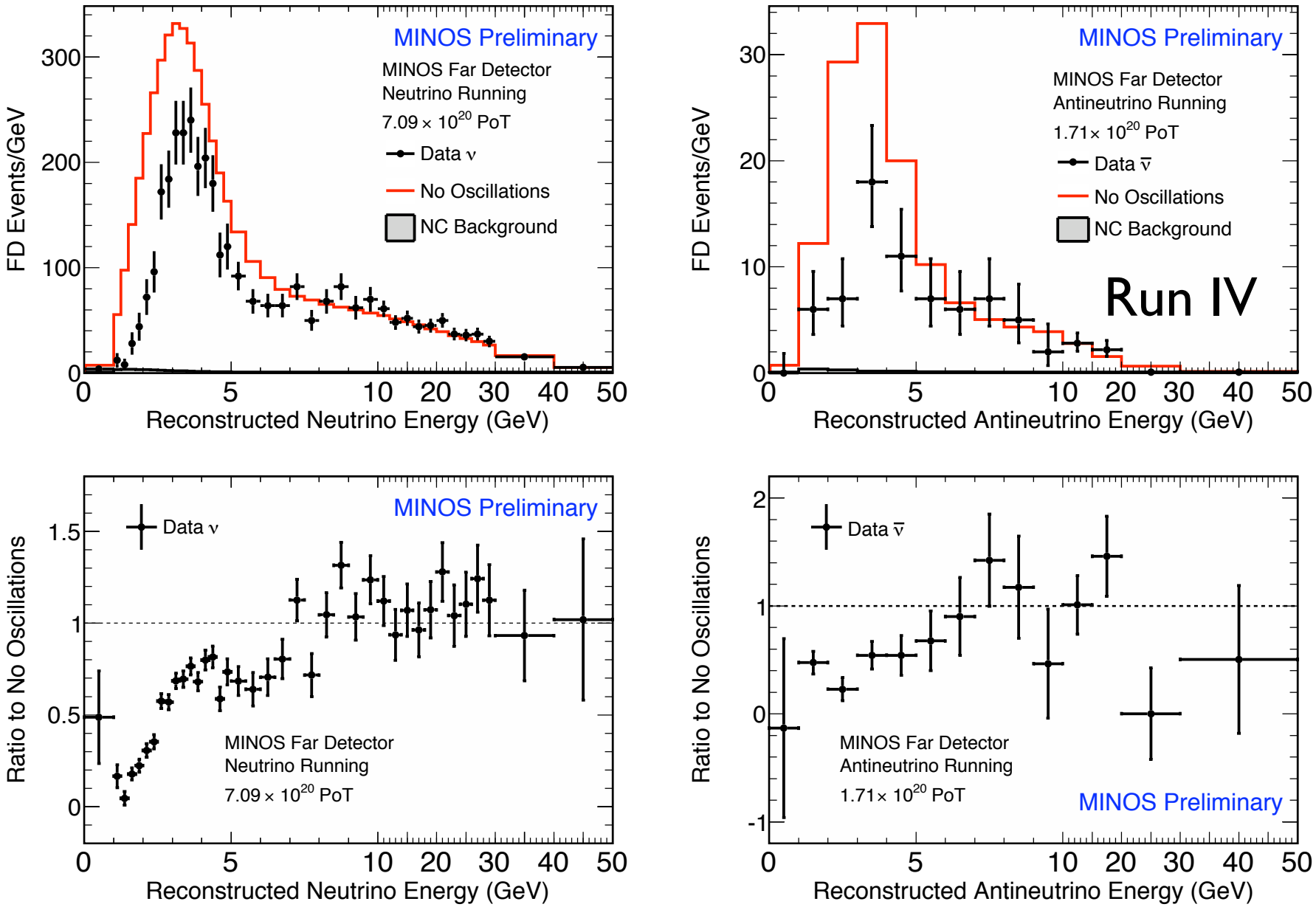


- Systematics <10% across all energies; preliminary conservative inclusion in the fit as a flat 10% normalization.

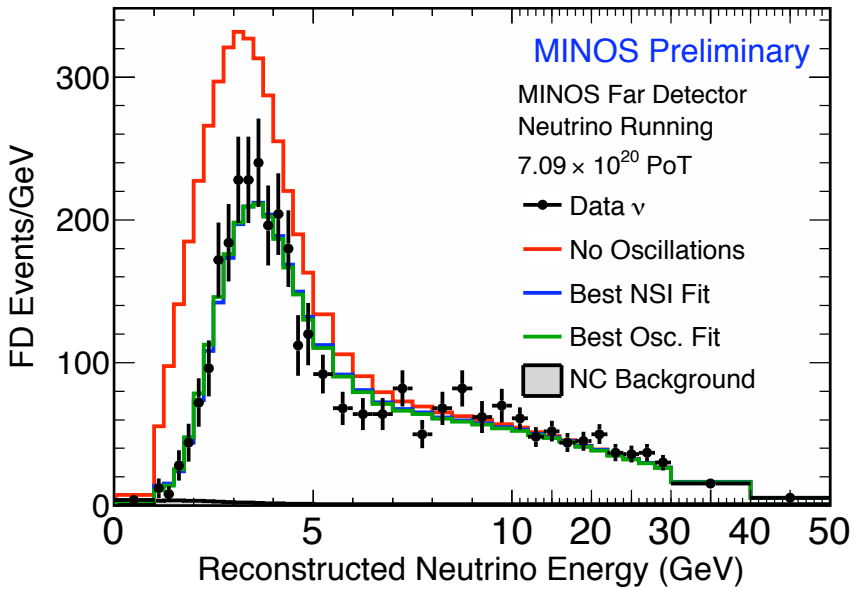
$$-2\ln\lambda = 2\sum_{r=1}^{4}\sum_{i=1}^{N} n_{ri}^{\mathrm{pred}} - n_{ri}^{\mathrm{data}} + n_{ri}^{\mathrm{data}} \ln\frac{n_{ri}^{\mathrm{data}}}{n_{ri}^{\mathrm{pred}}} + \left(\frac{S-1.0}{\sqrt{0.1}}\right)^2$$

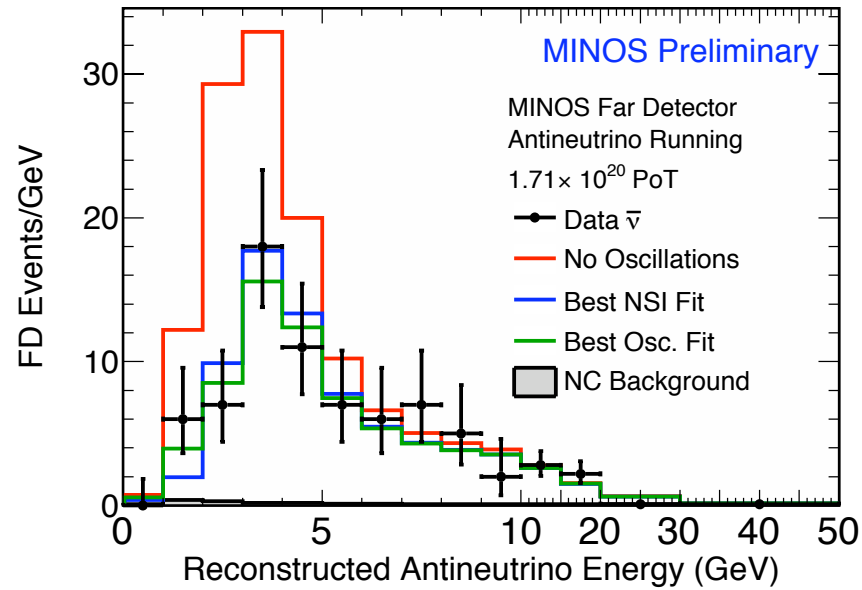
PRELIMINARY

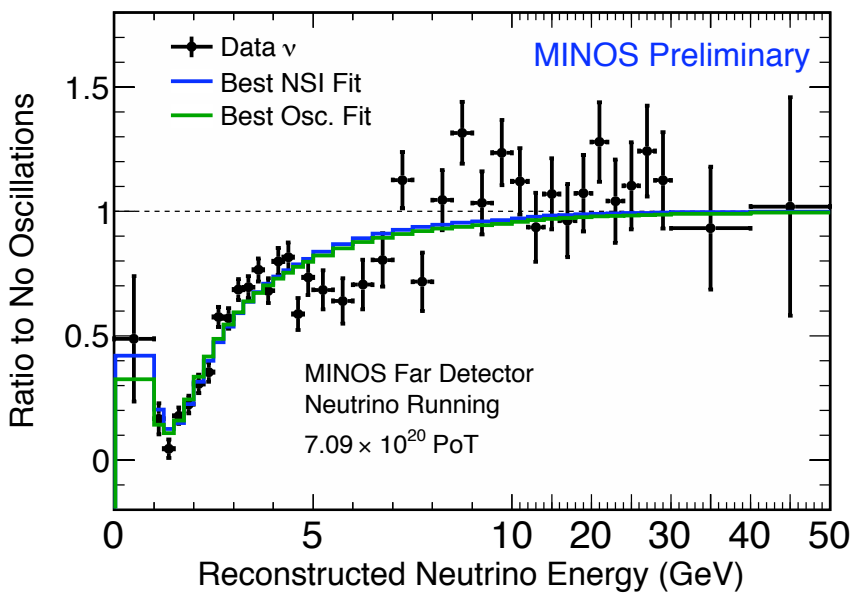
Far Detector Spectra

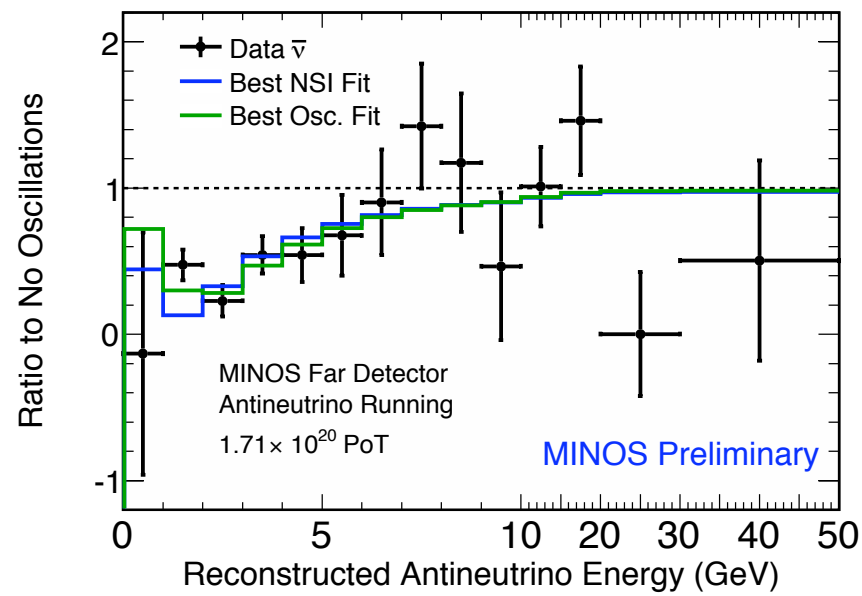


Results

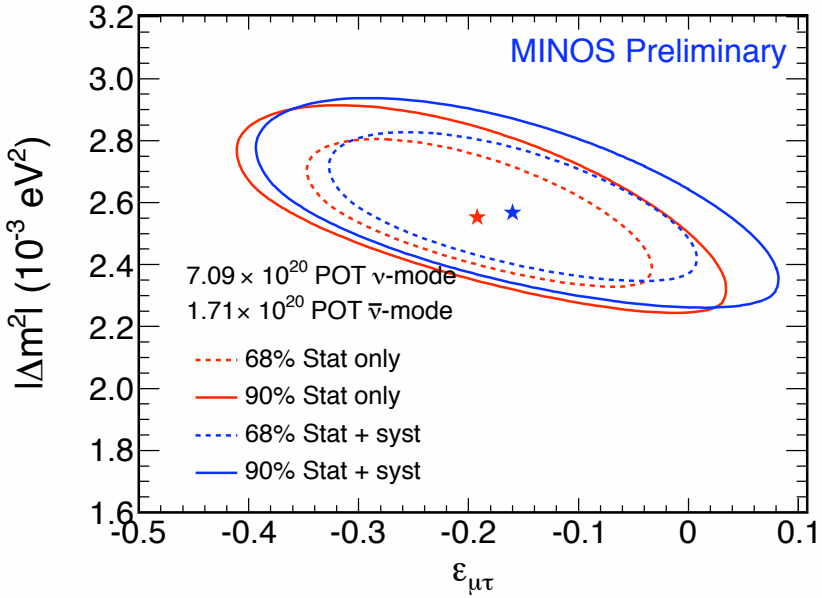

MINOS Preliminary
MINOS Far Detector
Neutrino Running
7.09 × 10^20 PoT
Data ν
No Oscillations
Best NSI Fit
Best Osc. Fit
NC Background
FD Events/GeV
Reconstructed Neutrino Energy (GeV)

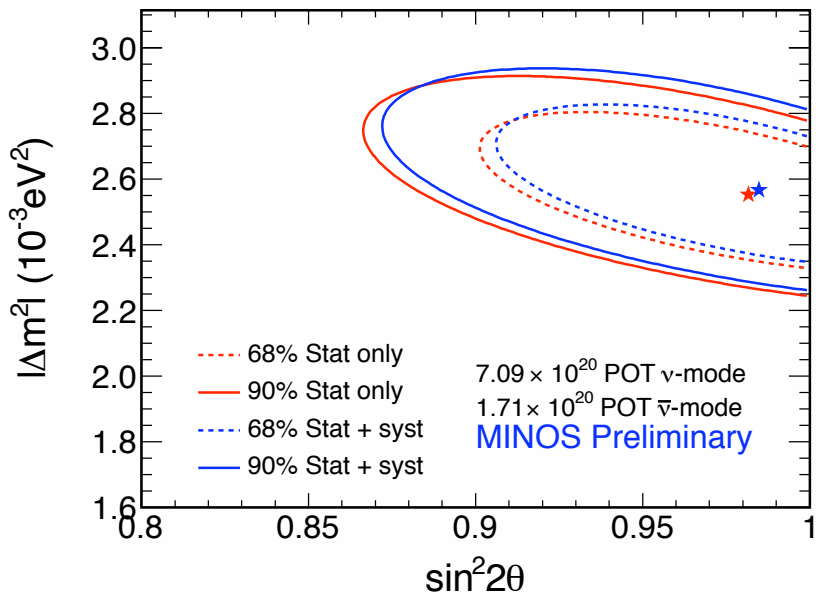

MINOS Preliminary
MINOS Far Detector
Antineutrino Running
1.71× 10^20 PoT
Data ν̄
No Oscillations
Best NSI Fit
Best Osc. Fit
NC Background
FD Events/GeV
Reconstructed Antineutrino Energy (GeV)

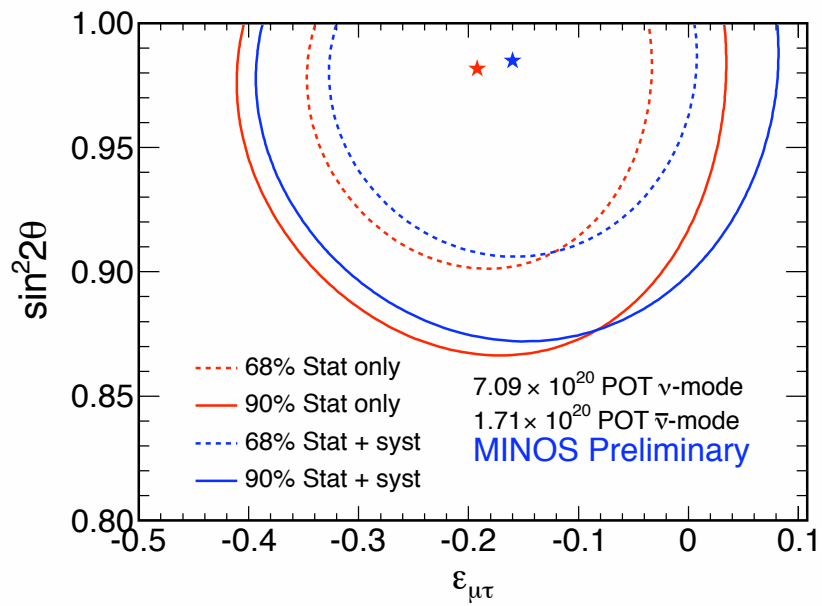

Data ν
Best NSI Fit
Best Osc. Fit
MINOS Preliminary
MINOS Far Detector
Neutrino Running
7.09 × 10^20 PoT
Ratio to No Oscillations
Reconstructed Neutrino Energy (GeV)


Data ν̄
Best NSI Fit
Best Osc. Fit
MINOS Far Detector
Antineutrino Running
1.71× 10^20 PoT
MINOS Preliminary
Ratio to No Oscillations
Reconstructed Antineutrino Energy (GeV)

Results







FHC neutrinos + RHC Run IV

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

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

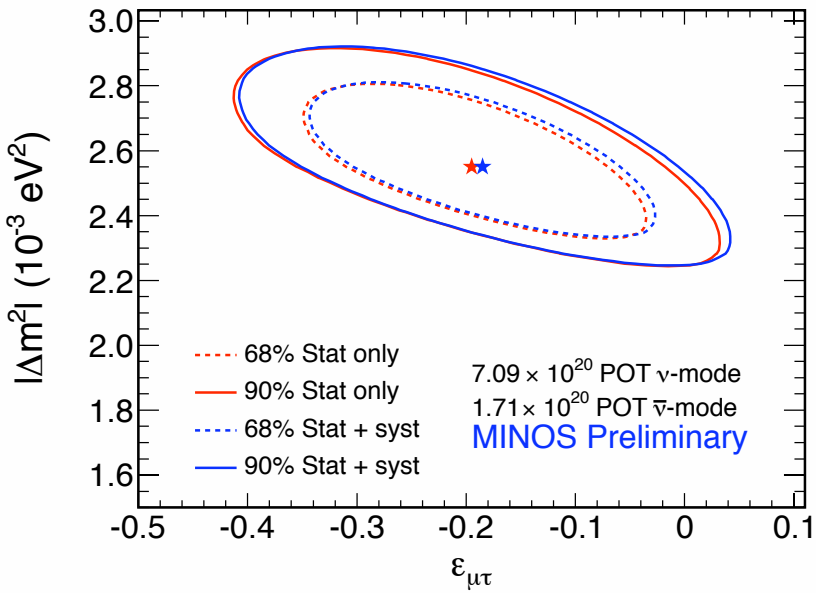
$$\epsilon_{\mu\tau} = -0.163 \pm 0.16$$

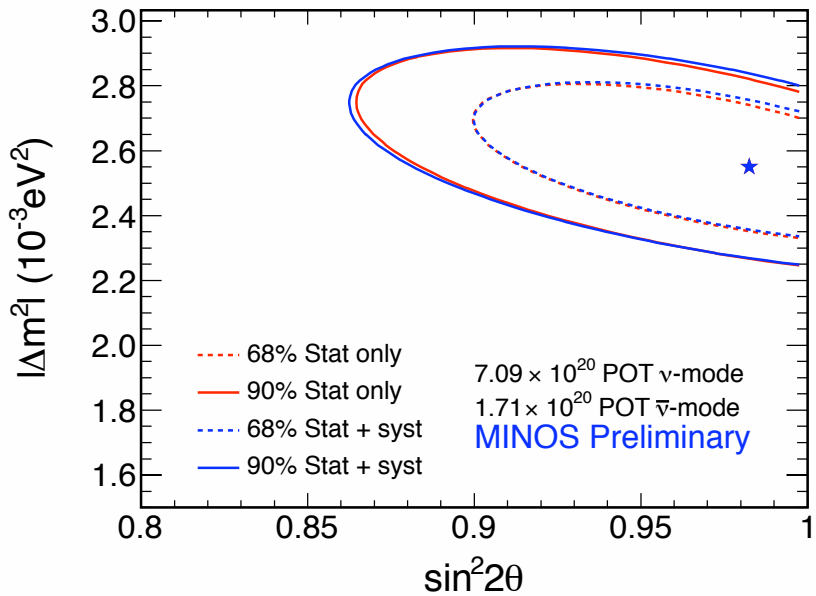
Add Run VII and Improve

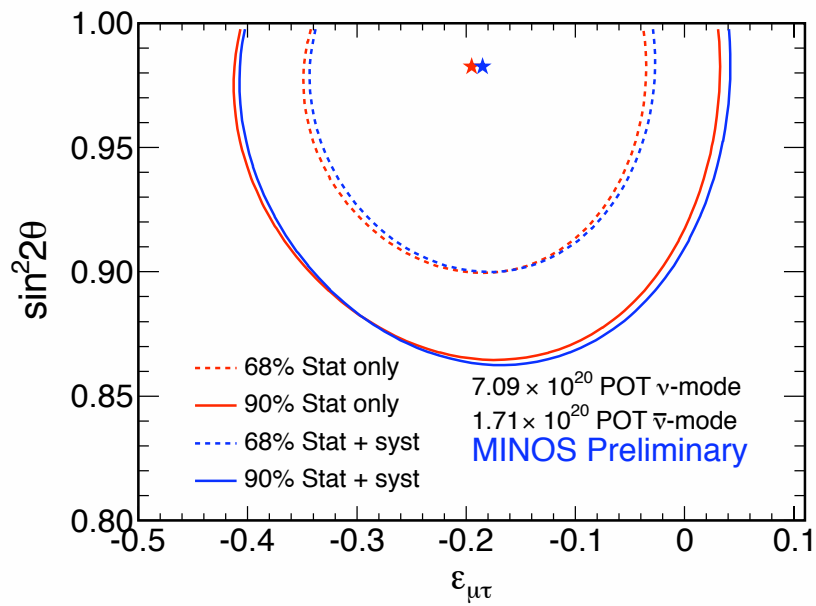
- Additional 1.24 x 10^{20} POT of antineutrino data
- Improved treatment of systematics:
  - Overall 10% normalization is a conservative overestimate
  - Instead, fit for four largest systematics: Muon energy scale, hadronic energy scale, normalization, neutral current background

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

Improved analysis with Run IV-only







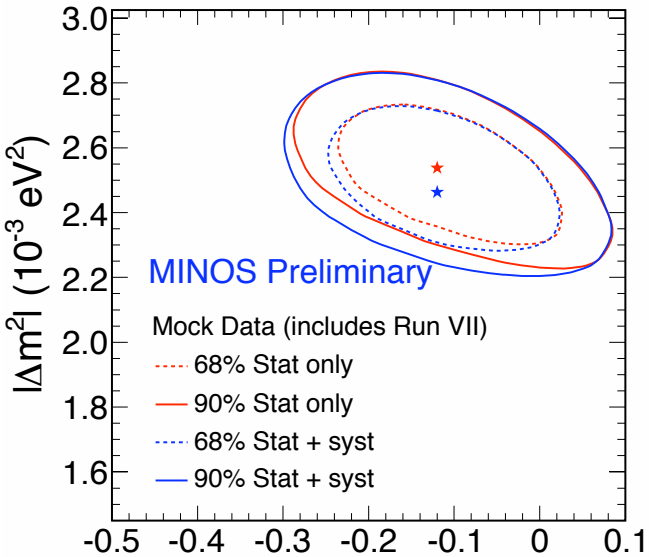
New analysis, Run IV

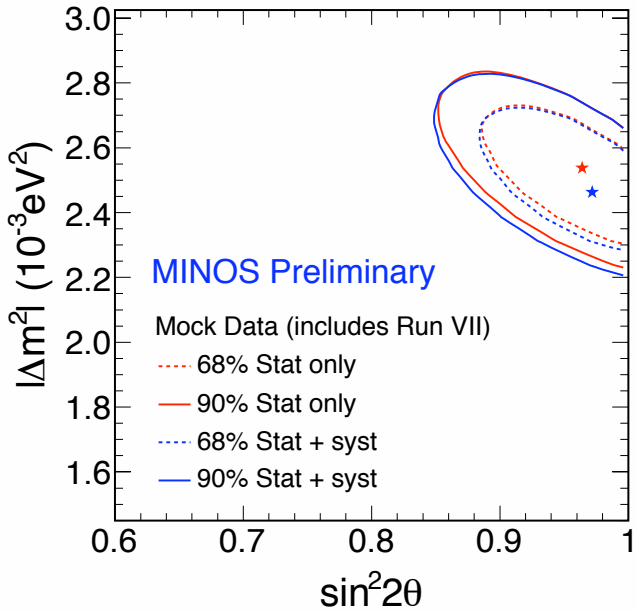
$$\Delta m^2 = 2.56 \pm 0.15 \times 10^{-3}\mathrm{eV}^2$$

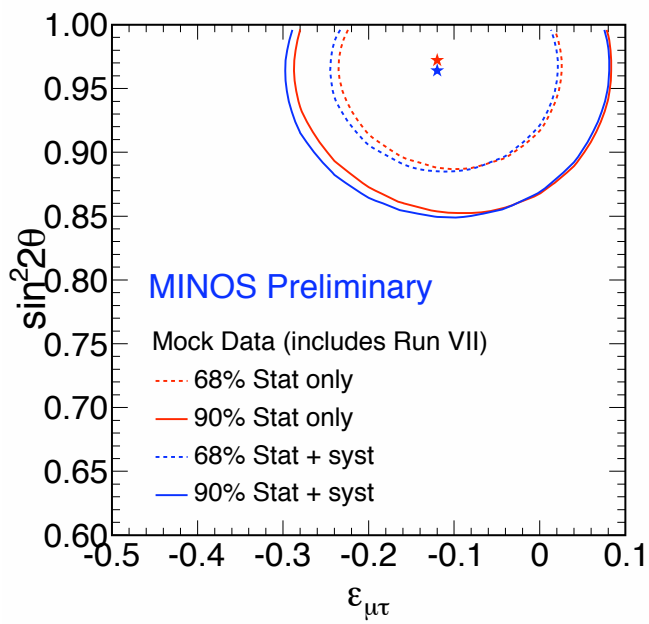
$$\sin^2(2\theta) = 0.98 \pm 0.08$$

$$\epsilon_{\mu\tau} = -0.187 \pm 0.16$$

Fake Run VII-like data



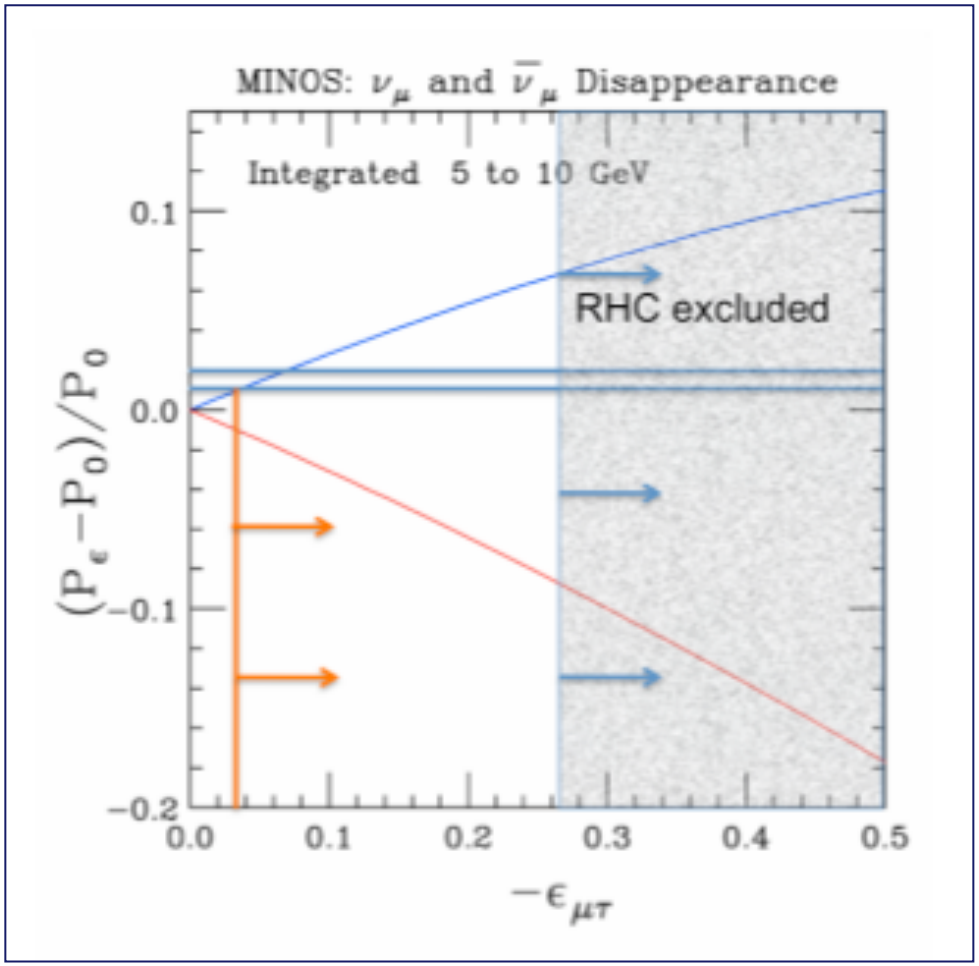




- Additional 1.24 x 10^{20} POT of antineutrino pseudo-data oscillated at Run VII oscillation values
- Improved sensitivity
- Best fit epsilon ~ 0.1; 0 more allowed
- Real result coming very soon!

Future

- **Longer-term future, MINOS+:** Collecting neutrino and antineutrino data in MINOS in the NOvA-era improves sensitivity to epsilon.



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 (old) antineutrino data gives

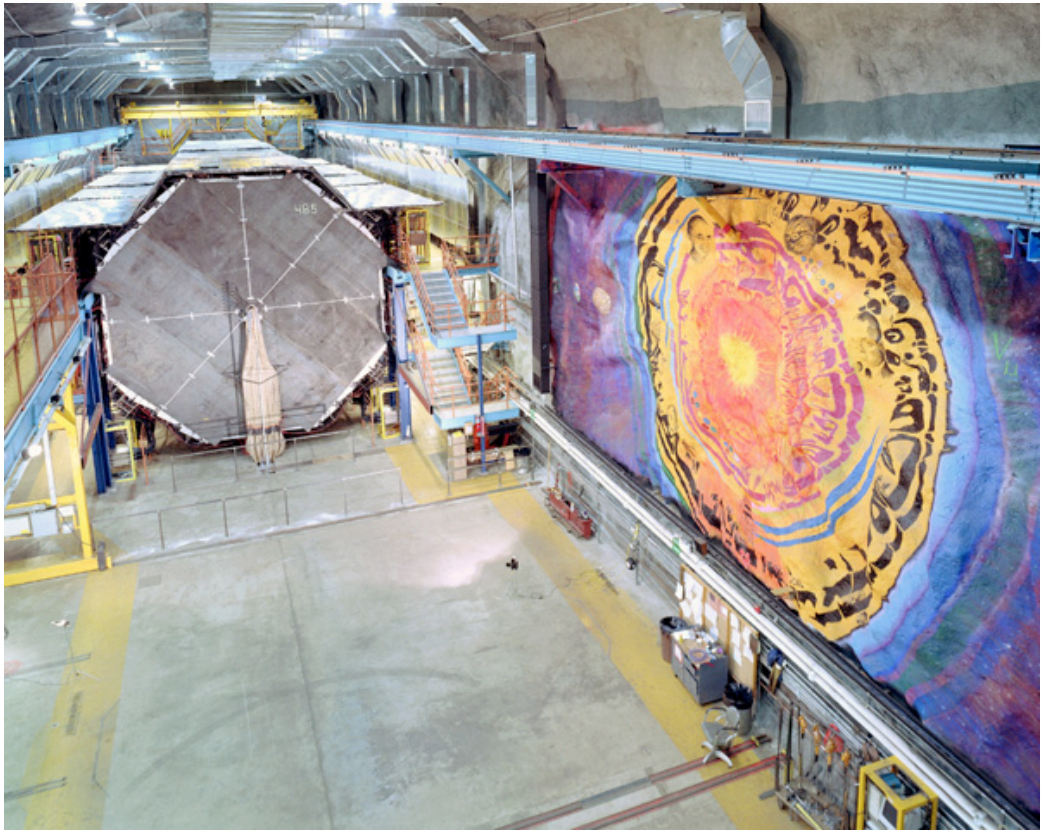
$$\Delta m^2 = 2.57 \pm 0.15 \times 10^{-3} \mathrm{eV}^2$$

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

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

- We analyzed an additional 1.24 x 10^{20} POT of antineutrino data, improved non-standard interactions results public very soon!
- MINOS+ can constrain NSI further with higher energy data.

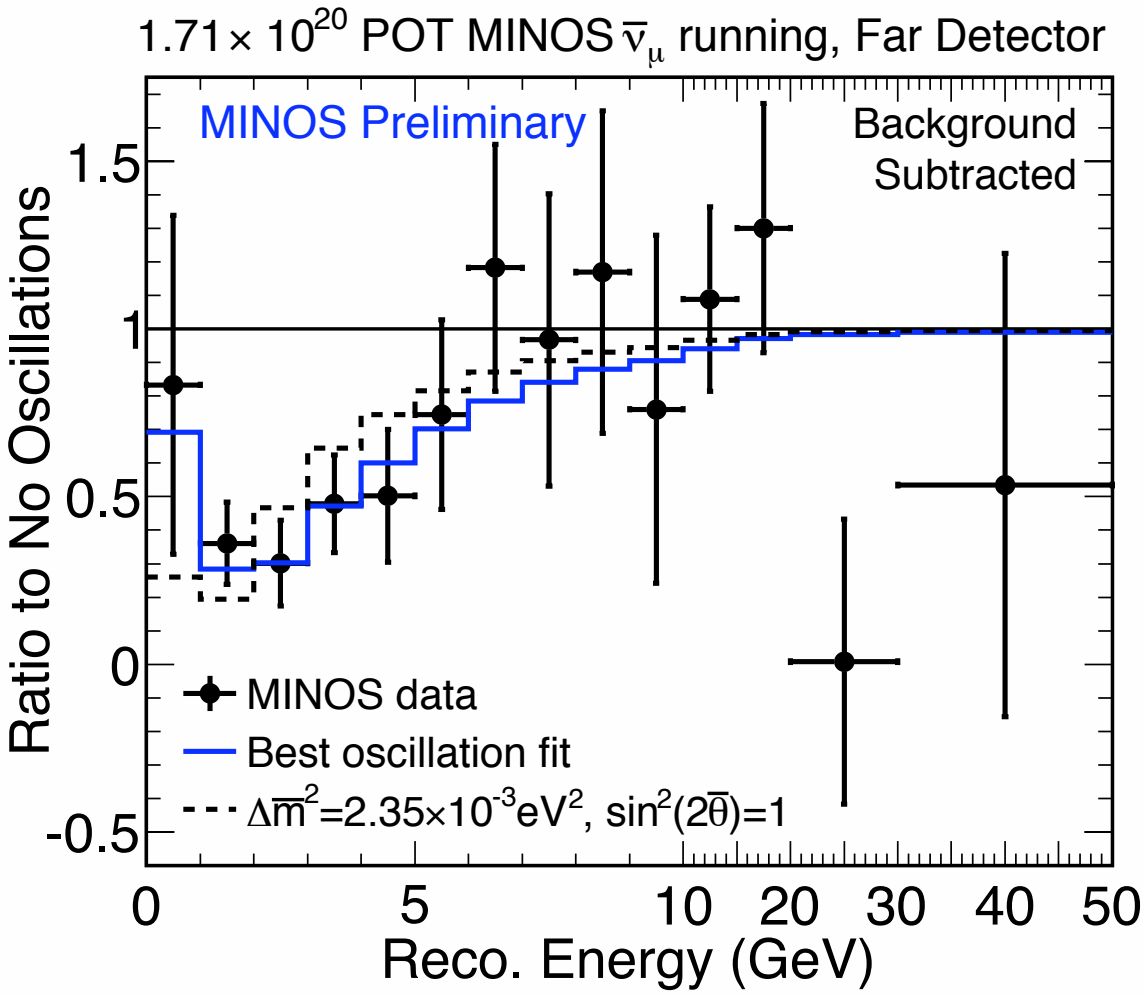
Thank you!



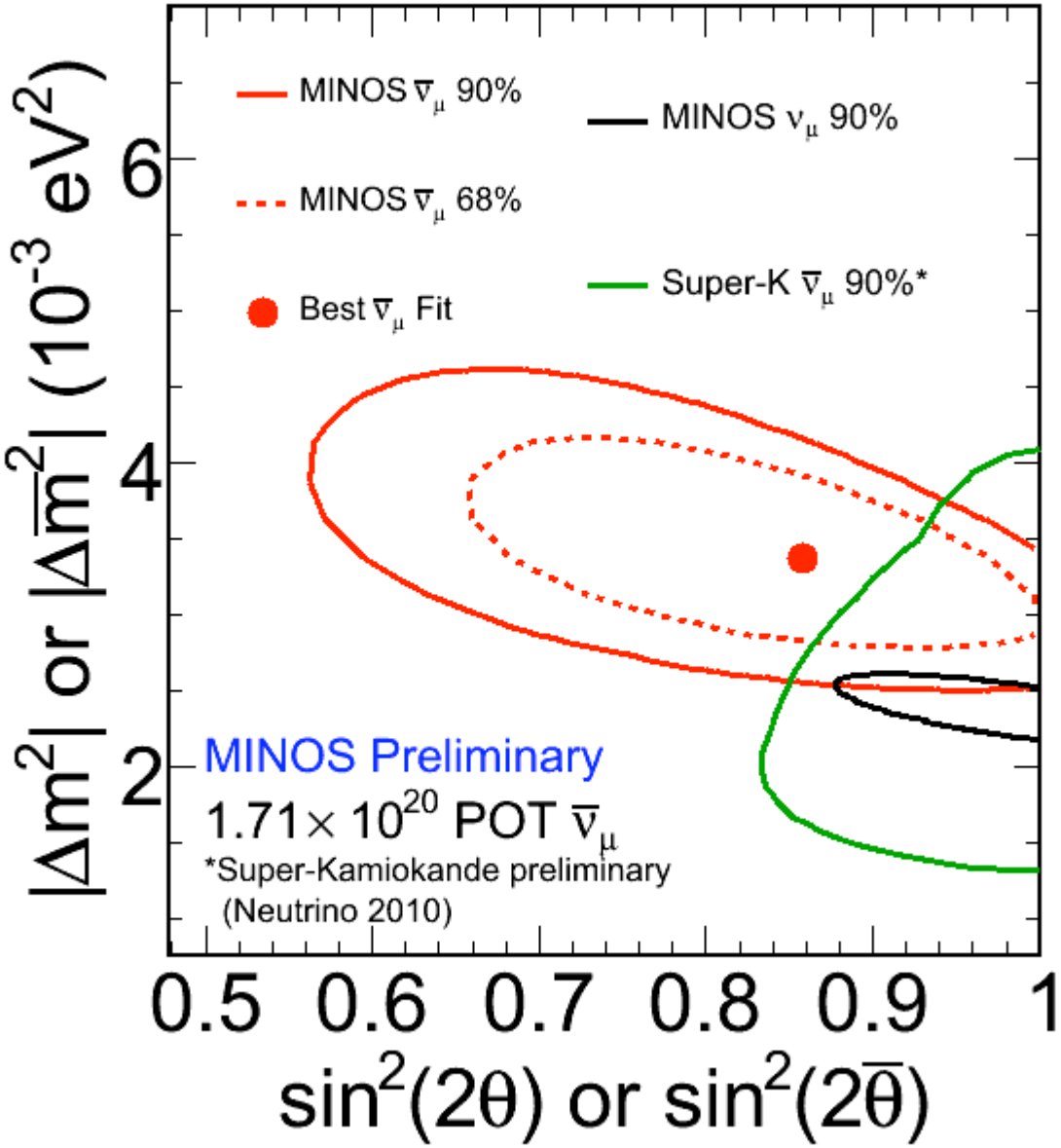
Feldman Cousins

- 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.

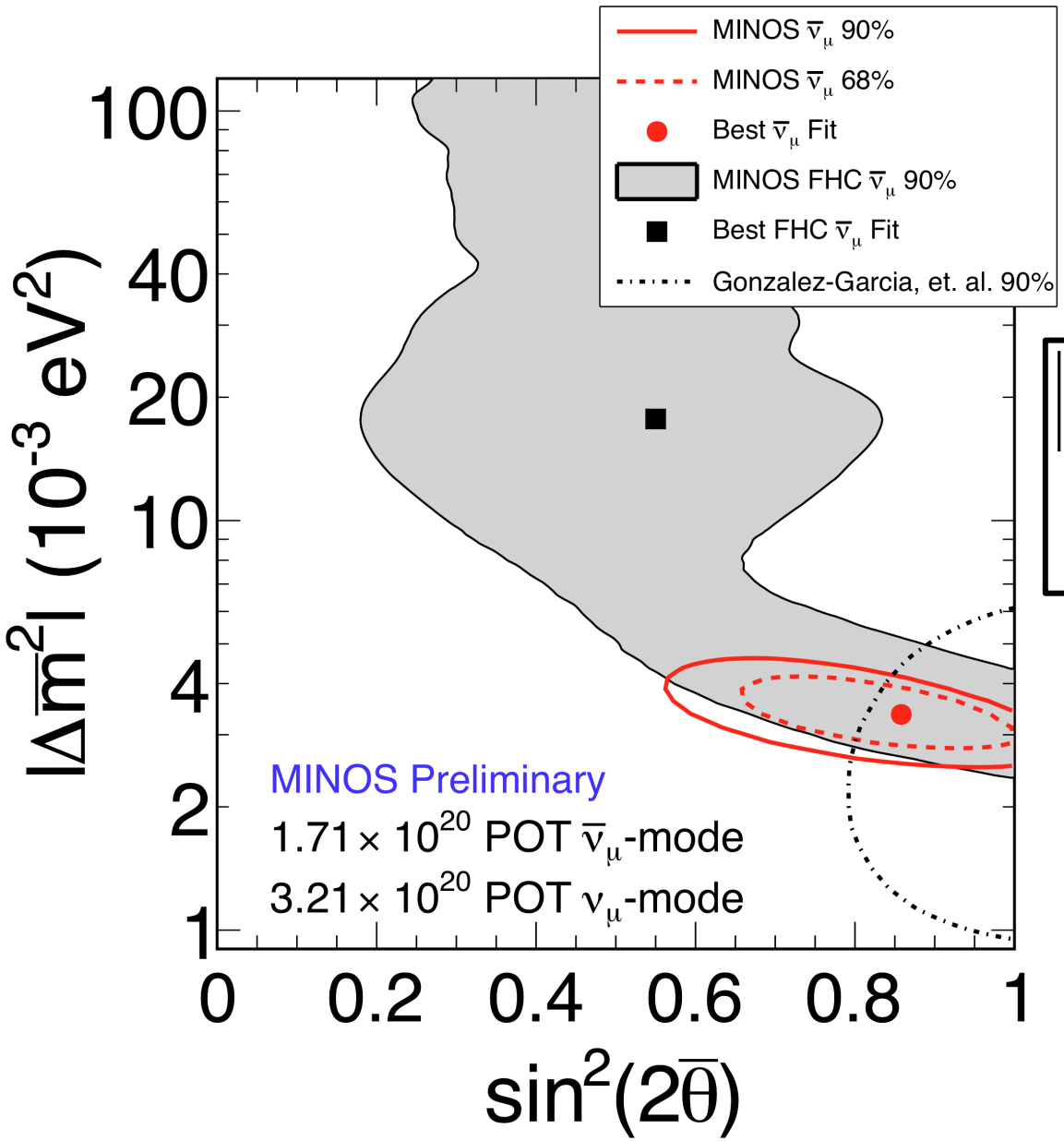
Neutrino-Antineutrino Comparison



With Super-K Antineutrino Result



Antineutrino Contour

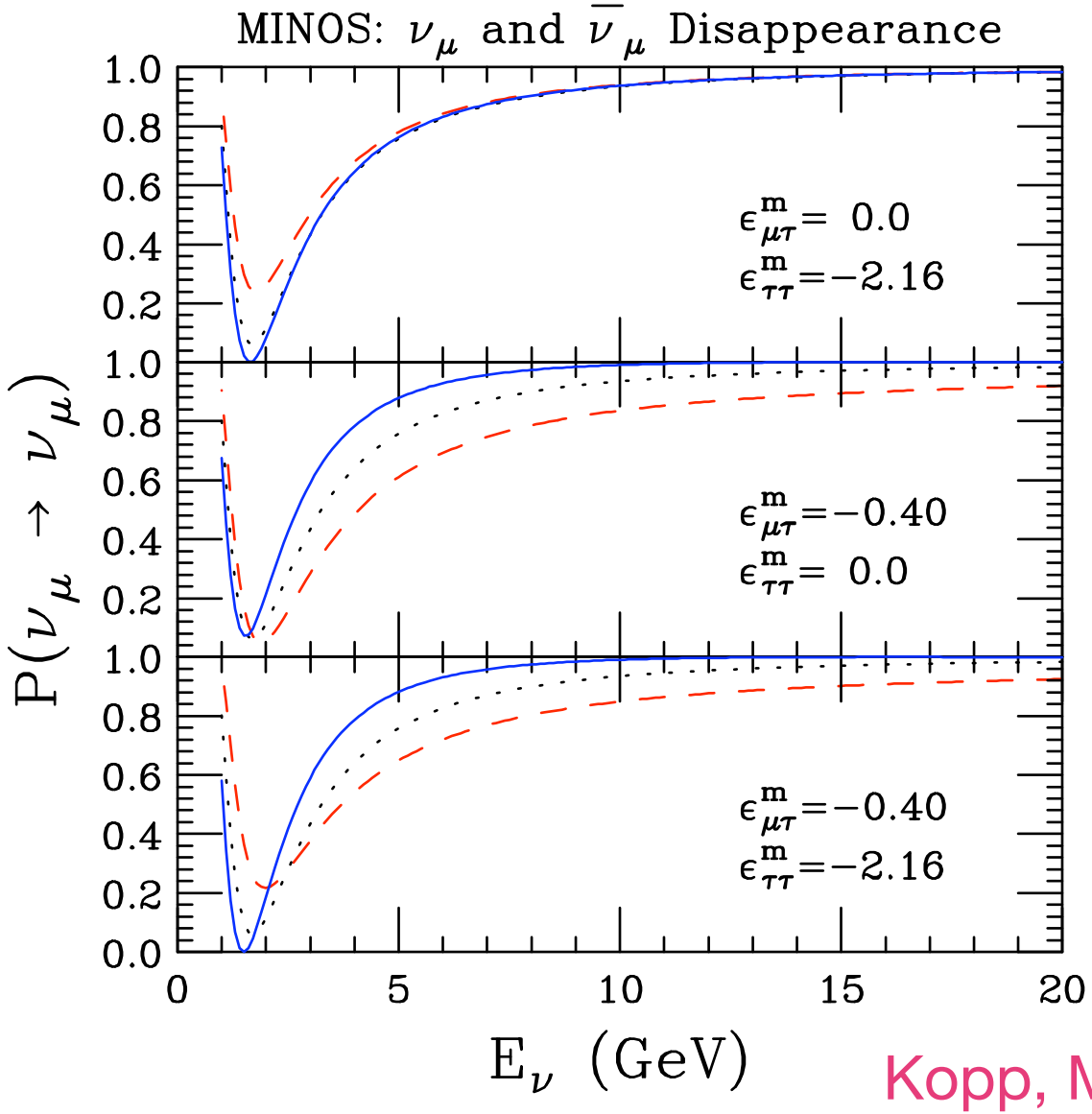


$$\left|\Delta\bar{m}^2_{\text{atm}}\right| = 3.36^{+0.45}_{-0.40} \times 10^{-3}\ \text{eV}^2$$

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

A combined analysis using all antineutrino data is planned.

Non-standard Interactions

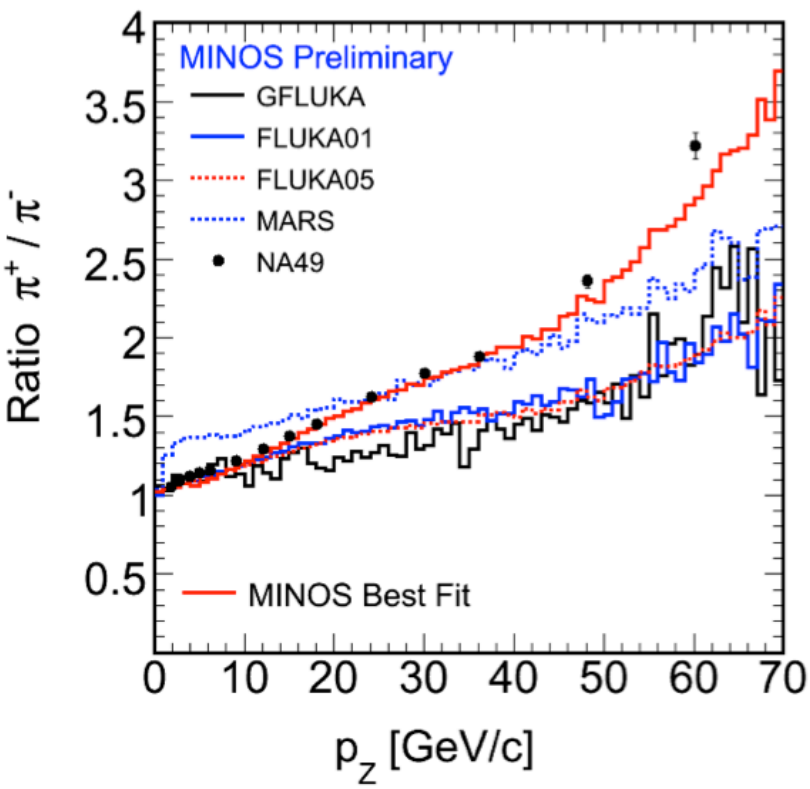


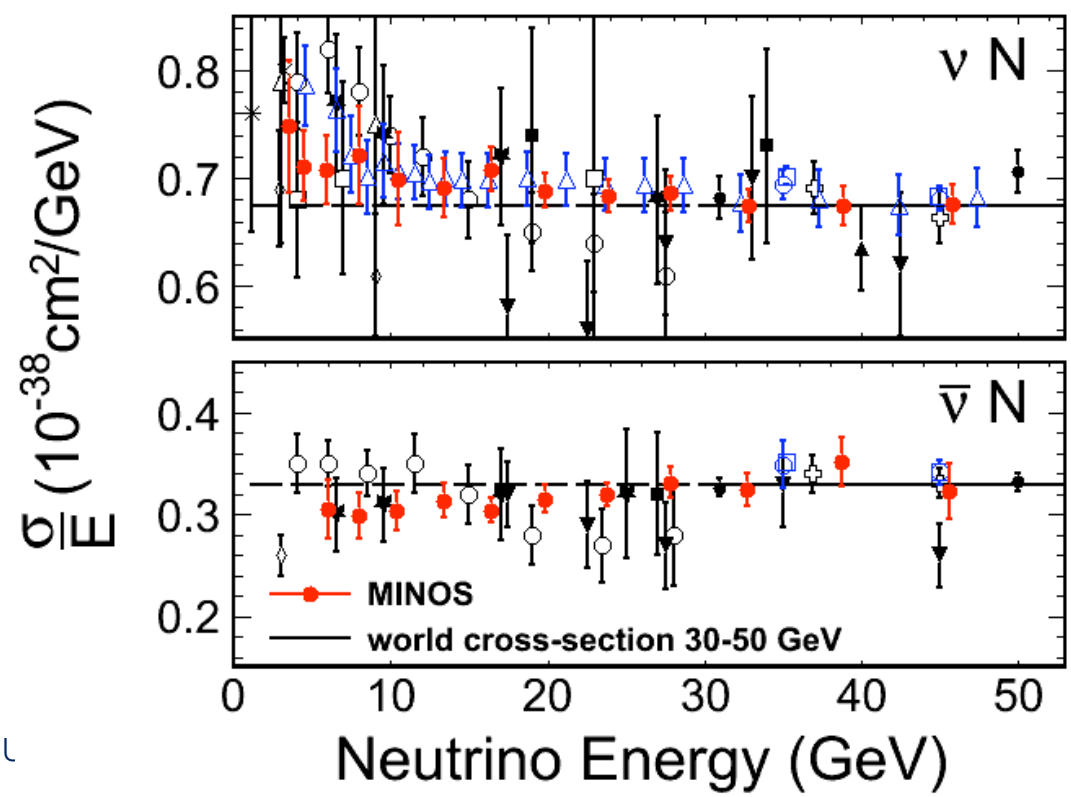
Kopp, Machado and Parke
arXiv:1009.0014v1

Making an antineutrino beam

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

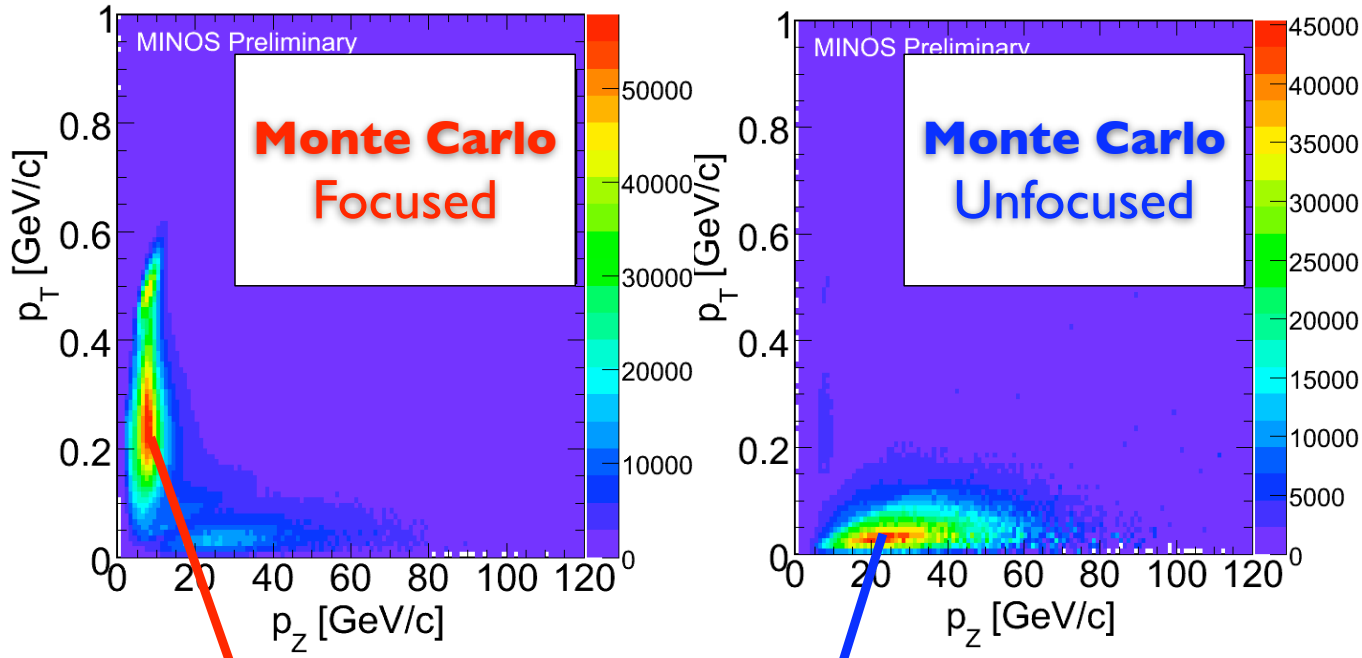
~3x fewer antineutrinos for the same exposure

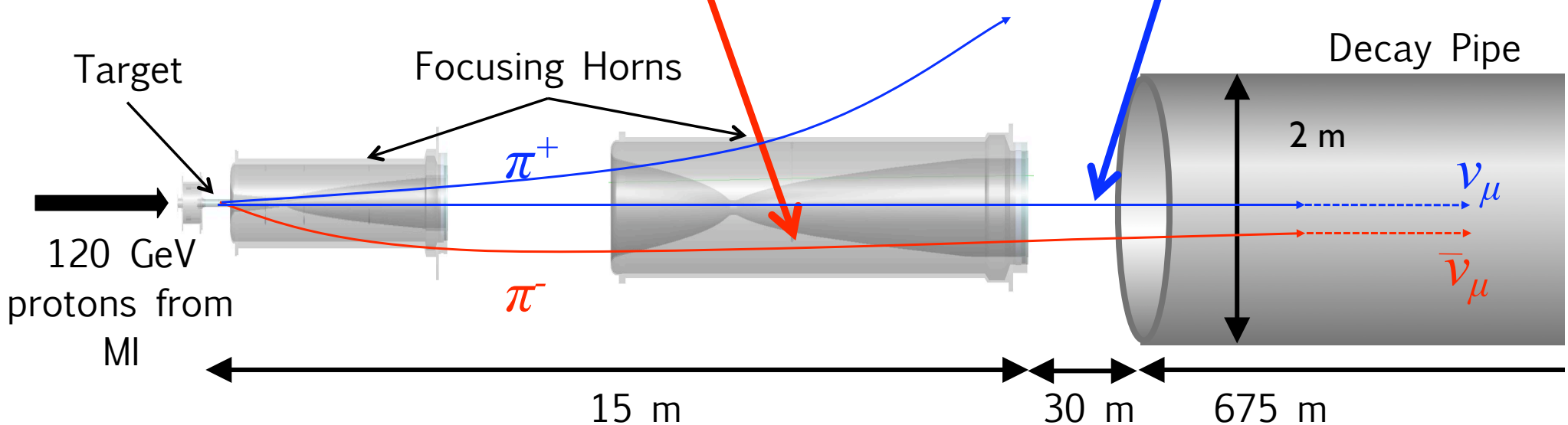


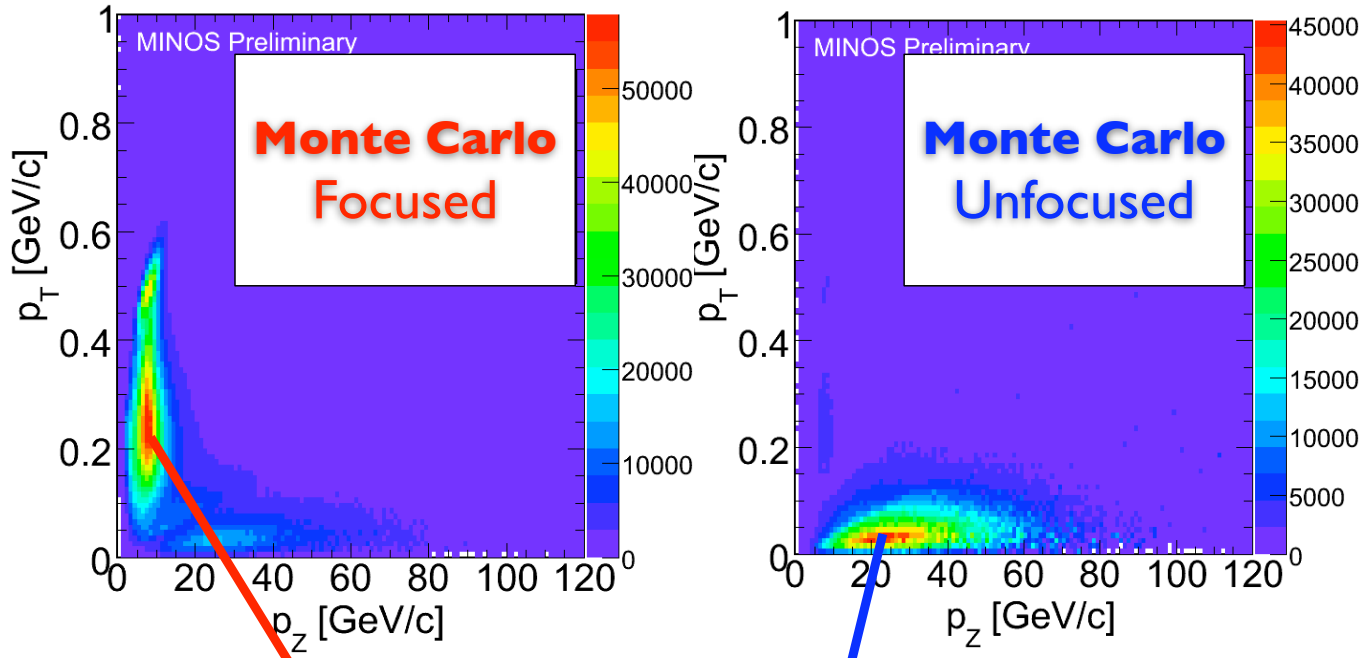
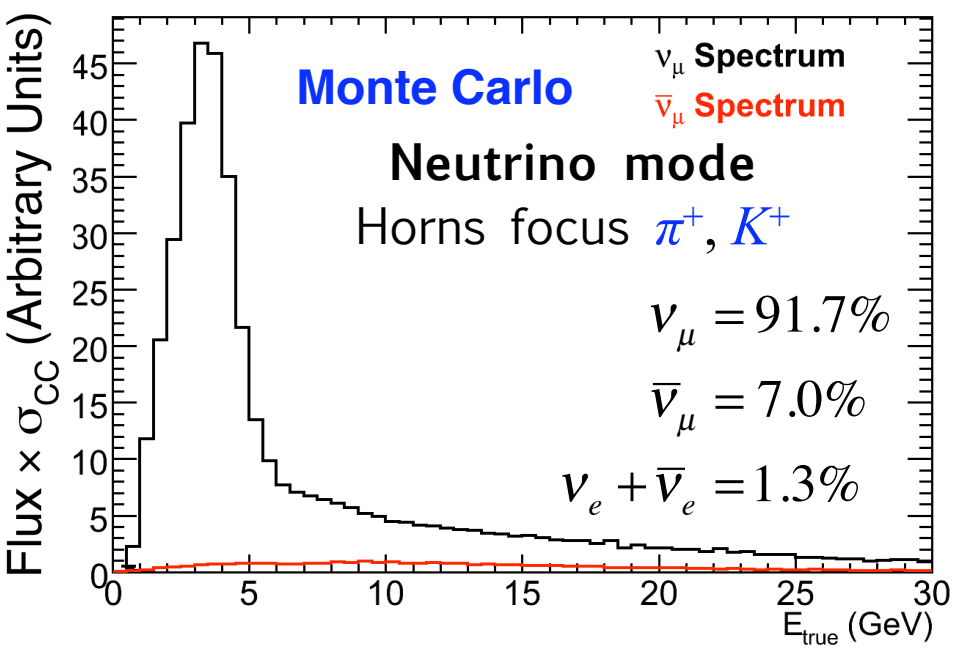
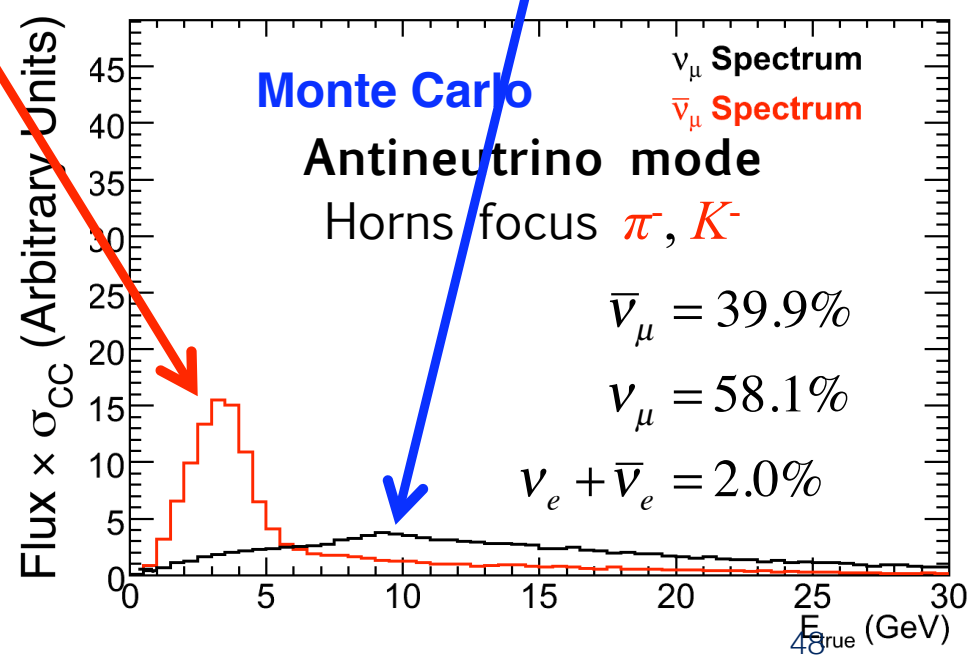


Peak vs. Tail

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





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