Muon Neutrino and Antineutrino Oscillations at MINOS

Alexander Himmel
Caltech
for the MINOS Collaboration

UC Santa Barbara, January 26th 2011

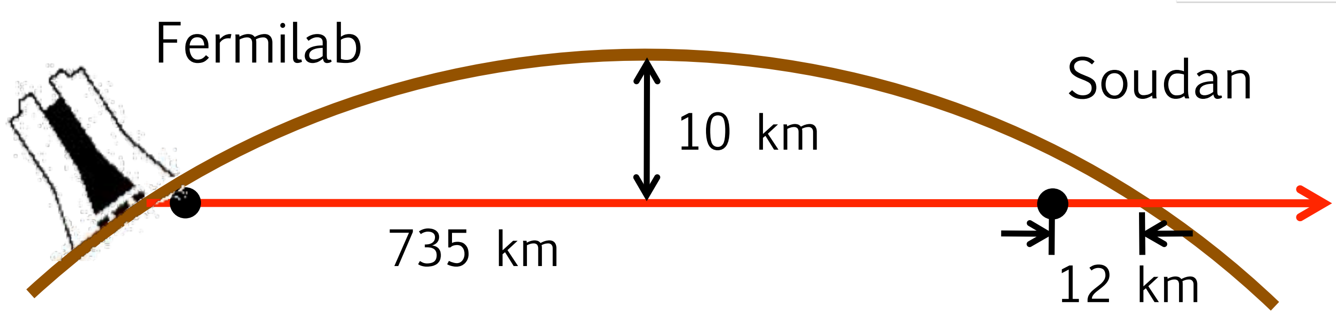
Introduction

- What is MINOS?
- Neutrino Physics
  - Oscillation Basics
  - MINOS Physics
- The Experiment
  - NuMI neutrino beam
  - MINOS detectors
- The Analyses
  - Neutrinos
  - Antineutrinos
- The Results

Argonne · Athens · Benedictine · Brookhaven · Caltech · Cambridge · Campinas · Fermilab · Harvard · Holy Cross · IIT
Indiana · Iowa State · Lebedev · Livermore
Minnesota-Twin Cities · Minnesota-Duluth · Otterbein · Oxford
Pittsburgh · Rutherford · Sao Paulo · South Carolina
Stanford · Sussex · Texas A&M · Texas-Austin · Tufts · UCL
Warsaw · William & Mary

What is MINOS?

- Three components:
  - **NuMI** high-intensity neutrino beam
  - **Near Detector** at Fermilab measures the initial beam composition and spectrum
  - **Far Detector** in Soudan, MN measures the oscillated spectrum
- Detectors are magnetized – unique among oscillation experiments

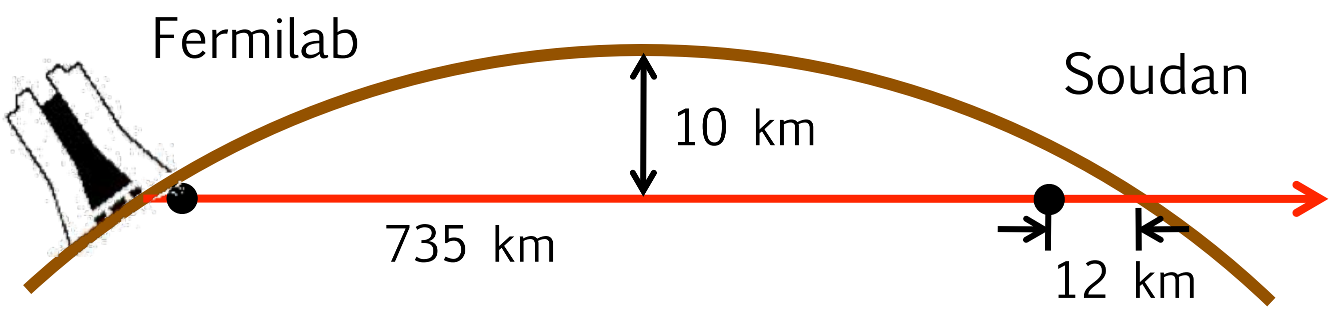


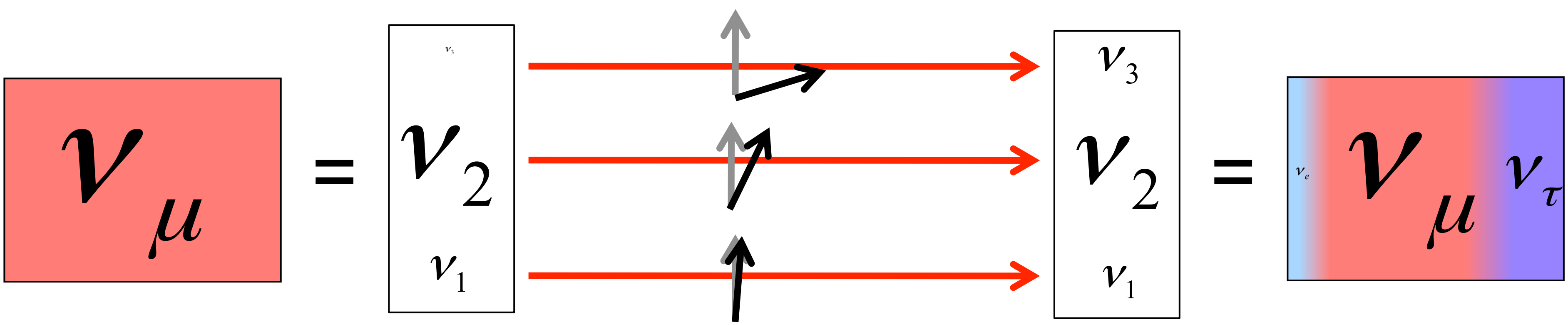
Neutrino Physics

– Oscillation Basics
– MINOS Physics

Neutrino Oscillations

- Interact in weak eigenstates (e, μ, τ)
- Propagate in mass eigenstates (1, 2, 3)
- Because the neutrinos have different masses, as they propagate they pick up relative phases, changing their relative amplitudes
- End up with a different weak eigenstates than we started with

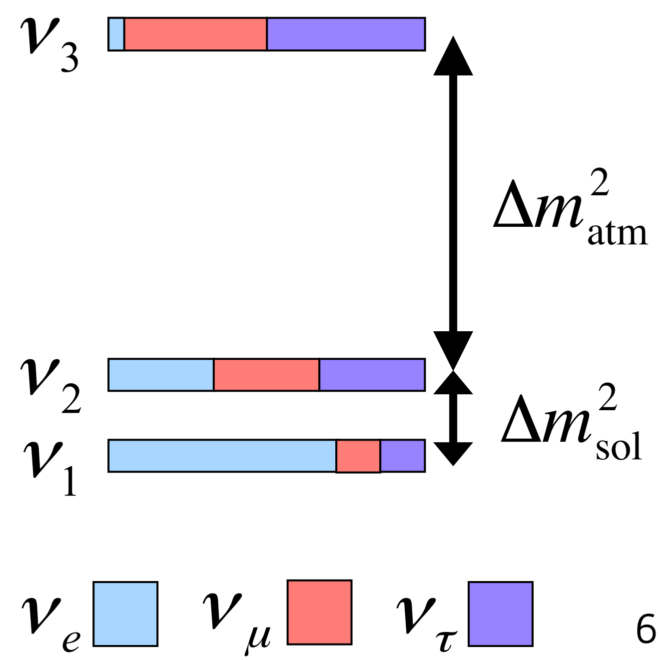




Neutrino Masses and Mixing

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

- Analogous to the quarks, neutrino mixing is parameterized with 3 angles and 1 complex phase
- With three active neutrinos there are two independent mass differences:
  - $\Delta m^2_{\text{sol}} \approx \Delta m^2_{21} \approx 8.0 \times 10^{-5}\ \text{eV}^2$
  - $\Delta m^2_{\text{atm}} \approx \Delta m^2_{32} \approx 2.4 \times 10^{-3}\ \text{eV}^2$

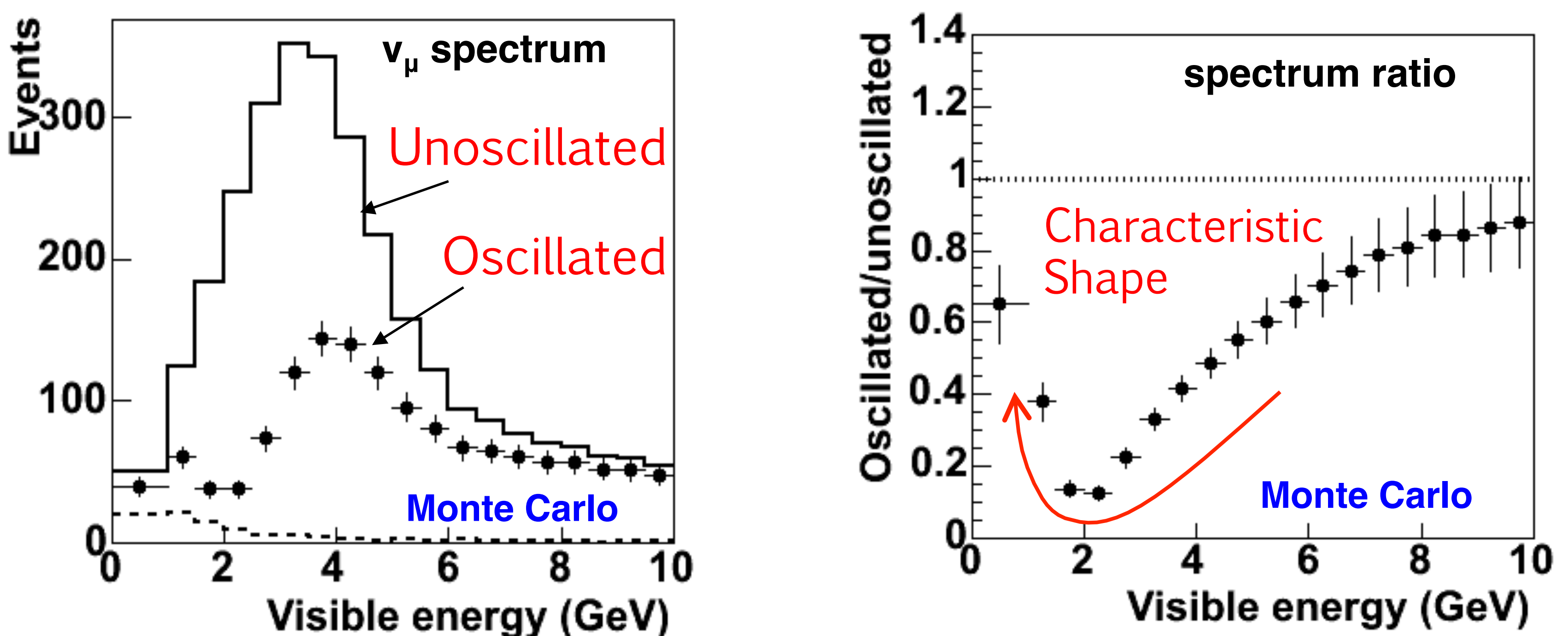


Measuring Oscillations

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

Monte Carlo

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

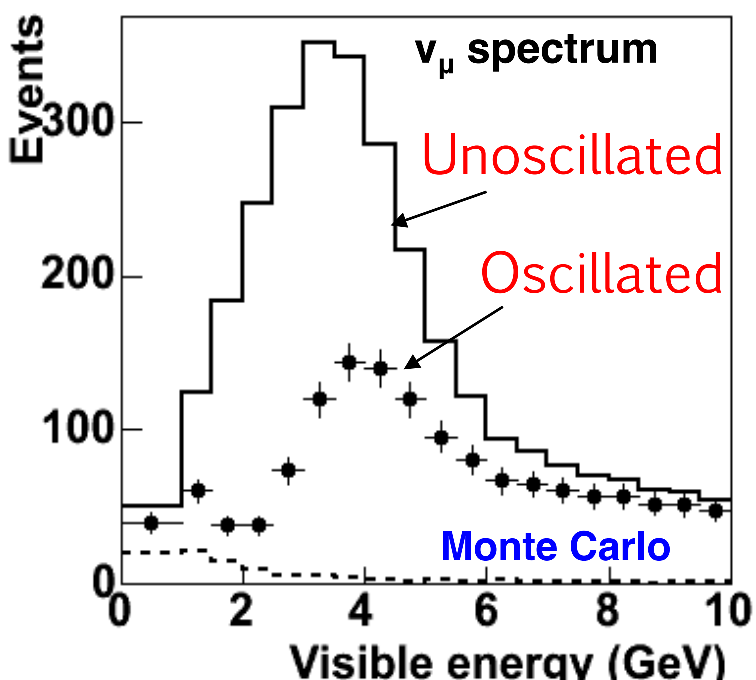


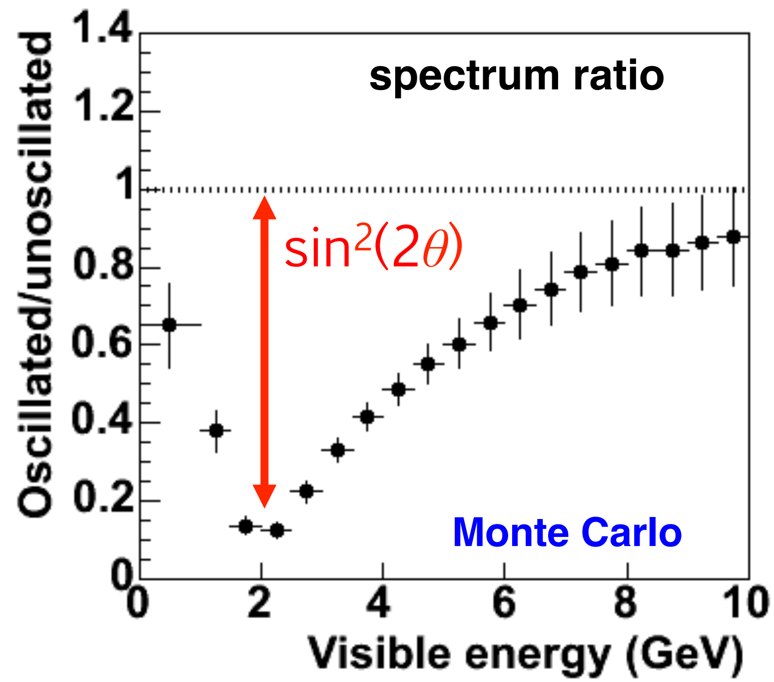
Measuring Oscillations

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

Monte Carlo

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



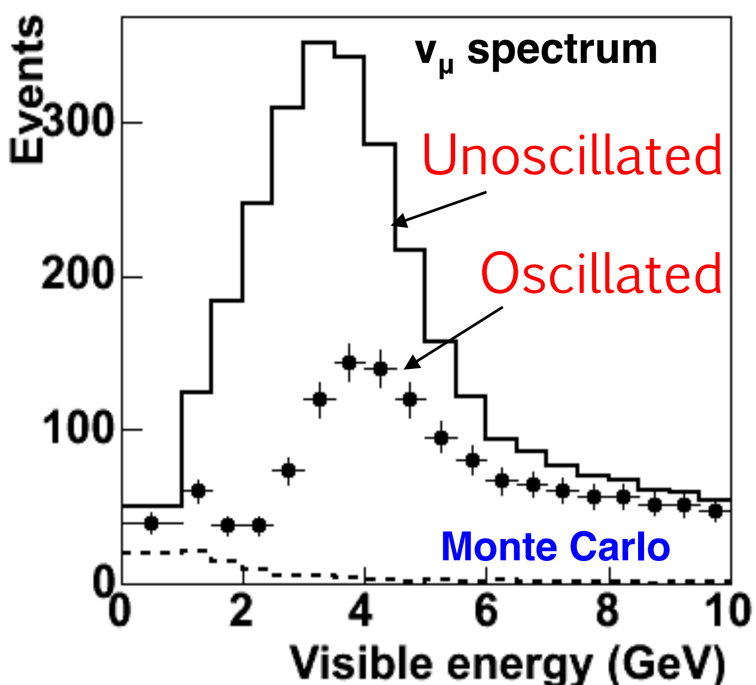


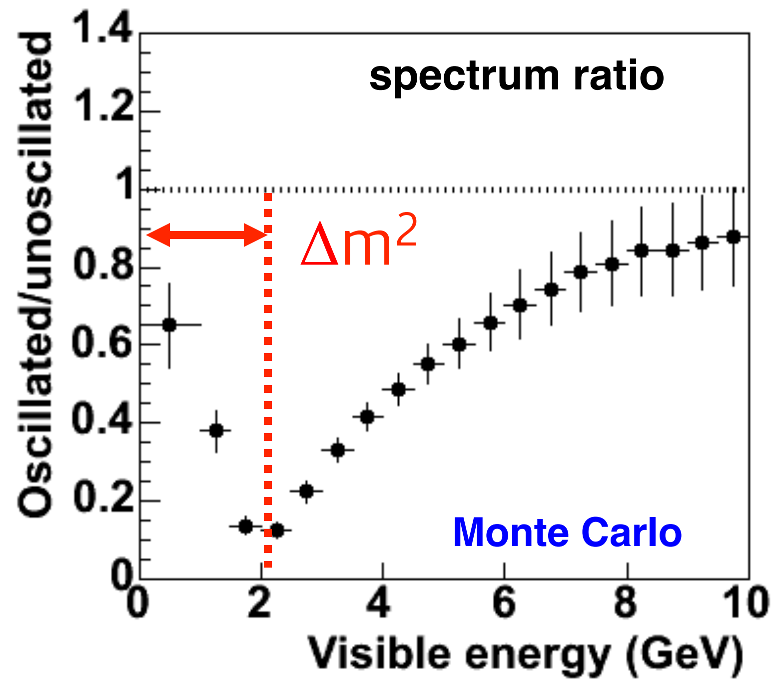
Measuring Oscillations

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

Monte Carlo

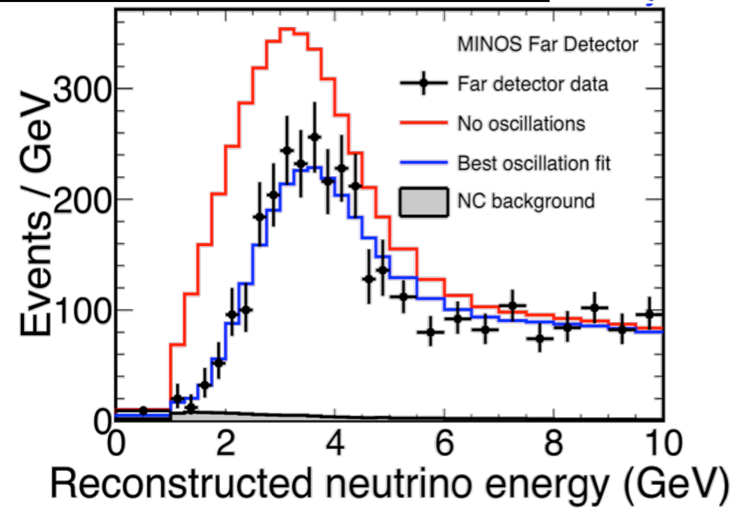
$\sin^2 2\theta = 1.0$, $\Delta m^2 = 3.35\times10^{-3}\ eV^2$

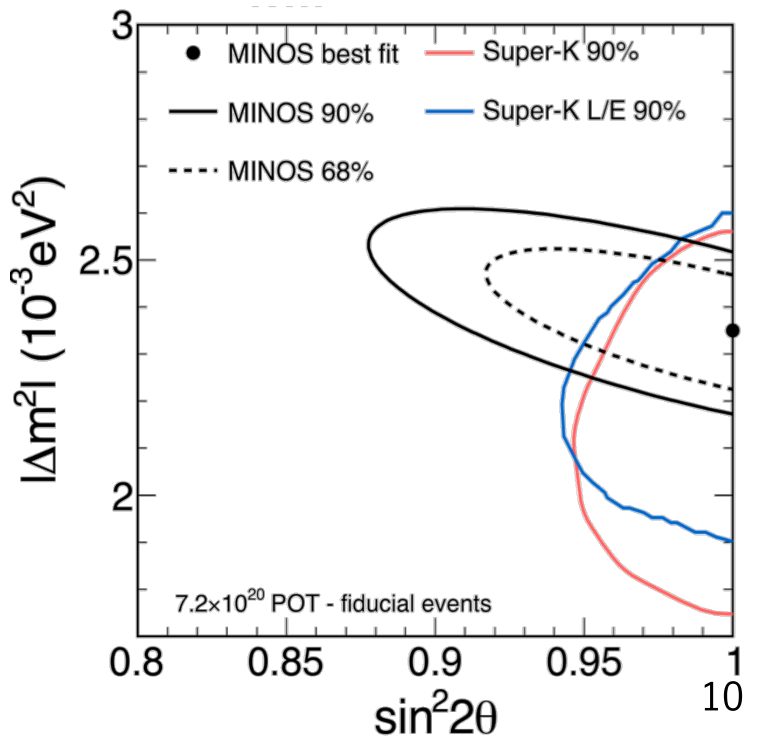




MINOS Physics

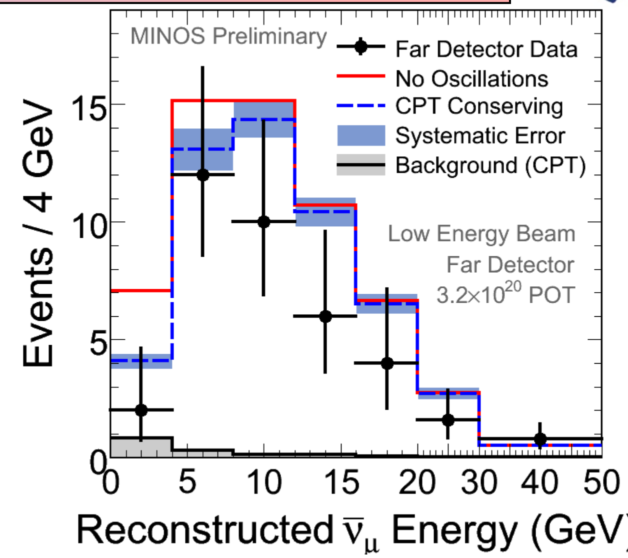
- Measurements of $|\Delta m^2_{atm}|$ and $\sin^2(2\theta_{23})$ via ν_μ disappearance
- Measurements of $|\Delta \overline{m}^2_{atm}|$ and $\sin^2(2\overline{\theta}_{23})$ via $\overline{\nu}_\mu$ disappearance
- Search for sub-dominant $\nu_\mu \rightarrow \nu_e$ oscillations via ν_e appearance
- Search for sterile ν, CPT/Lorentz violation
- Atmospheric neutrino and cosmic ray physics
- Study ν interactions and cross sections in Near Detector

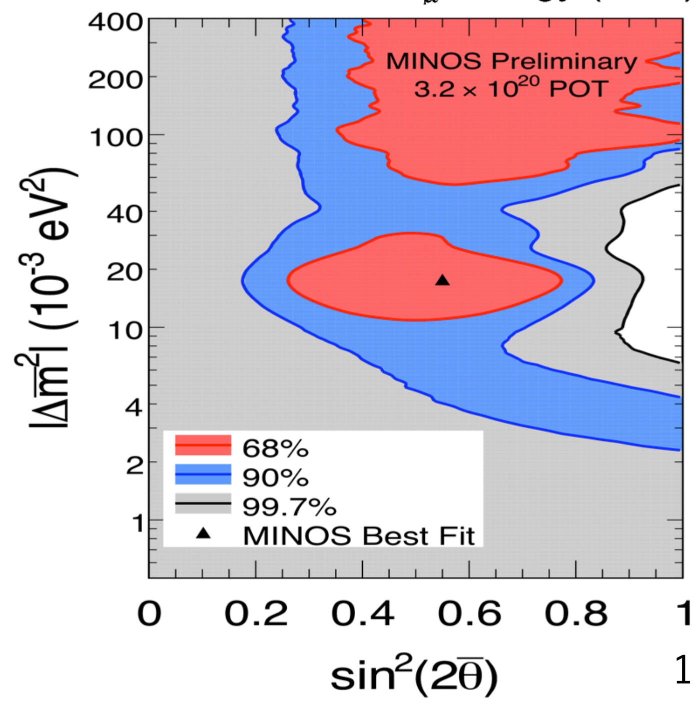




MINOS Physics

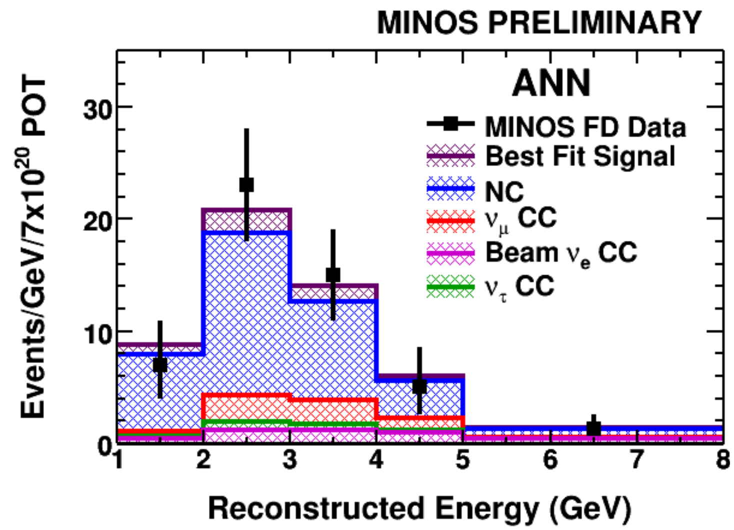
- Measurements of $|\Delta m^2_{atm}|$ and $\sin^2(2\theta_{23})$ via ν_μ disappearance
- Measurements of $|\Delta \overline{m}^2_{atm}|$ and $\sin^2(2\overline{\theta}_{23})$ via $\overline{\nu}_\mu$ disappearance
- Search for sub-dominant $\nu_\mu \rightarrow \nu_e$ oscillations via ν_e appearance
- Search for sterile ν, CPT/Lorentz violation
- Atmospheric neutrino and cosmic ray physics
- Study ν interactions and cross sections in Near Detector

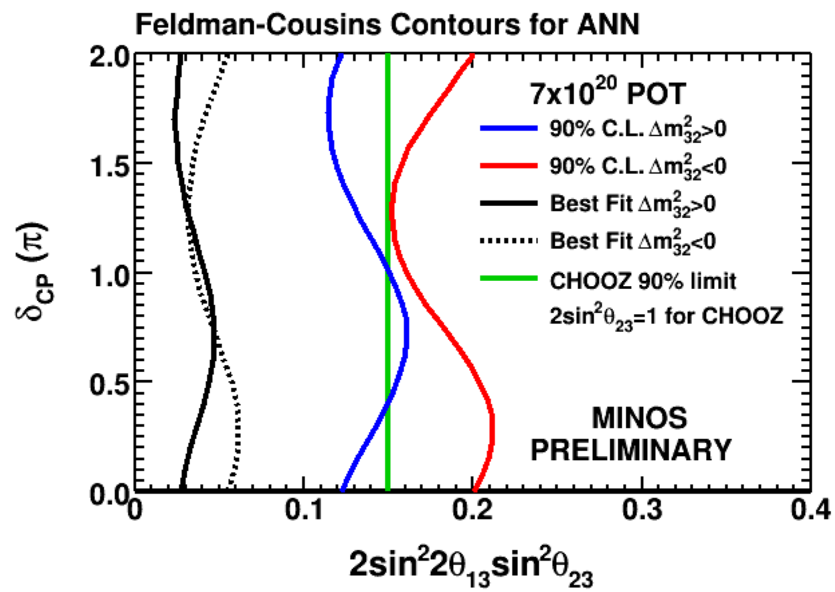




MINOS Physics

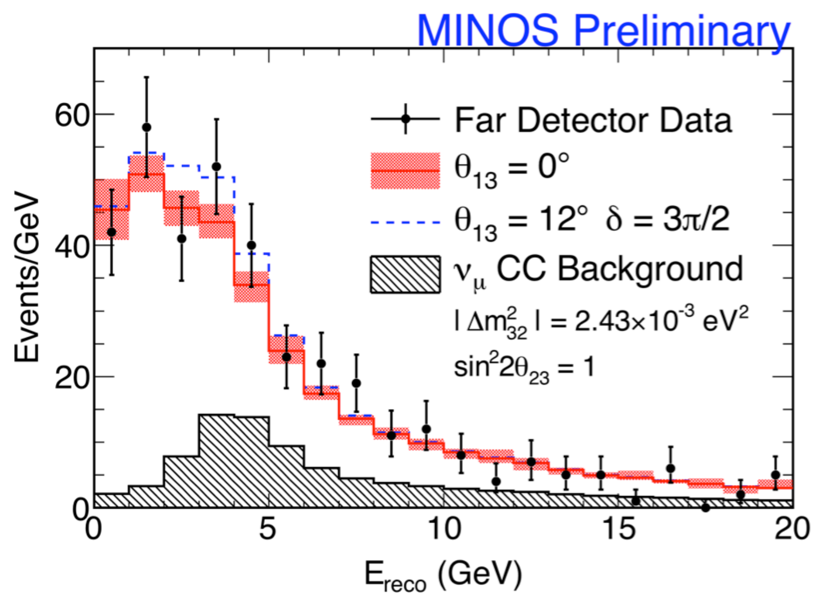
- Measurements of $|\Delta m^2_{atm}|$ and $\sin^2(2\theta_{23})$ via ν_μ disappearance
- Measurements of $|\Delta \bar{m}^2_{atm}|$ and $\sin^2(2\bar{\theta}_{23})$ via $\bar{\nu}_\mu$ disappearance
- Search for sub-dominant $\nu_\mu \rightarrow \nu_e$ oscillations via ν_e appearance
- Search for sterile ν, CPT/Lorentz violation
- Atmospheric neutrino and cosmic ray physics
- Study ν interactions and cross sections in Near Detector





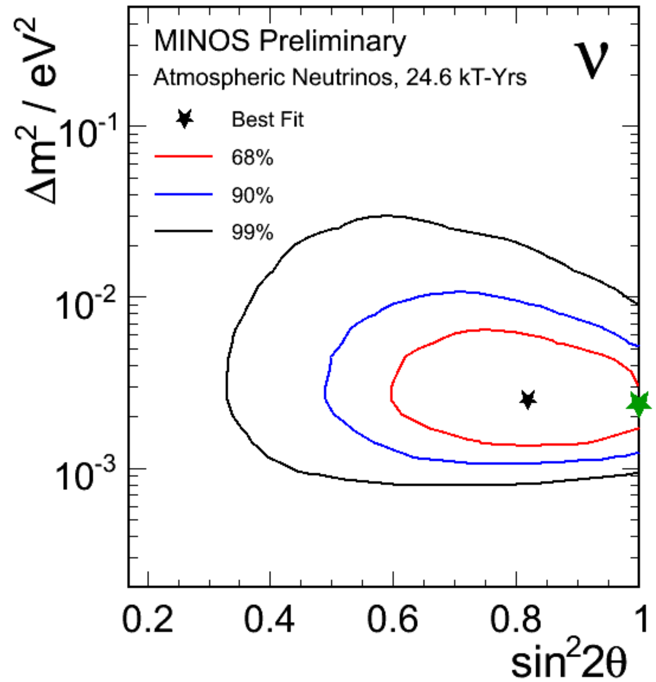
MINOS Physics

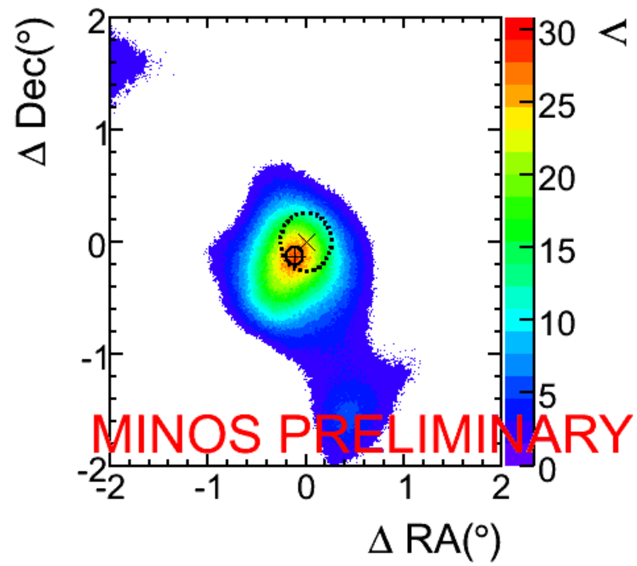
- Measurements of $|\Delta m^2_{atm}|$ and $\sin^2(2\theta_{23})$ via ν_μ disappearance
- Measurements of $|\Delta \overline{m}^2_{atm}|$ and $\sin^2(2\overline{\theta}_{23})$ via $\overline{\nu}_\mu$ disappearance
- Search for sub-dominant $\nu_\mu \rightarrow \nu_e$ oscillations via ν_e appearance
- Search for sterile ν, CPT/Lorentz violation
- Atmospheric neutrino and cosmic ray physics
- Study ν interactions and cross sections in Near Detector



MINOS Physics

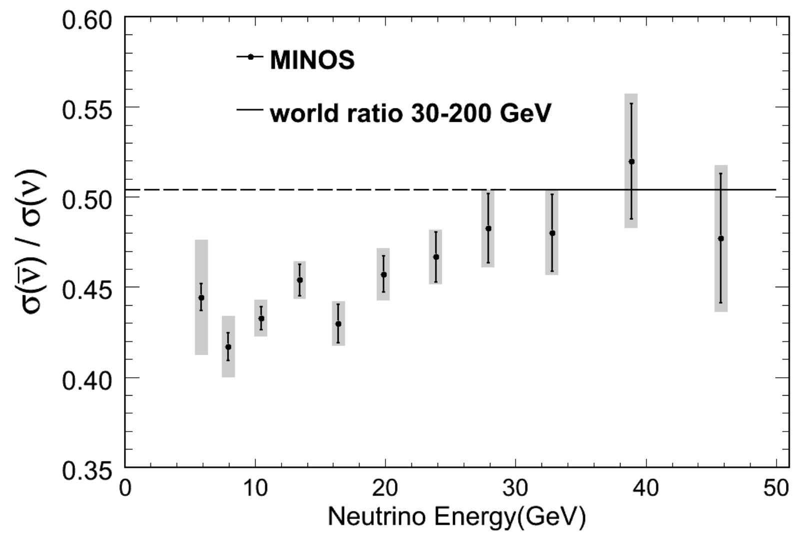
- Measurements of $|\Delta m^2_{atm}|$ and $\sin^2(2\theta_{23})$ via ν_μ disappearance
- Measurements of $|\Delta \overline{m}^2_{atm}|$ and $\sin^2(2\overline{\theta}_{23})$ via $\overline{\nu}_\mu$ disappearance
- Search for sub-dominant $\nu_\mu \rightarrow \nu_e$ oscillations via ν_e appearance
- Search for sterile ν, CPT/Lorentz violation
- Atmospheric neutrino and cosmic ray physics
- Study ν interactions and cross sections in Near Detector





MINOS Physics

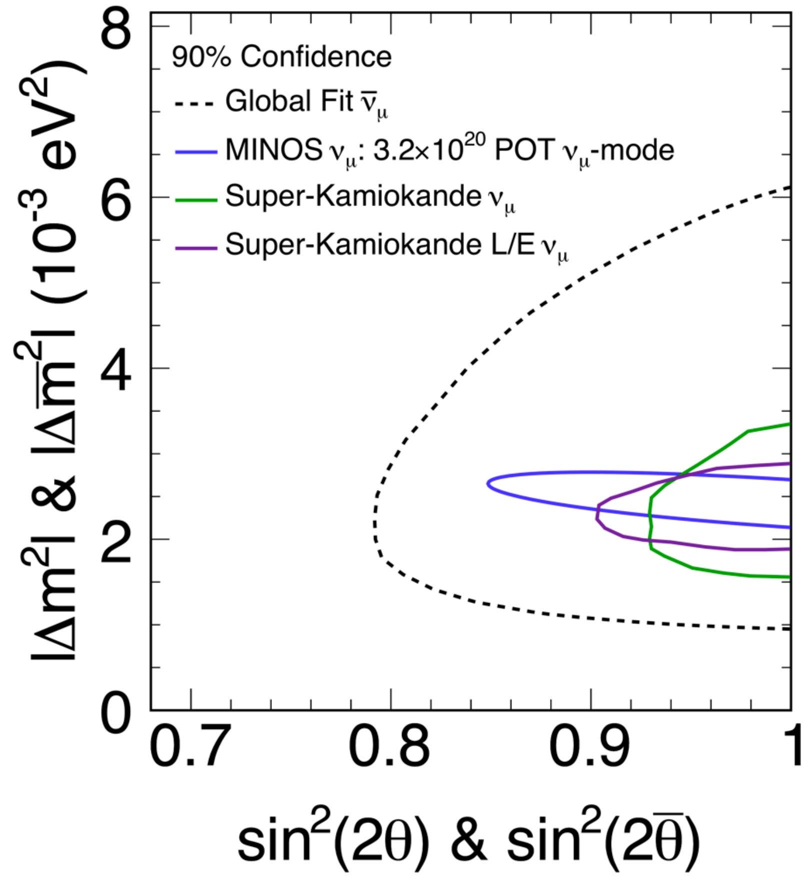
- Measurements of $|\Delta m^2_{atm}|$ and $\sin^2(2\theta_{23})$ via ν_μ disappearance
- Measurements of $|\Delta \overline{m}^2_{atm}|$ and $\sin^2(2\overline{\theta}_{23})$ via $\overline{\nu}_\mu$ disappearance
- Search for sub-dominant $\nu_\mu \rightarrow \nu_e$ oscillations via ν_e appearance
- Search for sterile ν, CPT/Lorentz violation
- Atmospheric neutrino and cosmic ray physics
- Study ν interactions and cross sections in Near Detector



Why study ν_μ and $\bar{\nu}_\mu$?

$$P(\nu_\mu \to \nu_\mu) \stackrel{?}{=} P(\bar{\nu}_\mu \to \bar{\nu}_\mu)$$

- Antineutrino parameters are less precisely known.
  - No direct precision measurements
  - MINOS is the only oscillation experiment that can do event-by-event separation



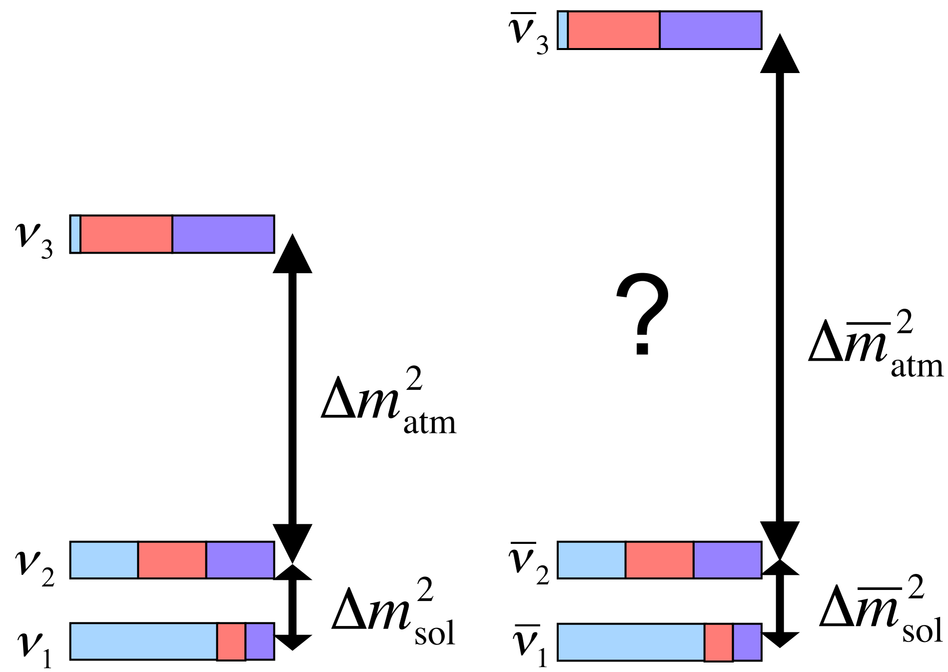
- Differences may imply new physics in the neutrino sector manifested as a difference in the effective mass-splitting.

P. Adamson, et. al, Phys. Rev. Lett. 101:131802 (2008)
Y. Ashie, et. al., Phys. Rev. D 71:112005 (2005)
Y. Ashie, et. al., Phys. Rev. D 71:112005 (2005)
M.C. Gonzalez-Garcia & M. Maltoni, Phys. Rept. 460:1-129 (2008)

Why study ν_μ and $\bar{\nu}_\mu$?

$$P(\nu_\mu \to \nu_\mu) \stackrel{?}{=} P(\bar{\nu}_\mu \to \bar{\nu}_\mu)$$

- Antineutrino parameters are less precisely known.
  - No direct precision measurements
  - MINOS is the only oscillation experiment that can do event-by-event separation



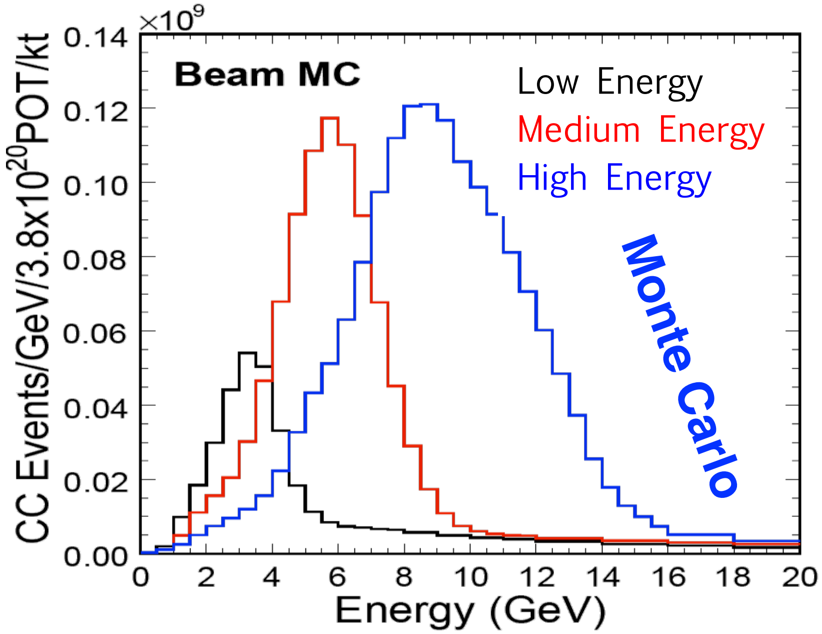
- Differences may imply new physics in the neutrino sector manifested as a difference in the effective mass-splitting.

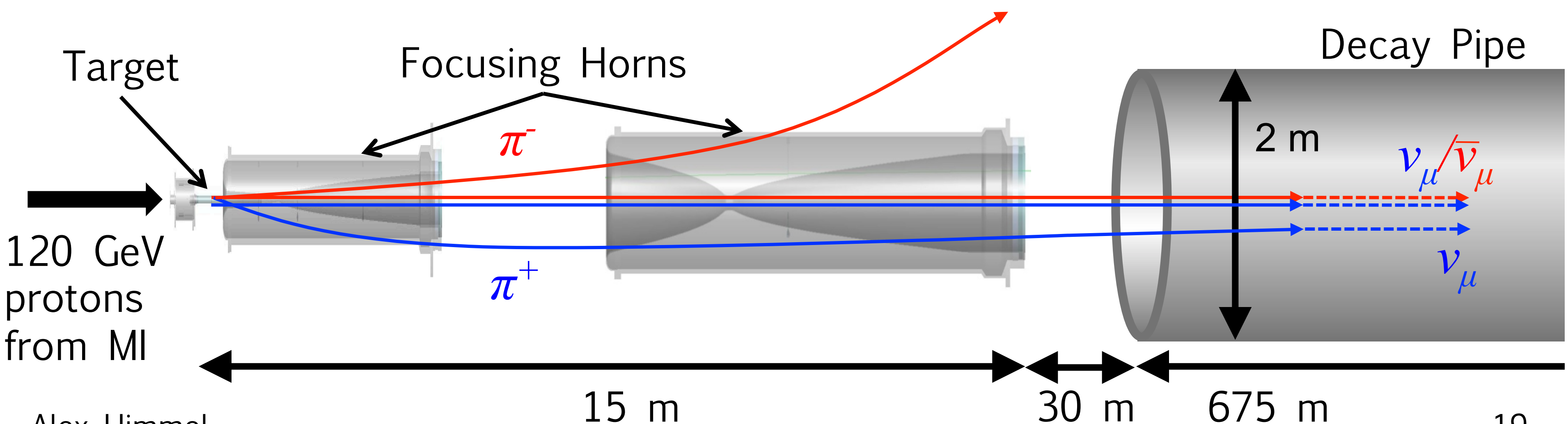
The Experiment

- NuMI neutrino beam
- MINOS detectors

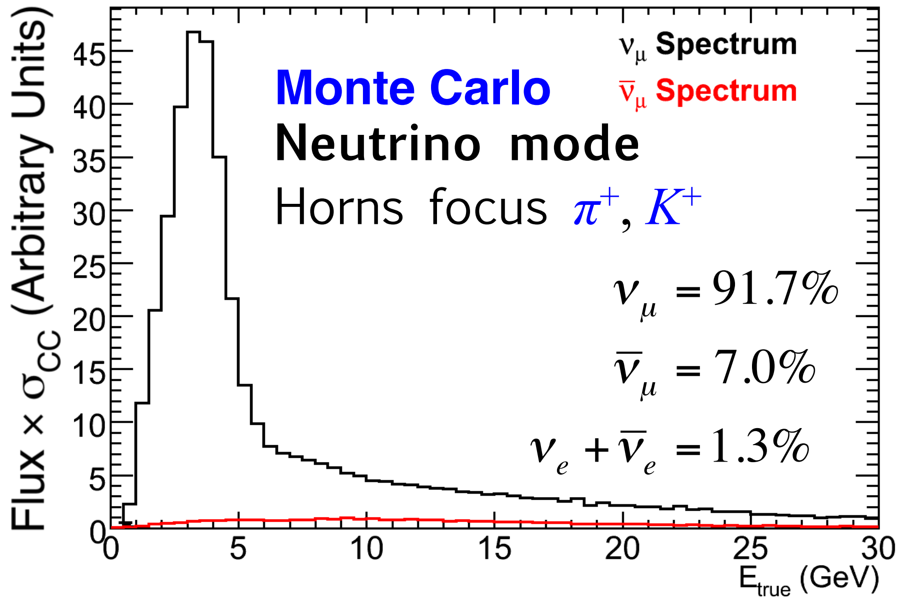
The NuMI Beam

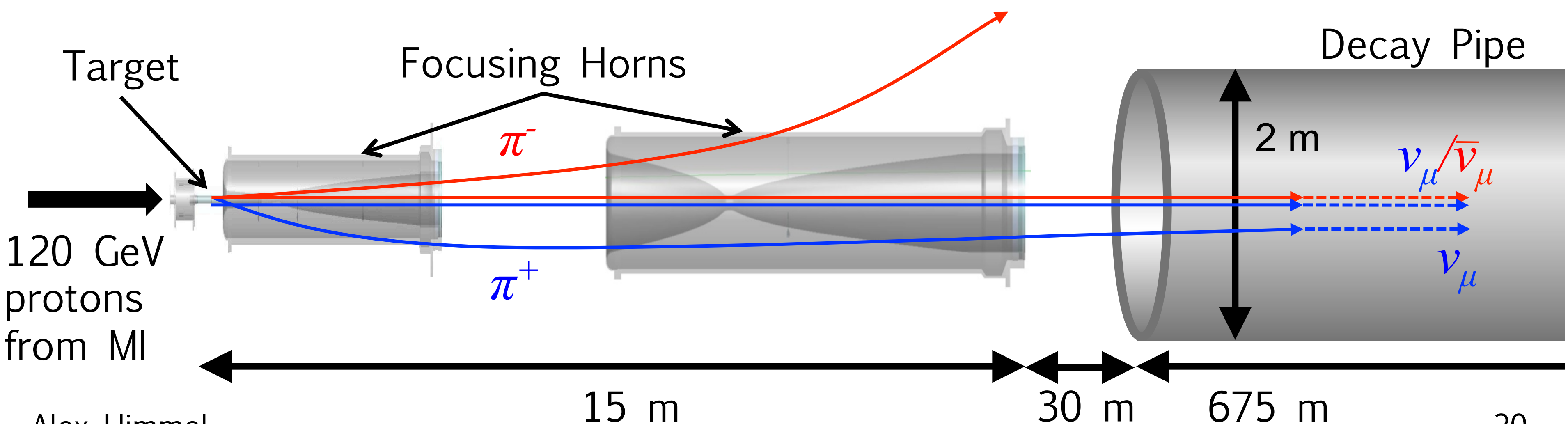
- 120 GeV protons incident on a thick, segmented graphite target
- Magnetic horns can focus either sign
- Enhance the ν_μ flux by focusing π^+, K^+
- Adjustable peak energy



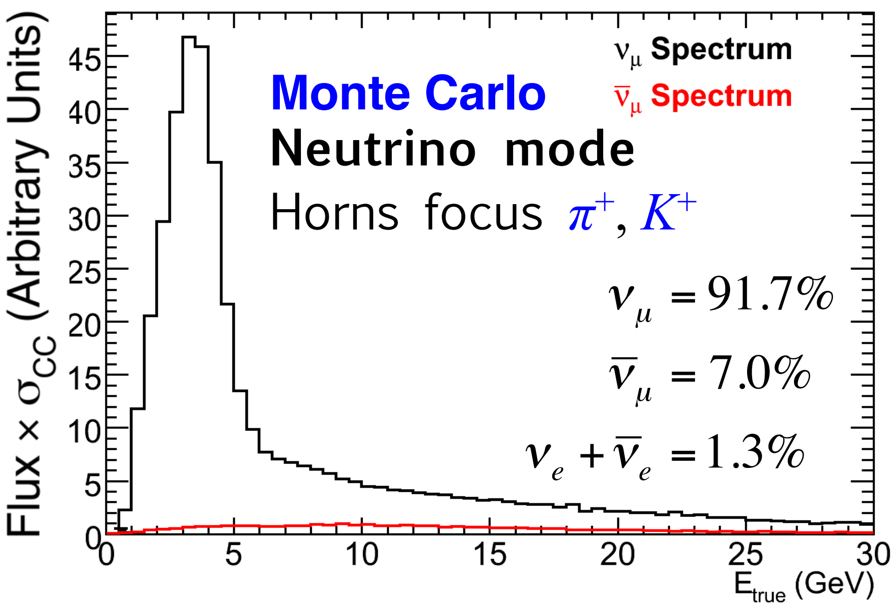


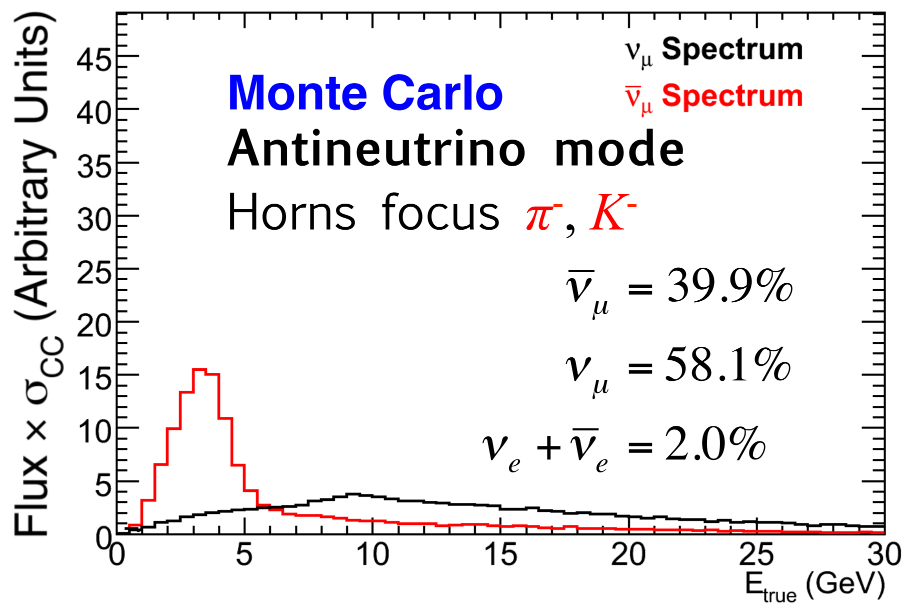
Neutrino Mode

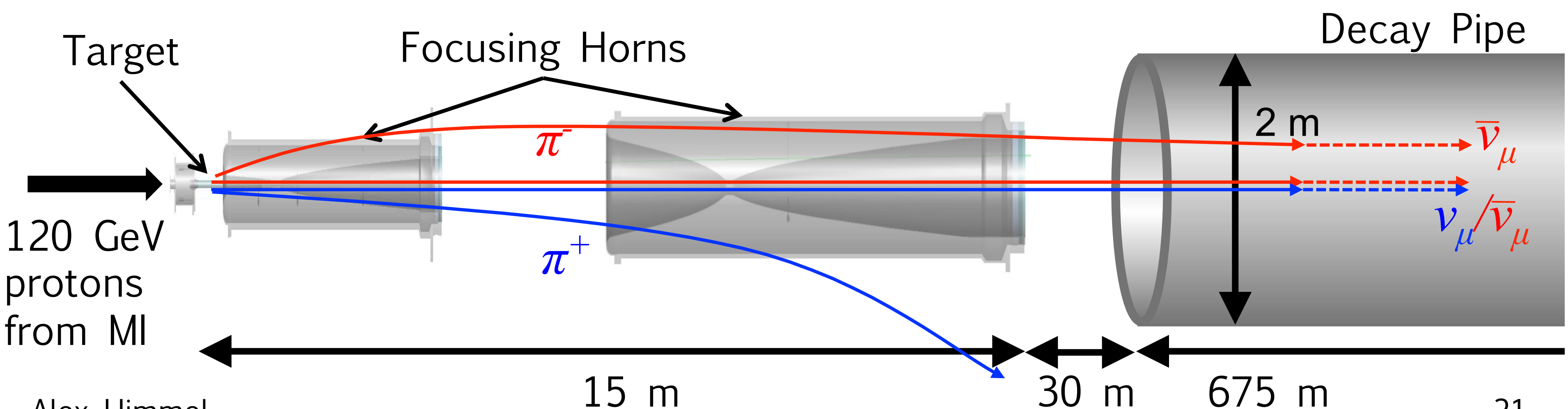




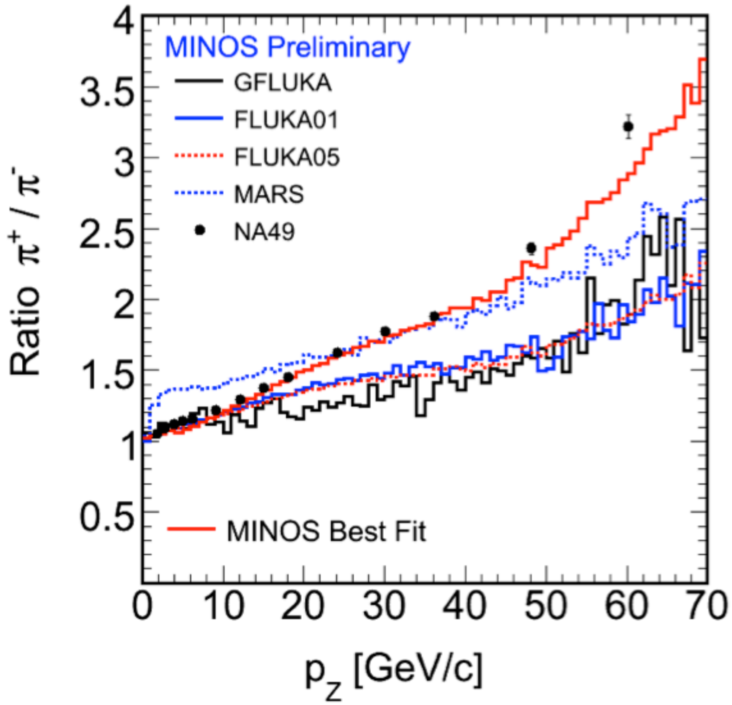
Antineutrino Mode



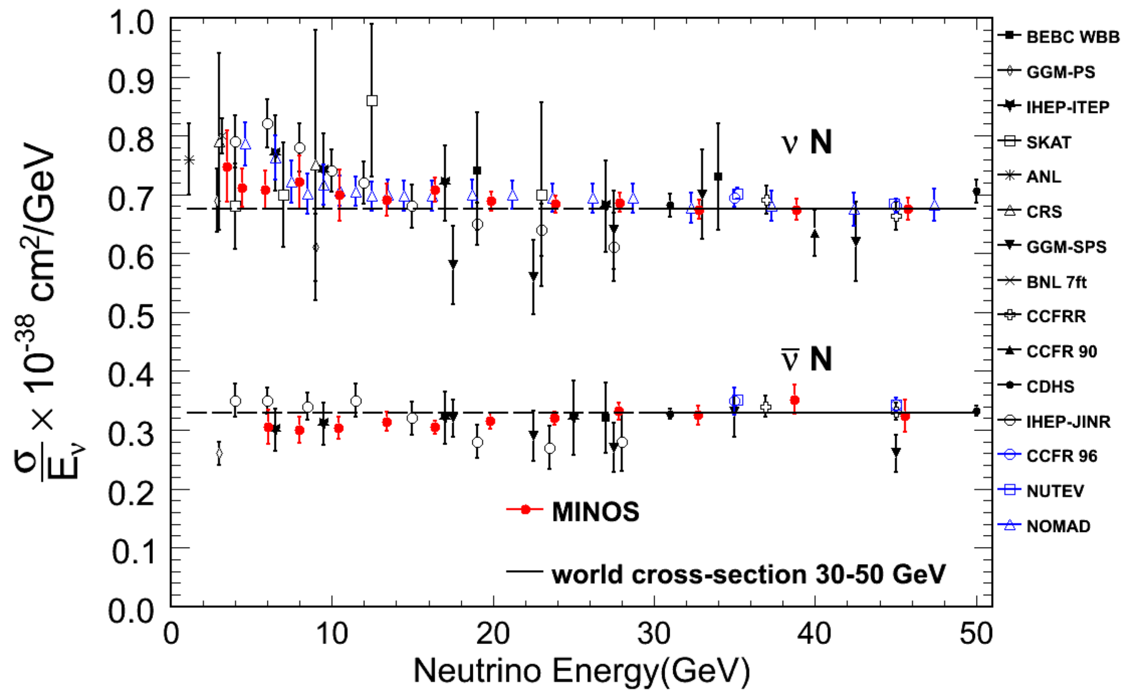




Antineutrino Cross-section



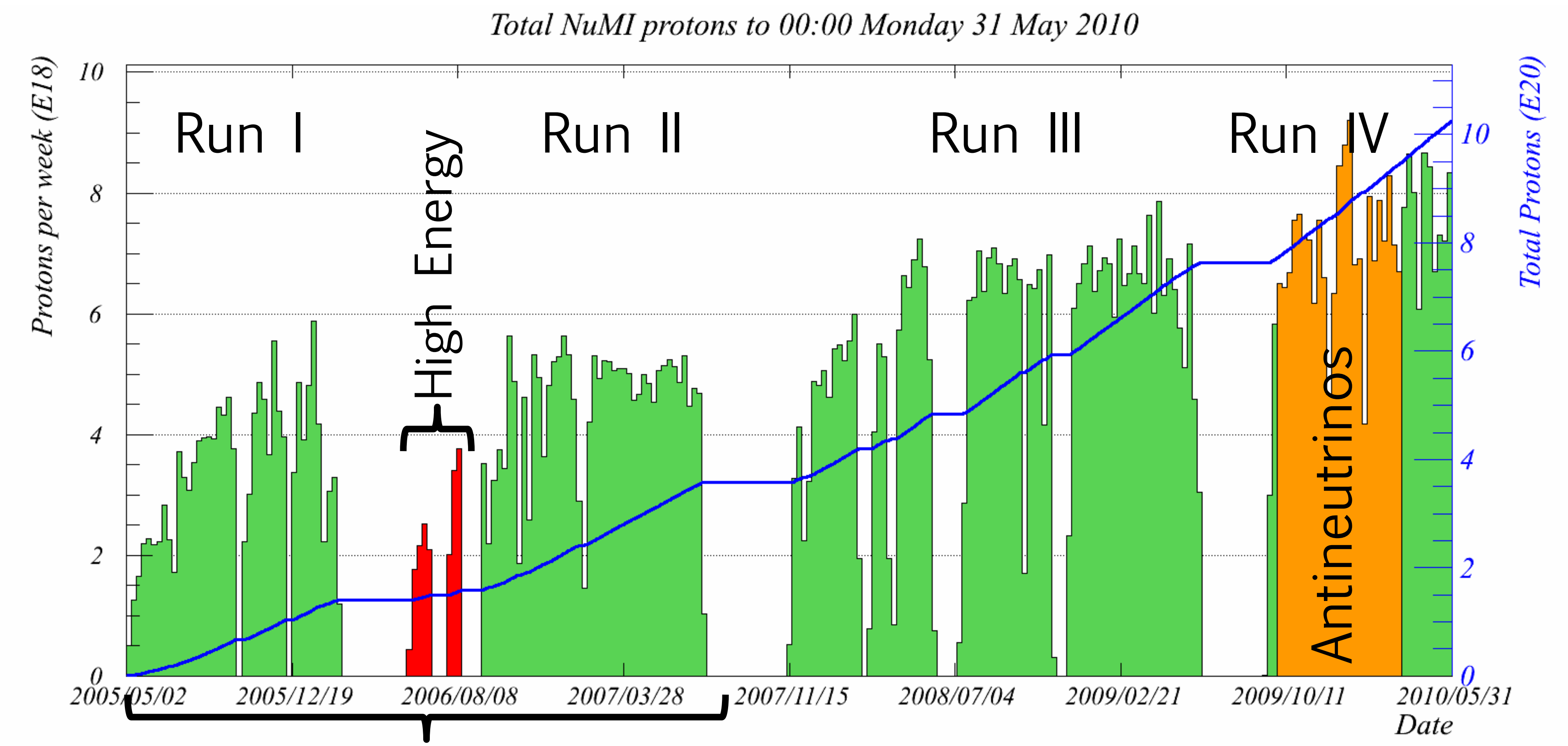
Eur. Phys. J. C 49 897 (2007)



Phys. Rev. D 81 072002 (2010)

- x1.3 lower π^- production
- x2.3 lower interaction cross-section

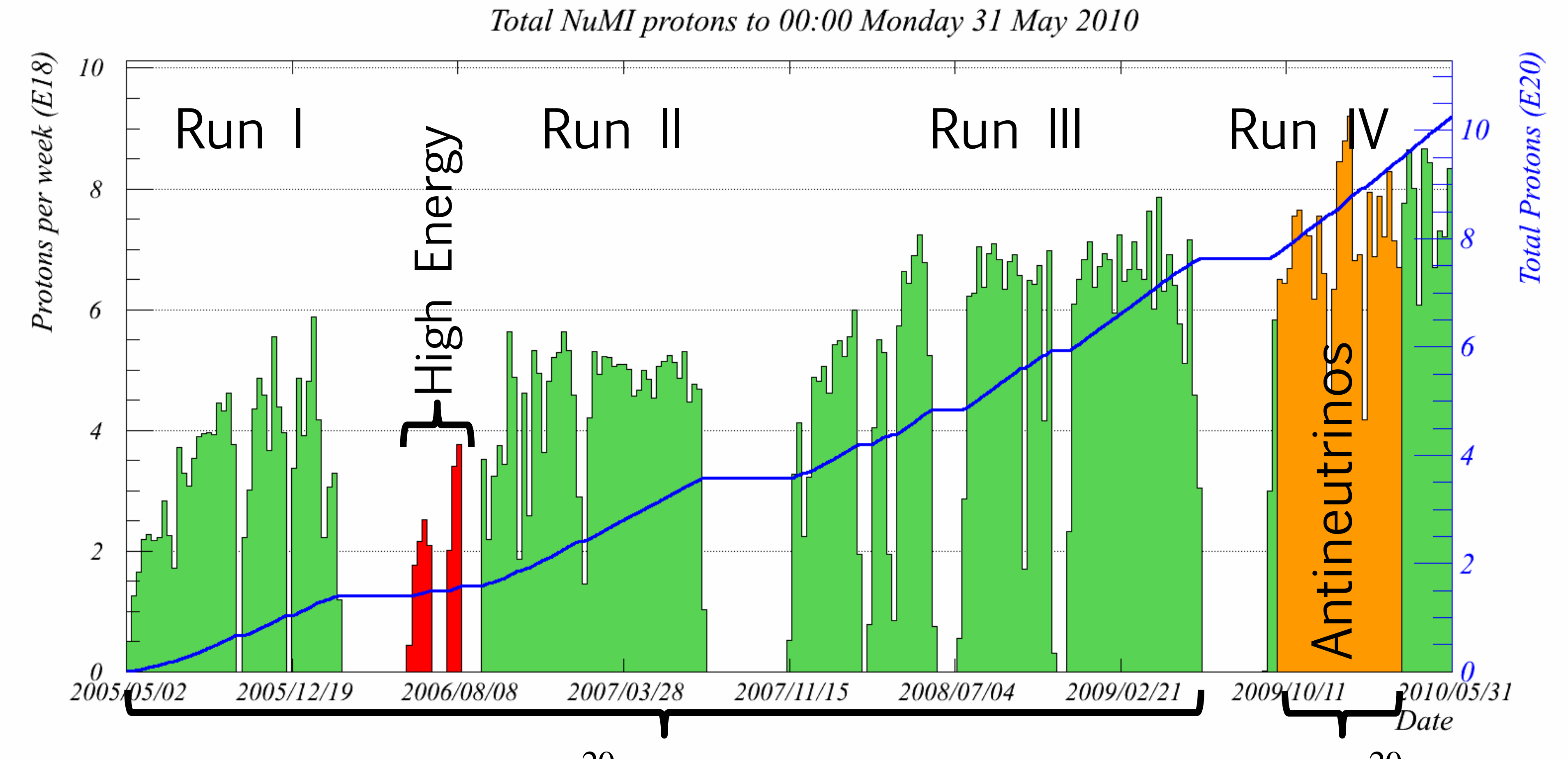
NuMI Beam Performance



3.21×10^{20} POT ν_μ mode

Previous Analyses

NuMI Beam Performance



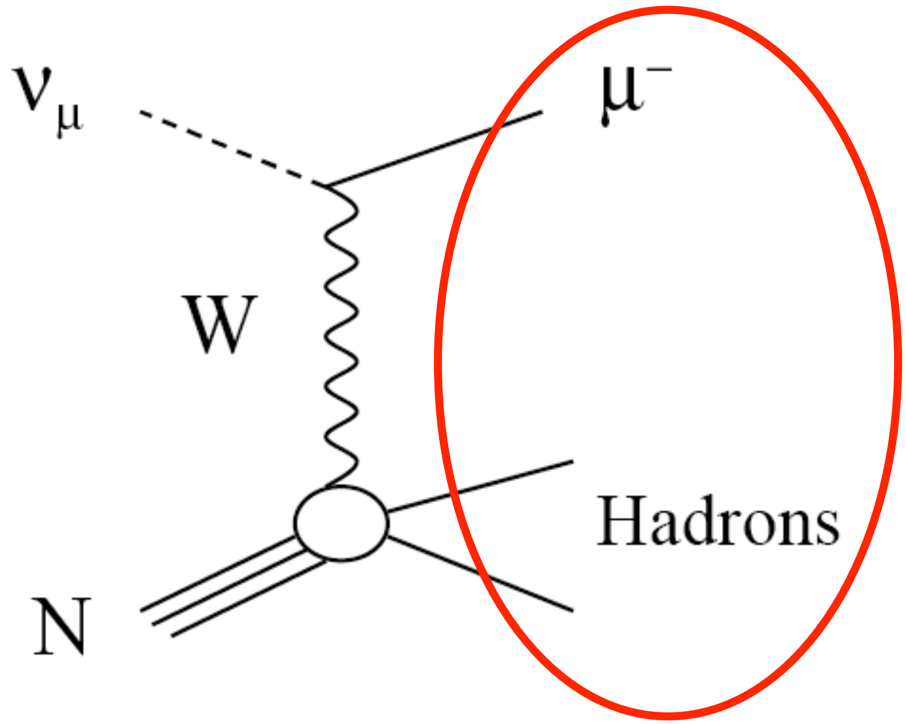
7.24×10^{20} POT ν_μ mode

Current ν_μ Analysis

1.71×10^{20} POT

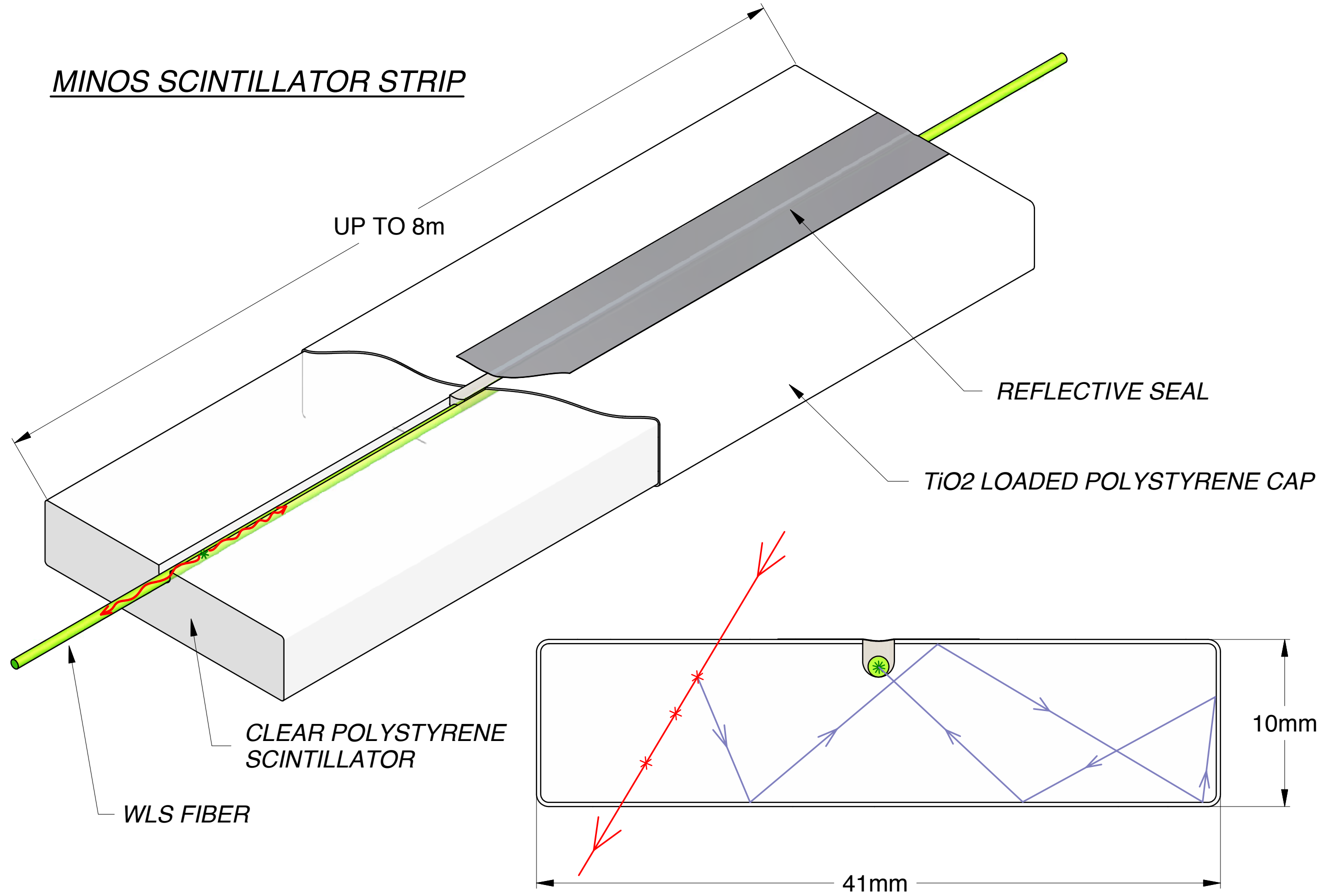
$\bar{\nu}_\mu$ mode

Detecting Neutrinos



- Cannot directly observe the neutrino
- Instead, observe the charged particles after a neutrino interacts with a nucleus in the detector

Detecting Charged Particles



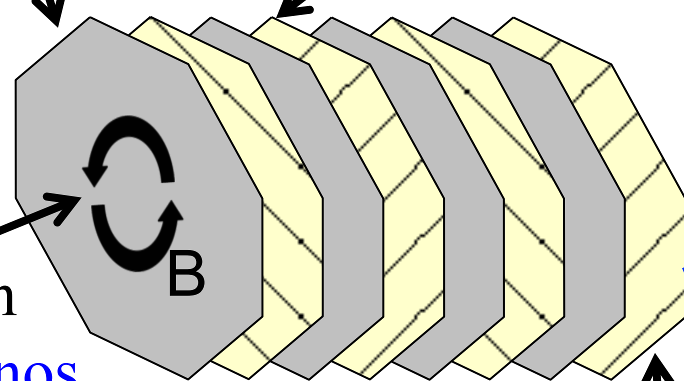
- 4 cm x 1 cm plastic scintillator strips
- Embedded wavelength-shifting fiber
- Scintillation light amplified by multi-anode PMTs

MINOS Detectors

1 in thick Steel

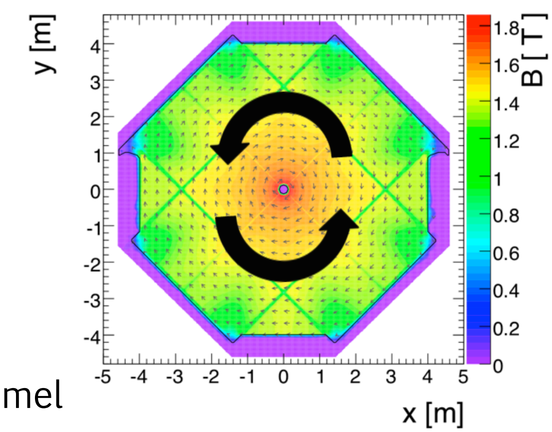
1 cm thick, 4.1 cm wide
Plastic Scintillator

Read out on
wavelength-shifting
fibre to multi-anode
PMTs

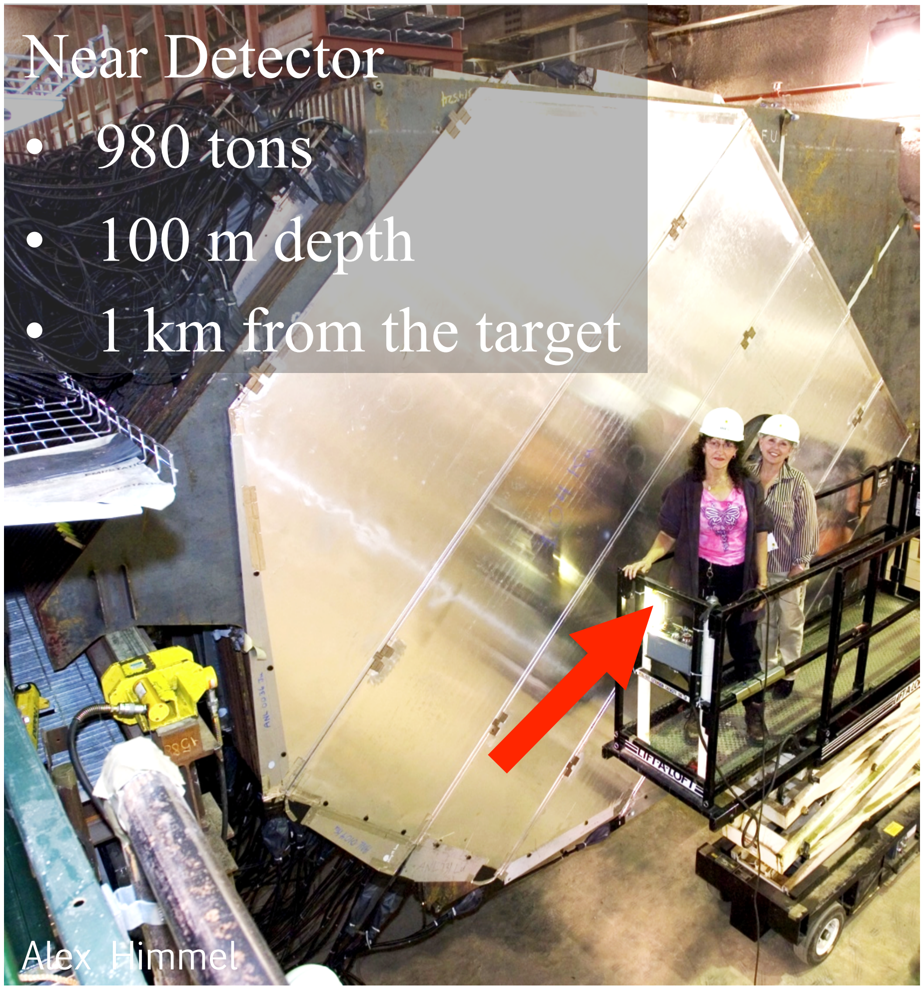


1.3 T toroidal magnetic field can distinguish neutrinos and antineutrinos

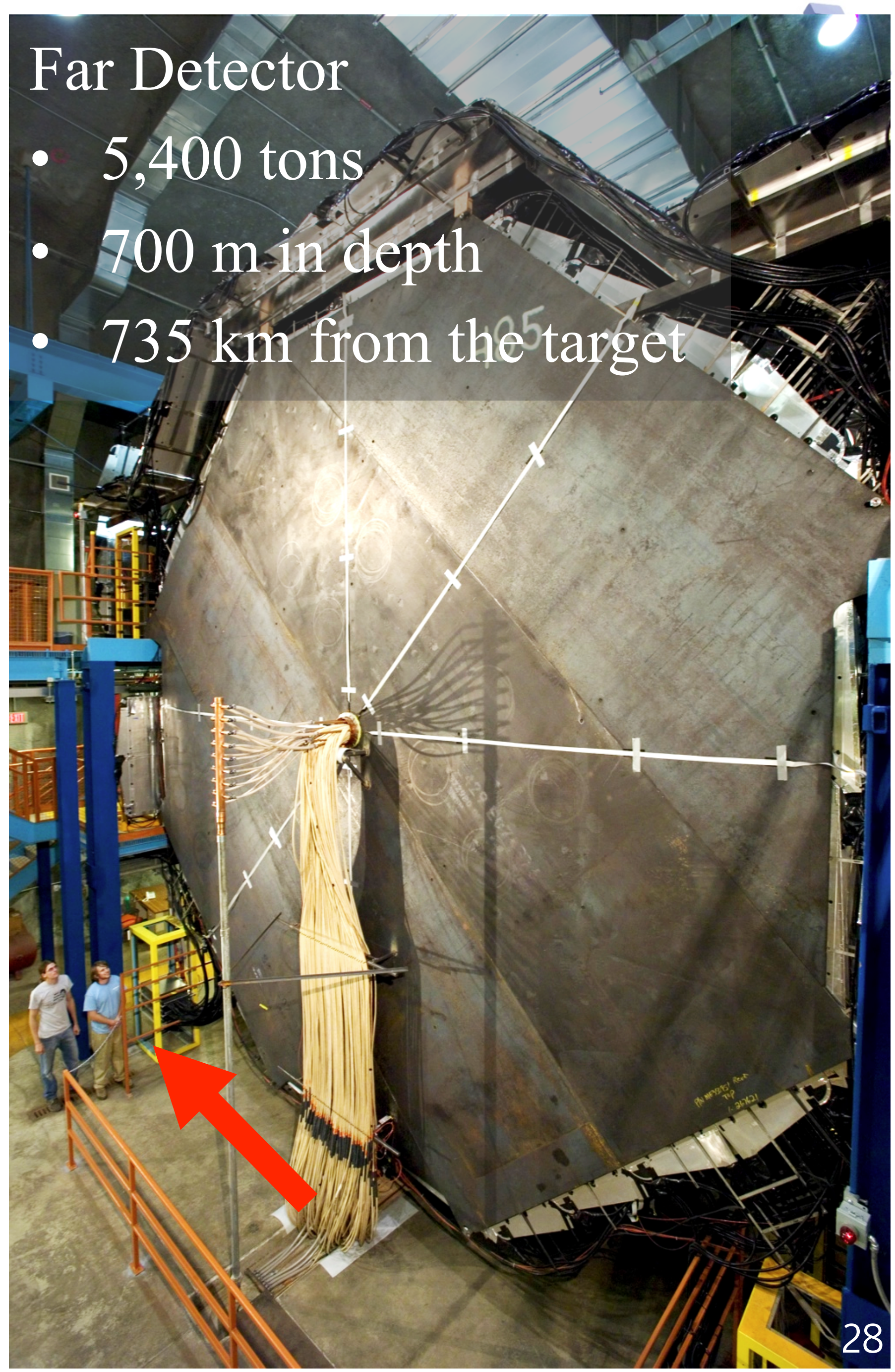
Strips in alternating directions allow 3D event reconstruction



MINOS Detectors



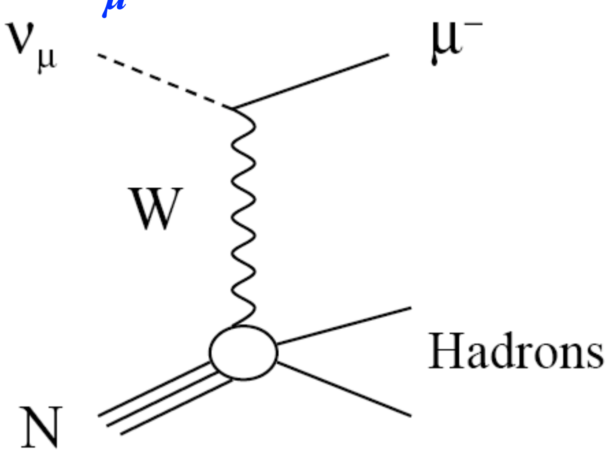
Near Detector
- 980 tons
- 100 m depth
- 1 km from the target

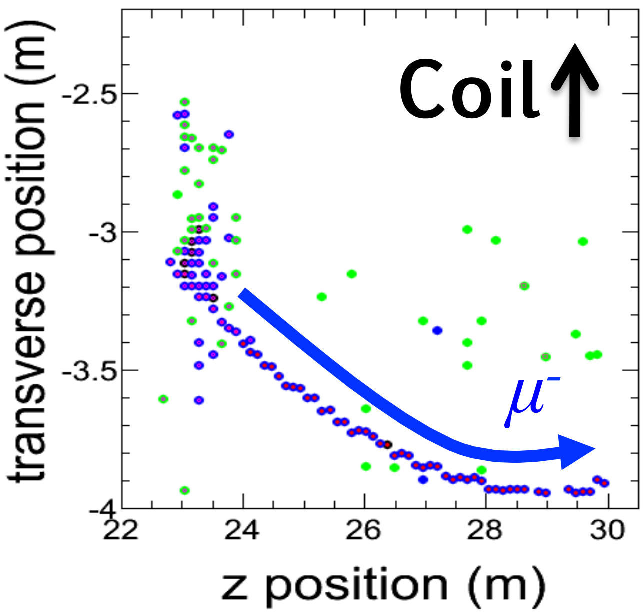


Far Detector
- 5,400 tons
- 700 m in depth
- 735 km from the target

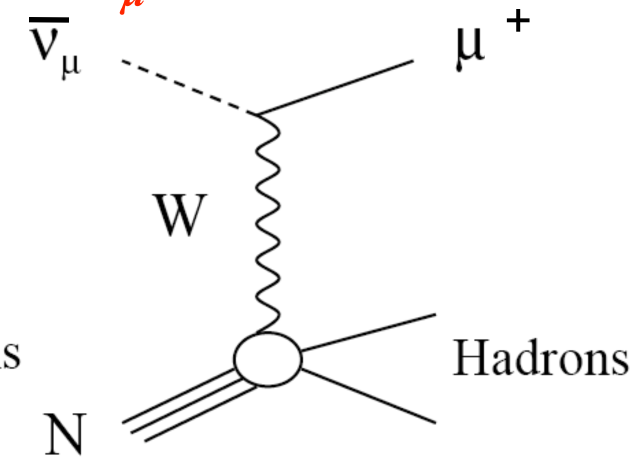
MINOS Events

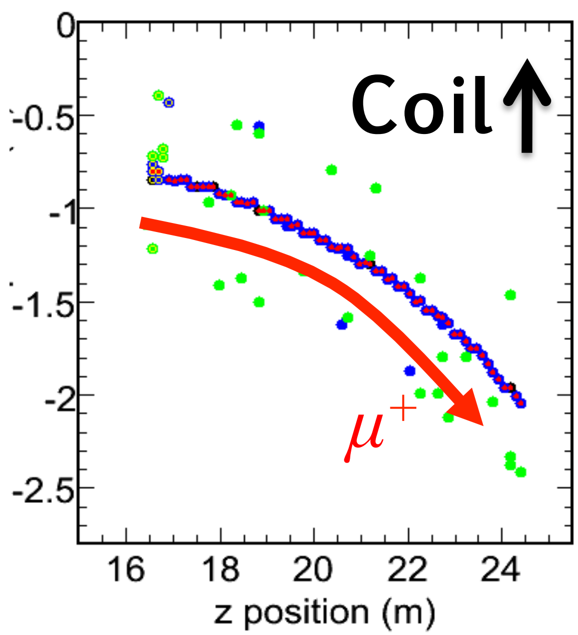
ν_μ CC Event



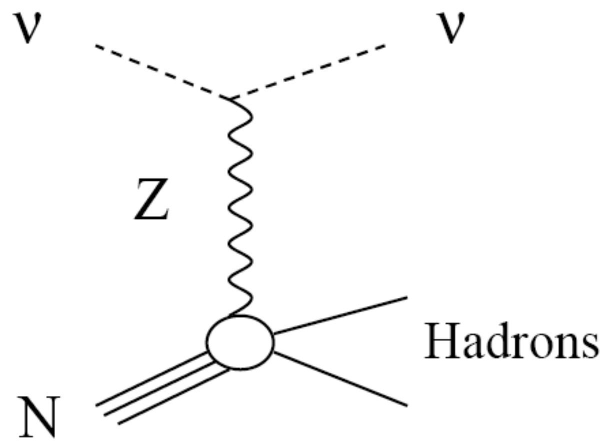


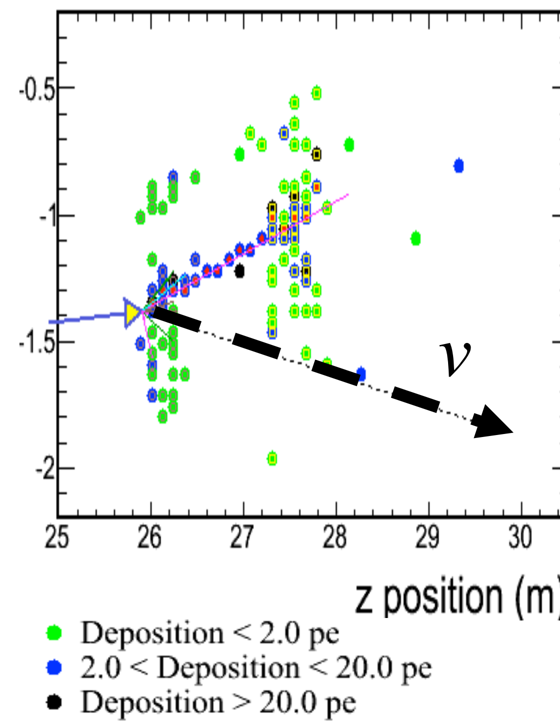
$\bar{\nu}_\mu$ CC Event





NC Event





Simulated Events

The Analyses

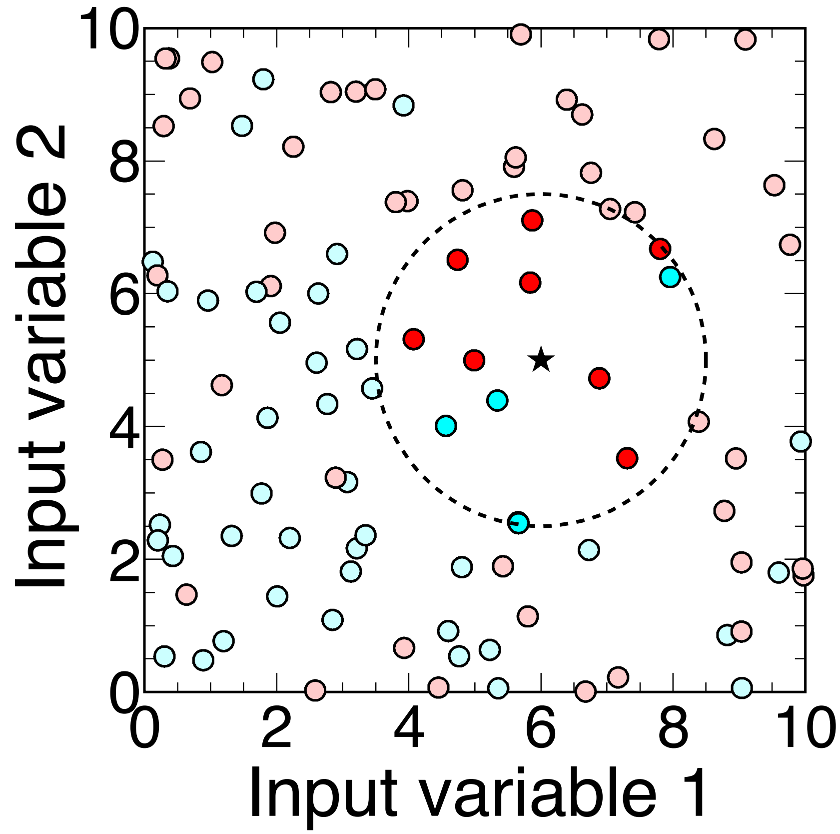
Oscillation Analysis in Brief

1. Select neutrino/antineutrino events in the detectors
2. Measure their energies to produce Near and Far detector spectra
3. Use the Near Detector spectrum to predict the Far Detector spectrum independent of oscillations
4. Fit the Far Detector data to measure oscillations

Selecting Charged Currents

- Basic selection
  - In-time with the spill
  - In the fiducial volume
  - At least 1 reconstructed track

- CC/NC separation using a kNN algorithm
  - Compare to Monte Carlo events
  - Fraction of signal in *k* most similar events is the discriminant

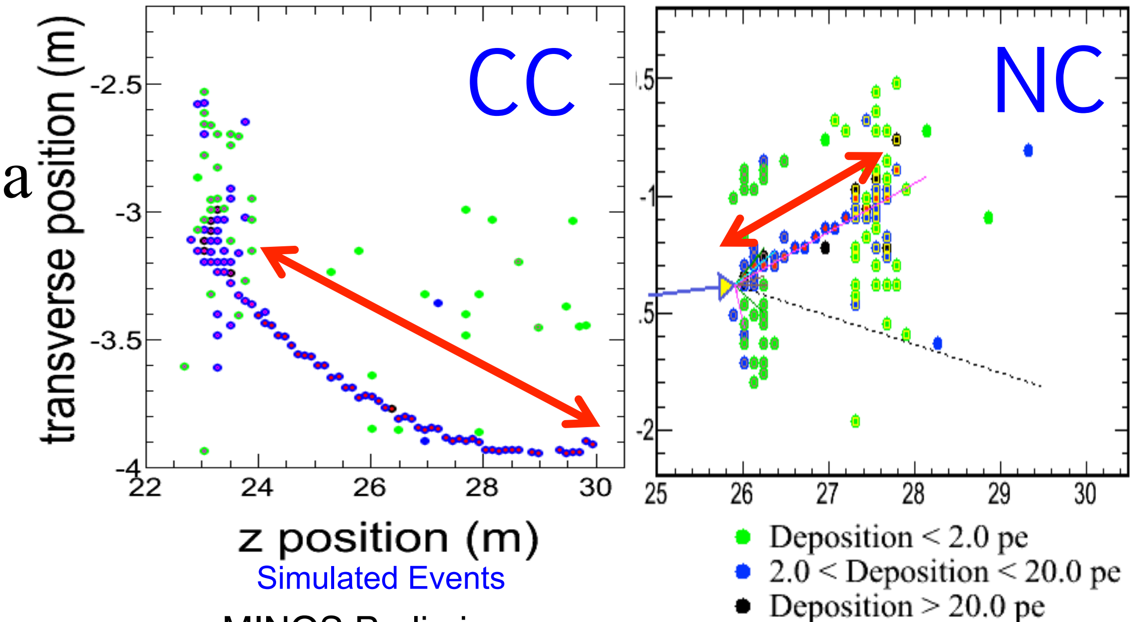


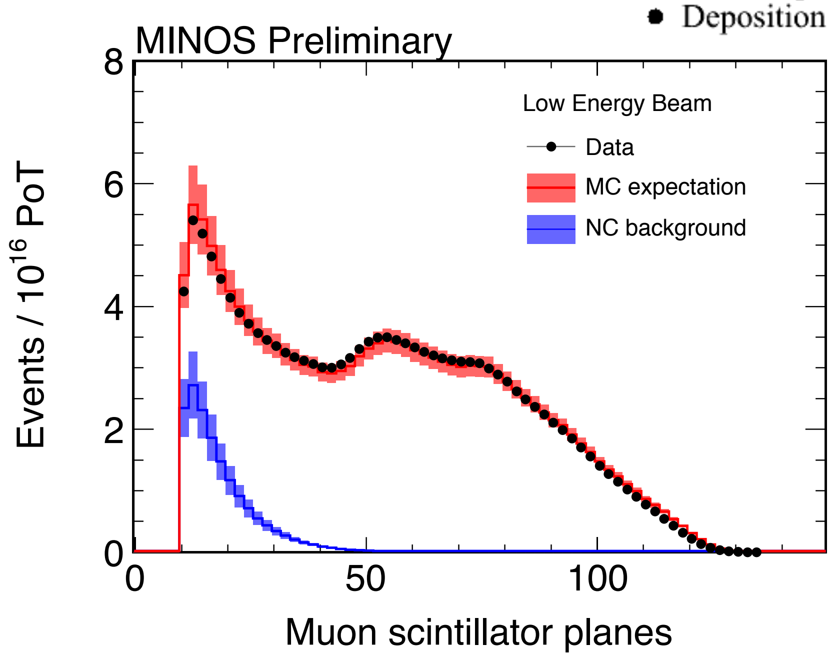
k-Nearest Neighbors

"kNN"

Selecting Charged Currents

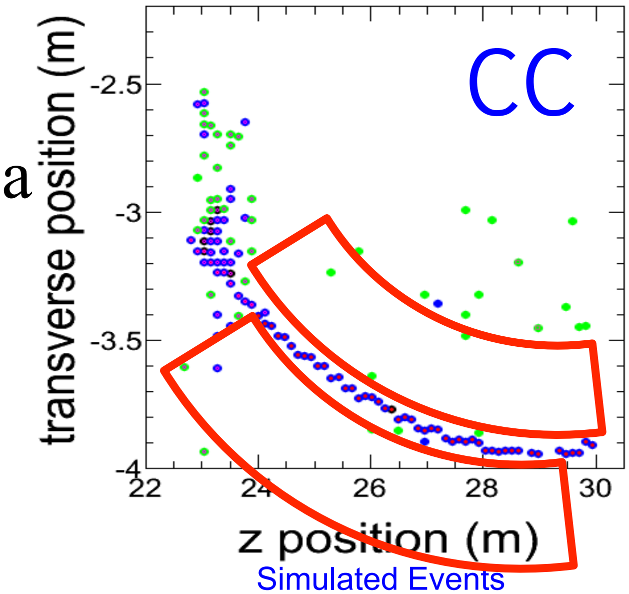
- CC/NC separation using a kNN algorithm
- 4-parameter comparison
  - Track length
  - Transverse energy profile
  - Energy deposited per plane
  - Energy fluctuations along the track

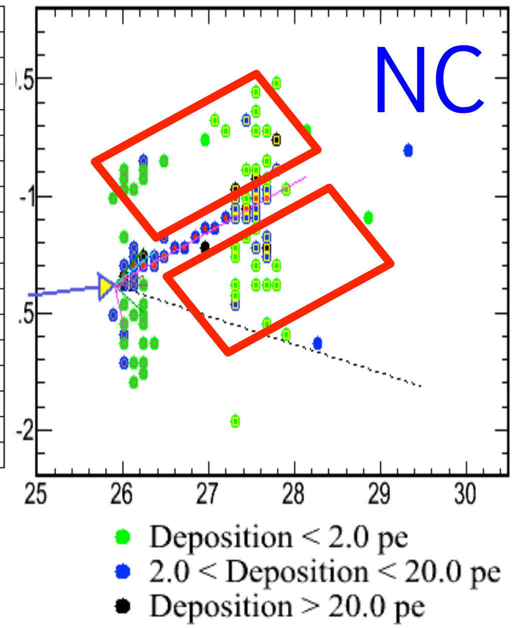


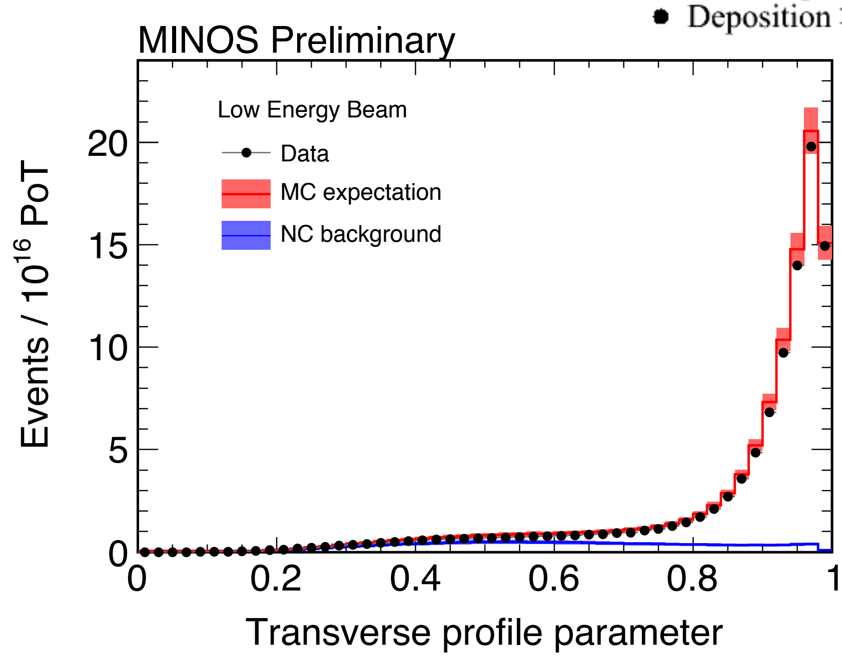


Selecting Charged Currents

- CC/NC separation using a kNN algorithm
- 4-parameter comparison
  - Track length
  - Transverse energy profile
  - Energy deposited per plane
  - Energy fluctuations along the track

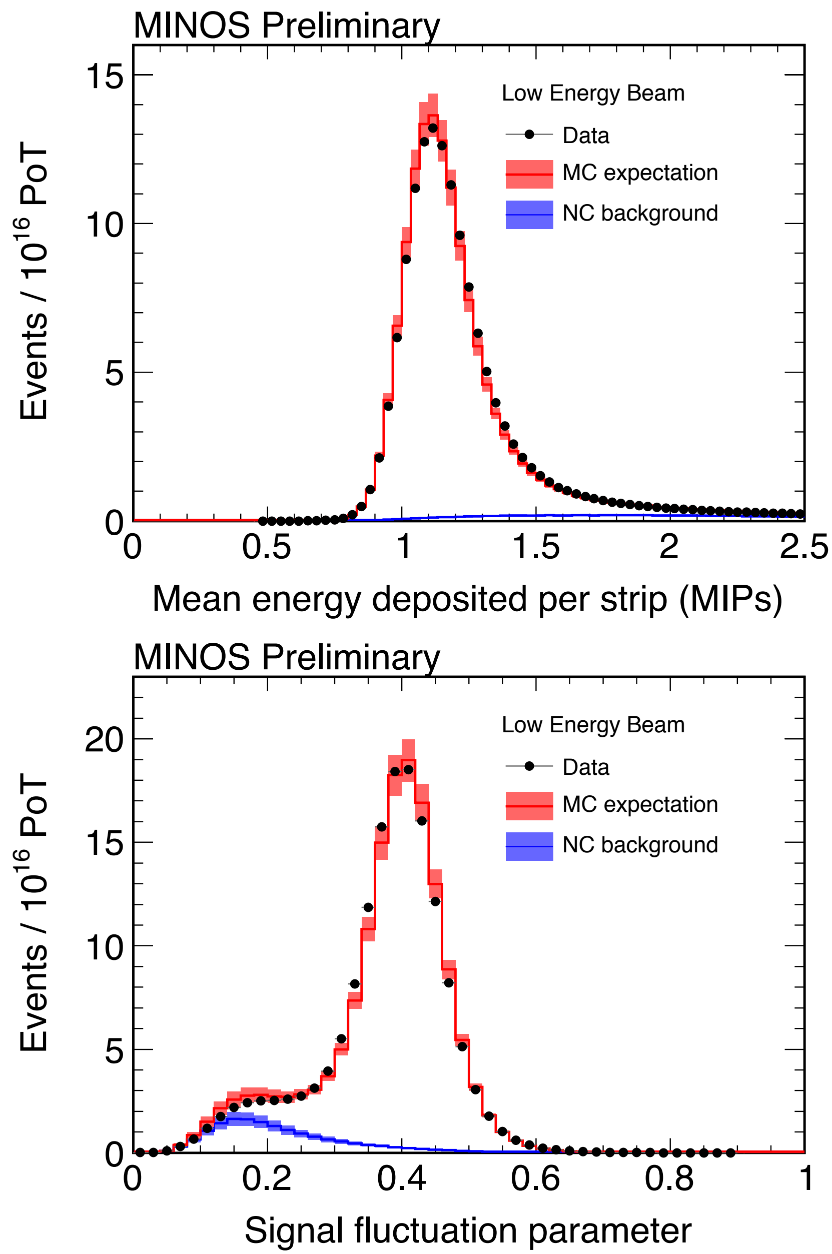




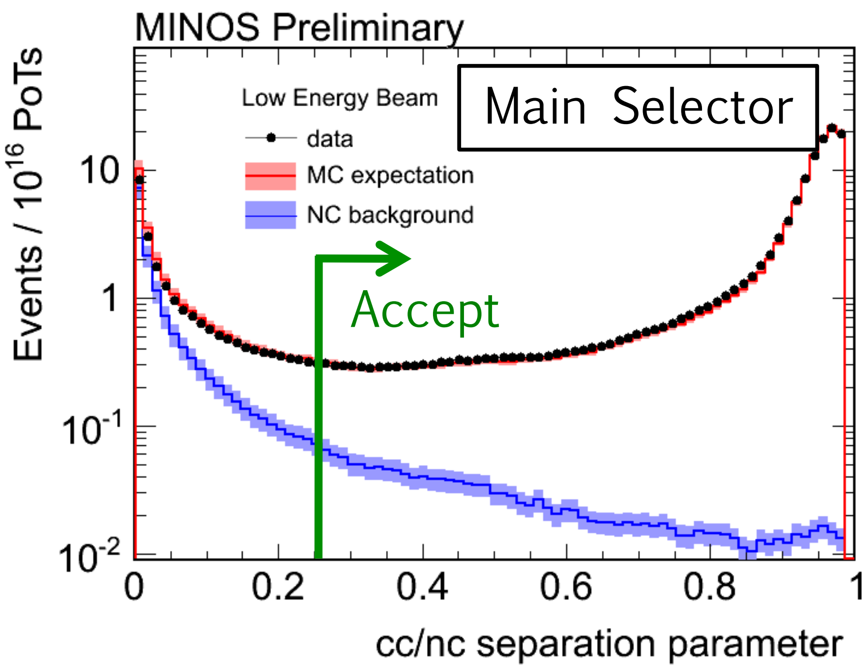


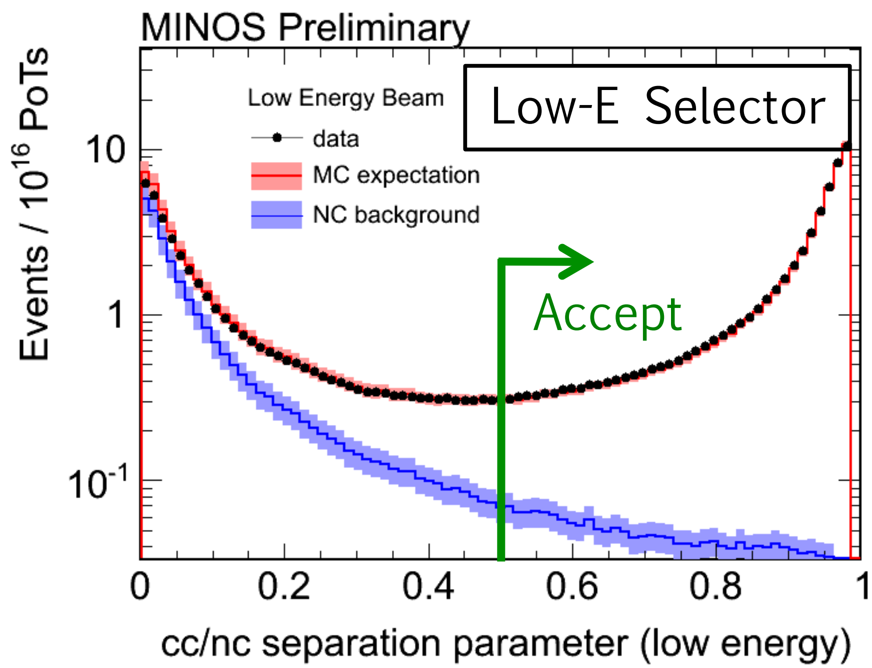
Selecting Charged Currents

- CC/NC separation using a kNN algorithm
- 4-parameter comparison
  - Track length
  - Transverse energy profile
  - Energy deposited per plane
  - Energy fluctuations along the track



Neutrino Selection



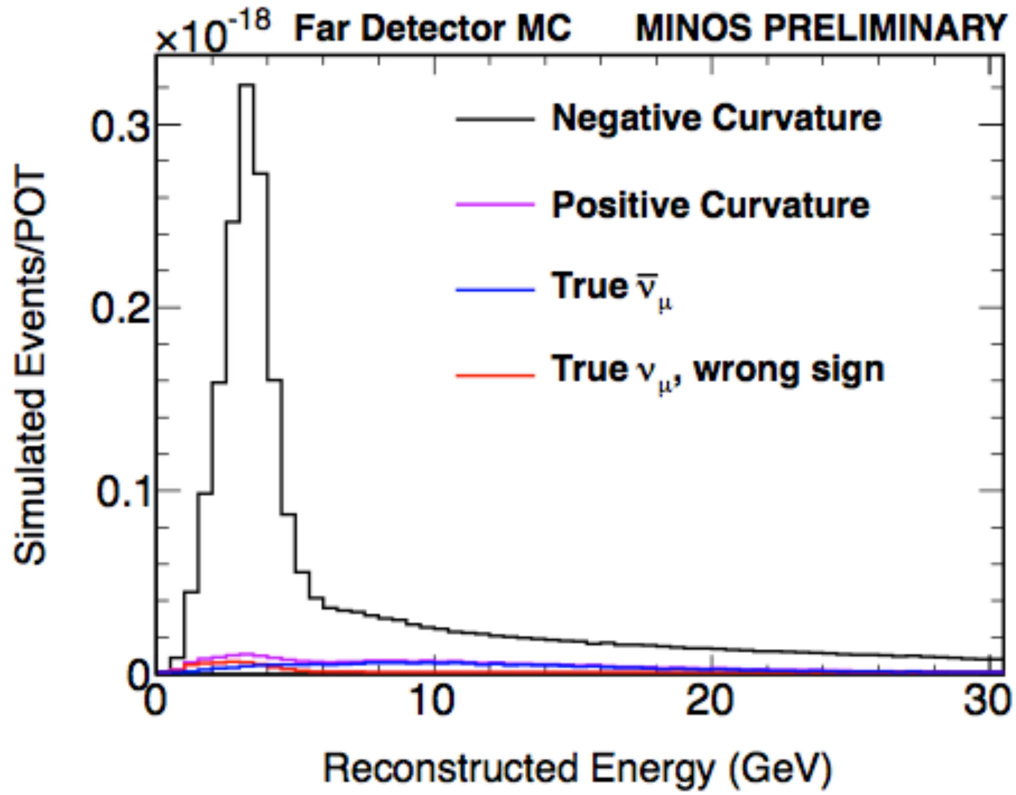


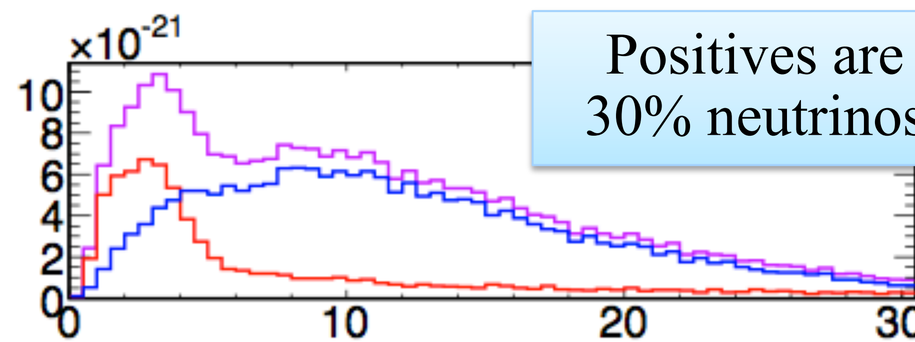
- Added a second selector that accepts lower energy tracks
  - Number of planes in the track
  - Energy deposition at the end of the track
  - Amount of scattering

- The final selection is a logical OR of these two cuts.

Neutrino Selection

- The neutrino analysis no longer uses a charge-sign cut
- Majority of low-energy positive events are really neutrinos
- Like the Low-E selector, improves low-energy efficiency

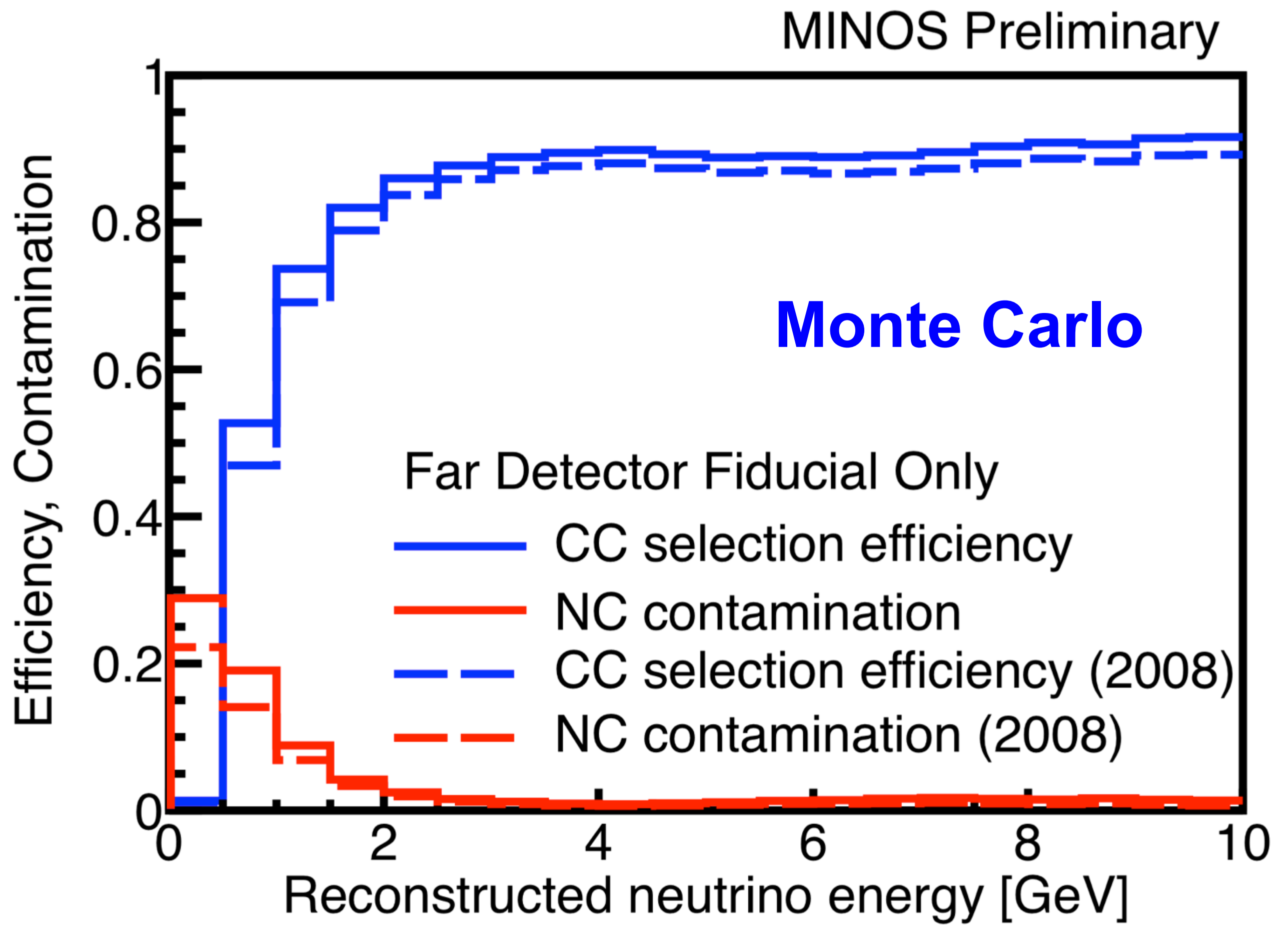




Positives are 30% neutrinos

Alex Himmel

Neutrino Selection

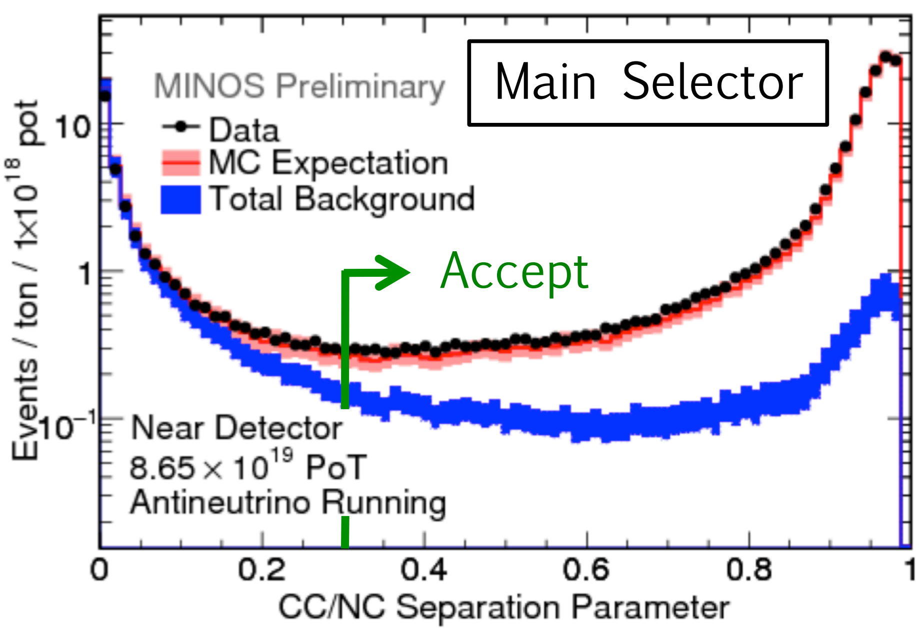


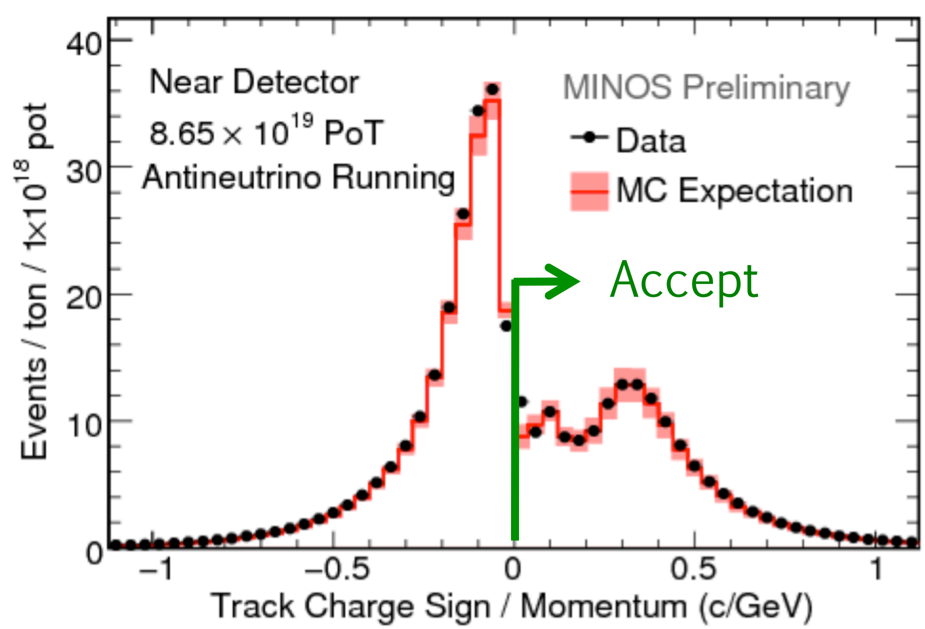
- Increase sensitivity by improving efficiency (89% vs. 87%) at the expense of contamination (1.7% vs. 1.2%)

Selecting CC Antineutrinos

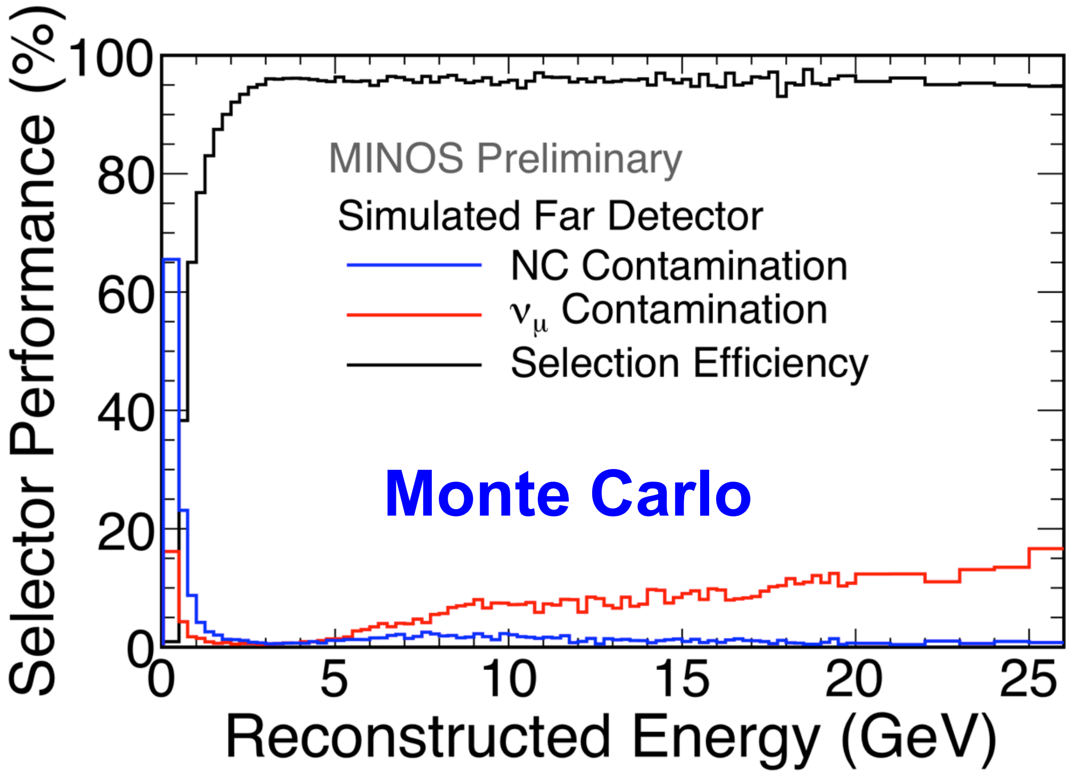
- Use the CC/NC Selector
  - Removes NC and high-y CC interactions

- Accept only events with positive reconstructed charge





Efficiency & Purity



	Signal	Bkgd.
0-6 GeV	106	1.9
6-20 GeV	38	4.3
> 20 GeV	8	3.0

High energy ν_μ contamination does not affect the oscillation result

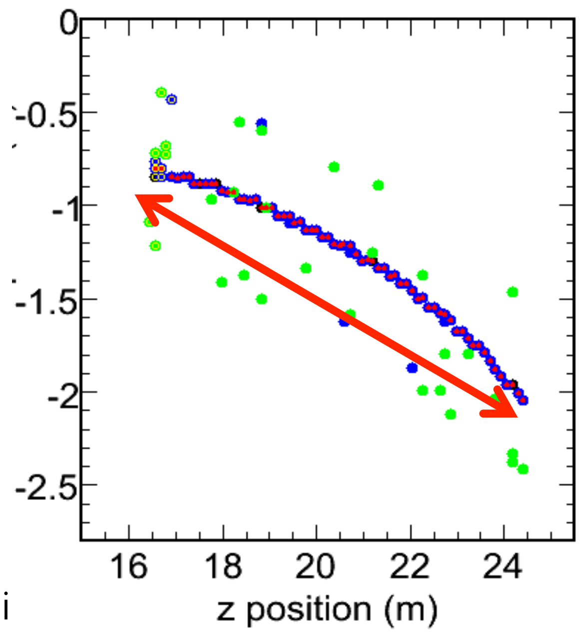
Oscillation Analysis in Brief

1. Select neutrino/antineutrino events in the detectors
2. Measure their energies to produce Near and Far detector spectra
3. Use the Near Detector spectrum to predict the Far Detector spectrum independent of oscillations
4. Fit the Far Detector data to measure oscillations

Muon Energy

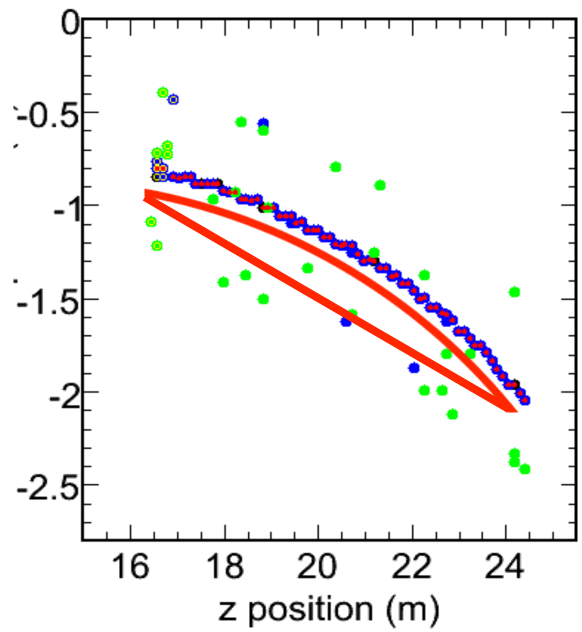
Contained Tracks

- Measure the track length in the detector
- Gives muon energy using *dE/dx*
- 4.6% resolution at 3 GeV



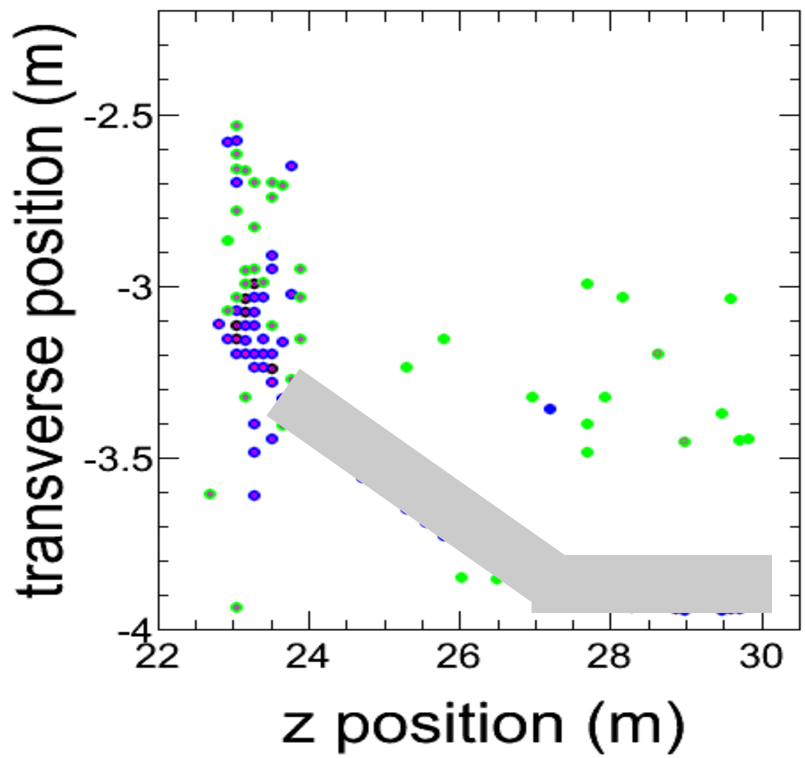
Exiting Tracks

- Measure the track curvature
- Proportional to charge/ momentum
- 11% resolution at 3 GeV



Hadronic Shower Energy

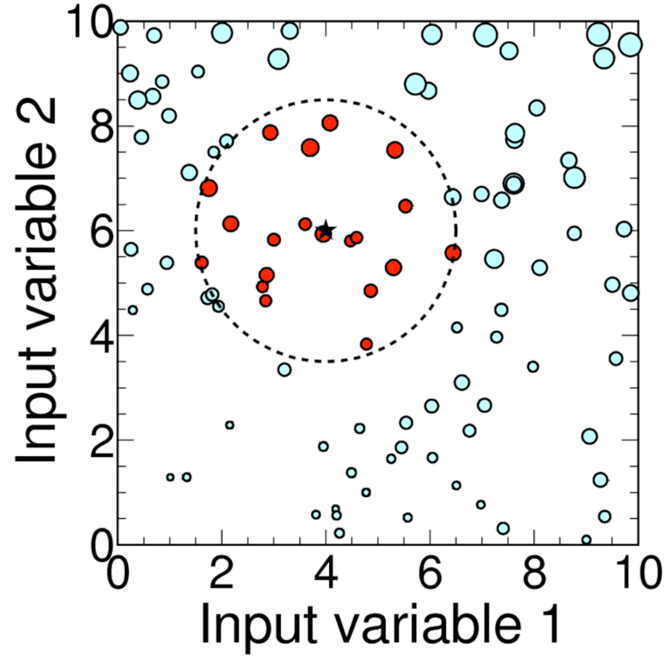
- Measure calorimetrically
  - Sum energy of all non-track hits in the event
- Standard for all previous MINOS analyses



Hadronic Shower Energy

Neutrinos

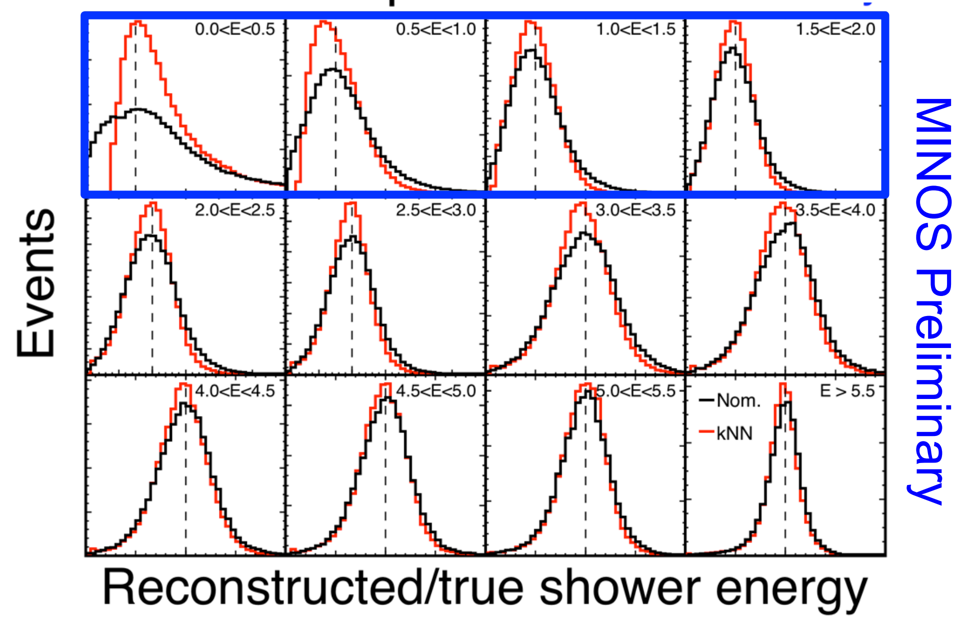
- New for 2010 analysis
- Use a *k*NN algorithm
  - Calorimetry and topology
- Average true MC energy of *k* nearest neighbors
- 43% resolution for 1-1.5 GeV showers



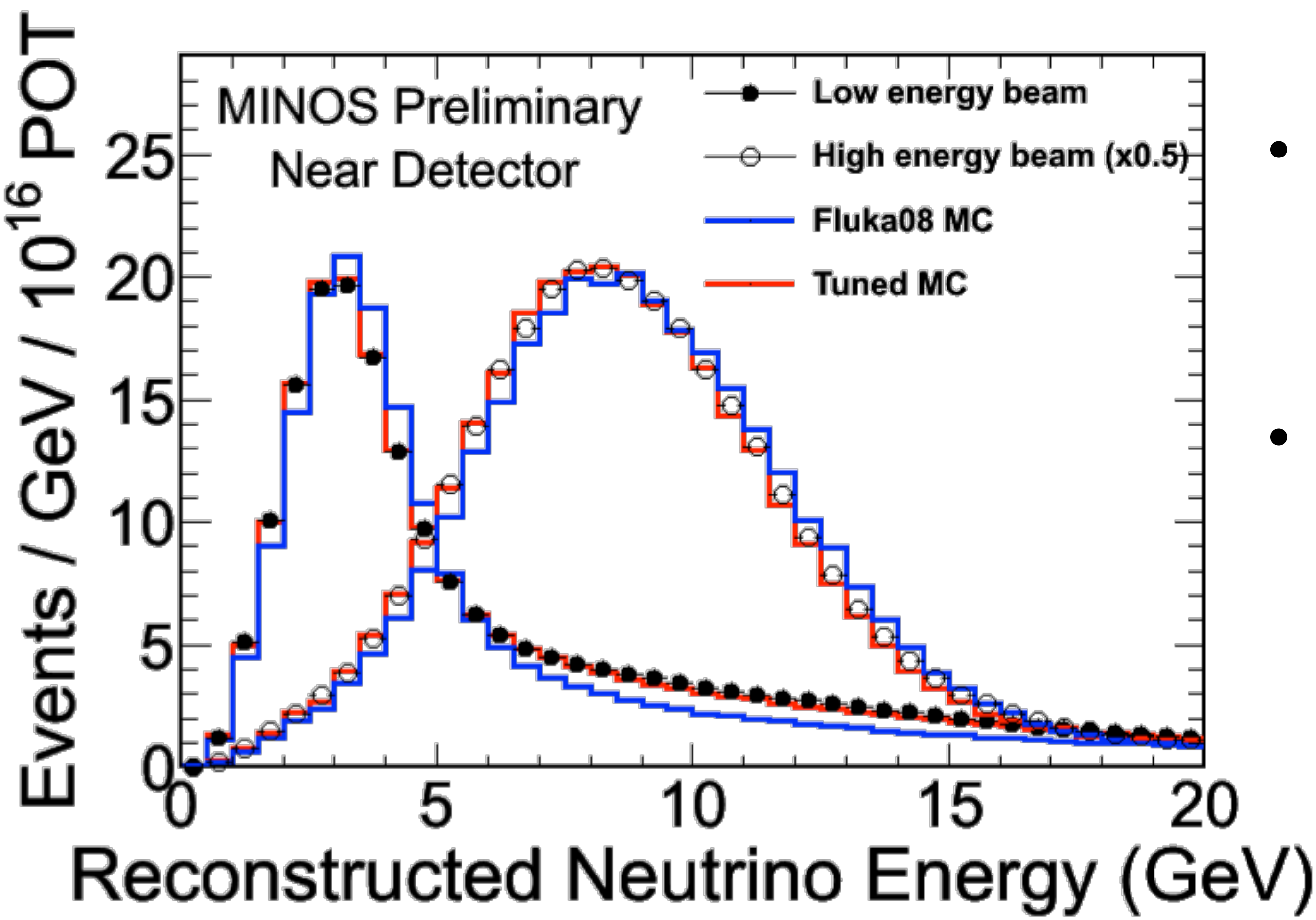
Monte Carlo

Original Energy

New Estimator

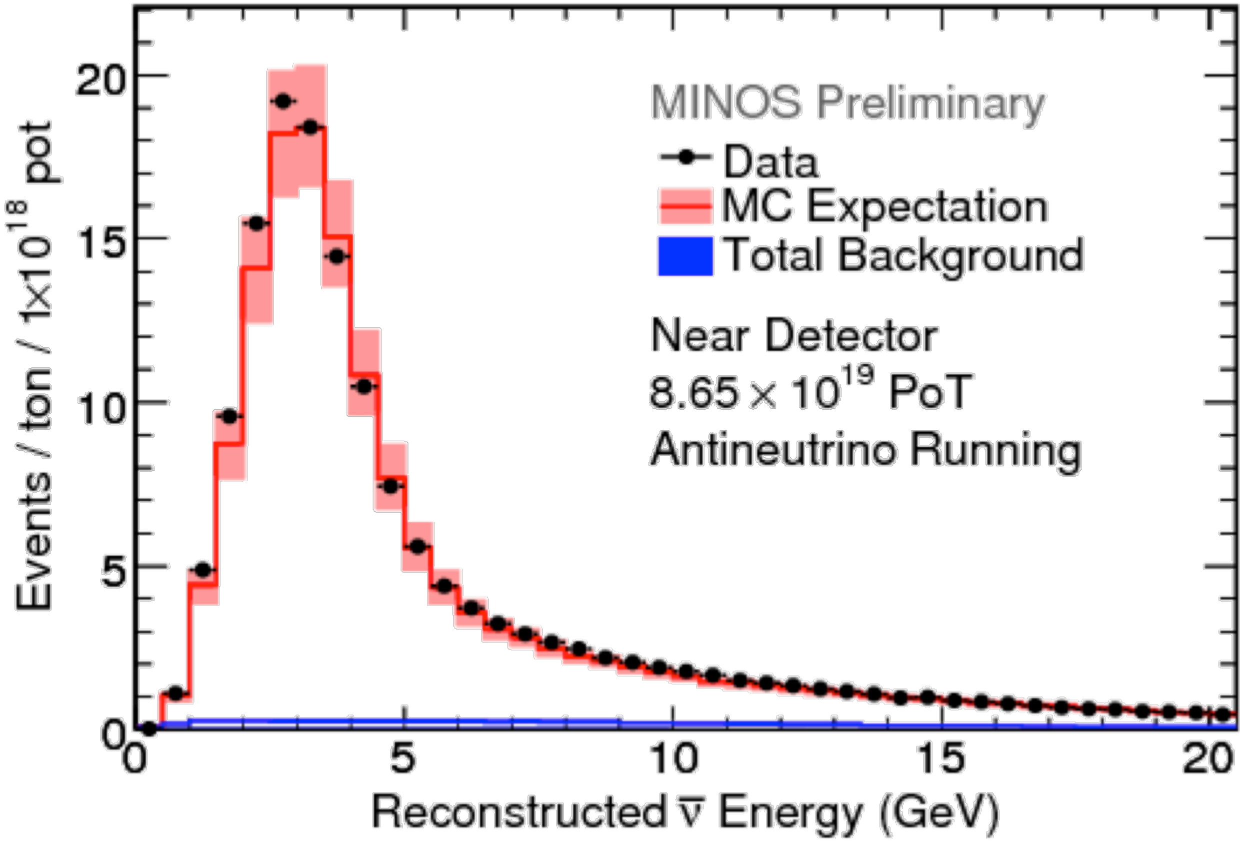


Neutrino Near Detector Data



- Majority of data taken in Low Energy Beam
- High Energy Beam gives us more events above the oscillation dip

Near Detector Spectrum

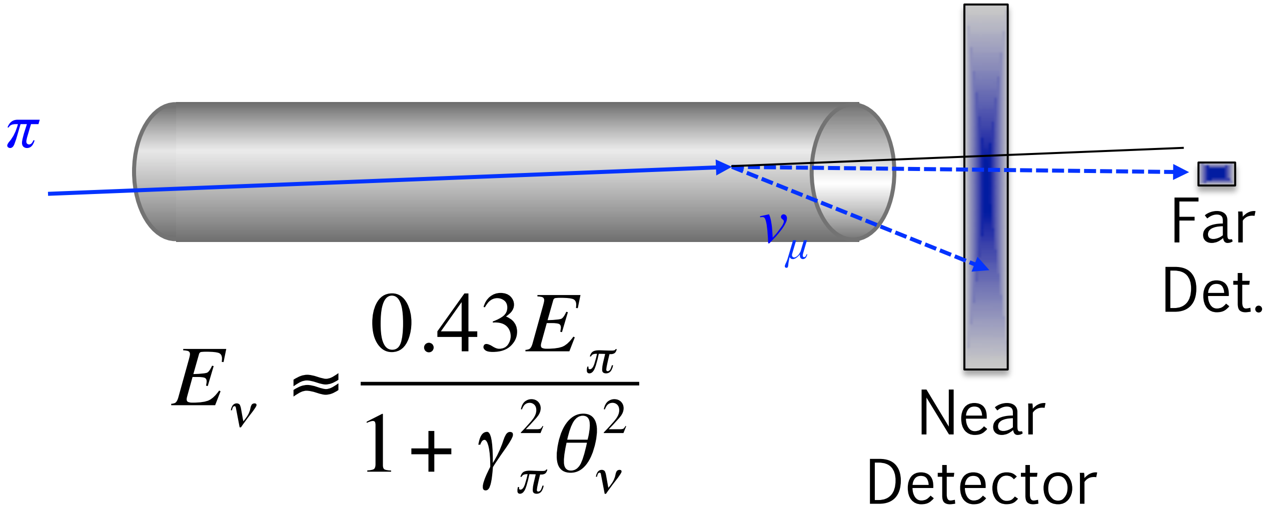


Flux and cross-section uncertainties
cancel when extrapolated
from Near to Far detector.

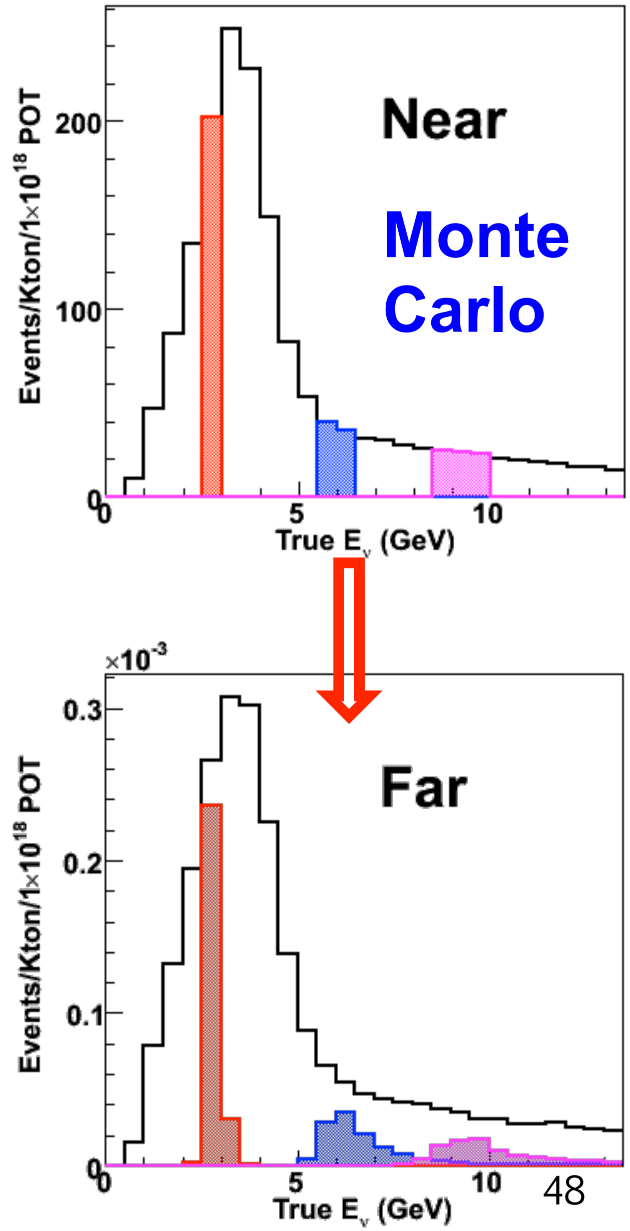
Oscillation Analysis in Brief

1. Select neutrino/antineutrino events in the detectors
2. Measure their energies to produce Near and Far detector spectra
3. Use the Near Detector spectrum to predict the Far Detector spectrum independent of oscillations
4. Fit the Far Detector data to measure oscillations

Near-to-Far Extrapolation

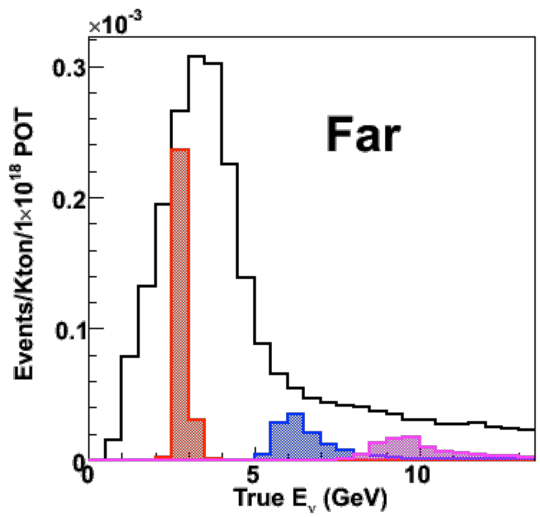


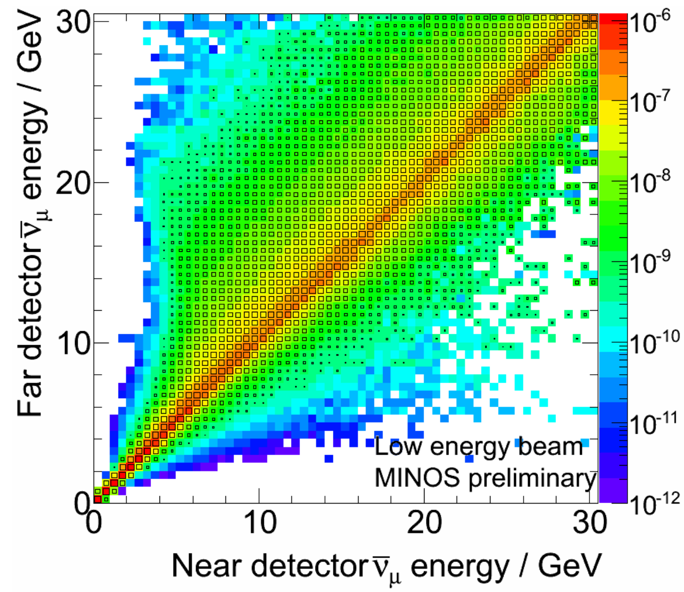
$$E_\nu \approx \frac{0.43 E_\pi}{1+\gamma_\pi^2 \theta_\nu^2}$$



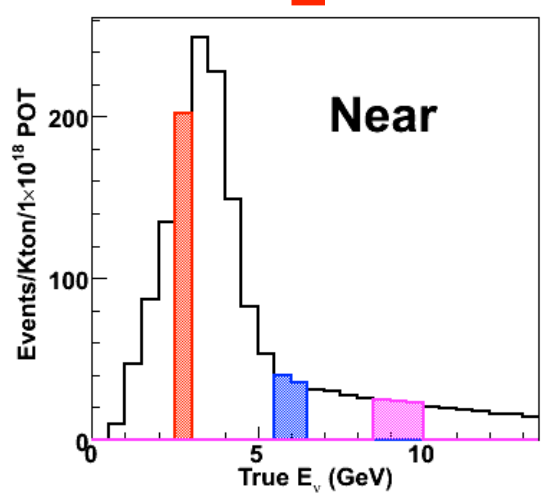
- The Near Detector and Far Detector spectra are not identical.
  - Due to π/K decay kinematics, neutrino energy varies with angle.
  - Near Detector covers a wider solid angle
  - Effect is larger with higher energy π
    - Travel further and decay closer to the ND

Beam Matrix Extrapolation





- A beam matrix transports measured Near Det. spectrum to the Far Det.
- Matrix encapsulates knowledge of meson decay kinematics and beamline geometry
- MC used to correct for energy smearing and acceptance



Monte Carlo

Oscillation Analysis in Brief

1. Select neutrino/antineutrino events in the detectors
2. Measure their energies to produce Near and Far detector spectra
3. Use the Near Detector spectrum to predict the Far Detector spectrum independent of oscillations
4. Fit the Far Detector data to measure oscillations

Fitting for Oscillations

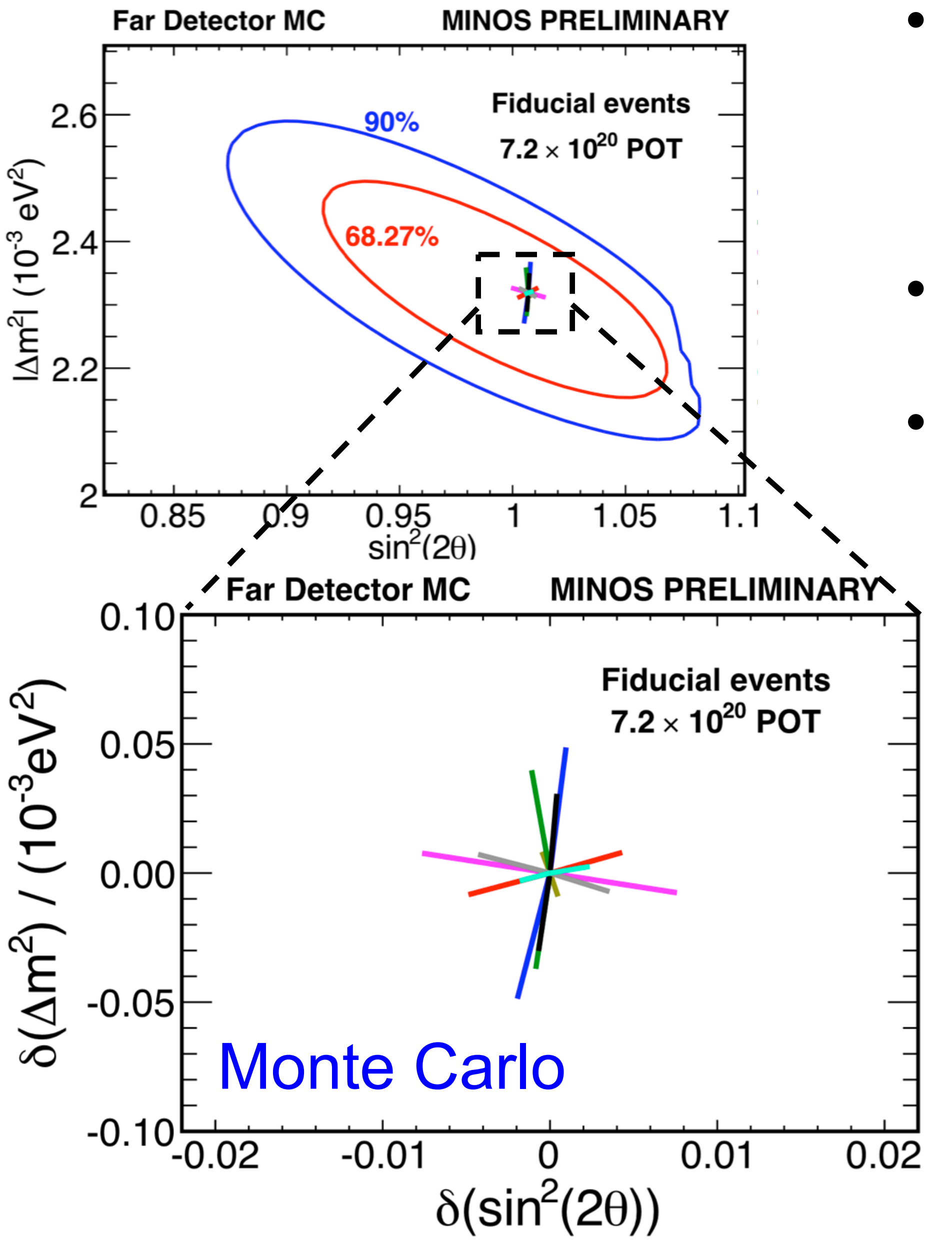
- Fit performed by minimizing a binned -log likelihood

$$-2\ln L(\vec{\alpha}) = 2\sum_i \left[p_i(\vec{\alpha}) - d_i + d_i \ln\frac{d_i}{p_i(\vec{\alpha})}\right] + \sum_j^{\text{N syst}} \frac{\Delta\alpha_j^2}{\sigma_{\alpha_j}^2}$$

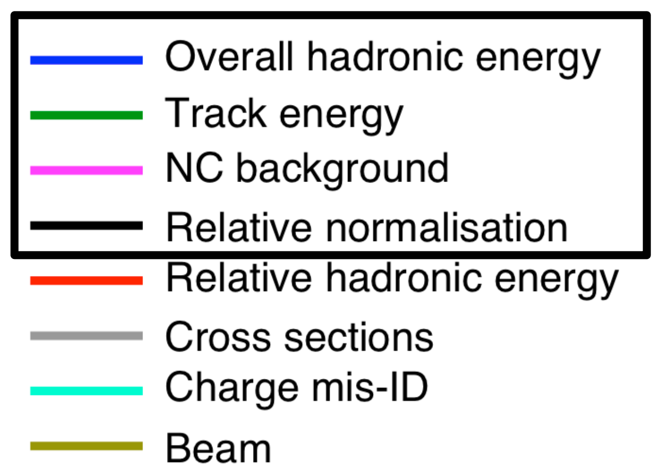
$$\vec{\alpha} = [\Delta m^2_{\text{atm}}, \sin^2(2\theta_{23}), \alpha_1^{\text{syst}}, \alpha_2^{\text{syst}}, \ldots]$$

- For neutrinos, systematics are included as parameters in the fit with penalty terms in the likelihood

Neutrino Systematics



- Effect of uncertainties estimated by fitting systematically shifted MC
- Analysis is still statistically limited
- The 4 largest systematics are included in the fit.



Fitting for Oscillations

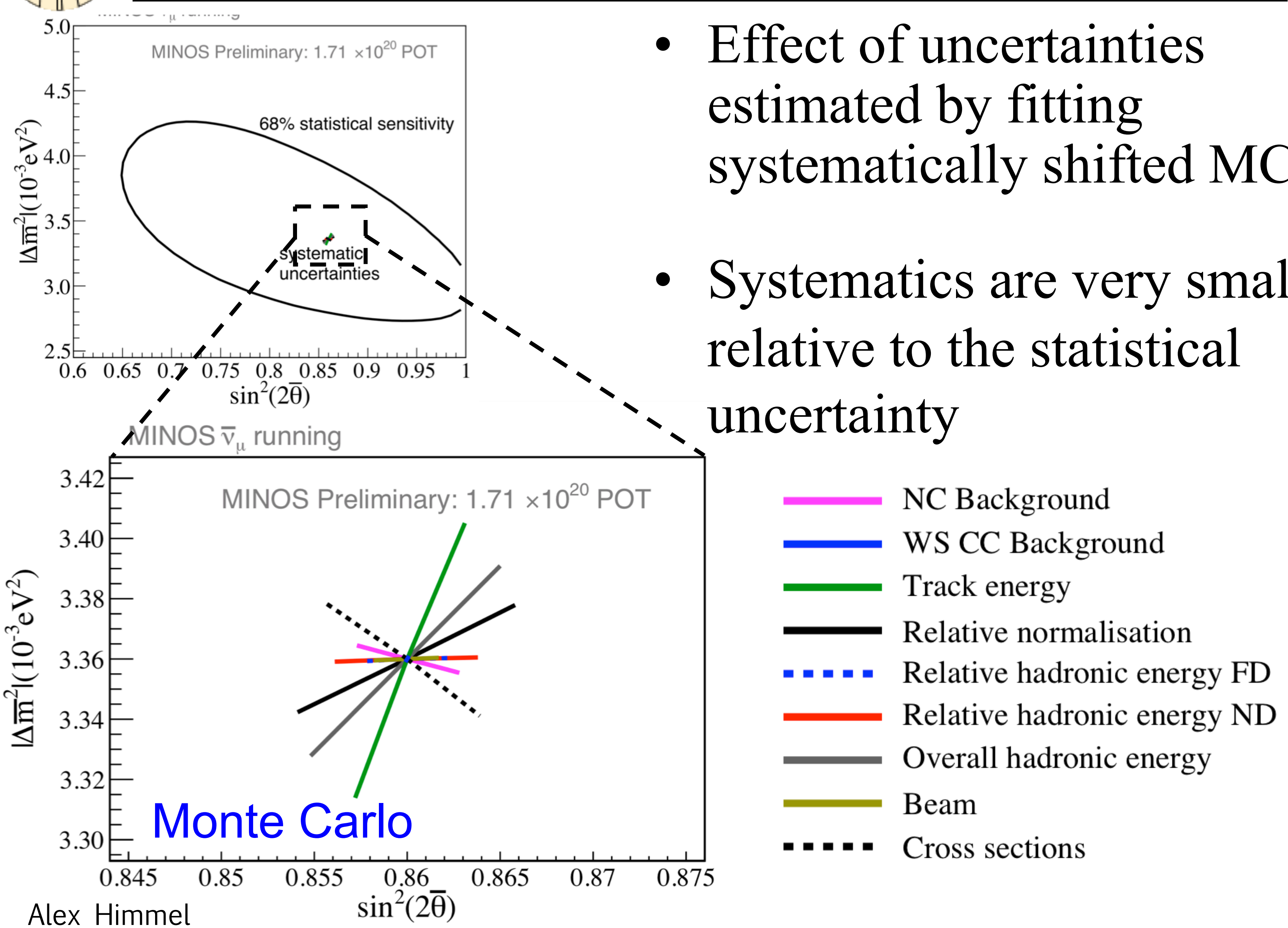
- Fit performed by minimizing a binned -log likelihood

$$-2\ln L(\vec{\alpha}) = 2\sum_i \left[p_i(\vec{\alpha}) - d_i + d_i \ln \frac{d_i}{p_i(\vec{\alpha})}\right]$$

$$\vec{\alpha} = [\Delta \overline{m}^2_{\mathrm{atm}}, \sin^2(2\overline{\theta}_{23})]$$

- For antineutrinos, a Feldman-Cousins approach is used
  - Many fake experiments used create empirical χ^2 distributions as a function of the parameters
  - Systematics included in the fake experiments

Systematics



- Effect of uncertainties estimated by fitting systematically shifted MC
- Systematics are very small relative to the statistical uncertainty

The Results

Blind Analysis

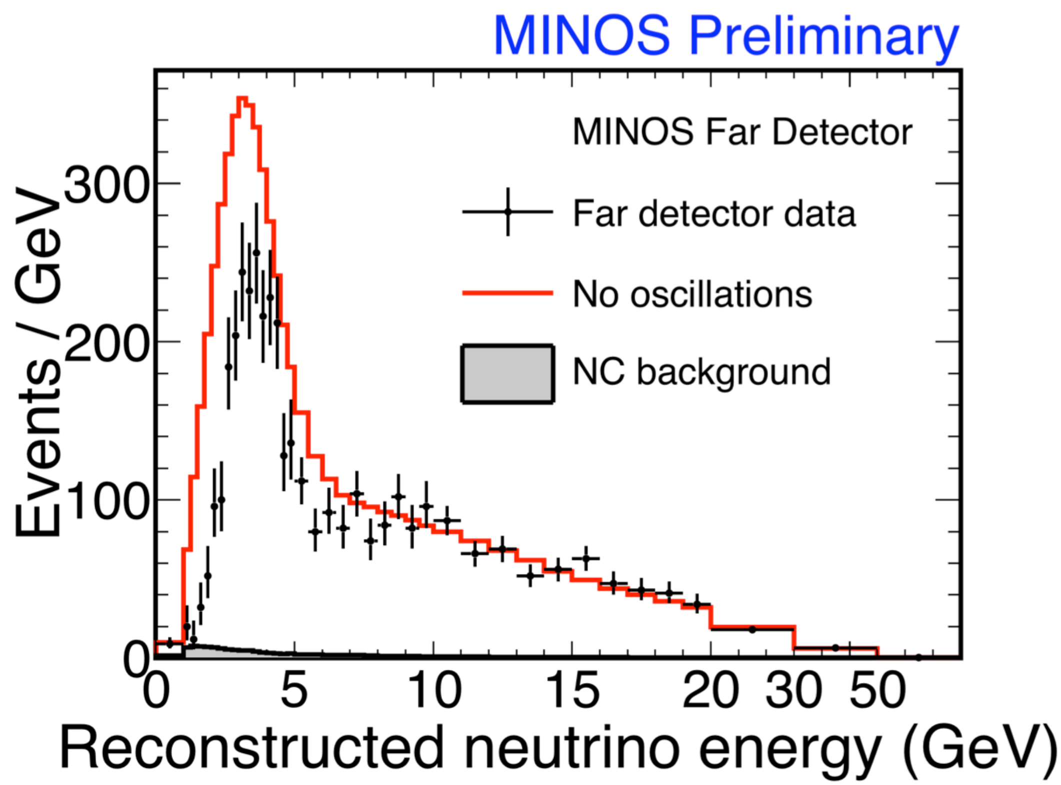
- These results are obtained from blind analyses
  - Finalized before looking at the full Far Detector data
    - selection cuts
    - data samples
    - extrapolation techniques
    - fitting routines
    - systematic uncertainties
- No changes have been made after box opening

And so…on to the results!

Far Detector Neutrino Data

➔**2,451** expected without oscillations

➔**1,986** observed events

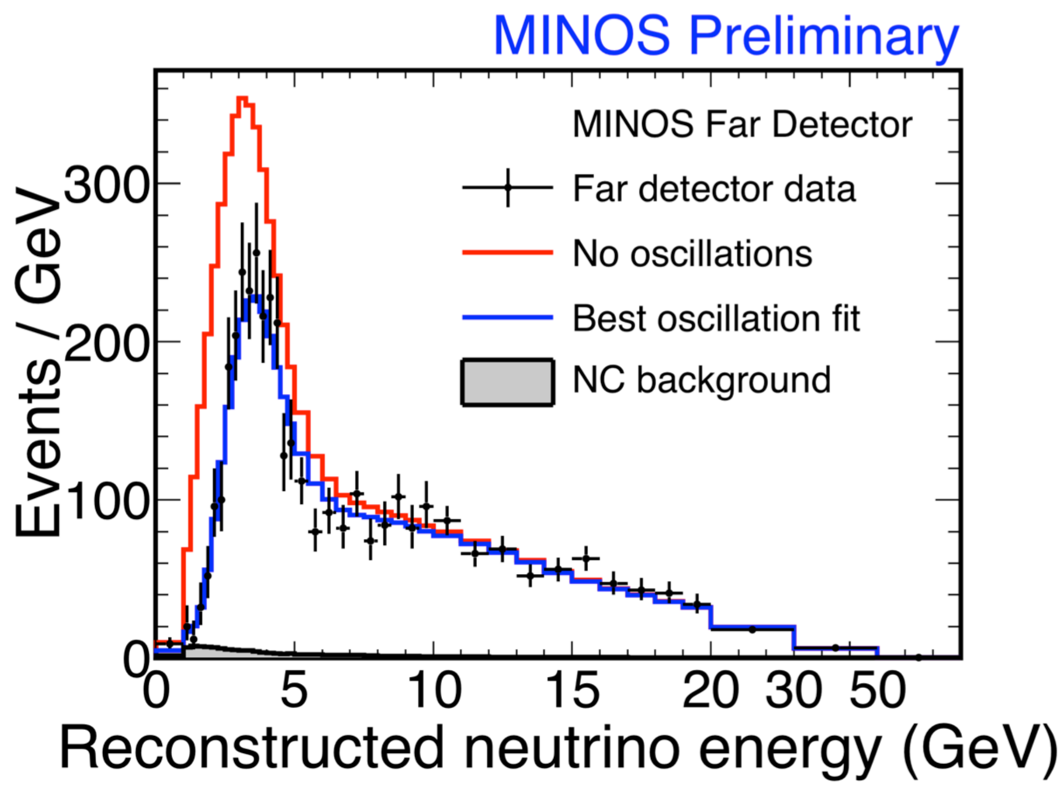


Far Detector Neutrino Data

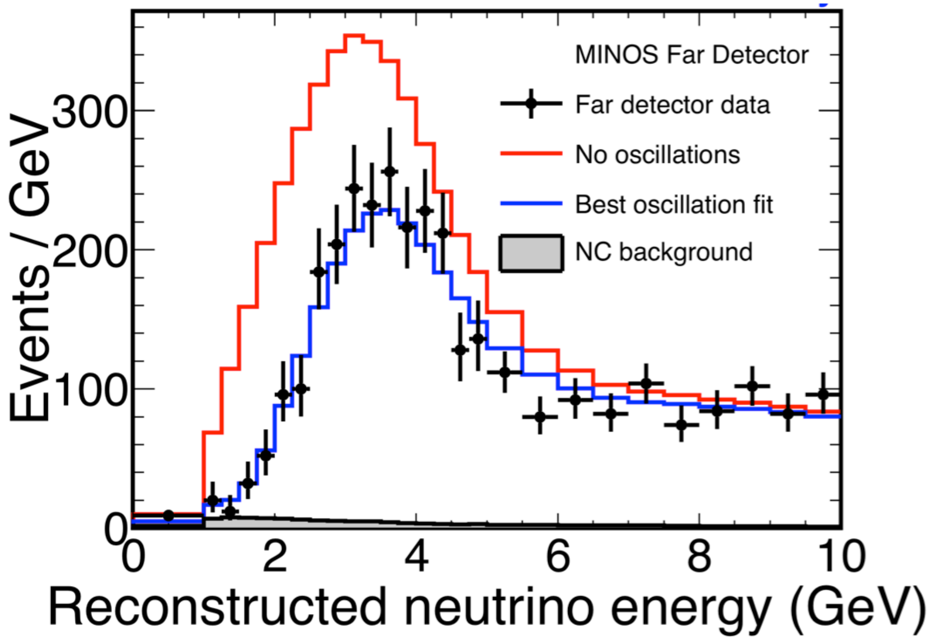
➔**2,451** expected without oscillations

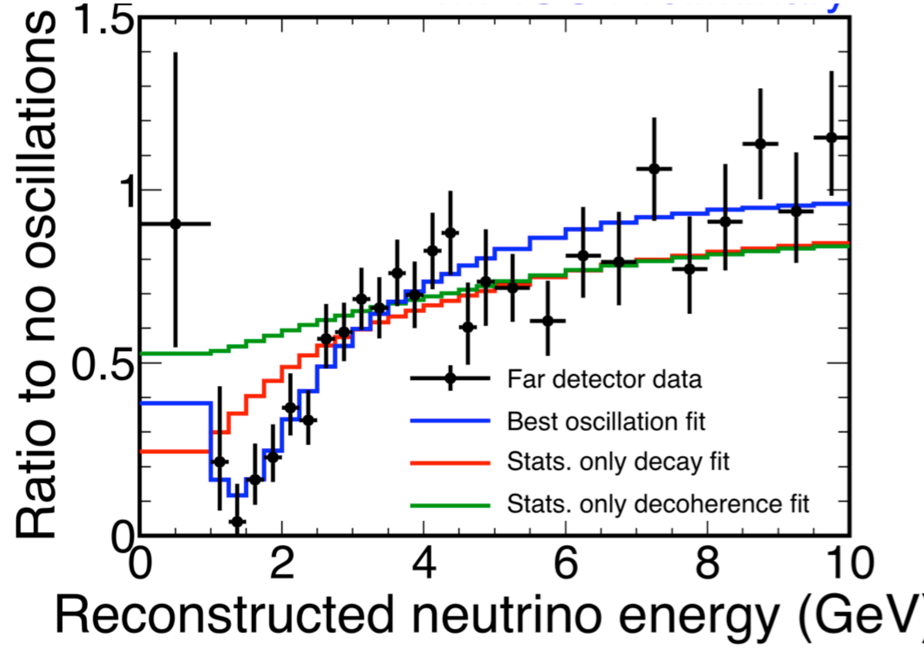
➔**1,986** observed events

Oscillations fit the data well – 66% of fake experiments have a worse χ^2



Far Detector Neutrino Data

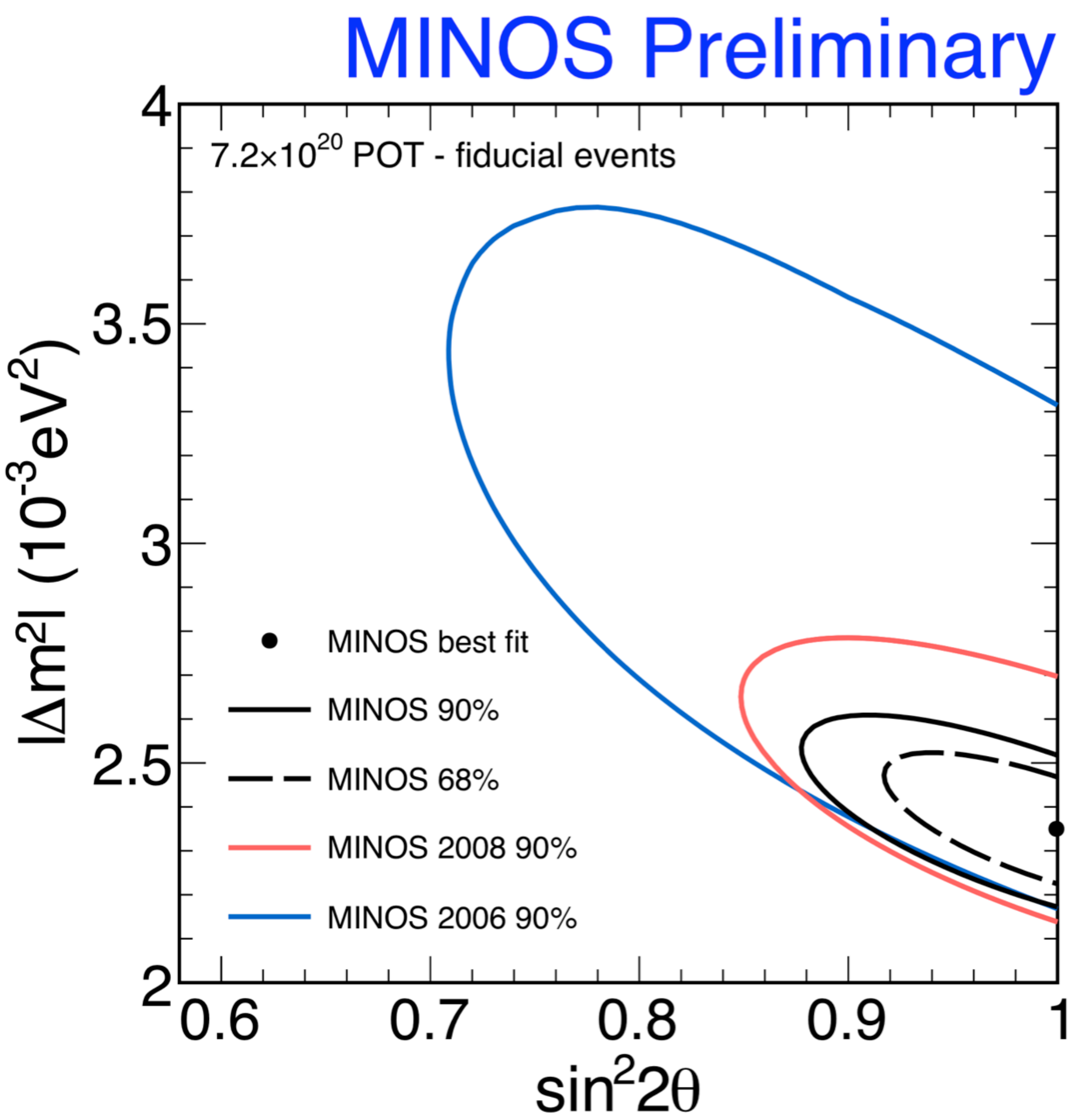




- Can see the characteristic dip of oscillations.
- Disfavor in a statistics-only fit:
  - Pure decay† at > **6σ**
  - Pure decoherence‡ at > **8σ**

†G.L. Fogli *et al.*, PRD 67:093006 (2003)
‡V. Barger *et al.*,PRL 82:2640 (1999)

Neutrino Contour

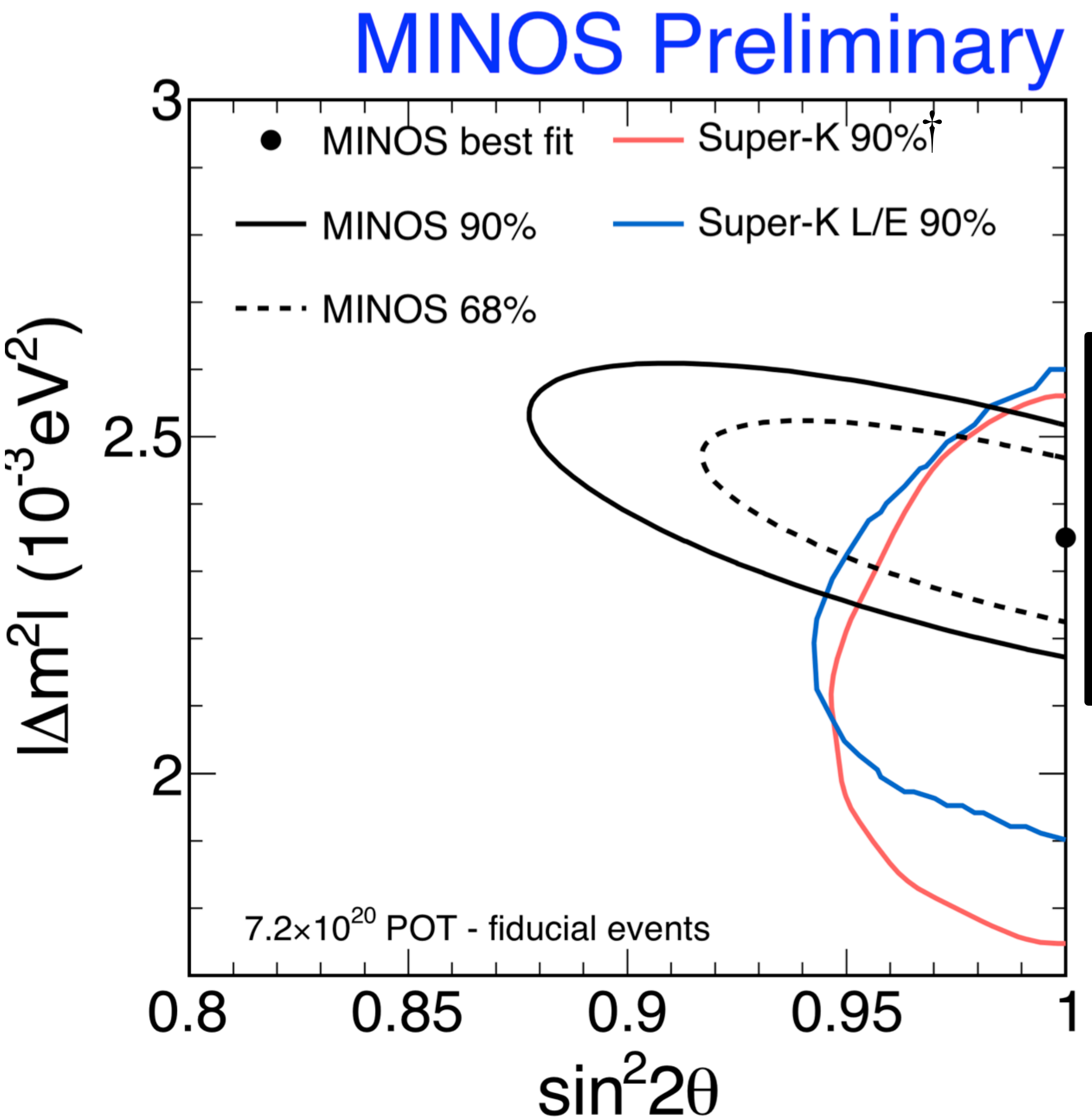


$$\left|\Delta m^2_{\mathrm{atm}}\right| = 2.35^{+0.11}_{-0.08} \times 10^{-3}\ \mathrm{eV}^2$$

$$\sin^2(2\theta_{23}) = 1$$

$$\sin^2(2\theta_{23}) > 0.91\ (90\%\ \mathrm{C.L.})$$

Neutrino Contour



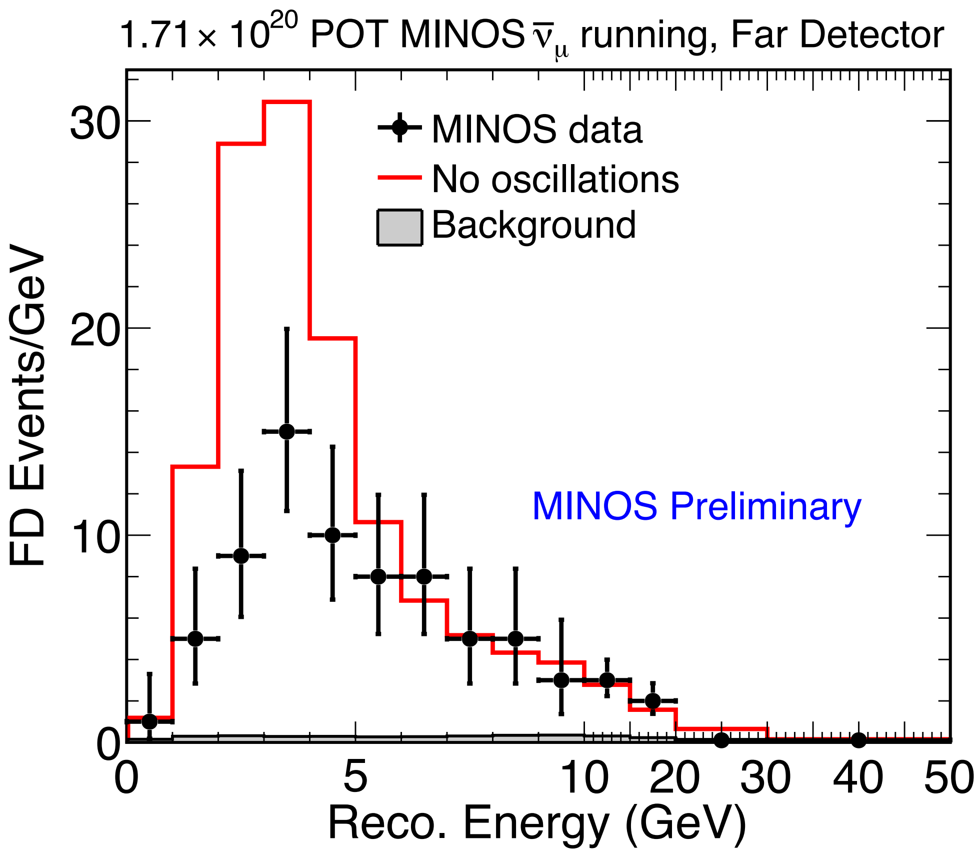
$$\left|\Delta m^2_{atm}\right| = 2.35^{+0.11}_{-0.08} \times 10^{-3}\ \text{eV}^2$$

$$\sin^2(2\theta_{23}) = 1$$

$$\sin^2(2\theta_{23}) > 0.91\ (90\%\ \text{C.L.})$$

†Super-Kamiokande Collaboration (preliminary)

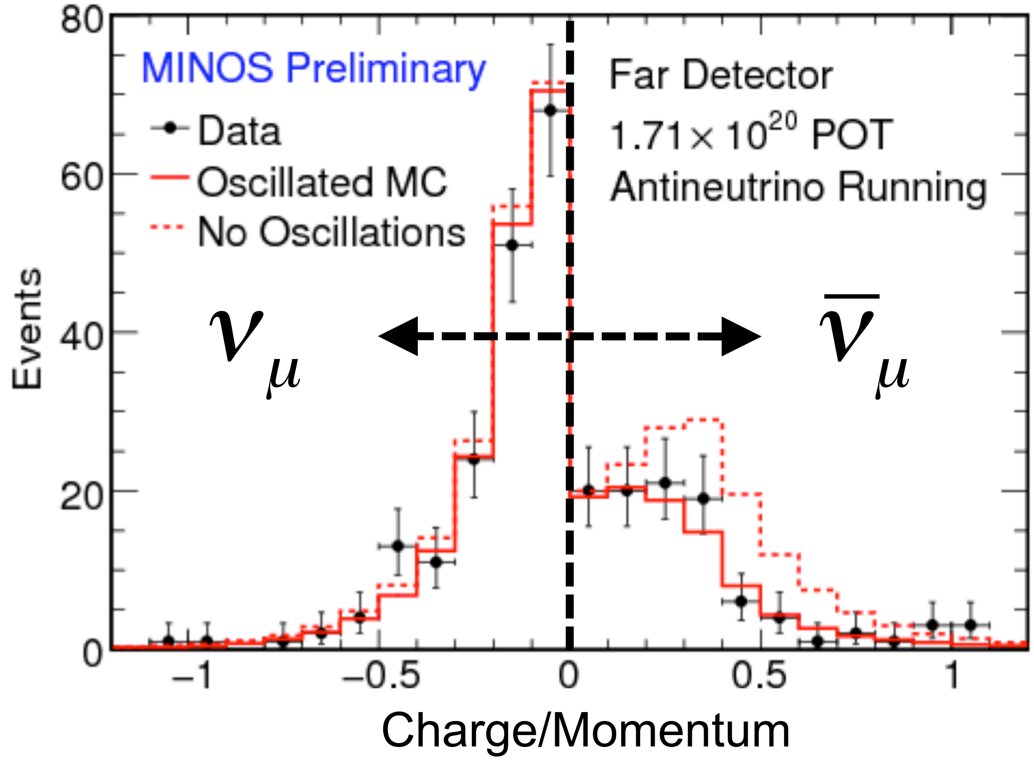
Far Detector Data

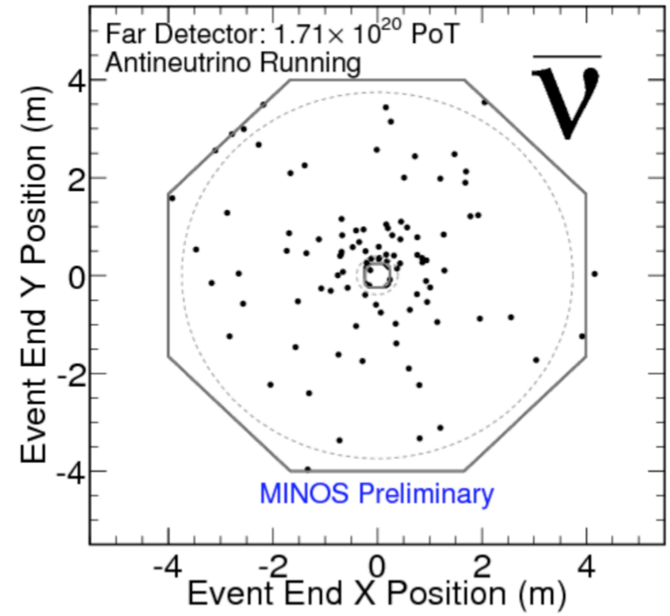


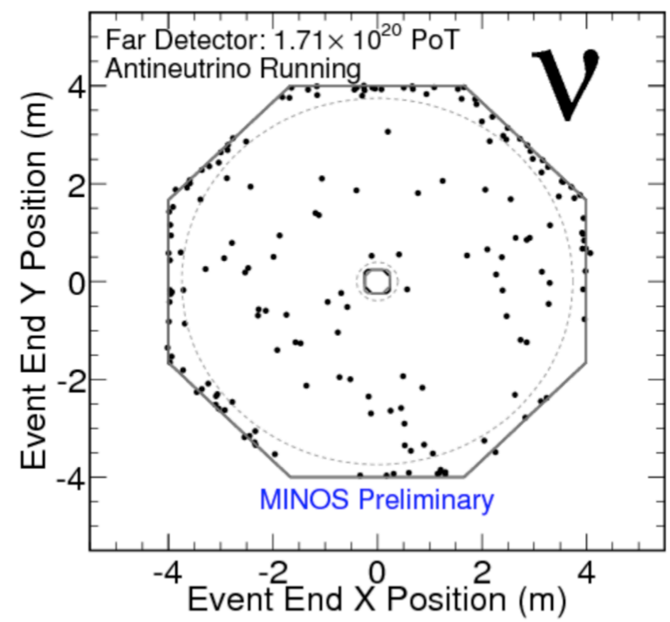
➔**155** expected without oscillations

➔ **97** observed events

Far Detector Data

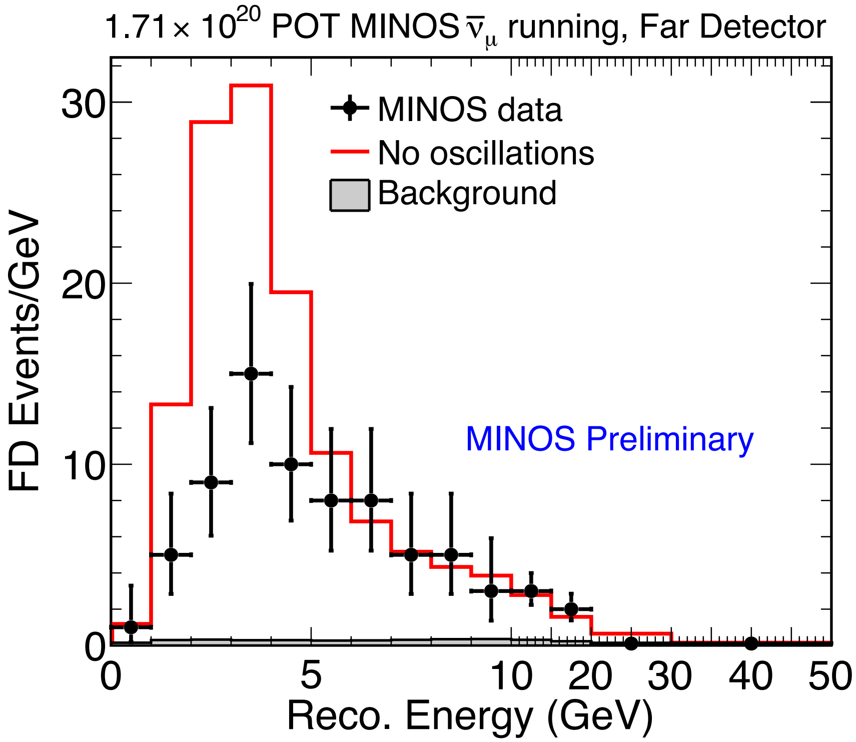


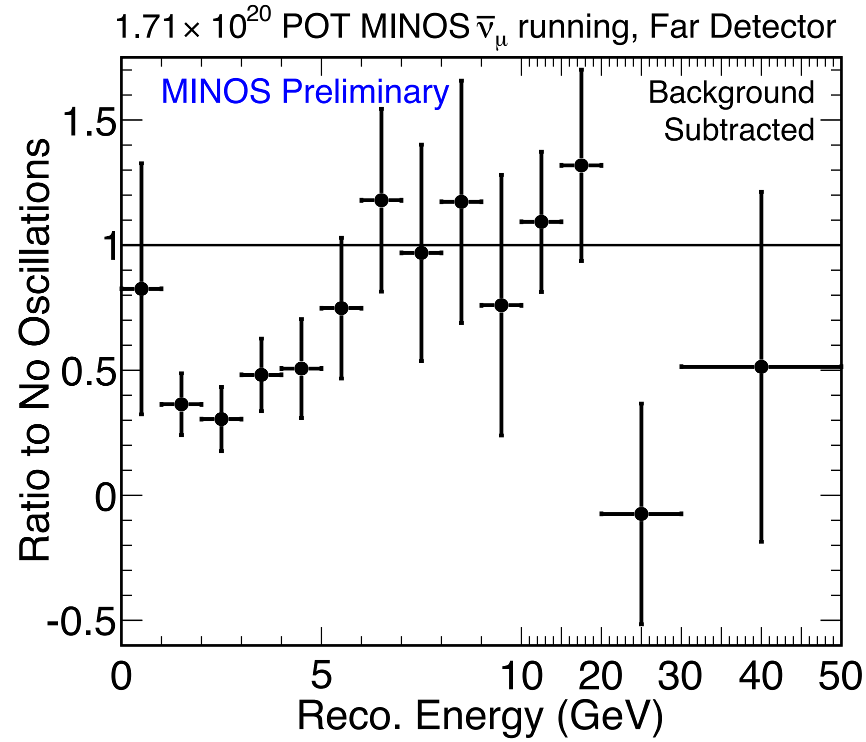




- Good data/mc agreement in charge/momentum
- Antineutrinos focused inwards
- Neutrinos defocused outwards

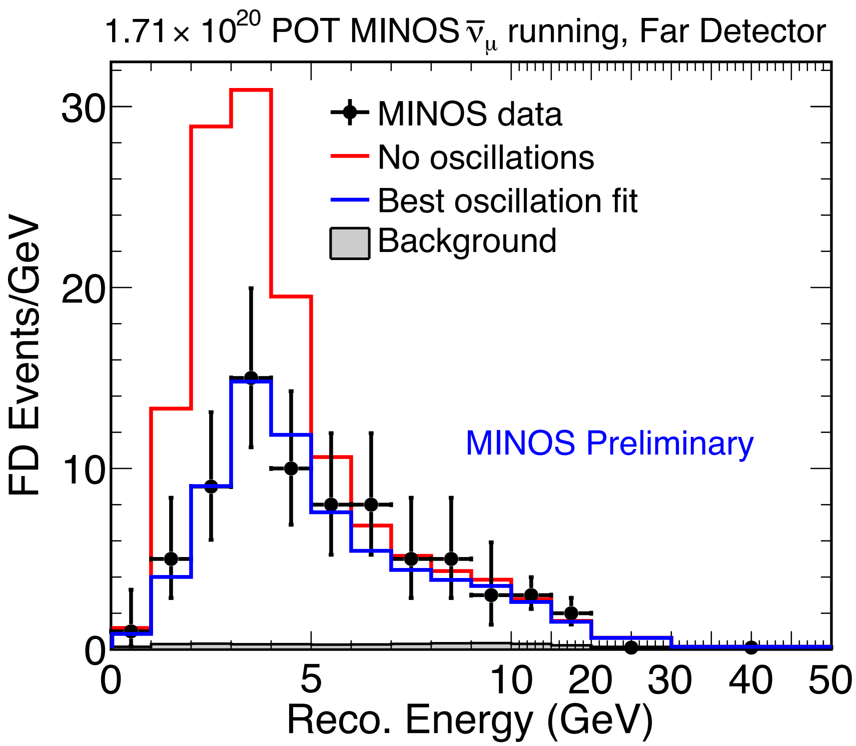
Far Detector Data

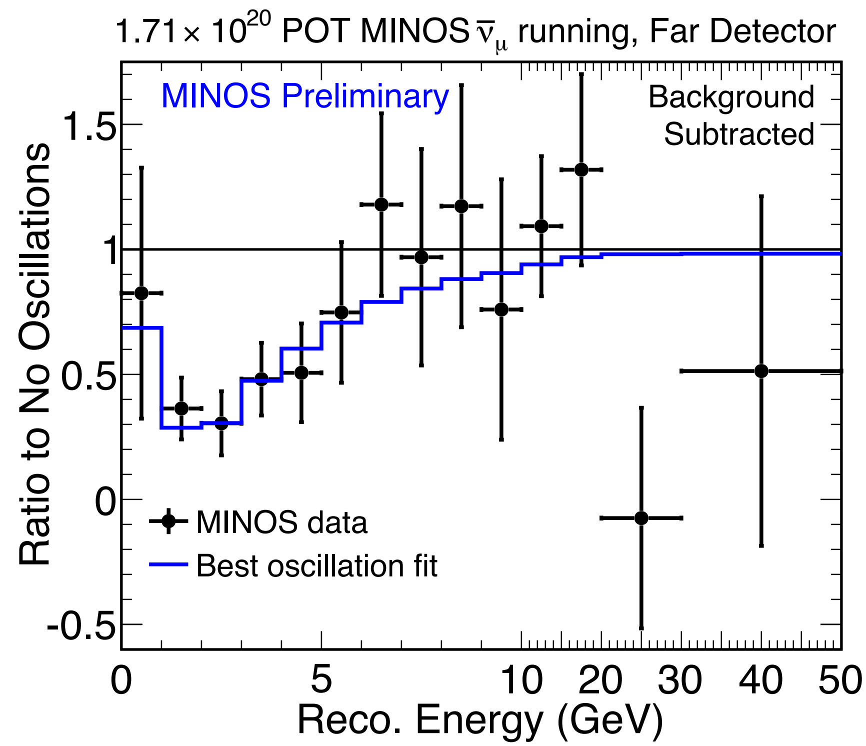




- ➔ **155** expected without oscillations
- ➔ **97** observed events

Far Detector Data

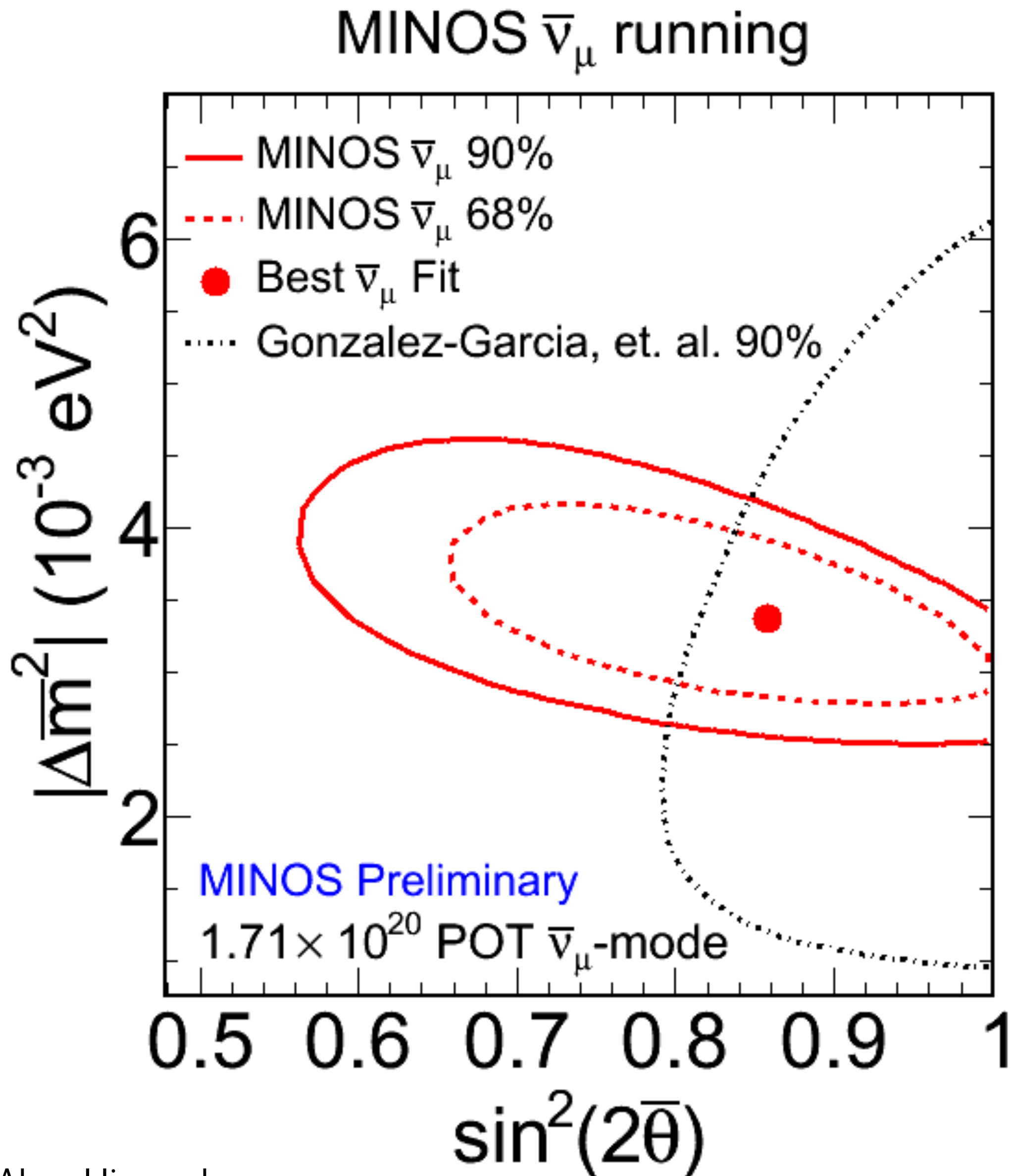




- **155** expected without oscillations
- **97** observed events

No-oscillations hypothesis is disfavored at **6.3σ**

Antineutrino Contour



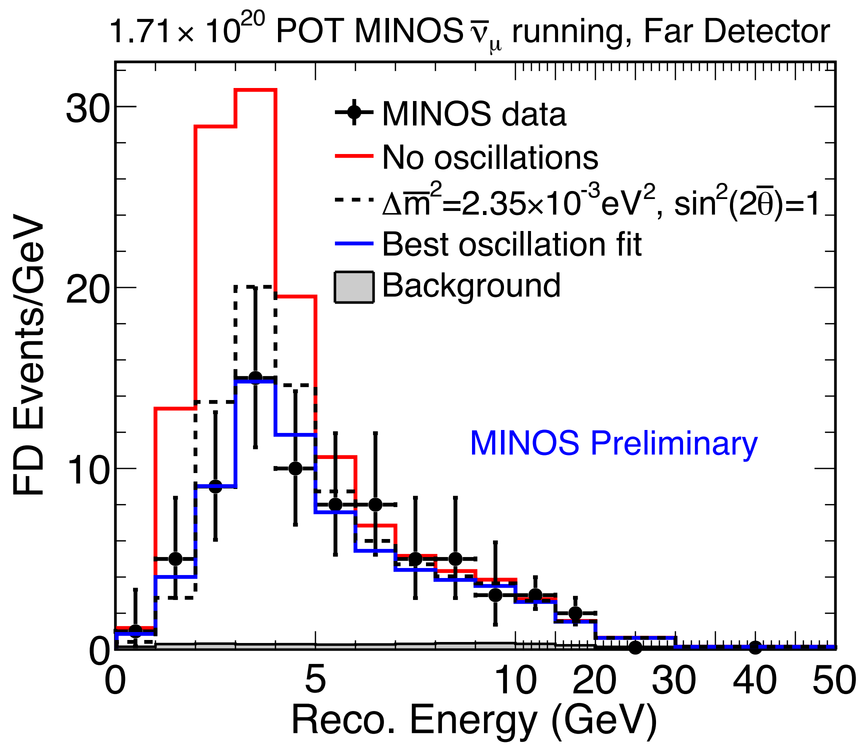
$$\left|\Delta\overline{m}^2_{\text{atm}}\right| = 3.36^{+0.45}_{-0.40} \times 10^{-3}\ \text{eV}^2$$

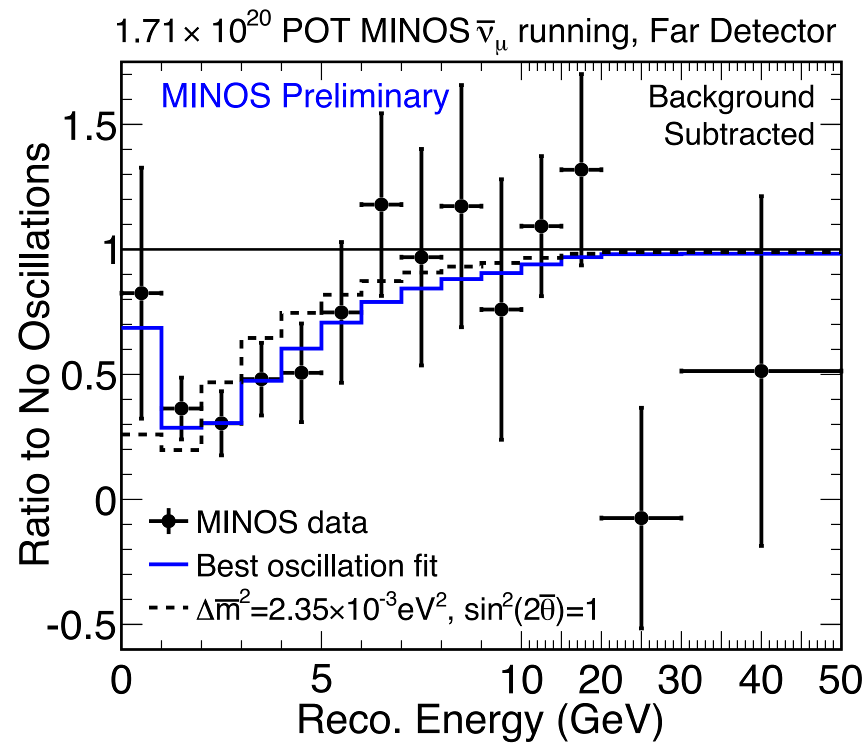
$$\sin^2\left(2\overline{\theta}_{23}\right) = 0.86 \pm 0.11$$

Dot-dash line is a fit to all non-MINOS data

M.C. Gonzalez-Garcia and M. Maltoni Phys. Rept. 460, 2008

Neutrinos and Antineutrinos





- Dashed line shows the antineutrino prediction at the neutrino best fit point.

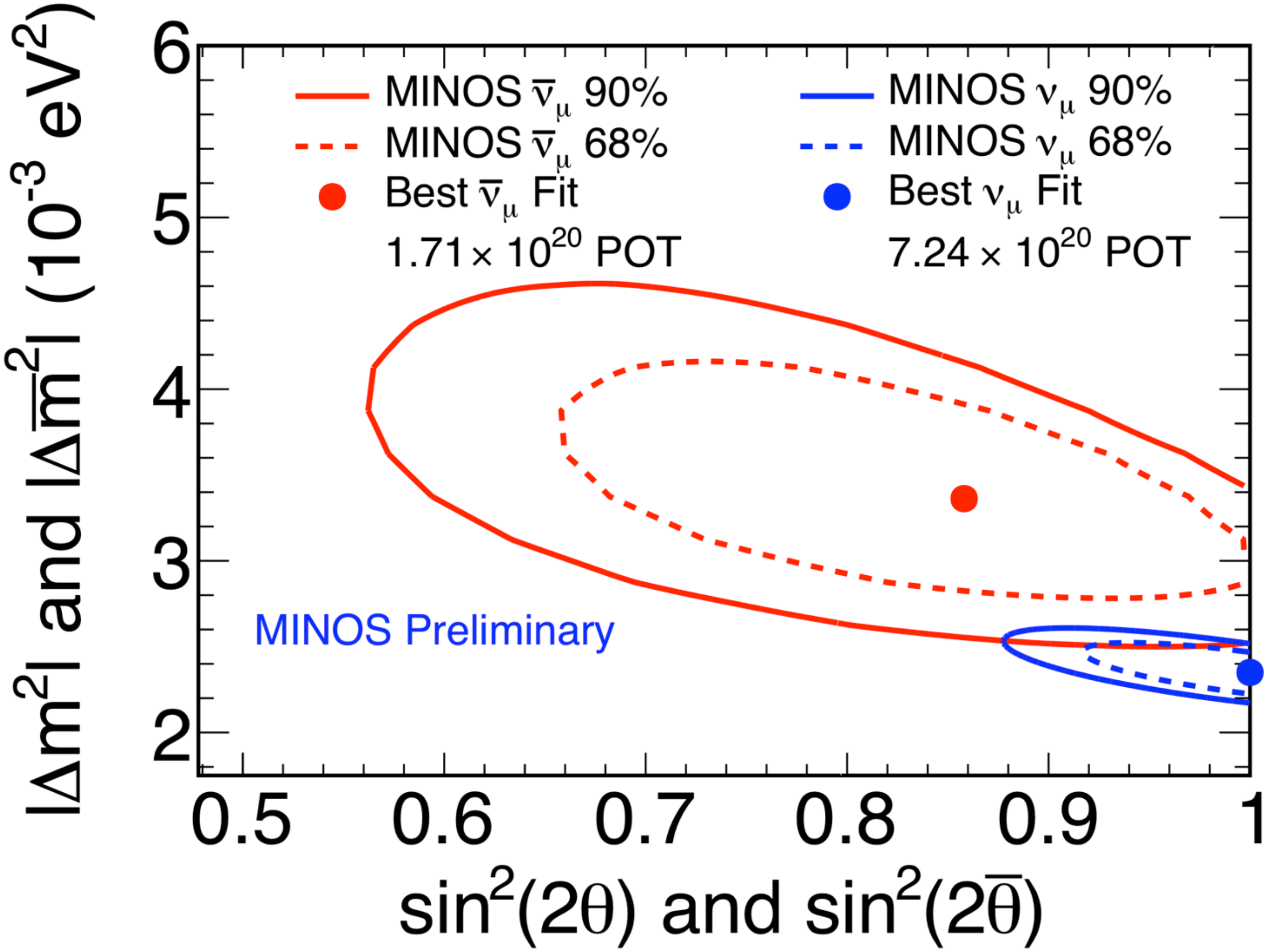
Neutrinos and Antineutrinos

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

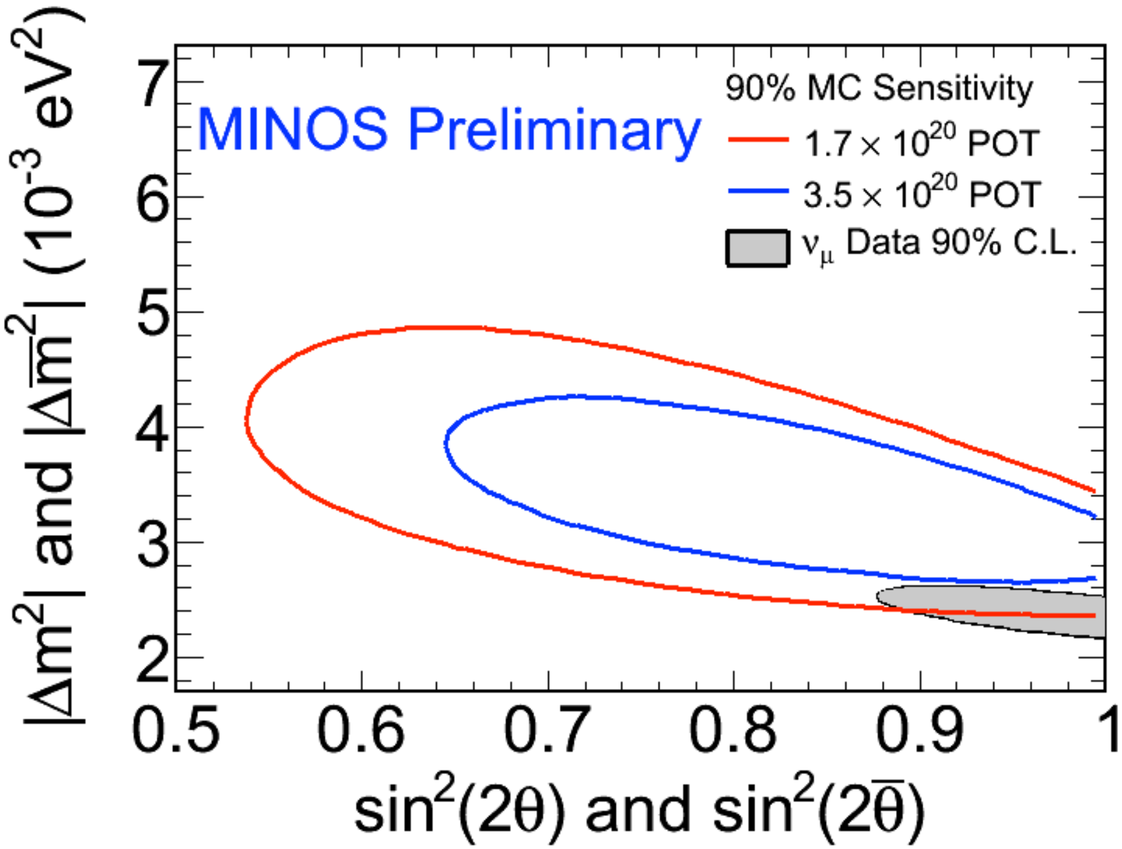
$$\sin^2\left(2\overline{\theta}_{23}\right) = 0.86 \pm 0.11$$

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

$$\sin^2\left(2\theta_{23}\right) > 0.91\ (90\%\ \mathrm{C.L.})$$



With More Antineutrinos...



- NuMI has begun accumulating another ~2x10^{20} POT of antineutrino running.
  - More than double the dataset
  - Can reduce Δm^2 error by more than 30%

Conclusions

- MINOS has the most precise measurement of $|\Delta m^2_{atm}|$
- MINOS has the first direct, precision measurement $|\Delta \overline{m}^2_{atm}|$

$$\left|\Delta m^2_{atm}\right| = 2.35^{+0.11}_{-0.08} \times 10^{-3}\ \mathrm{eV}^2$$
$$\sin^2(2\theta_{23}) > 0.91\ (\text{at } 90\%)$$

$$\left|\Delta \overline{m}^2_{atm}\right| = 3.36^{+0.45}_{-0.40} \times 10^{-3}\ \mathrm{eV}^2$$
$$\sin^2(2\overline{\theta}_{23}) = 0.86 \pm 0.11$$

- Measured with double the neutrino data and a dedicated antineutrino run
- With more antineutrino beam we can rapidly improve the precision on the antineutrino oscillation parameters

Acknowledgements

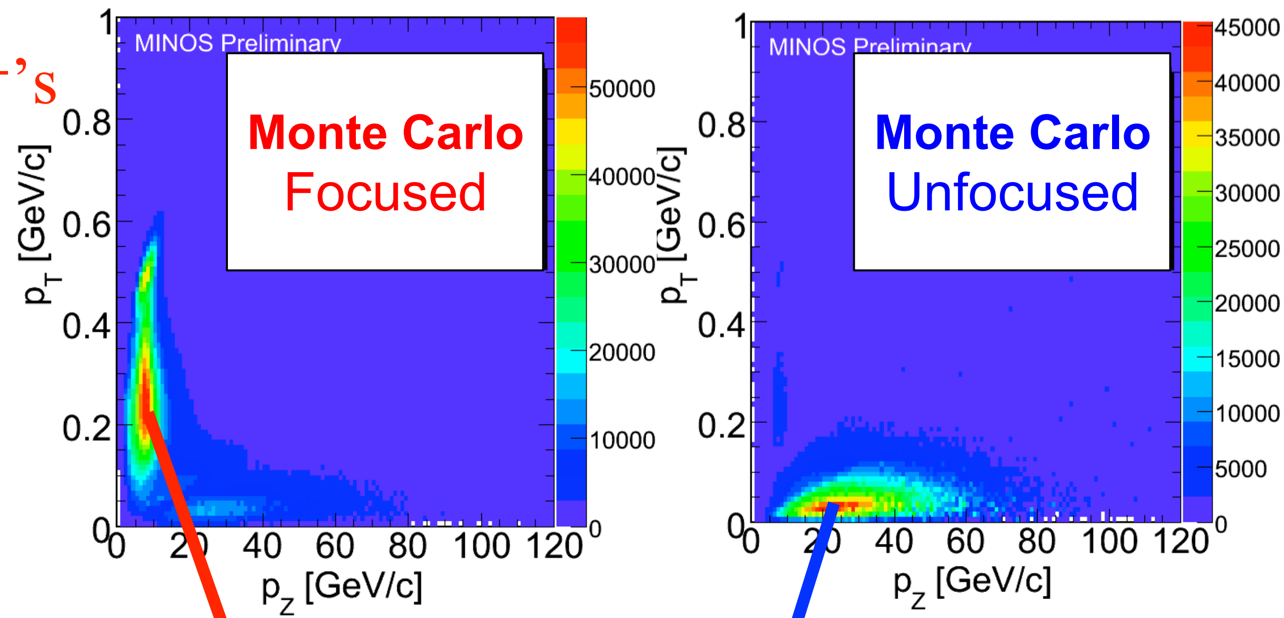
- On behalf of the MINOS Collaboration, I would like to express our gratitude to the many Fermilab groups who provided technical expertise and support in the design, construction, installation and operation of the experiment

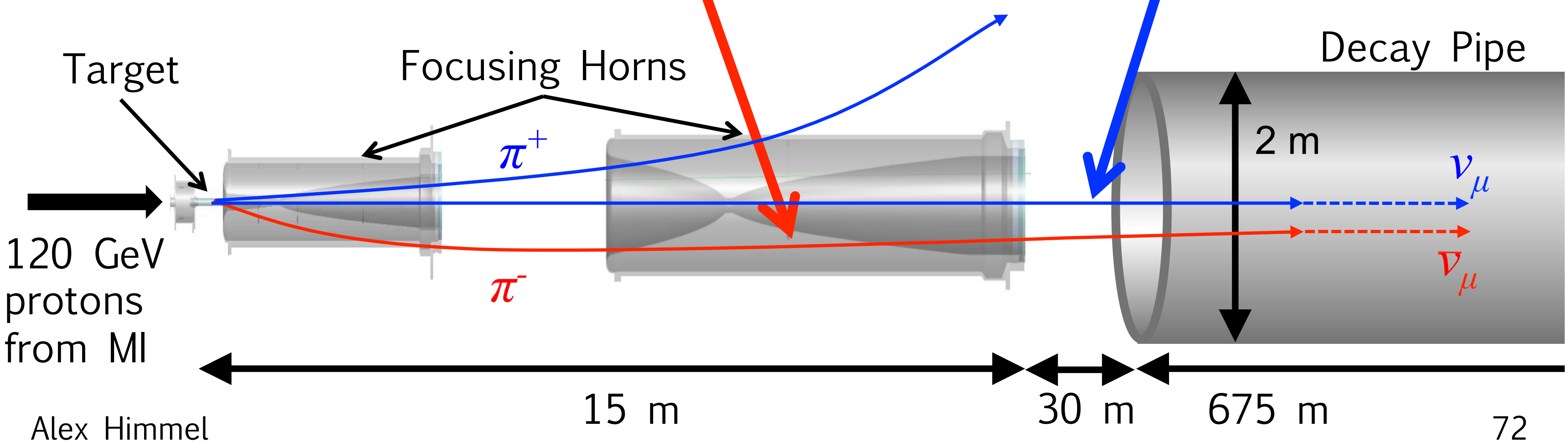
- We also wish to thank the crew at the Soudan Underground Laboratory for keeping the Far Detector running so well

- We also gratefully acknowledge financial support from DOE, STFC(UK), NSF and thank the University of Minnesota and the Minnesota DNR for hosting us

Peak vs. Tail

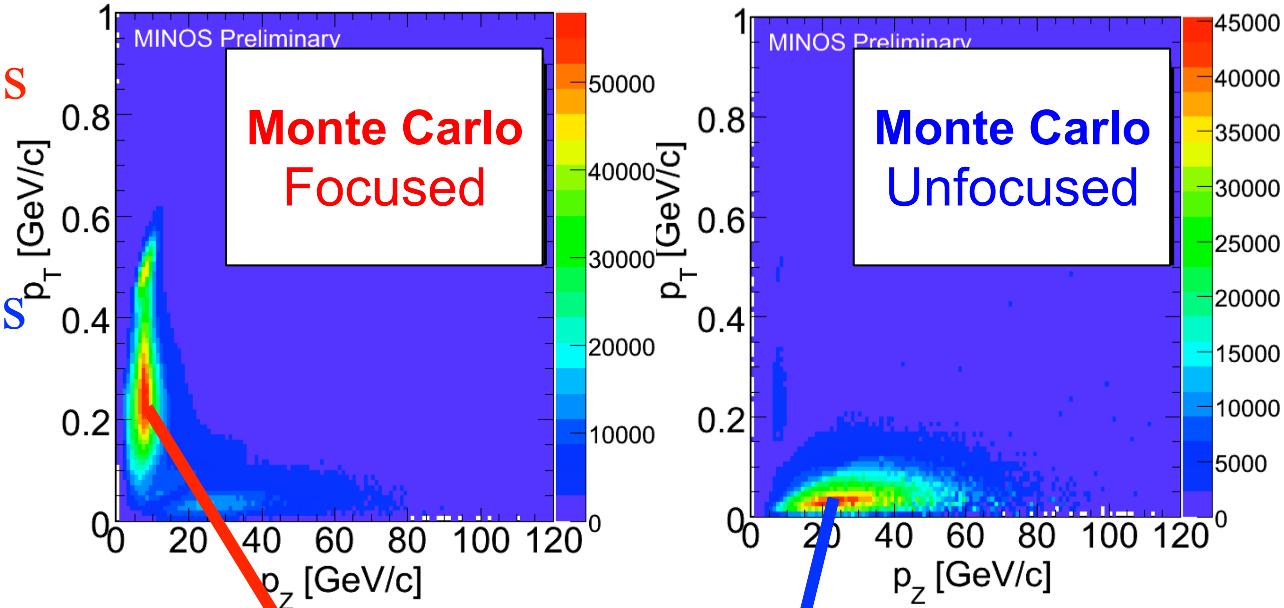
- $\bar{\nu}_\mu$'s from **high-p_t π^-'s**
  - Focused by horns
- ν_μ's from **low-p_t π^+'s**
  - Pass through horn center

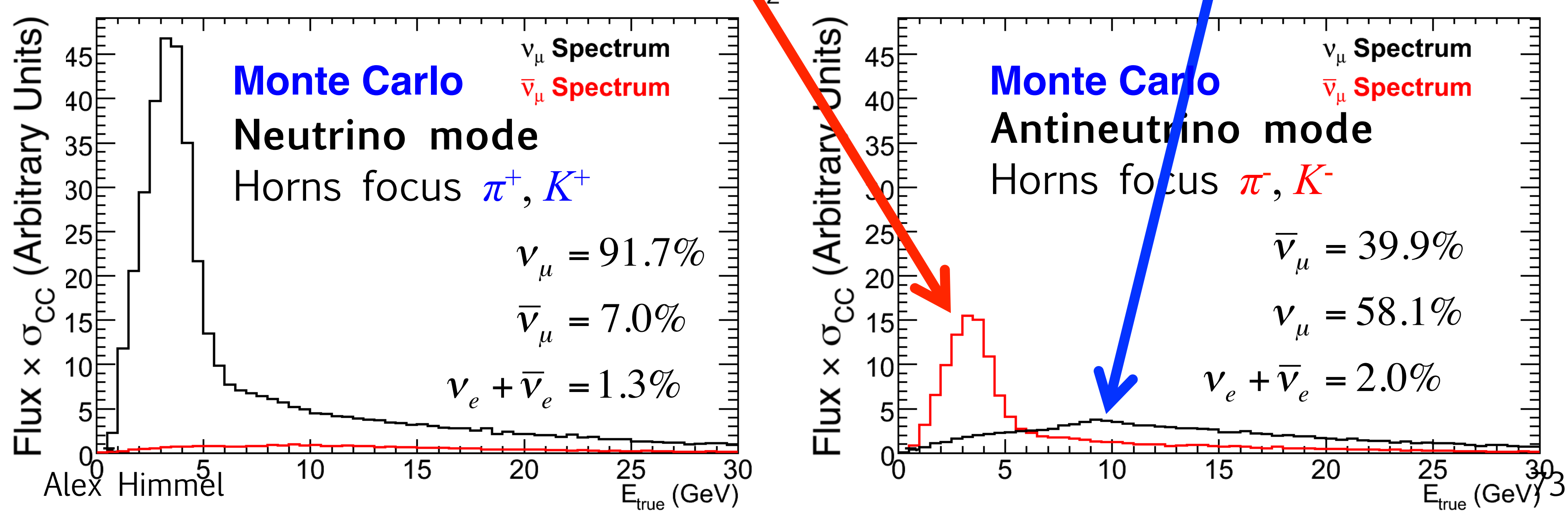




Peak vs. Tail

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



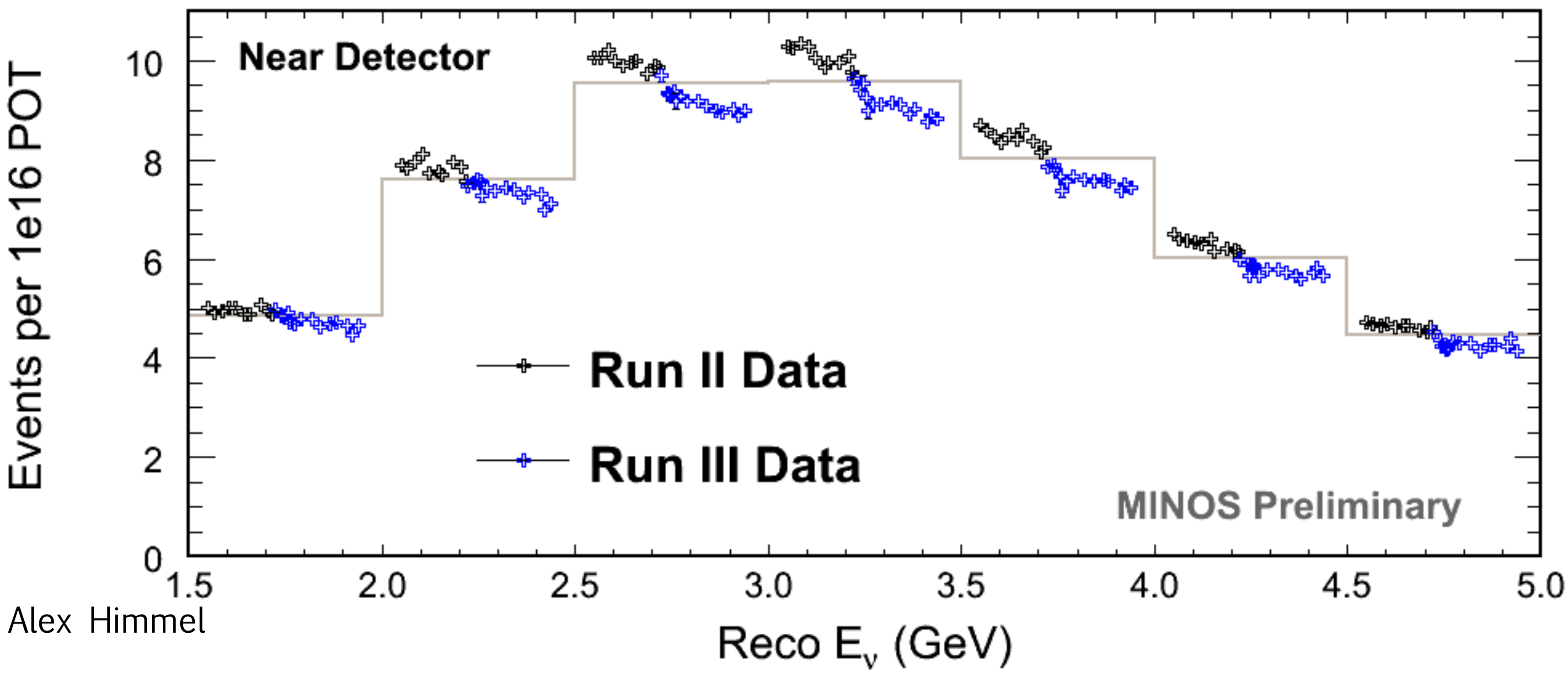


Helium in the Decay Pipe

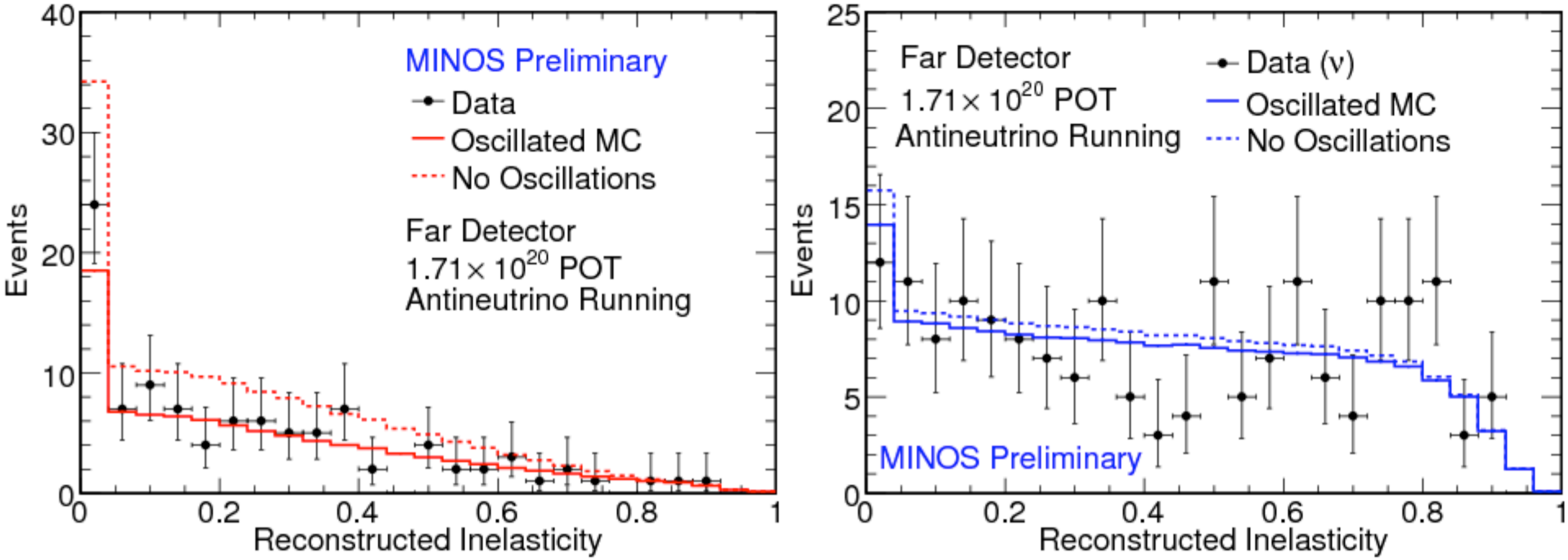
- At the beginning of Run III, helium was added to the decay pipe to prevent failure of the upstream window.
  - Our previous flux simulation could not model the helium using GFLUKA as part of GEANT3
  - Replaced it with a new flux simulation that is all FLUKA which accurately predicts the effects of helium.

Target Degradation

- Began during Run II and continued through Run III
- The exact mechanism of the decay is not known
- Missing fins at the shower max in the target model the energy-dependent effect
- Target to undergo post-mortem later this year
- Cancels between the two detector



Far Detector Data

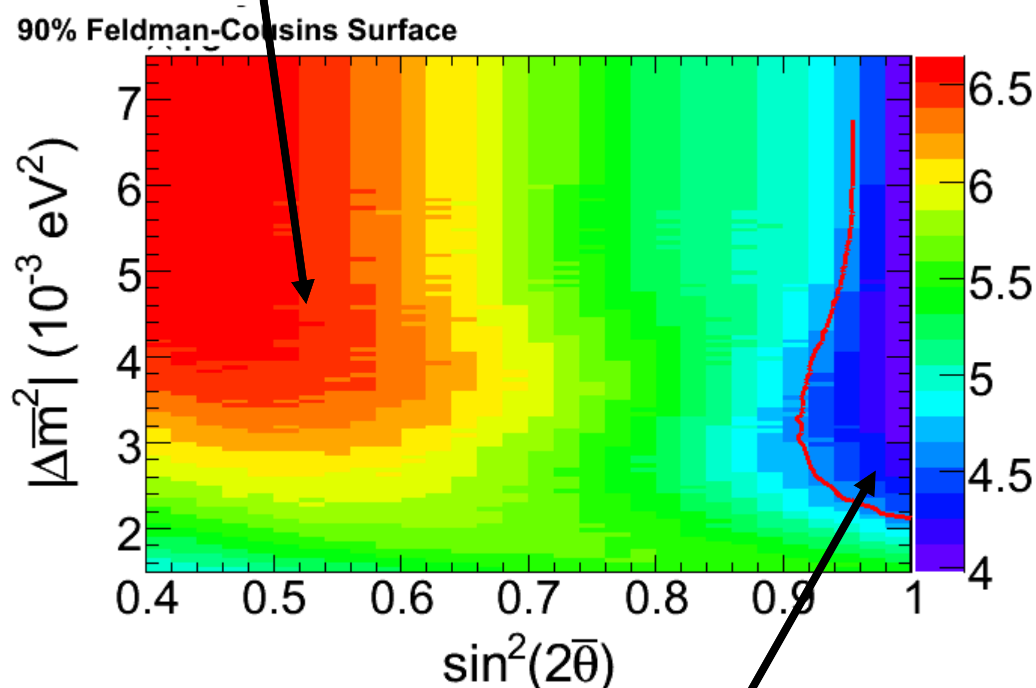


- Data shows the expected distributions of hadronic energy fraction for both neutrinos and antineutrinos

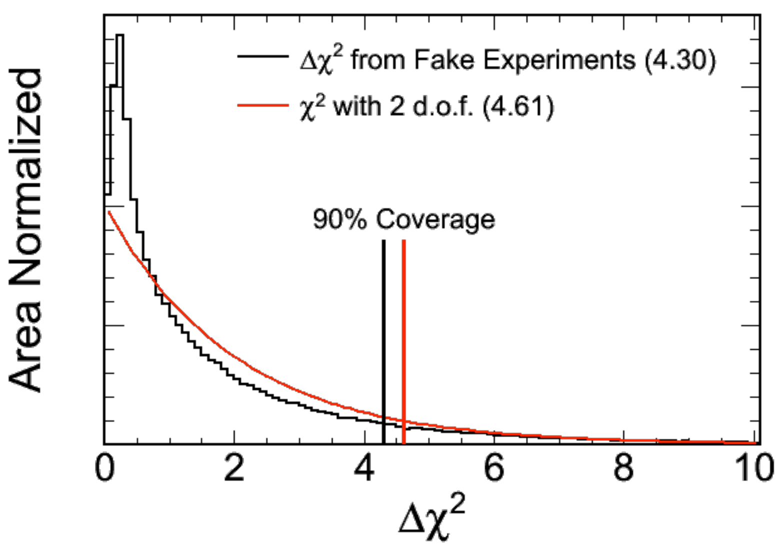
Feldman-Cousins

- Each point is the $\Delta\chi^2$ that encompasses 90% of fake experiments
  - A perfectly Gaussian surface would be 4.7 everywhere.

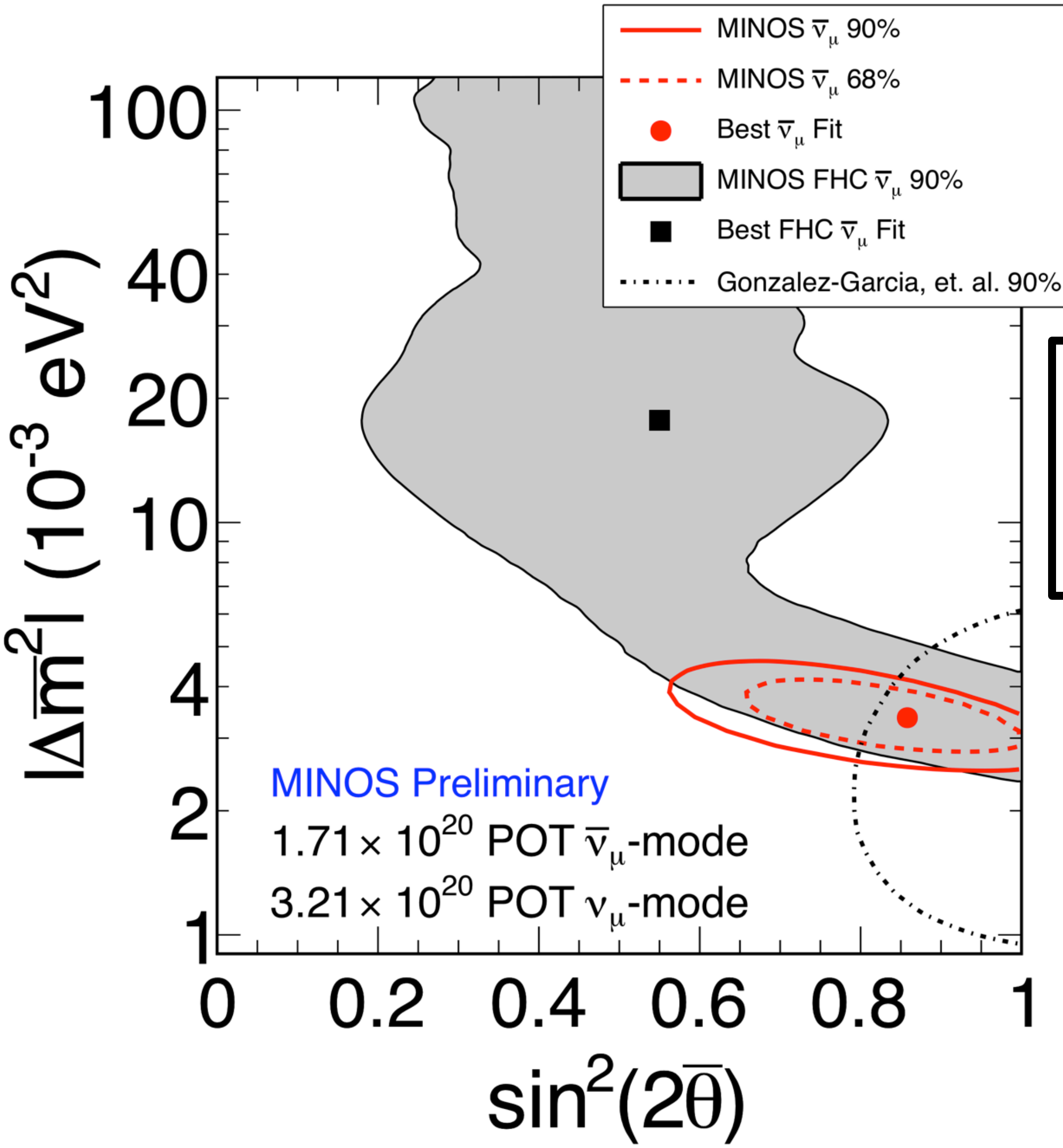
Worse than Gaussian
Degeneracy with fast oscillations



Better than Gaussian
Physical boundary gives extra information



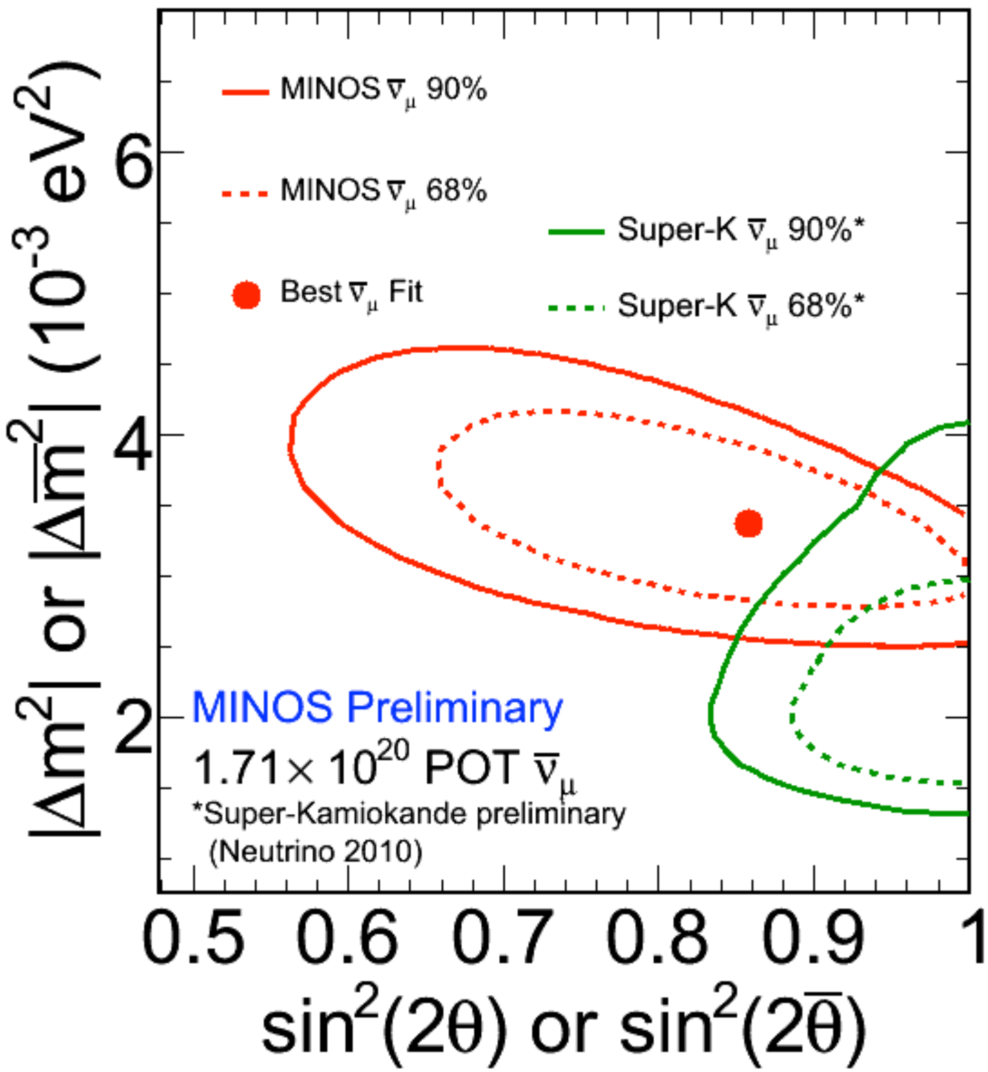
Antineutrino Contour



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

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

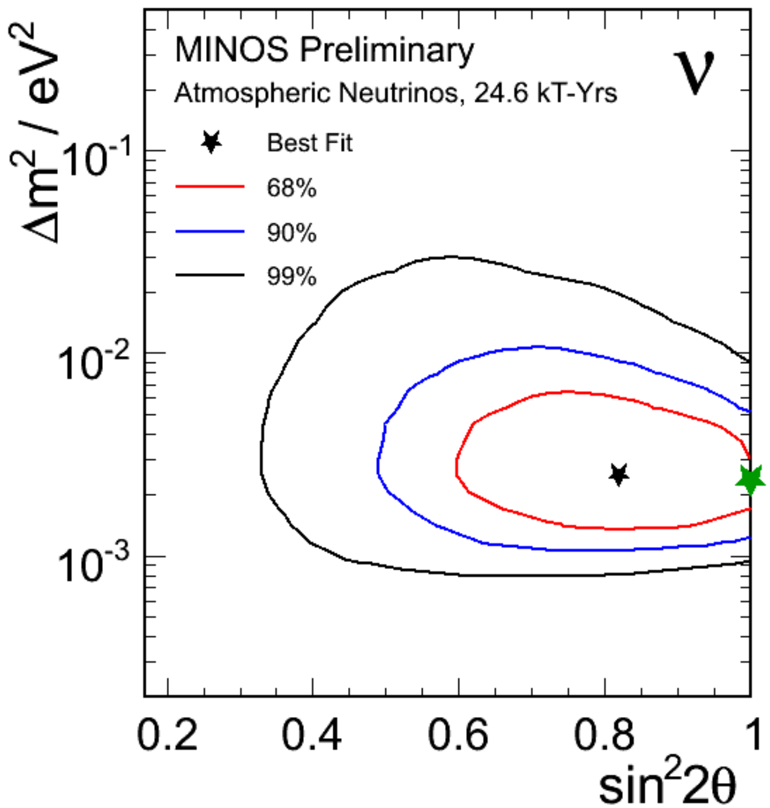
Antineutrino Contour

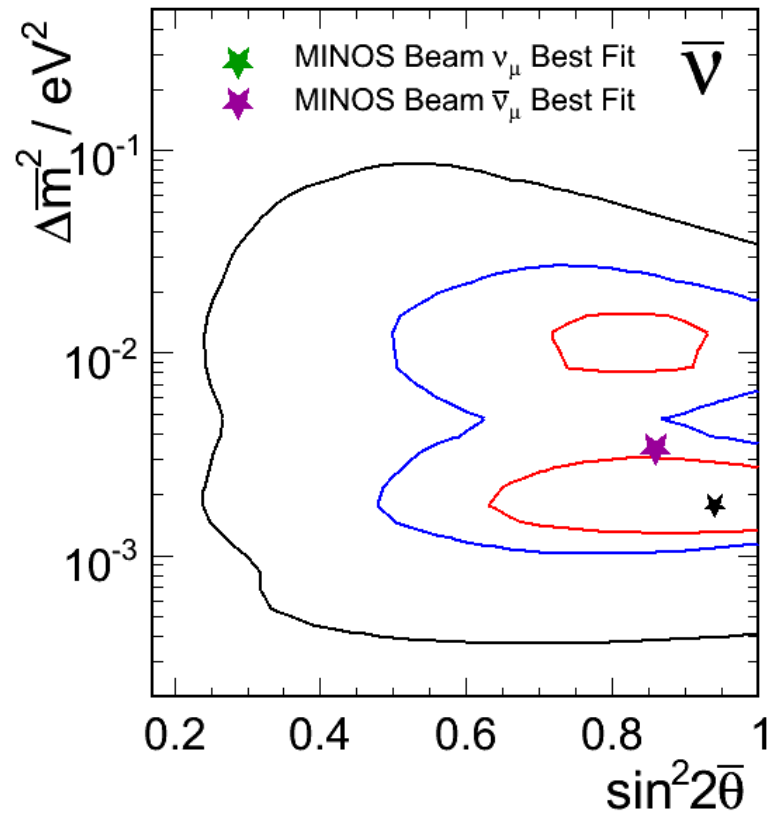


$$\left|\Delta \overline{m}^2_{\text{atm}}\right| = 3.36^{+0.45}_{-0.40} \times 10^{-3}\ \text{eV}^2$$

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

Atmospheric Neutrinos

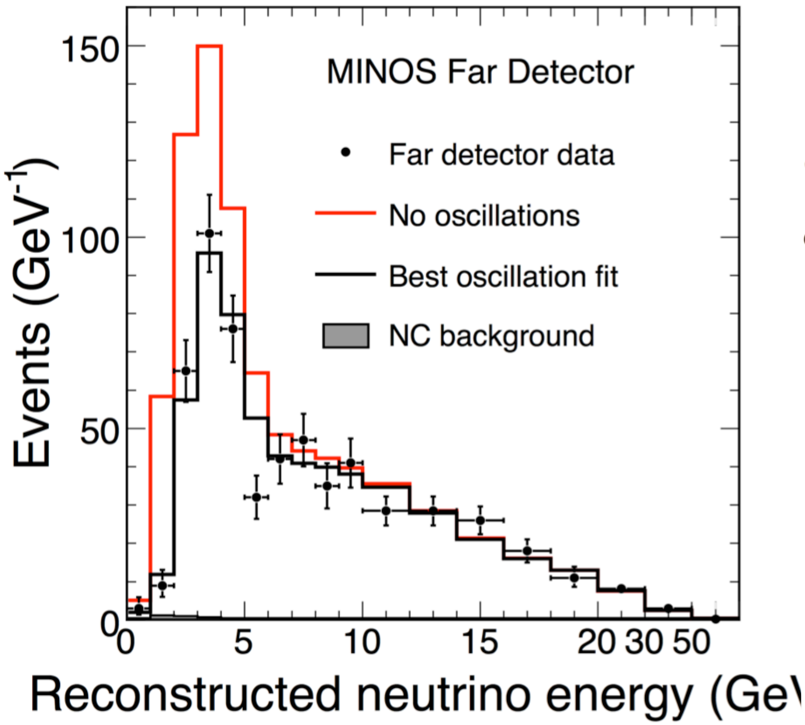


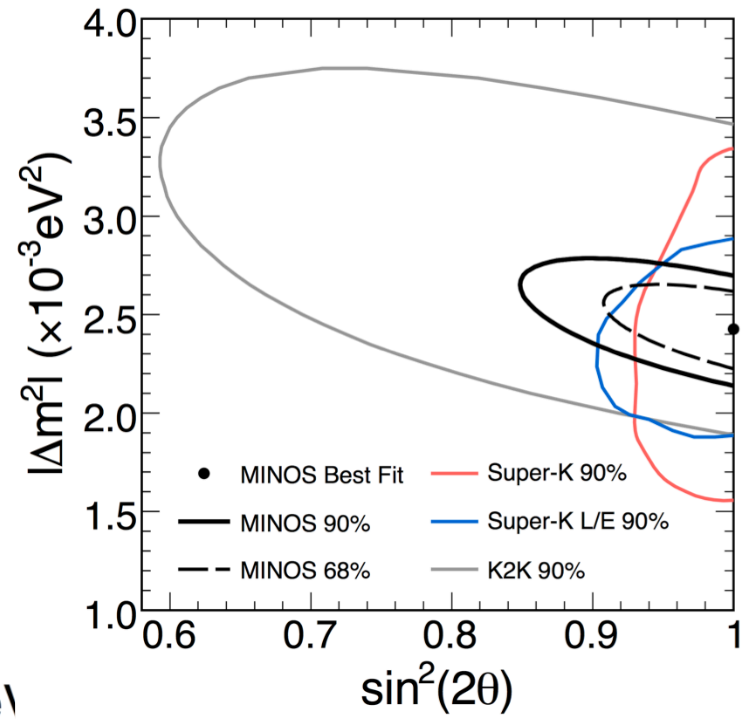


$$R^{data}_{\bar{\nu}/\nu} / R^{MC}_{\bar{\nu}/\nu} = 1.04^{+0.11}_{-0.10} \pm 0.10$$

$$\left|\Delta m^2\right| - \left|\overline{\Delta m^2}\right| = 0.4^{+2.5}_{-1.2} \times 10^{-3}\,\mathrm{eV}^2$$

The Neutrino Analysis





Since our previous measurement…

- P. Adamson, et. al, Phys. Rev. Lett. 101:131802 (2008)

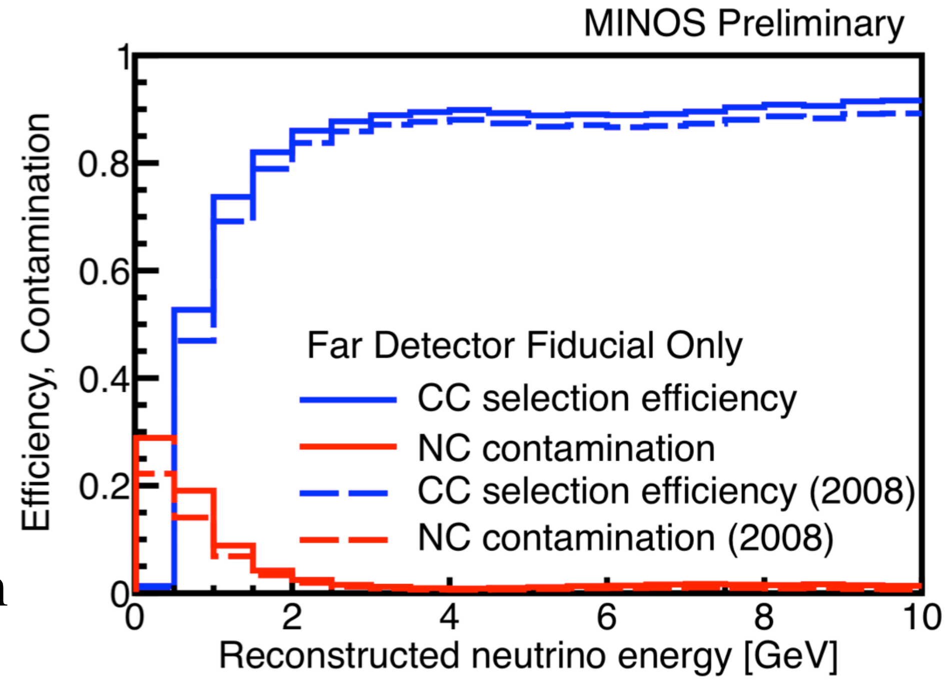
- Additional data
  - 3.4×10^{20} to 7.2×10^{20} protons-on-target
- Analysis Improvements

Analysis Improvements

- Updated simulation and reconstruction
- New selection improves low-energy efficiency
- New shower energy estimator
  - 30% better low-energy resolution
- No charge sign cut
  - Reclaim mis-identified neutrino events at low energy
- Split data set into resolution bins
  - Increased statistical power

Analysis Improvements

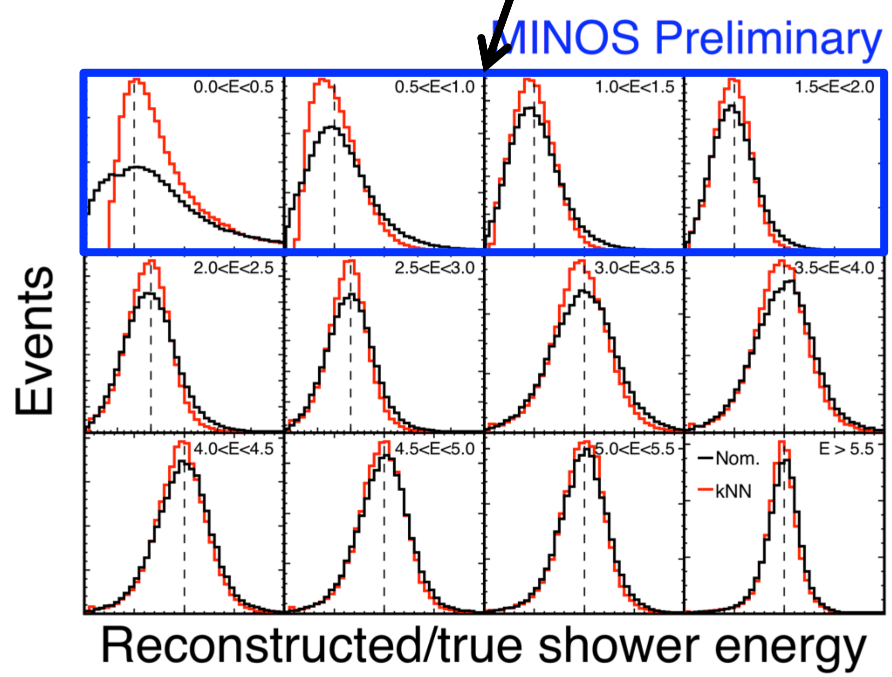
- Updated simulation and reconstruction
- New selection improves low-energy efficiency
- New shower energy estimator
  - 30% better low-energy resolution
- No charge sign cut
  - Reclaim mis-identified neutrino events at low energy
- Split data set into resolution bins
  - Increased statistical power



Analysis Improvements

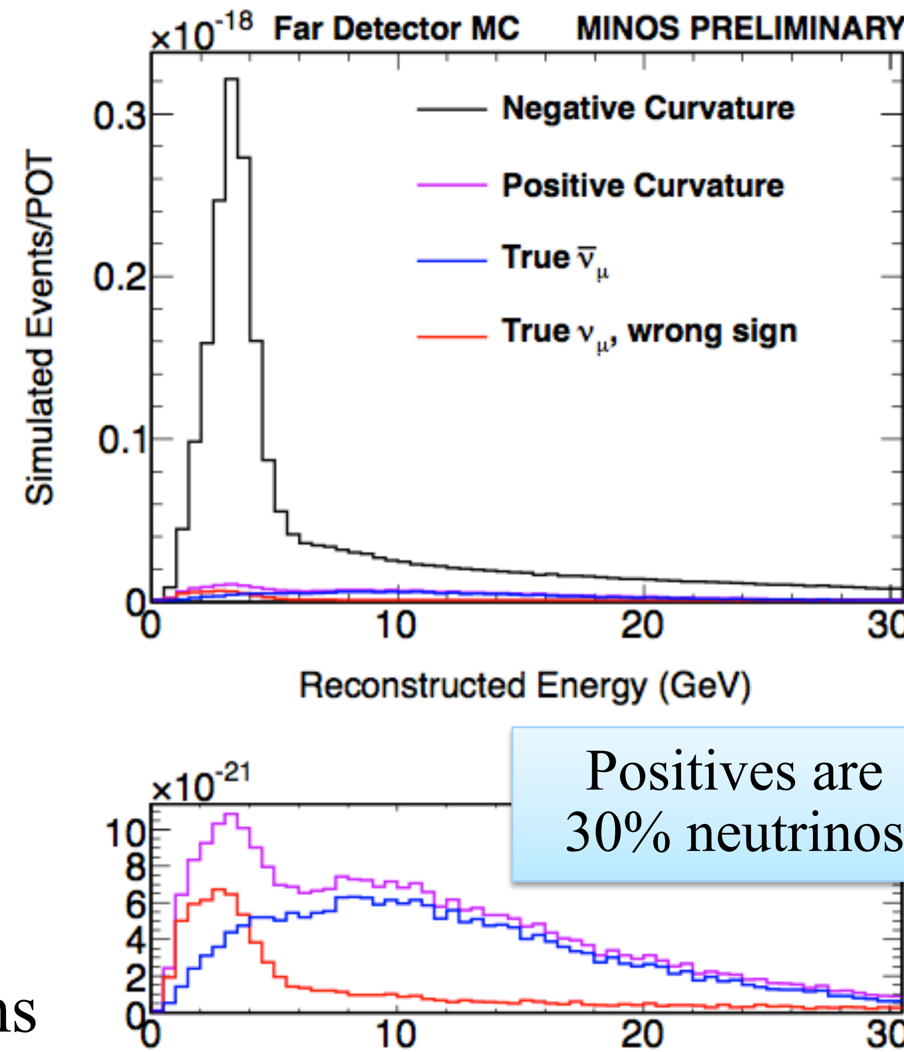
- Updated simulation and reconstruction
- New selection improves low-energy efficiency
- New shower energy estimator
  - 30% better low-energy resolution
- No charge sign cut
  - Reclaim mis-identified neutrino events at low energy
- Split data set into resolution bins
  - Increased statistical power

~30% better resolution below 2 GeV



Analysis Improvements

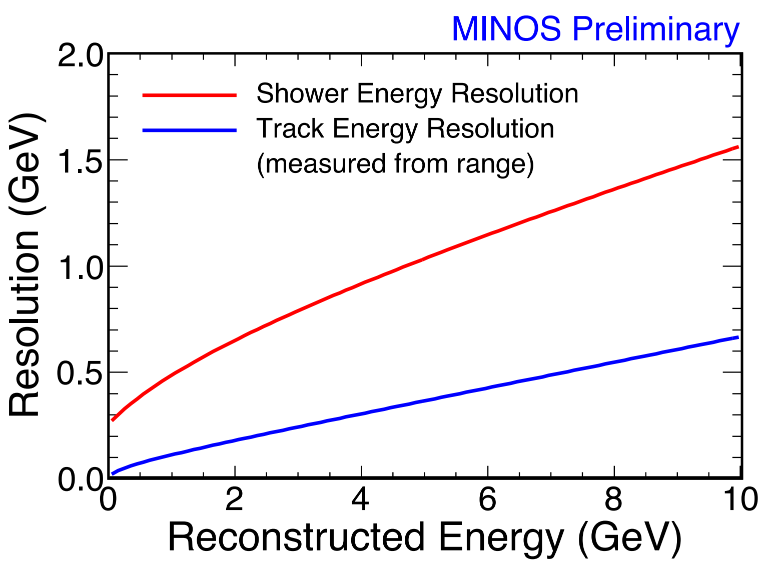
- Updated simulation and reconstruction
- New selection improves low-energy efficiency
- New shower energy estimator
  - 30% better low-energy resolution
- No charge sign cut
  - Reclaim mis-identified neutrino events at low energy
- Split data set into resolution bins
  - Increased statistical power



Positives are 30% neutrinos

Resolution Binning

- Separate high-resolution and low-resolution events
  - High-resolution events give the most information about the oscillation dip
- Use the MC to parameterize resolution as a function of track and shower energy
- 6 bins – 5 resolution quantiles, and 1 for positives



$$\frac{\sigma_{trk}}{E} = \frac{5.1\%}{\sqrt{E}} \oplus 6.9\%$$

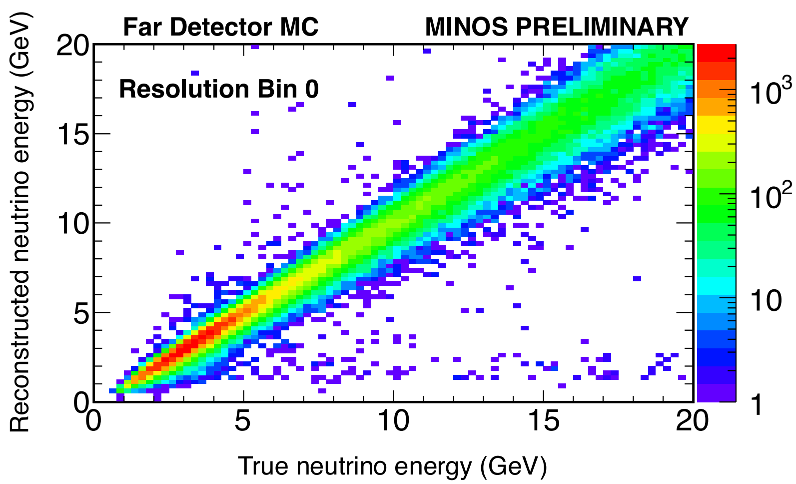
$$\frac{\sigma_{shw}}{E} = \frac{40.4\%}{\sqrt{E}} \oplus 8.6\% \oplus \frac{275\text{MeV}}{E}$$

$$\sigma_{evt} = \sigma_{trk} \oplus \sigma_{shw}$$

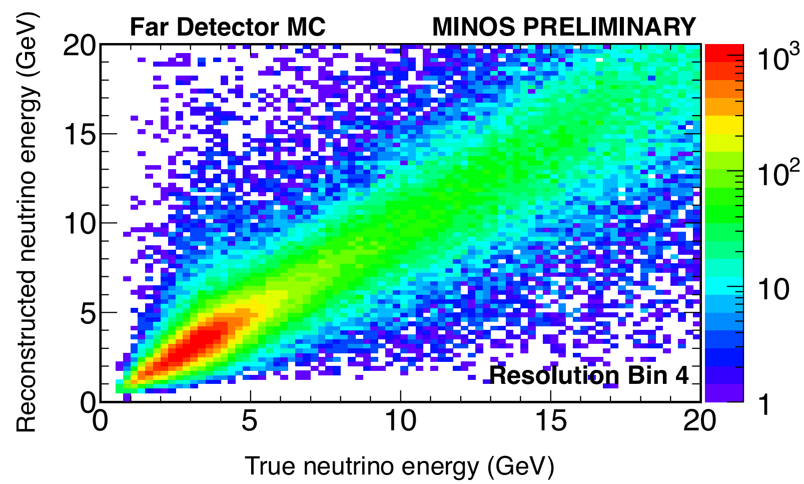
Resolution Binning

- Separate high-resolution and low-resolution events
  - High-resolution events give the most information about the oscillation dip
- Use the MC to parameterize resolution as a function of track and shower energy
- 6 bins – 5 resolution quantiles, and 1 for positives

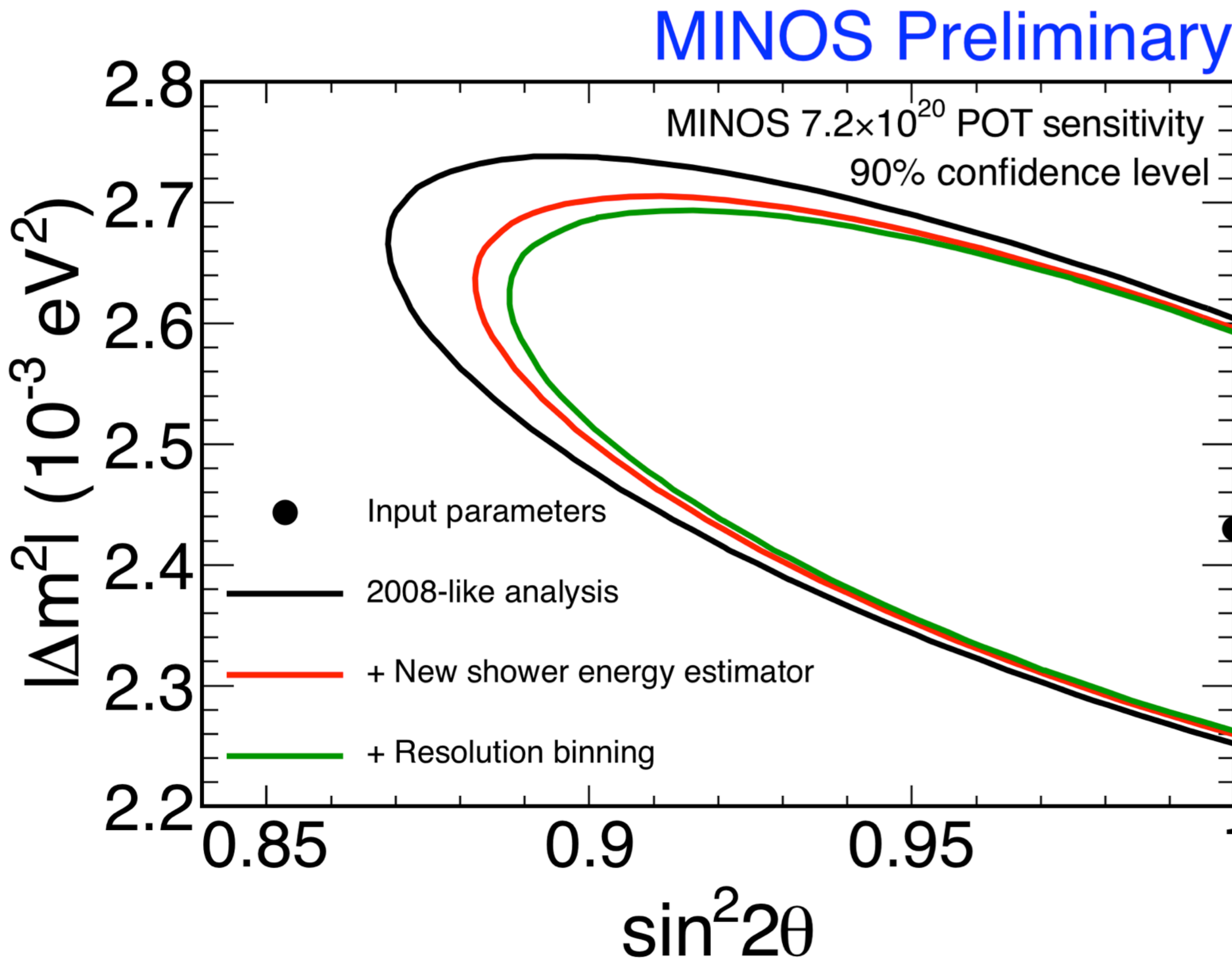
Best 20%



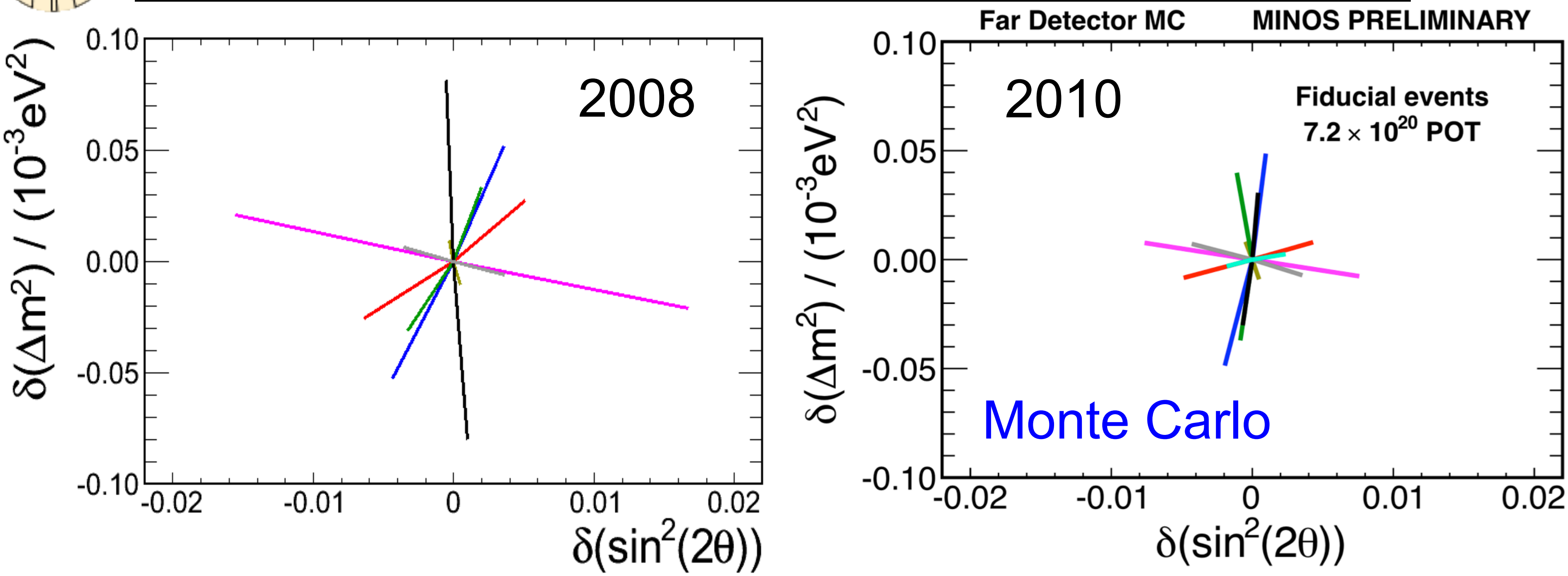
Worst 20%

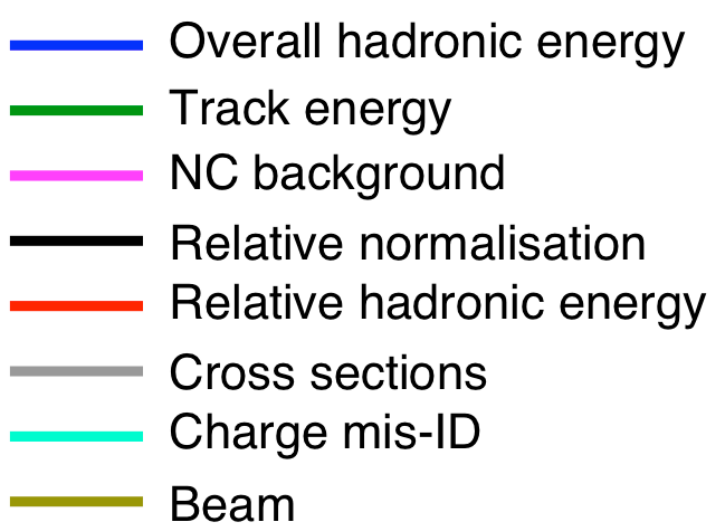


Analysis Improvements

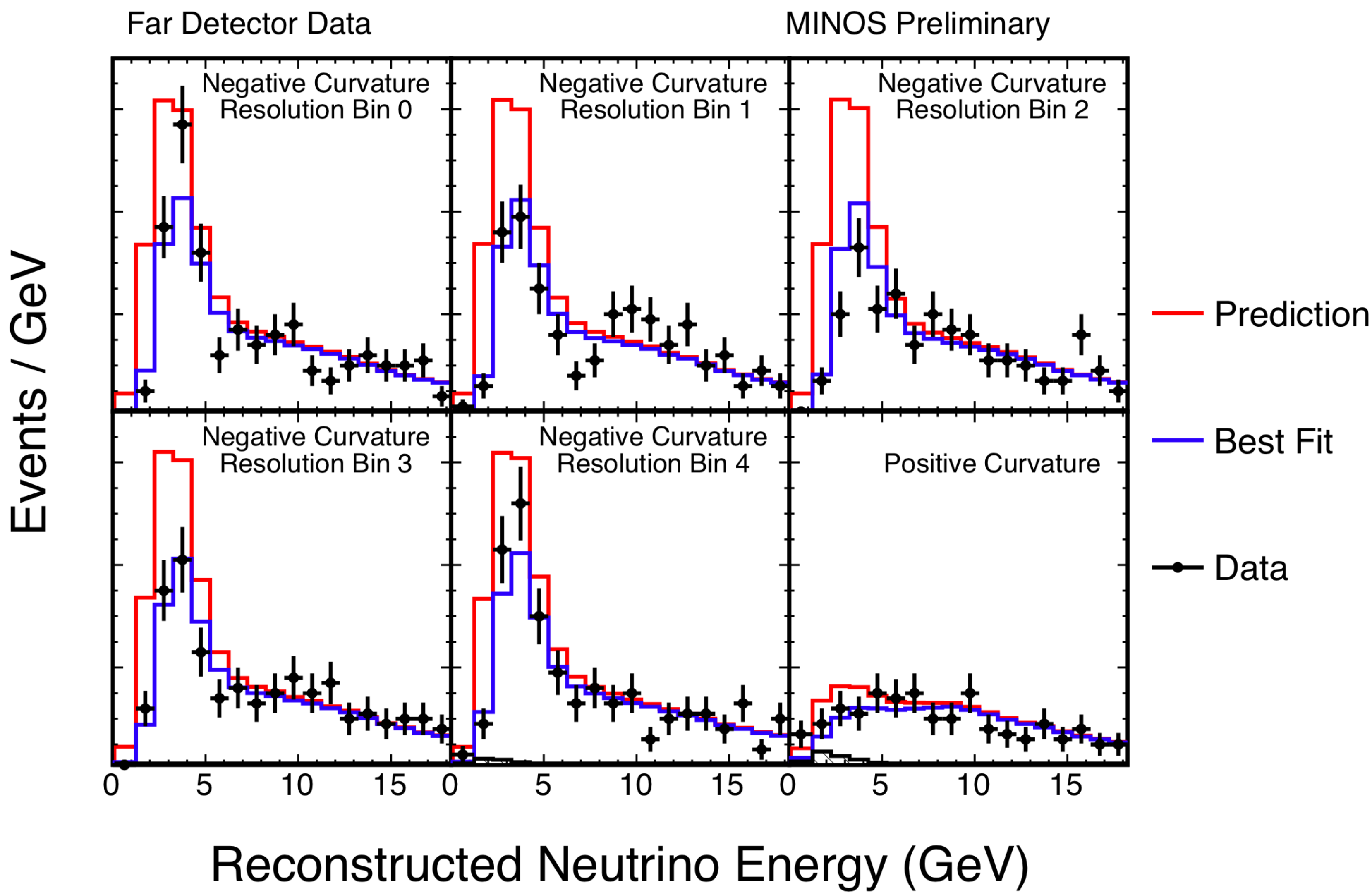


Change in Systematics

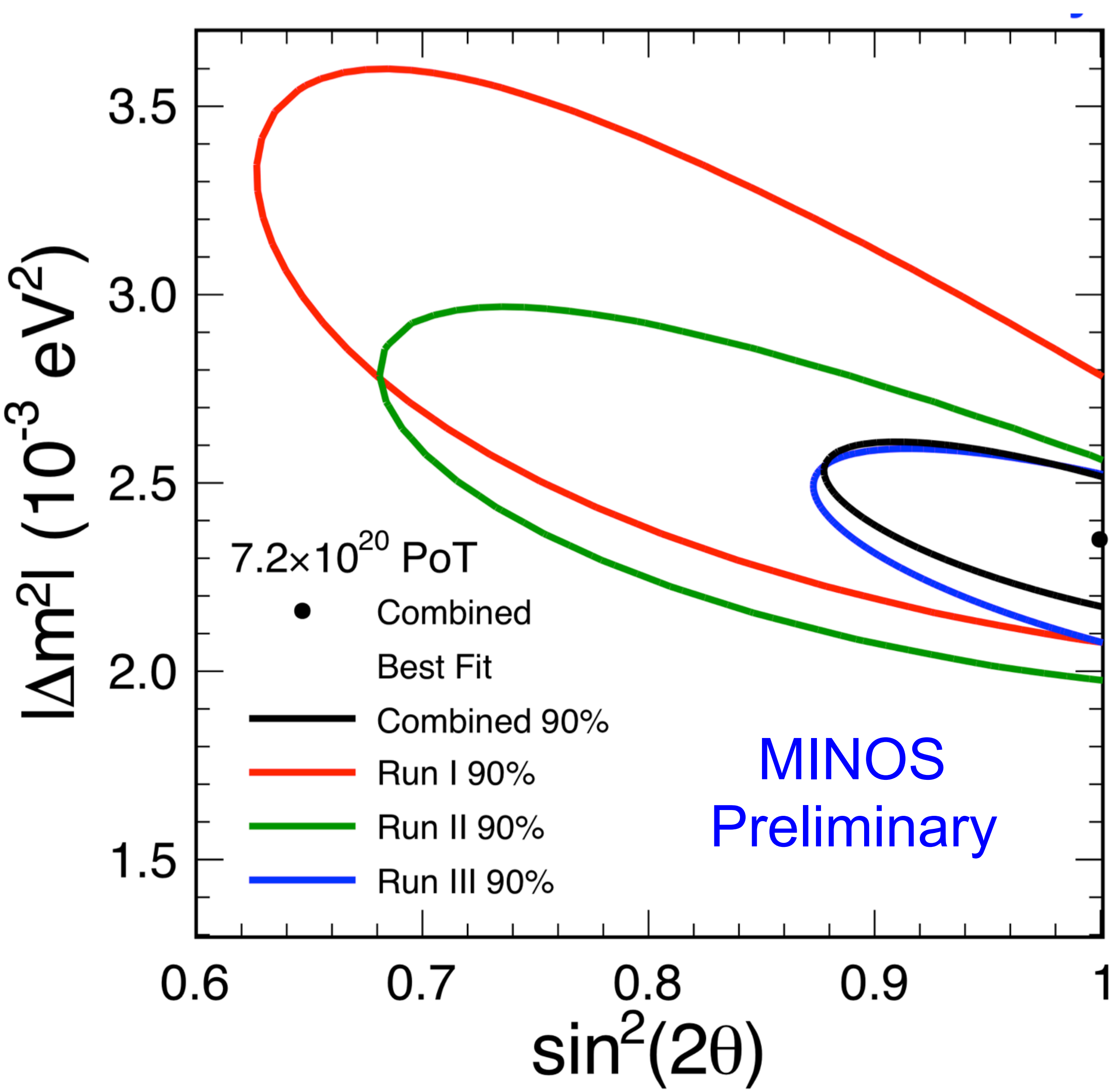




Neutrino Spectrum



Neutrino Contour by Run

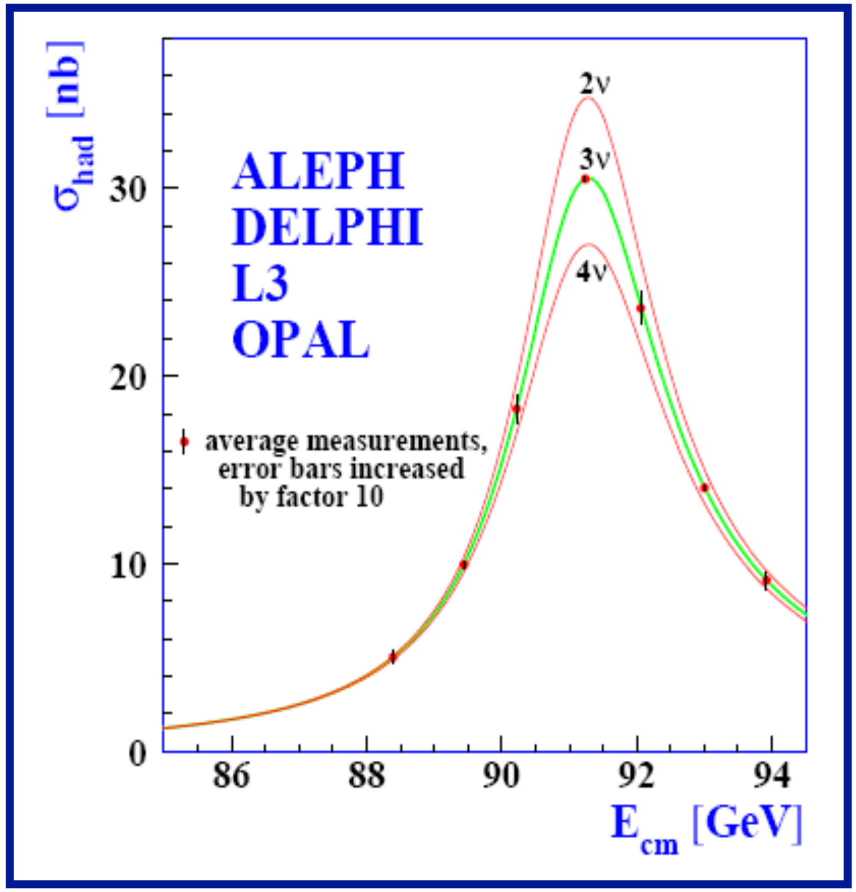


Neutral Currents

Sterile Neutrino Search

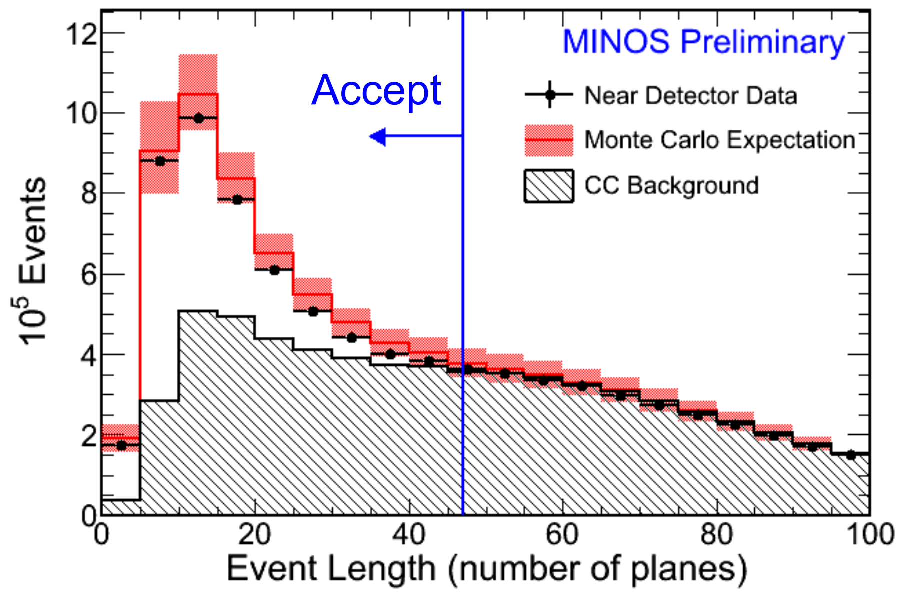
Sterile Neutrinos

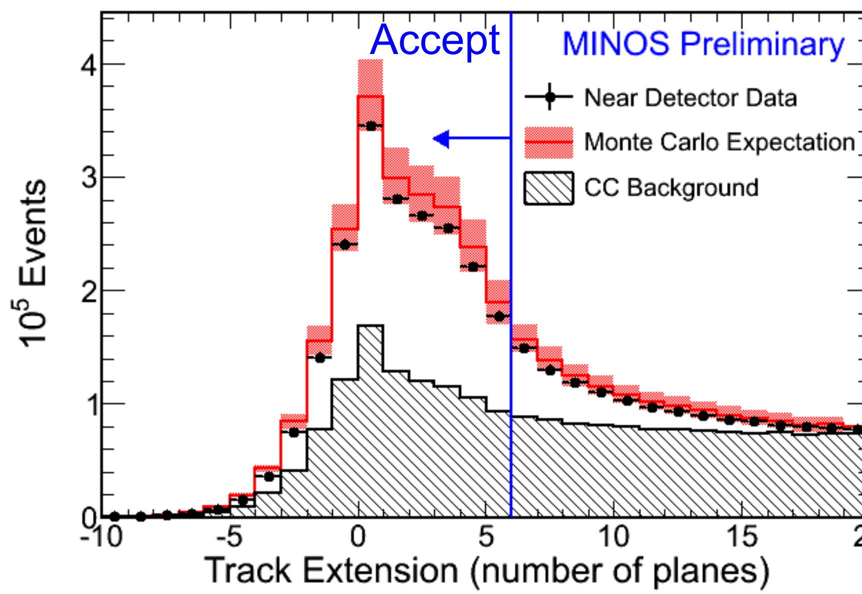
- Measurements of the Z^0 width at LEP limit the number of active neutrinos to 3
- A 4th neutrino cannot couple to the Z^0
  - Cannot participate in weak interactions
  - Hence is must be "sterile"
- Signature is a deficit in all active flavors
  - Neutral current interaction rate is independent of neutrino flavor
  - Look for a deficit in neutral currents at the Far Detector



Selecting Neutral Currents

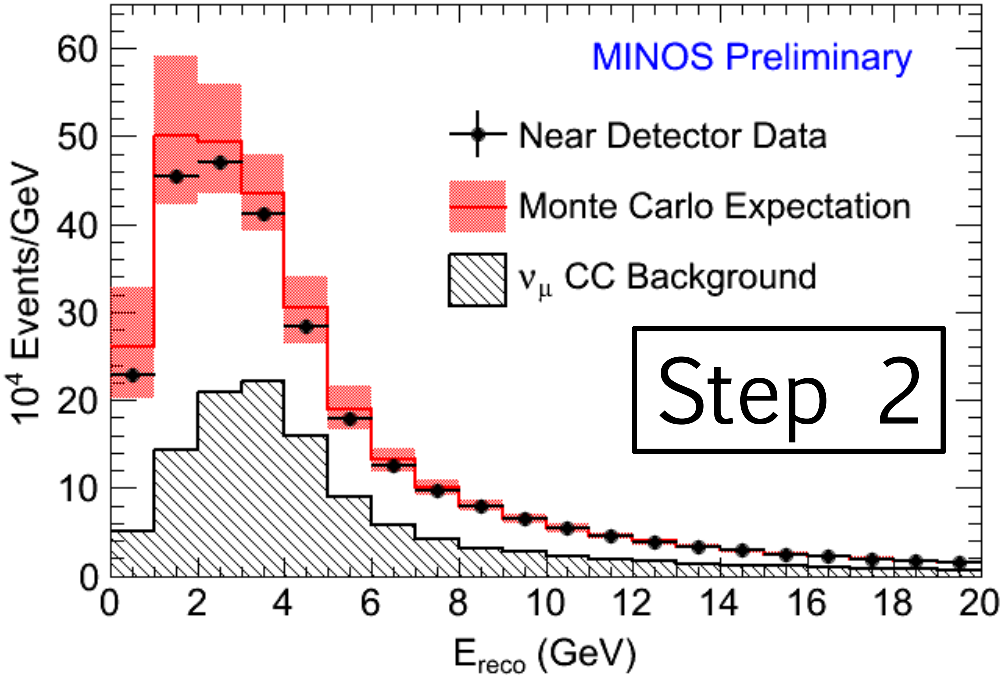
- Now CC (track) events are the background
  - Want to eliminate events with long tracks.
- Selection
  - Whole event must be short
    - < 47 planes
  - And either:
    - No reconstructed track
    - Track extends less than 6 planes out of the shower



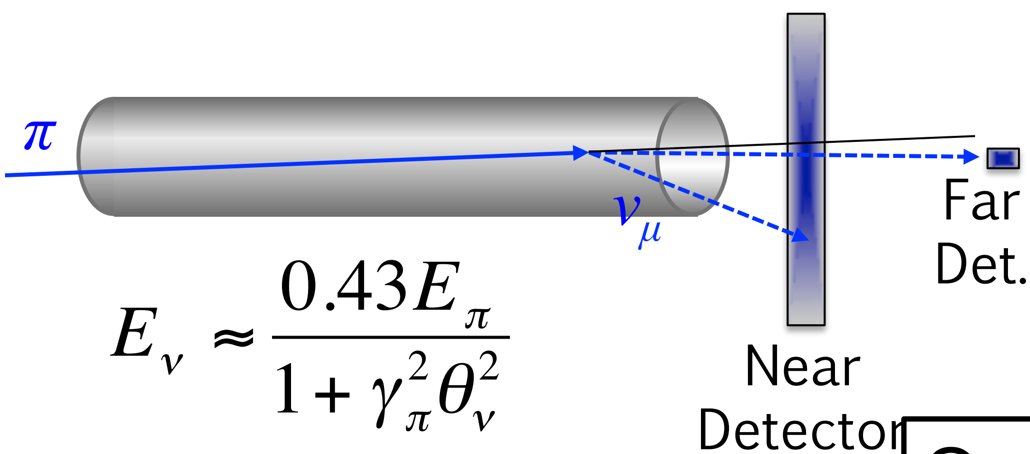


Step 1

Extrapolation



- The Near and Far Detector spectra are not identical
- Again, we use the MC to account for these differences
- Far/Near ratio relates to the two detector spectra
  - Insufficient energy resolution for a beam matrix



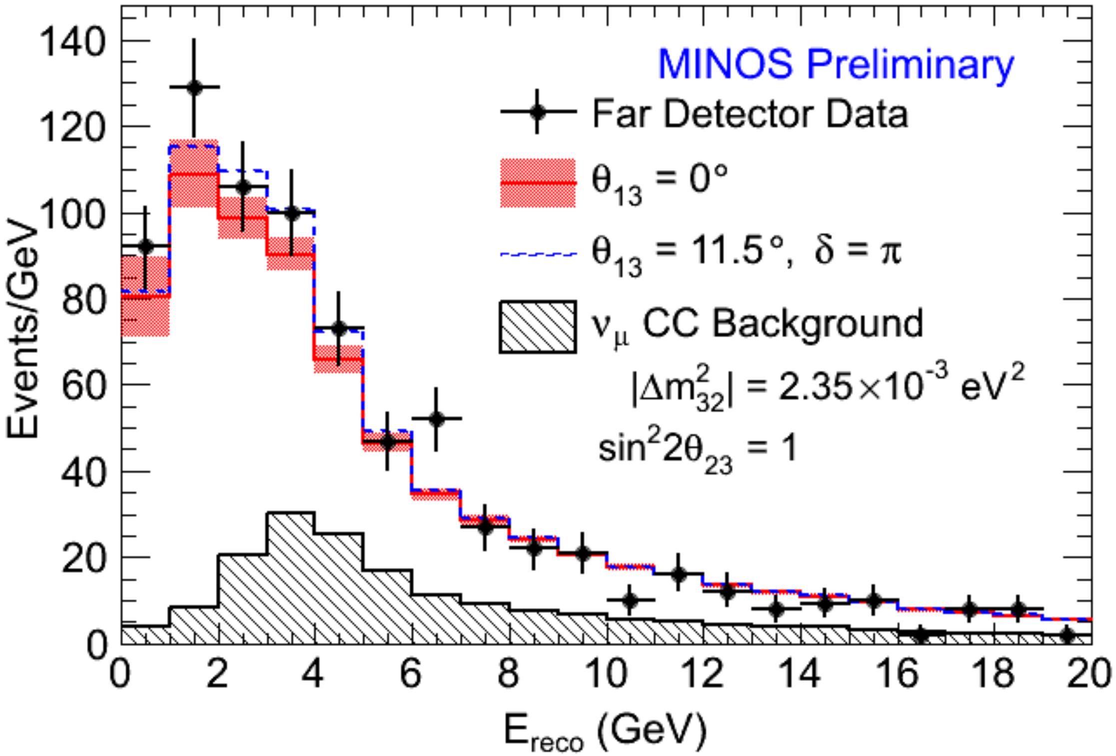
$$E_\nu \approx \frac{0.43 E_\pi}{1 + \gamma_\pi^2 \theta_\nu^2}$$

Step 3

$$FD_i^{pred} = \frac{FD_i^{MC}}{ND_i^{MC}} ND_i^{Data}$$

i refers to Energy bin

Sterile Neutrino Results



Step 4

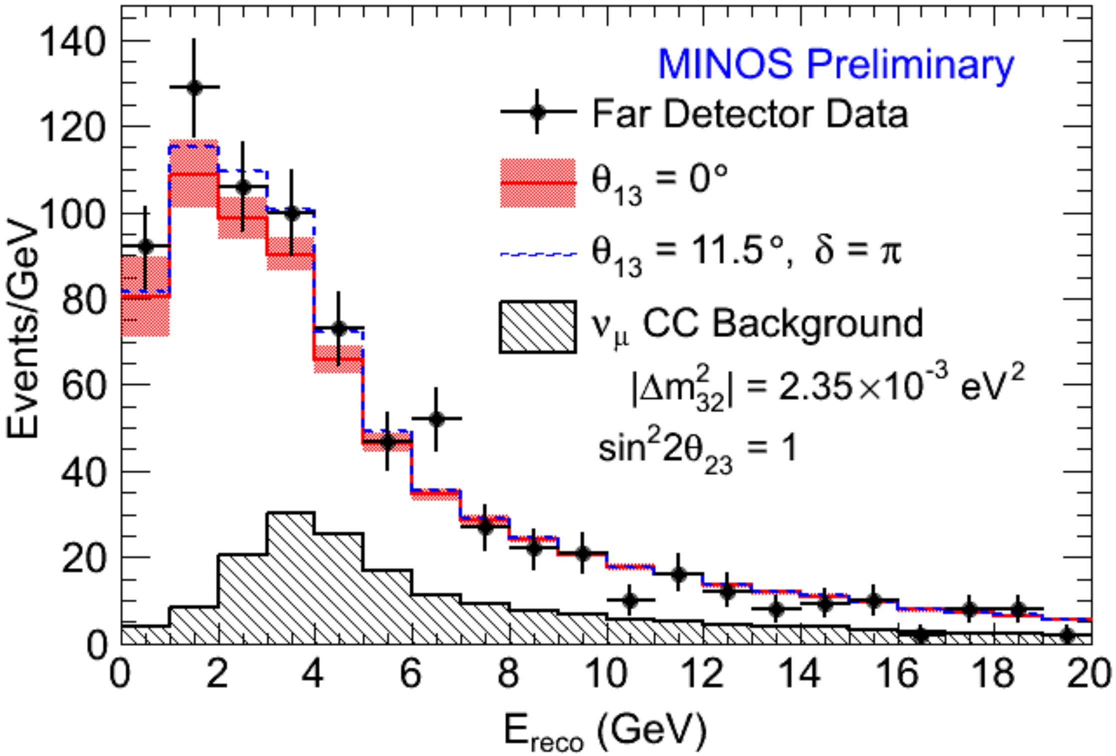
- Expected: **757** events
- Observe: **802** events
- No deficit of NC events

$$R = \frac{N_{\text{Data}} - N_{\text{BG}}}{N_{\text{NC Signal}}} \pm (stat) \pm (syst)$$

$$= 1.09 \pm 0.06 \pm 0.05 \text{ (no } \nu_e)$$

$$= 1.01 \pm 0.06 \pm 0.05 \; (\theta_{13} = 11.5^\circ)$$

Sterile Neutrino Results



Step 4

- Expected: **757** events
- Observe: **802** events
- No deficit of NC events

$$f_s \equiv \frac{P_{\nu_\mu \to \nu_s}}{1 - P_{\nu_\mu \to \nu_\mu}} < 0.22\ \ (0.40) \text{ at } 90\% \text{ C.L.}$$

no (with) ν_e appearance

f_s is the fraction of disappearing neutrinos that are becoming sterile neutrinos

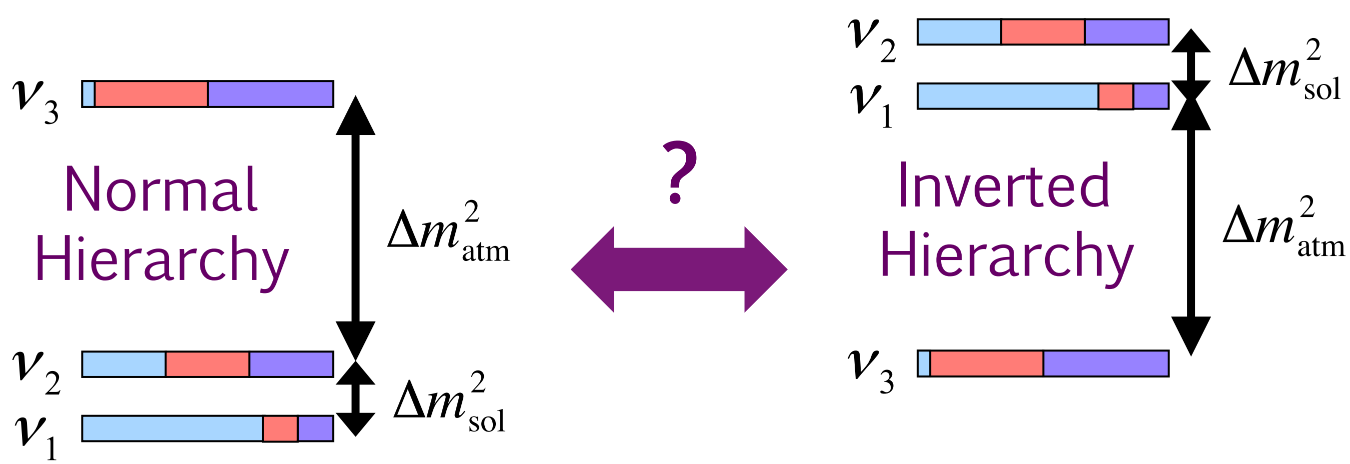
Electron Neutrinos

Search for θ_{13}

ν_e Appearance

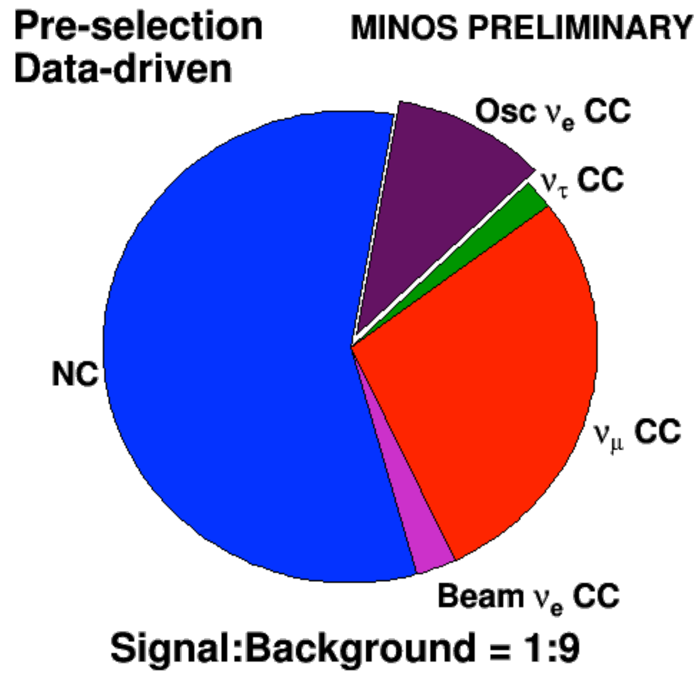
$$P(\nu_\mu \to \nu_e) \approx \sin^2(2\theta_{13})\sin^2(\theta_{23})\sin^2\left(1.27\Delta m^2_{31}\frac{L}{E}\right) +$$
$$\sin^2(2\theta_{12})\cos^2(\theta_{23})\sin^2\left(1.27\Delta m^2_{21}\frac{L}{E}\right) +$$
$$\sin(2\theta_{13})\sin(2\theta_{23})\sin(2\theta_{12})\sin\left(1.27\Delta m^2_{31}\frac{L}{E}\right)\sin\left(1.27\Delta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

- If $\theta_{13} \neq 0$ a few percent of the disappearing ν_μ's could be become ν_e's
- The appearance probability also depends on the complex phase δ_{CP} and the **mass hierarchy** (via matter effects, not shown above)



Selecting Electron Neutrinos

- Preselection
  - Require good beam and in-time fiducial events
  - Cut events with long tracks (CC ν_μ)
  - Cut events above 8 GeV where no oscillation signal is expected

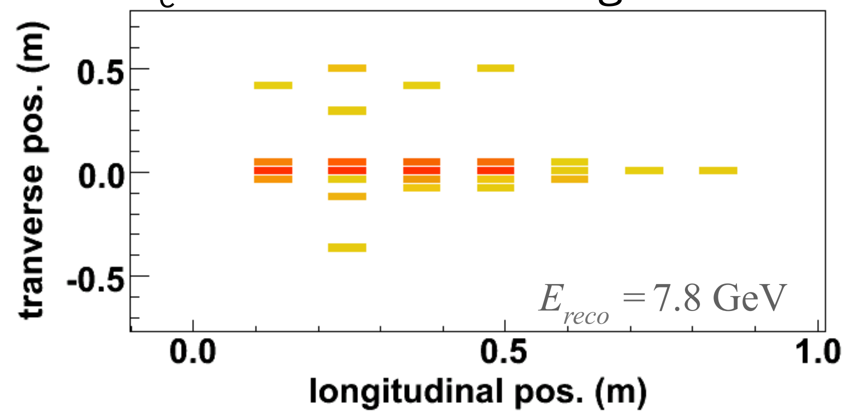


Step 1

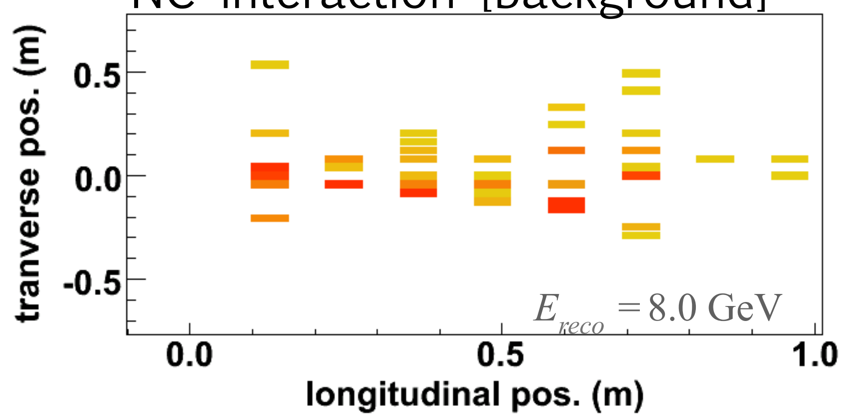
Selecting Electron Neutrinos

- Preselection
  - Require good beam and in-time fiducial events
  - Cut events with long tracks (CC ν_μ)
  - Cut events above 8 GeV where no oscillation signal is expected
- Selection
  - Distinguish a compact EM shower from a diffuse hadronic shower
  - Construct variables that parameterize shower shape
  - Use an Artificial Neural Network (ANN) based on 11 parameters

ν_e CC interaction [signal]

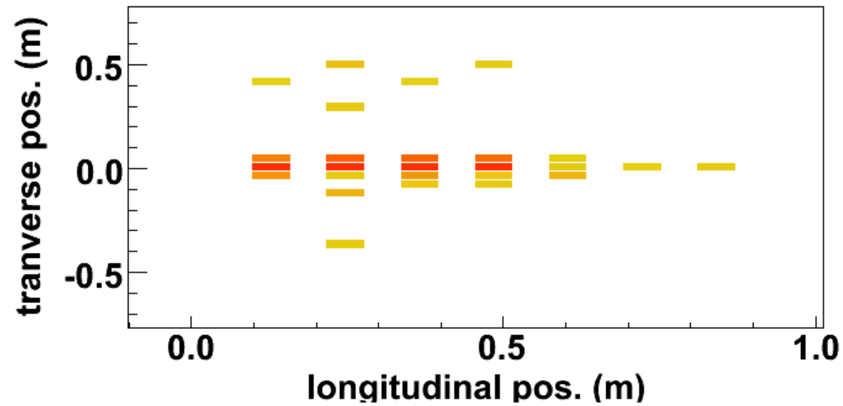


NC interaction [background]



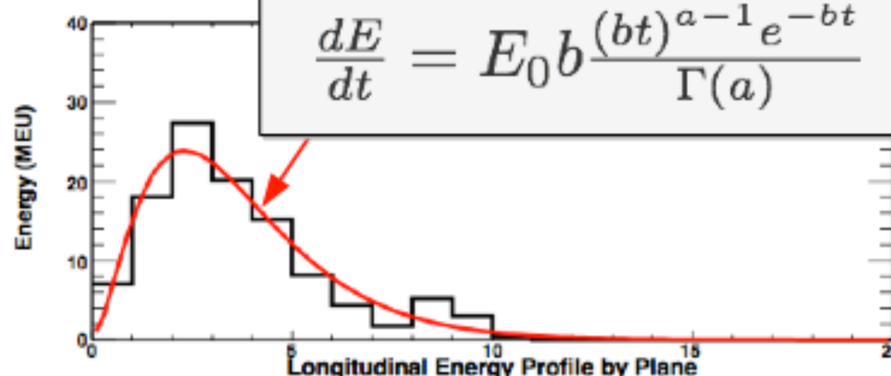
Selecting Electron Neutrinos

- Preselection
  - Require good beam and in-time fiducial events
  - Cut events with long tracks (CC ν_μ)
  - Cut events above 8 GeV where no oscillation signal is expected
- Selection
  - Distinguish a compact EM shower from a diffuse hadronic shower
  - Construct variables that parameterize shower shape
  - Use an Artificial Neural Network (ANN) based on 11 parameters



Example EM shower profile

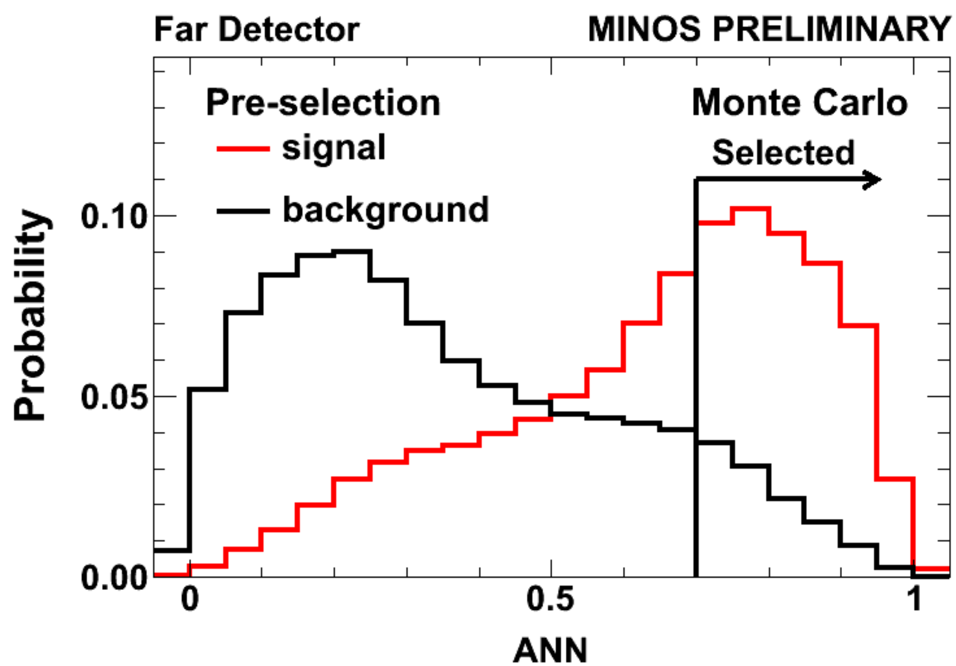
$$\frac{dE}{dt} = E_0 b \frac{(bt)^{a-1} e^{-bt}}{\Gamma(a)}$$

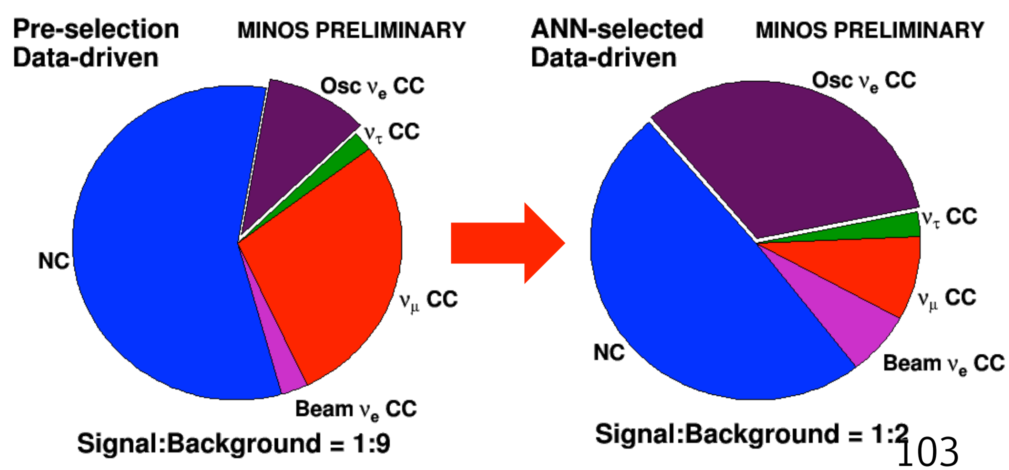


a, b

Selecting Electron Neutrinos

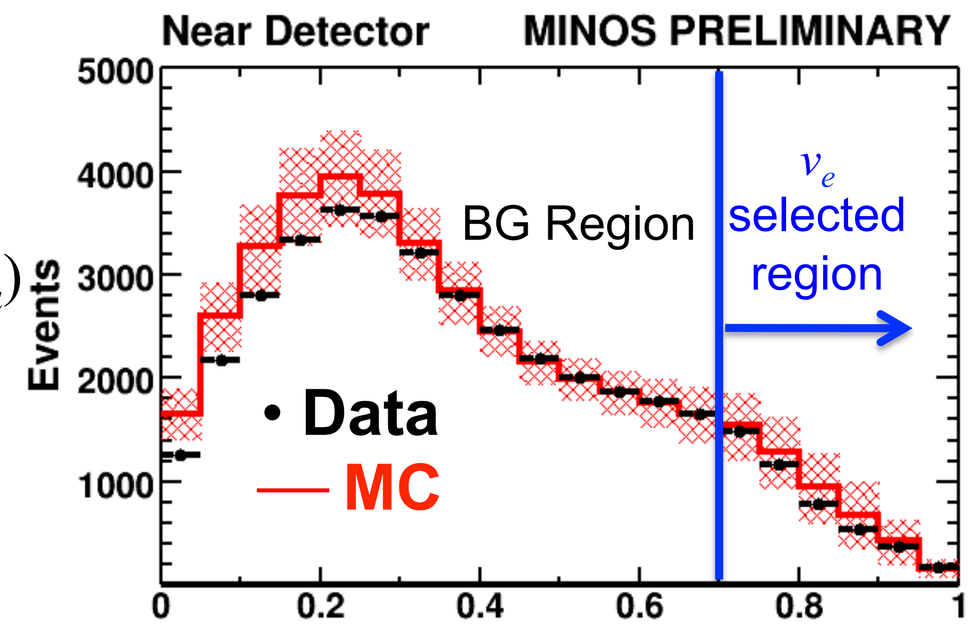
- Preselection
  - Require good beam and in-time fiducial events
  - Cut events with long tracks (CC ν_μ)
  - Cut events above 8 GeV where no oscillation signal is expected
- Selection
  - Distinguish a compact EM shower from a diffuse hadronic shower
  - Construct variables that parameterize shower shape
  - Use an Artificial Neural Network (ANN) based on 11 parameters



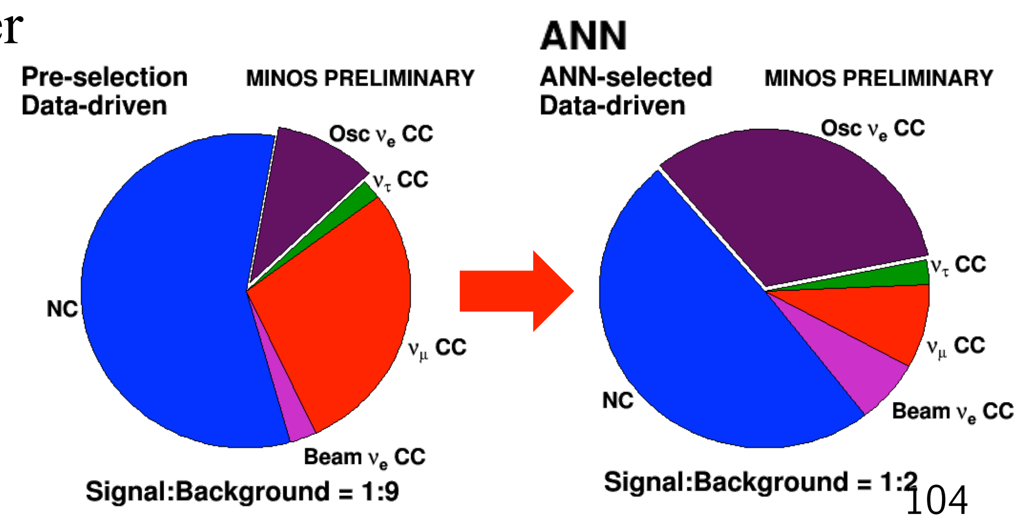


Selecting Electron Neutrinos

- Preselection
  - Require good beam and in-time fiducial events
  - Cut events with long tracks (CC ν_μ)
  - Cut events above 8 GeV where no oscillation signal is expected

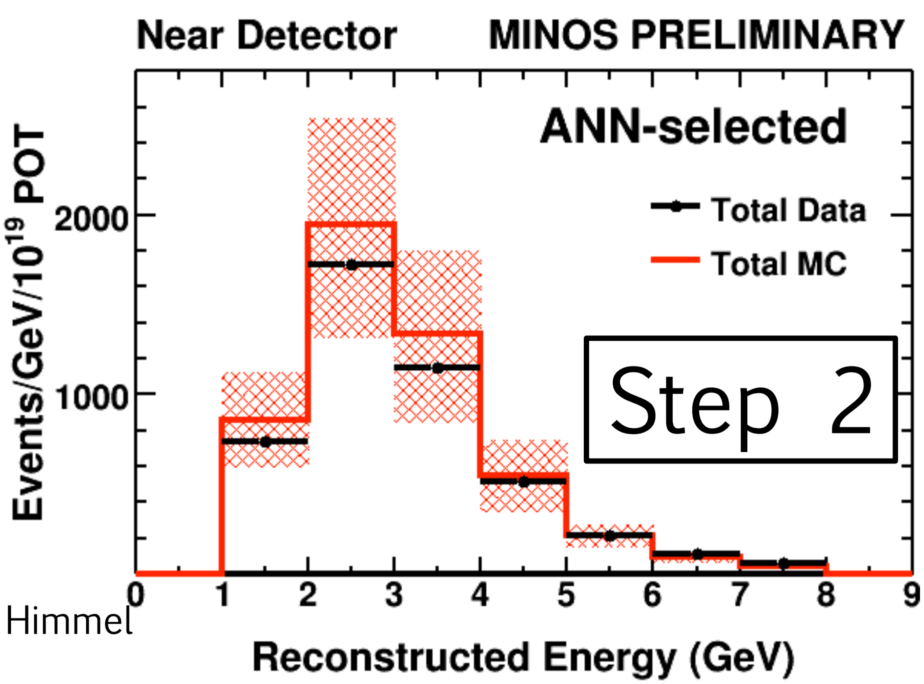


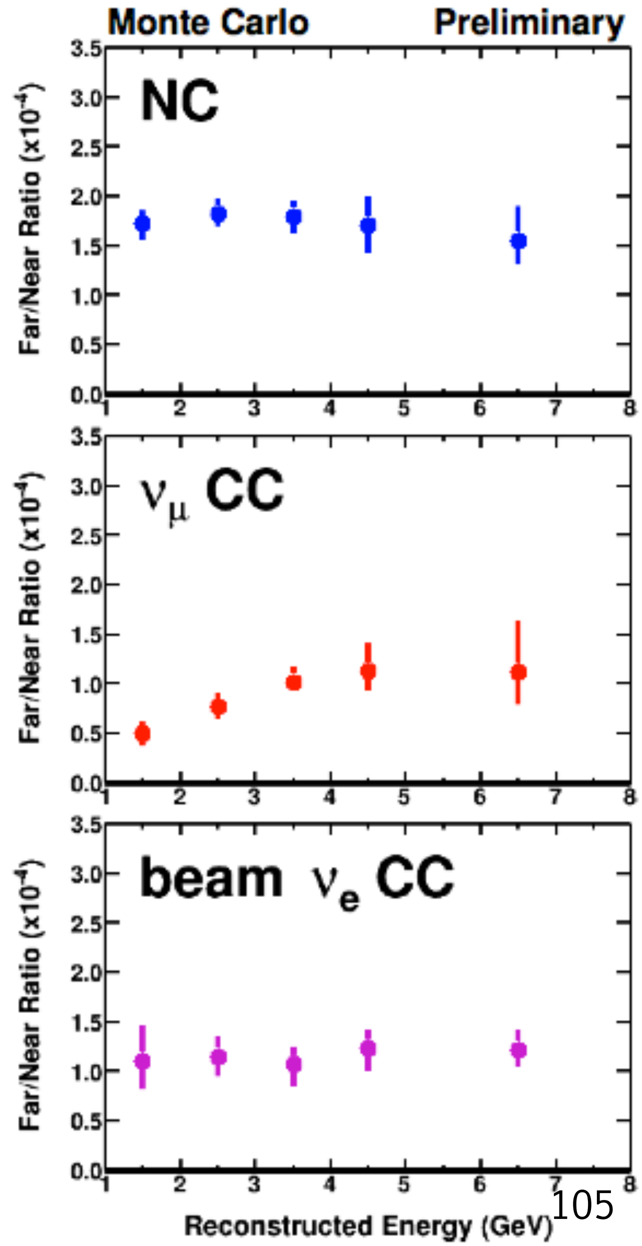
- Selection
  - Distinguish a compact EM shower from a diffuse hadronic shower
  - Construct variables that parameterize shower shape
  - Use an Artificial Neural Network (ANN) based on 11 parameters



Extrapolation

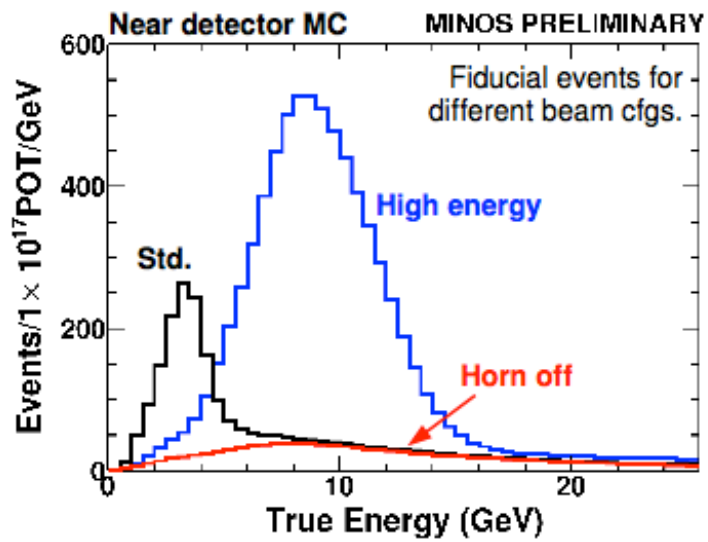
- Near Detector consists of 3 background components:
  - Neutral Currents
  - Charged Current ν_μ
  - Beam ν_e's
- Each component extrapolates differently to the Far Detector
  - As with NC analysis, Far/Near is used

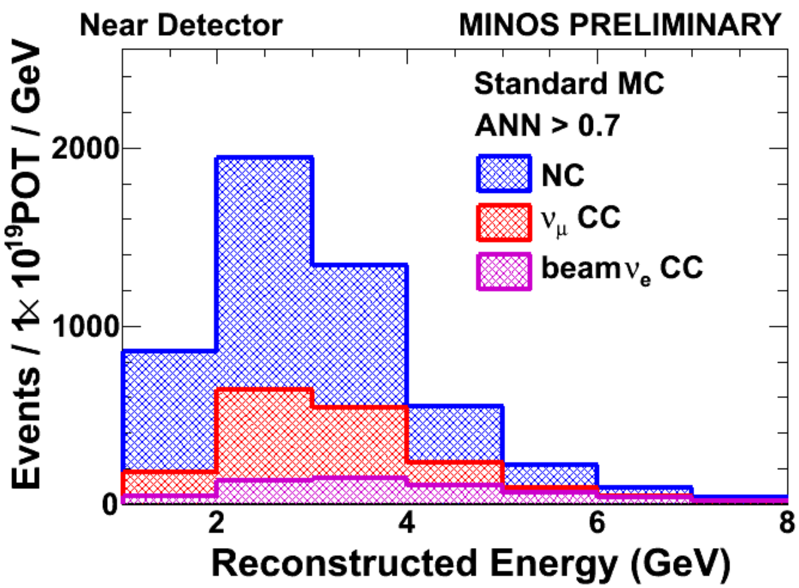




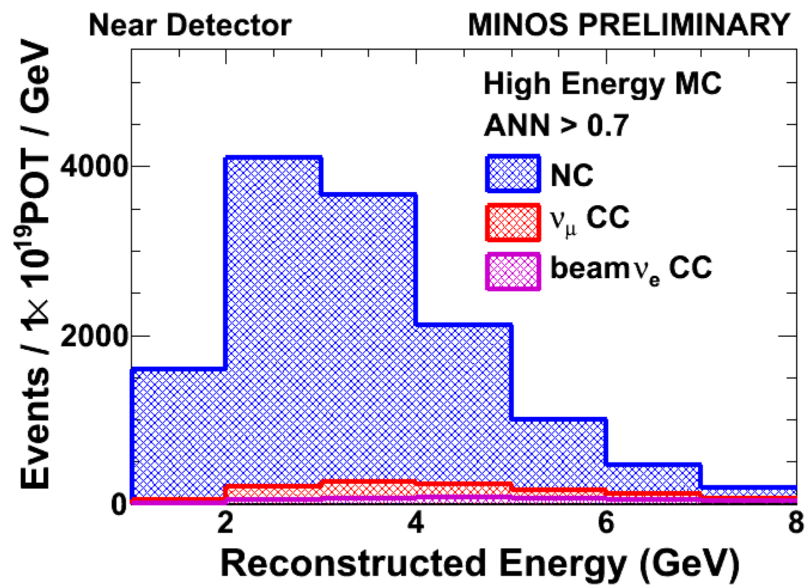
ND Decomposition

- Changing horn focusing changes the balance of the three components
- Fit three different focusing configurations
  - Low Energy (standard)
  - Horn Off
  - High Energy





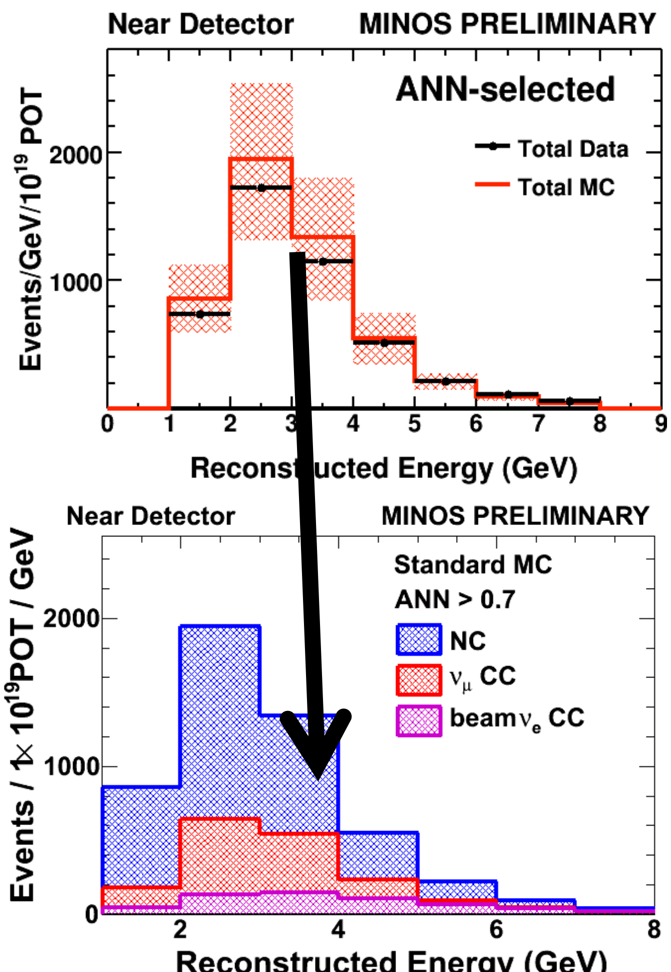
Turn off focusing horns



Extrapolation

Step 3

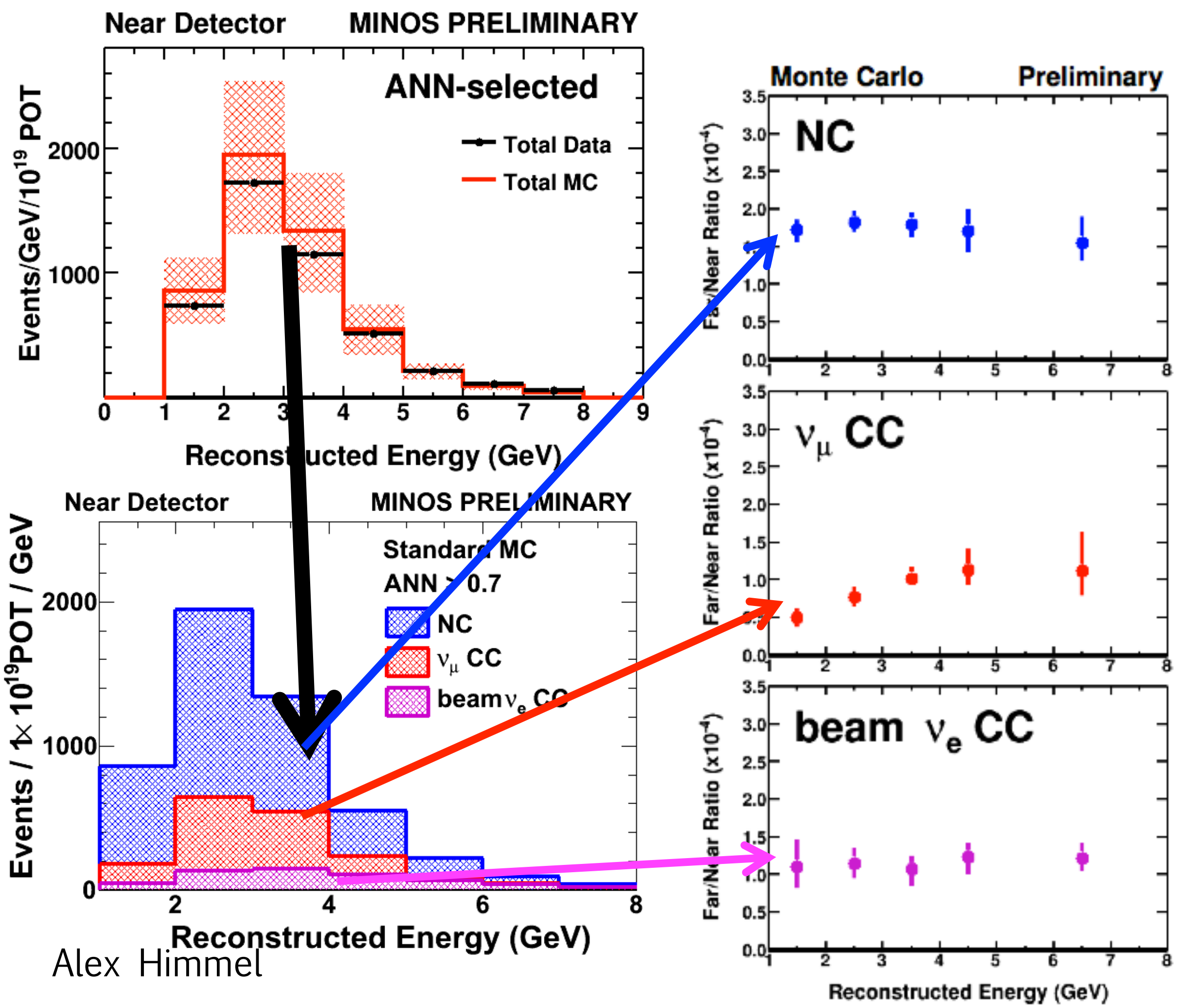
- Apply decomposition to the Near Detector data



Extrapolation

Step 3

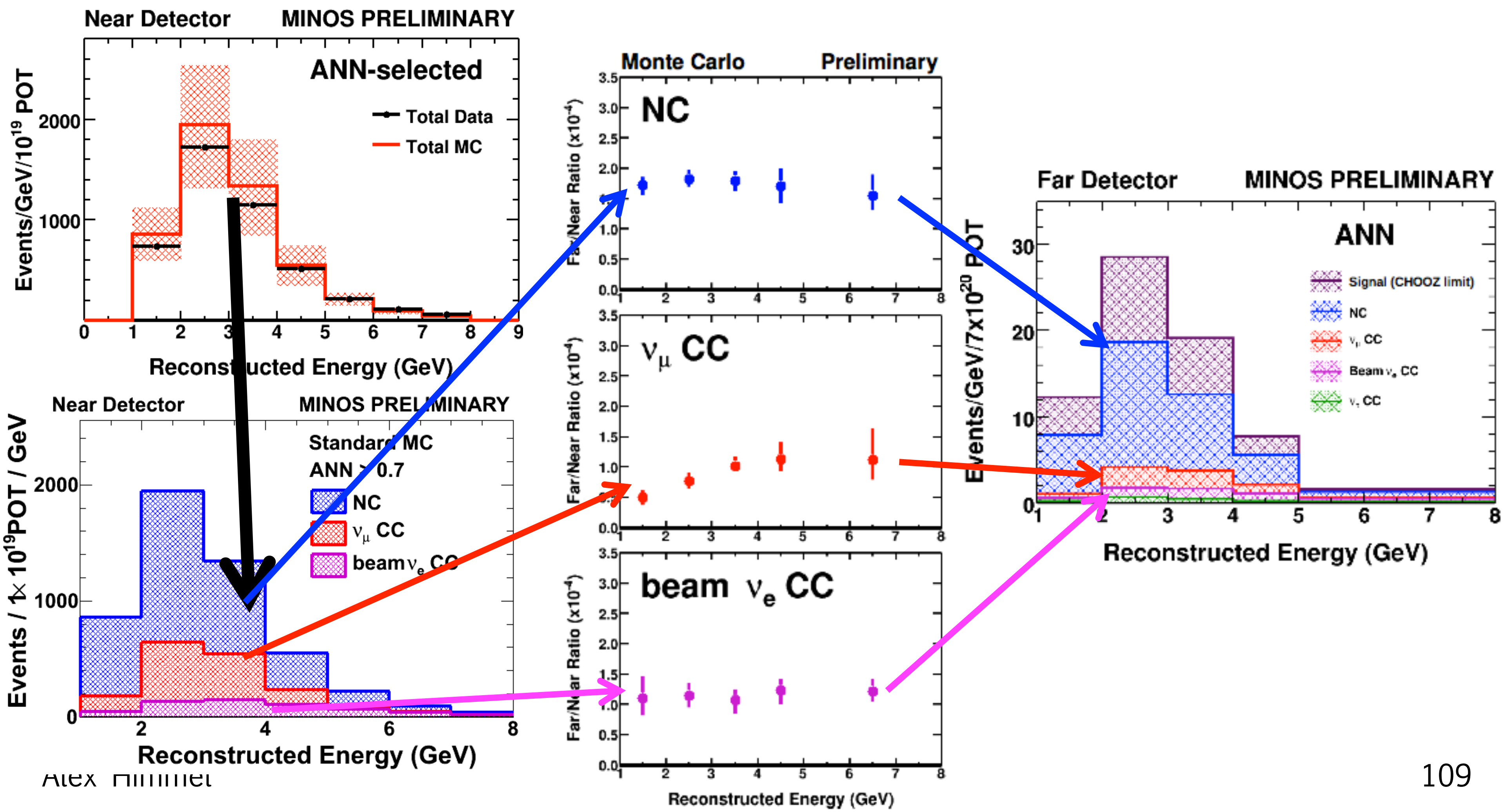
- Apply decomposition to the Near Detector data
- Extrapolate each component to get a Far Detector prediction



Extrapolation

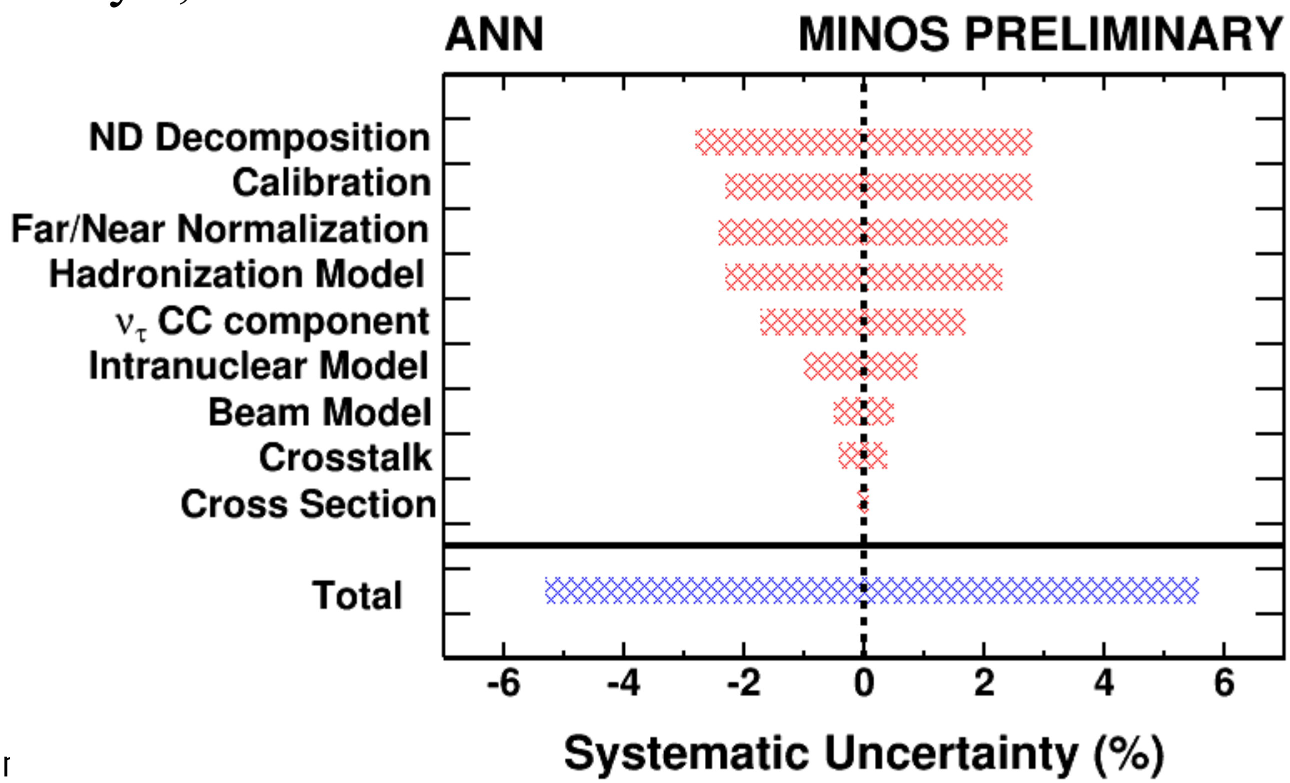
Step 3

- Apply decomposition to the Near Detector data
- Extrapolate each component to get a Far Detector prediction



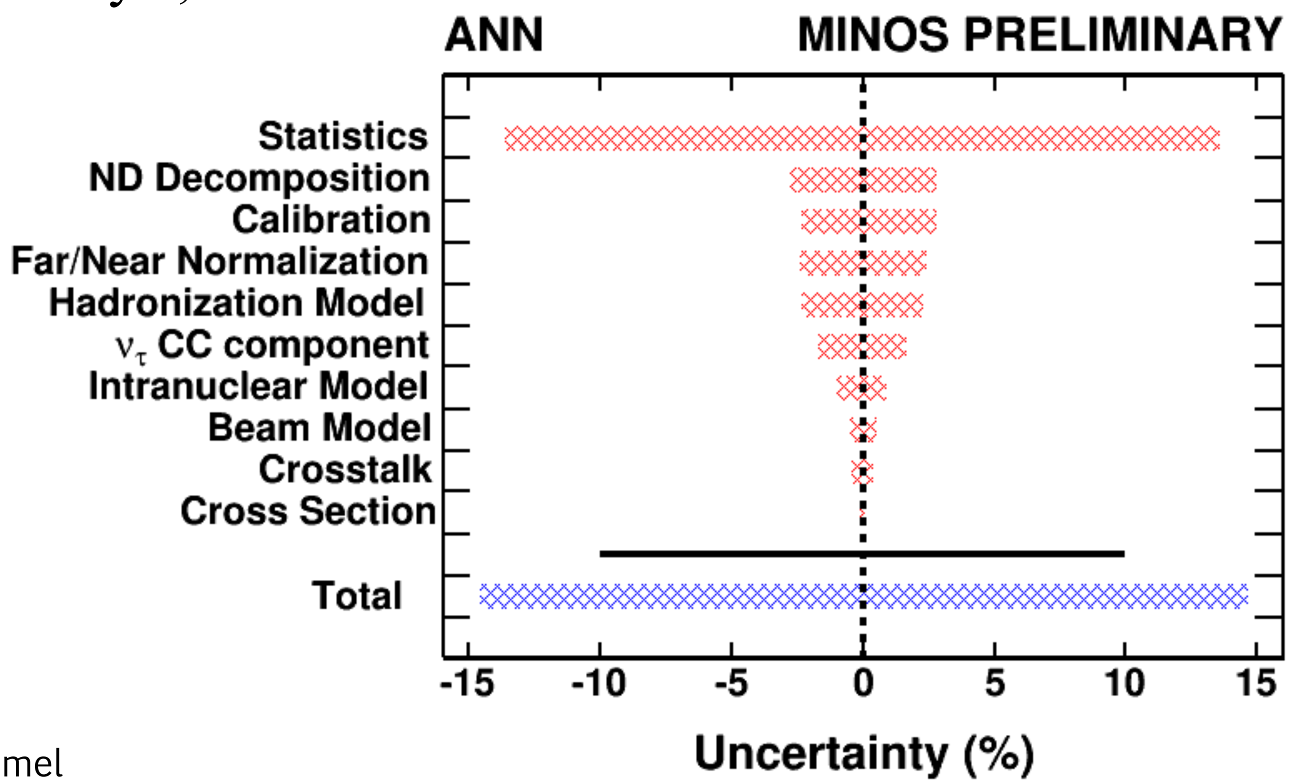
Systematics

- Systematic uncertainty on the prediction from:
  - Near decomposition
  - Near and far detector differences
  - Cross-section and interaction models
- Uncertainty still dominated by statistics
  - 5% syst, 15% stat



Systematics

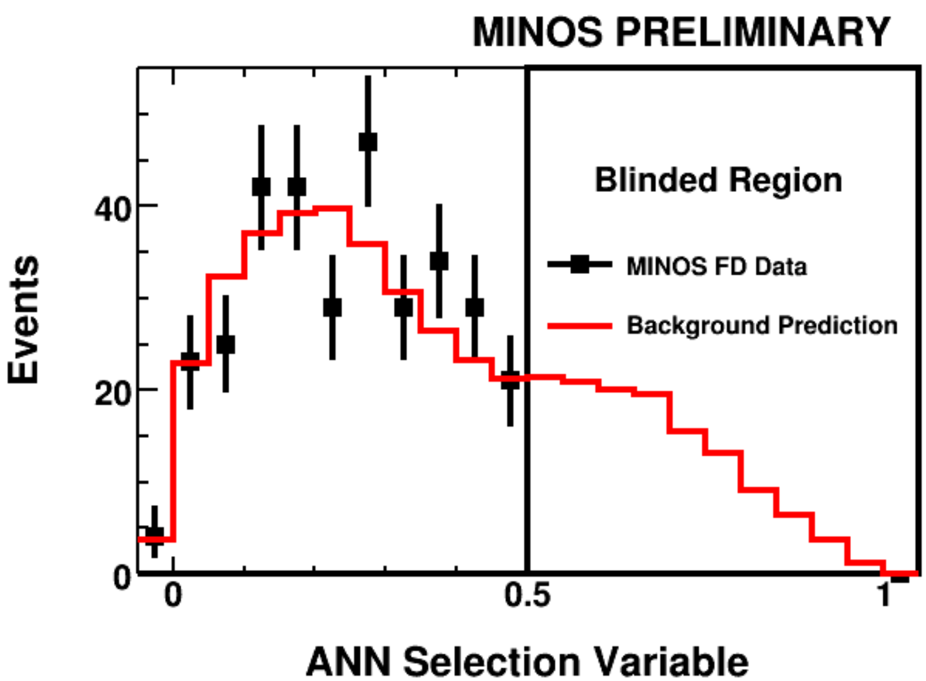
- Systematic uncertainty on the prediction from:
  - Near decomposition
  - Near and far detector differences
  - Cross-section and interaction models
- Uncertainty still dominated by statistics
  - 5% syst, 15% stat

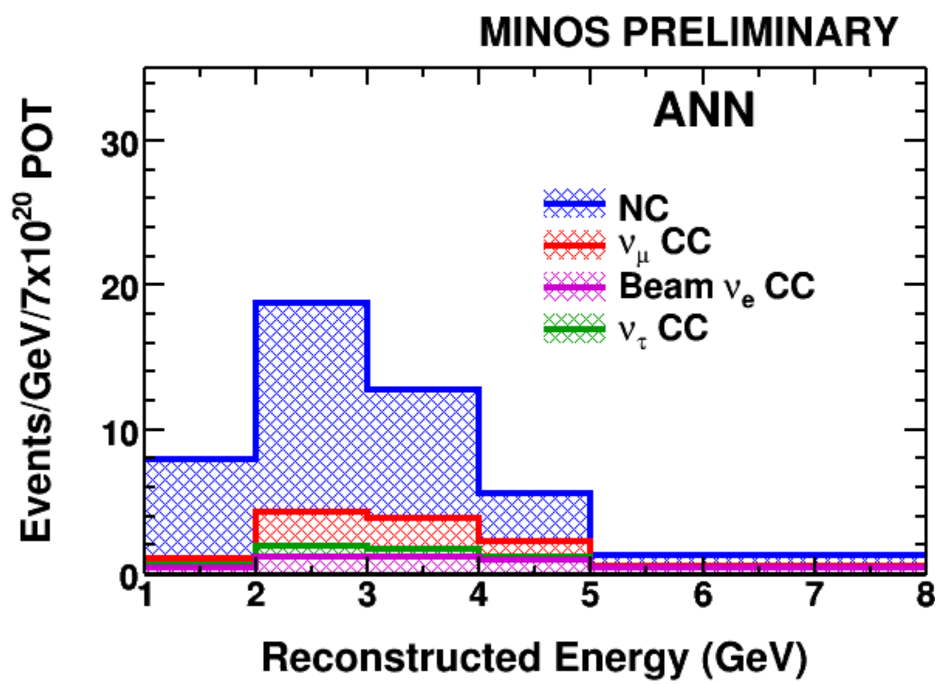


ν_e Appearance Results

Step 4

- Expect: 49.1 ± 7.0 (stat.) ± 2.7 (syst.)

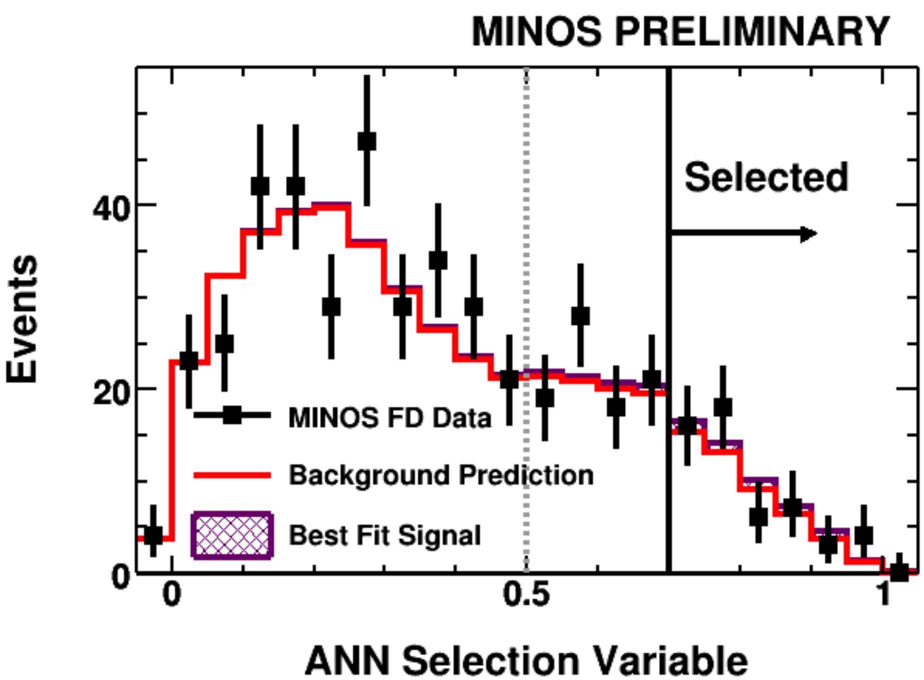


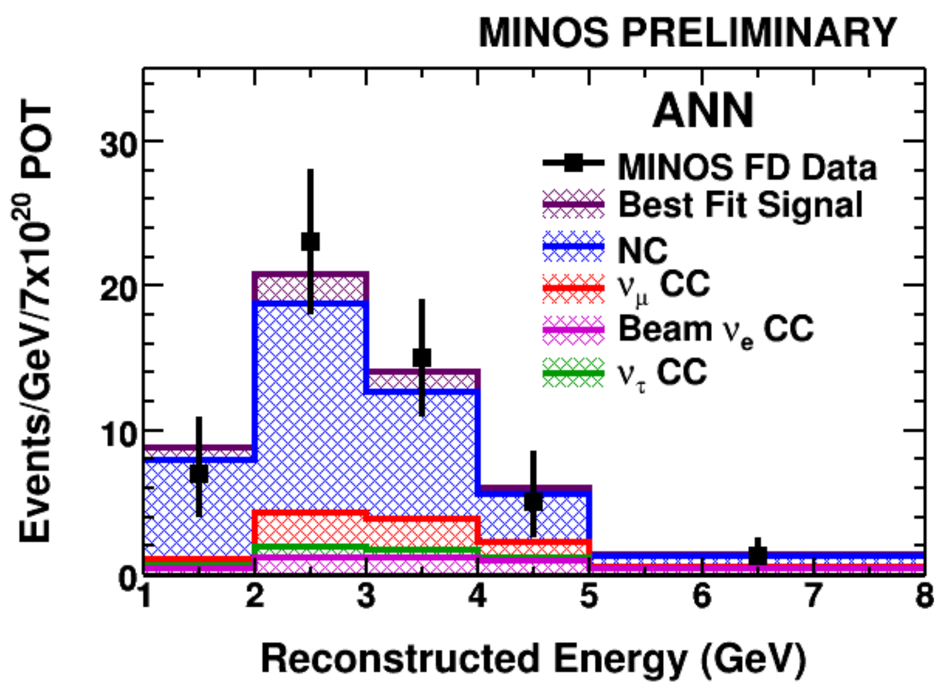


ν_e Appearance Results

Step 4

- Expect: 49.1 ± 7.0 (stat.) ± 2.7 (syst.)
- Observe: 54 events, a 0.7σ excess





ν_e Appearance Results

for $\delta_{CP} = 0, \sin^2(2\theta_{23}) = 1,$

$\left|\Delta m^2_{32}\right| = 2.43 \times 10^{-3}\ \mathrm{eV}^2$

$\sin^2(2\theta_{13}) < 0.12$ normal hierarchy

$\sin^2(2\theta_{13}) < 0.20$ inverted hierarchy

at 90% C.L.

A new analysis is coming next year with improved sensitivity

- More data
- Significantly better background rejection