Neutrino Oscillation Results from MINOS

Alexander Himmel
Caltech
for the MINOS Collaboration

IPMU Mini-workshop on Neutrinos, November 8th 2010

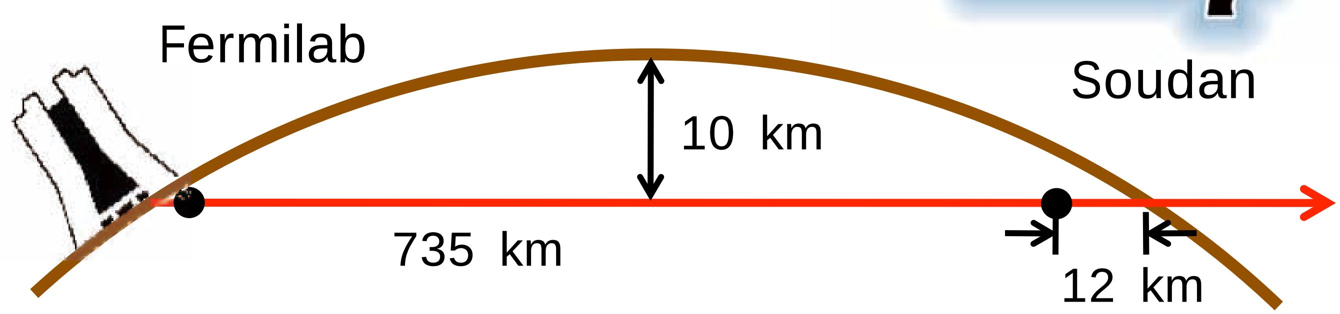
Introduction

- What is MINOS?
- Neutrino Physics
  - Oscillation Basics
  - MINOS Physics Goals
- The Experiment
  - NuMI neutrino beam
  - MINOS detectors
- The Analyses
  - Atmospheric-sector oscillations
  - Sterile Neutrinos
  - Electron Neutrino Appearance

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

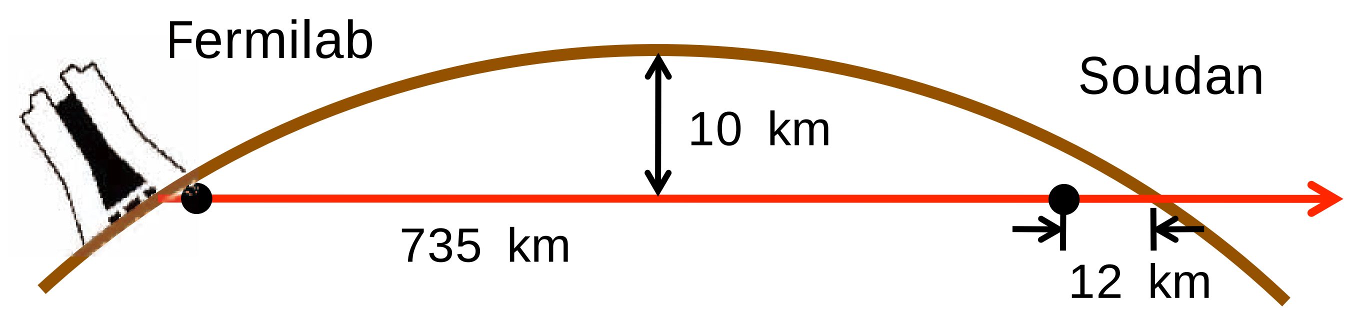


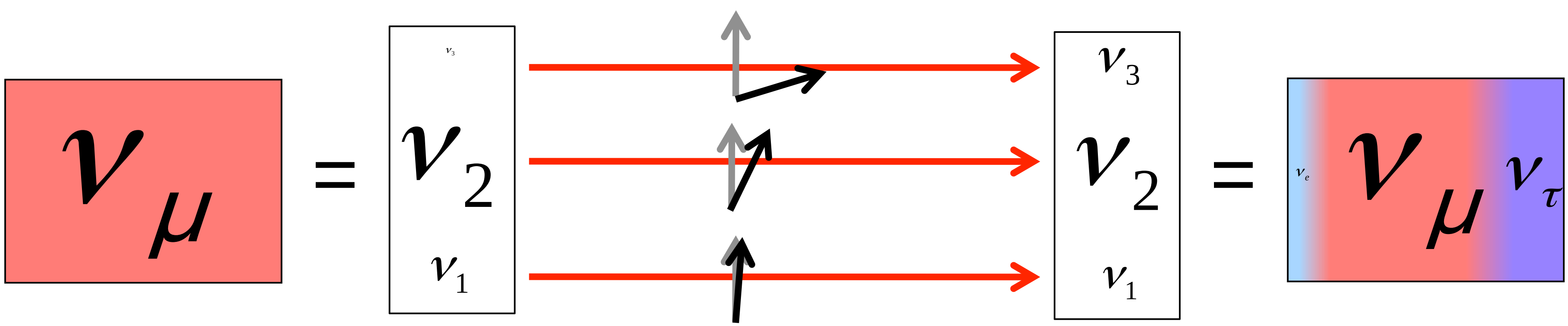
Neutrino Physics

– Oscillation basics
– MINOS Physics Goals

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

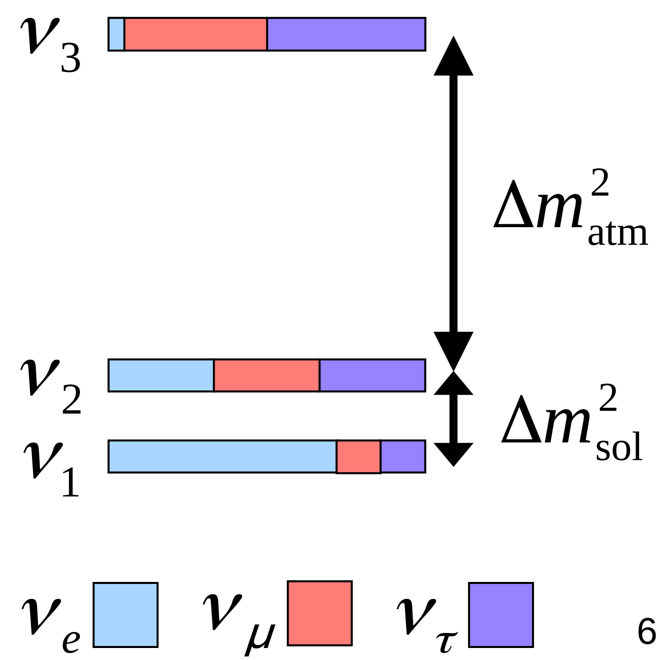




Neutrino Masses and Mixing

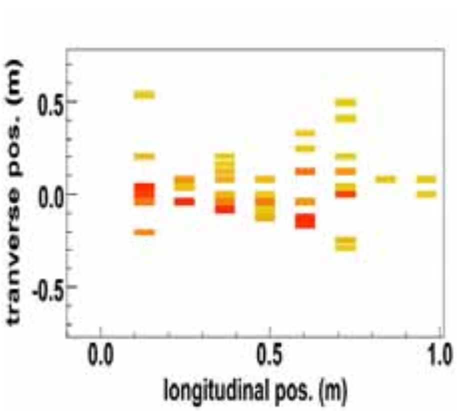
$$
\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} =
\overbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}^{\text{Solar, Reactor}}
\overbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}}^{\text{Mixed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

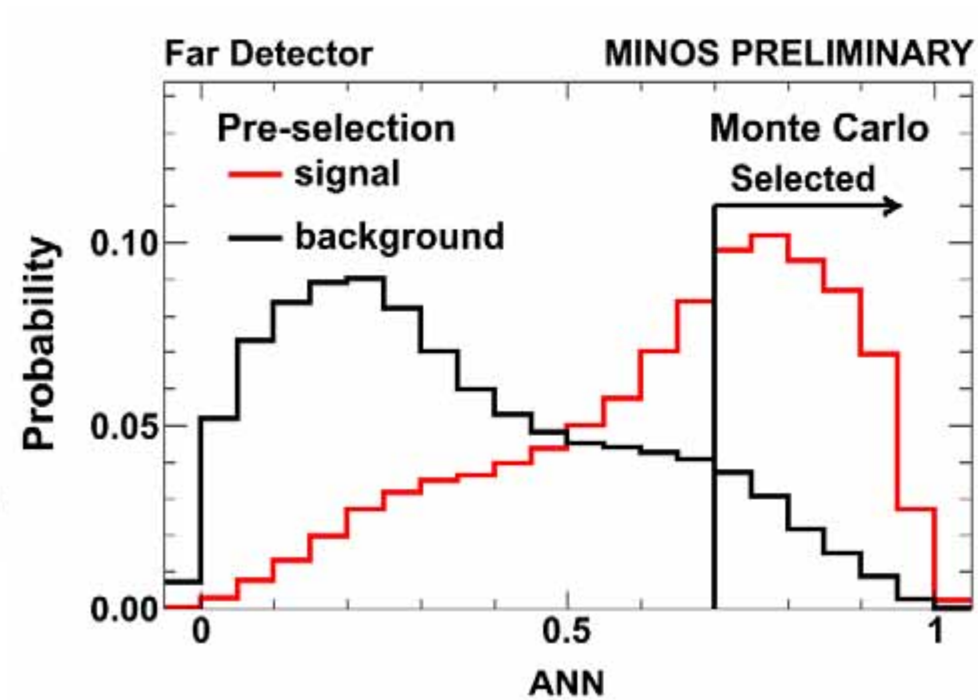
- Analogous to the quarks, neutrino mixing is parameterized with 3 angles and 1 complex phase
- With three active neutrinos there are two independent mass differences:
  - $\Delta m^2_{\text{sol}} \approx \Delta m^2_{21} \approx 8.0 \times 10^{-5}\ \text{eV}^2$
  - $\Delta m^2_{\text{atm}} \approx \Delta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

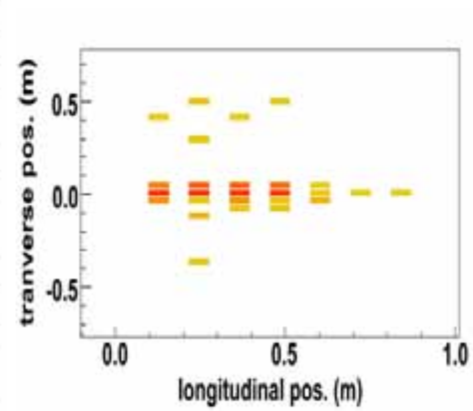


A MINOS Oscillation Analysis

1. Select a sample of events in the detectors
   – Which events you select defines the physics you probe







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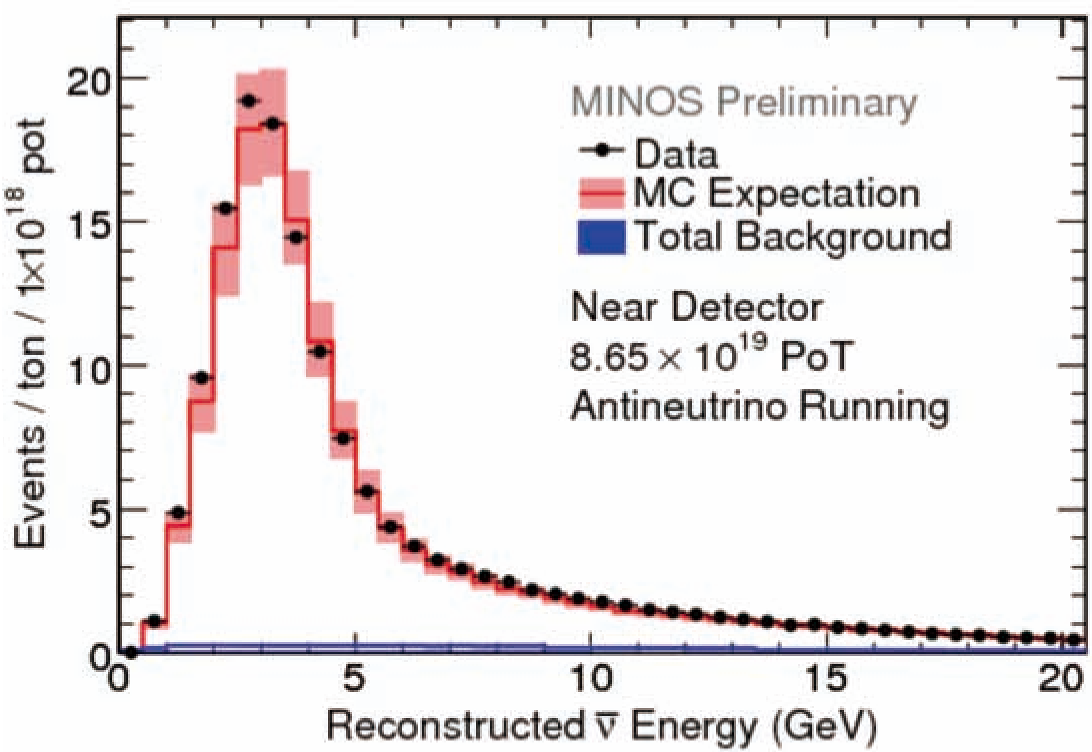
1. Select a sample of events in the detectors
2. Measure the energy of those events to construct Near and Far detector spectra



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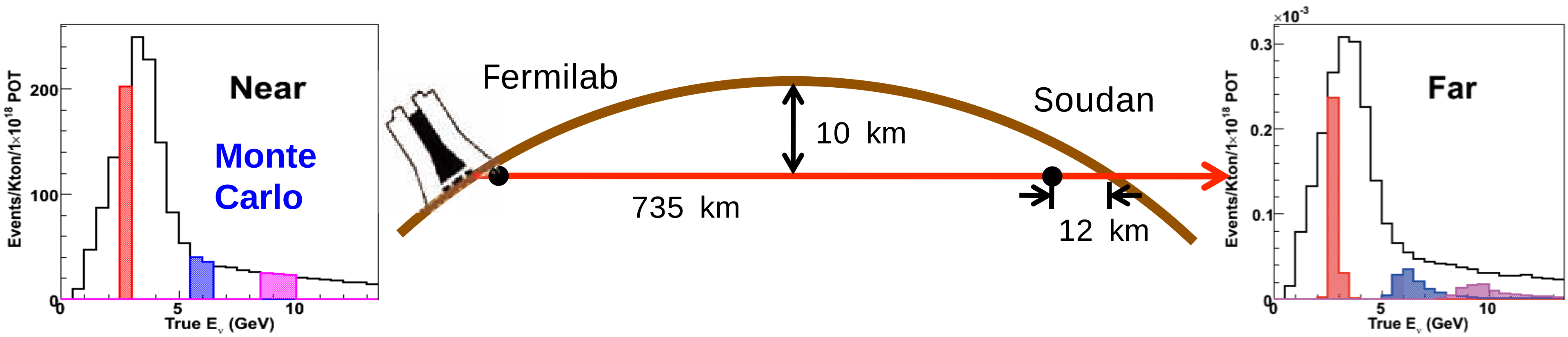

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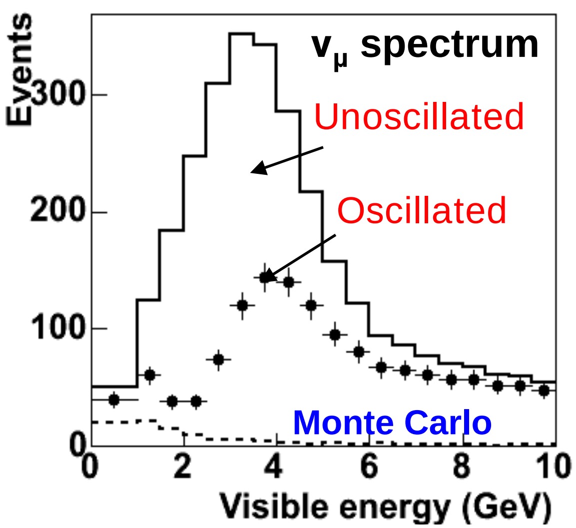

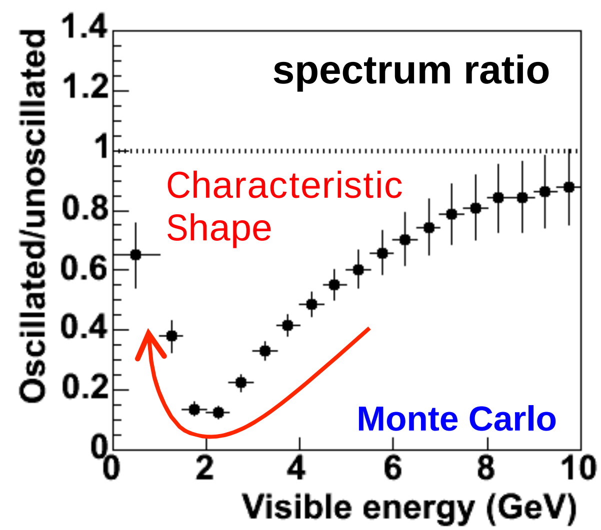

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2(2\theta_{23})\sin^2\left(1.27\Delta m^2_{atm}\frac{L}{E}\right)$$

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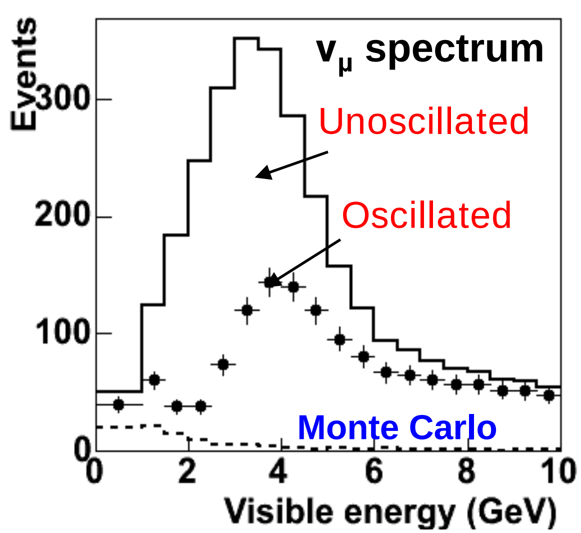

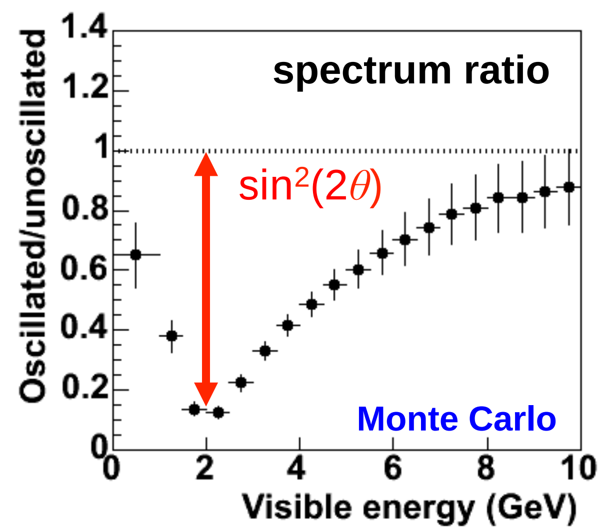

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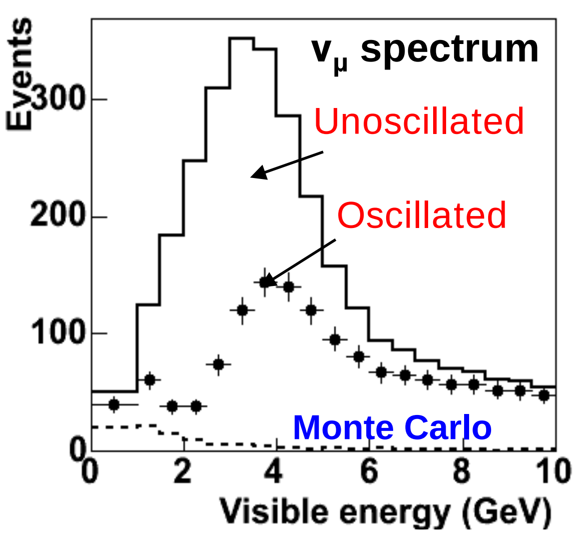
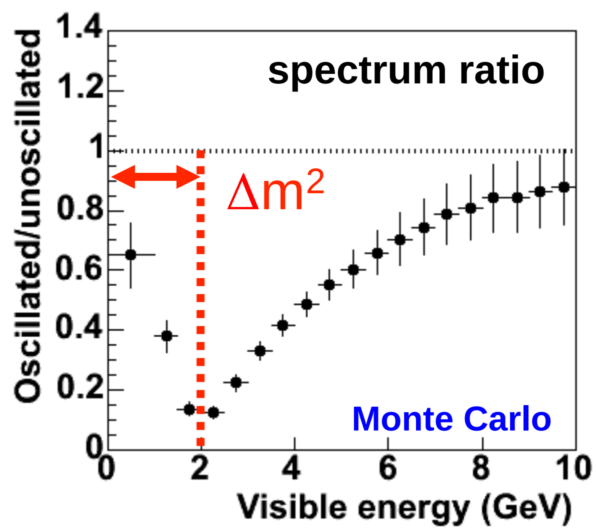
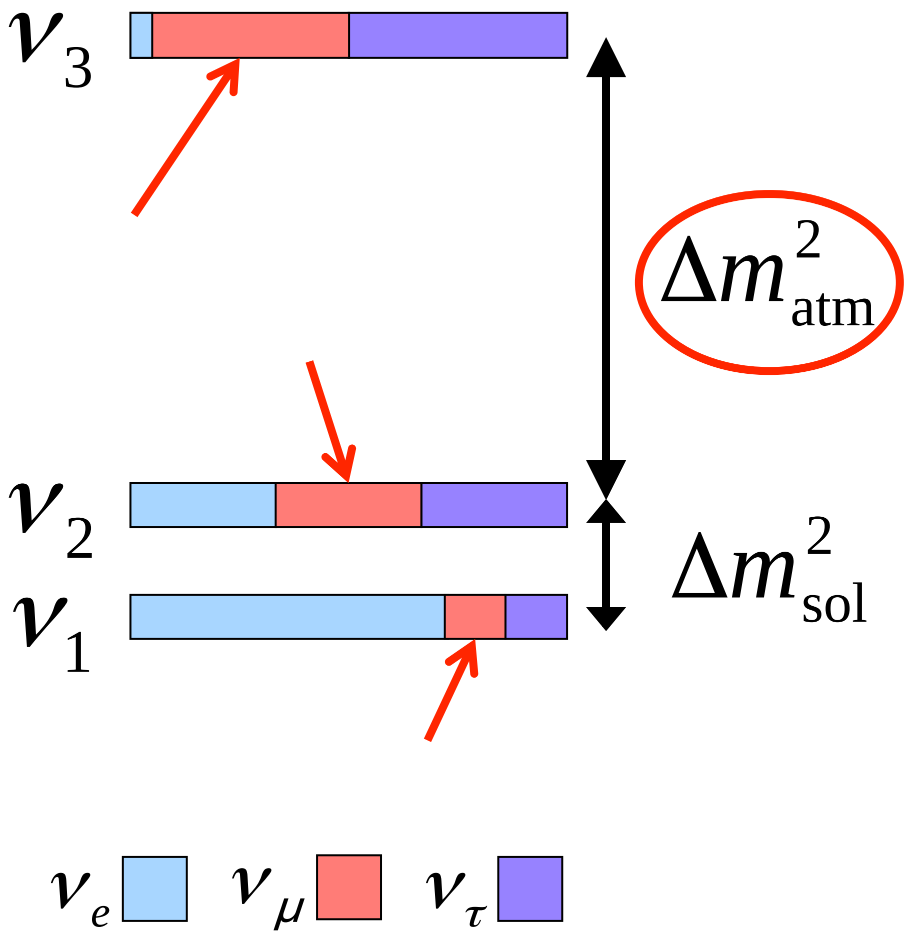




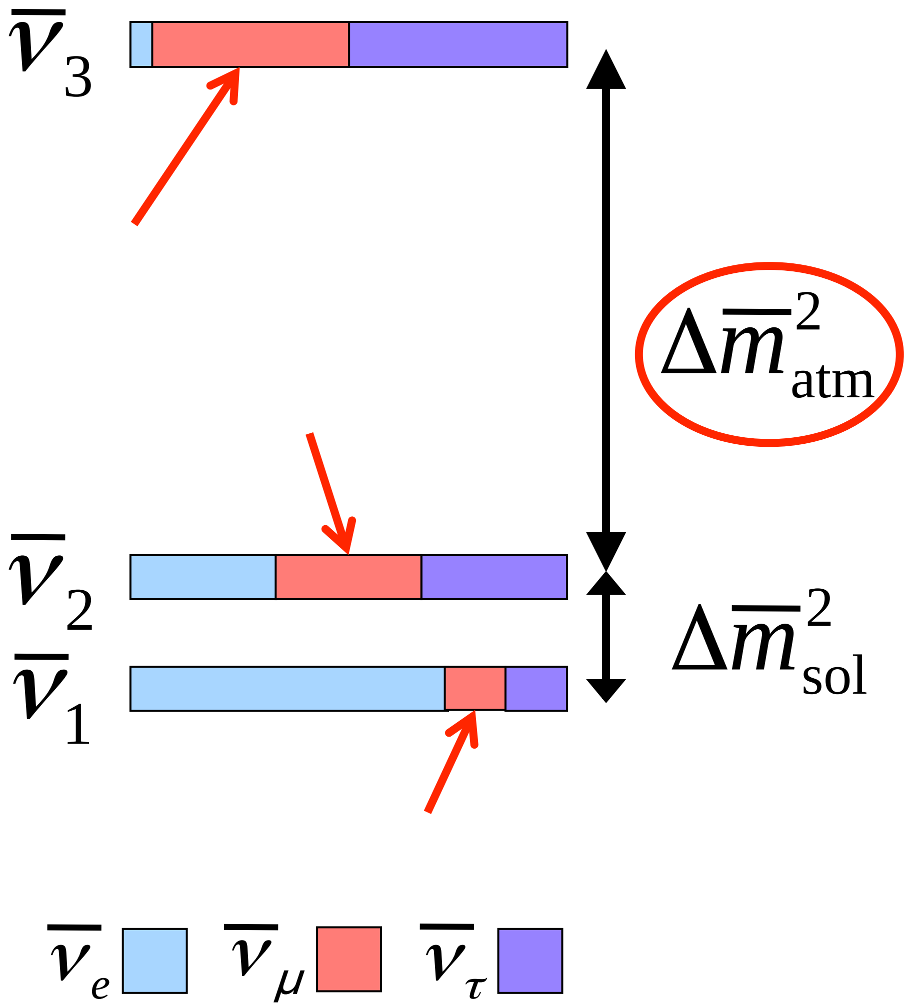
$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta_{23})\sin^2\left(1.27\Delta m^2_{atm}\frac{L}{E}\right)$$

MINOS Physics Goals



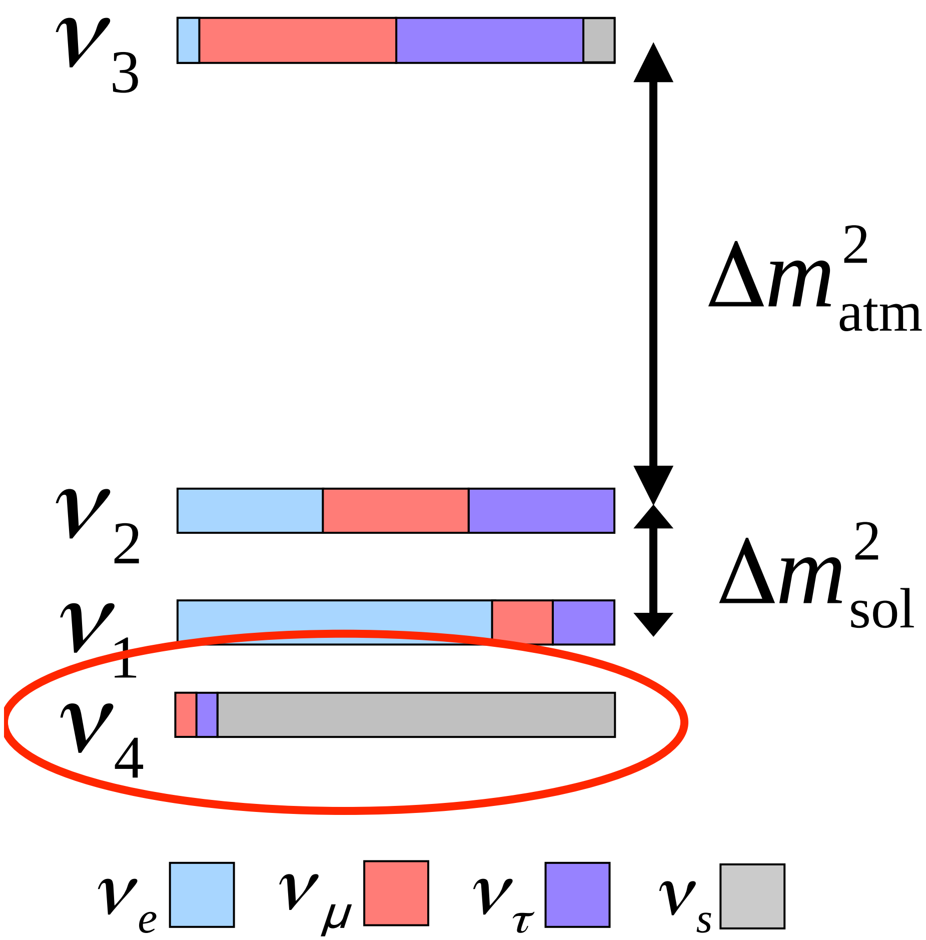
- Measure ν_μ disappearance
  - Use charged currents so we can know the flavor
  - Δm^2_{atm} and $\sin^2(2\theta_{23})$
  - Test oscillations against alternatives like decay and decoherence
- MINOS has the world's best sensitivity to the mass splitting

MINOS Physics Goals



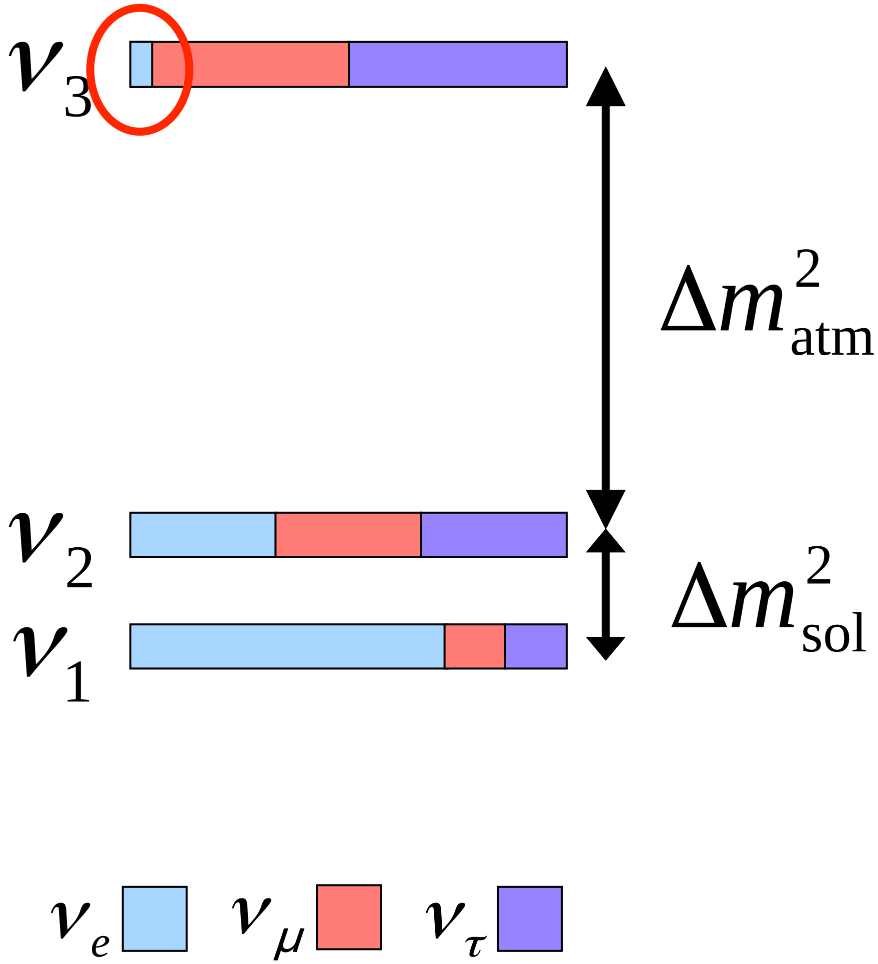
- Measure $\bar{\nu}_\mu$ disappearance
  - $\Delta\bar{m}^2_{atm}$ and $\sin^2(2\bar{\theta}_{23})$
- Compare with ν_μ's
- Differences from neutrinos may imply new physics in the neutrino sector

MINOS Physics Goals



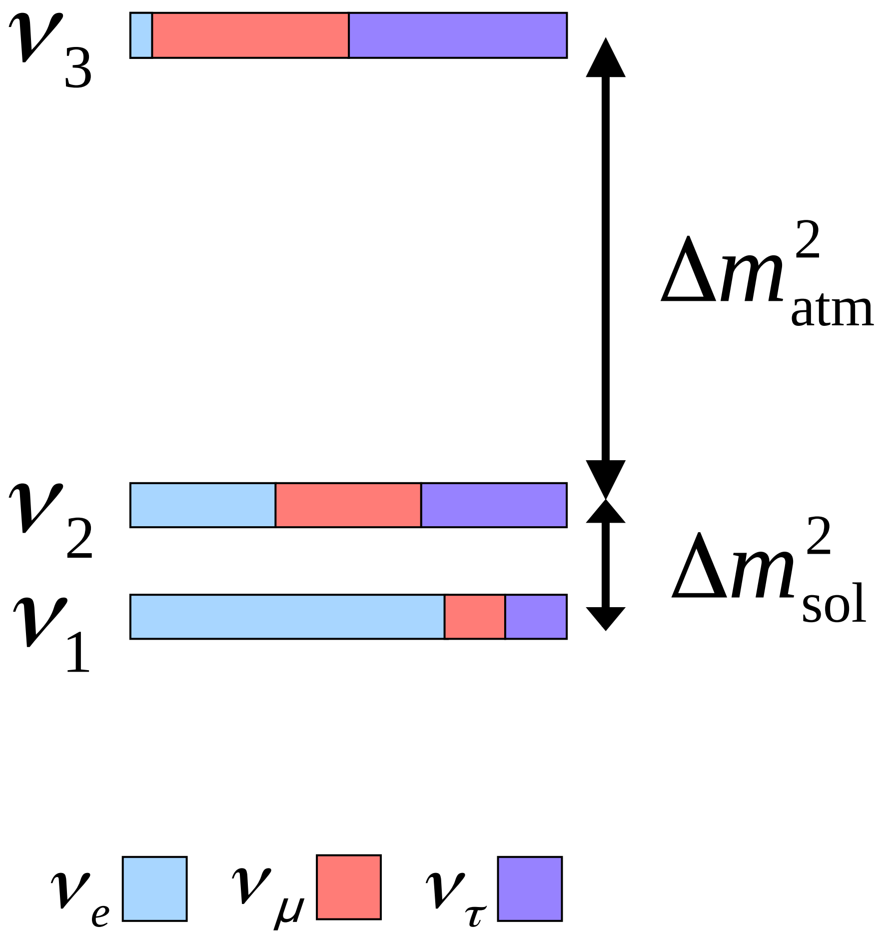
- Search for ν_x disappearance
  - Neutral currents measure the combined rate of active species
  - A deficit would imply mixing with a light sterile neutrino species

MINOS Physics Goals



- Search for ν_e appearance
  - Measure θ_{13}
- Measuring θ_{13} is the goal of the next generation of oscillation experiments
  - Measuring θ_{13} is a prerequisite for measuring CP-violation and the sign of Δm^2_{atm}

MINOS Physics Goals



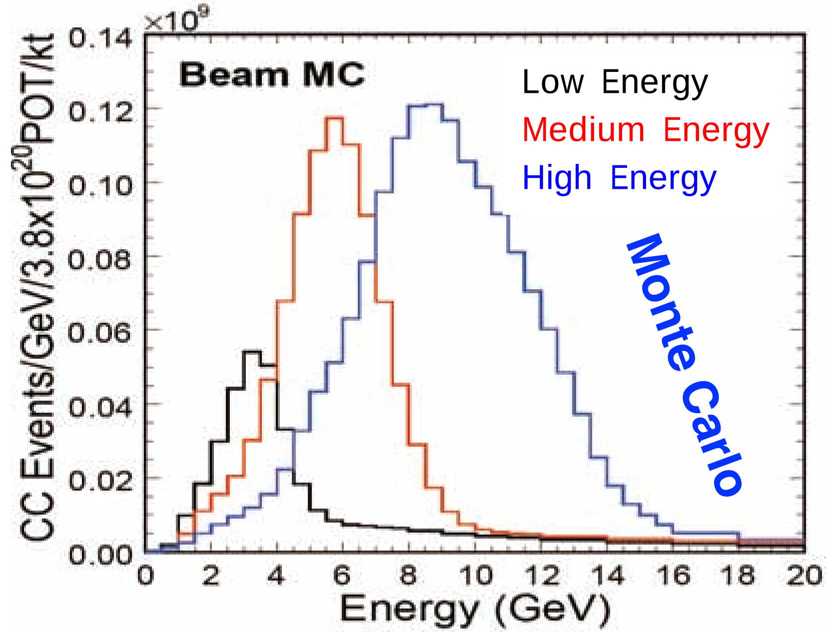
- More physics I won't have time to discuss:
  - Atmospheric neutrinos
  - Neutrino cross-sections
  - Lorentz invariance
  - Cosmic ray physics

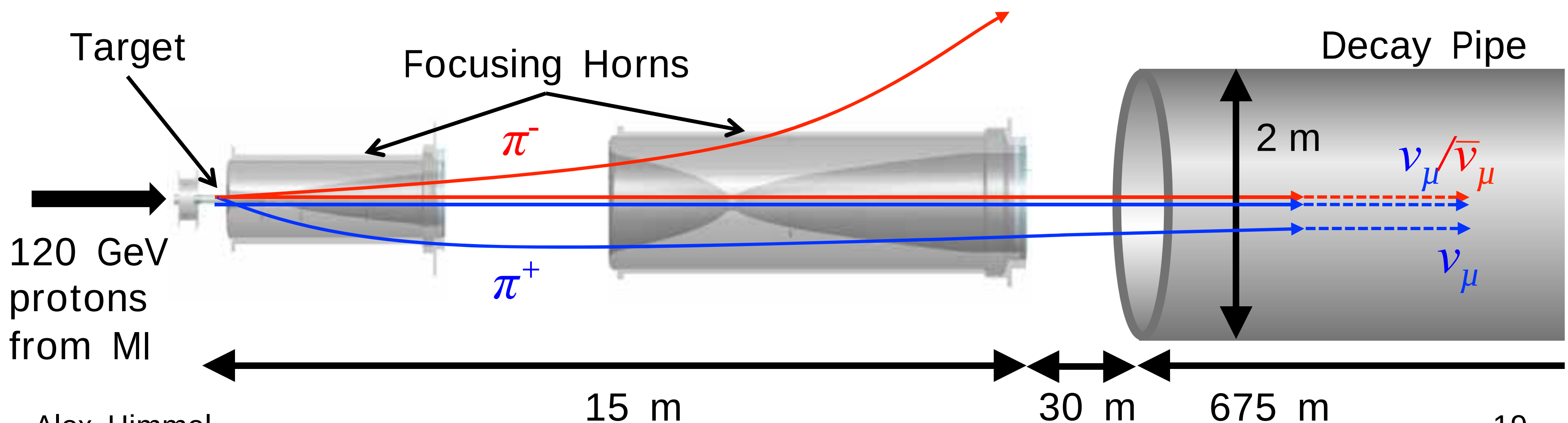
The Experiment

- NuMI neutrino beam
- MINOS detectors

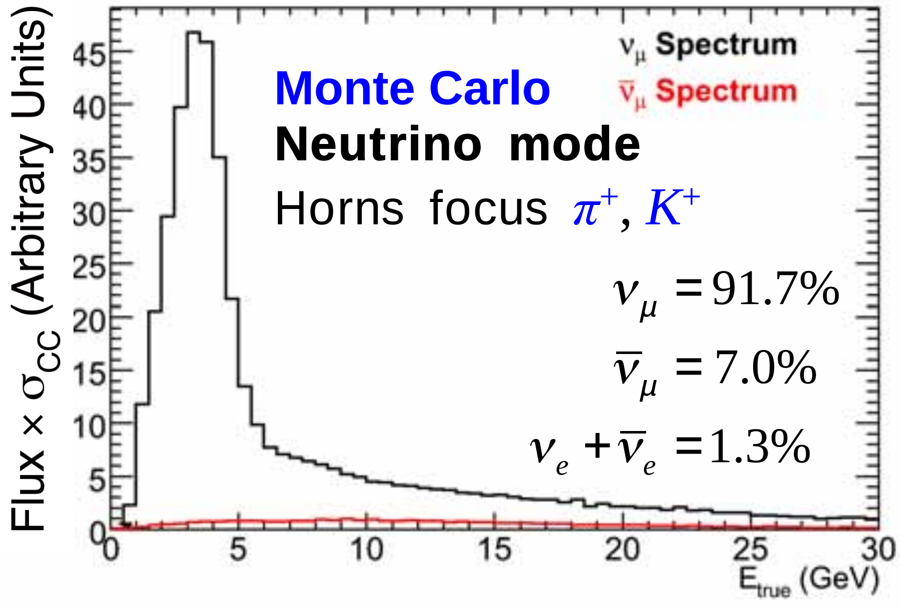
The NuMI Beam

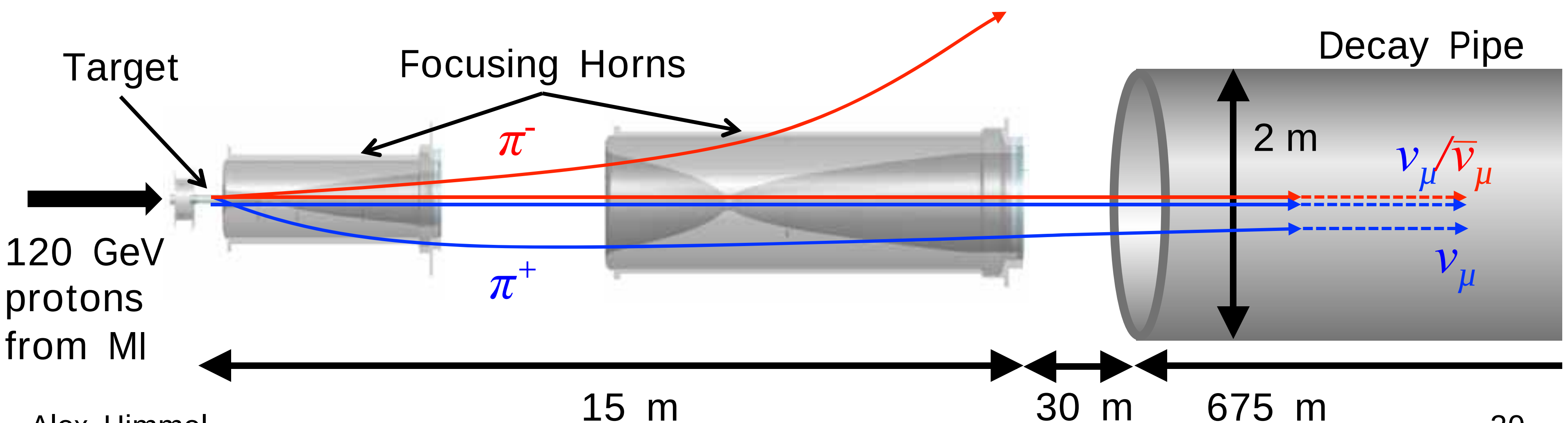
- 120 GeV protons incident on a thick, segmented graphite target
- Magnetic horns can focus either sign
- Enhance the ν_μ flux by focusing π^+, K^+
- Adjustable peak energy



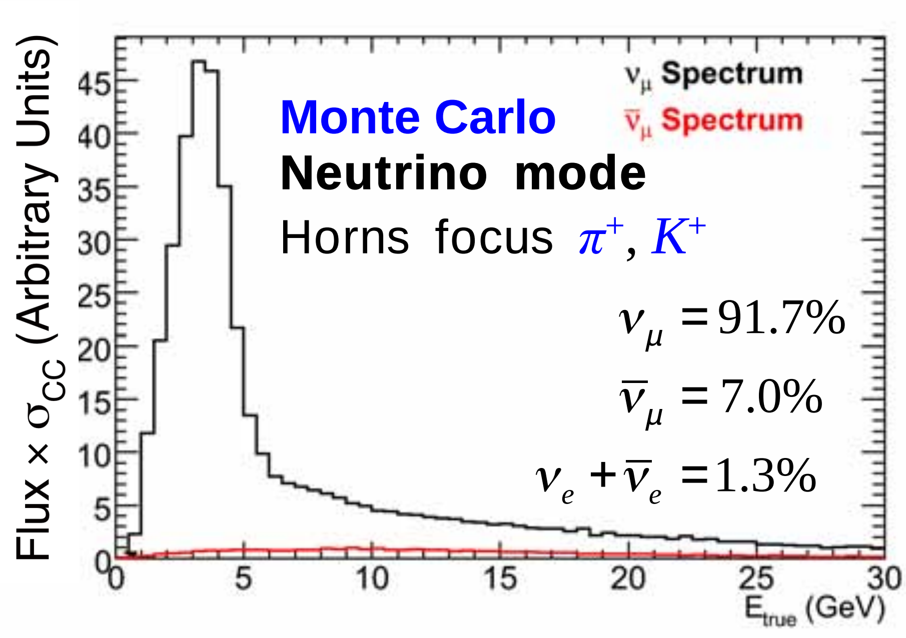


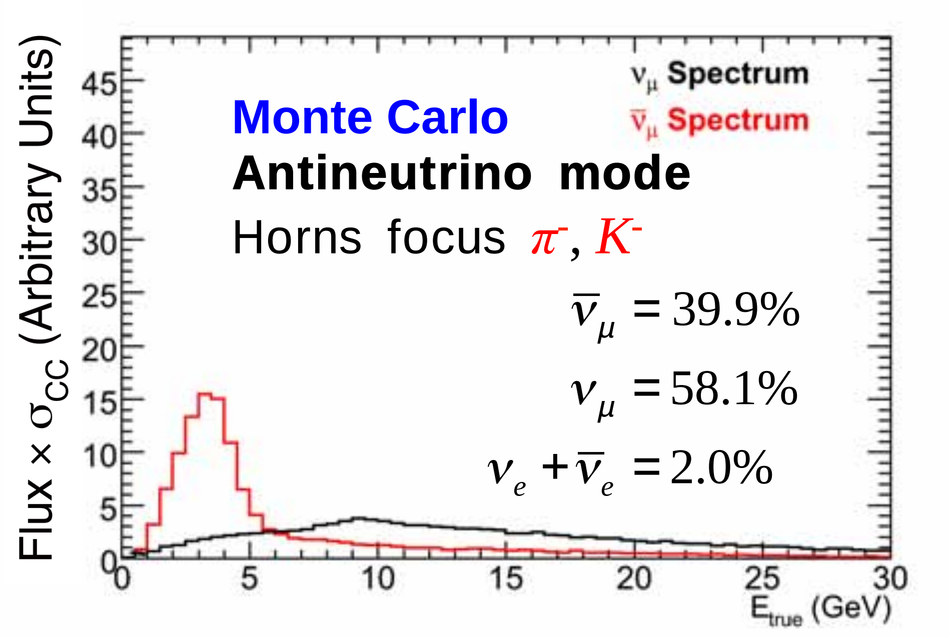
Neutrino Mode

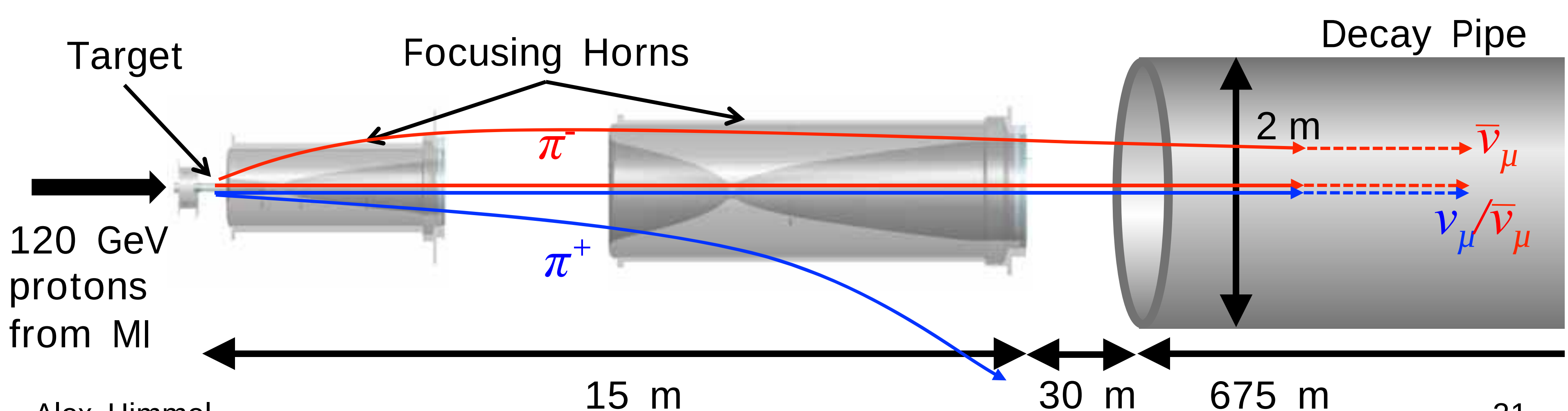




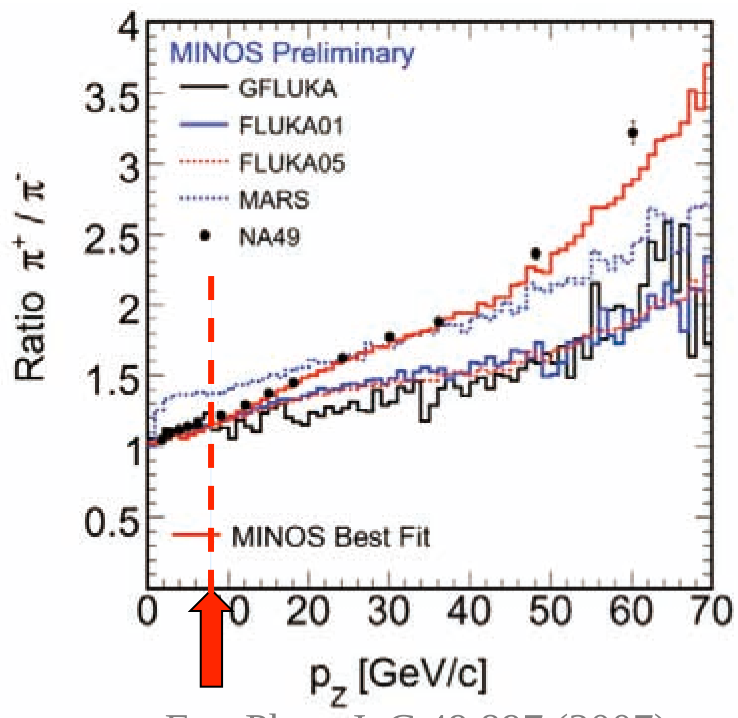
Antineutrino Mode



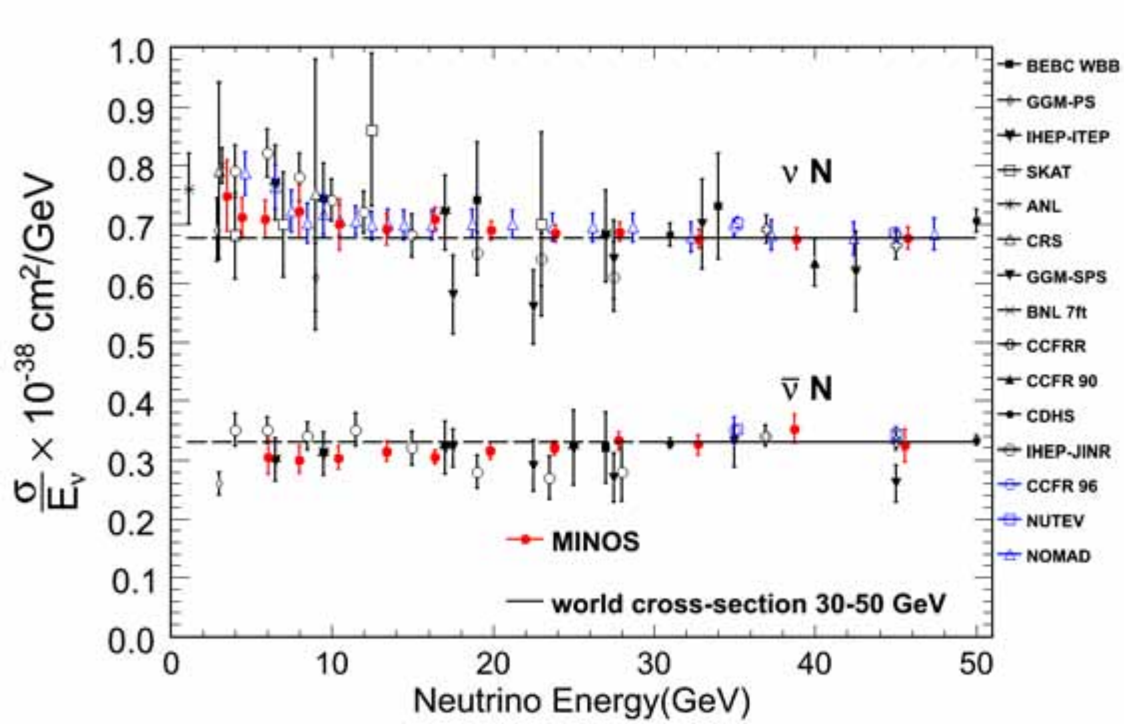




Antineutrino Cross-section



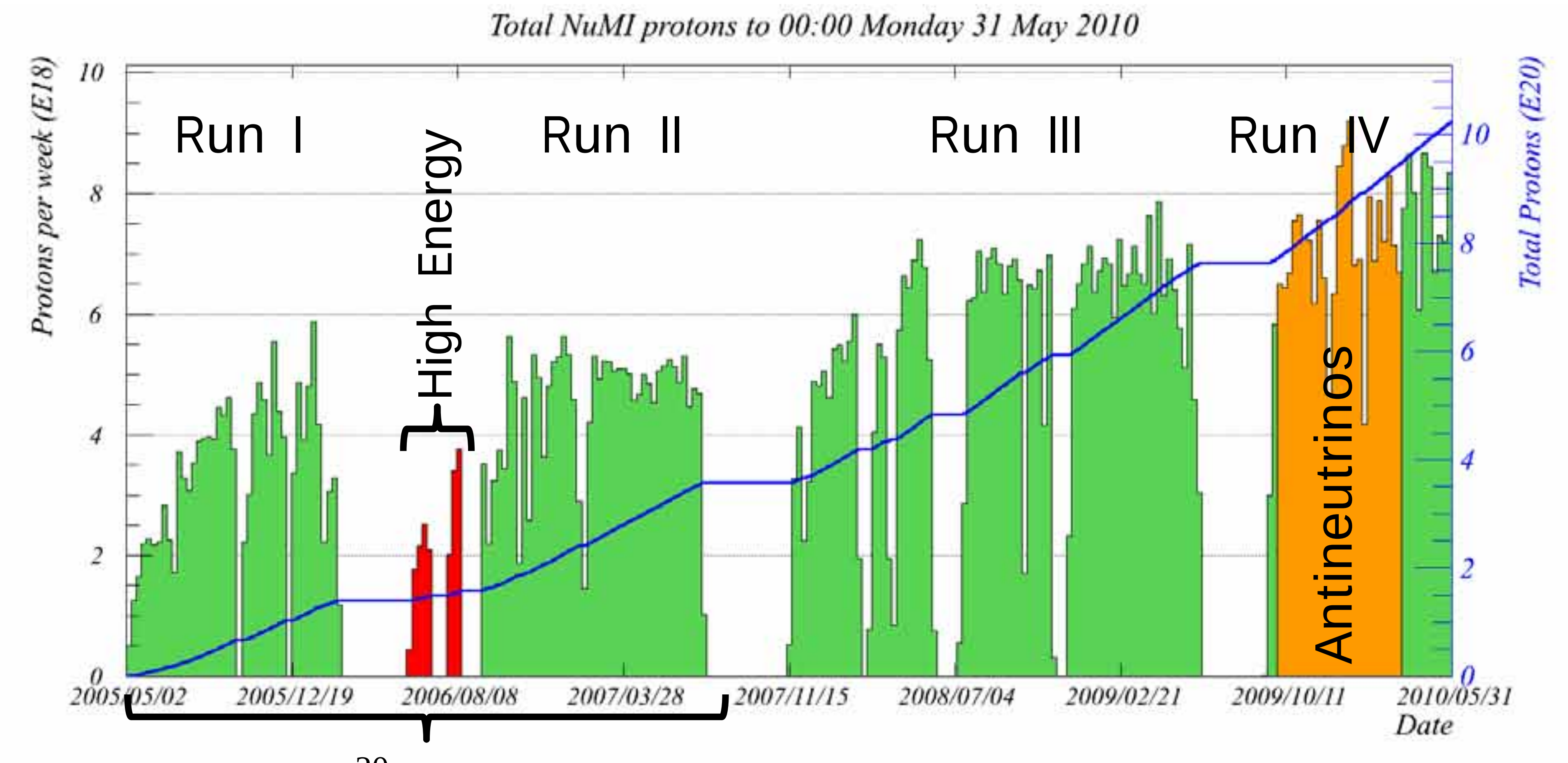
Eur. Phys. J. C 49 897 (2007)



Phys. Rev. D 81 072002 (2010)

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

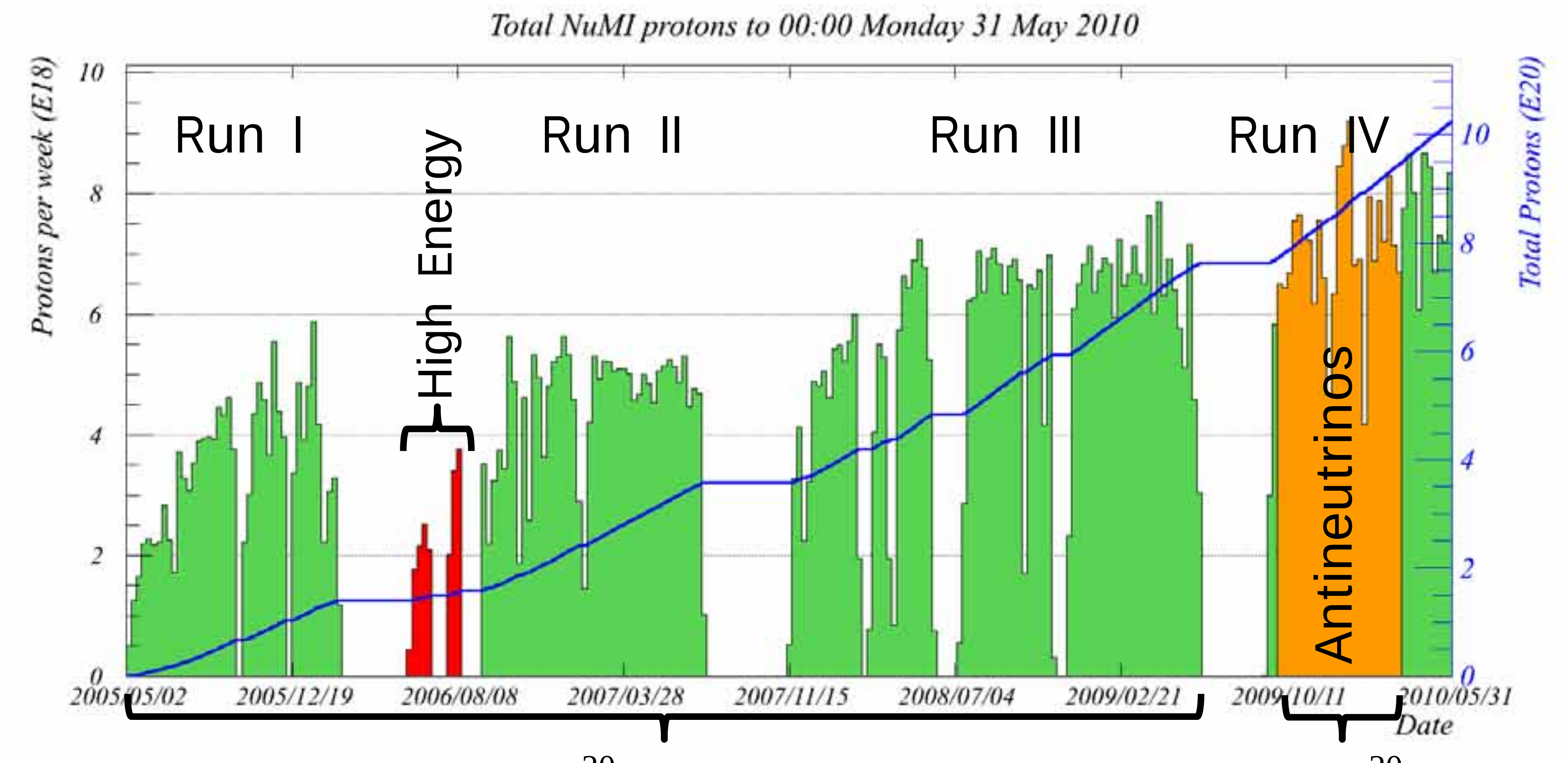
NuMI Beam Performance



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

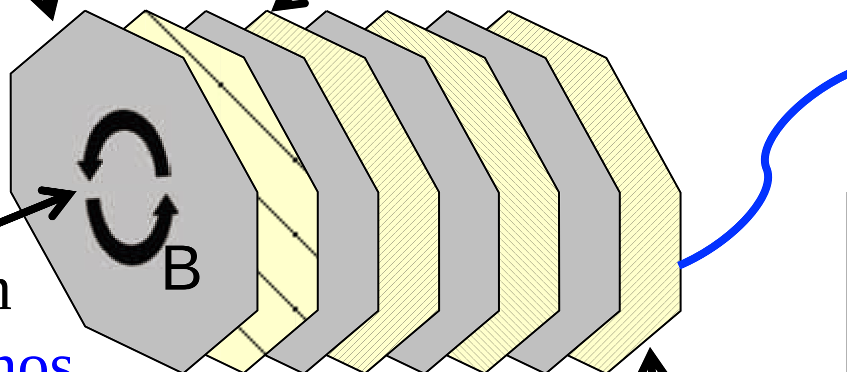
$\bar{\nu}_\mu$ mode

MINOS Detectors

1 in thick Steel

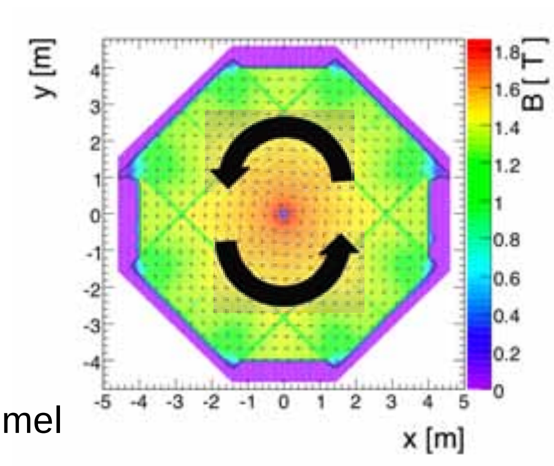
1 cm thick, 4.1 cm wide
Plastic Scintillator

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



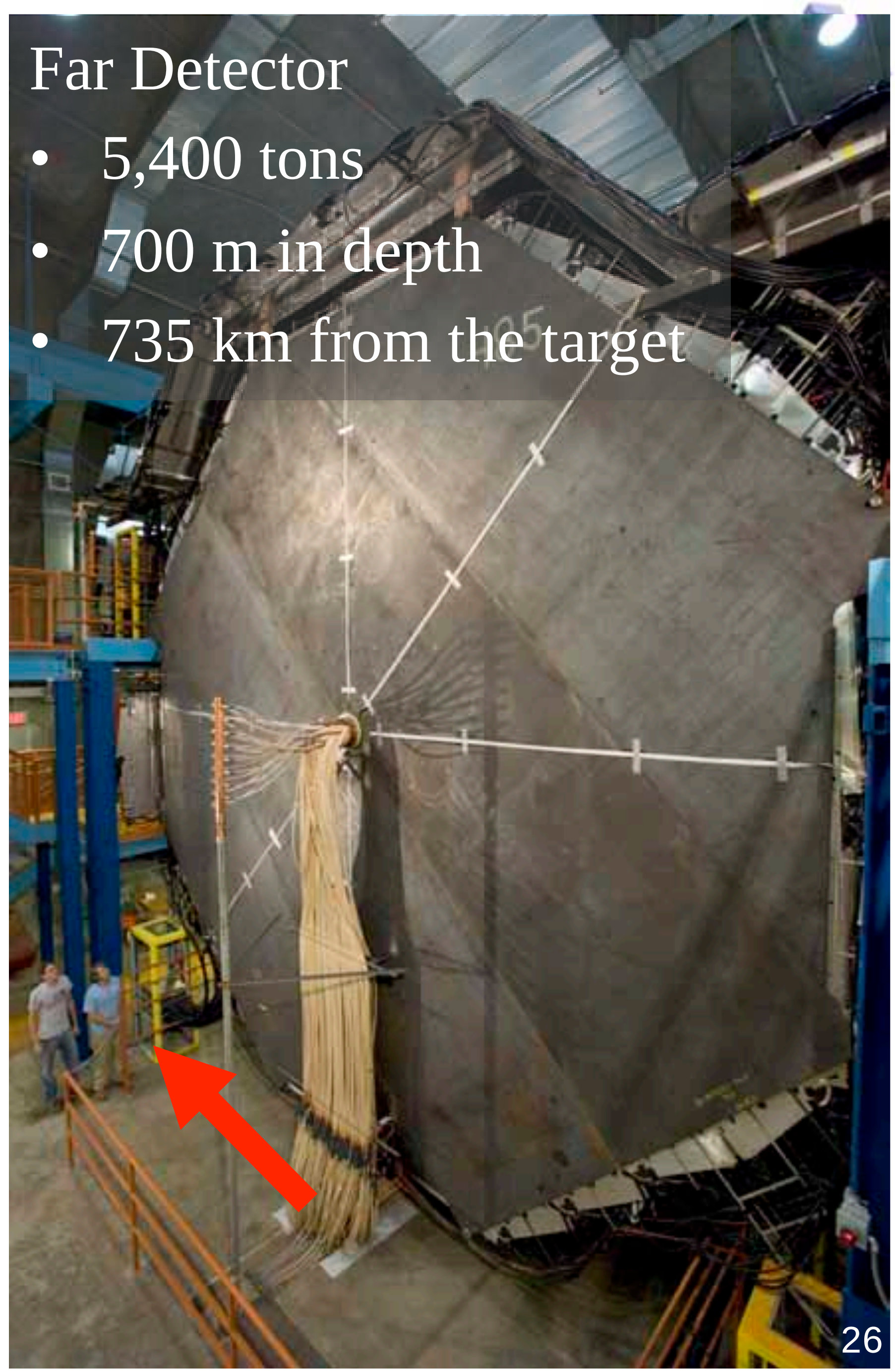
MINOS Detectors

Near Detector

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

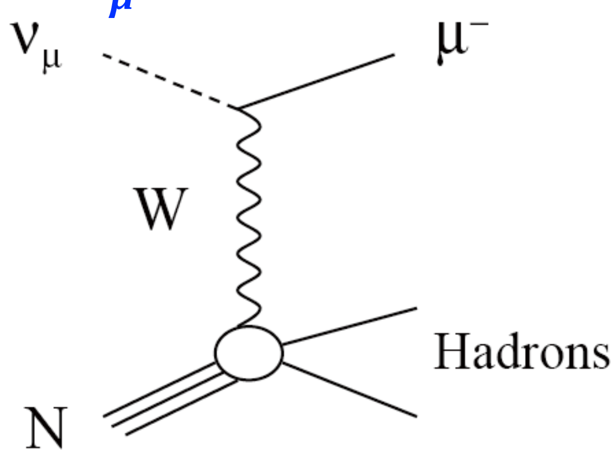
Far Detector

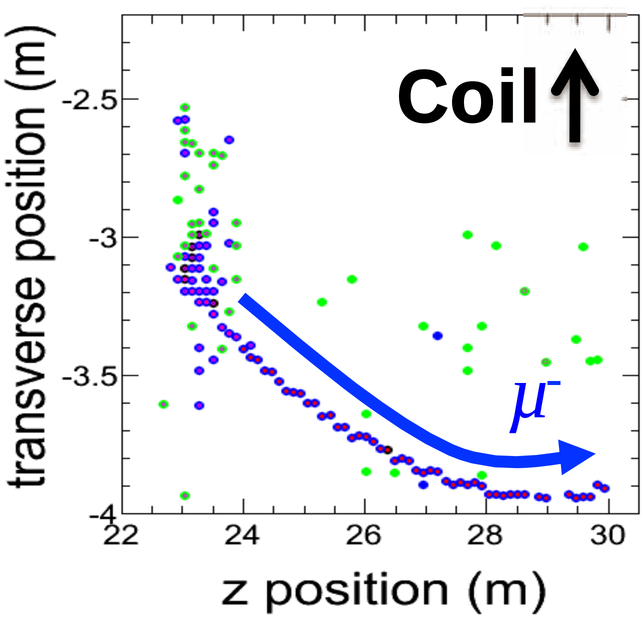
- 5,400 tons
- 700 m in depth
- 735 km from the target



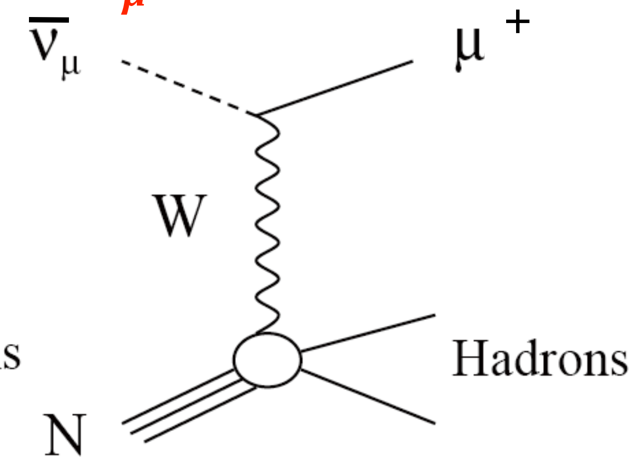
MINOS Events

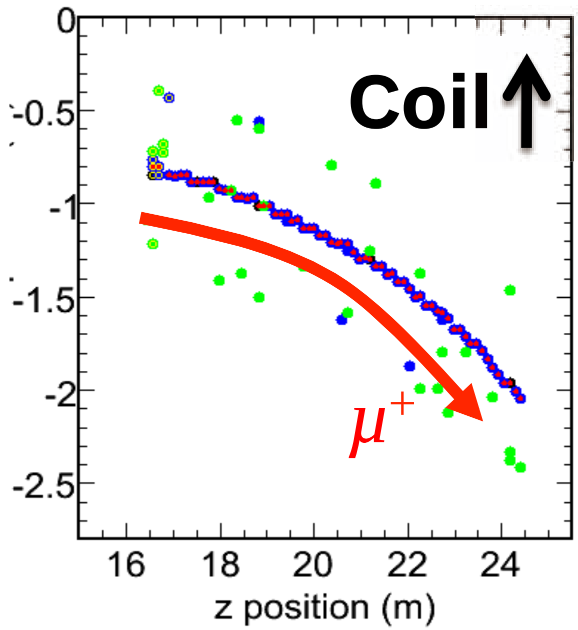
ν_μ CC Event



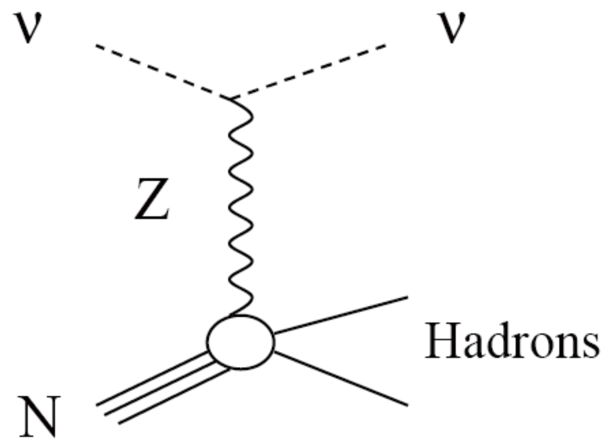


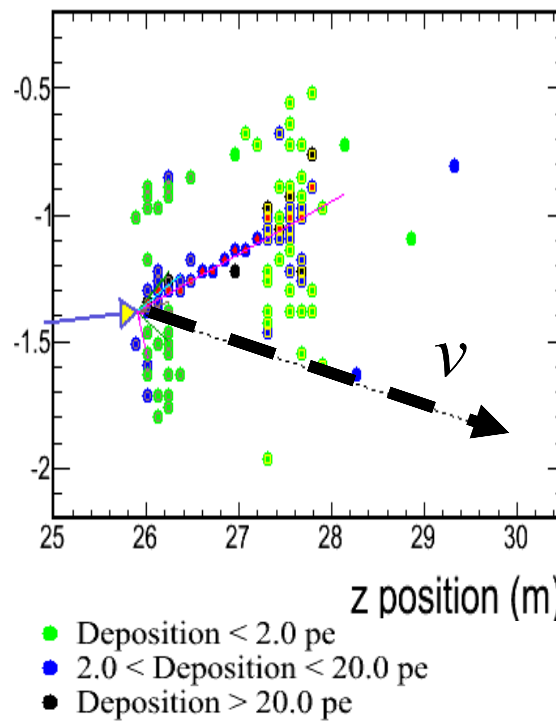
$\bar{\nu}_\mu$ CC Event





NC Event





Simulated Events

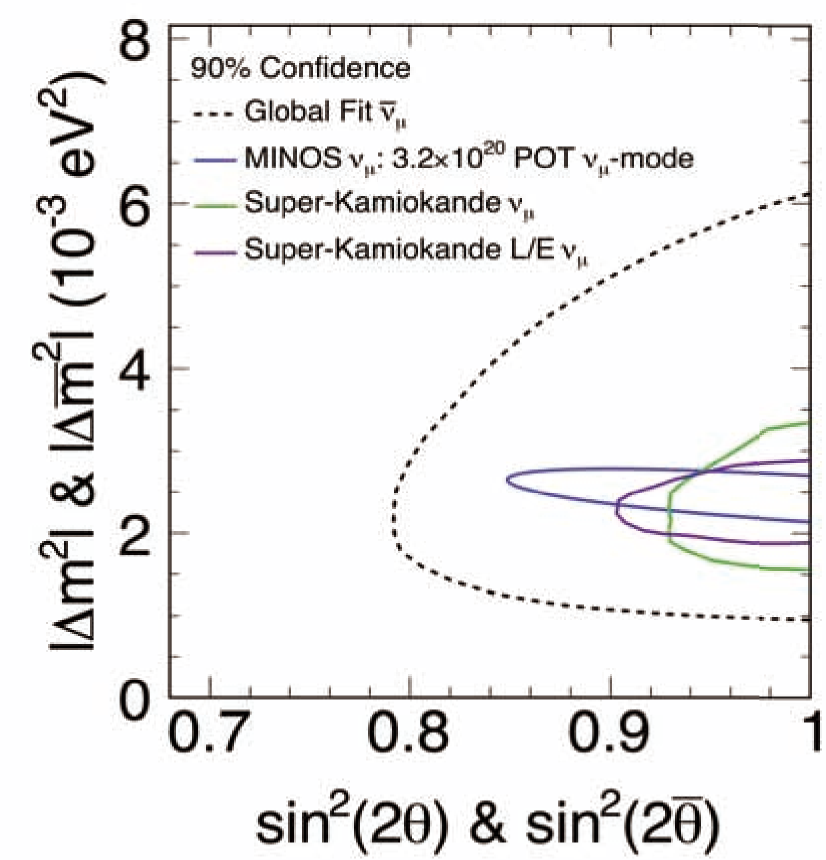
Muon Antineutrinos

Measure Δm^2_{atm}, $\sin^2(2\theta_{23})$

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



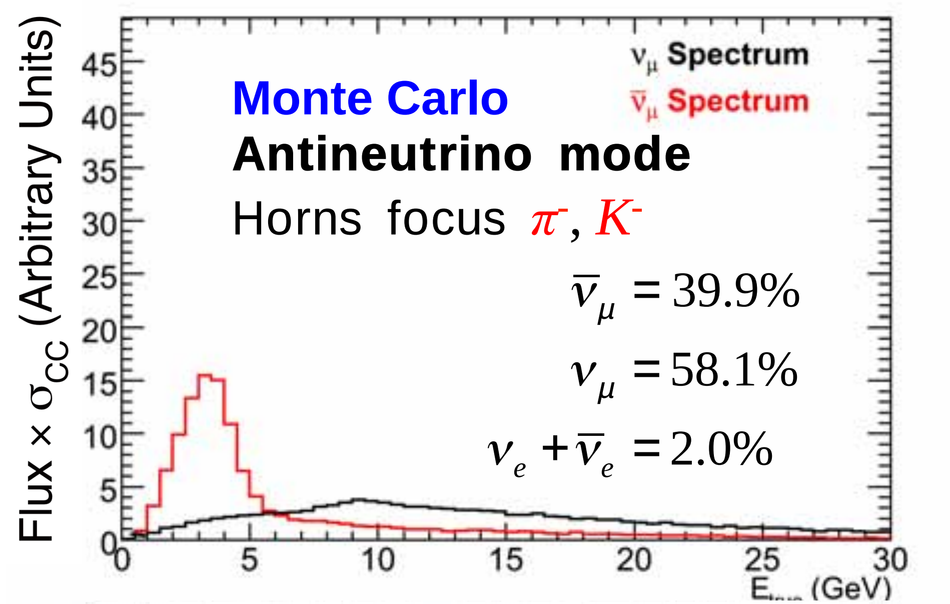
- Differences may imply new physics in the neutrino sector manifested as a difference in the effective mass-splitting.

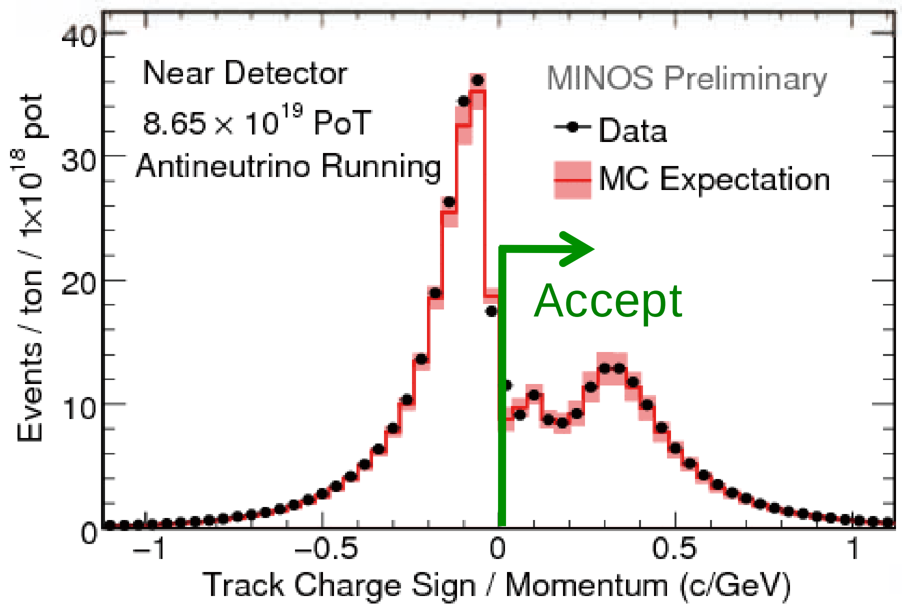
P. Adamson, et. al, Phys. Rev. Lett. 101:131802 (2008)
Y. Ashie, et. al., Phys. Rev. D 71:112005 (2005)
Y. Ashie, et. al., Phys. Rev. D 71:112005 (2005)
M.C. Gonzalez-Garcia & M. Maltoni, Phys. Rept. 460:1-129 (2008)

Selecting CC Antineutrinos

Step 1

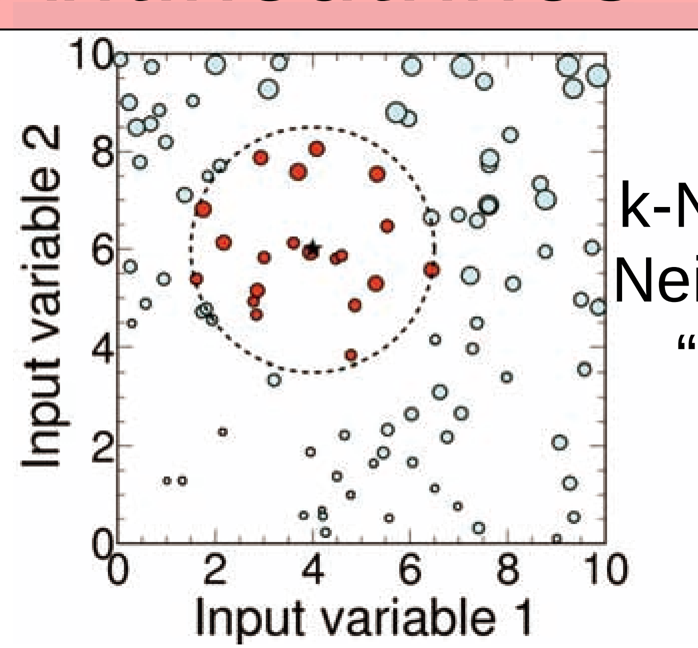
- Preselection
  - In-time with the spill
  - In the fiducial volume
  - At least 1 reconstructed track
- Accept only positive reconstructed charge
  - Kalman filter measures q/p (~curvature) for each track
  - Eliminates the majority of the ν_μ component of the beam





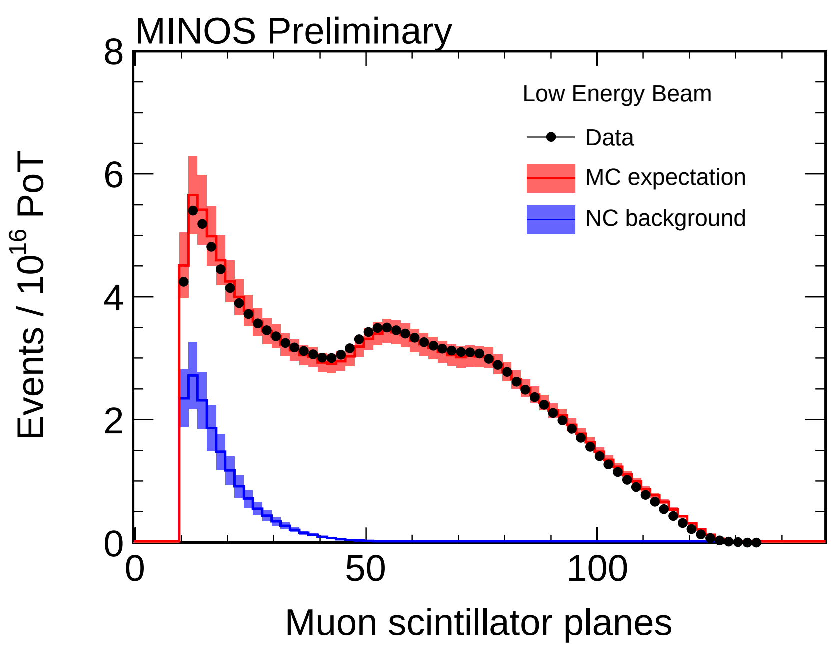
Selecting CC Antineutrinos

- CC/NC separation
  - kNN algorithm
    - Compare to Monte Carlo events



k-Nearest Neighbors "kNN"

- 4-parameter comparison
  - Track length
  - Energy deposited per strip
  - Energy fluctuations along the track
  - Transverse energy profile



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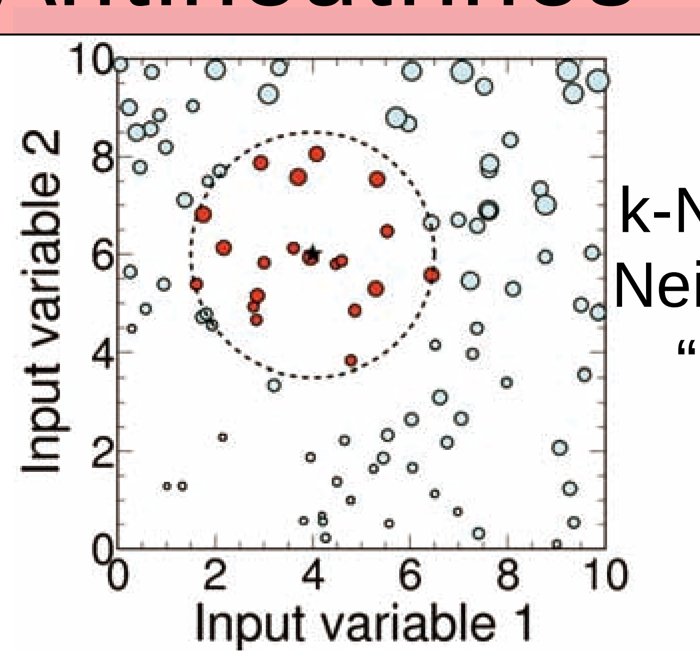

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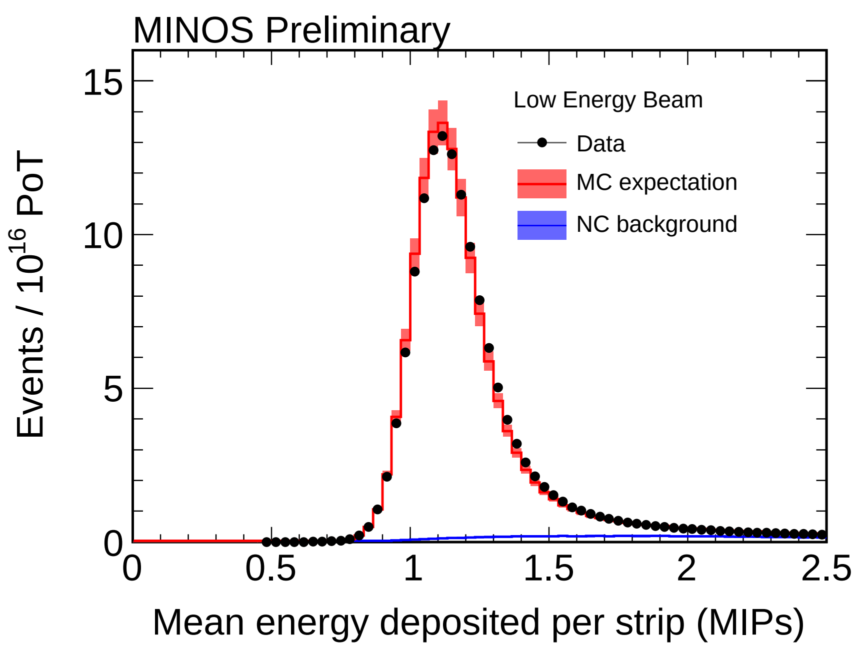

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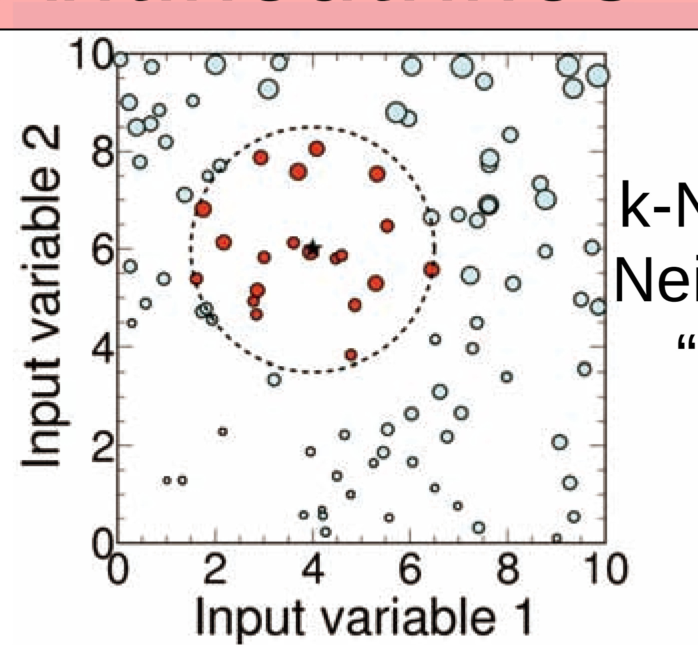

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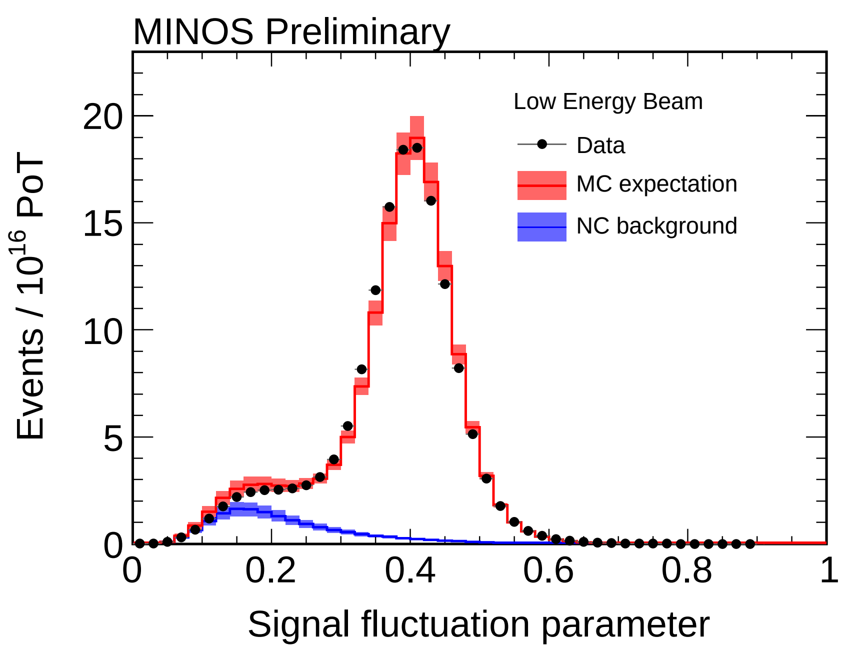

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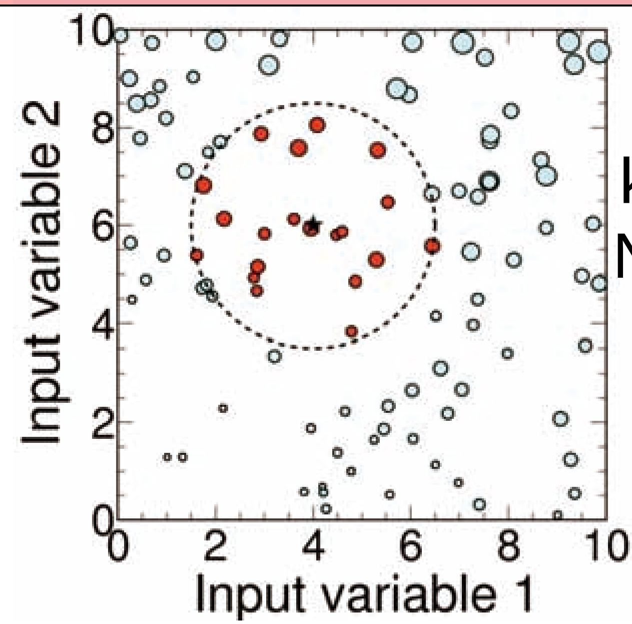

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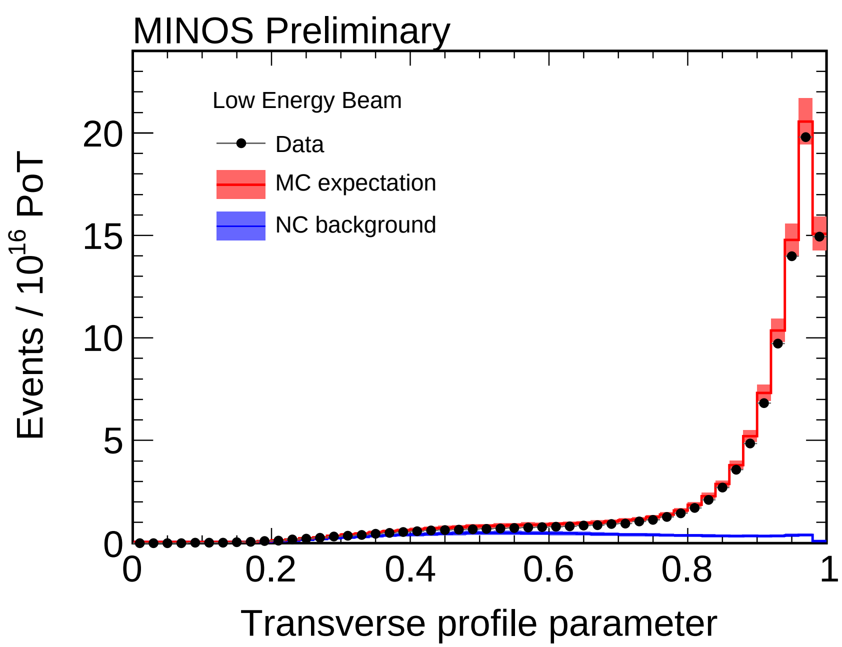
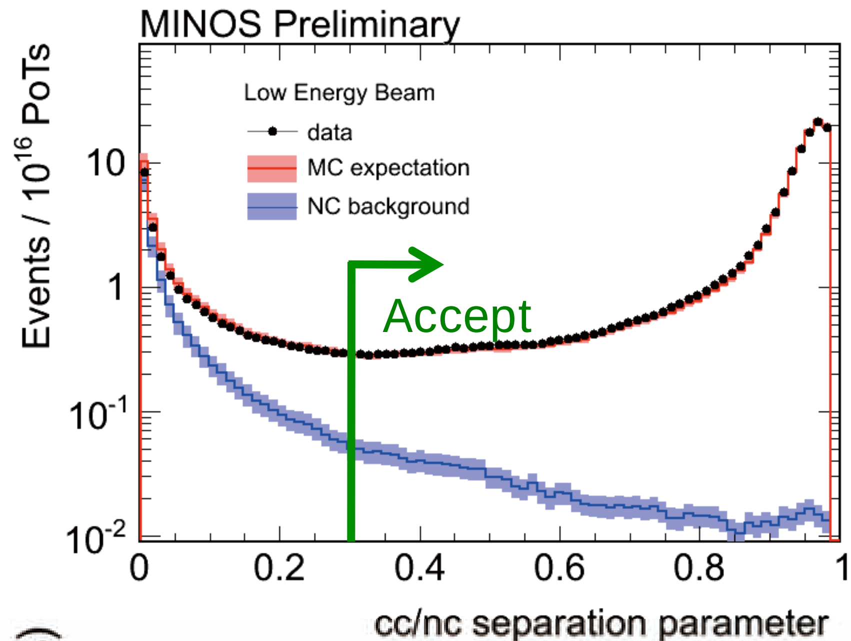
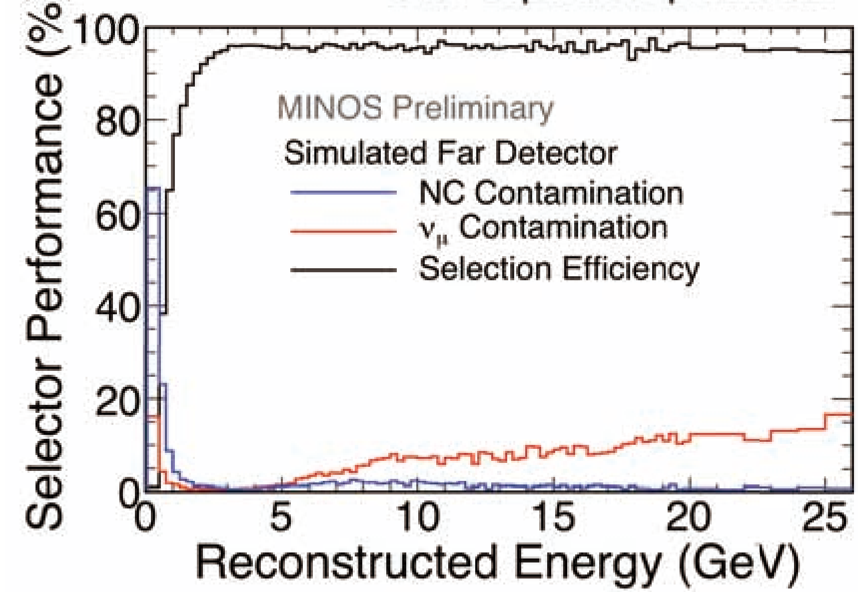


Selecting CC Antineutrinos

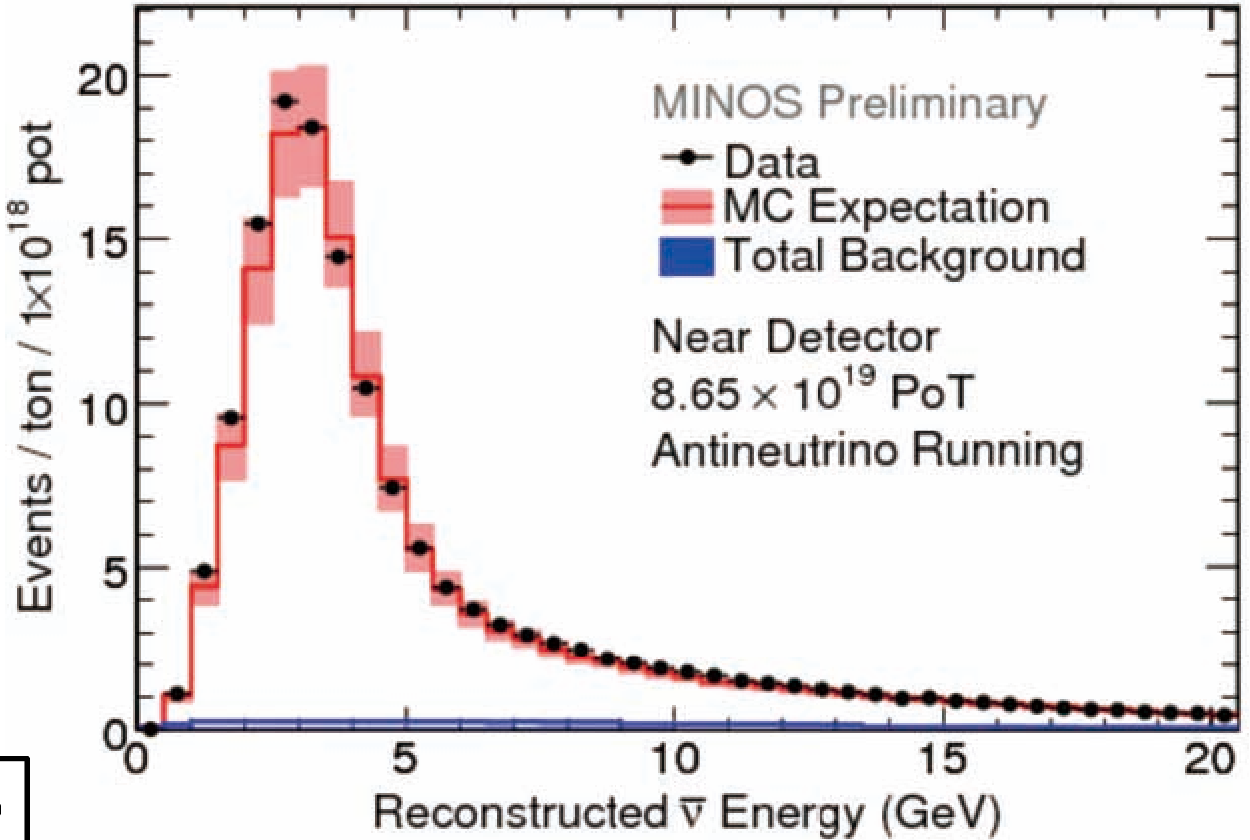
- Cut applied to the output of the kNN algorithm
  - Output is the fraction of *k* neighbors that are signal
- Started below 50% signal
- After selection:
  - Purity: 95%
  - Efficiency: 93%

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





Antineutrino Near Detector Data

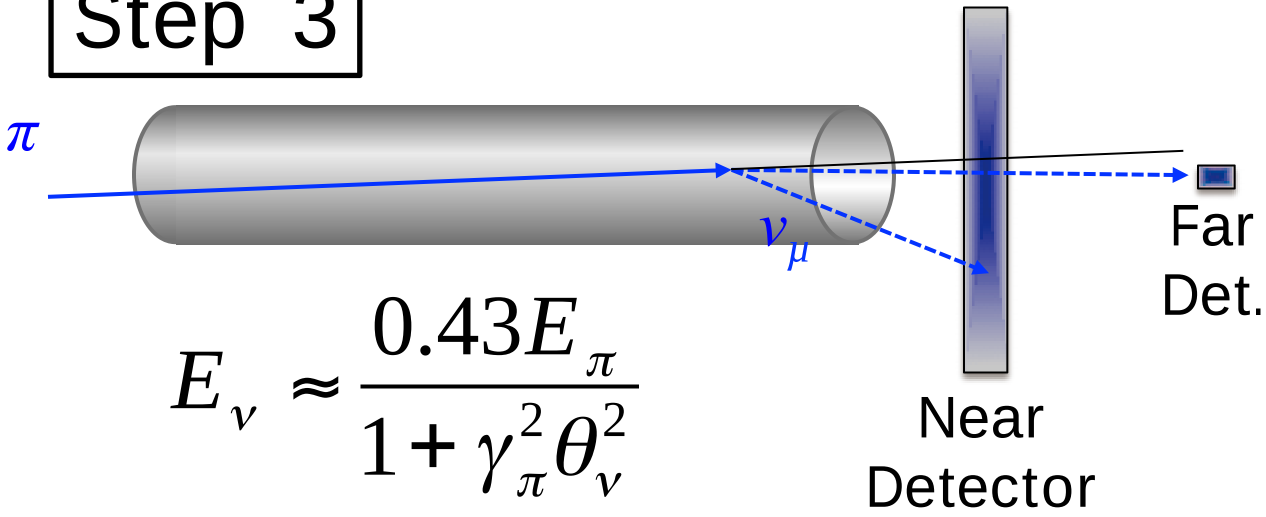


Step 2

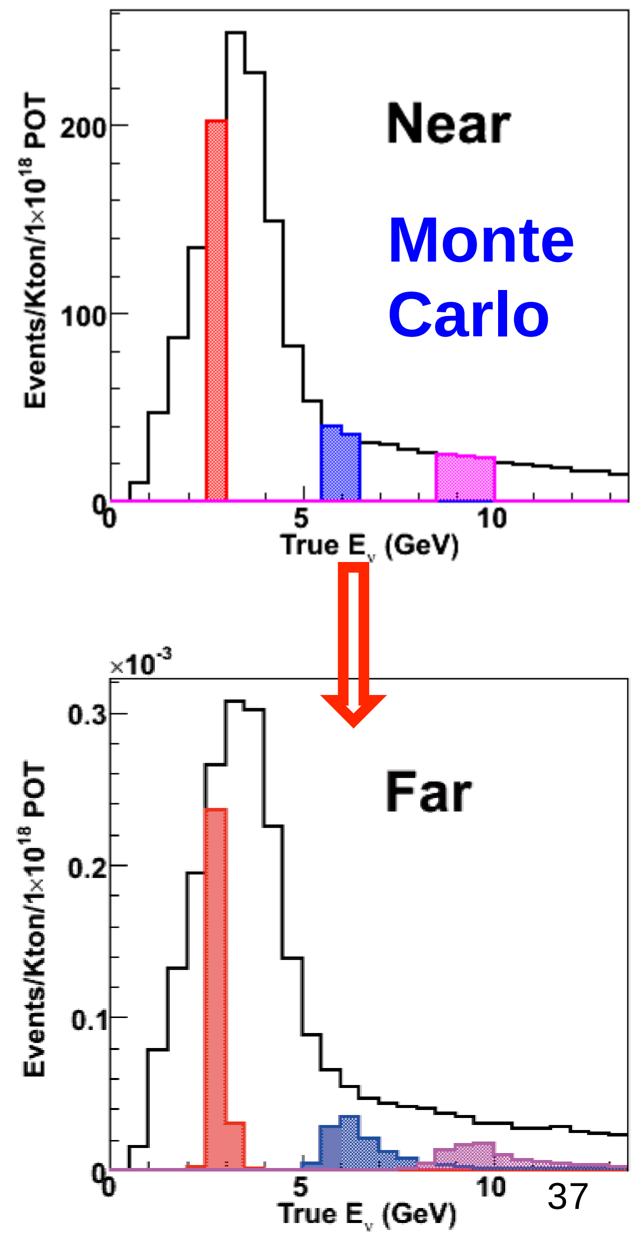
Flux and cross-section uncertainties
cancel when extrapolated
from Near to Far detector.

Near-to-Far Extrapolation

Step 3

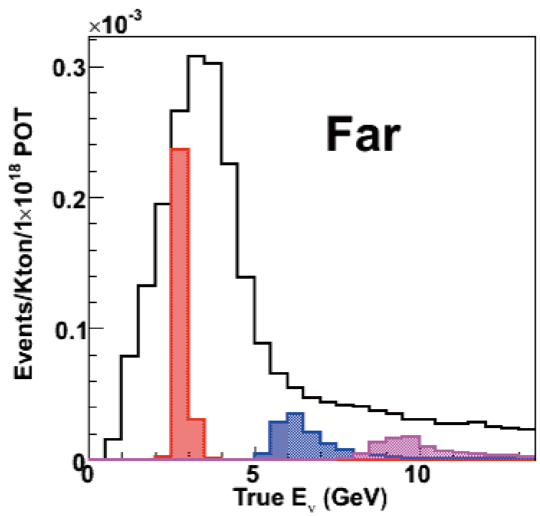


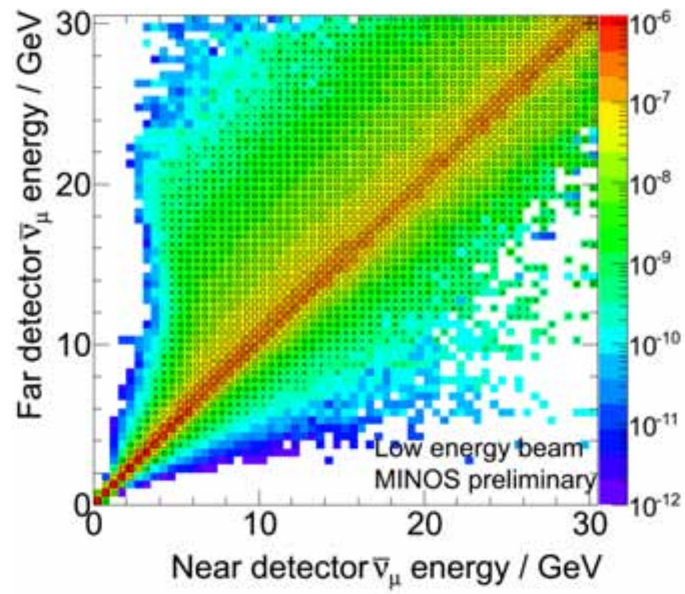
$$E_\nu \approx \frac{0.43 E_\pi}{1 + \gamma_\pi^2 \theta_\nu^2}$$

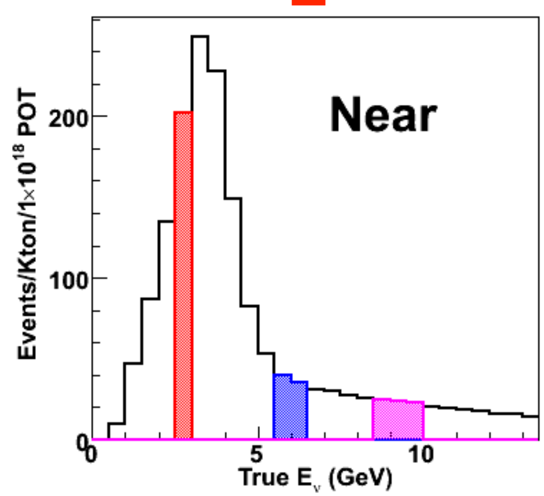


- The Near Detector and Far Detector spectra are not identical.
  - Due to π/K decay kinematics, neutrino energy varies with angle.
  - Near Detector covers a wider solid angle
  - Effect is larger with higher energy π
    - Travel further and decay closer to the ND

Beam Matrix Extrapolation





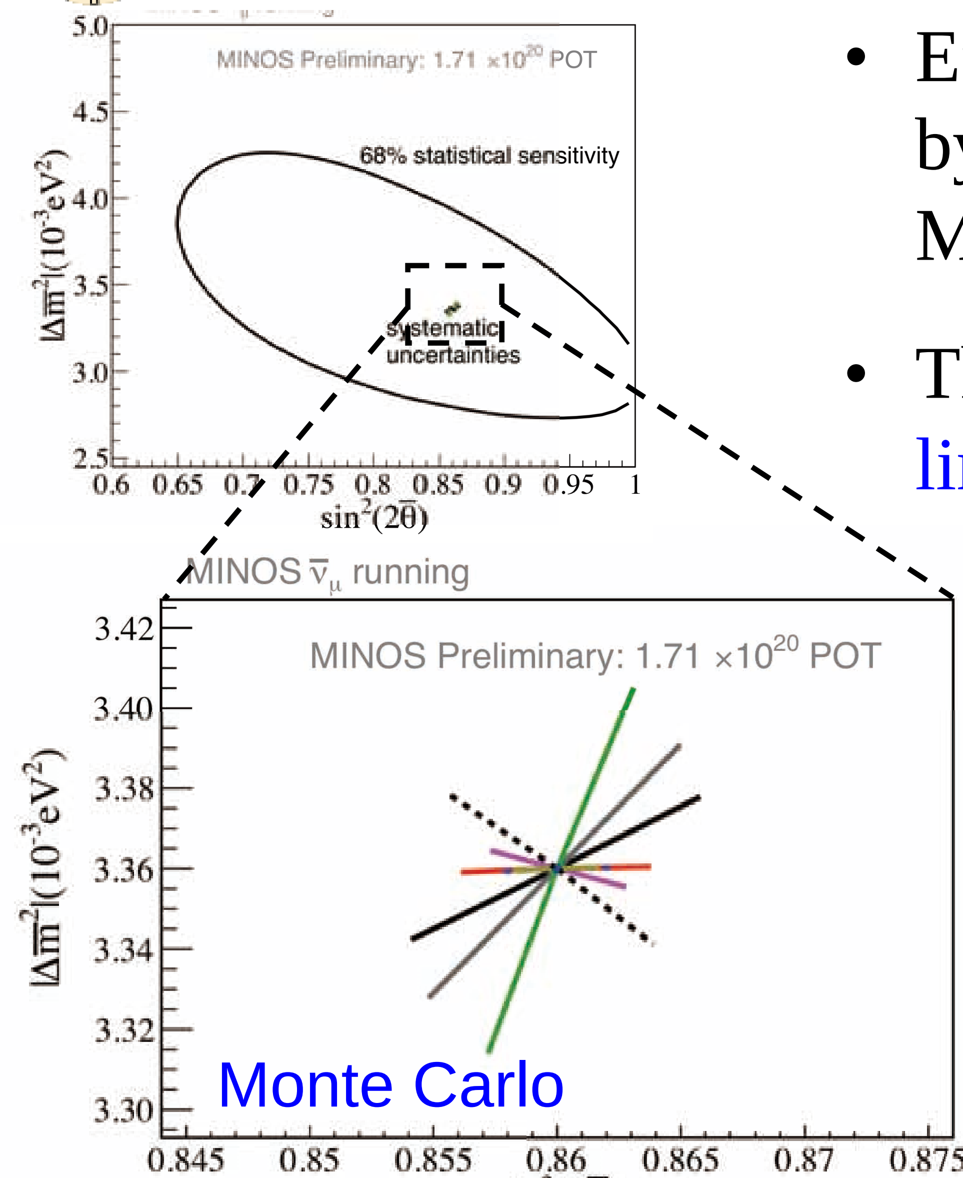


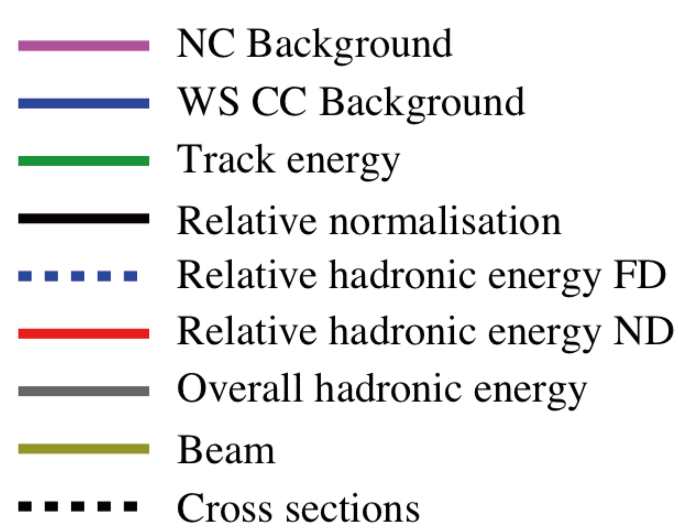
Monte Carlo

- 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

Antineutrino Systematics

- Effect of uncertainties estimated by fitting systematically shifted MC
- The analysis is statistically limited.



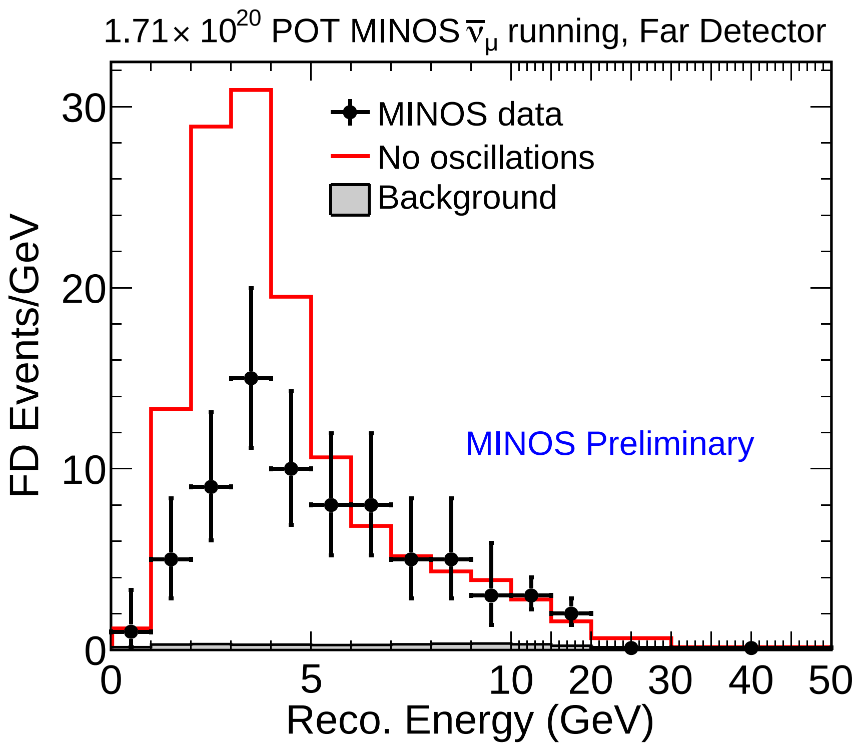


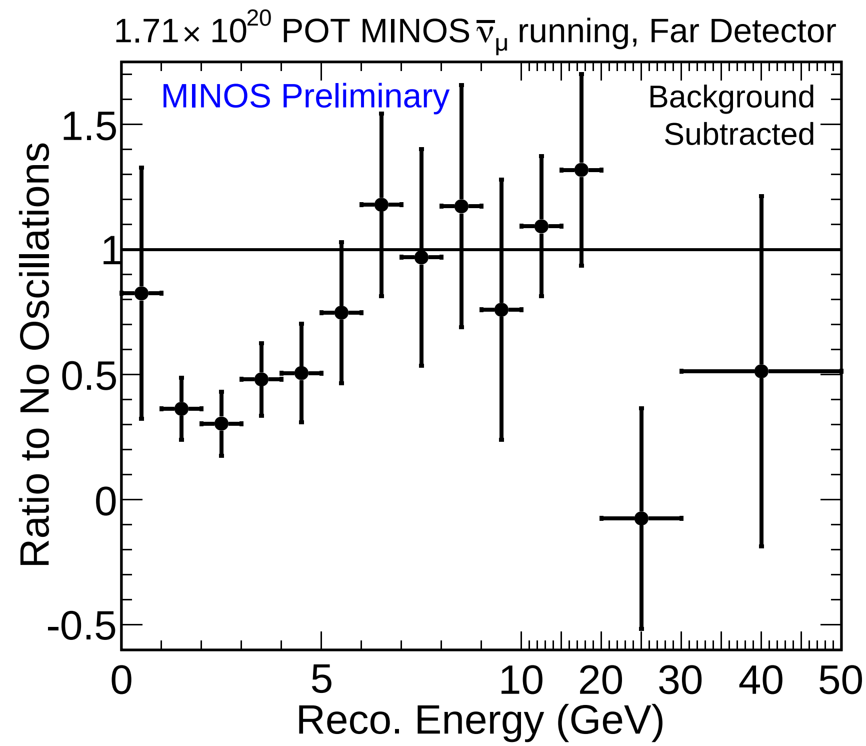
Blind Analysis

- 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 Antineutrino Data



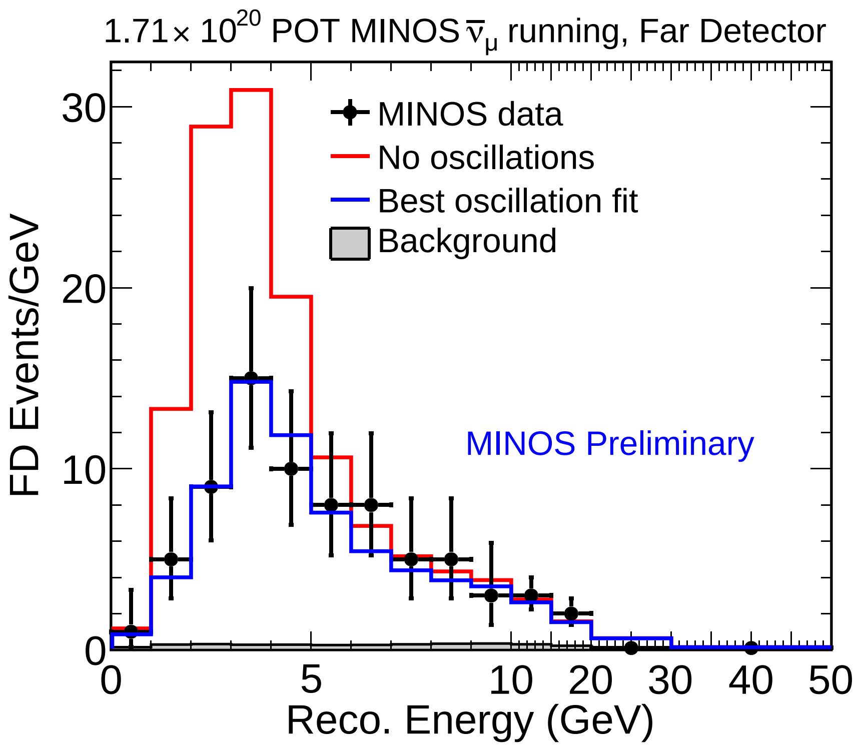


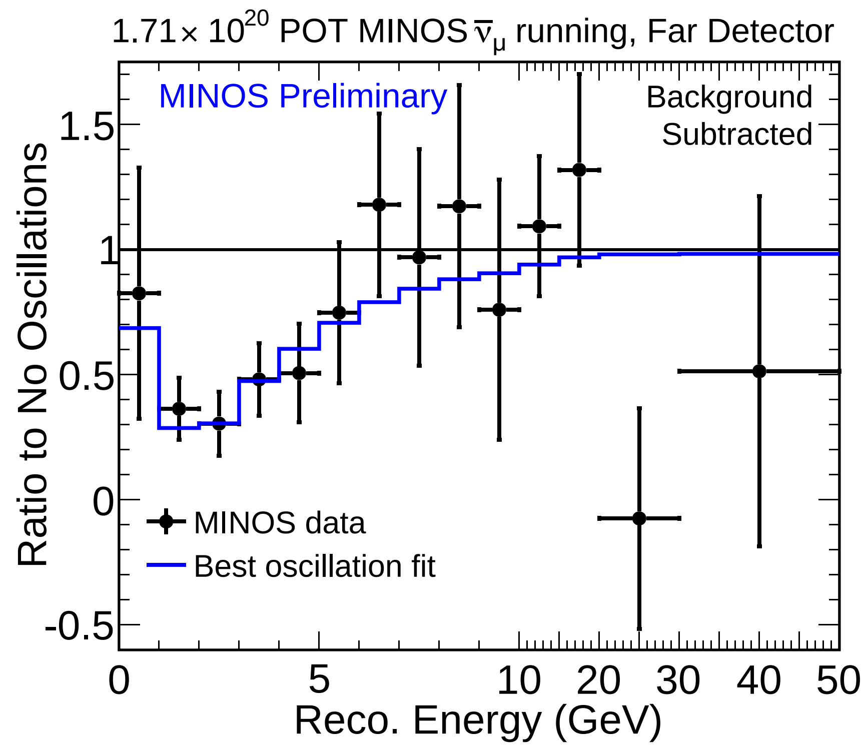
➔ **155** expected without oscillations

➔ **97** observed events

Step 4

Far Detector Antineutrino Data





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

Step 4

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

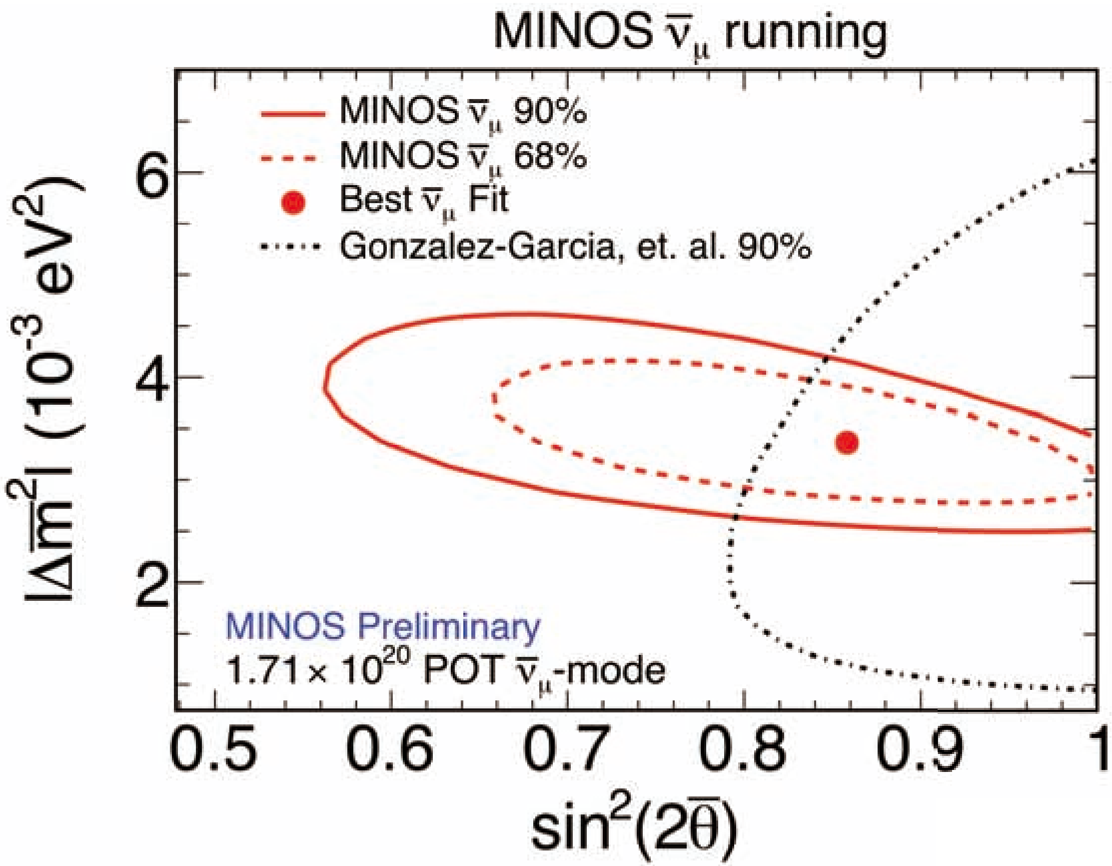
Antineutrino Contour

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

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

- Oscillation probabilities are non-linear and there are physical boundaries
  - Simple Gaussian confidence intervals don't work
  - Use the Feldman-Cousins technique to get correct contours and incorporate systematics
- Dot-dash line is a fit to all non-MINOS data

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



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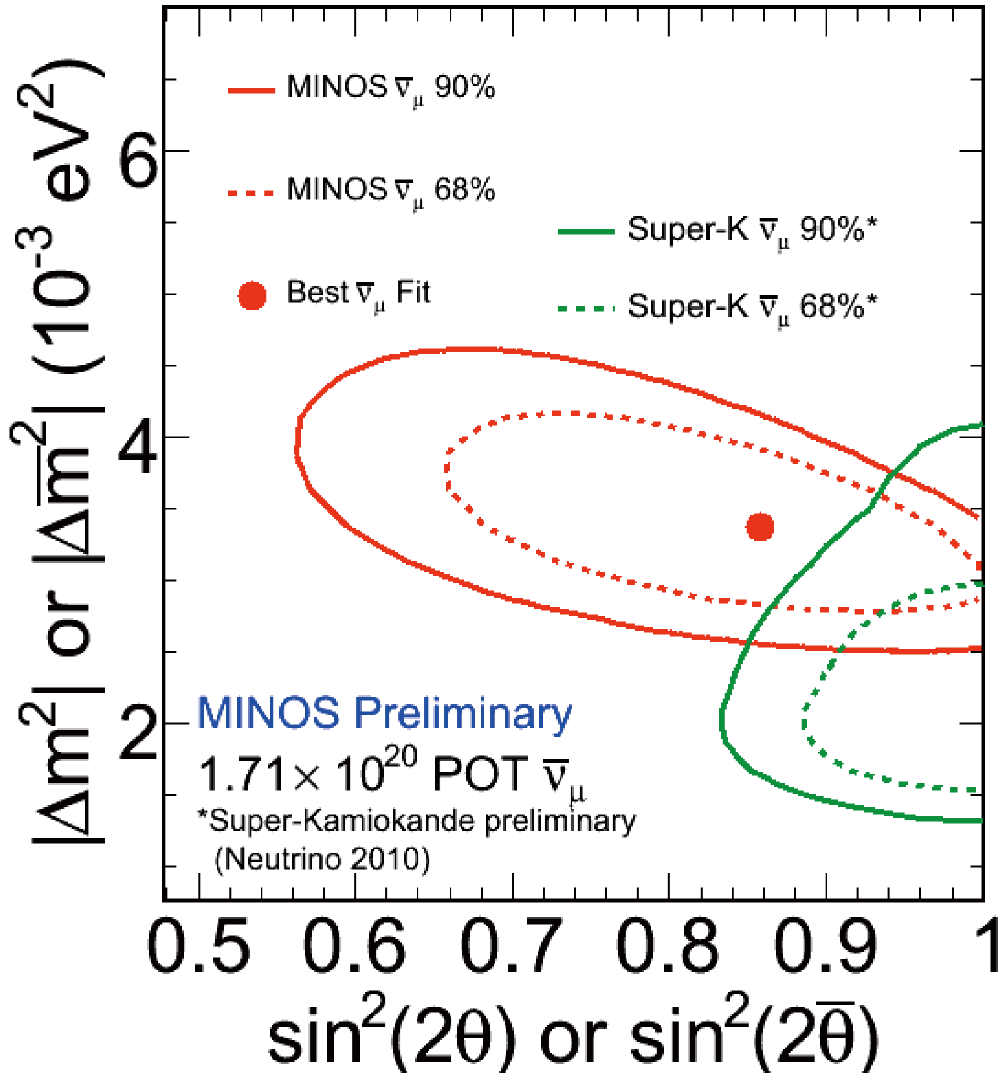
$$\sin^2\left(2\overline{\theta}_{23}\right) = 0.86 \pm 0.11$$

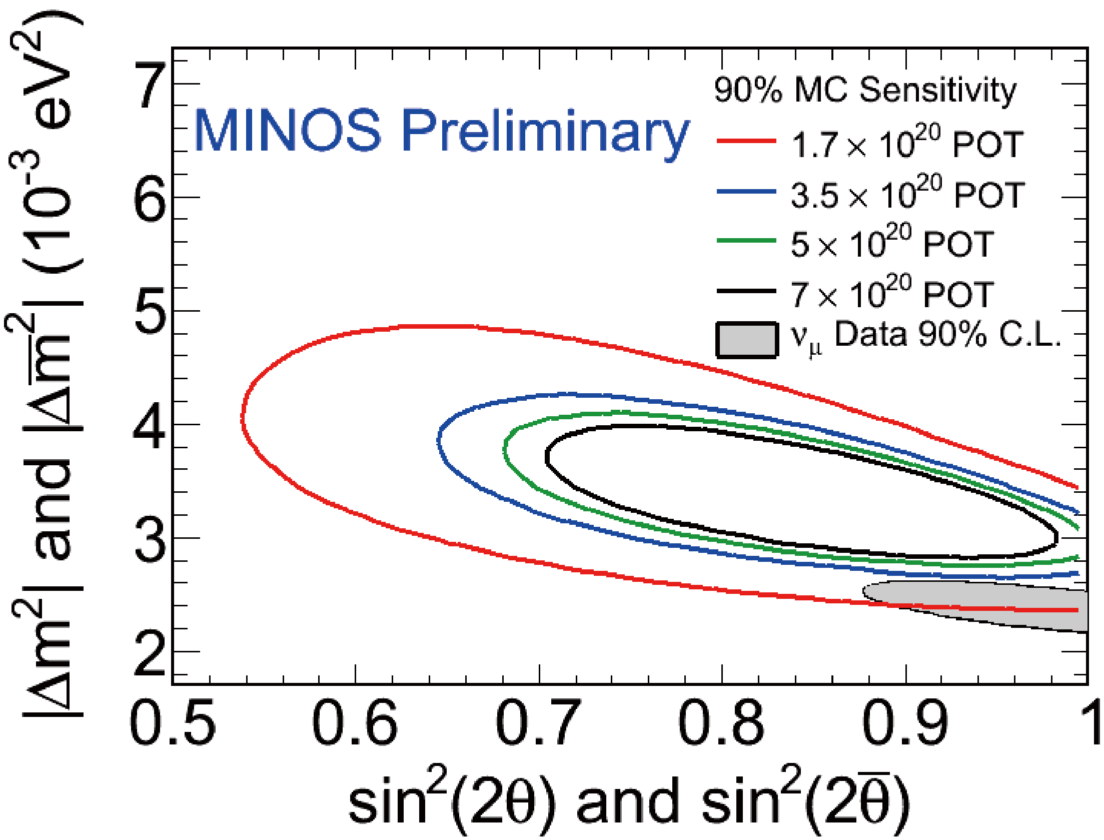
- Green contours are from SuperK at Neutrino2010
- Note that SuperK cannot separate neutrinos and antineutrinos event-by-event



Antineutrino Future

- More data has the potential to rapidly improve the contours
  - Doubling the data set reduces uncertainty on Δm^2 by 30%

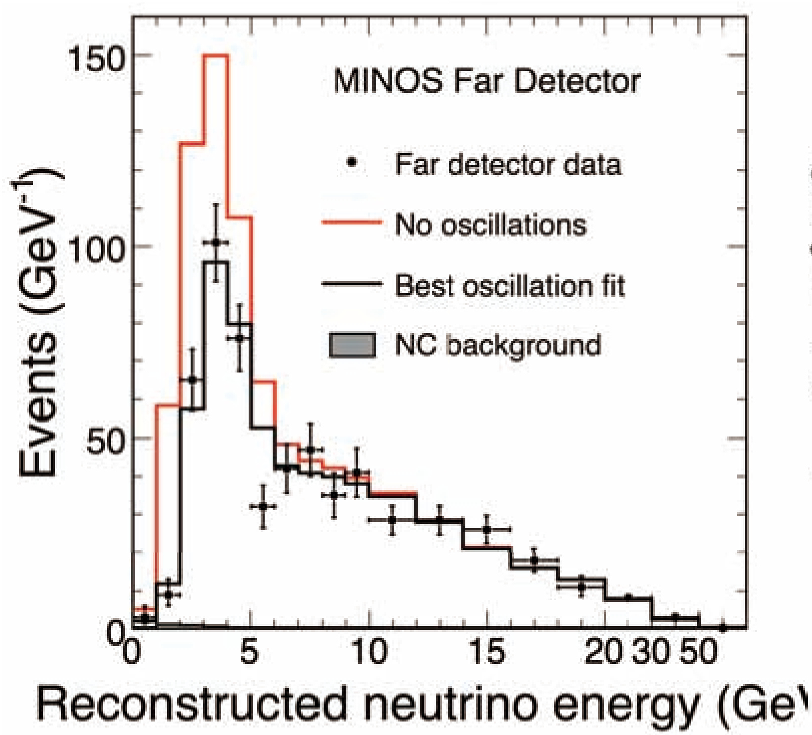
- NuMI approved for another $2x10^{20}$ POT of antineutrino running
  - Beginning ~now

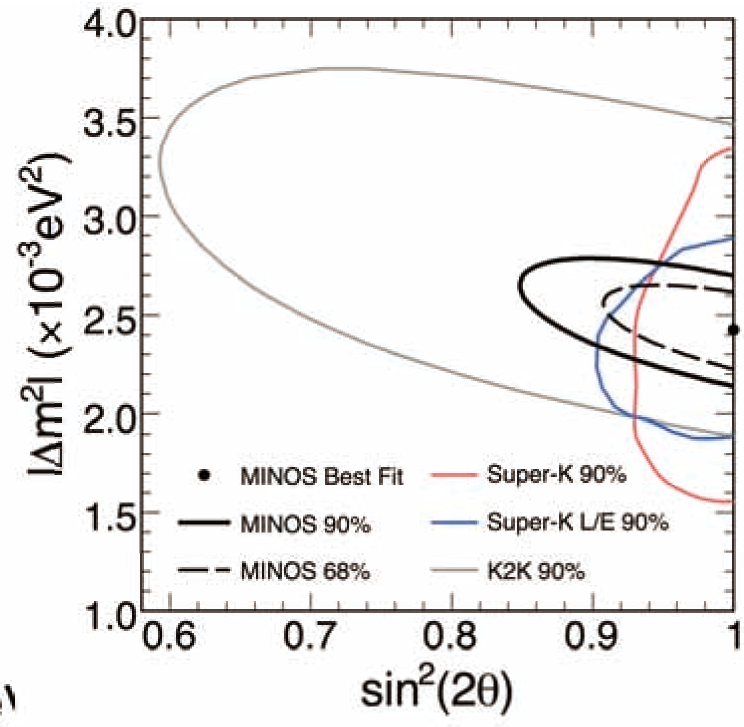


Muon Neutrinos

Measure Δm^2_{atm}, $\sin^2(2\theta_{23})$
Distinguish oscillations from decay
and decoherence

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

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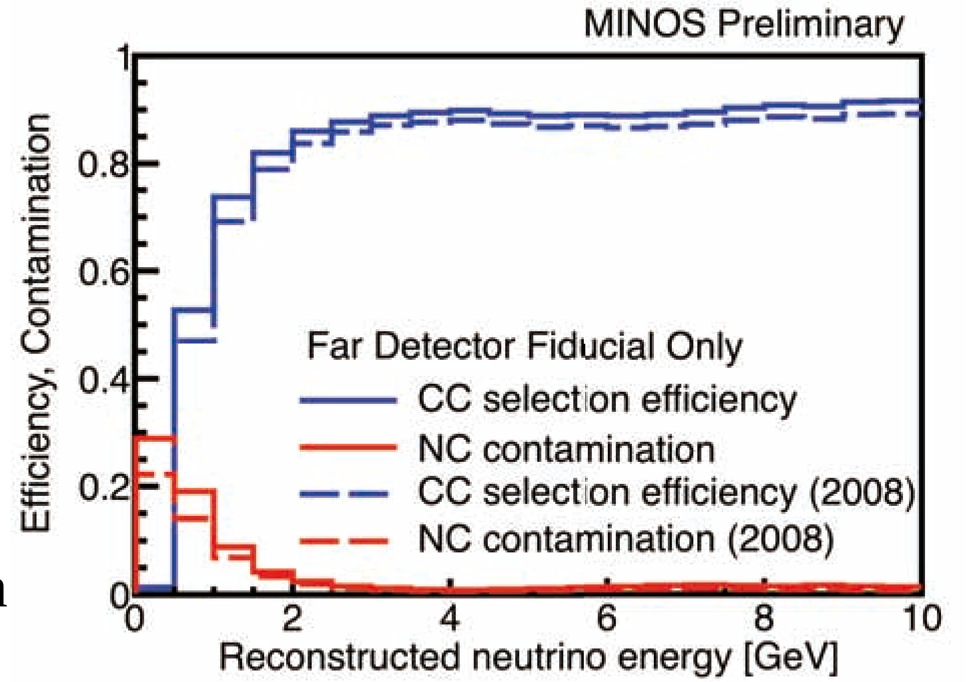

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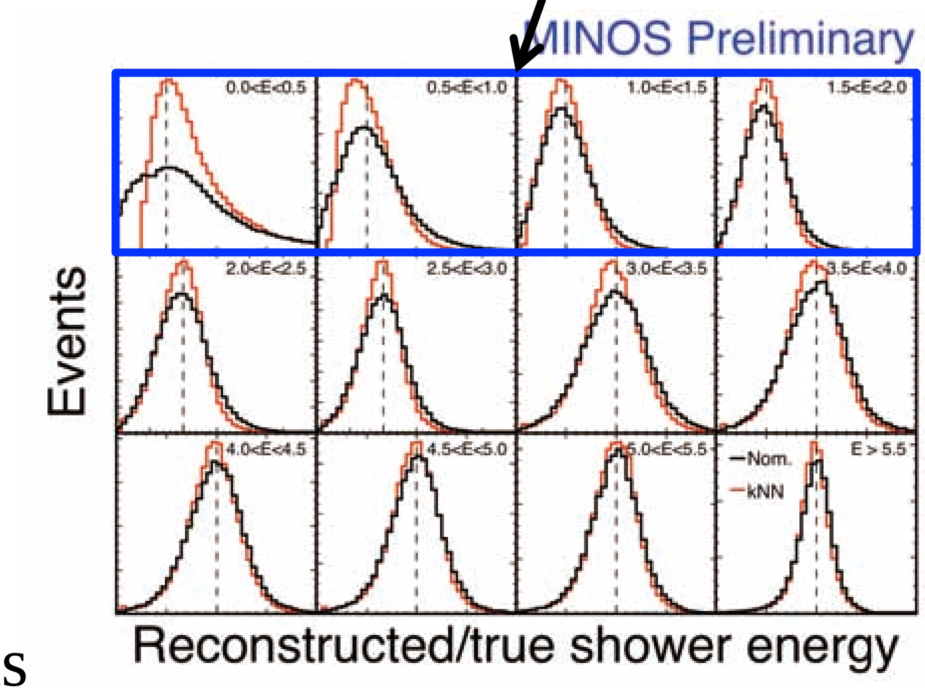
- New selection improves low-energy efficiency
- New shower energy estimator
  - 30% better low-energy resolution
- No charge sign cut
  - Reclaim mis-identified neutrino events at low energy
- Split data set into resolution bins
  - Increased statistical power

~30% better resolution below 2 GeV



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- New selection improves low-energy efficiency
- New shower energy estimator
  - 30% better low-energy resolution
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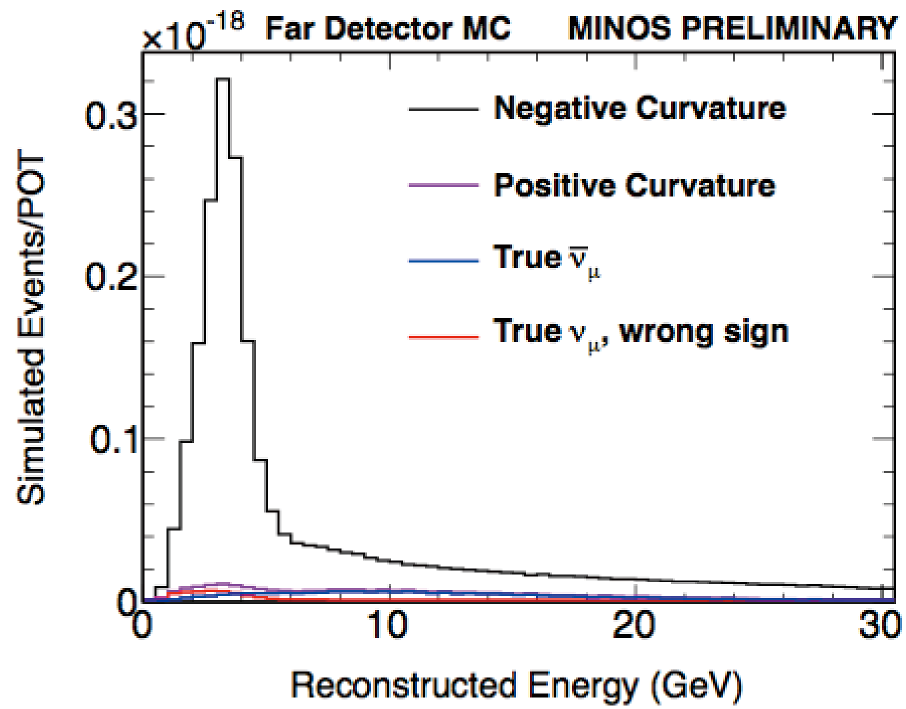
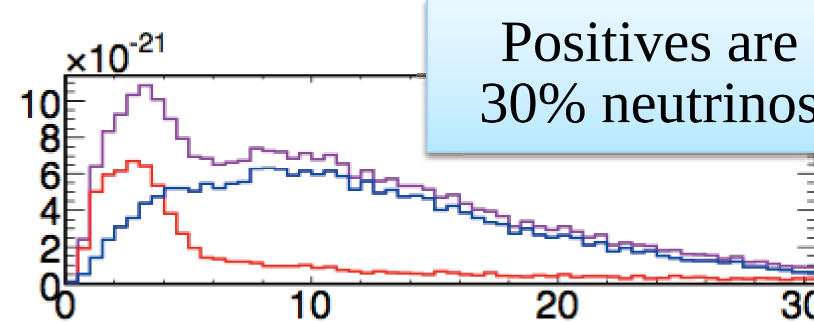
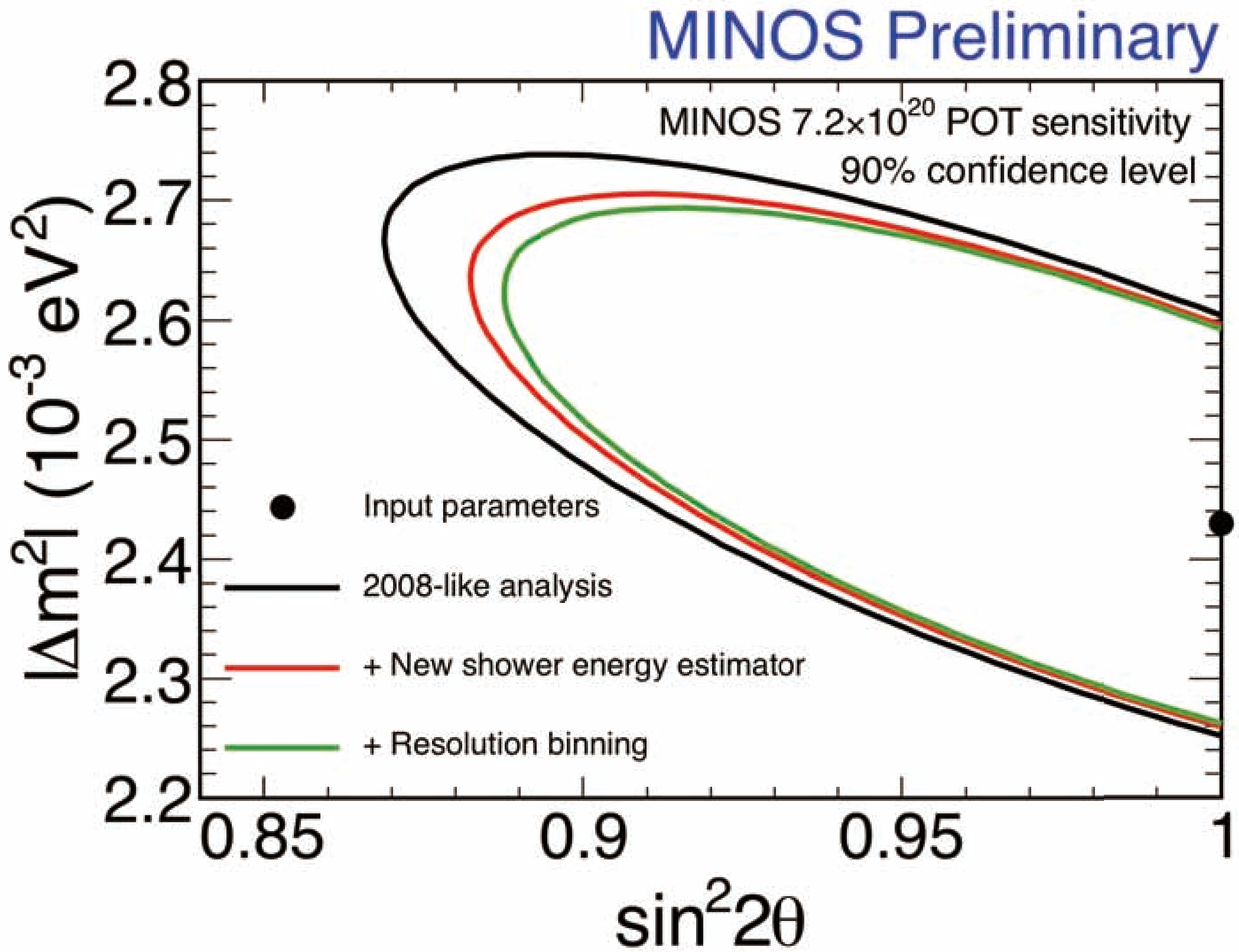
  - Increased statistical power



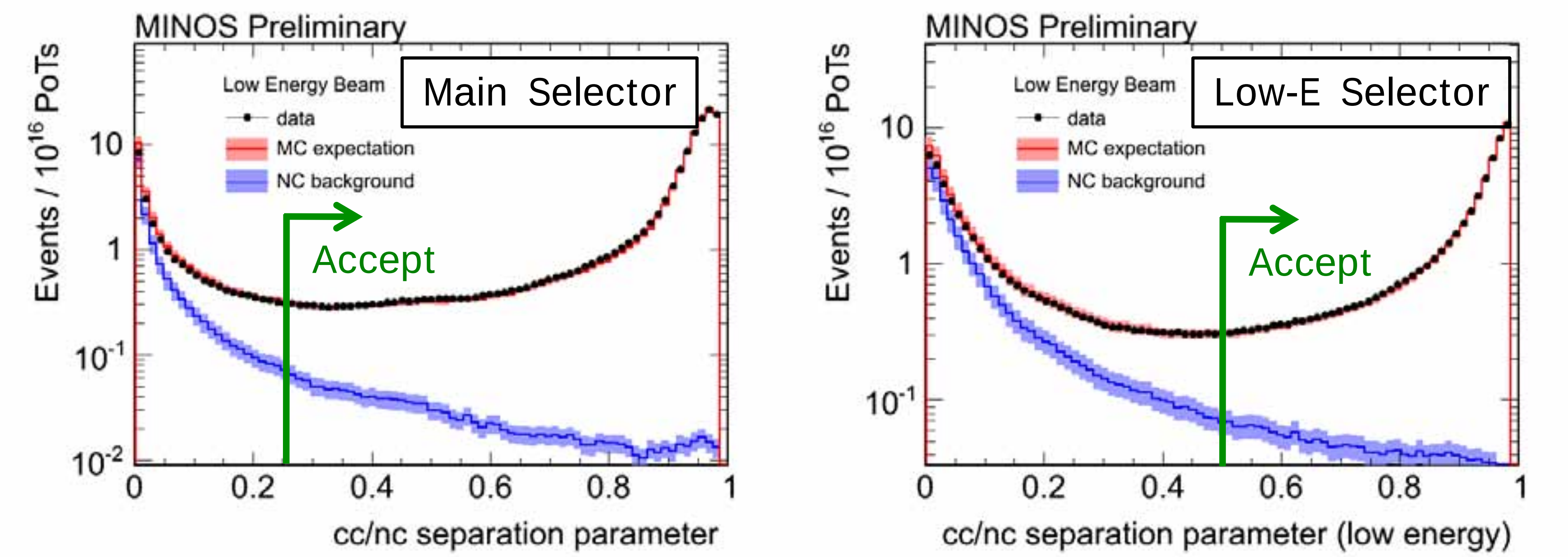


Positives are 30% neutrinos

Analysis Improvements



Selecting CC Neutrinos

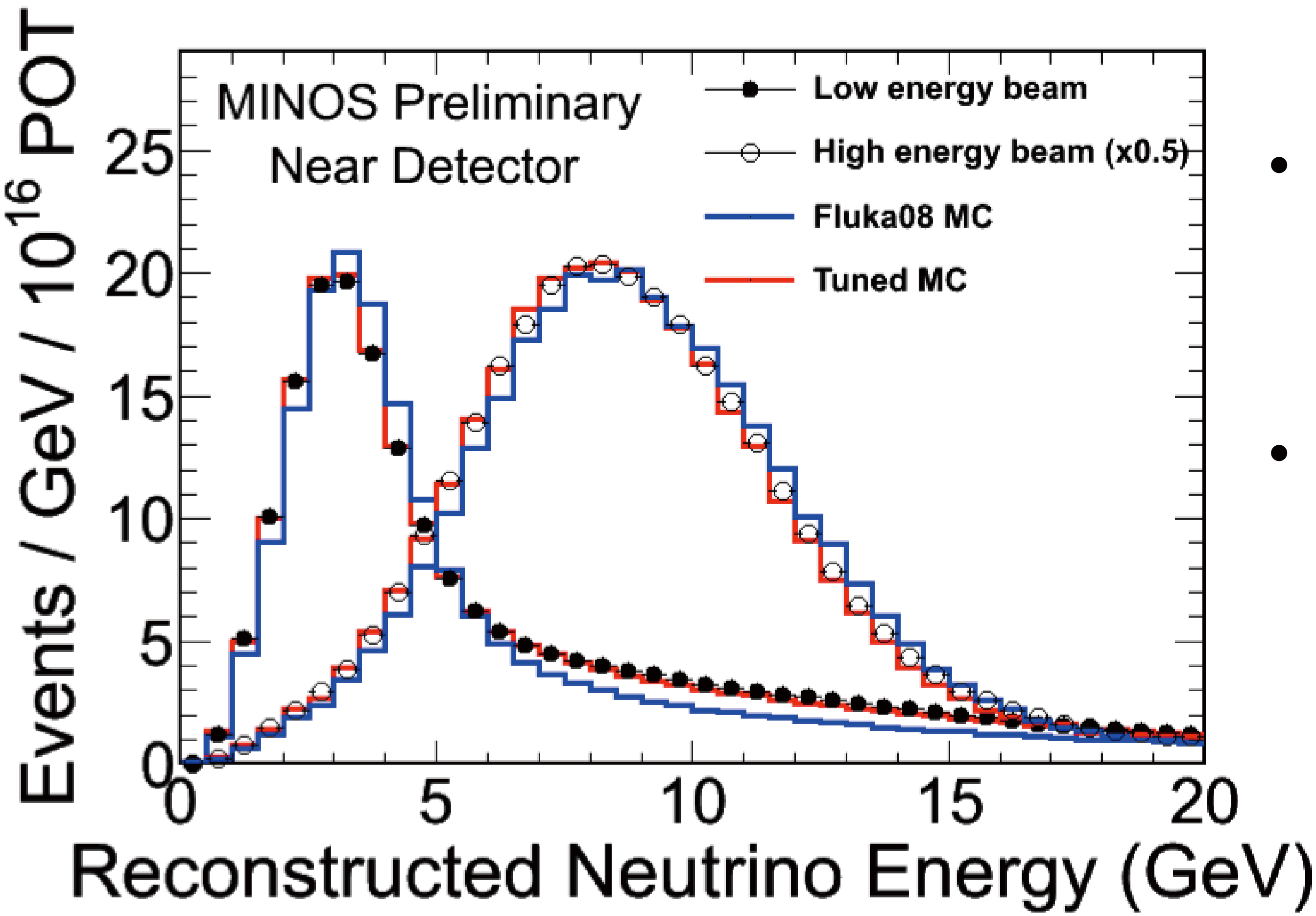


- The selection is a logical OR between:
  - The CC/NC selector also used for antineutrinos
  - The new selector optimized for low-energy tracks

Step 1

Neutrino Near Detector Data

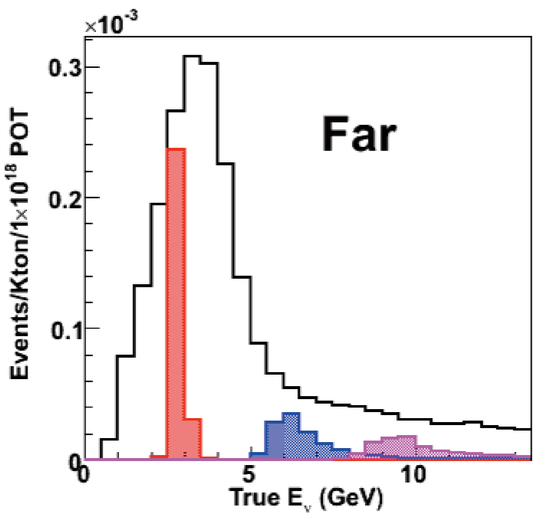
Step 2

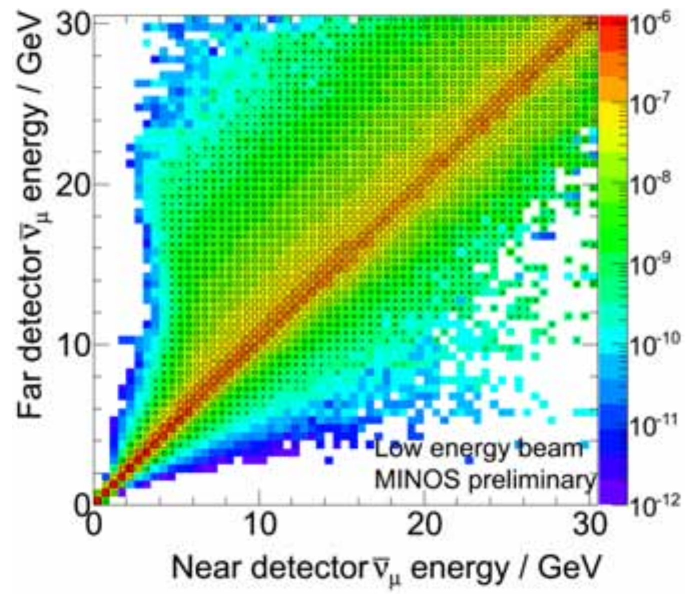


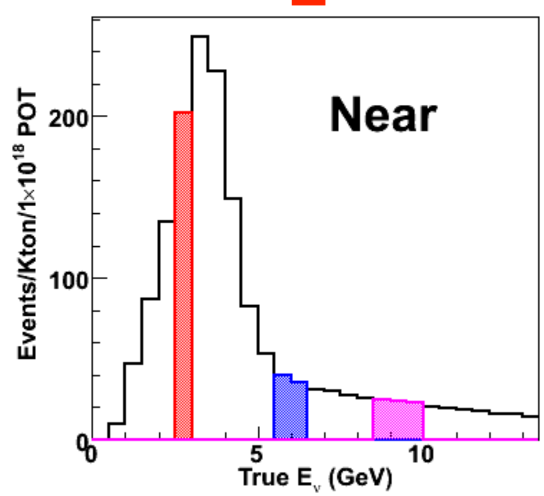
- Majority of data taken in Low Energy Beam
- High Energy Beam gives us more events above the oscillation dip

Beam Matrix Extrapolation

Step 3





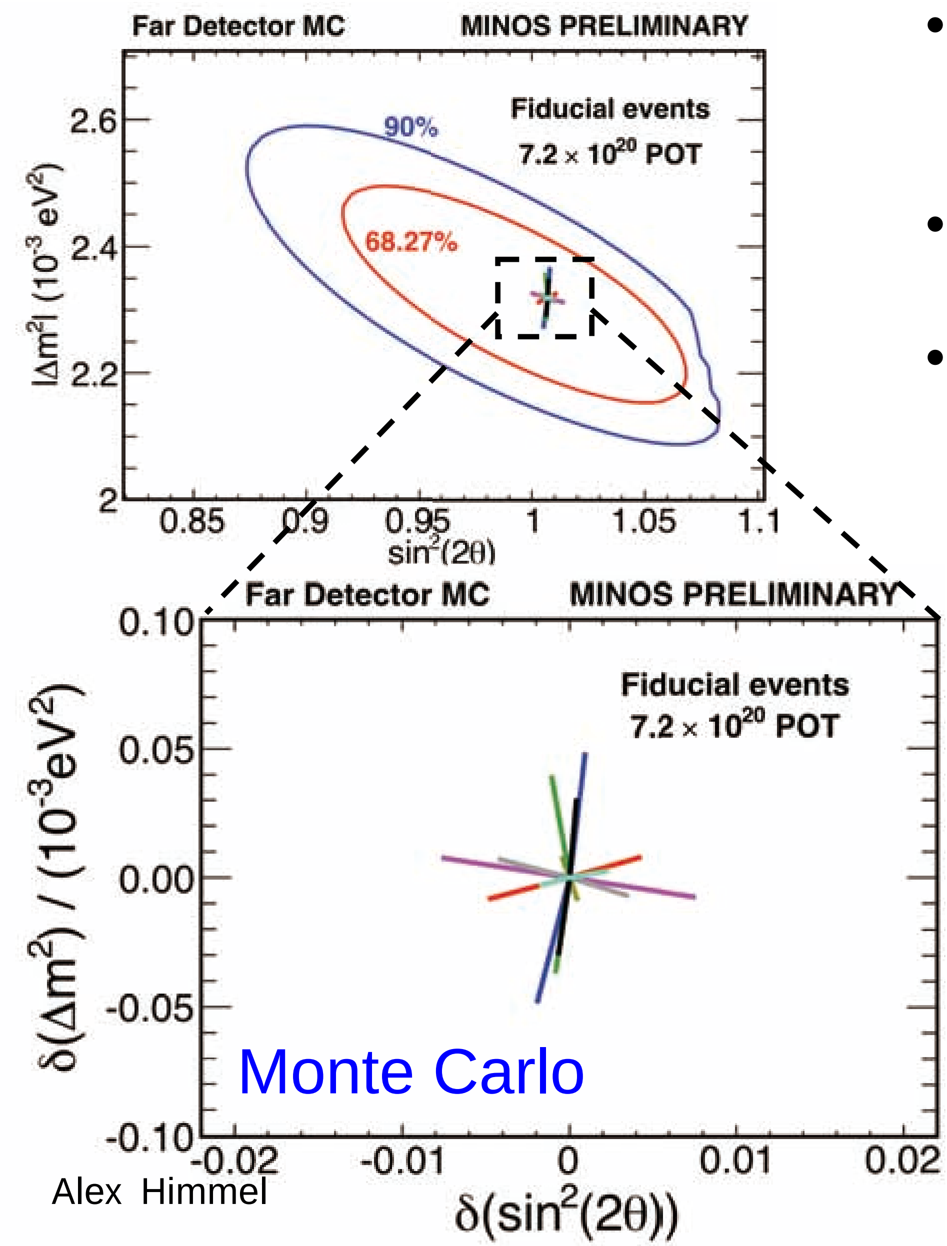


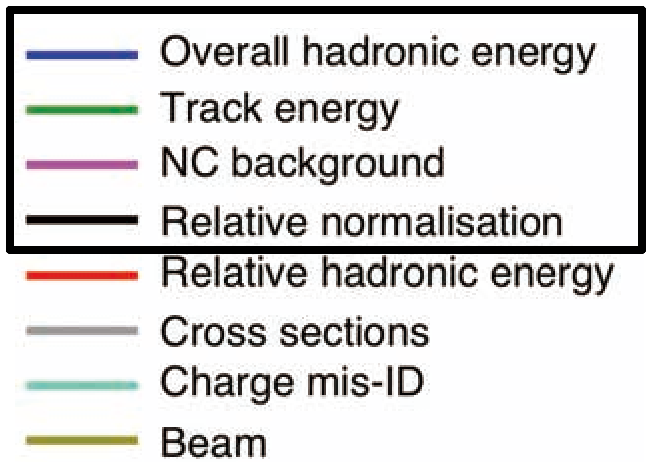
Monte Carlo

- The muon neutrino analysis also uses the beam matrix extrapolation

Neutrino Systematics

- Systematics similar between neutrinos and antineutrinos
- Analysis is still statistically limited
- The 4 largest systematics are included as penalty terms in the fit.

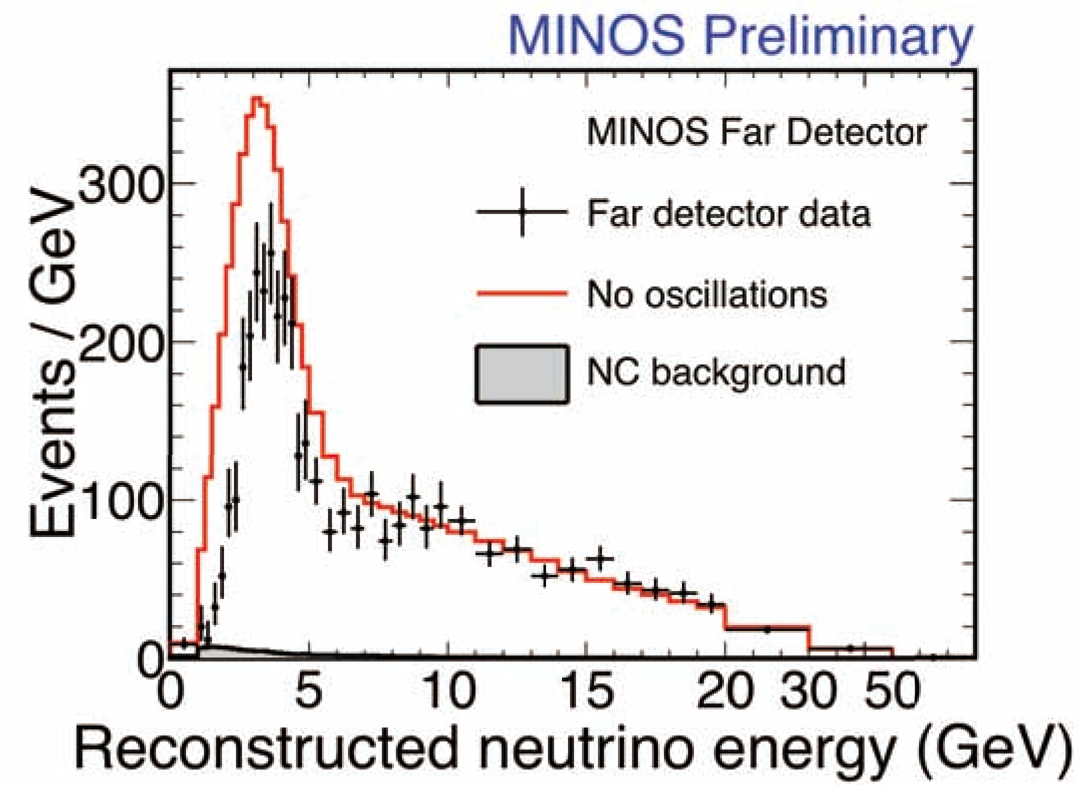




Far Detector Neutrino Data

➔**2,451** expected without oscillations

➔**1,986** observed events



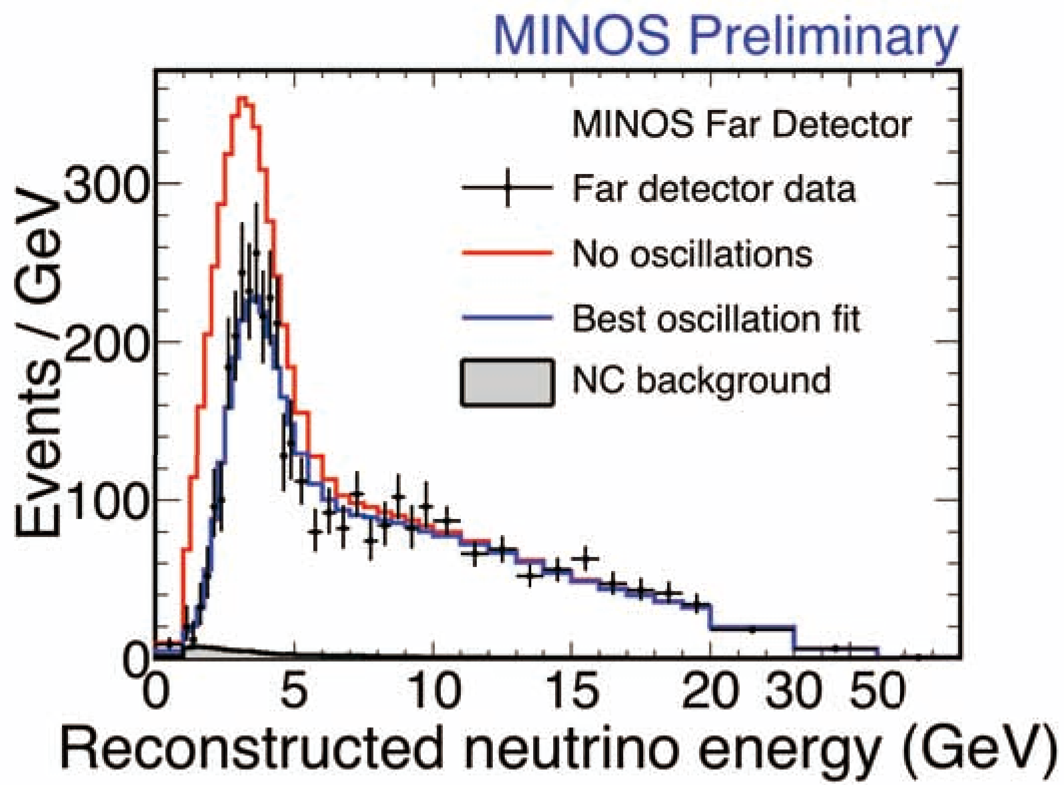
Step 4

Far Detector Neutrino Data

➔**2,451** expected without oscillations

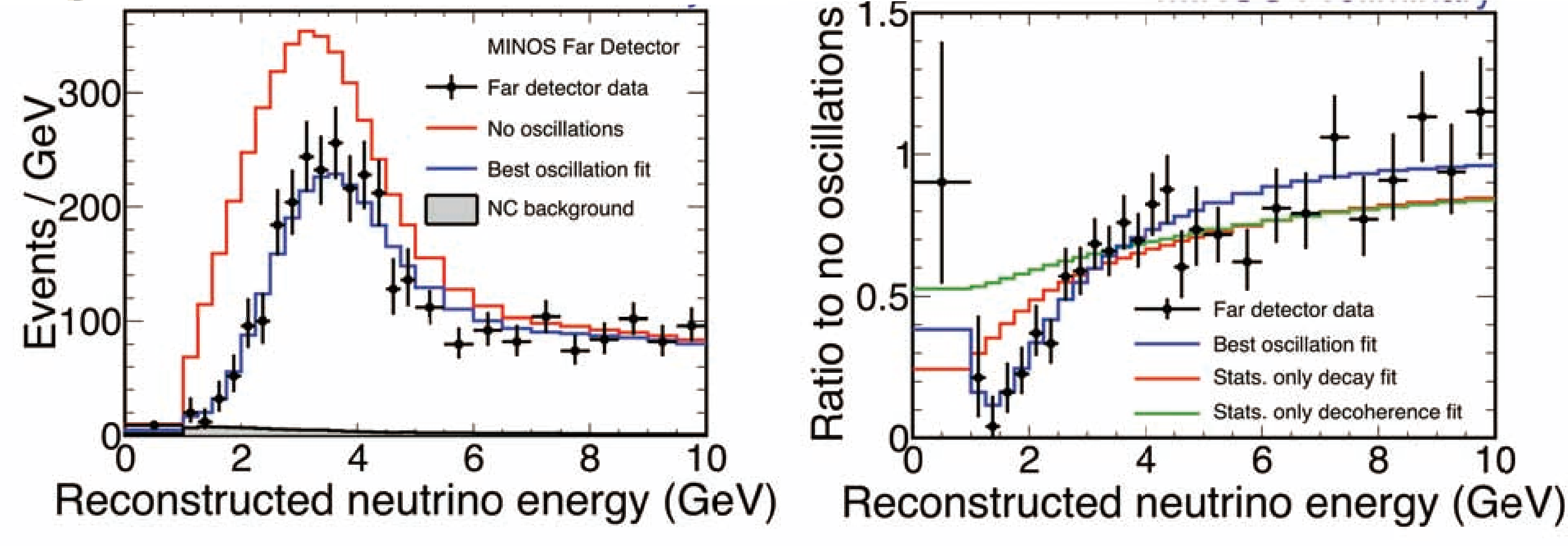
➔**1,986** observed events

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



Step 4

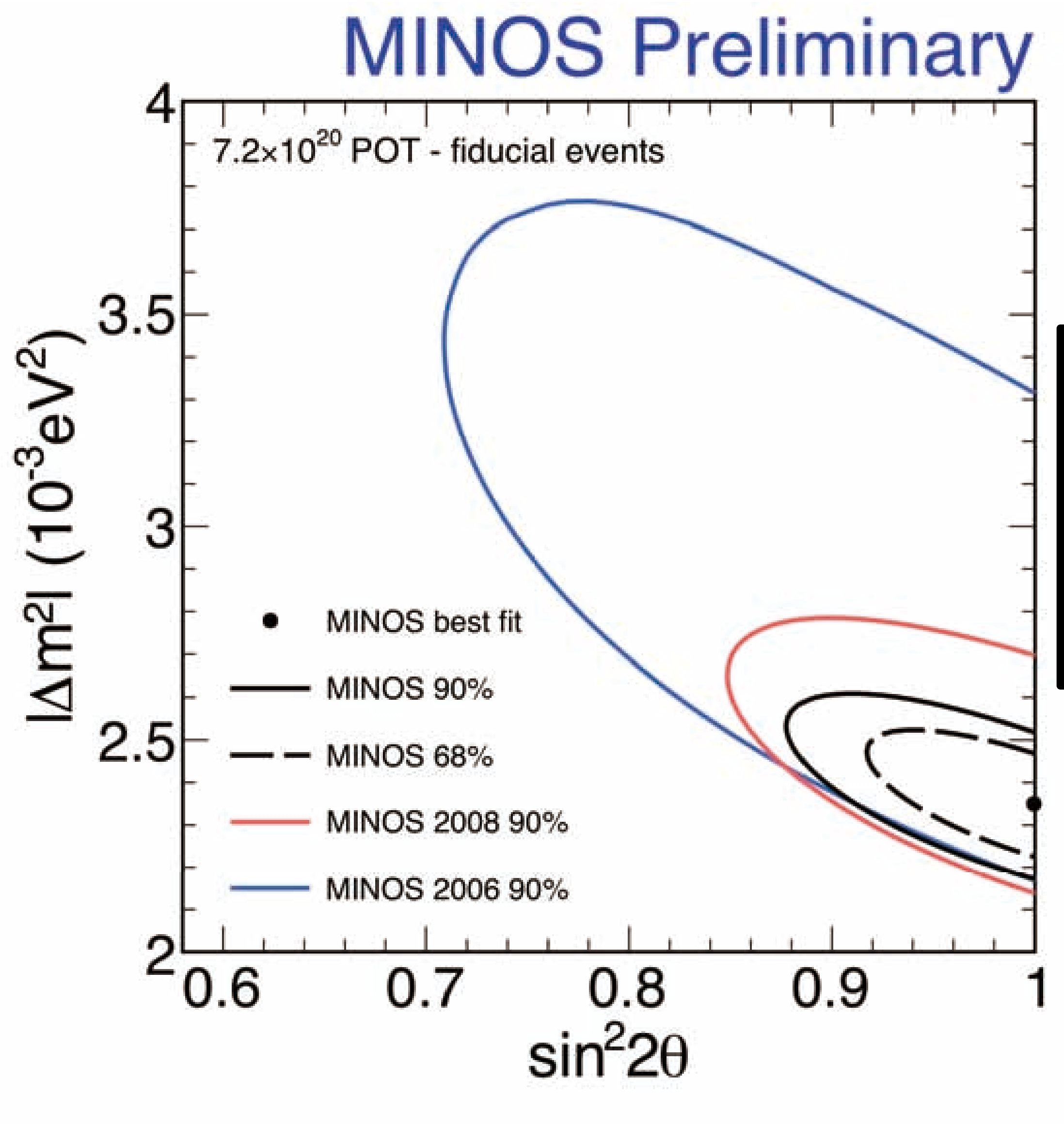
Far Detector Neutrino Data



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

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

Neutrino Contour

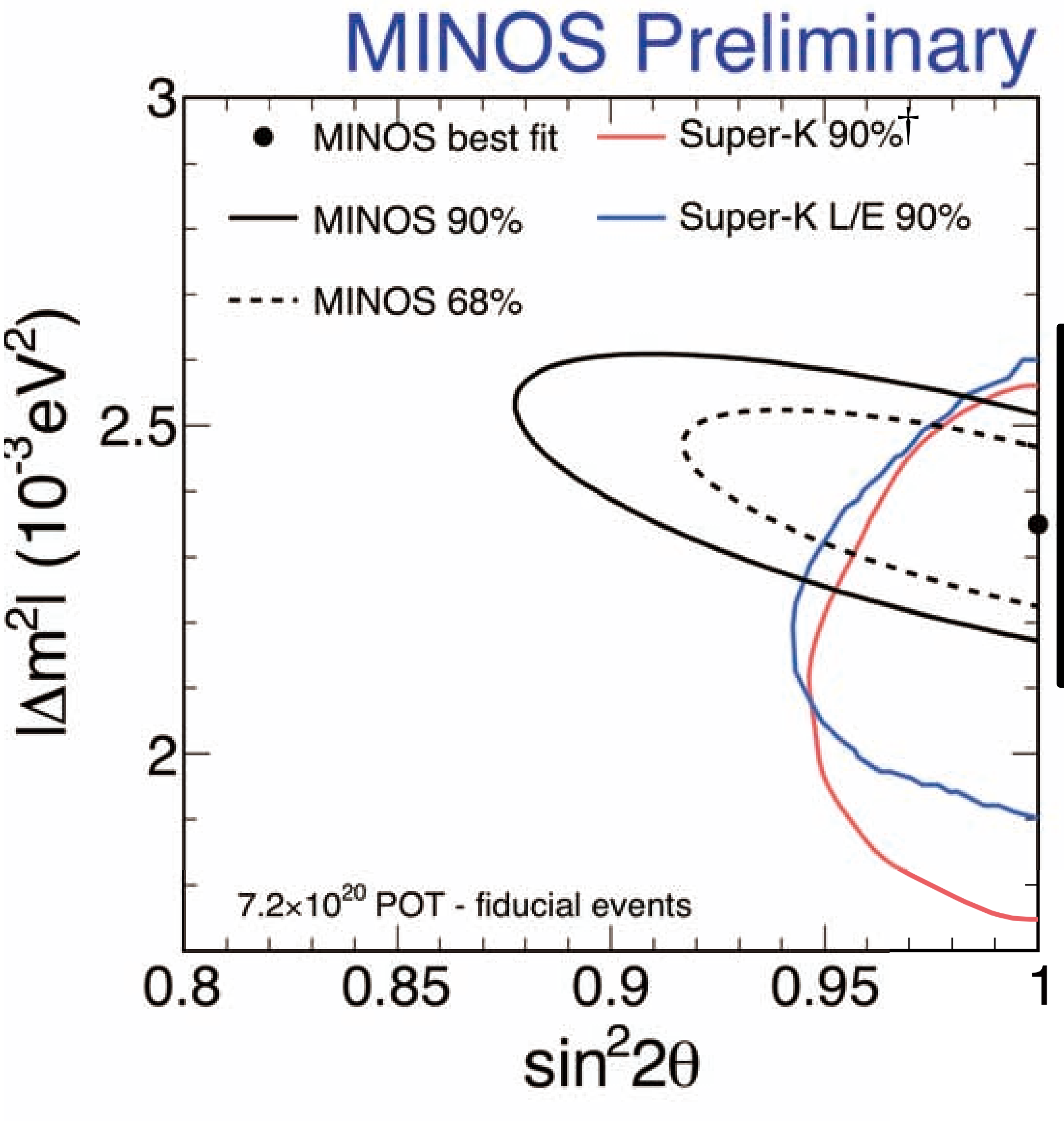


$$\left|\Delta m^2_{\mathrm{atm}}\right| = 2.35^{+0.11}_{-0.08} \times 10^{-3}\ \mathrm{eV}^2$$

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

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

Neutrino Contour



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

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

†Super-Kamiokande Collaboration (preliminary)

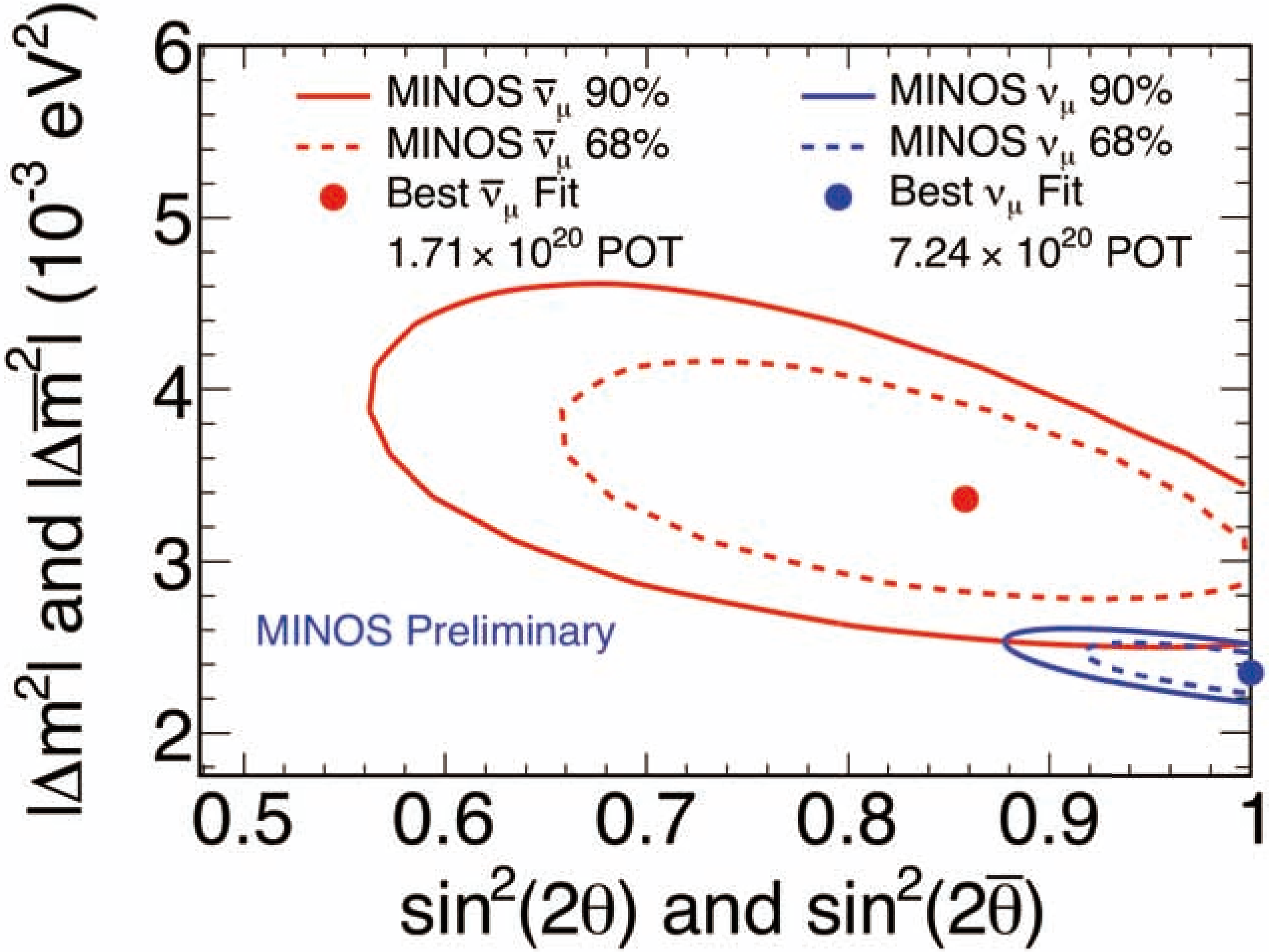
Neutrinos and Antineutrinos

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

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

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

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

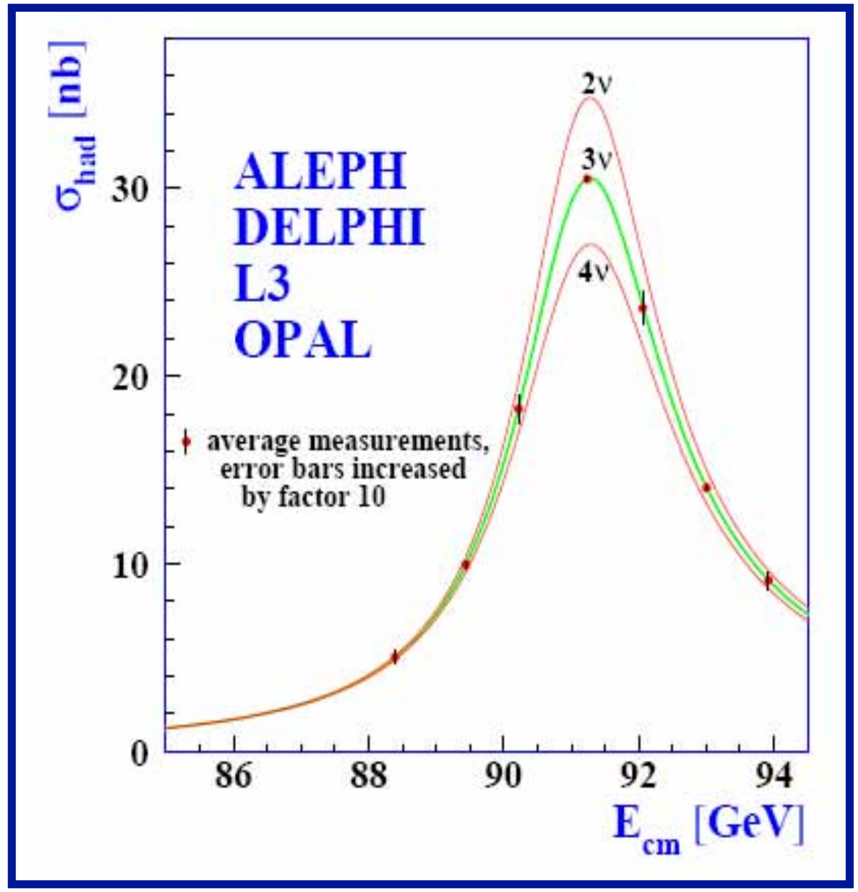


Neutral Currents

Sterile Neutrino Search

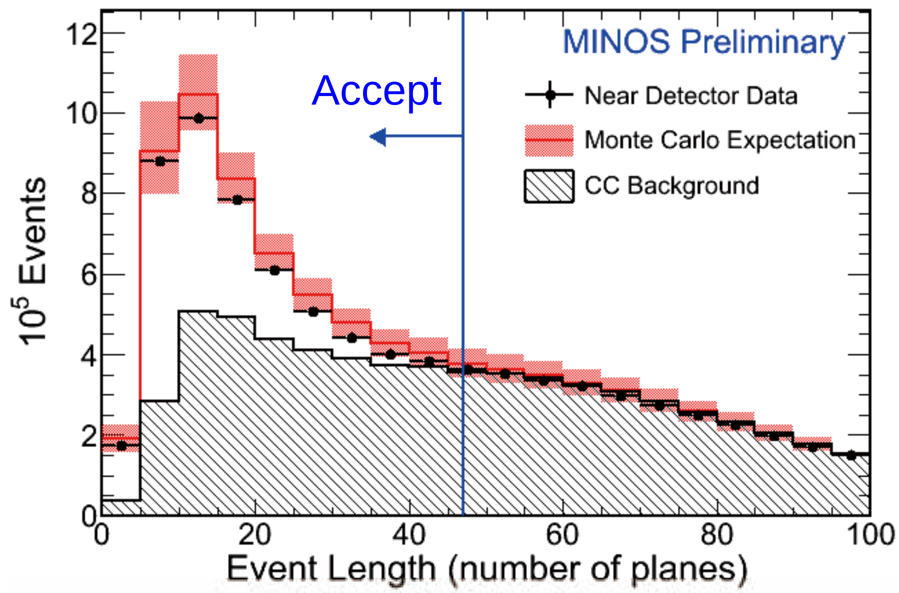
Sterile Neutrinos

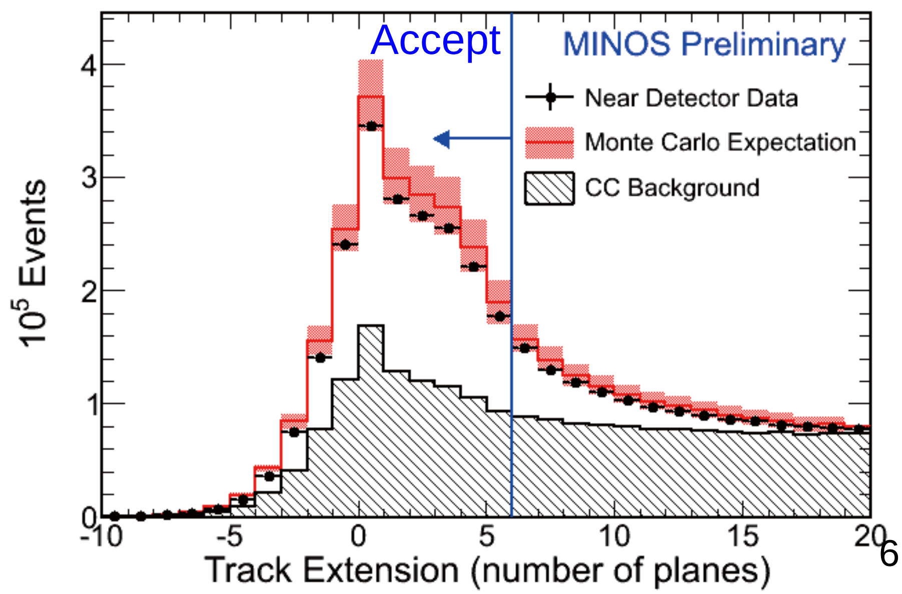
- Measurements of the Z^0 width at LEP limit the number of active neutrinos to 3
- A 4th neutrino cannot couple to the Z^0
  - Cannot participate in weak interactions
  - Hence is must be "sterile"
- Signature is a deficit in all active flavors
  - Neutral current interaction rate is independent of neutrino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



Selecting Neutral Currents

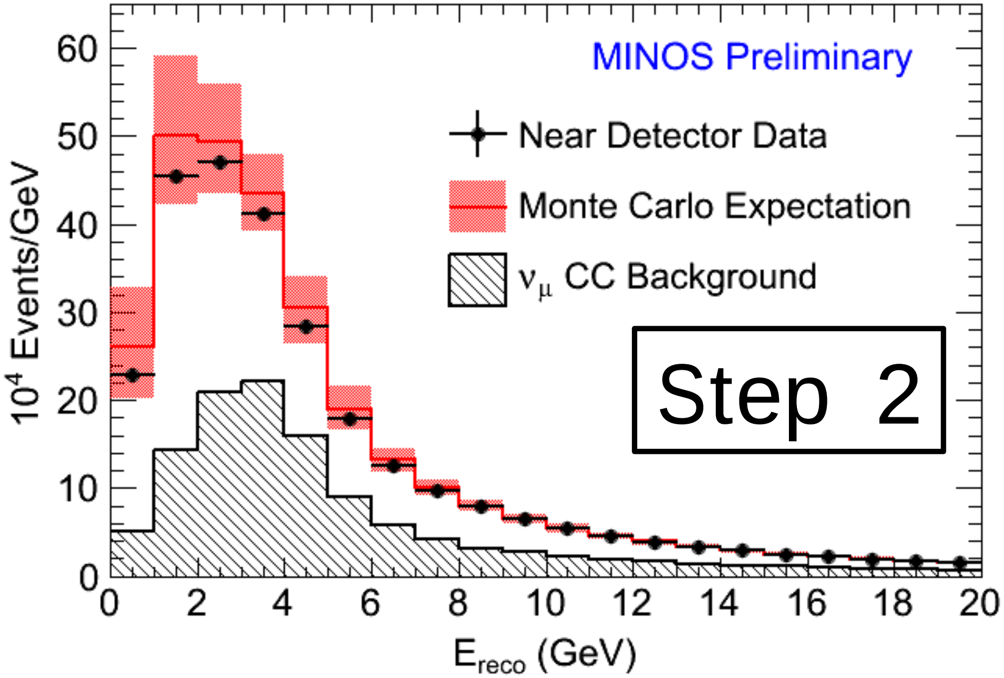
- Now CC (track) events are the background
  - Want to eliminate events with long tracks.
- Selection
  - Whole event must be short
    - < 47 planes
  - And either:
    - No reconstructed track
    - Track extends less than 6 planes out of the shower



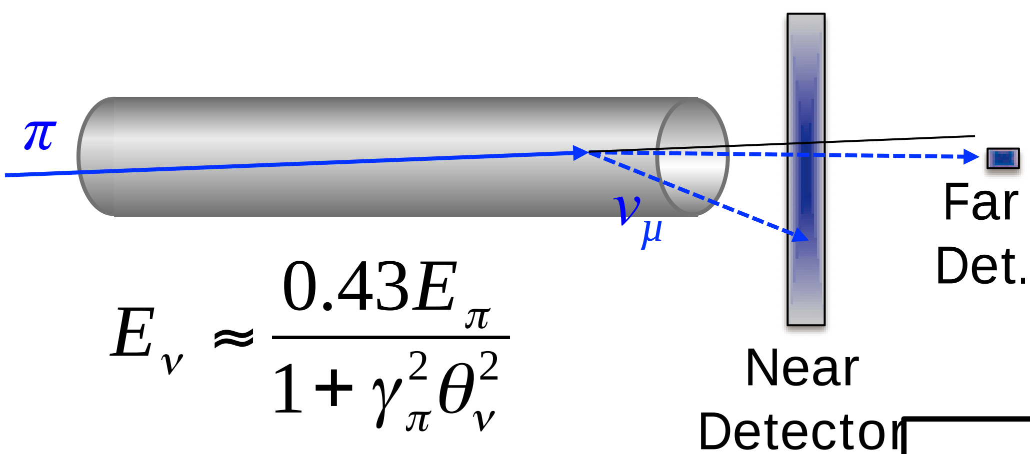


Step 1

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



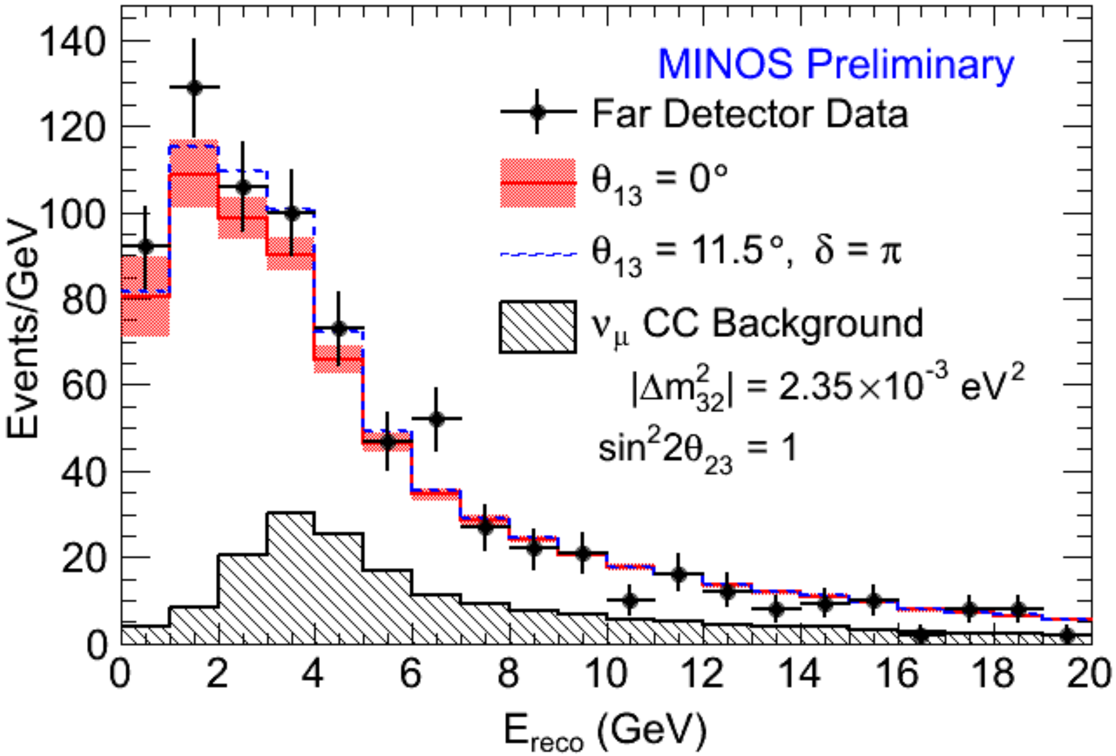
$$E_\nu \approx \frac{0.43 E_\pi}{1+\gamma_\pi^2 \theta_\nu^2}$$

Step 3

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

i refers to Energy bin

Sterile Neutrino Results



Step 4

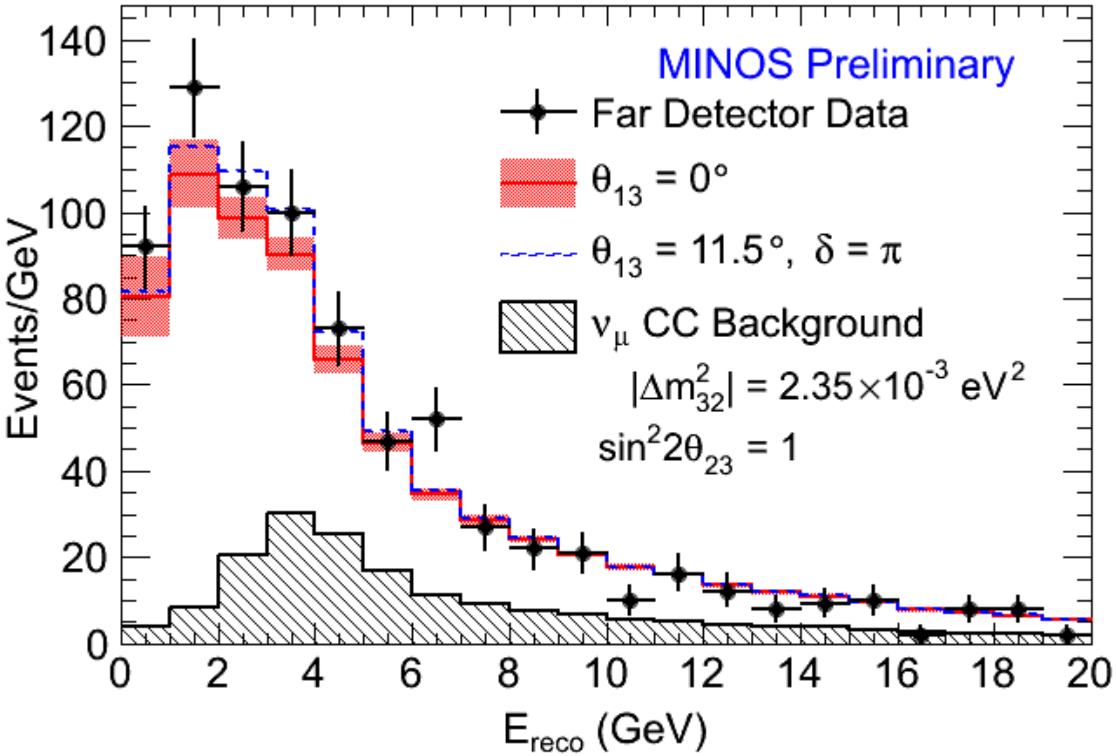
- Expected: **757** events
- Observe: **802** events
- No deficit of NC events

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

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

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

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}

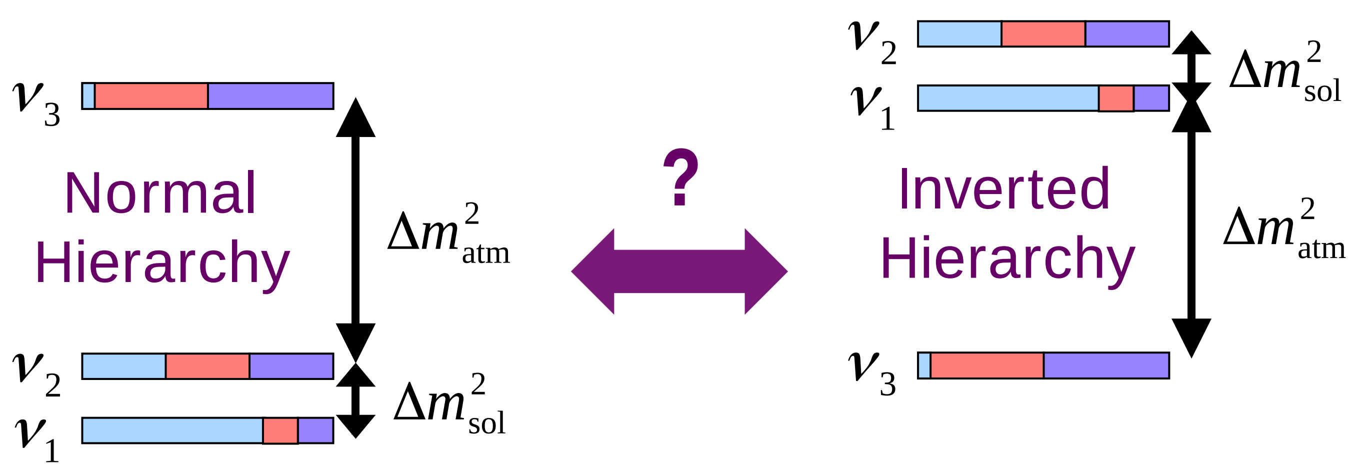
ν_e Appearance

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

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

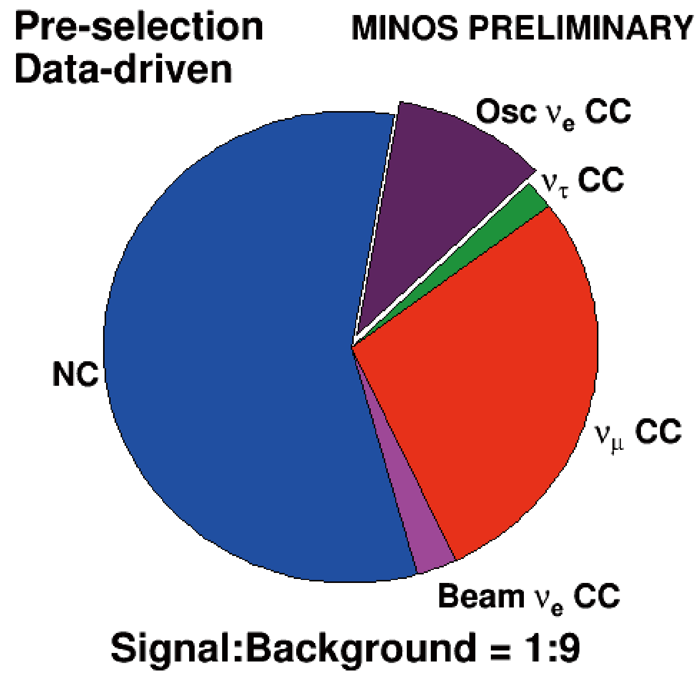
$$\mathbf{\sin(2\theta_{13})}\sin(2\theta_{23})\sin(2\theta_{12})\sin\left(1.27\Delta m^2_{31}\frac{L}{E}\right)\sin\left(1.27\Delta m^2_{21}\frac{L}{E}\right)\cos\left(1.27\Delta m^2_{32}\frac{L}{E} \pm \delta_{\mathrm{CP}}\right)$$

- 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

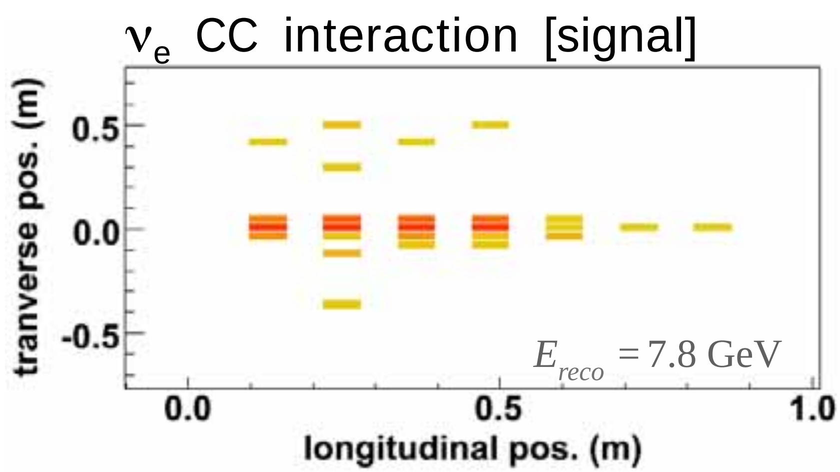
- Preselection
  - Require good beam and in-time fiducial events
  - Cut events with long tracks (CC ν_μ)
  - Cut events above 8 GeV where no oscillation signal is expected

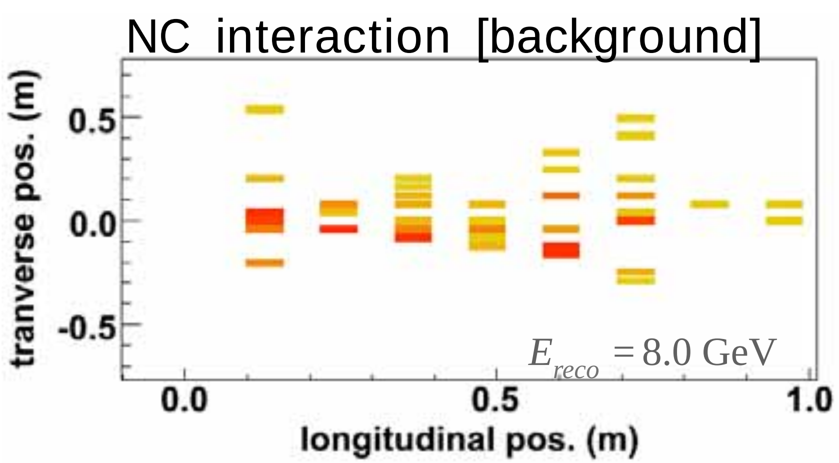


Step 1

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





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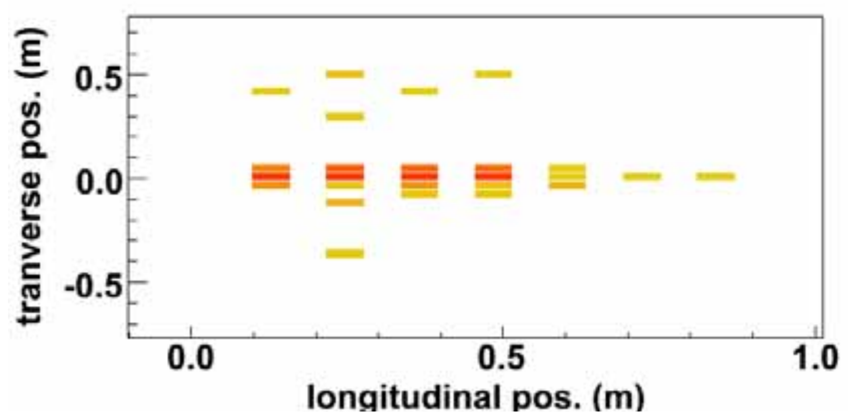
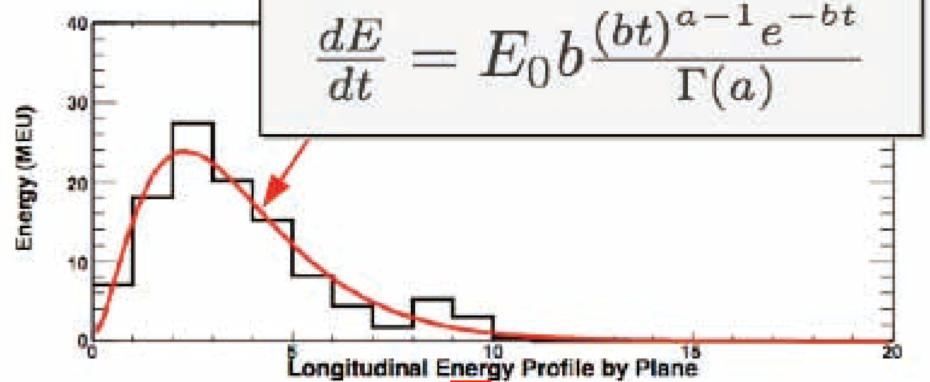


Example EM shower profile



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

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
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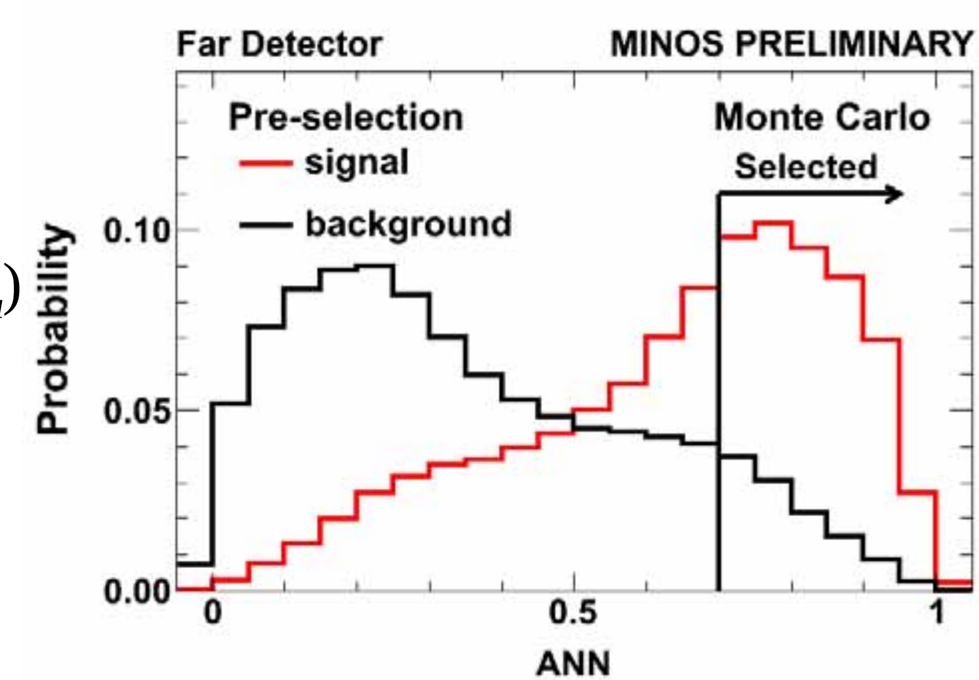

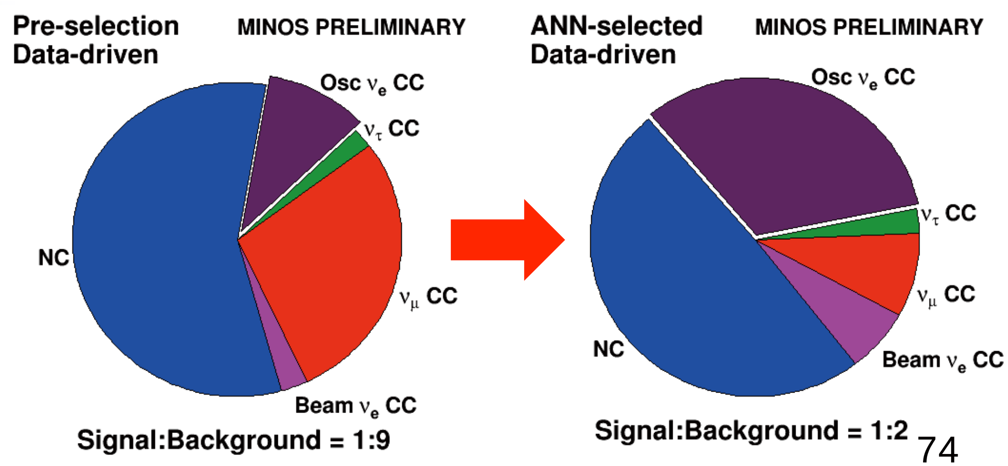

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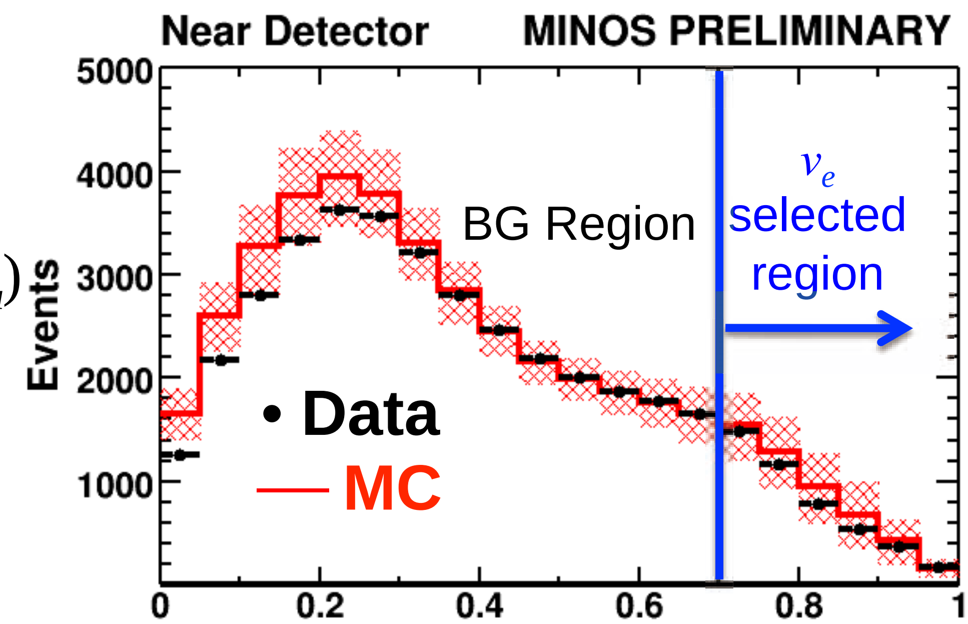
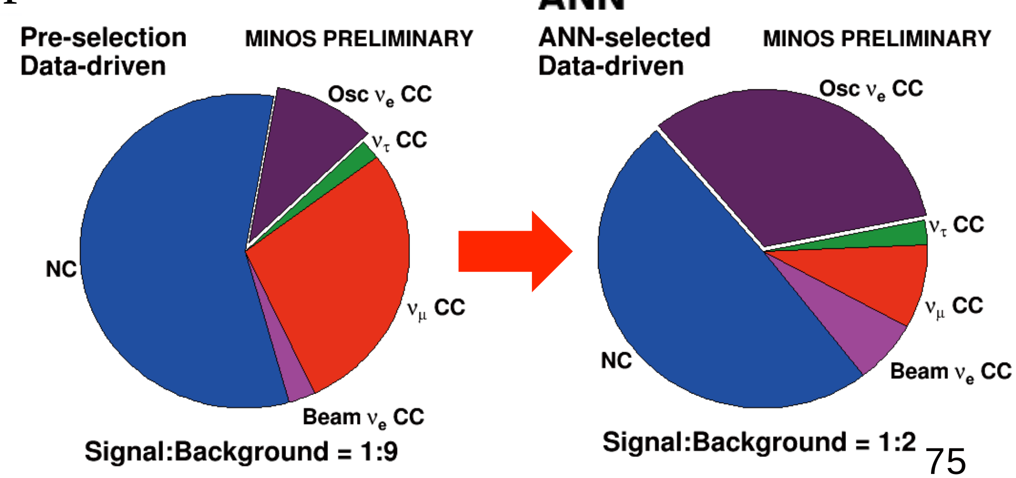
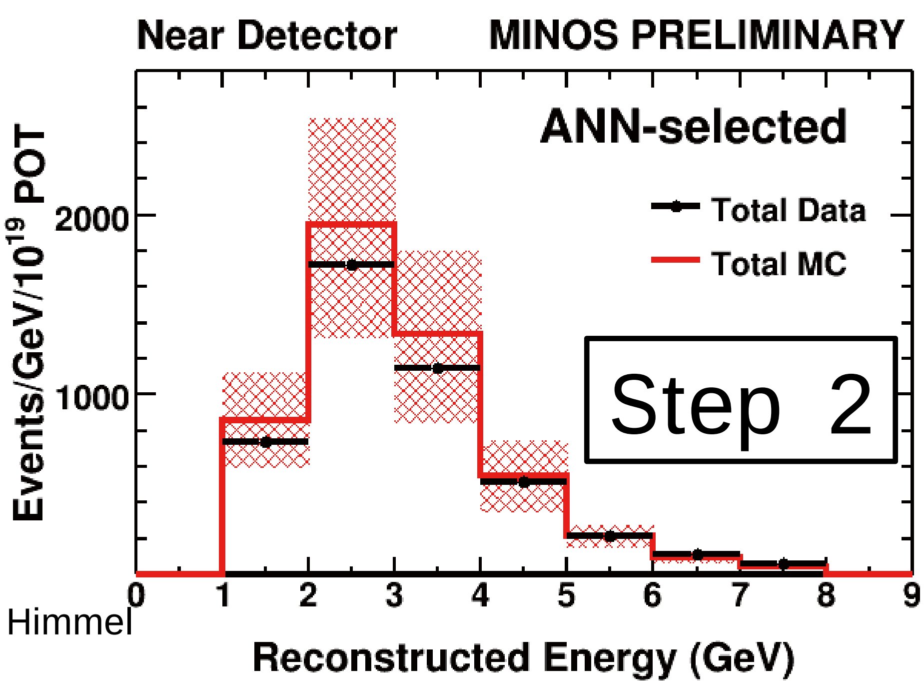
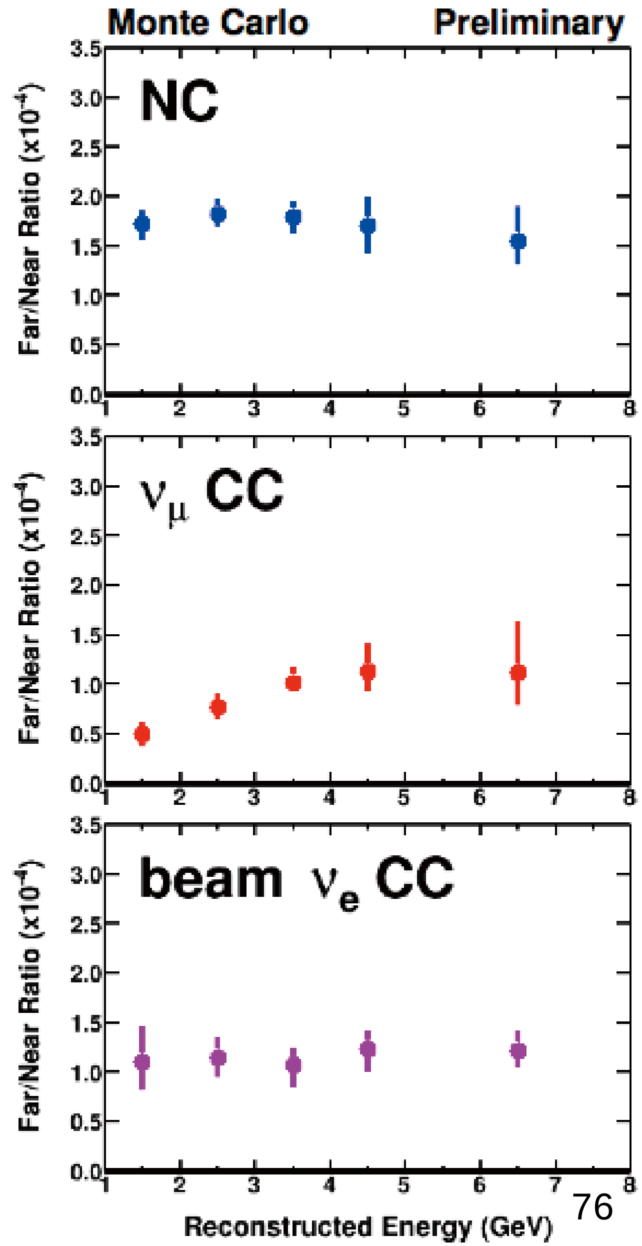




Extrapolation

- 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

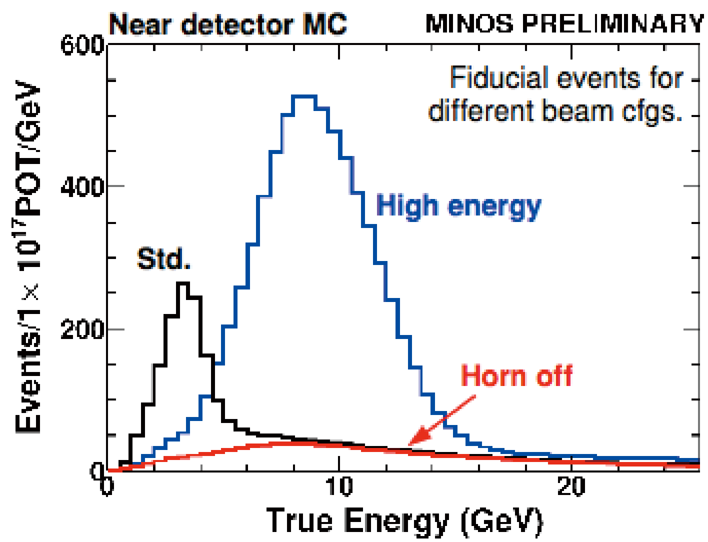


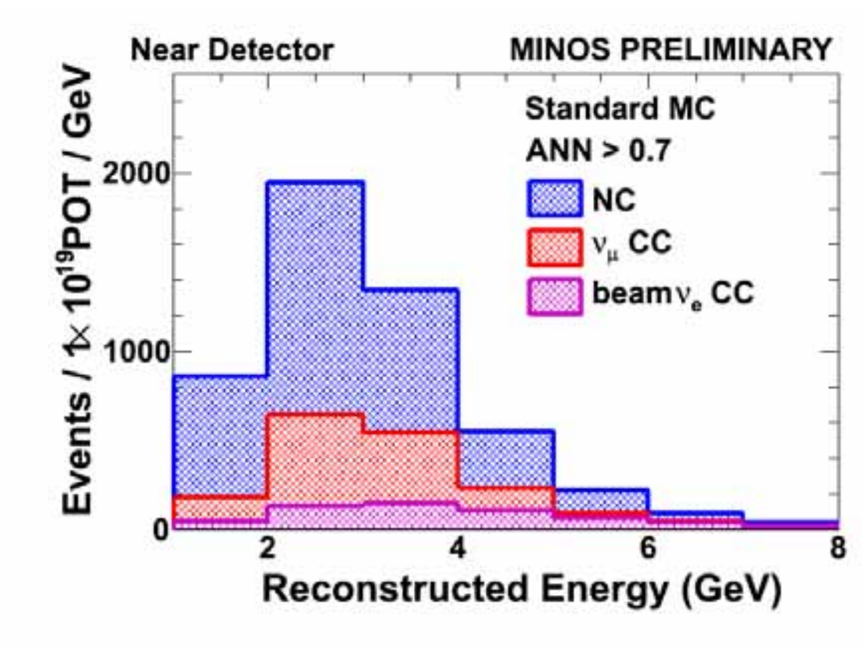


Alex Himmel

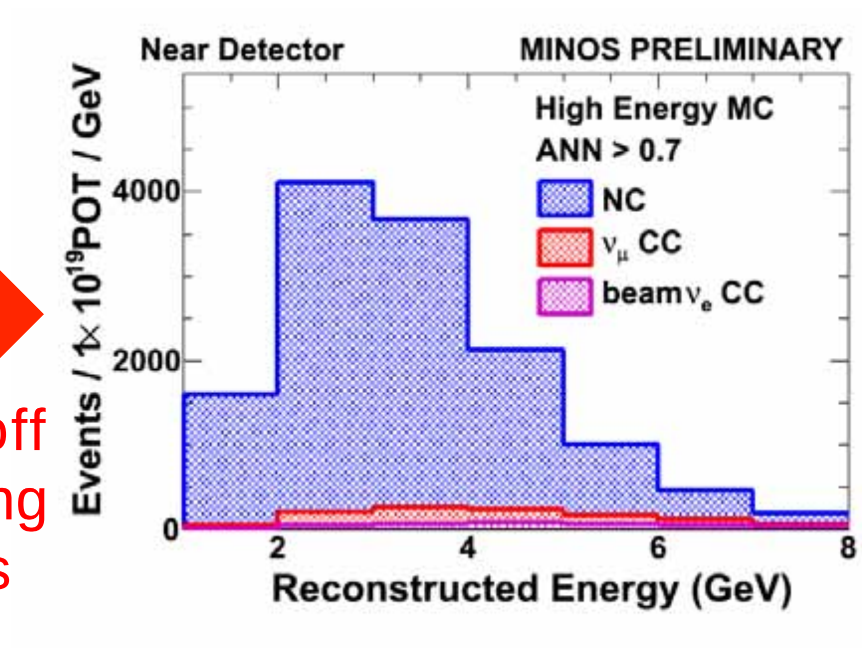
ND Decomposition

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





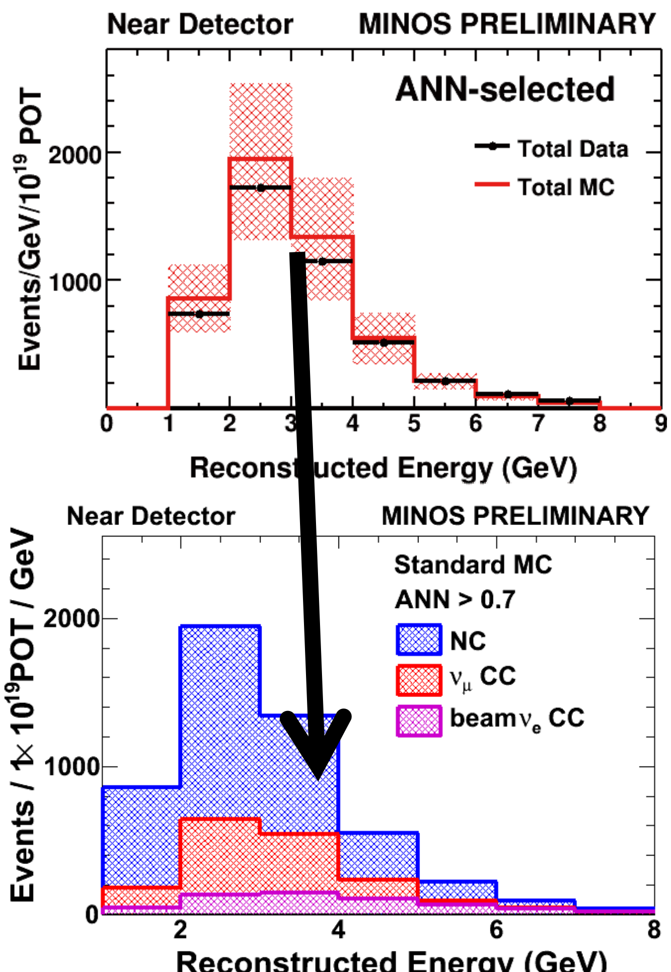
Turn off focusing horns



Extrapolation

Step 3

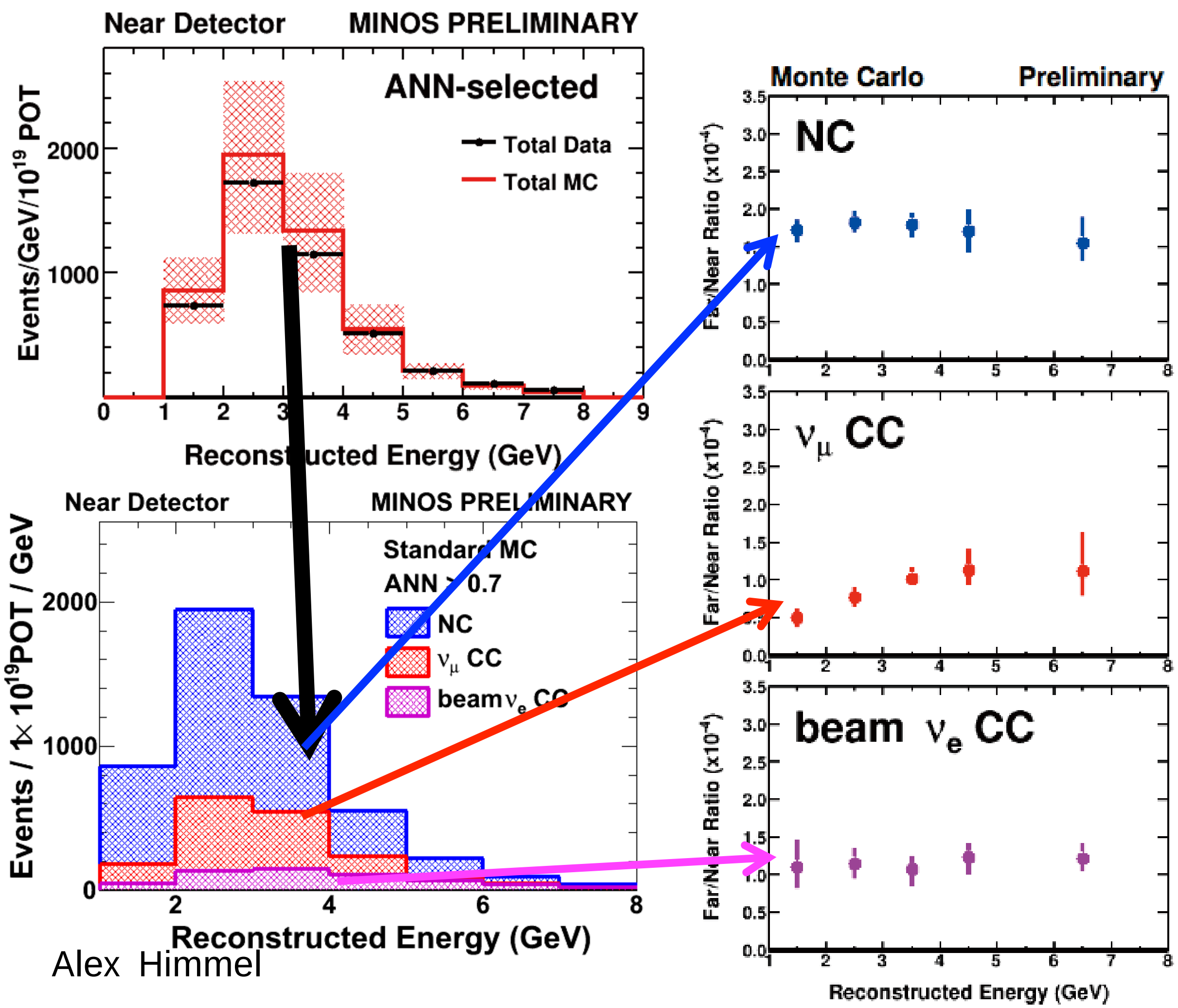
- Apply decomposition to the Near Detector data



Extrapolation

Step 3

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



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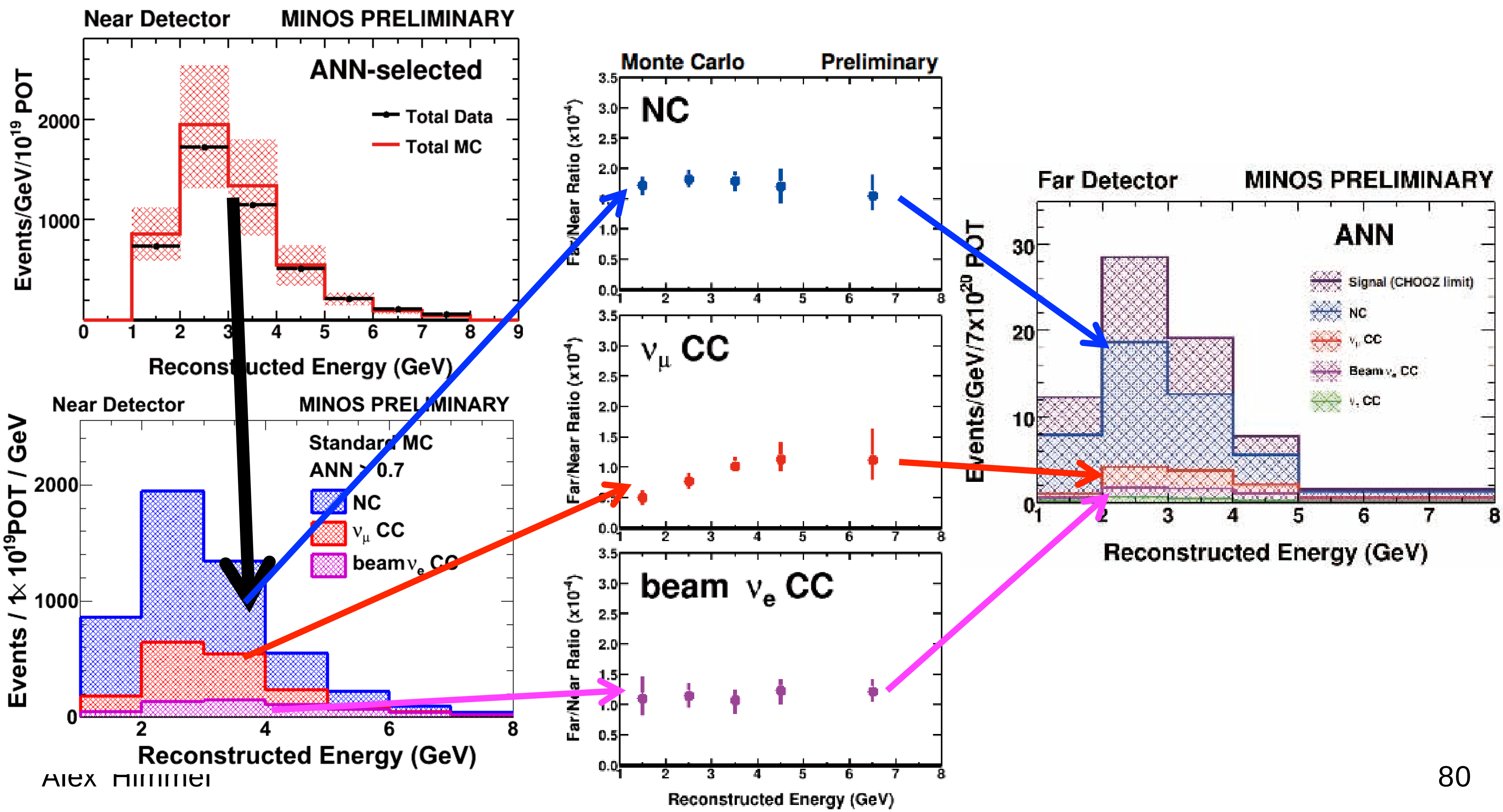
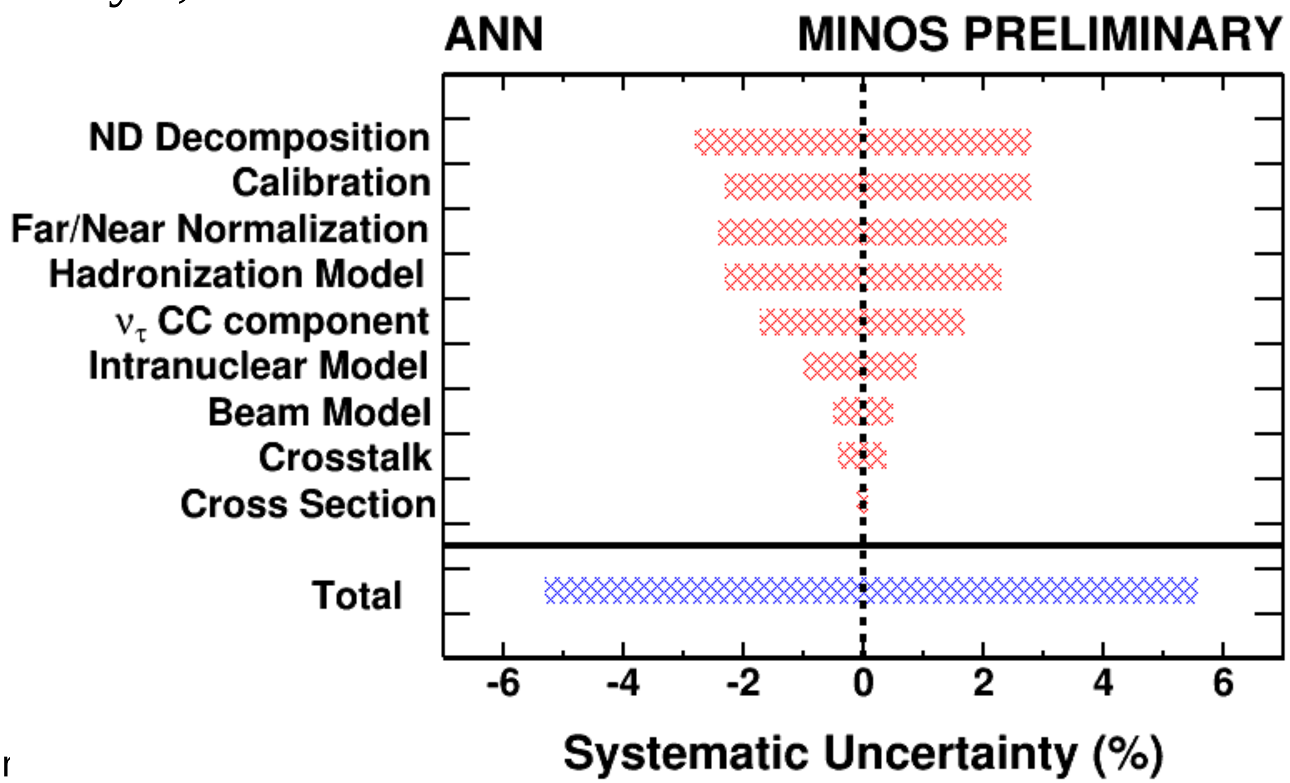


Systematics

- 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



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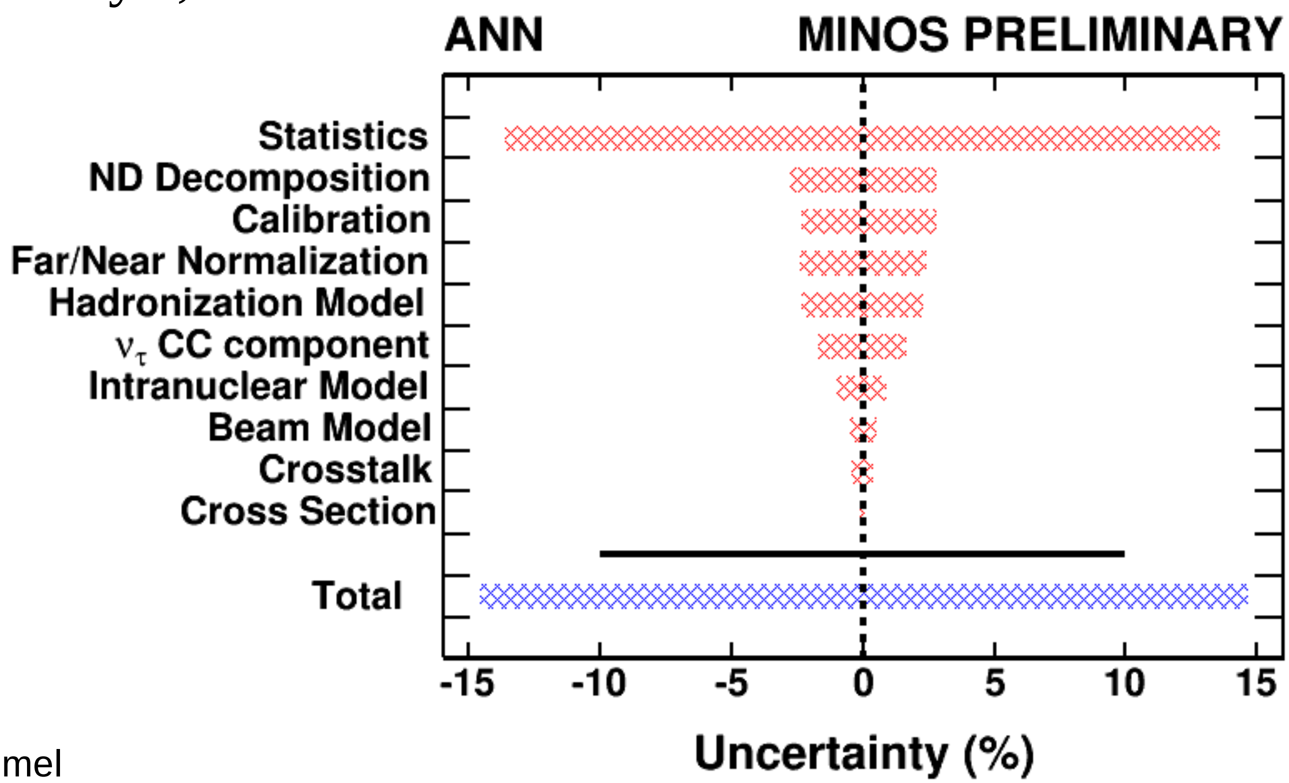
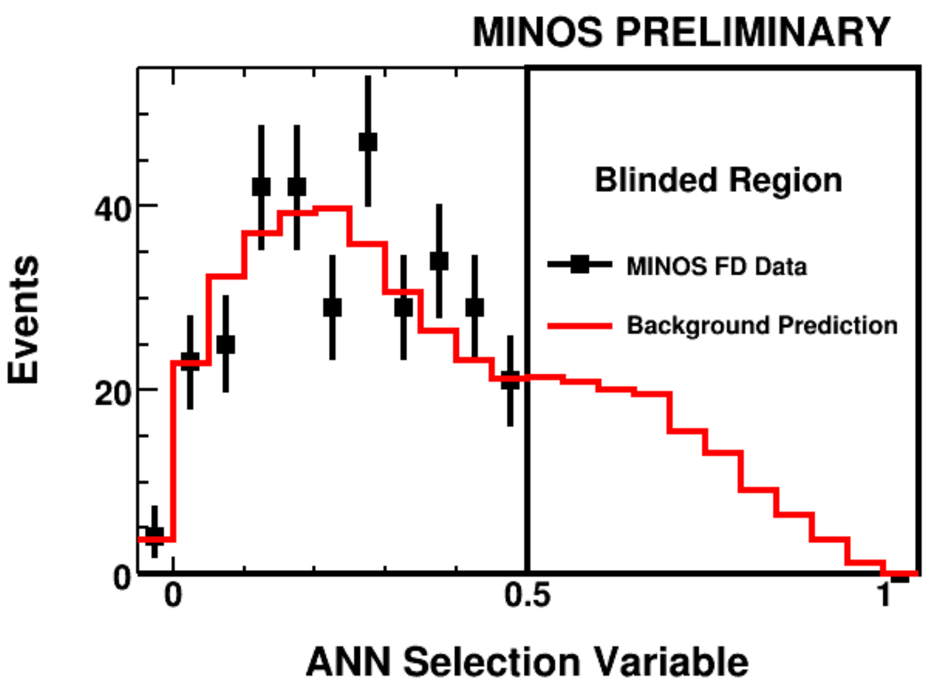
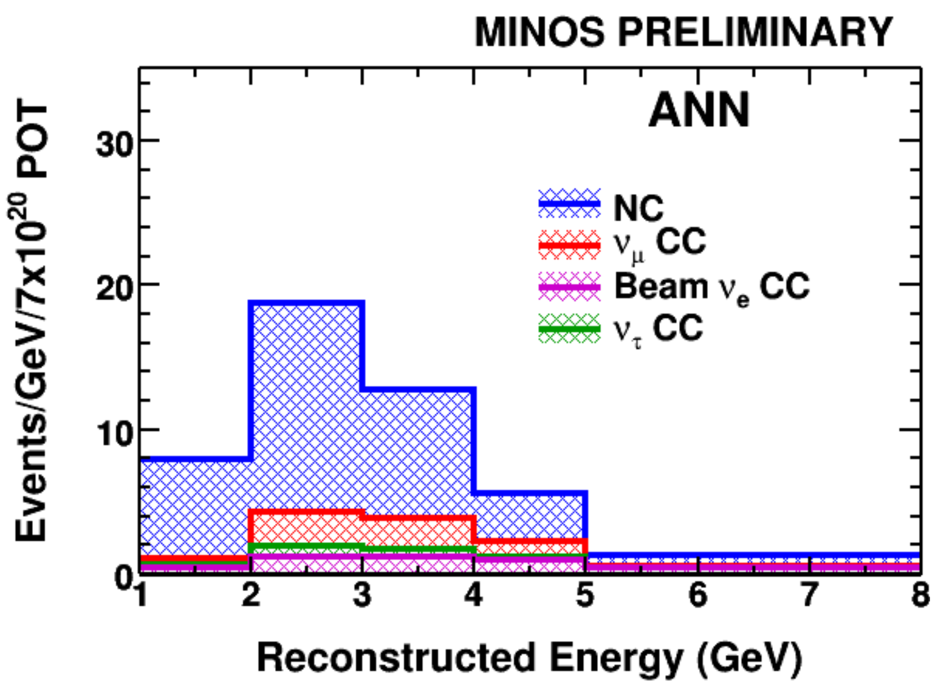


ν_e Appearance Results

Step 4

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

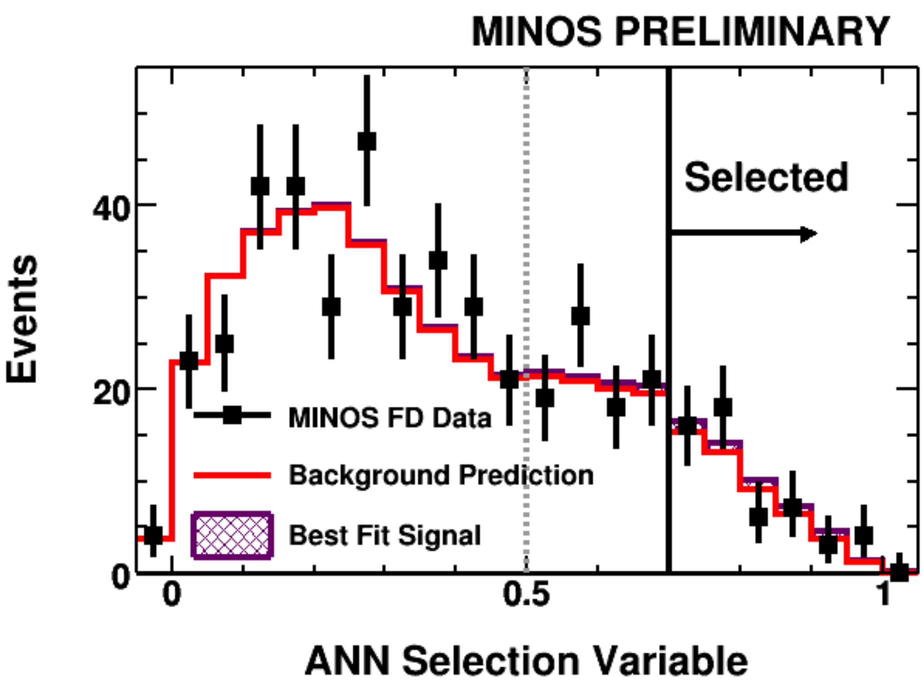


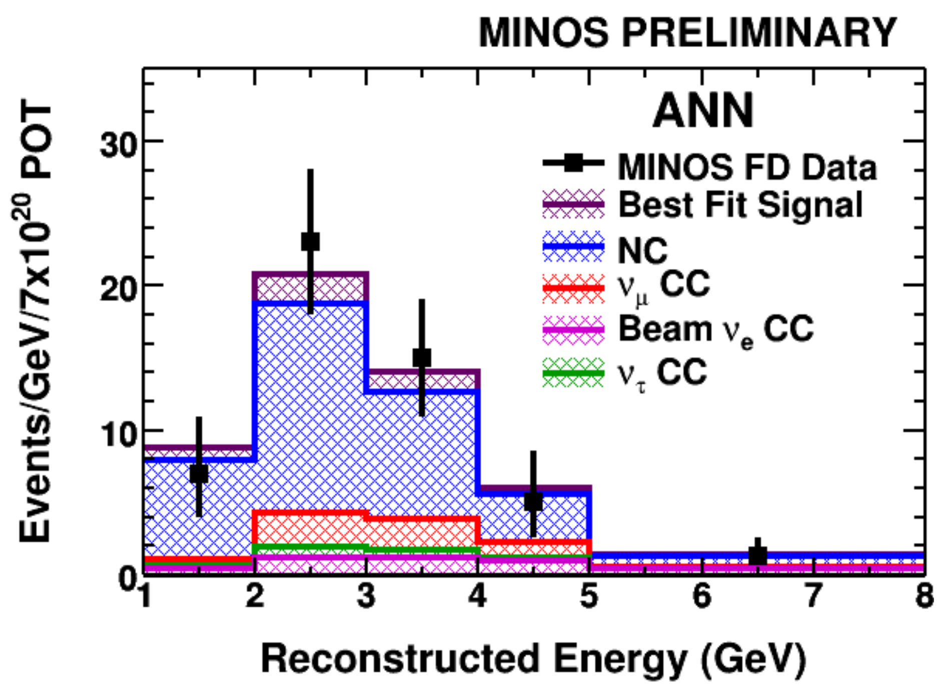


ν_e Appearance Results

Step 4

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





ν_e Appearance Results

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

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

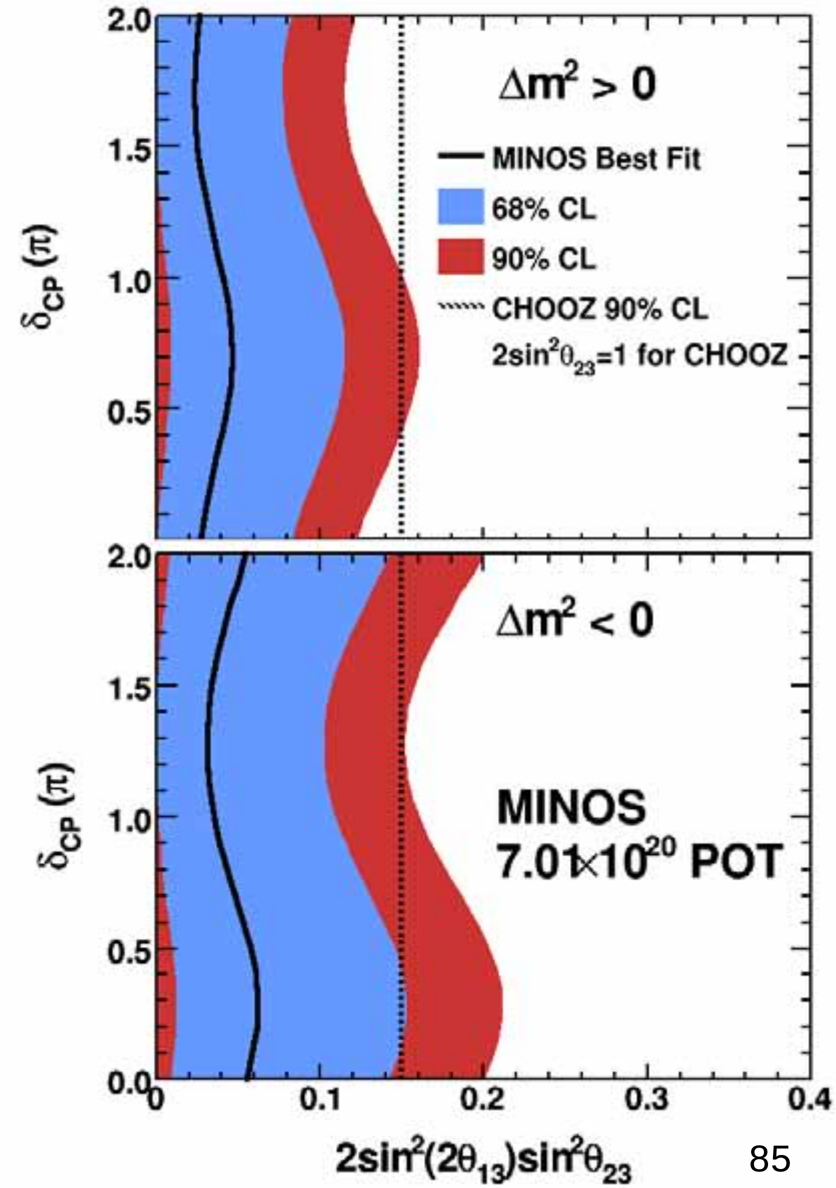
$\sin^2(2\theta_{13}) < 0.12$ normal hierarchy

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

at 90% C.L.

A new analysis is coming next year with improved sensitivity

- More data
- Significantly better background rejection



Summary

- Neutrino oscillations in the atmospheric sector
  - World's best measurement of Δm^2_{atm}
  - Find $\left|\Delta m^2_{\text{atm}}\right| = 2.35^{+0.11}_{-0.08} \times 10^{-3}\ \text{eV}^2$ and $\sin^2(2\theta_{23}) > 0.91$ (90% C.L.)

- Antineutrino oscillations in the atmospheric sector
  - First direct, precision measurement of muon antineutrino disappearance
  - Find $\left|\Delta \overline{m}^2_{\text{atm}}\right| = 3.36^{+0.45}_{-0.40} \times 10^{-3}\ \text{eV}^2$ and $\sin^2(2\overline{\theta}_{23}) = 0.86 \pm 0.11$
  - New antineutrino data to address the tension with neutrinos

- Sterile neutrinos
  - No evidence of oscillations to sterile neutrinos

- The last mixing angle: θ_{13}
  - A non-significant excess gives an upper limit of $\sin^2(2\theta_{13}) < 0.12$
  - An improved analysis with much better sensitivity next year

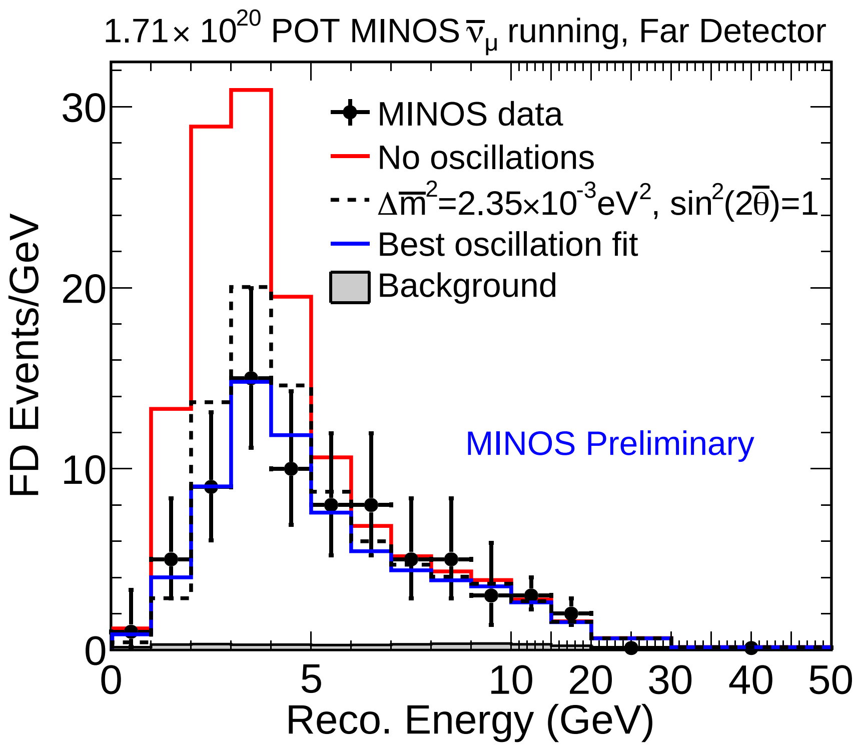
Acknowledgements

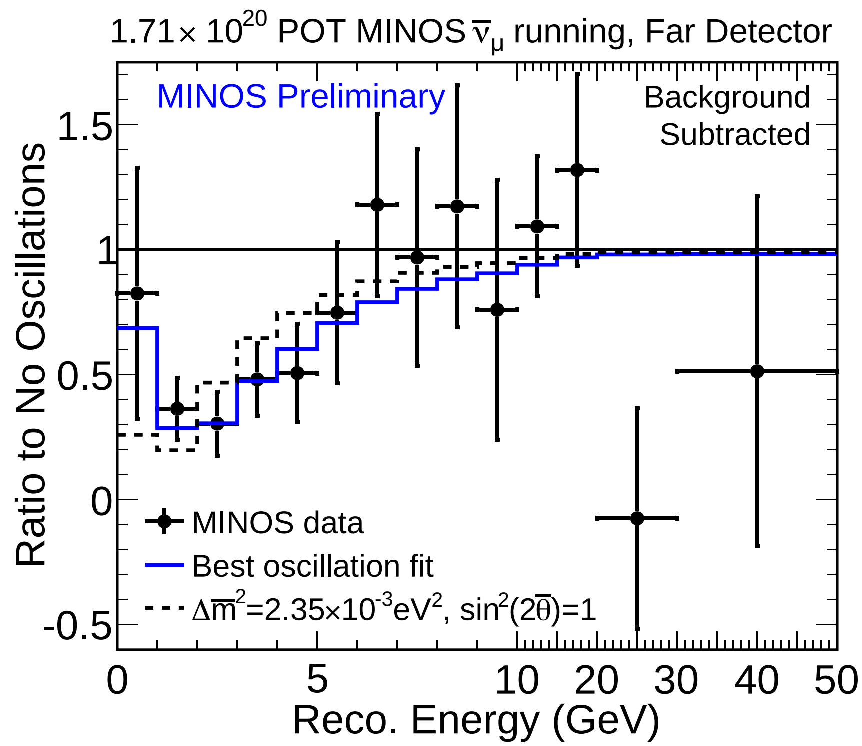
- On behalf of the MINOS Collaboration, I would like to express our gratitude to the many Fermilab groups who provided technical expertise and support in the design, construction, installation and operation of the experiment

- 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

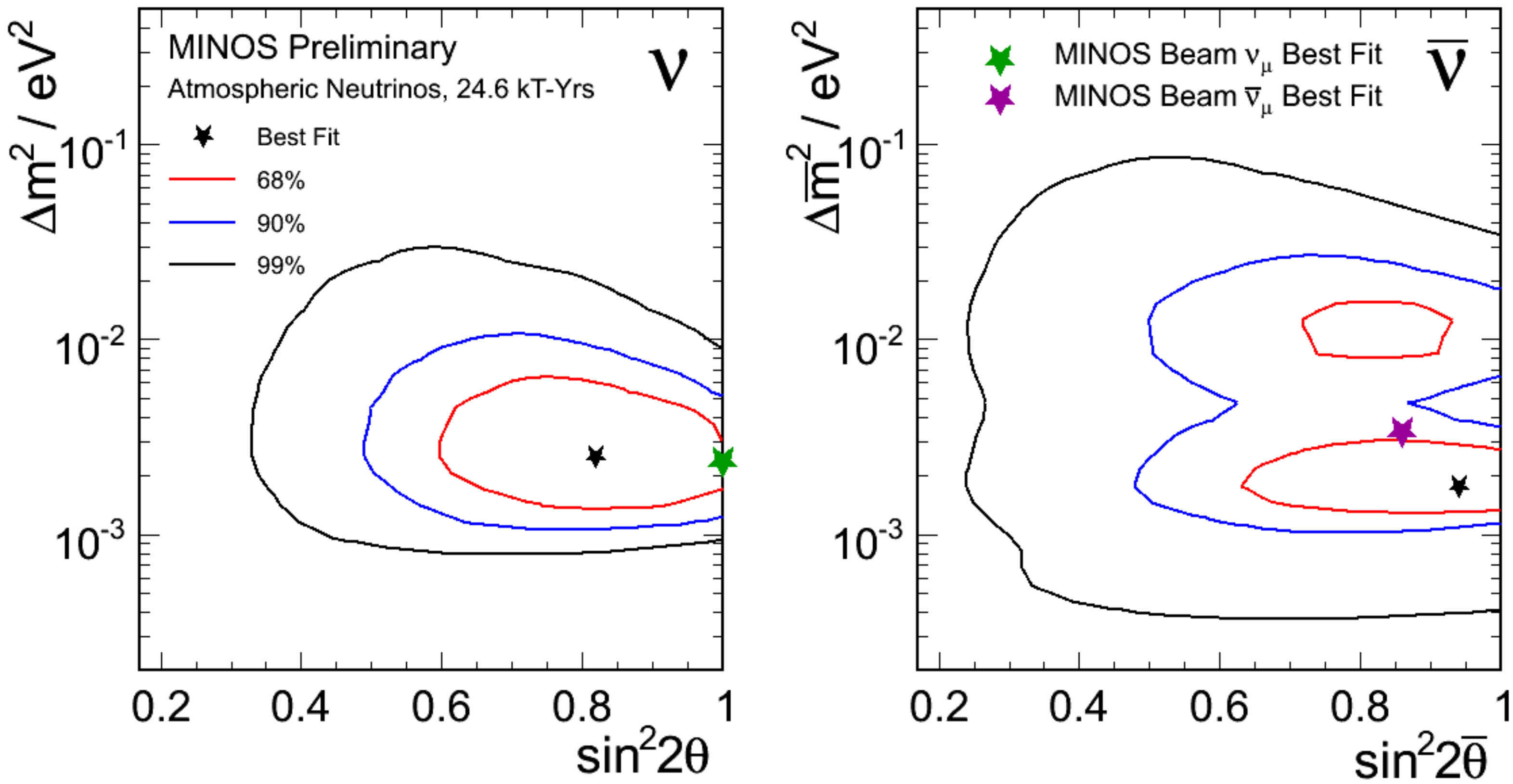
Neutrinos and Antineutrinos





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

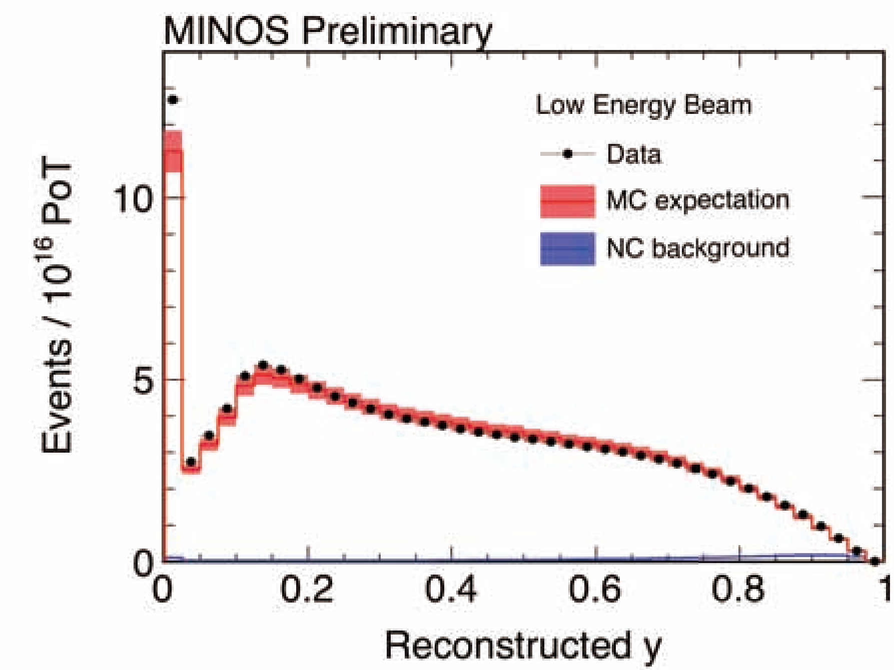
Atmospheric Neutrinos



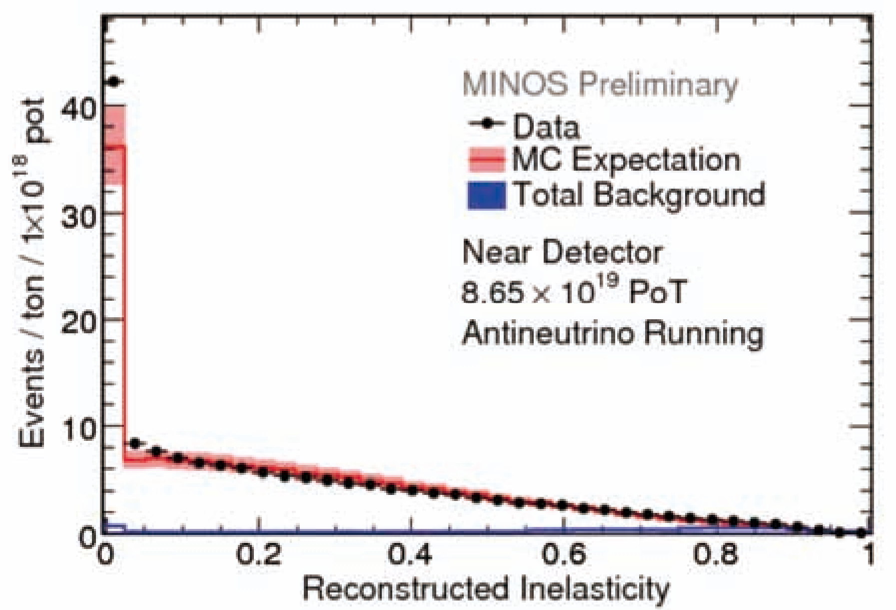
$$R^{data}_{\bar{\nu}/\nu} \,/\, R^{MC}_{\bar{\nu}/\nu} = 1.04^{+0.11}_{-0.10} \pm 0.10$$

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

Neutrino and Antineutrino *y*

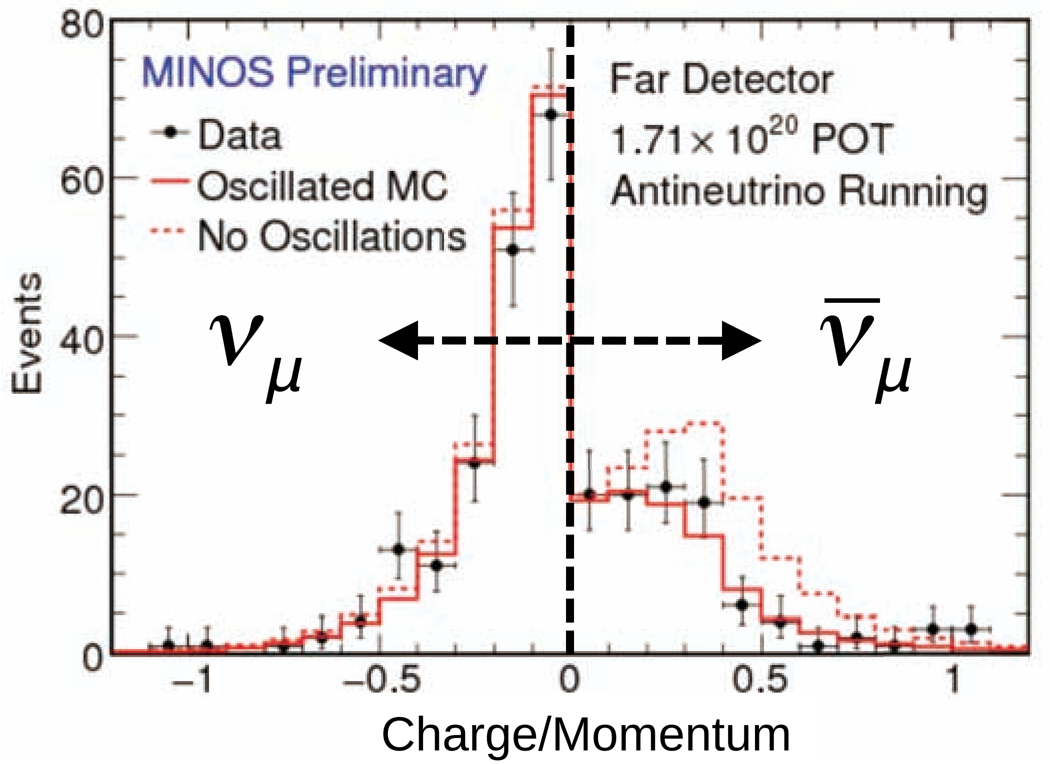


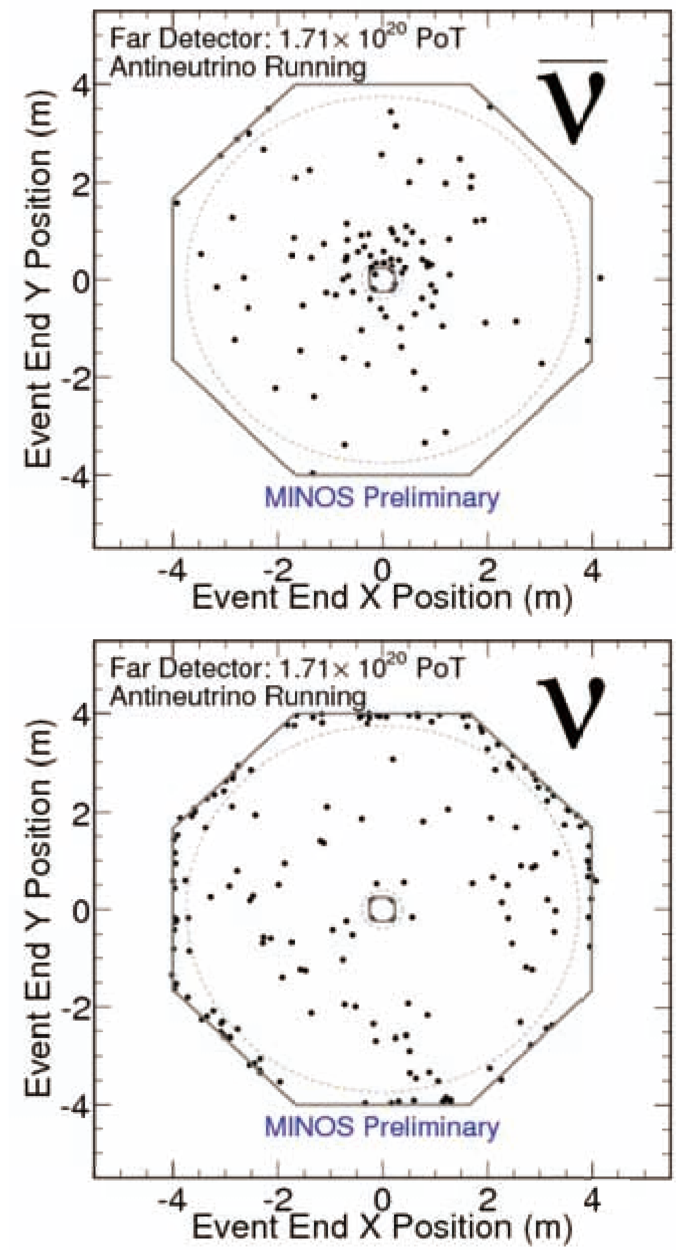
Neutrinos



Antineutrinos

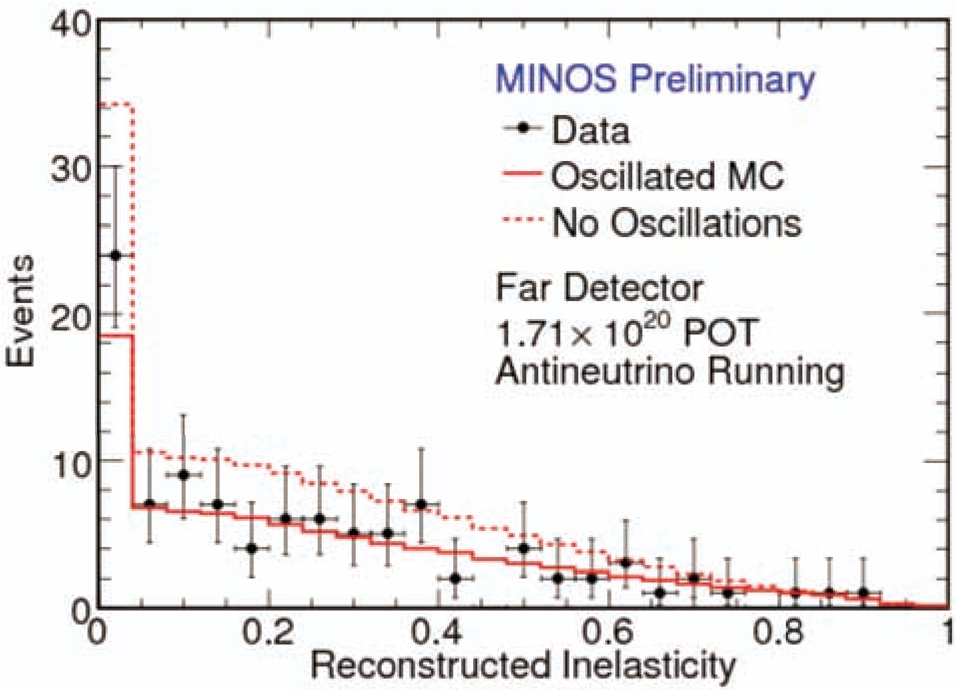
Far Detector Data

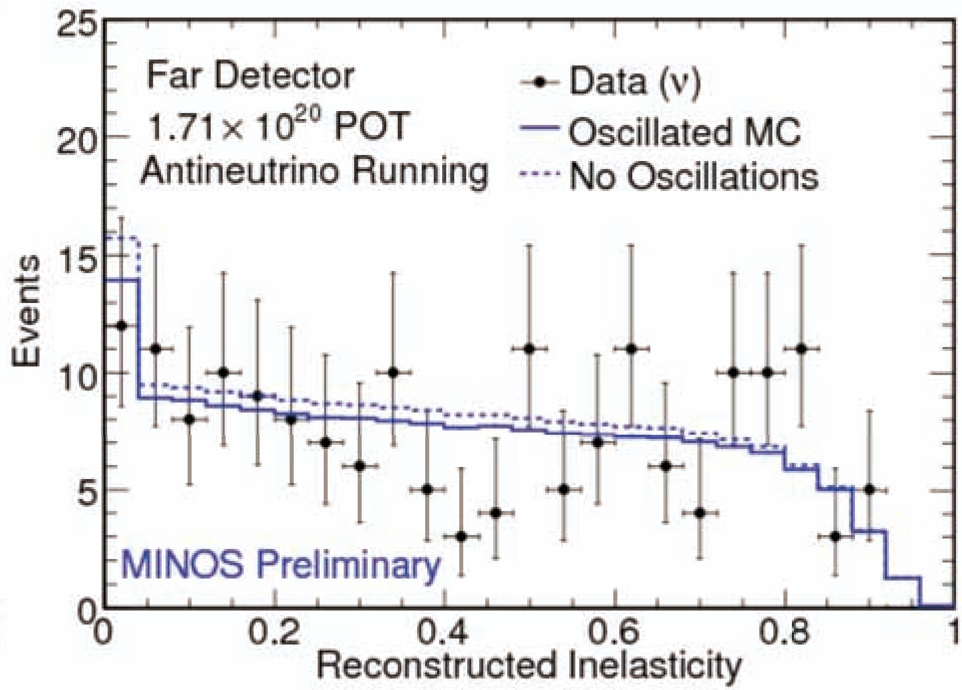




- Good data/mc agreement in charge/momentum
- Antineutrinos focused inwards
- Neutrinos defocused outwards

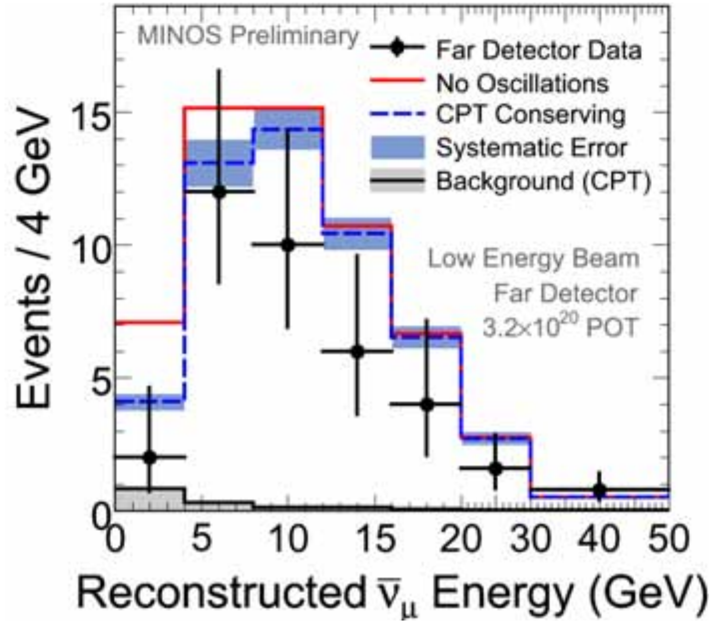
Far Detector Data

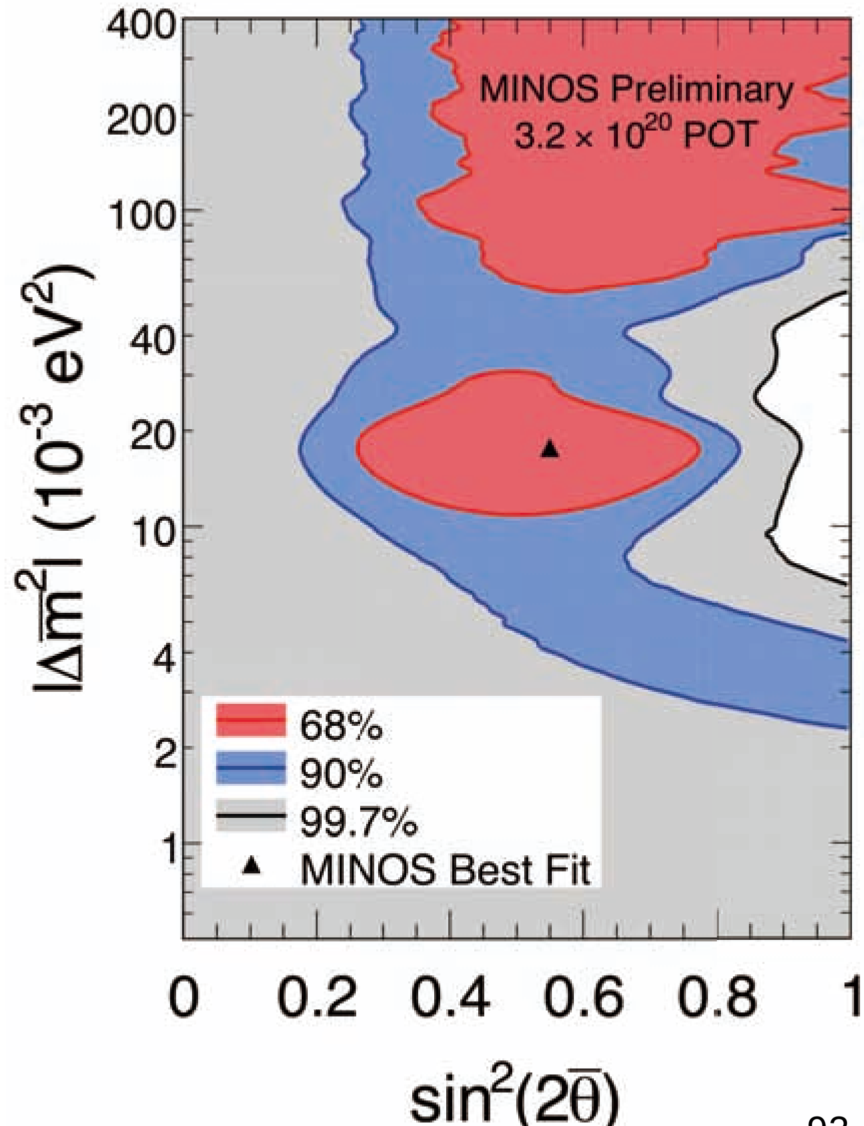




- Data shows the expected distributions of hadronic energy fraction for both neutrinos and antineutrinos

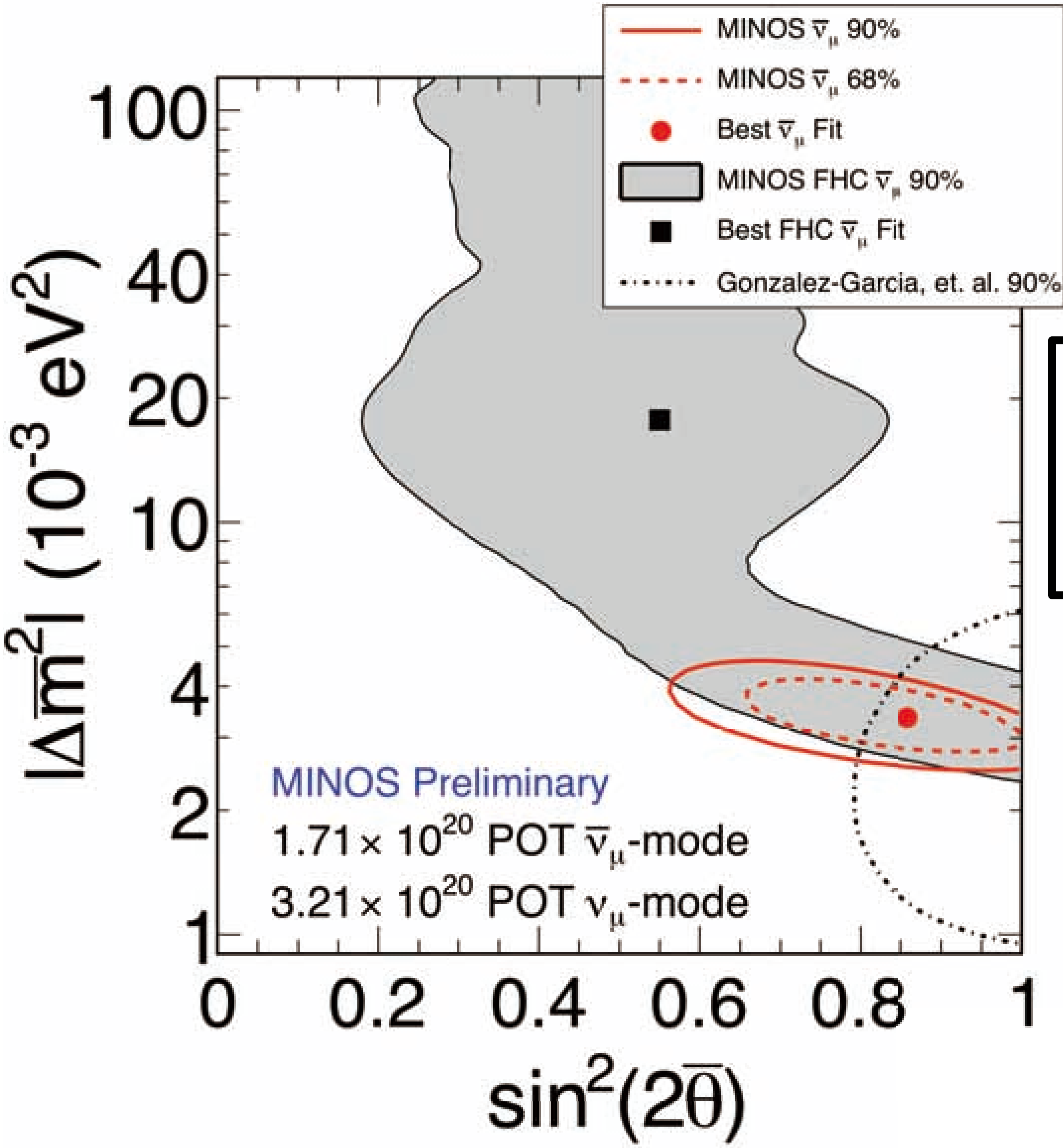
Antineutrinos in Neutrino Mode





- We've already presented an analysis of the antineutrino component of the neutrino beam.
- This sample has poor sensitivity to oscillations.

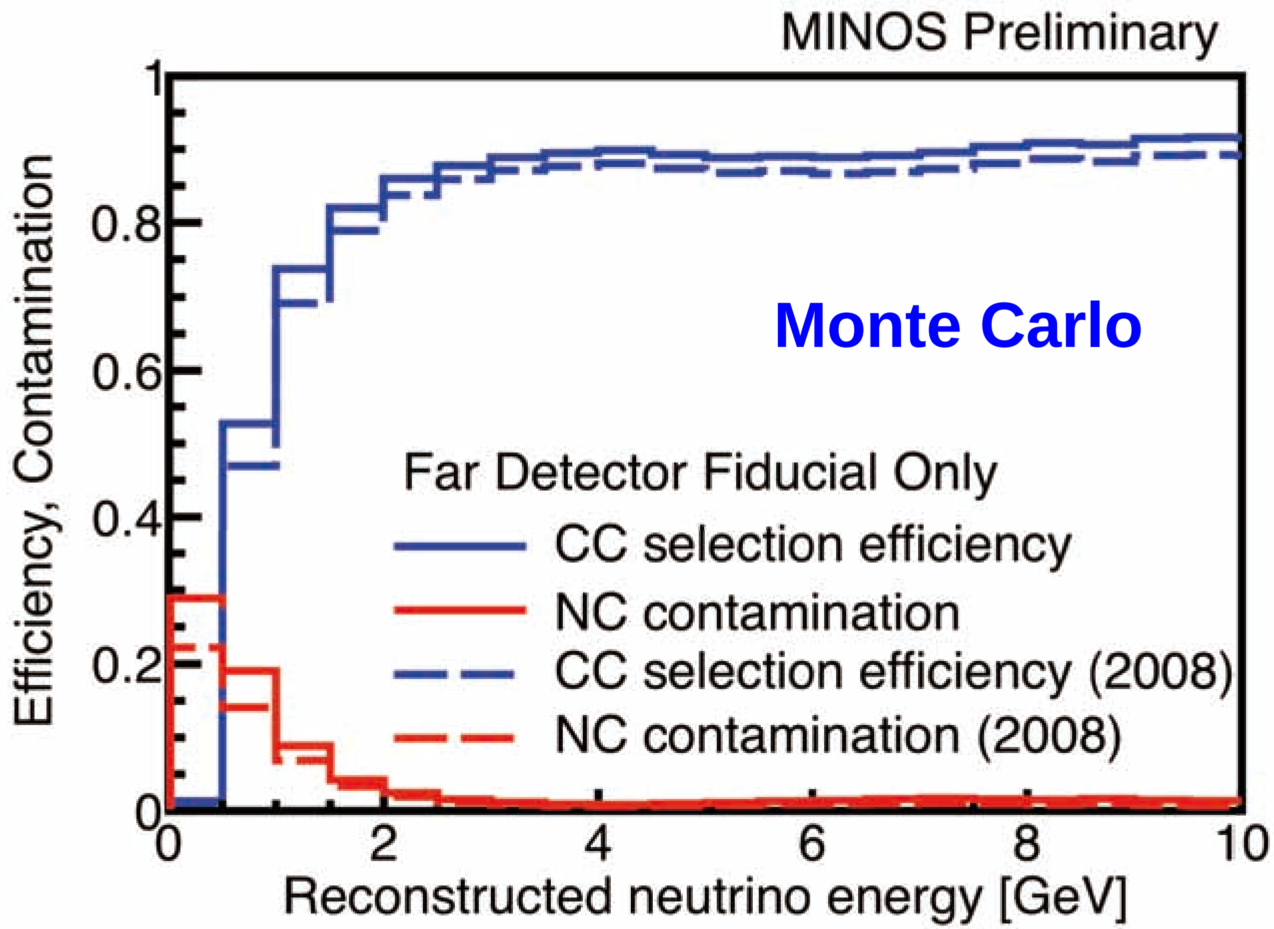
Antineutrino Contour



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

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

Neutrino Selection

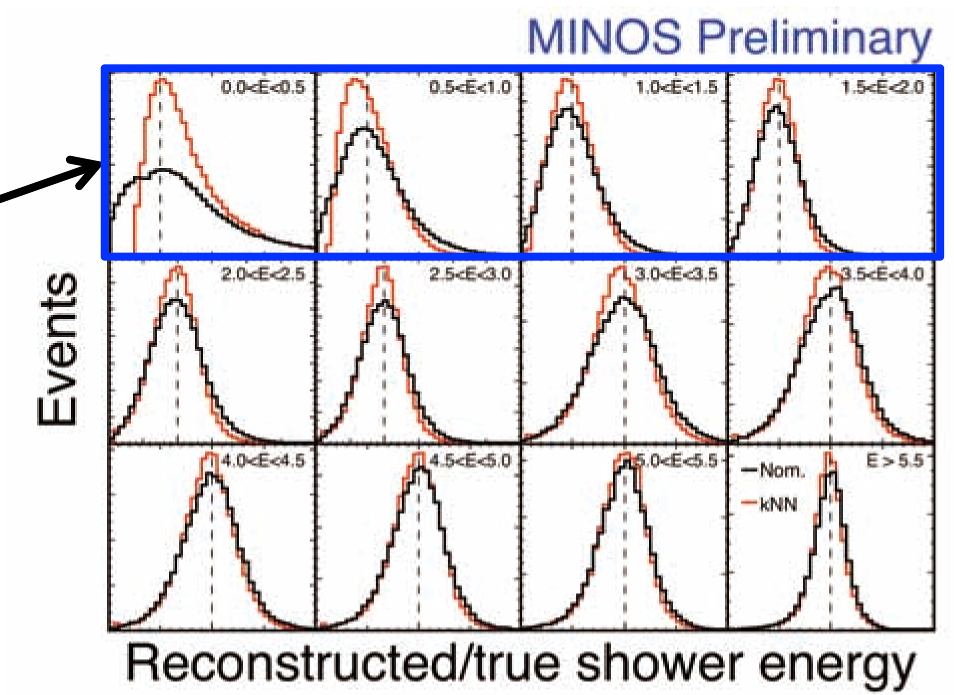


- Increase sensitivity by improving efficiency (89% vs. 87%) at the expense of contamination (1.7% vs. 1.2%)

New Shower Energy Estimator

- Construct a three-parameter kNN using:
  - the shower energy within 1 m of the track vertex
  - the number of planes in the shower
  - the energy in the second reconstructed shower
- Estimator is the mean energy of the nearest neighbors

~30% better resolution below 2 GeV



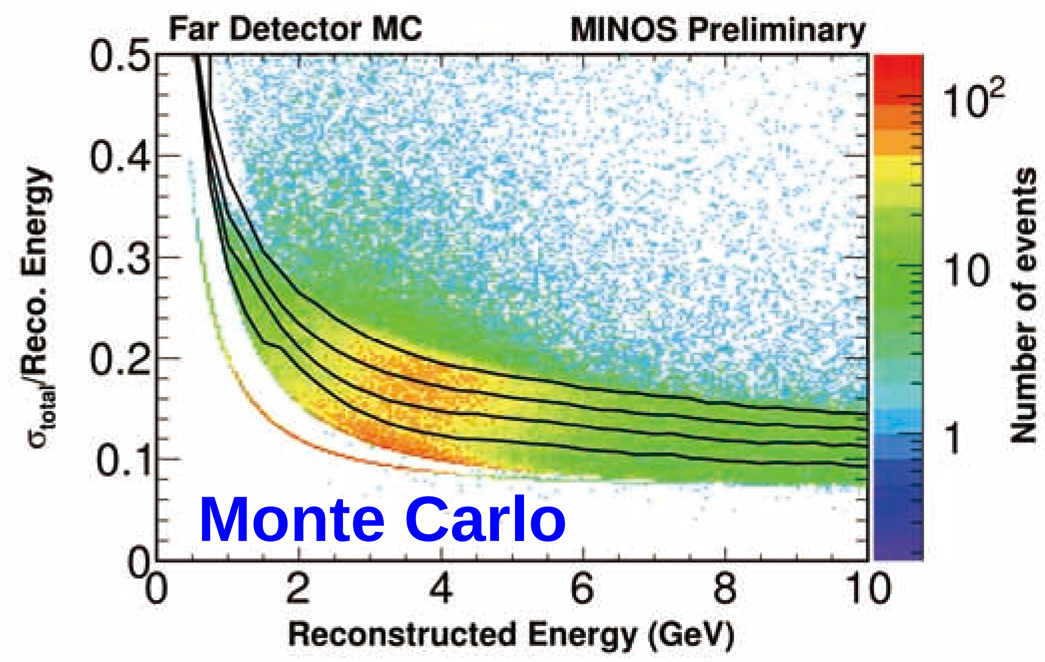
Monte Carlo

Original Energy

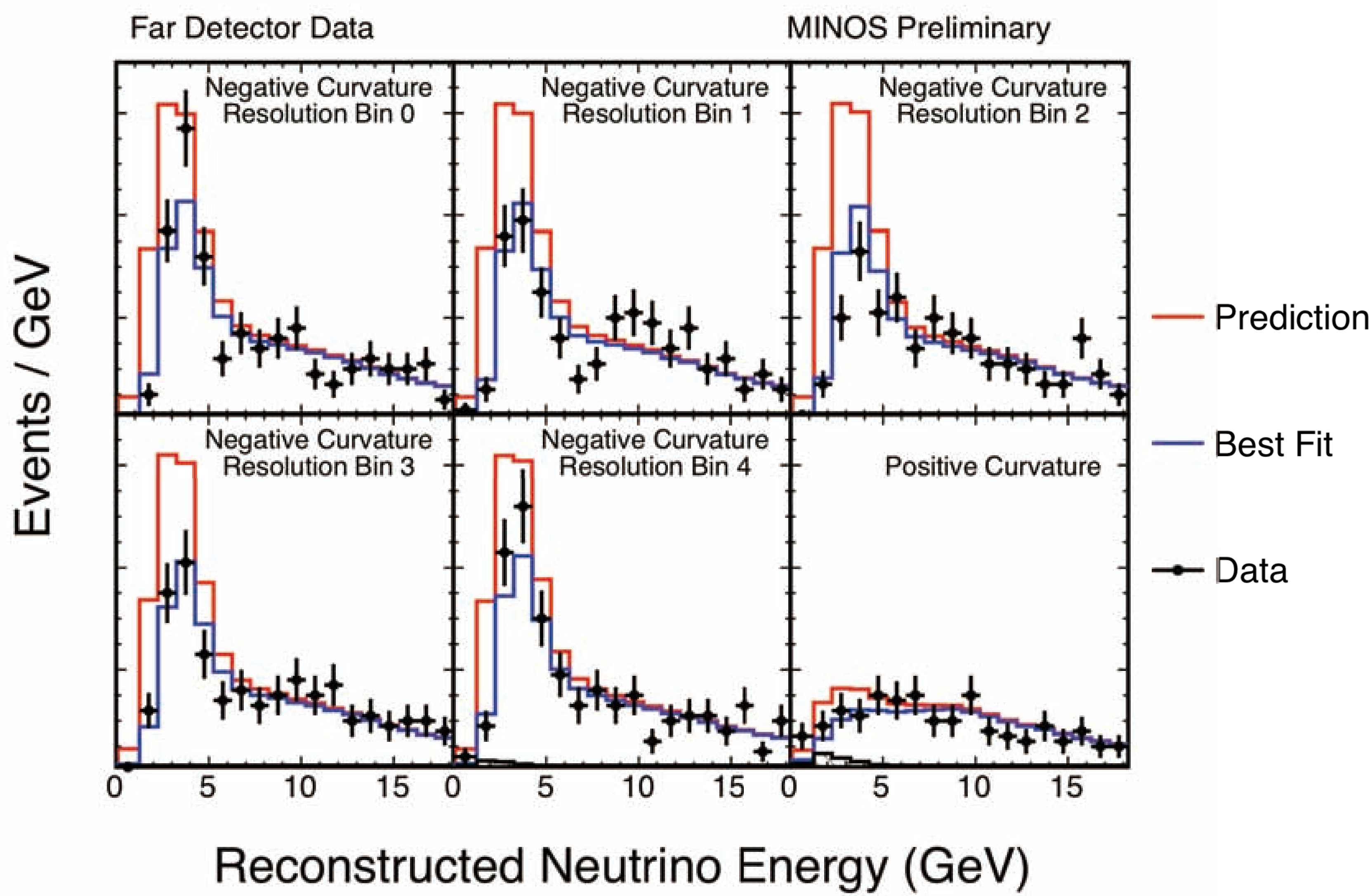
New Estimator

Resolution Binning

- Improve statistical power by separating high and low resolution events.
- MC parameterization of the energy resolution
- 6 Resolution bins
  - 5 bins for events with negative reconstructed curvature
  - 1 bin for events with positive reconstructed curvature (30% true ν_μ)

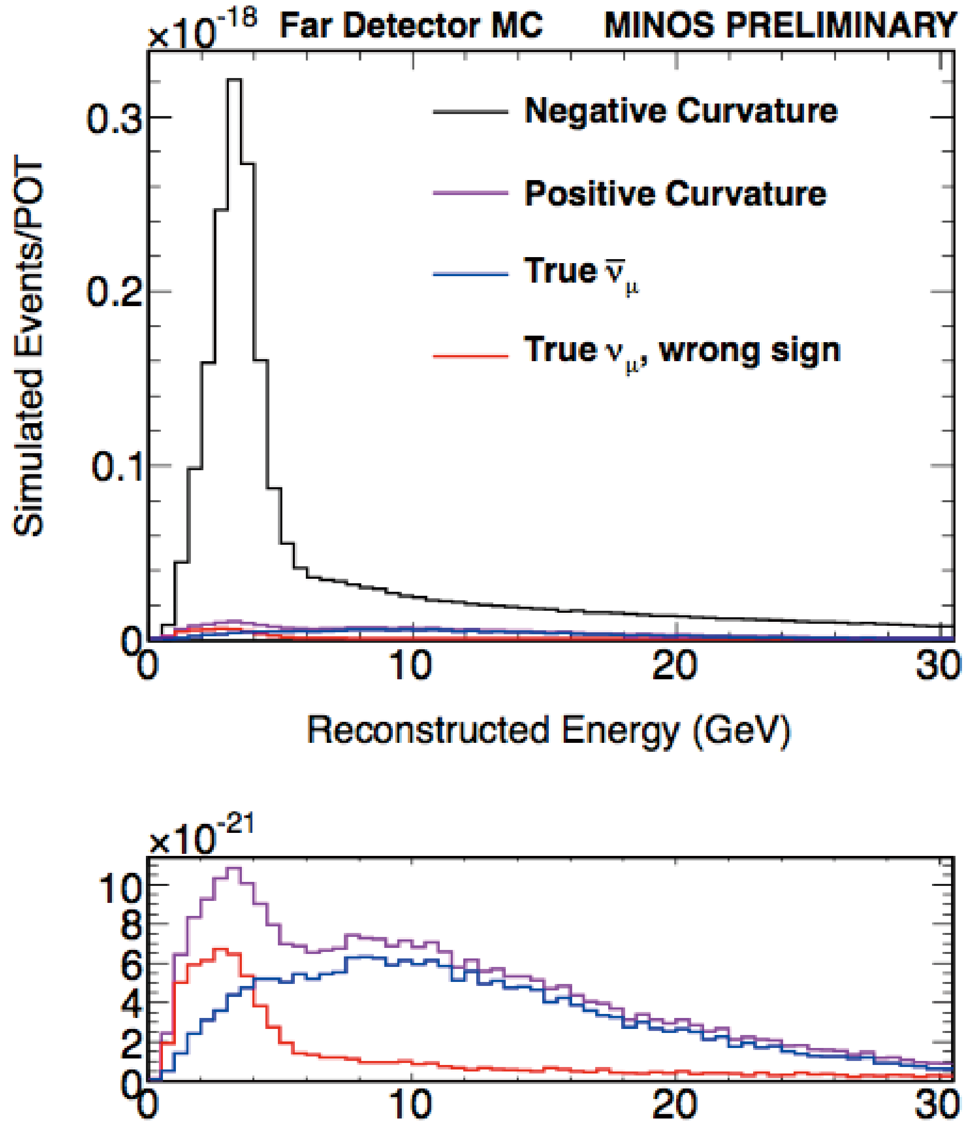


Neutrino Spectrum

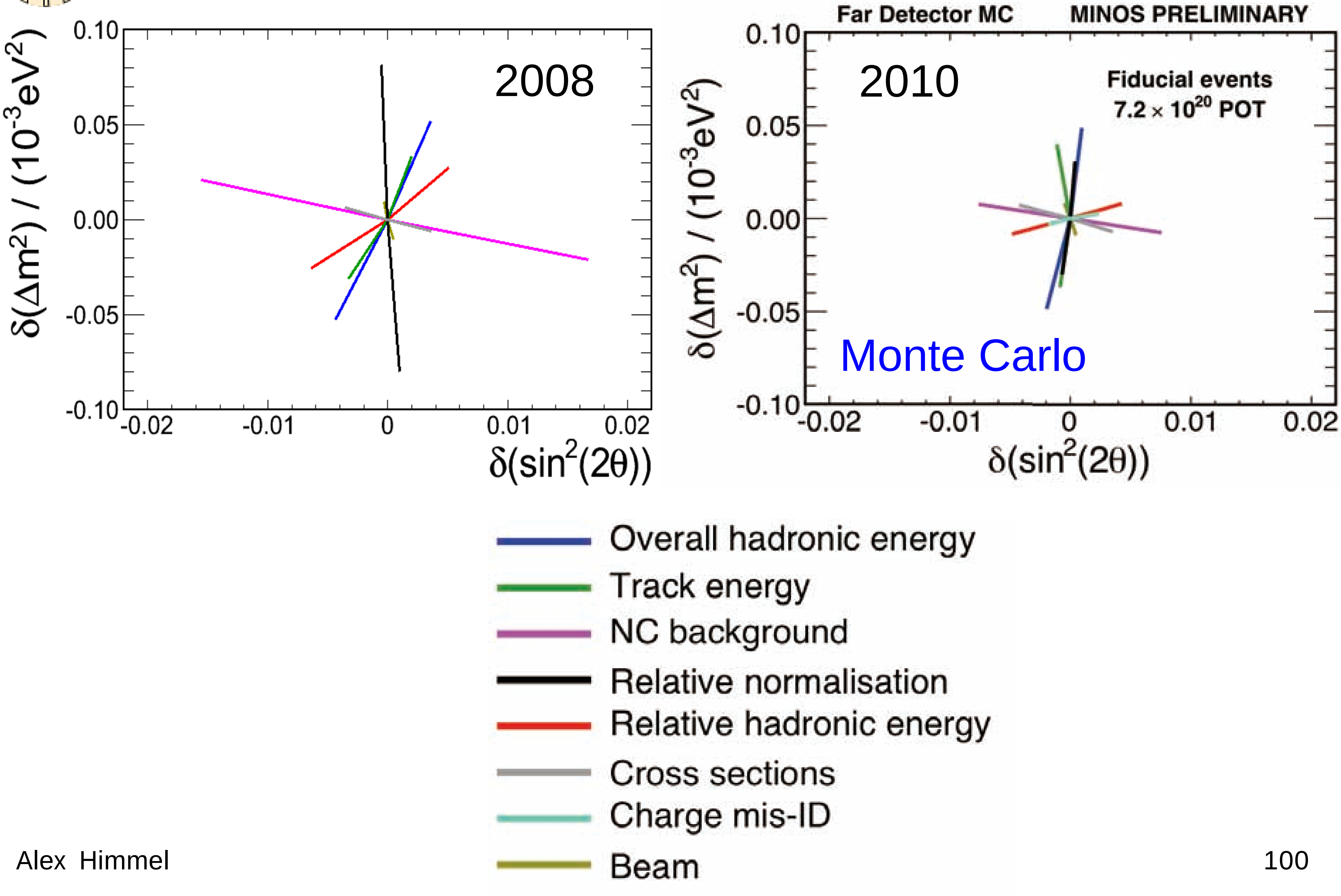


Removing the Charge Cut

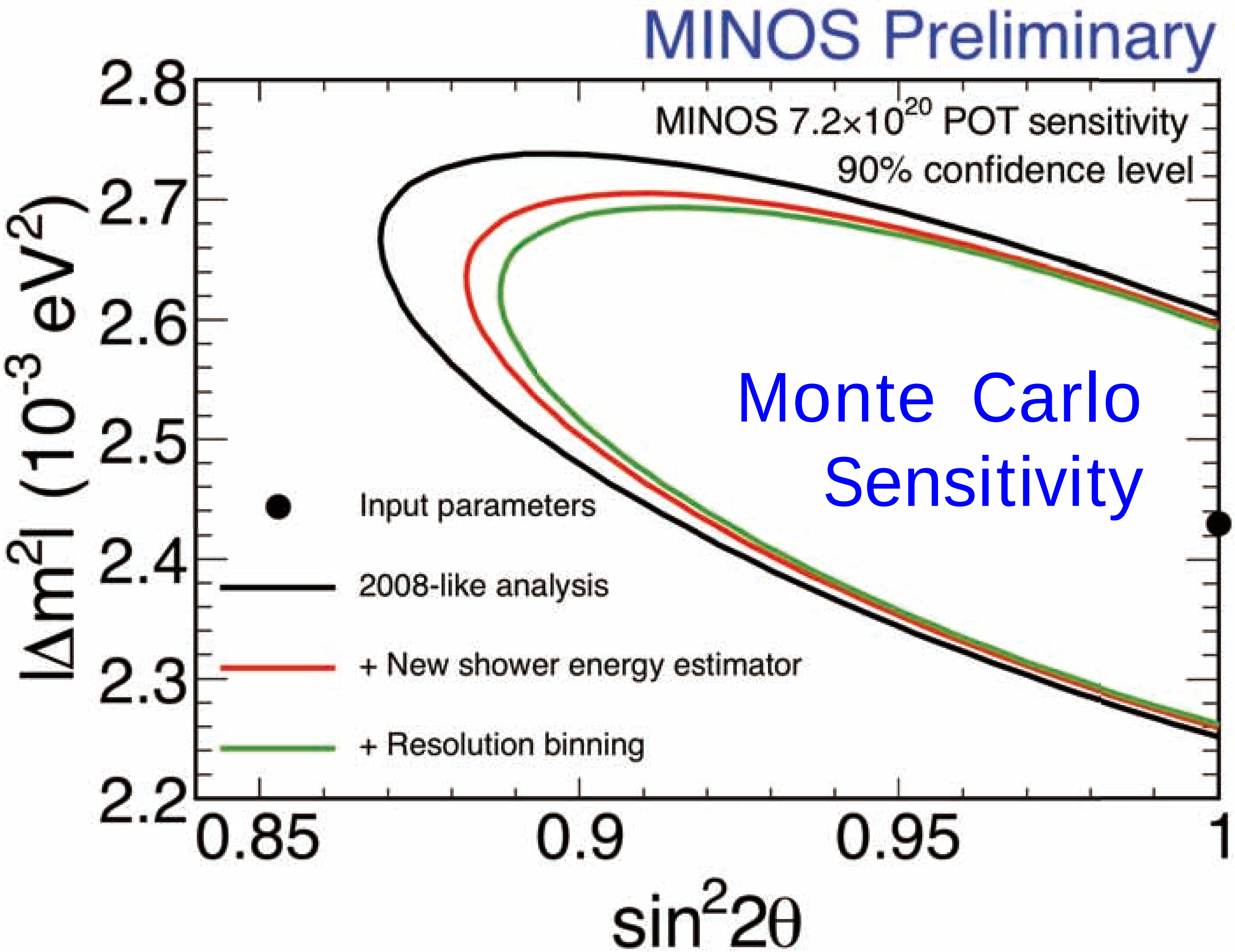
- The positive-curvature sample is ~30% true CC neutrinos.
- If the antineutrinos are oscillated at the antineutrino best fit point, makes a change only in 3rd significant digit of the result.



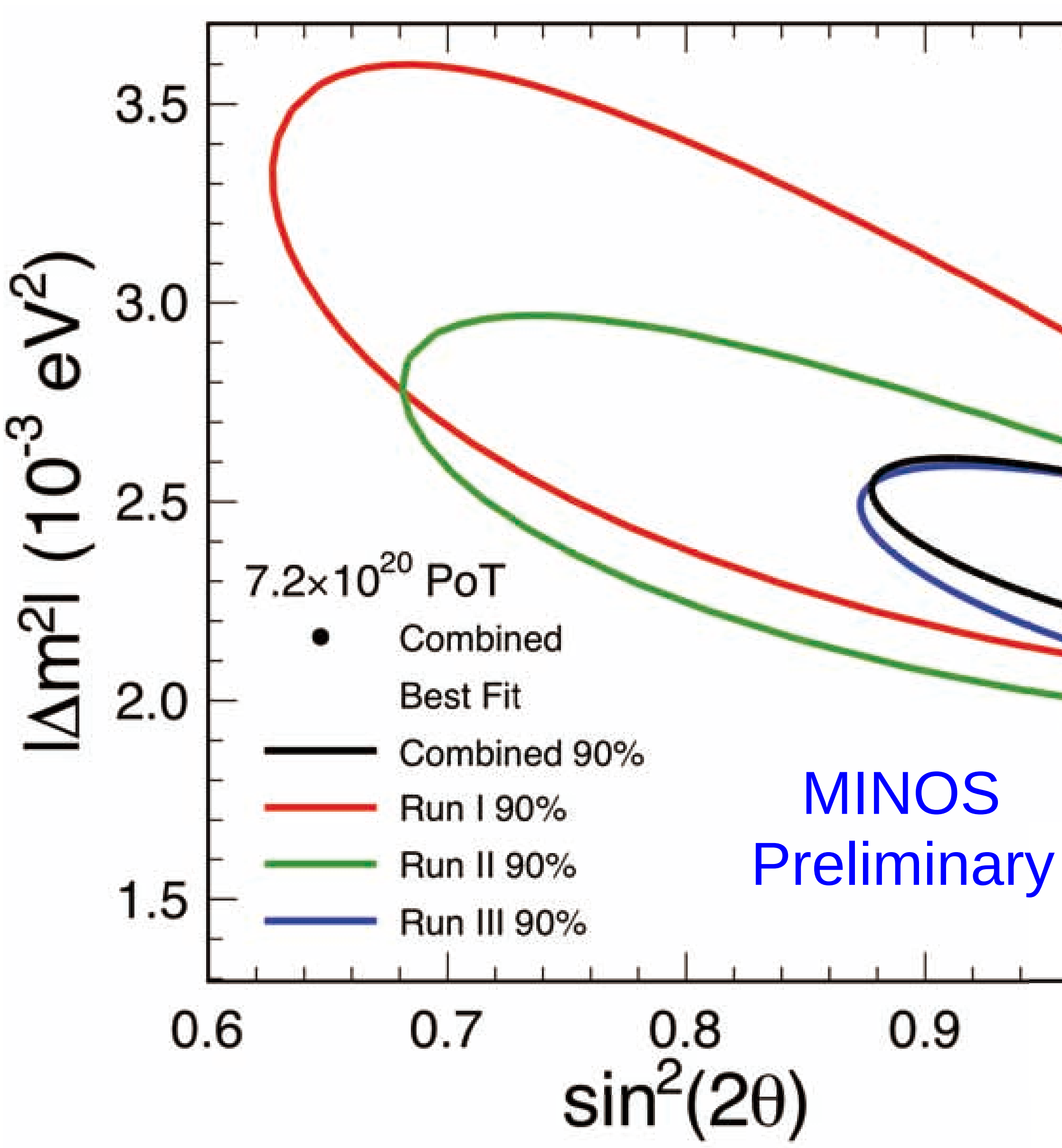
Change in Systematics



Analysis Improvements

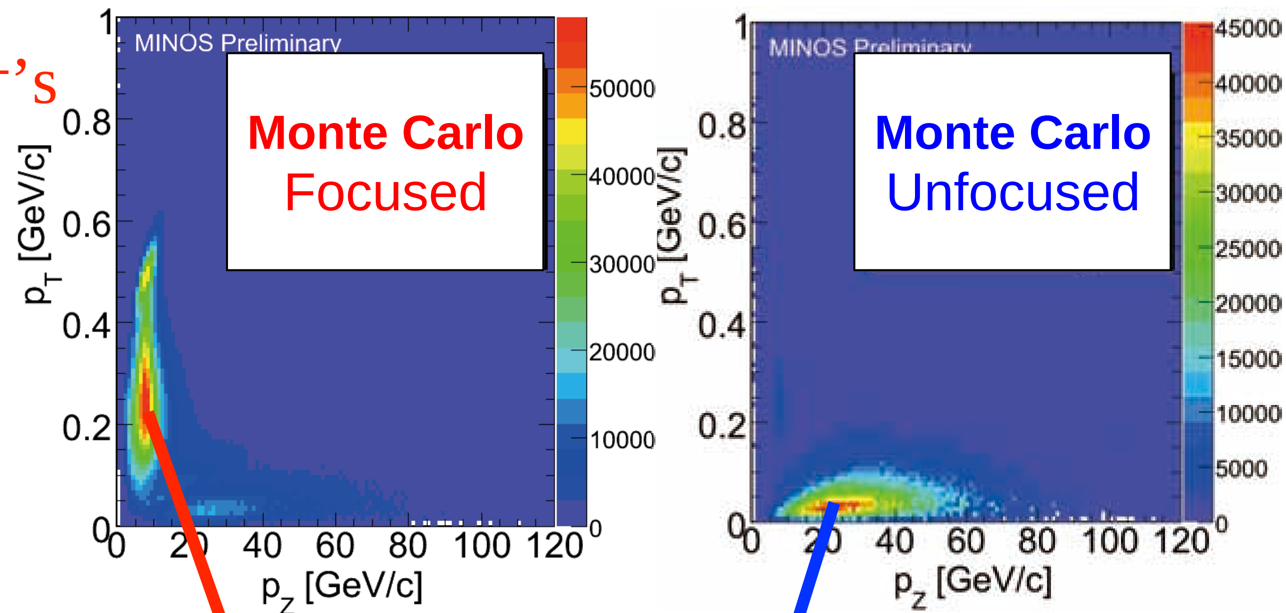


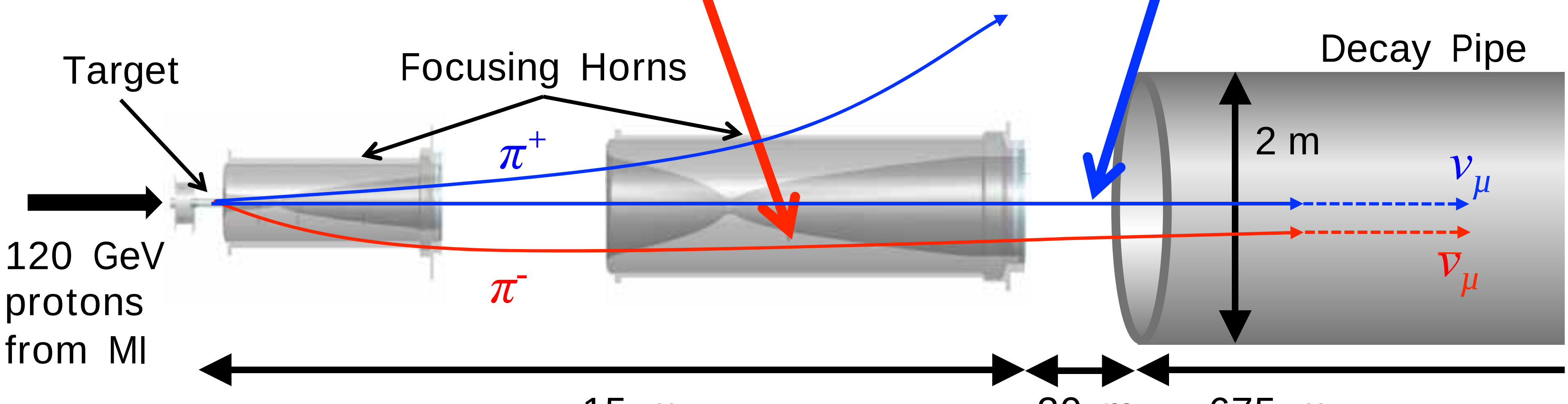
Neutrino Contour by Run



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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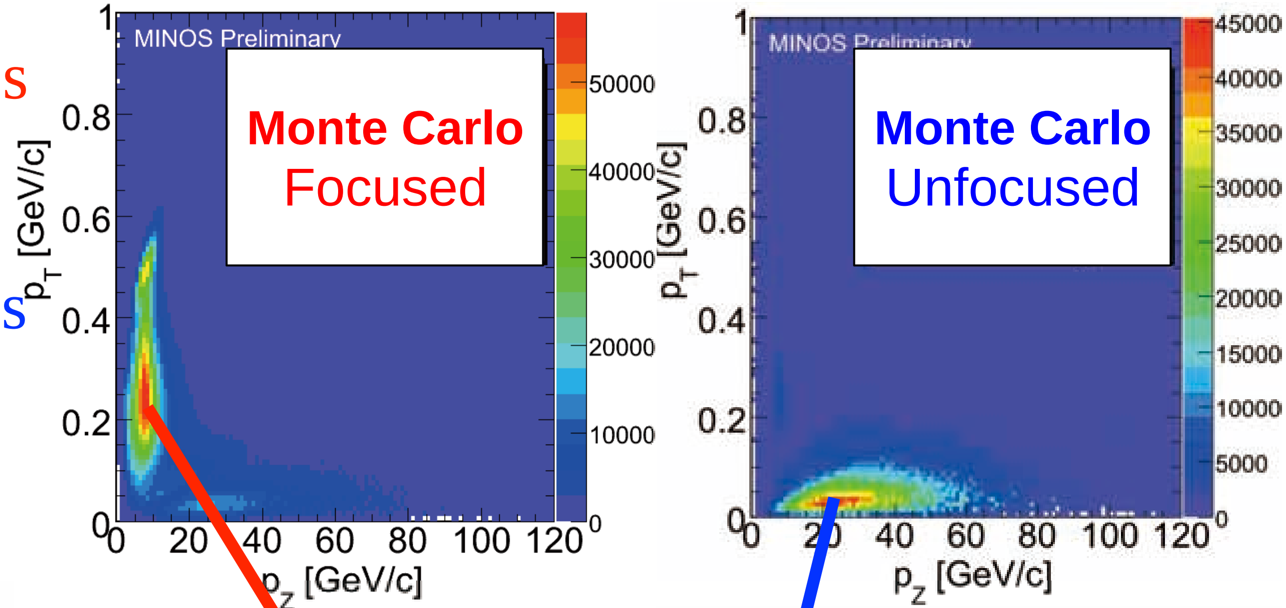

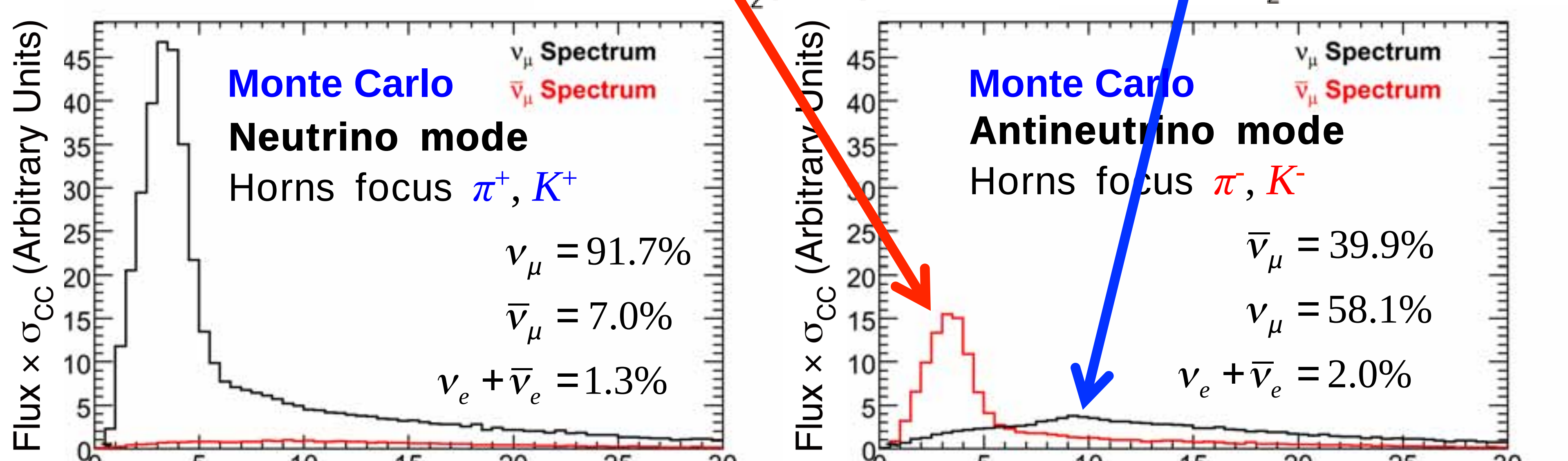

Helium in the Decay Pipe

- 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