RESULTS FROM MINOS

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Outline

- Review of neutrino oscillations
- The MINOS experiment and results
  - Muon neutrino disappearance
  - Muon antineutrino disappearance
  - NC event rate
  - Electron neutrino appearance
- MINOS+

Neutrinos Have Mass!

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = U^\dagger \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

$$P(\nu_\alpha \rightarrow \nu_\beta) = \left| \sum_j U^*_{\beta j} e^{-i\frac{m_j^2 L}{2E}} U_{\alpha j} \right|^2$$

- $\nu_e, \nu_\mu, \nu_\tau \leftrightarrow \nu_1, \nu_2, \nu_3$
  - Flavor States: creation and detection
  - Mass States: propagation
- A neutrino created as one flavor can later be detected as another flavor, depending on:
  - distance traveled (L)
  - neutrino energy (E)
  - difference in the squared masses ($\Delta m^2_{ij} = m^2_i - m^2_j$)
  - The mixing amplitudes ($U_{\alpha i}$)

The PMNS Mixing Matrix

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- (12) Sector: Reactor + Solar, L/E~15,000 km/GeV

$$^{\dagger}\Delta m^2_{21} = 7.50^{+0.19}_{-0.20} \times 10^{-5}\ \text{eV}^2 \quad \tan^2\theta_{12} = 0.452^{+0.035}_{-0.033}$$

- (23) Sector: atmospheric and accelerator, L/E~500 km/GeV

$$^{\dagger\dagger}\left|\Delta m^2_{32}\right| = 2.32^{+0.12}_{-0.08} \times 10^{-3}\ \text{eV}^2 \quad ^{*}\sin^2(2\theta_{23}) > 0.96\,(90\%\ \text{C.L.})$$

- (13) Sector mixing not yet observed

$$^{**}\sin^2(2\theta_{13}) < 0.15 - 0.16$$

†PRD 83.052002(2011)
††PRL 106. 181801(2011)
*SuperK Preliminary, Nu2010
** Eur.Phys. C27:331-374,2003

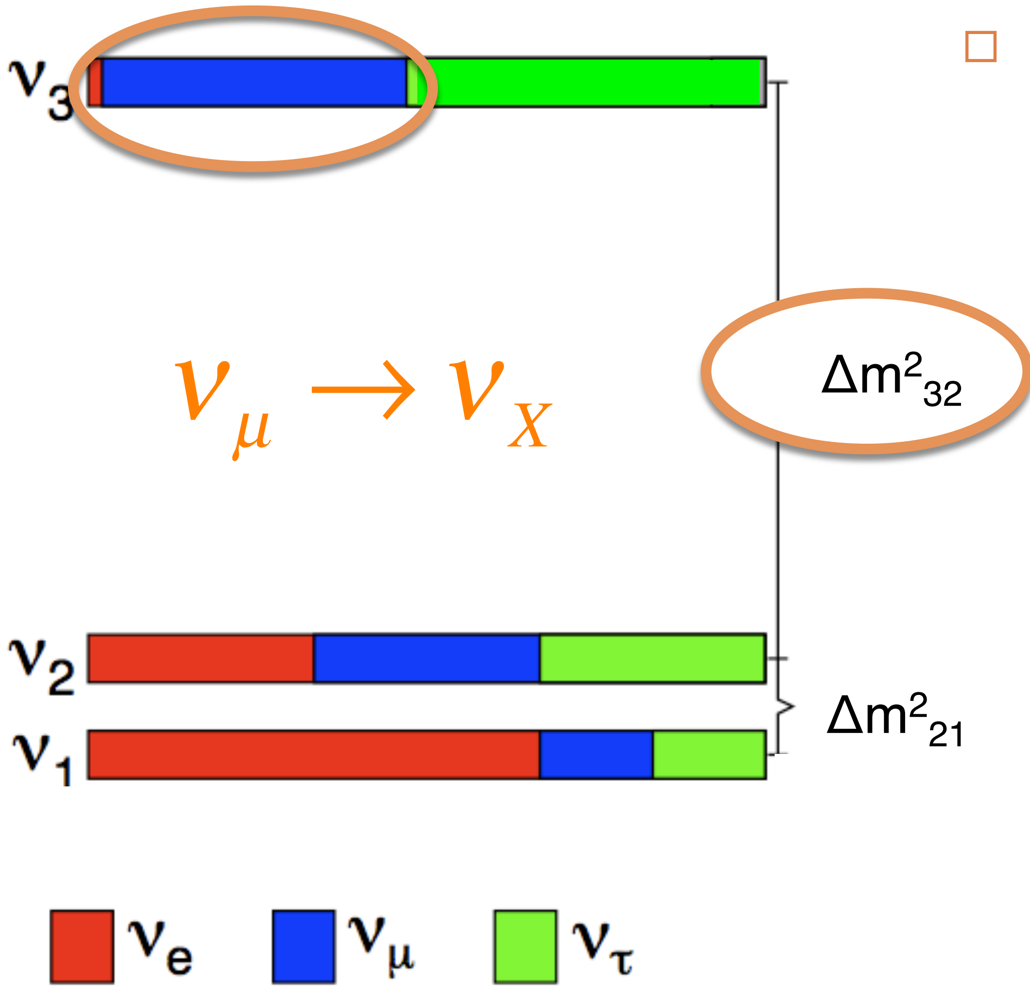
Why Measure All These Angles?

- Precision measurements provide a valuable check that neutrino oscillations are the solution to neutrino anomalies
- PMNS matrix analogous to CKM matrix
  - lepton sector mixing much larger than quark sector mixing
  - θ_{23} maximal, θ_{12} moderately large, θ_{13} small, zero? why?
  - Is there CP violation in the lepton sector?
  - Is it big enough to account for matter vs. antimatter asymmetry in the Universe?
- Small neutrino mass suggests a heavy partner (see-saw mechanism)—Neutrinos provide a window to physics at the GUT scale!

The MINOS Experiment

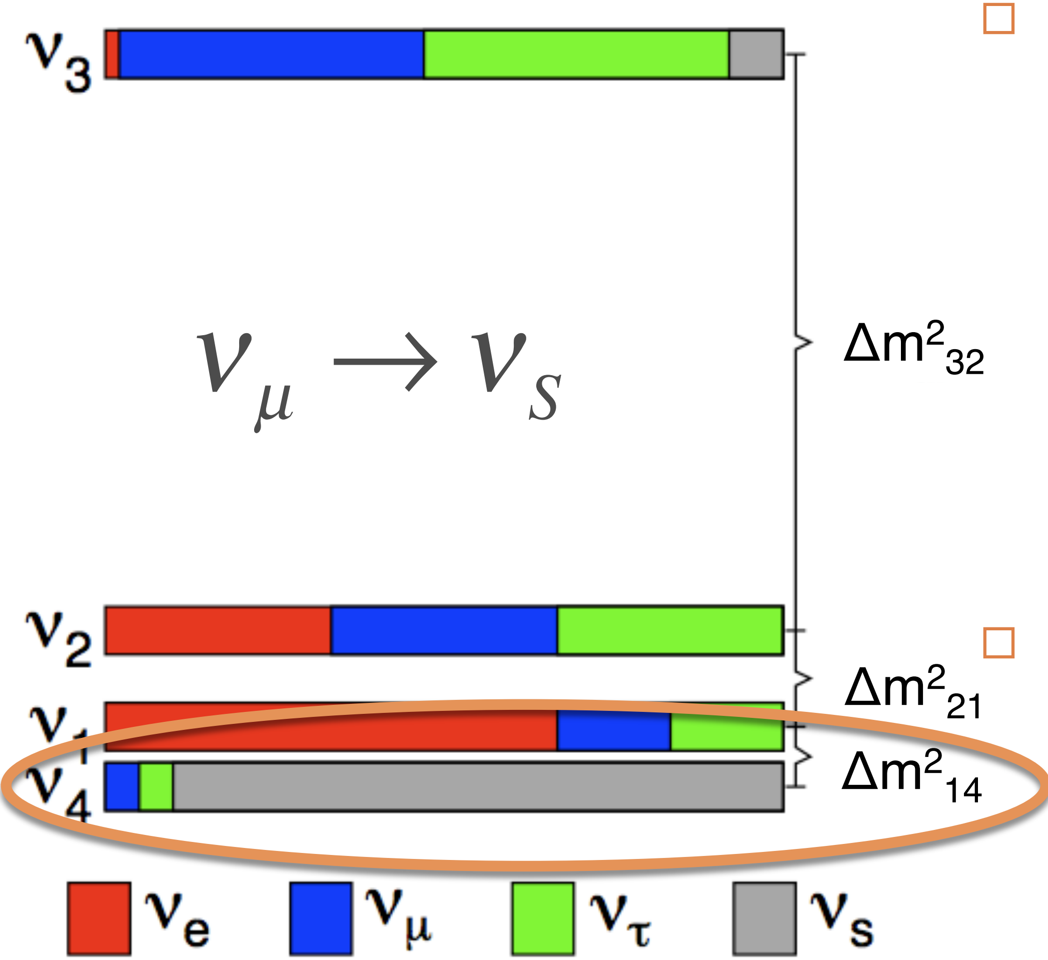
- Long-baseline neutrino oscillation experiment
- Neutrinos from NuMI beam line
- L/E ~ 500 km/GeV
  - atmospheric Δm^2
- Two detectors mitigate systematic effects
  - beam flux mis-modeling
  - neutrino interaction uncertainties

MINOS Physics Goals



- **Measure ν_μ disappearance as a function of energy**
  - Δm^2_{32} and $\sin^2(2\theta_{23})$
  - test oscillations vs. decay/ decoherence
  - look for differences between neutrino and anti-neutrinos

MINOS Physics Goals



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- **Mixing to sterile neutrinos?**

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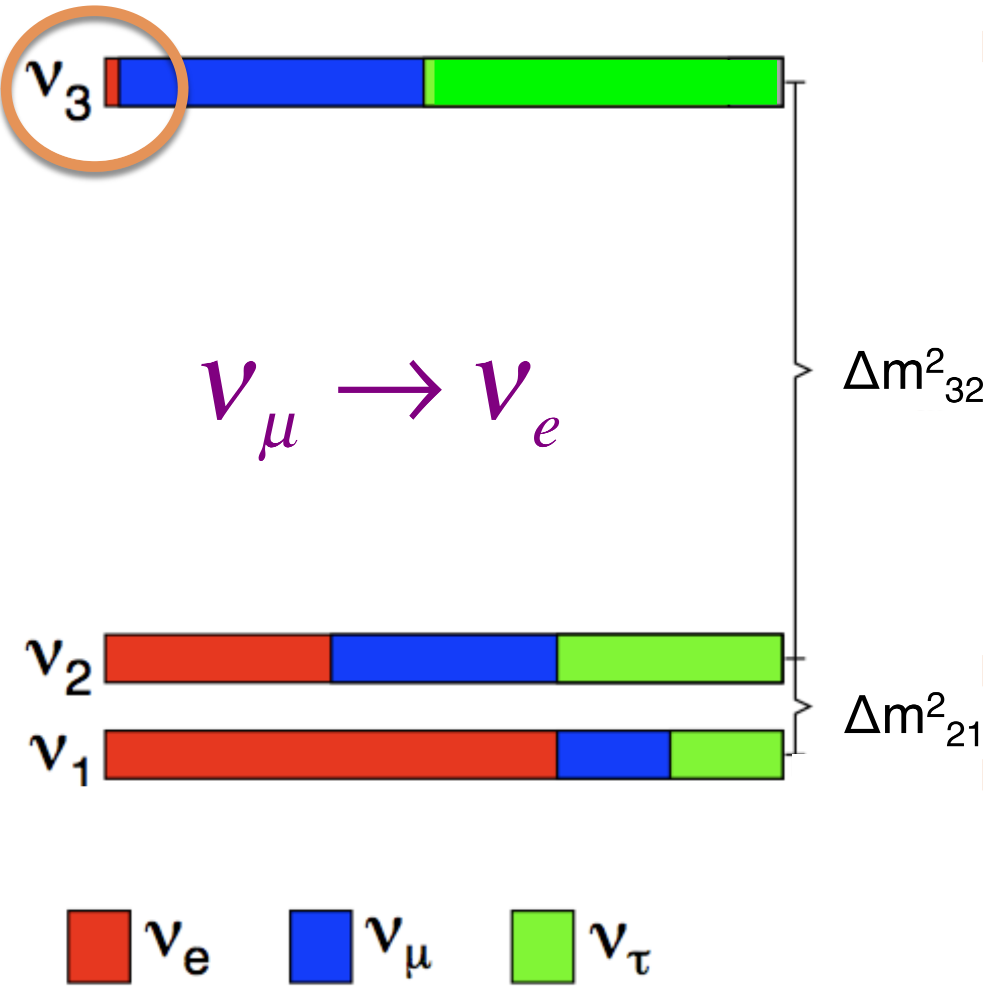

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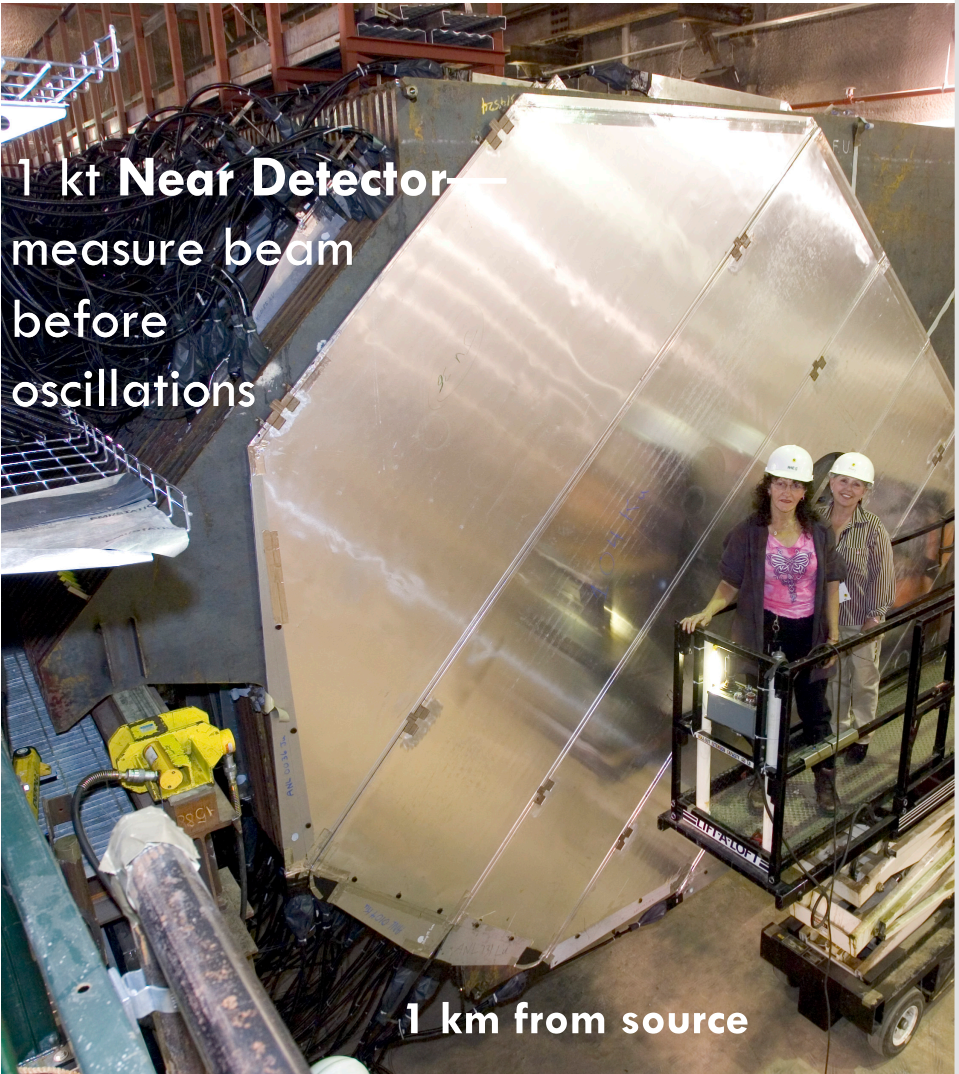
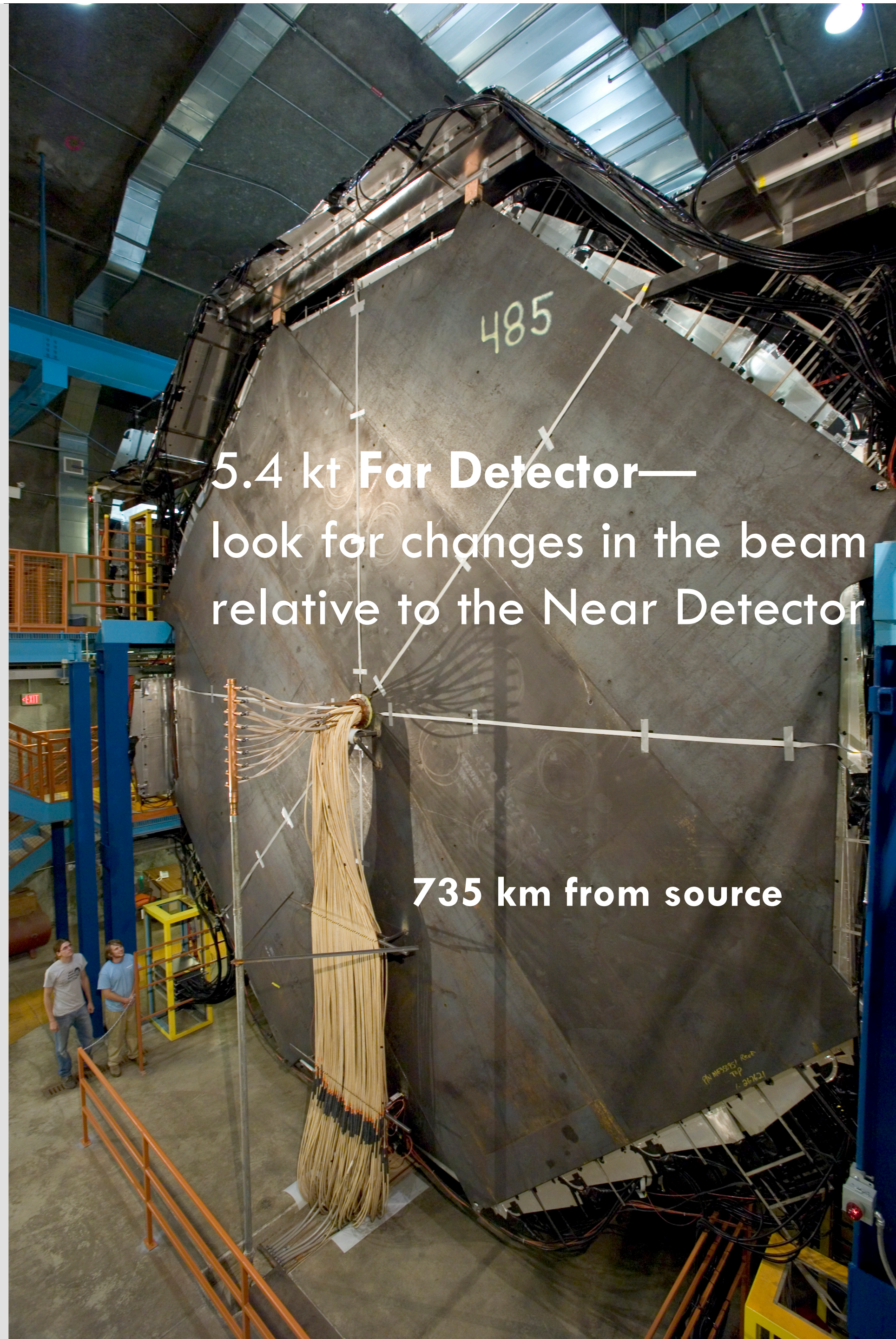
  - Δm^2_{32} and $\sin^2(2\theta_{23})$
  - test oscillations vs. decay/ decoherence
  - look for differences between neutrino and anti-neutrinos
- Mixing to sterile neutrinos?
- **Study $\nu_\mu \rightarrow \nu_e$ mixing**
  - measure θ_{13}

The Detectors

Magnetized, tracking calorimeters



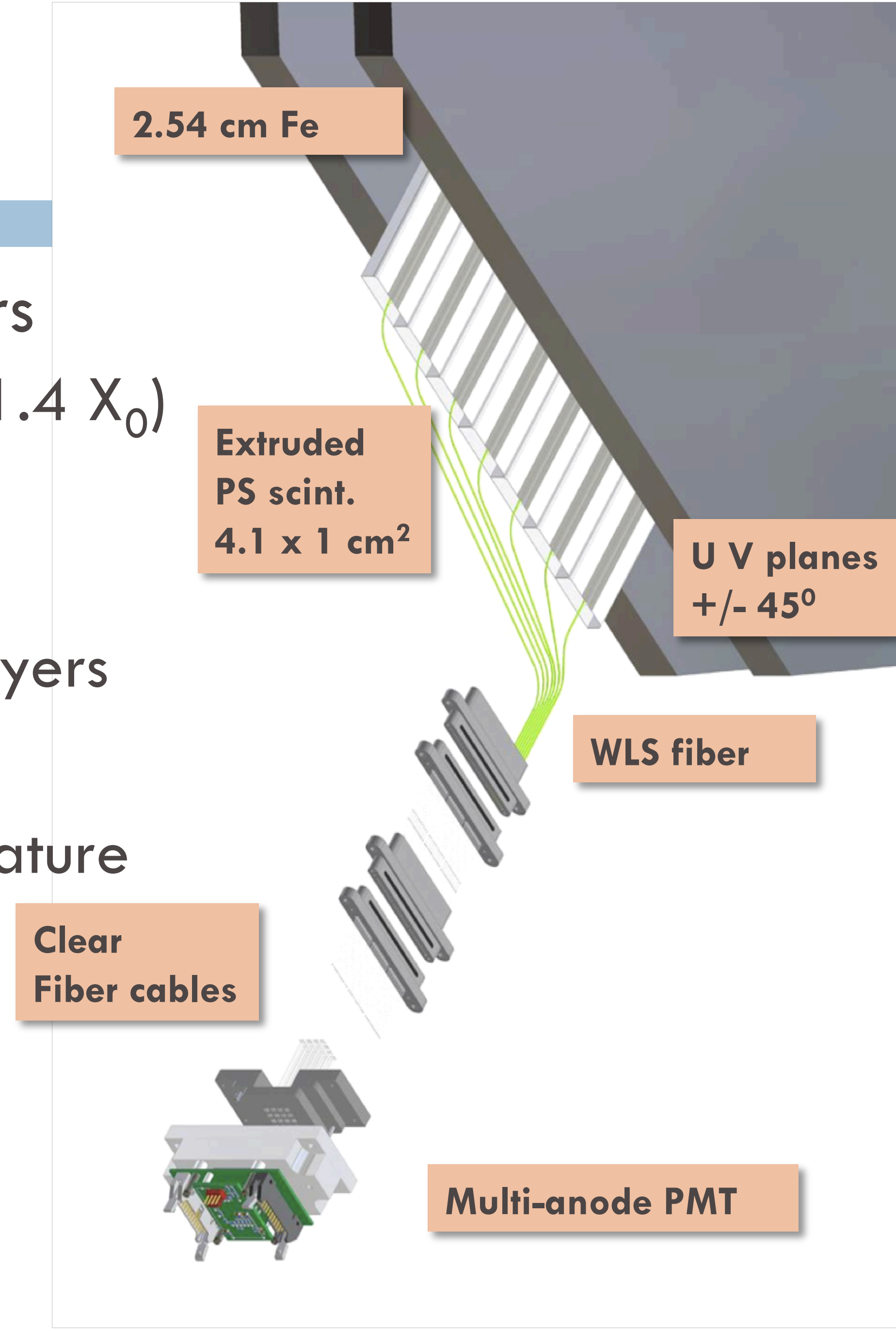


Soudan Fire

- March 17, smoke detected in FD hall due to a fire in the shaft
- Power to the lab shut off automatically
- Foam pumped in to extinguish the fire
- No damage to the MINOS detector
- Detector returned to full operations May 19

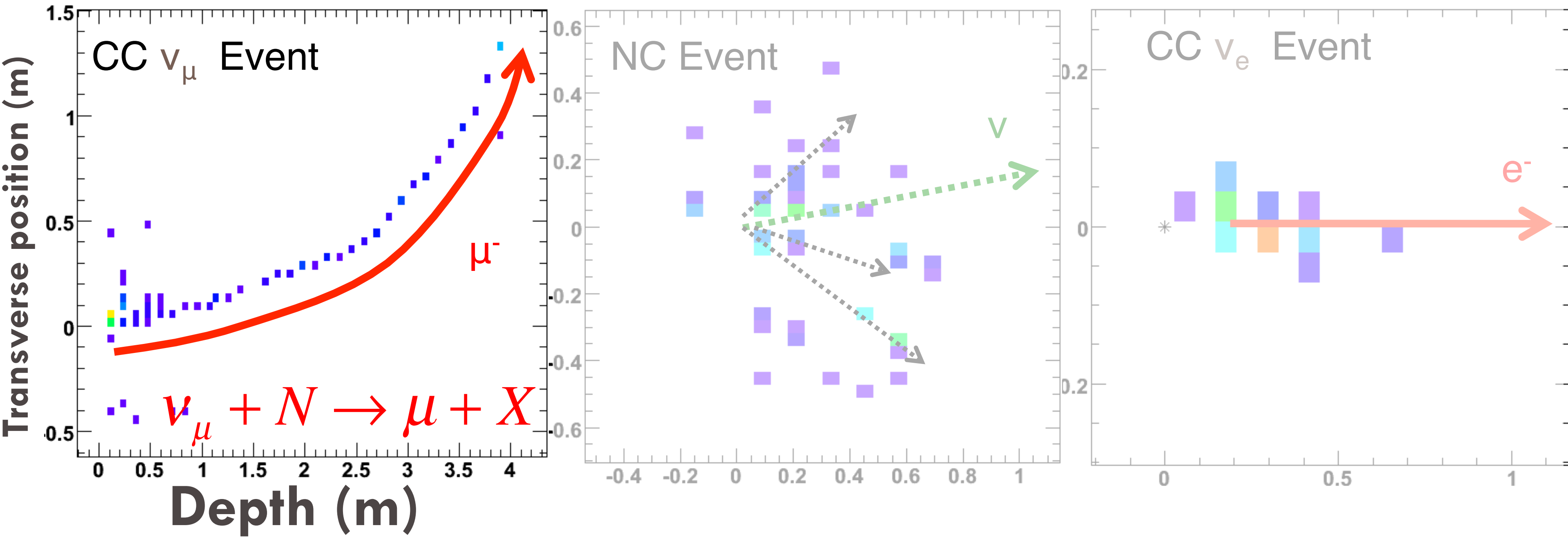
Detector Technology

- Tracking sampling calorimeters
  - steel absorber 2.54 cm thick (1.4 X_0)
  - scintillator strips 4.1 cm wide (1.1 Moliere radii)
  - 1 GeV muons penetrate 28 layers
- Magnetized
  - muon energy from range/curvature
  - distinguish μ^+ from μ^-
- Functionally equivalent
  - same segmentation
  - same materials
  - same mean B field (1.3 T)



Events in MINOS

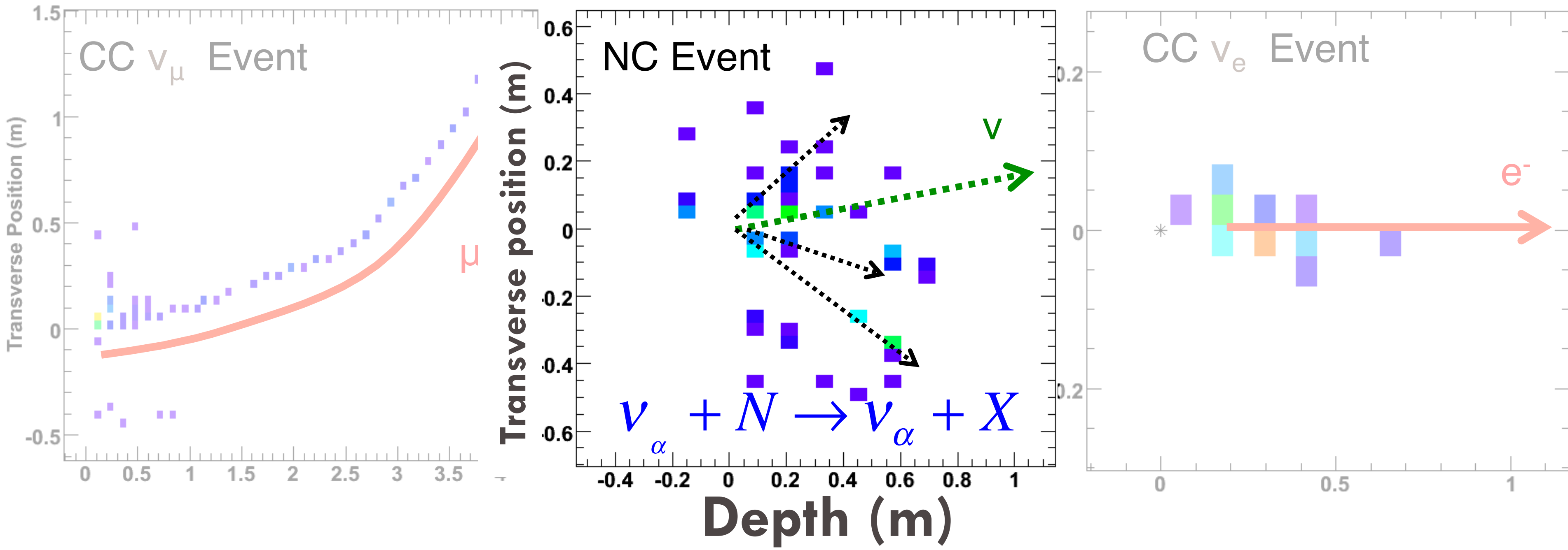
Simulated Events



- ν_μ Charged Current events:
  - long μ track, with hadronic activity at vertex
  - neutrino energy from sum of muon energy (range or curvature) and shower energy

Events in MINOS

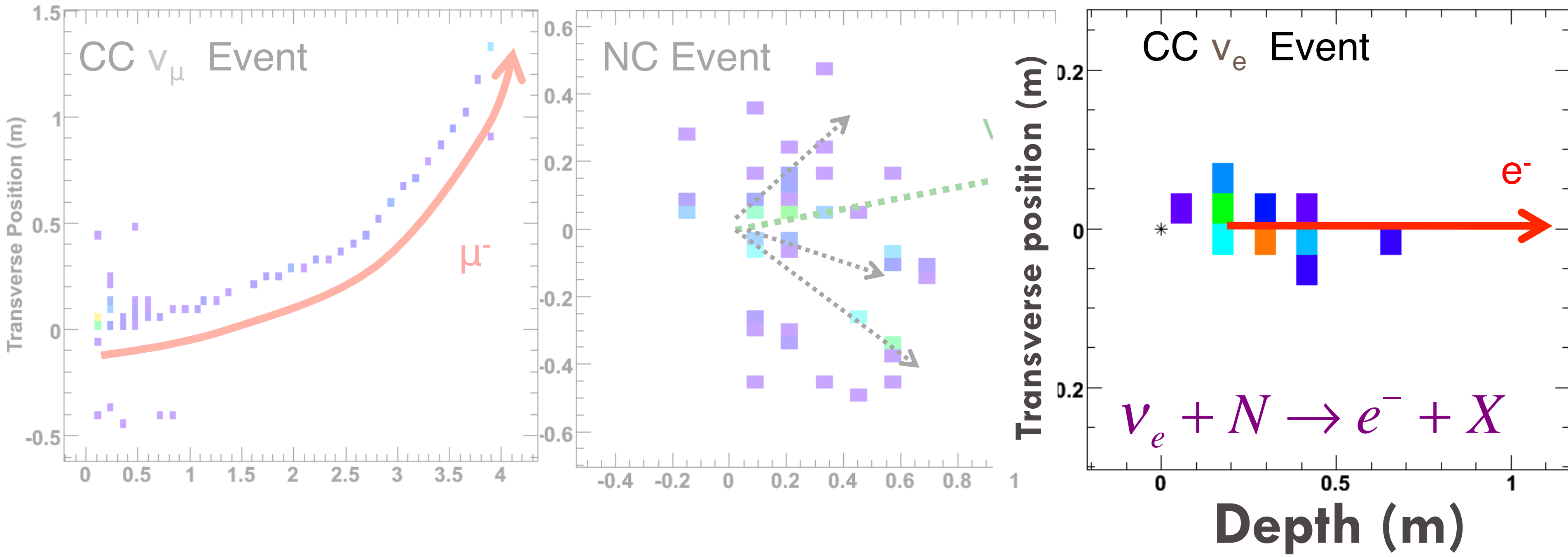
Simulated Events



- Neutral Current events:
  - short, diffuse shower event
  - shower energy from calorimetric response

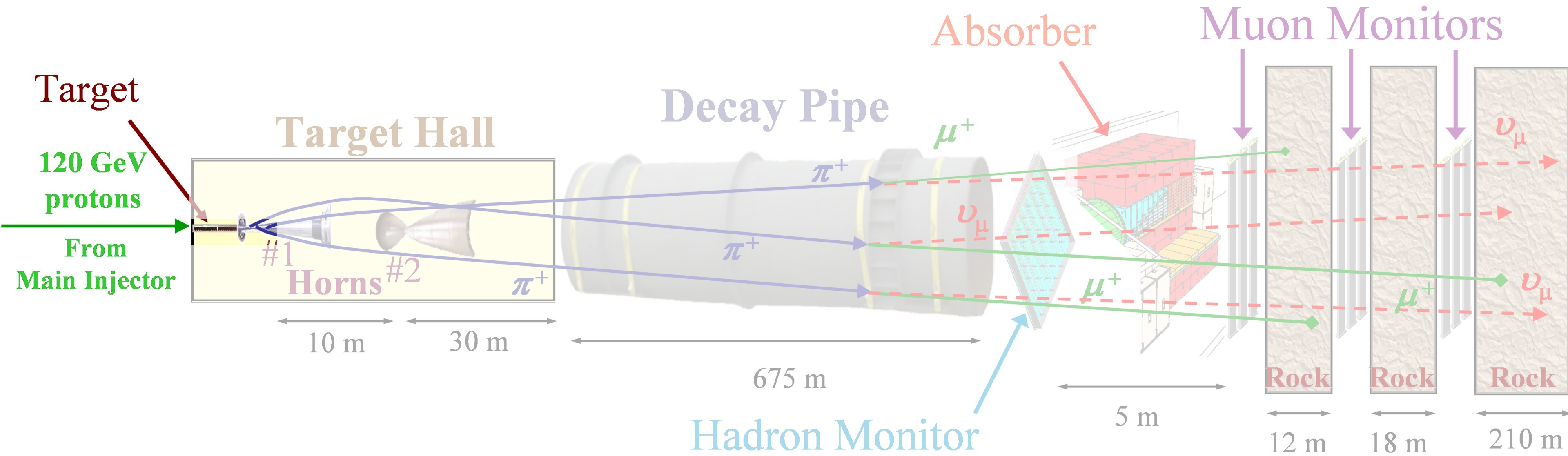
Events in MINOS

Simulated Events



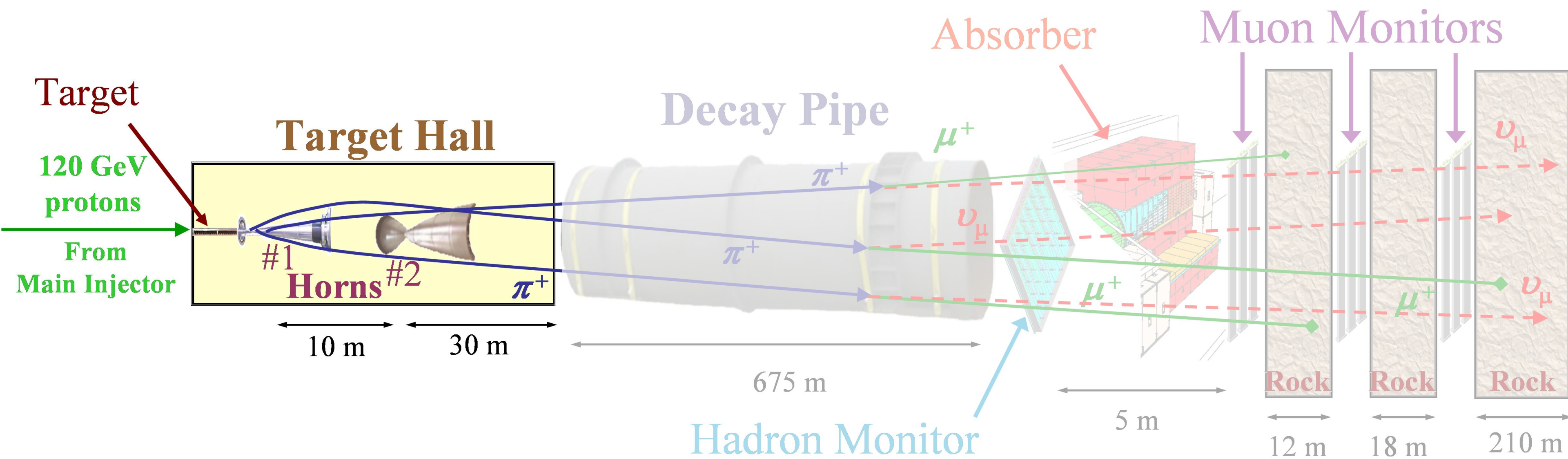
- ν_e Charged Current events:
  - compact shower event with an EM core
  - neutrino energy from calorimetric response

Making a Neutrino Beam



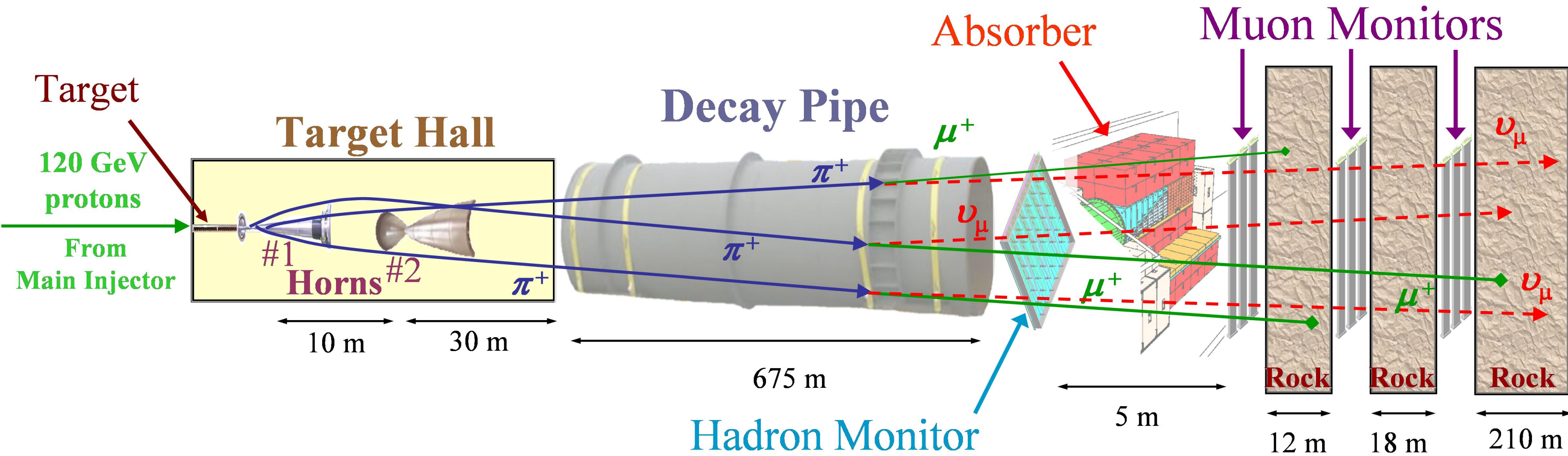
- Production
  - bombard graphite target with 120 GeV p^+ from Main Injector
    - 2 interaction lengths
    - 310 kW typical power
  - produce hadrons, mostly π and K

Making a Neutrino Beam



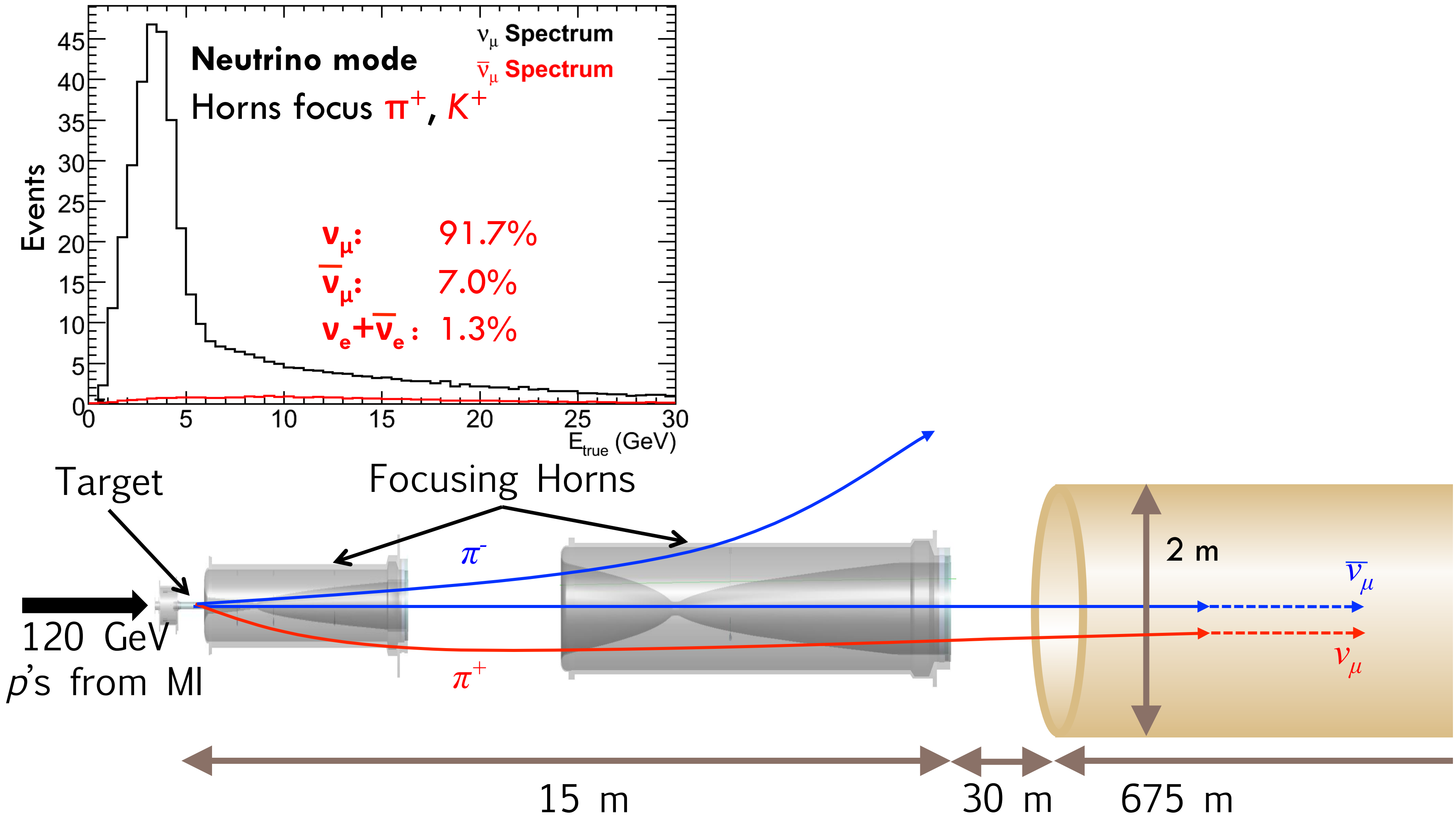
- Focusing
  - hadrons focused by 2 magnetic focusing horns
  - energy of focused particles depends on separation between target and horns
  - sign selected hadrons
    - forward current, (+) for standard neutrino beam runs
    - reverse current, (–) for anti-neutrino beam

Making a Neutrino Beam

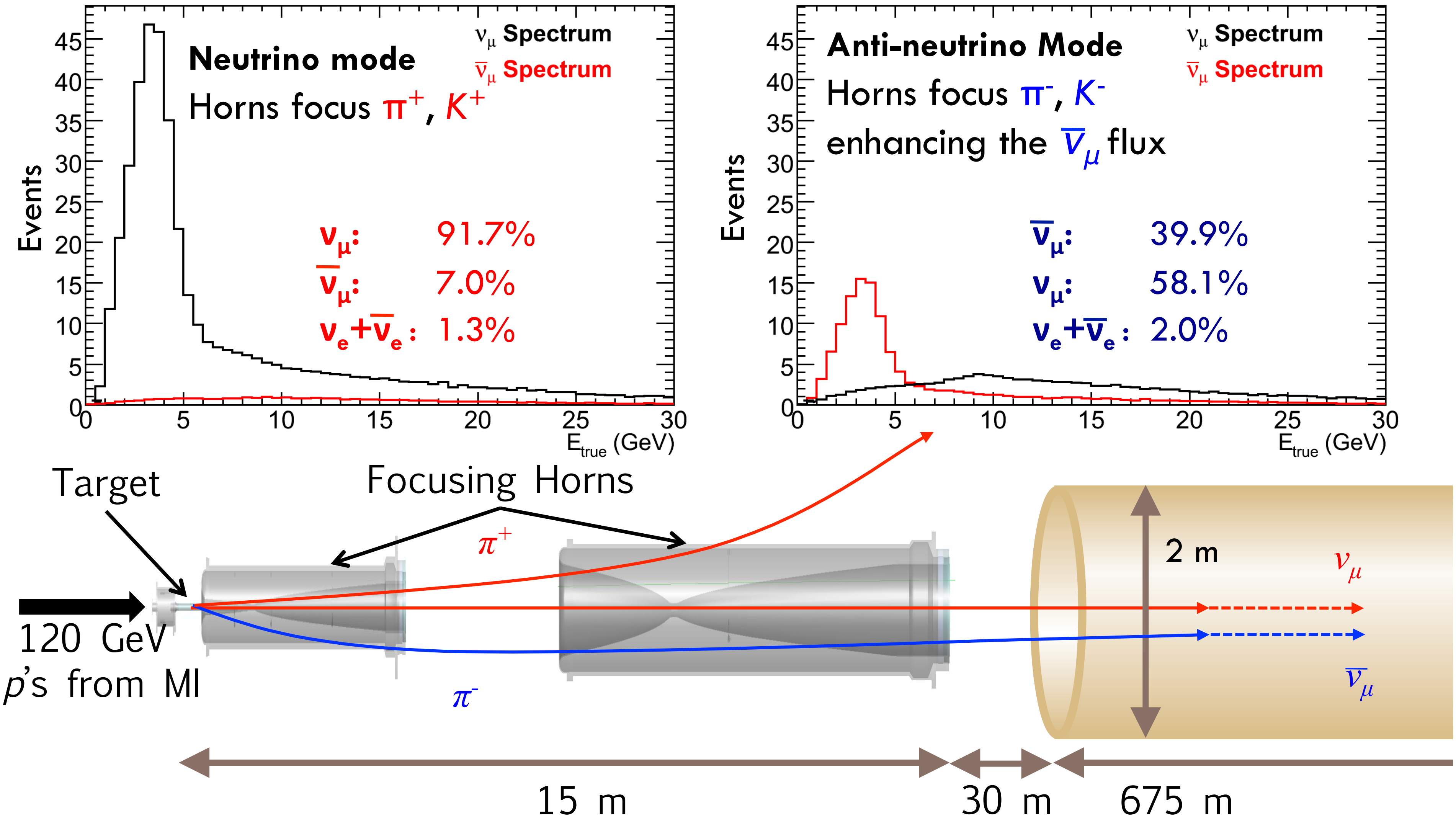


- Decay
  - 2 m diameter decay pipe
  - result: wide band neutrino beam
  - secondary beam monitored

Making a Neutrino Beam



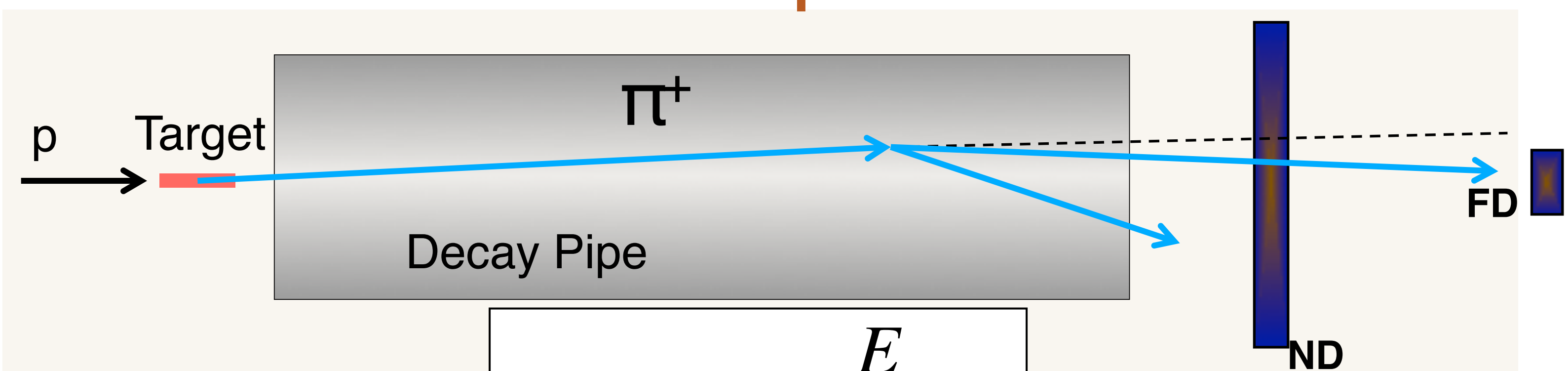
Making an Anti-neutrino Beam



P. Vahle, INFO 2011

Near to Far

Far spectrum without oscillations is similar, but not identical to the Near spectrum!

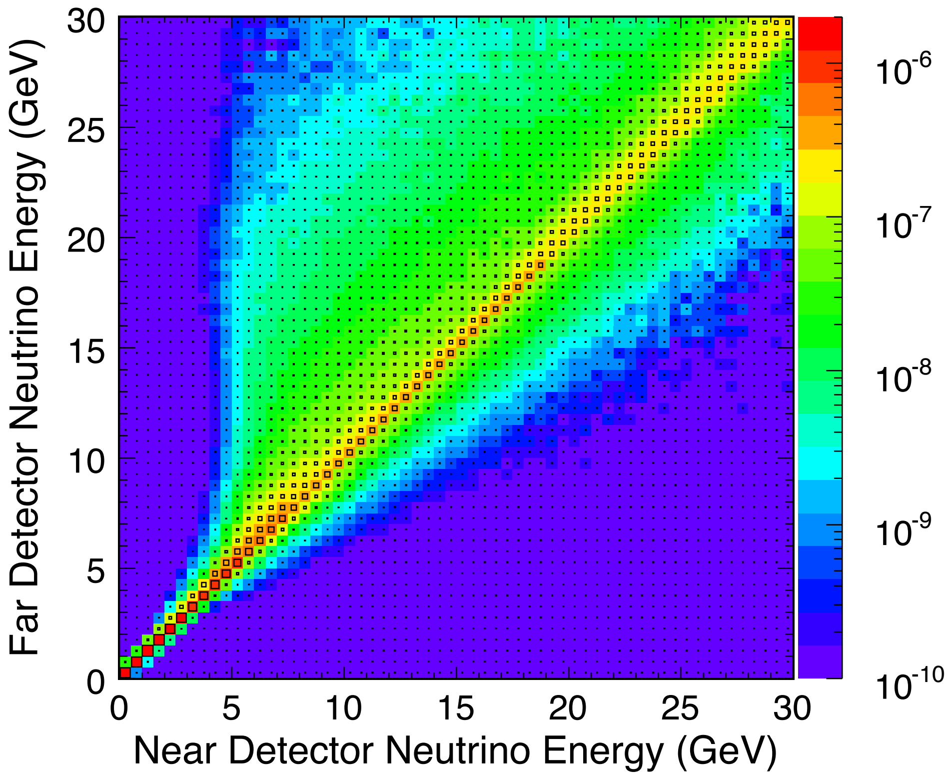


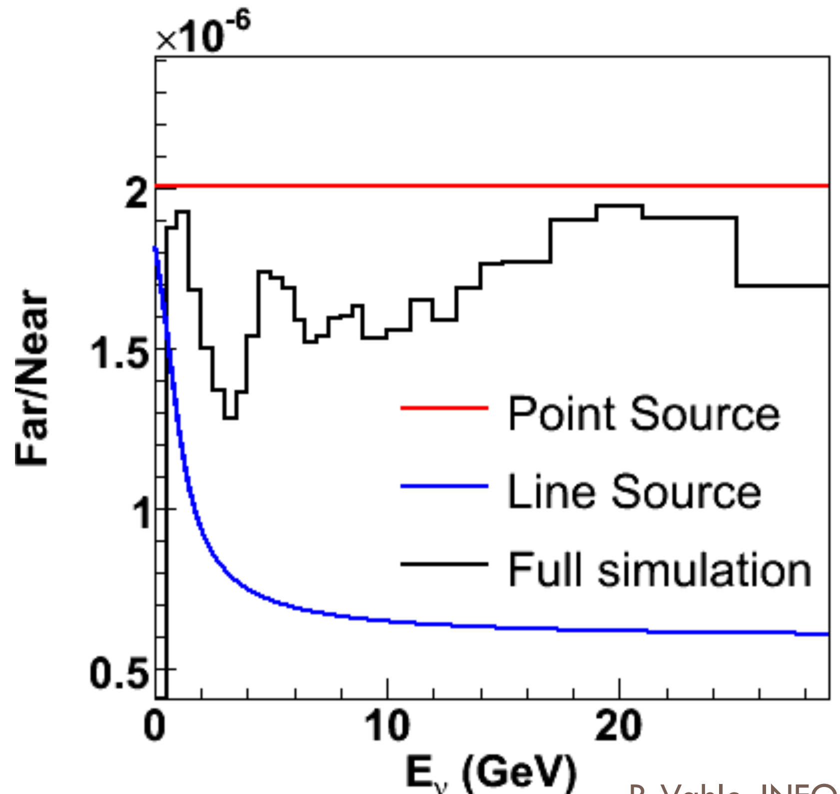
$$E_\nu \approx 0.43 \frac{E_\pi}{1+\gamma^2\theta_\nu^2}$$

- Neutrino energy depends on angle wrt original pion direction and parent energy
  - higher energy pions decay further along decay pipe
  - angular distributions different between Near and Far

Extrapolation

- Muon-neutrino and anti-neutrino analyses: beam matrix for FD prediction of track events
- NC and electron-neutrino analyses: Far to Near spectrum ratio for FD prediction of shower events





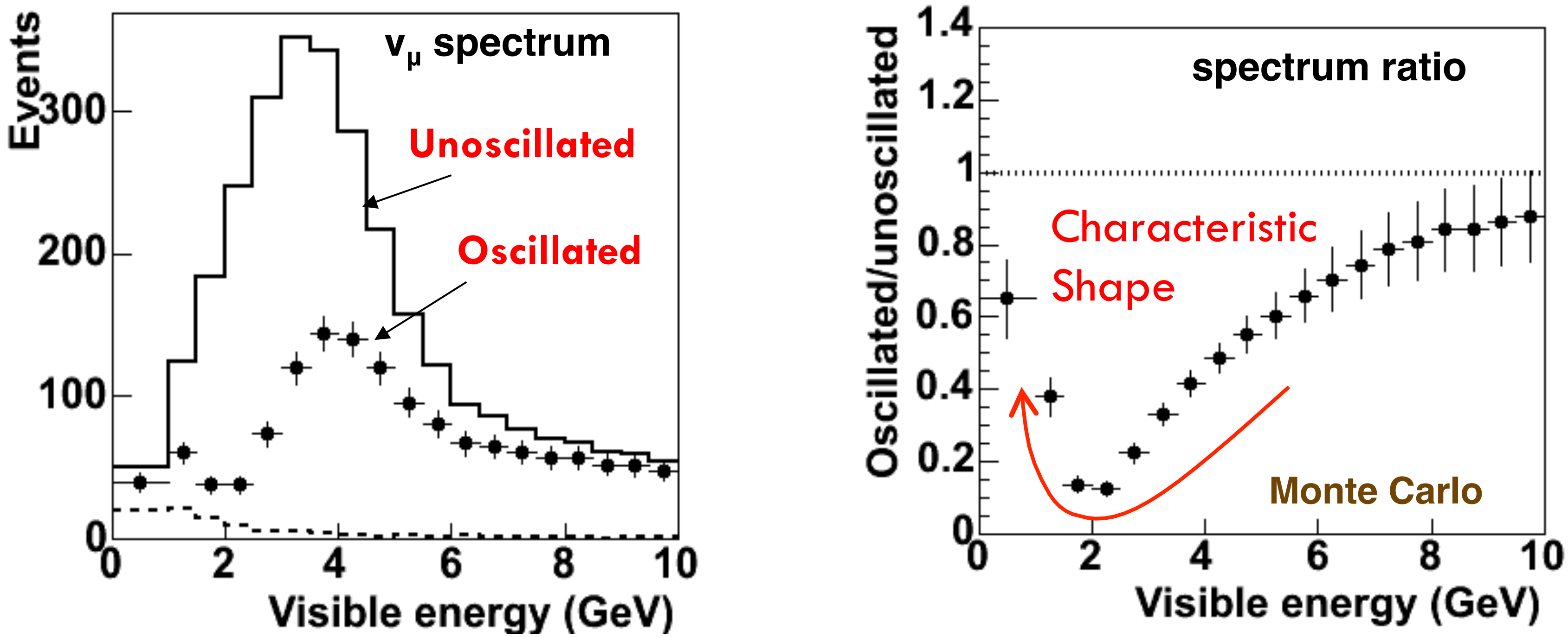
P. Vahle, INFO 2011

ν_μ Disappearance

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

Monte Carlo

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



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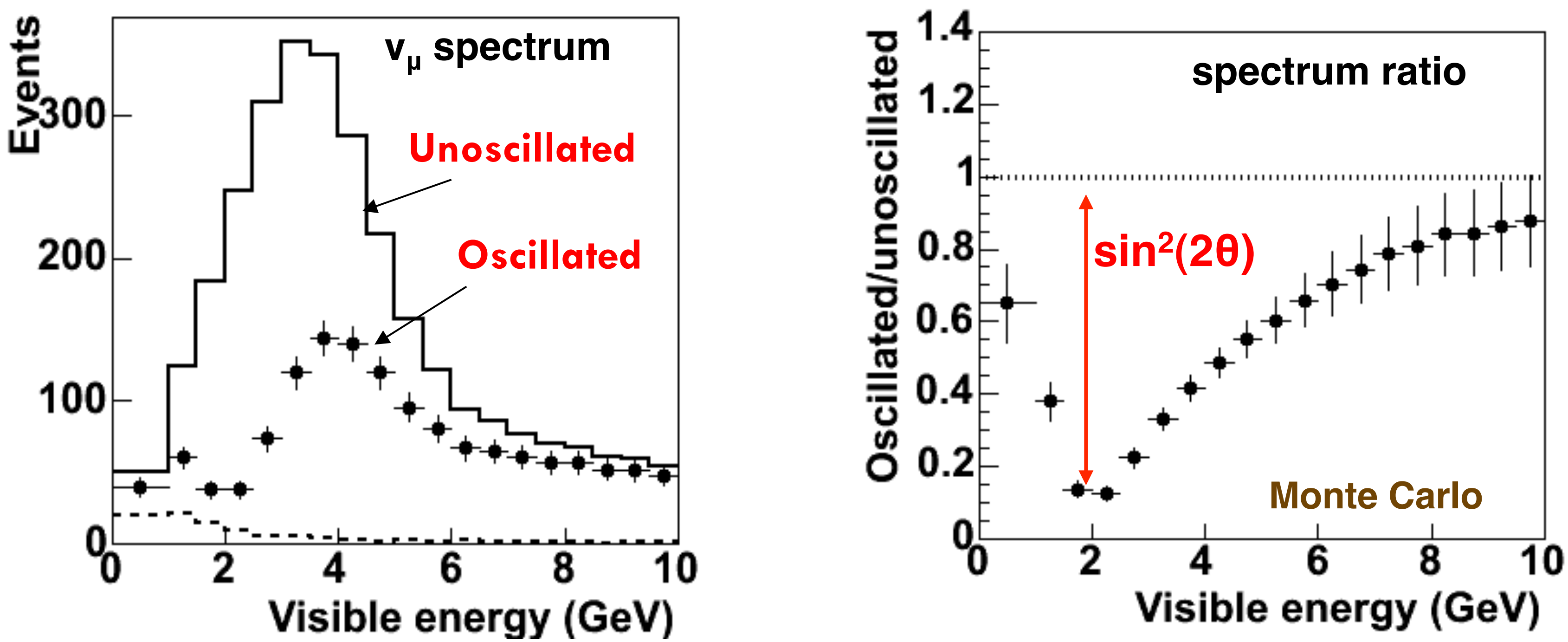

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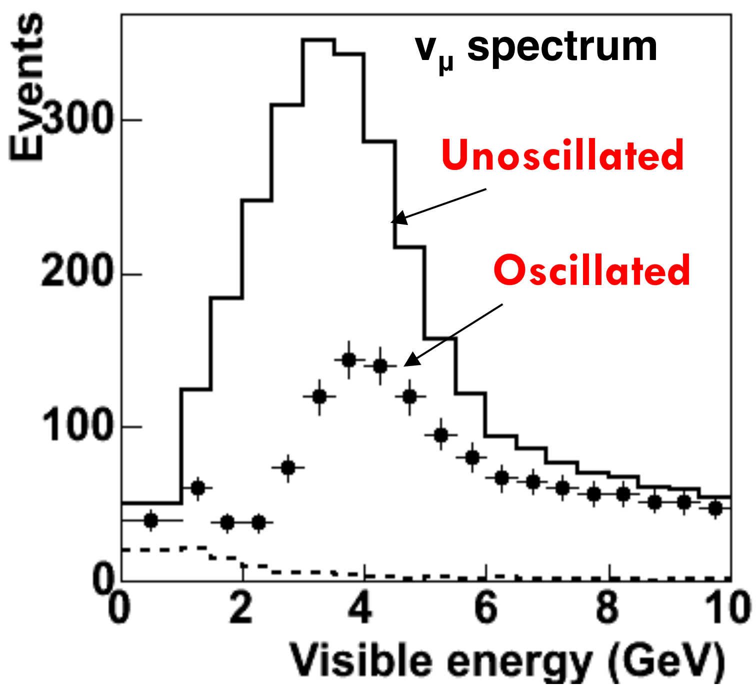
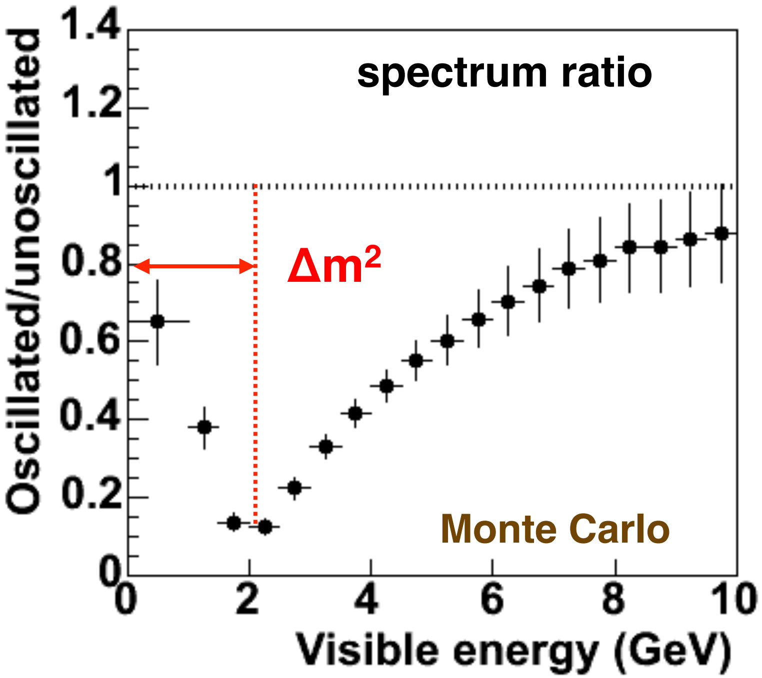
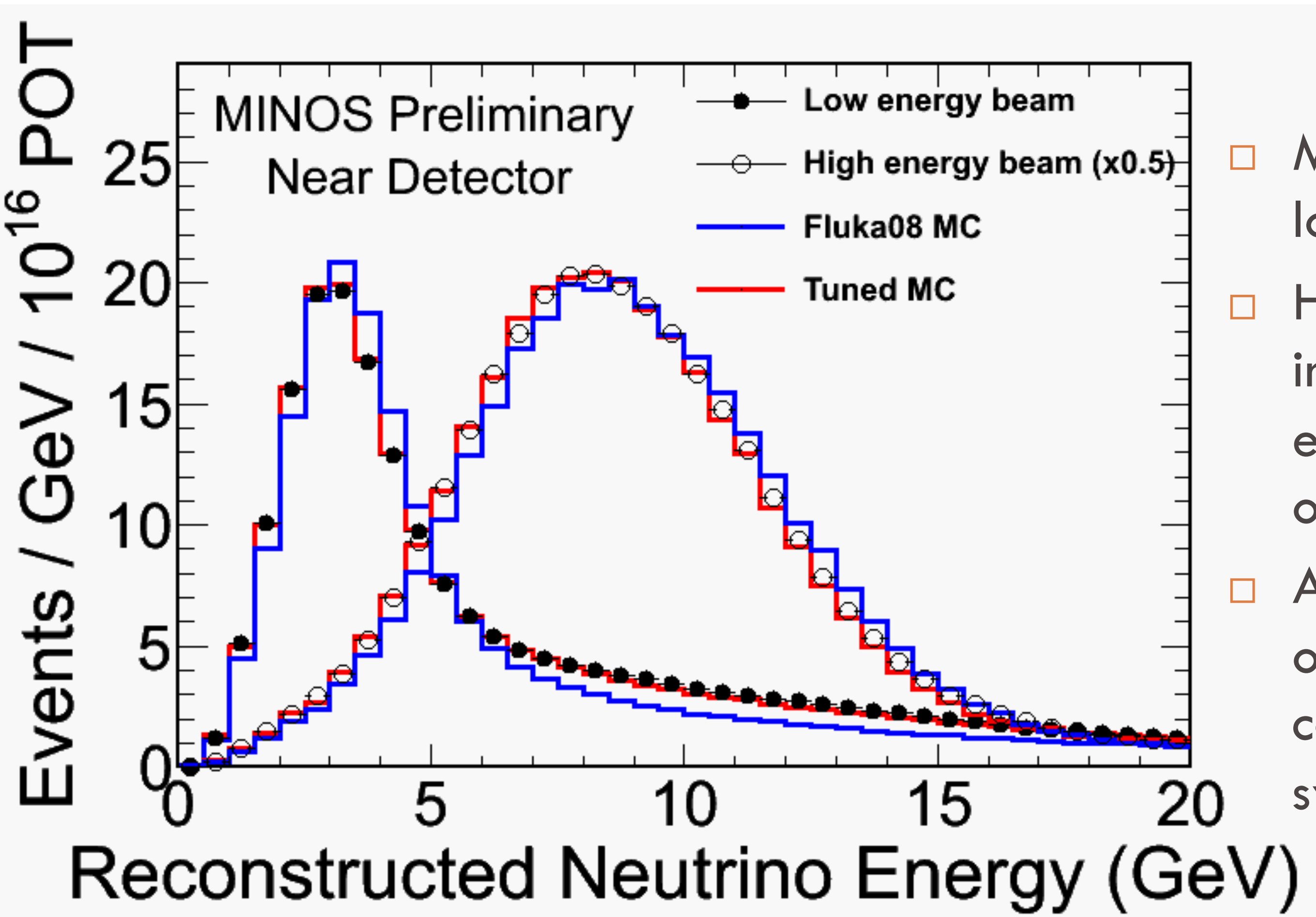


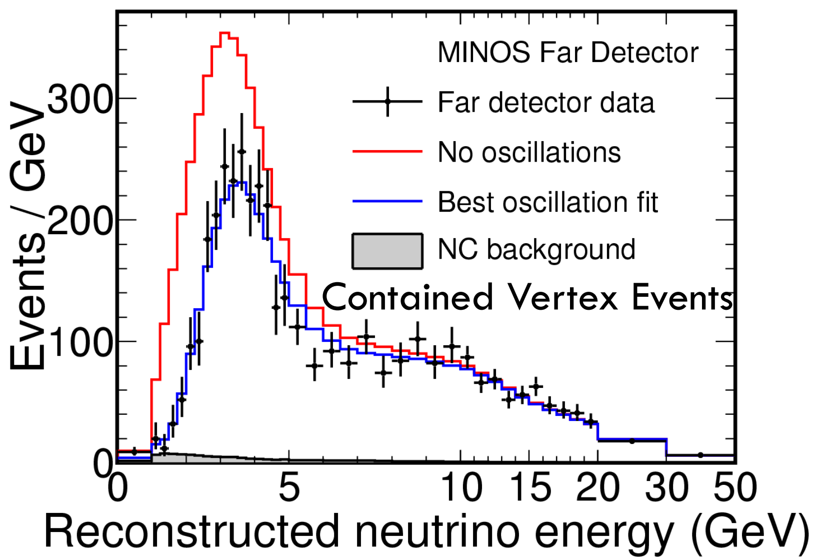


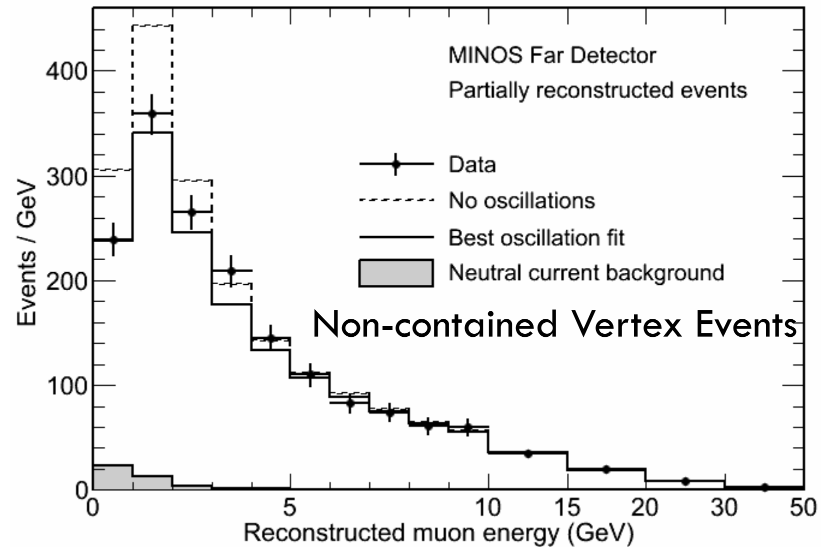
CC events in the Near Detector

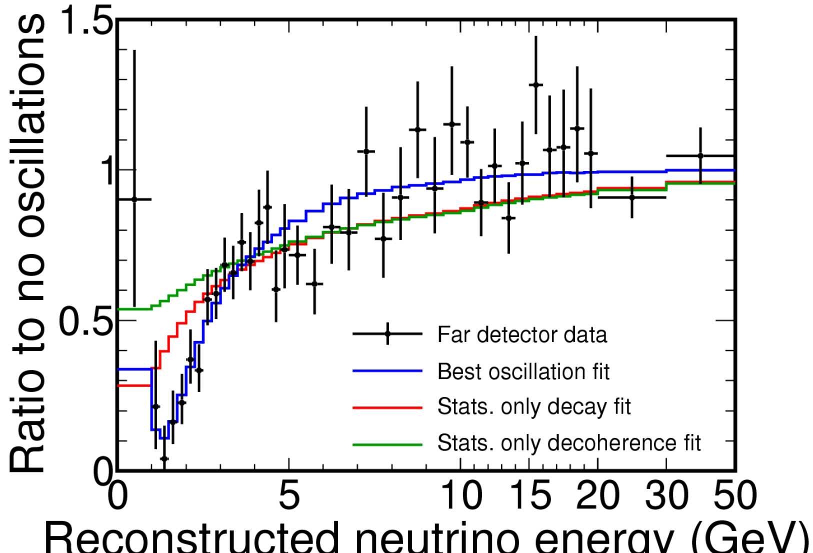


- Majority of data from low energy beam
- High energy beam improves statistics in energy range above oscillation dip
- Additional exposure in other configurations for commissioning and systematics studies

Far Detector CC Events







	Predicted (no osc.)	Observed
Contained	2451	1986
Non-contained	2206	2017

- Oscillations fit the data well, 66% of experiments have worse χ^2

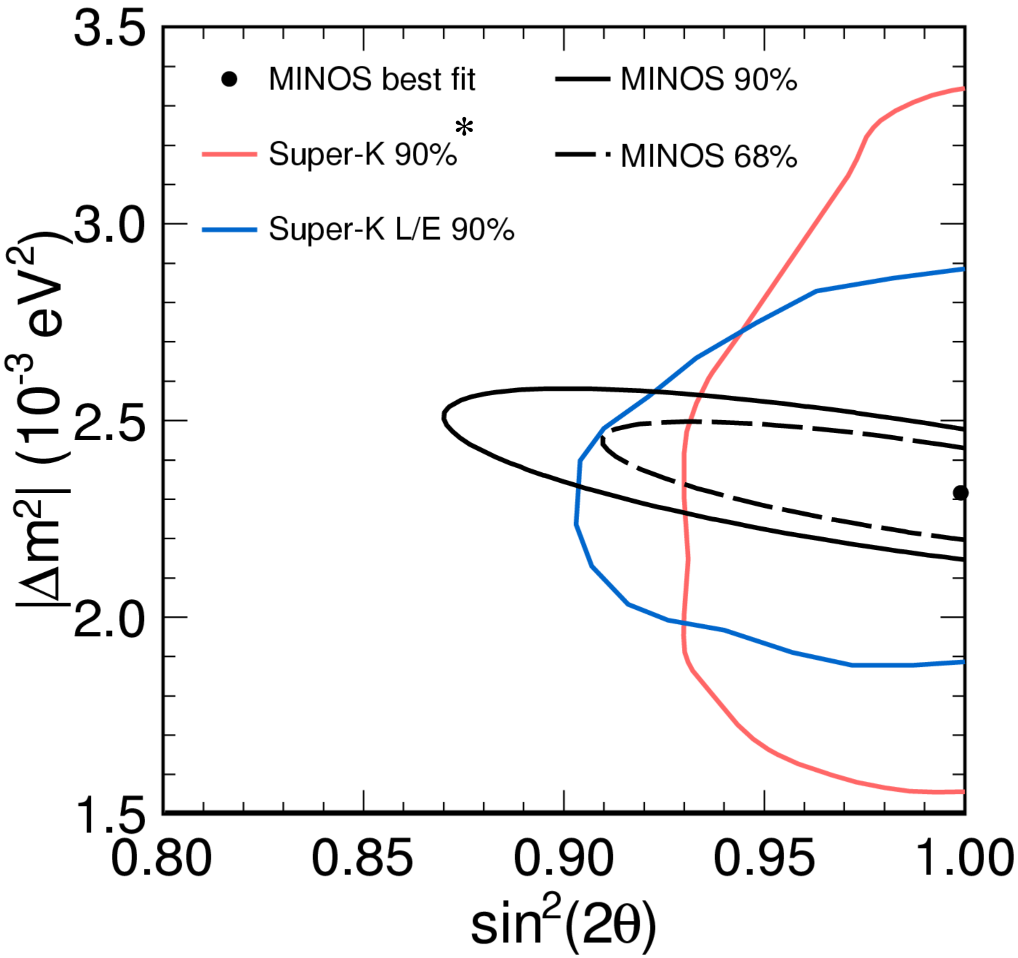
P. Adamson *et al.*, Phys.Rev.Lett. 106 181801 (2011)

Contours

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

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

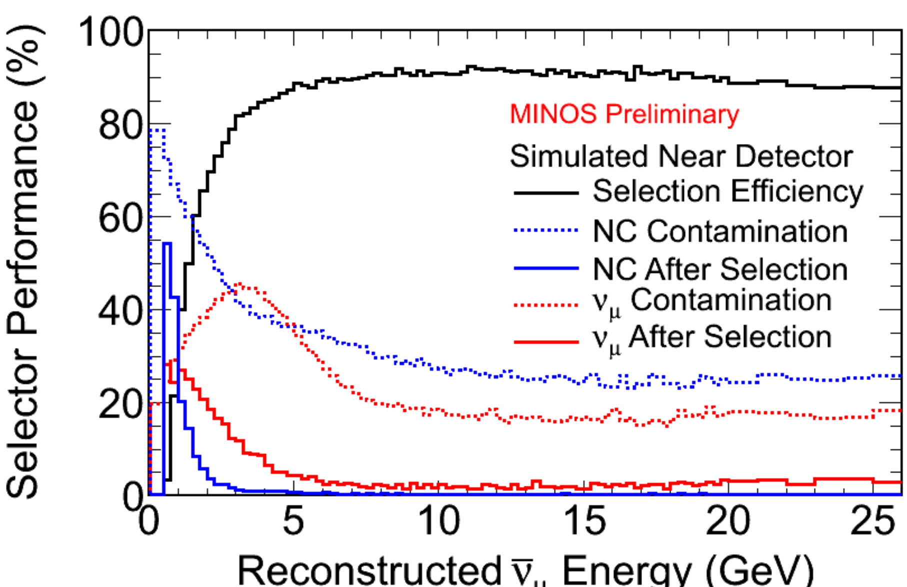
- Pure decoherence† disfavored at **9σ**
- Pure decay‡ disfavored at **7σ**

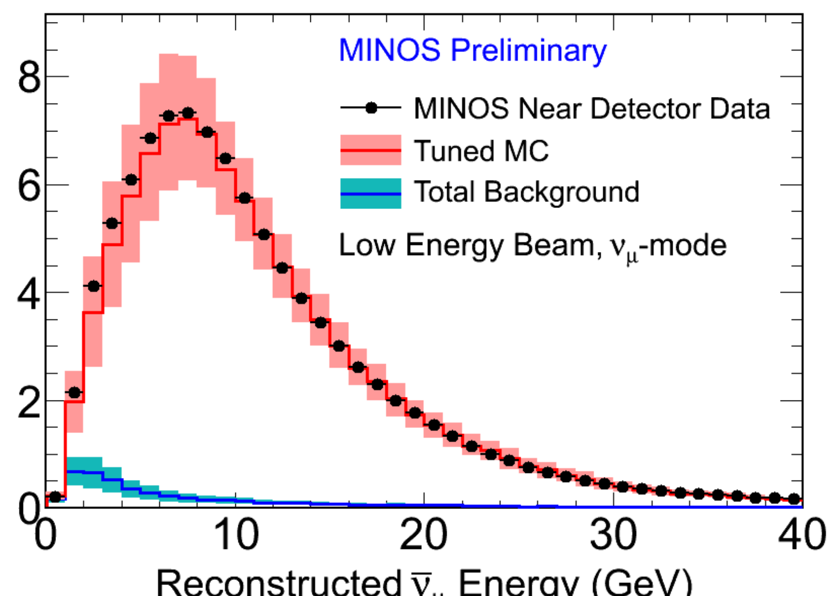


†G.L. Fogli *et al.*, PRD 67:093006 (2003)
‡V. Barger *et al.*, PRL 82:2640 (1999)
*J. Hosaka et al., Phys. Rev. D 74, 032002 (2006)

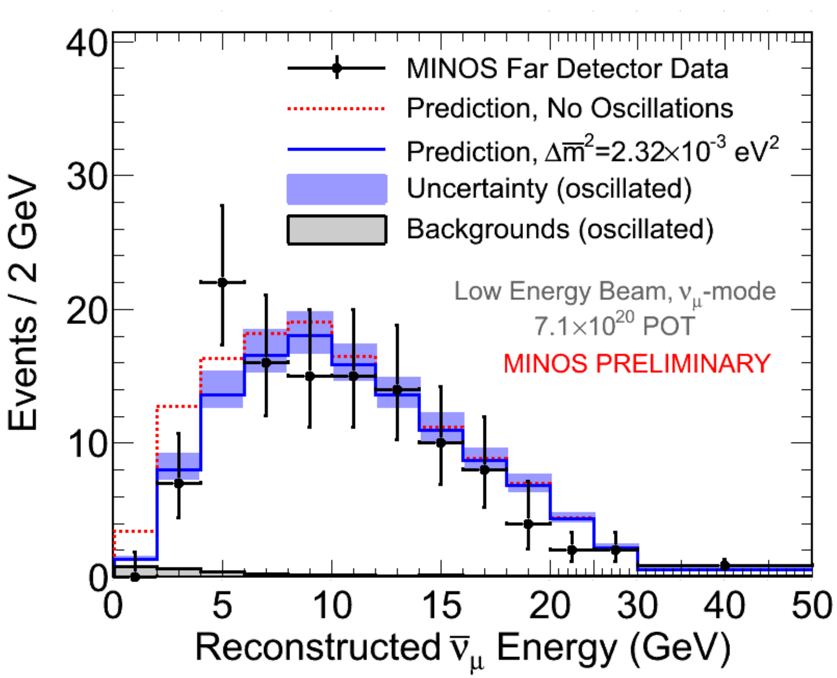
Anti-neutrino Disappearance

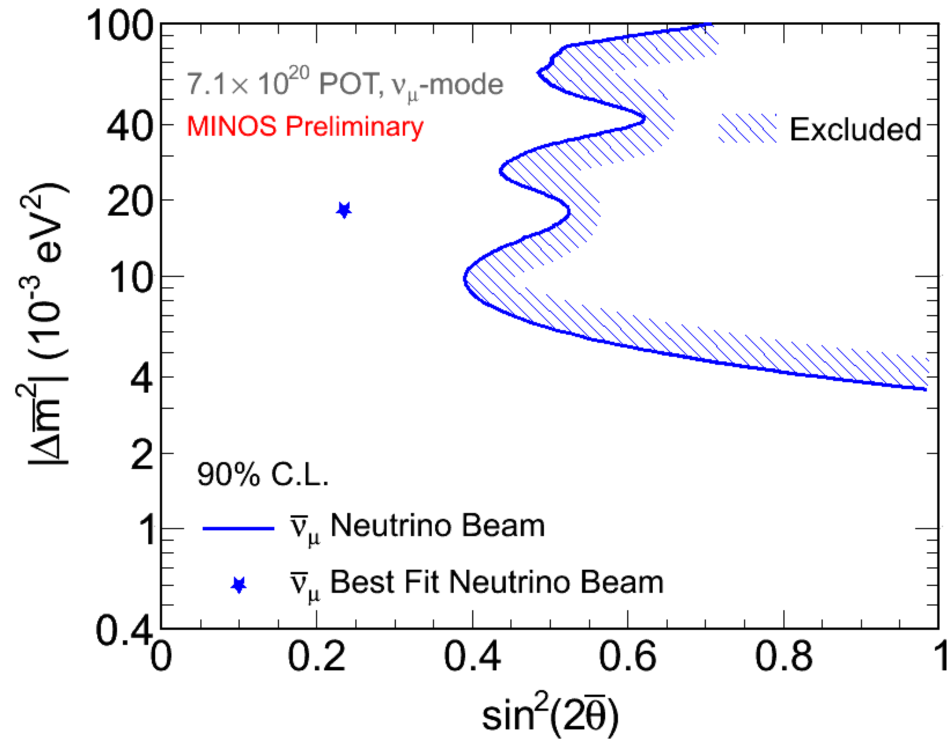
- Measure oscillations using 7% anti-neutrino component of the neutrino beam
- Peaked at higher energies
- Selection efficiency 90%, purity 95%





Anti-neutrino Disappearance





No Oscillations: $150.3^{+16.3}_{-18.2}$

With Oscillations: $136.4^{+15.2}_{-14.9}$

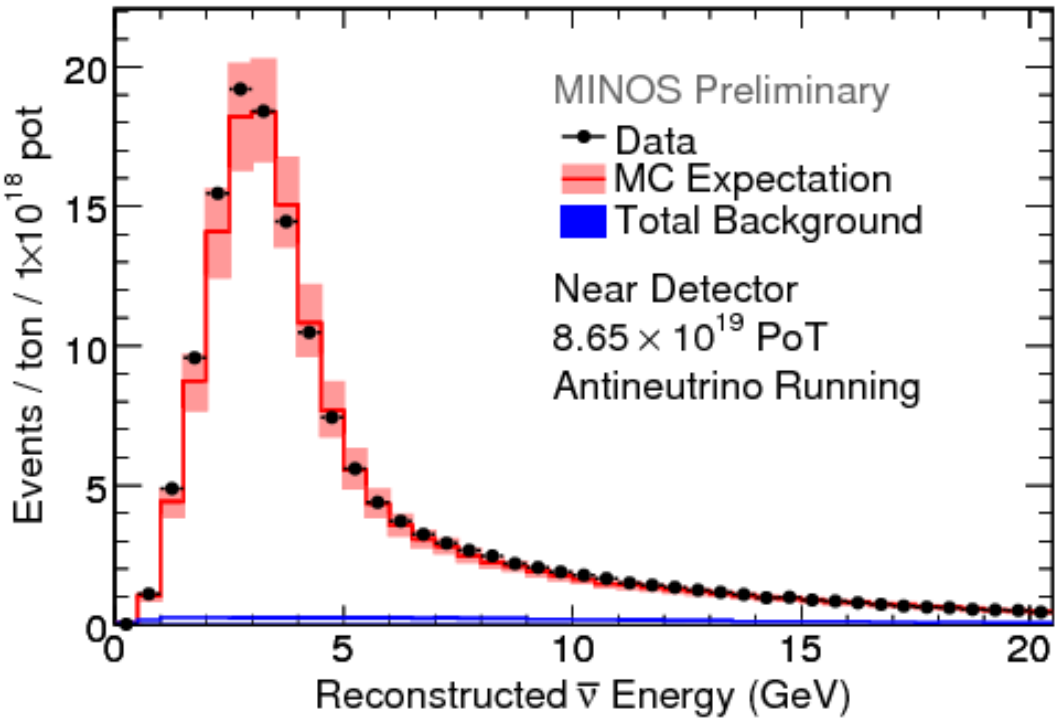
Observed: 130

at $\sin^2(2\bar{\theta}_{23}) = 1$

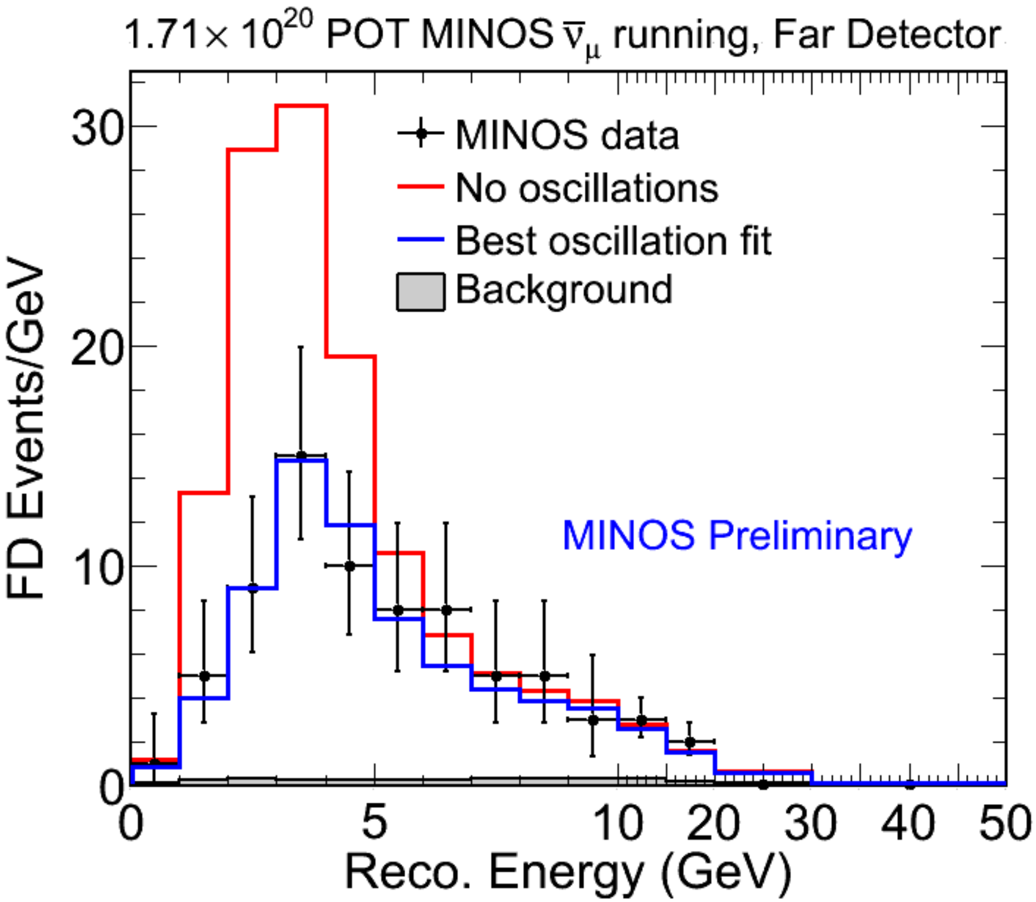
$$\left|\Delta\bar{m}^2\right| < 3.37 \times 10^{-3} \text{ eV}^2 \text{ (90\% C.L.)}$$

ND Anti-neutrino Data

- Focus and select positive muons
  - purity 94.3% after charge sign cut
  - purity 98% < 6GeV
- Analysis proceeds as (2008) neutrino analysis
- Data/MC agreement comparable to neutrino running
  - different average kinematic distributions
  - more forward muons



FD Data

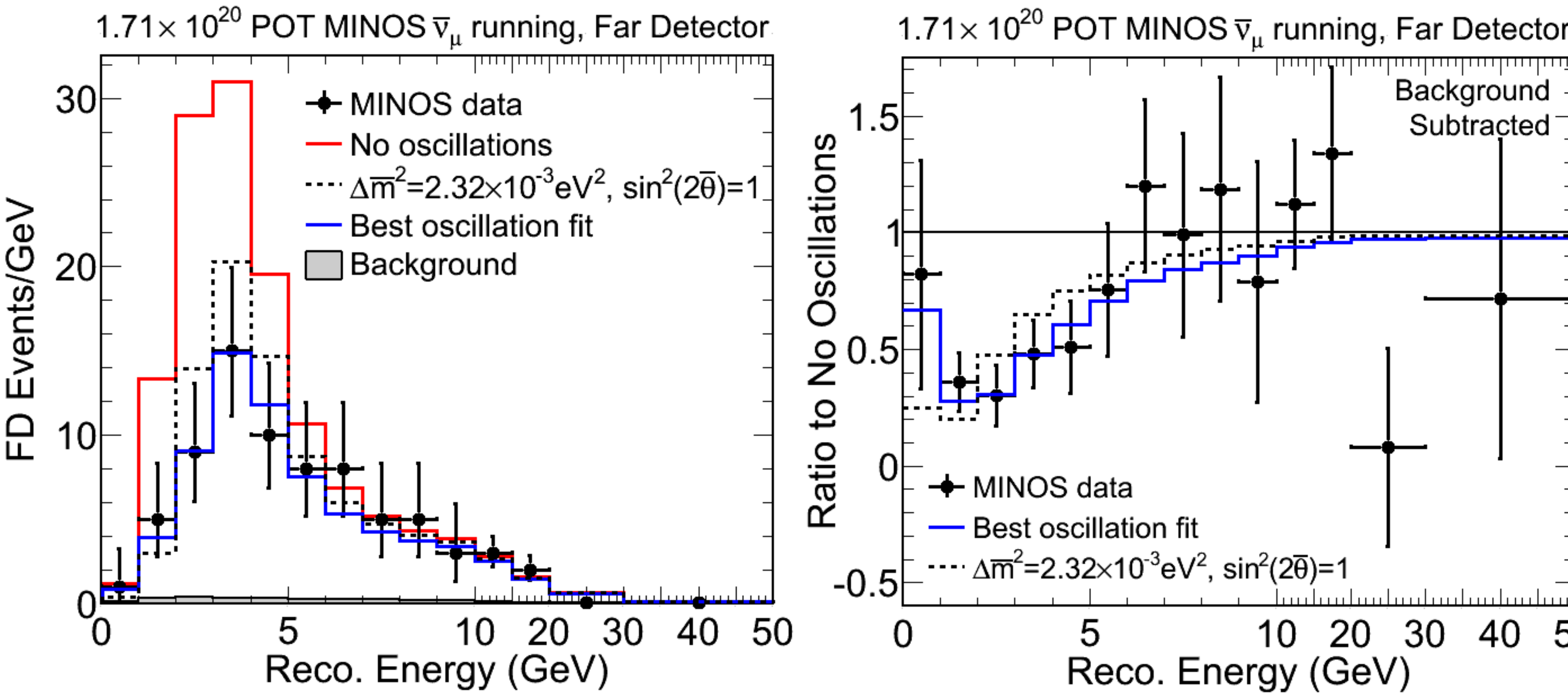


- No oscillation Prediction: **156**
- Observe: **97**
- No oscillations disfavored at 6.3σ

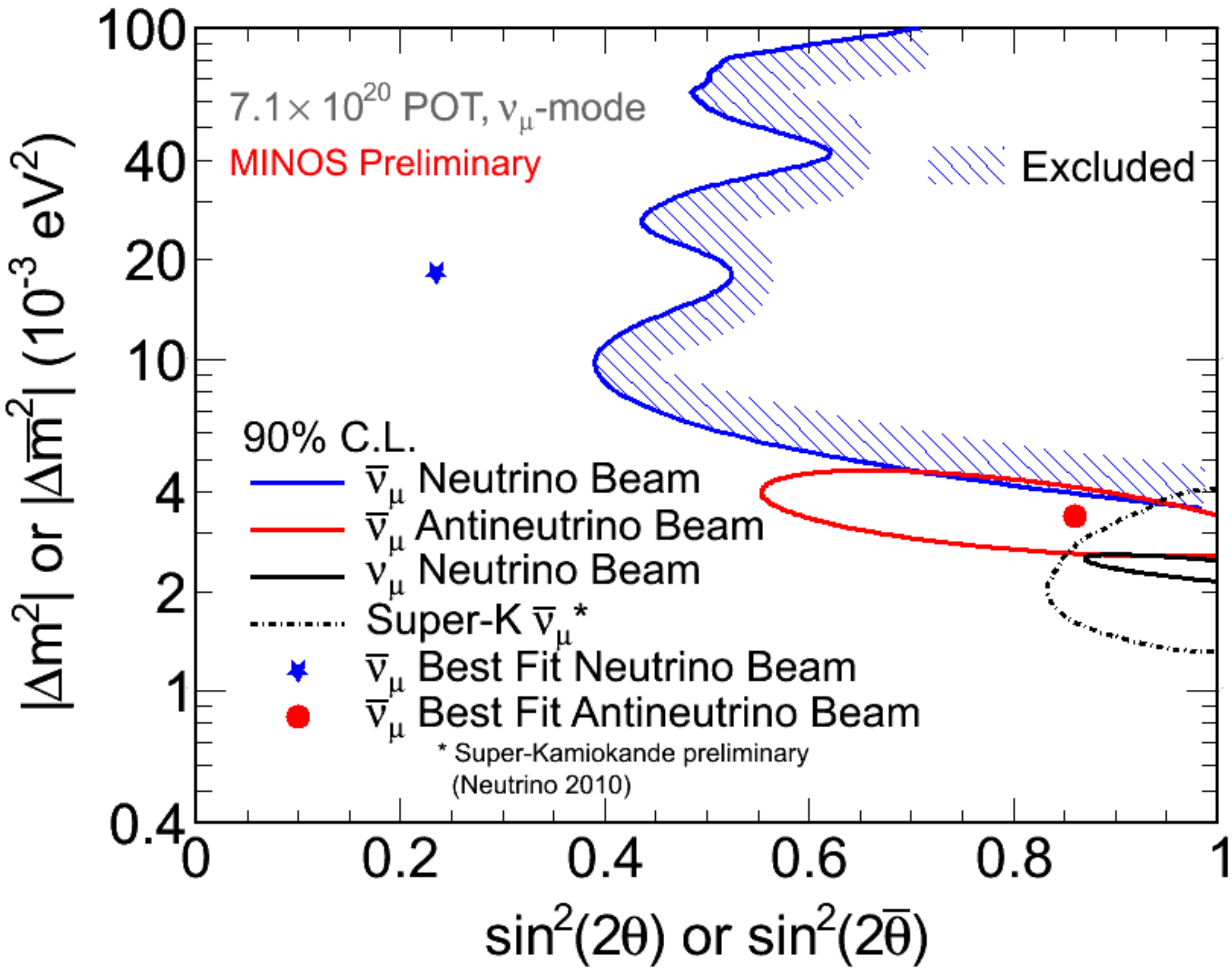
$$\left|\overline{\Delta m^2}\right| = 3.36^{+0.46}_{-0.40} \times 10^{-3}\,\mathrm{eV}^2$$

$$\sin^2(2\bar{\theta}) = 0.86^{+0.11}_{-0.12}$$

Comparisons to Neutrinos

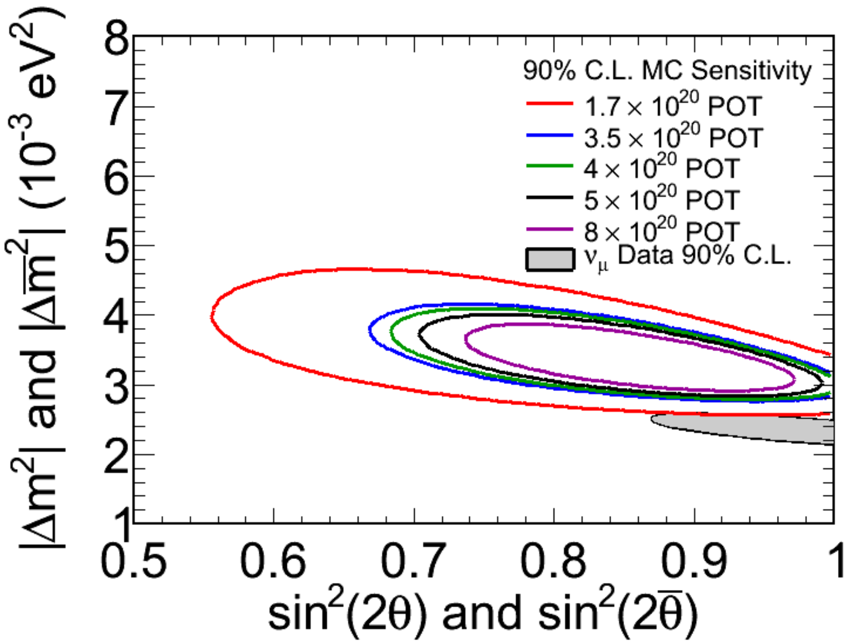


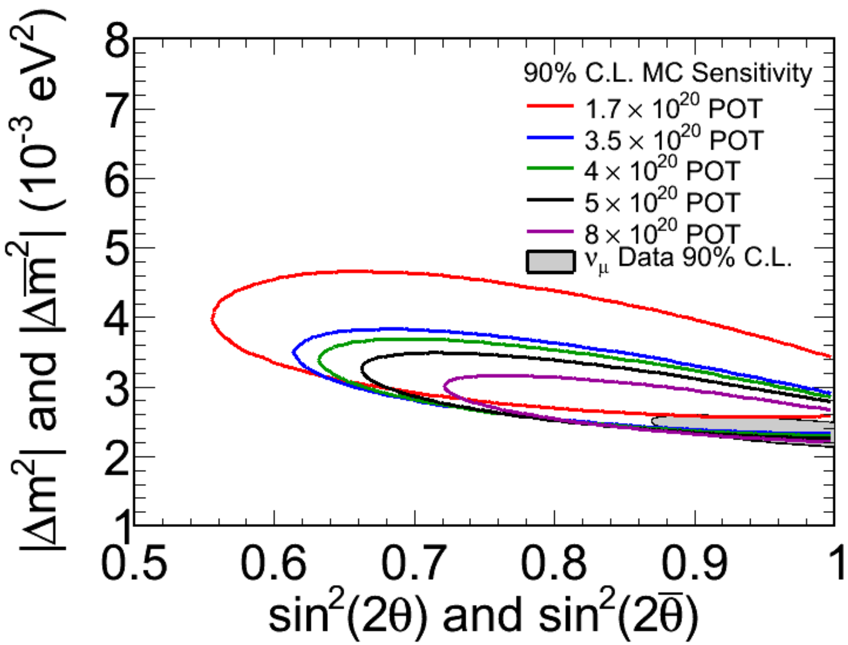
All Contours Together



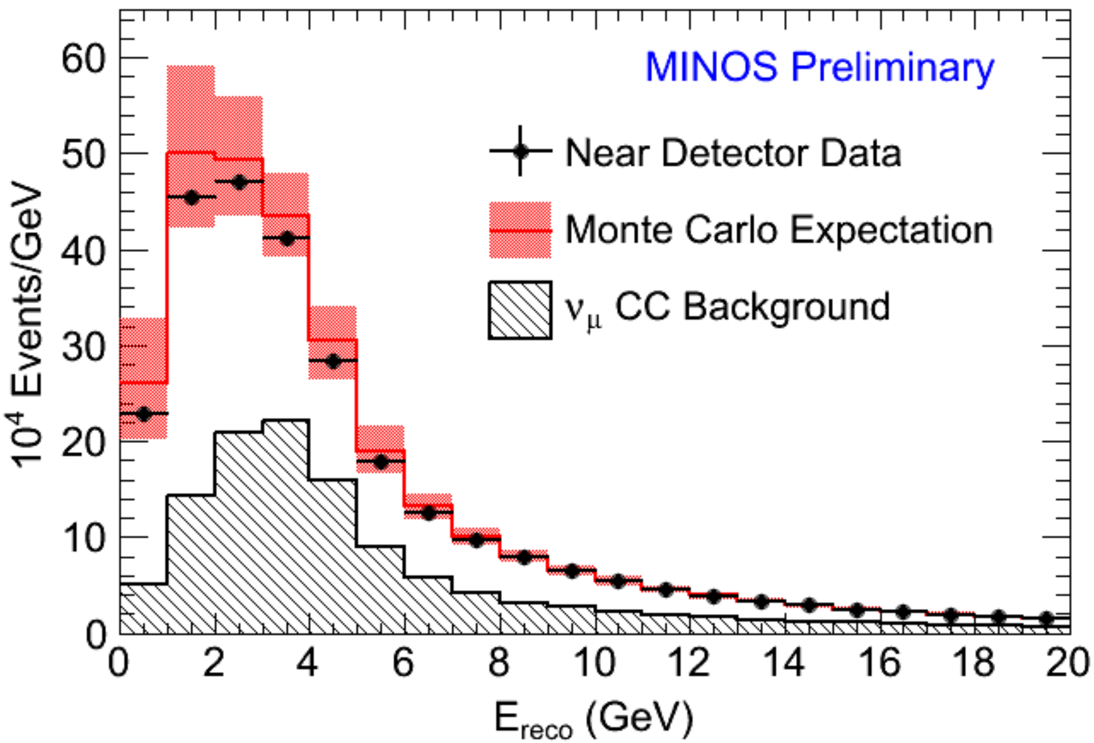
Anti-neutrino Disappearance Outlook

- Updated anti-neutrino disappearance analysis with 3×10^{20} POT exposure expected this summer



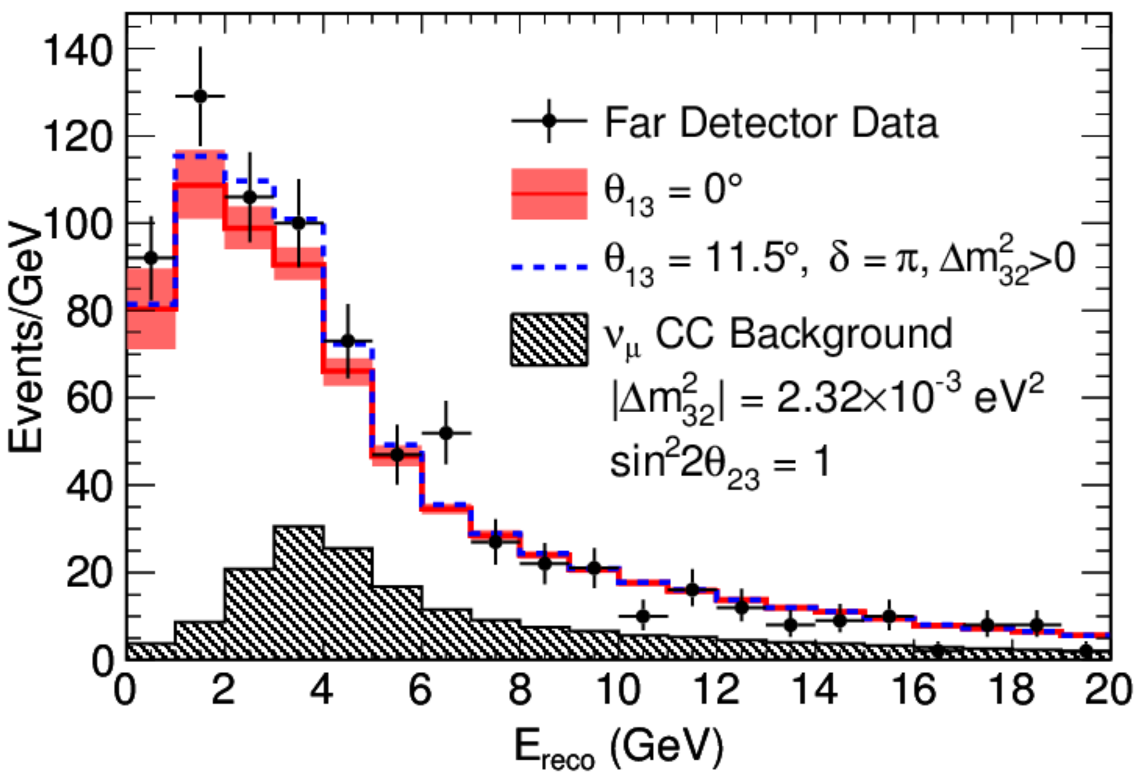


Neutral Current Near Event Rates



- Neutral Current event rate should not change in standard 3 flavor oscillations
- A deficit in the Far event rate could indicate mixing to sterile neutrinos
- ν_e CC events would be included in NC sample, results depend on the possibility of ν_e appearance

Neutral Currents in the Far Detector



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

$$R = \frac{N_{data} - BG}{S_{NC}}$$

$1.09 \pm 0.06\ (\text{stat.}) \pm 0.05\ (\text{syst.})$

(no ν_e appearance)

$1.01 \pm 0.06\ (\text{stat.}) \pm 0.05\ (\text{syst.})$

(with ν_e appearance)

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

no (with) ν_e appearance

ν_e Appearance

- At L/E~500 km/GeV, dominant oscillation mode is $\nu_\mu \rightarrow \nu_\tau$
- A few percent of the missing ν_μ could change into ν_e

$$P(\nu_\mu \rightarrow \nu_e) = \left| \sqrt{P_{atm}}\, e^{-i\left(\frac{\Delta m_{32}^2 L}{4E} + \delta_{cp}\right)} + \sqrt{P_{sol}} \right|^2$$

$$P_{atm} = \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right) \qquad P_{sol} \approx \cos^2\theta_{23} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}^2 L}{4E}\right)$$

"Atmospheric" Term
Depends on Δm^2
and unknown θ_{13}

"Solar" Term
<1% for current
accelerator experiments

ν_e Appearance

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$$2\sqrt{P_{atm}}\sqrt{P_{sol}} \cos\left(\frac{\Delta m^2_{32} L}{4E}\right) \cos\delta_{CP} \mp 2\sqrt{P_{atm}}\sqrt{P_{sol}} \sin\left(\frac{\Delta m^2_{21} L}{4E}\right) \sin\delta_{CP}$$

Interference Term

- for neutrinos

+ for antineutrinos

if $\delta_{CP} \neq 0$,

$$P(\nu_\mu \to \nu_e) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e)$$

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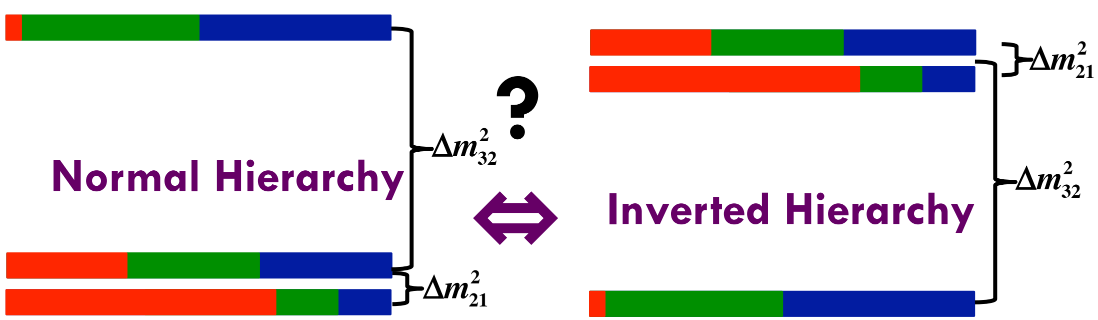
$$P_{atm} = \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E} - aL\right)\left(\frac{\frac{\Delta m^2_{31} L}{4E}}{\left(\frac{\Delta m^2_{31} L}{4E} - aL\right)}\right)^2$$

$$P_{sol} \approx \cos^2\theta_{23} \sin^2 2\theta_{12} \sin^2(aL)\left(\frac{\frac{\Delta m^2_{21} L}{4E}}{aL}\right)^2$$

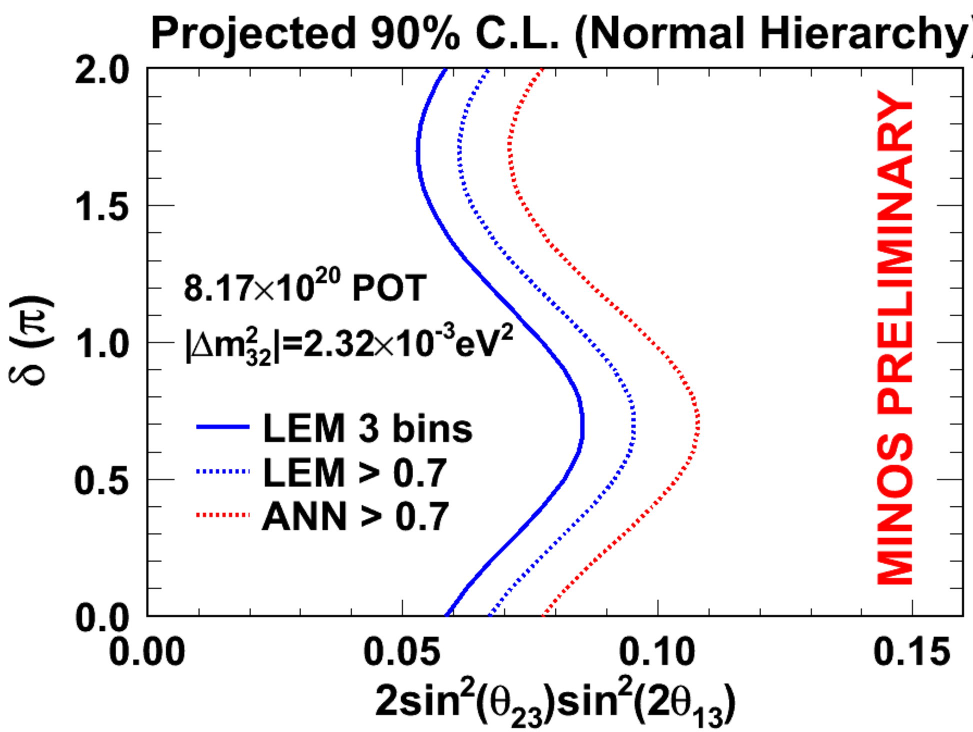
$$a = \pm\frac{G_F N_e}{\sqrt{2}} \approx (4000\ \text{km})^{-1}$$



In matter, additional term in Hamiltonian from ν_e + e CC scattering modifies oscillation probability, ~30% effect in MINOS

The Updated Analysis

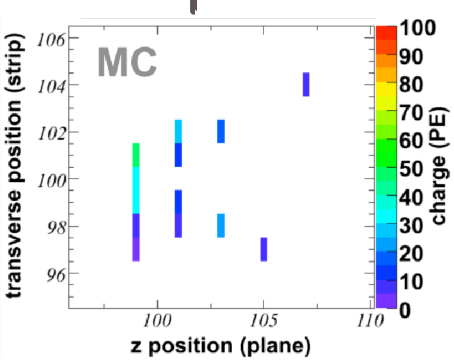
- Look for an excess of ν_e in the FD compared to prediction from ND measurement
  - select events with a ν_e topology
  - apply selection to ND, determine fraction of each background type
  - extrapolate each background type separately
  - fit FD data to extract oscillation parameters
- Updated analysis:
  - new event selection
  - new fitting technique in the FD
  - more data



Looking for Electron-neutrinos

- New electron neutrino selection technique
- Compare candidate events to a library of simulated signal and background events
- Comparison made on a strip by strip basis
- Discriminating variables formed using information from 50 best matches

Input (data or MC)

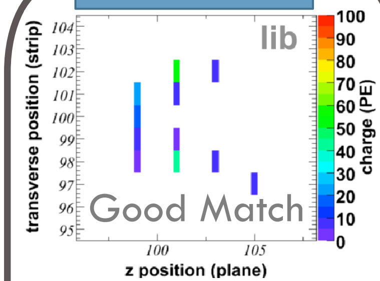


Compare to MC Library

$$L = \sum_{i=1}^{N_{\text{strips}}} \ln\left(\int_0^\infty P(n_A^i;\lambda) P(n_B^i;\lambda)\, d\lambda \right)$$

$$\Delta L = -(L_{lib} - L_{self})$$

Library Event #1

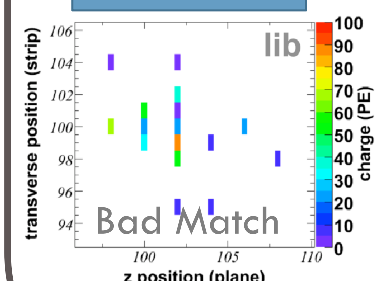


Library Event #2

Library Event #3

. . .

Library Event #k



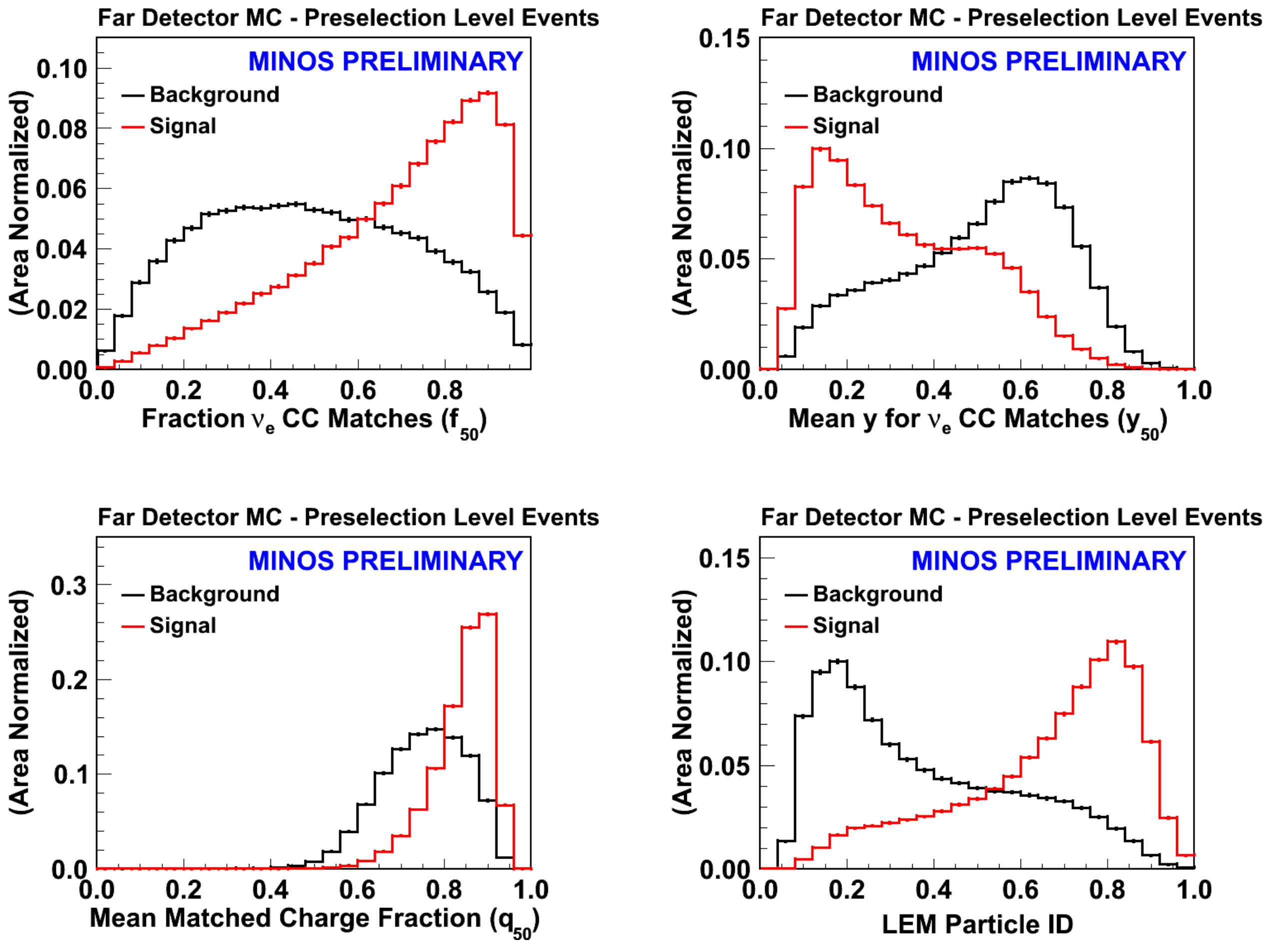
. . .

Library Event #30M

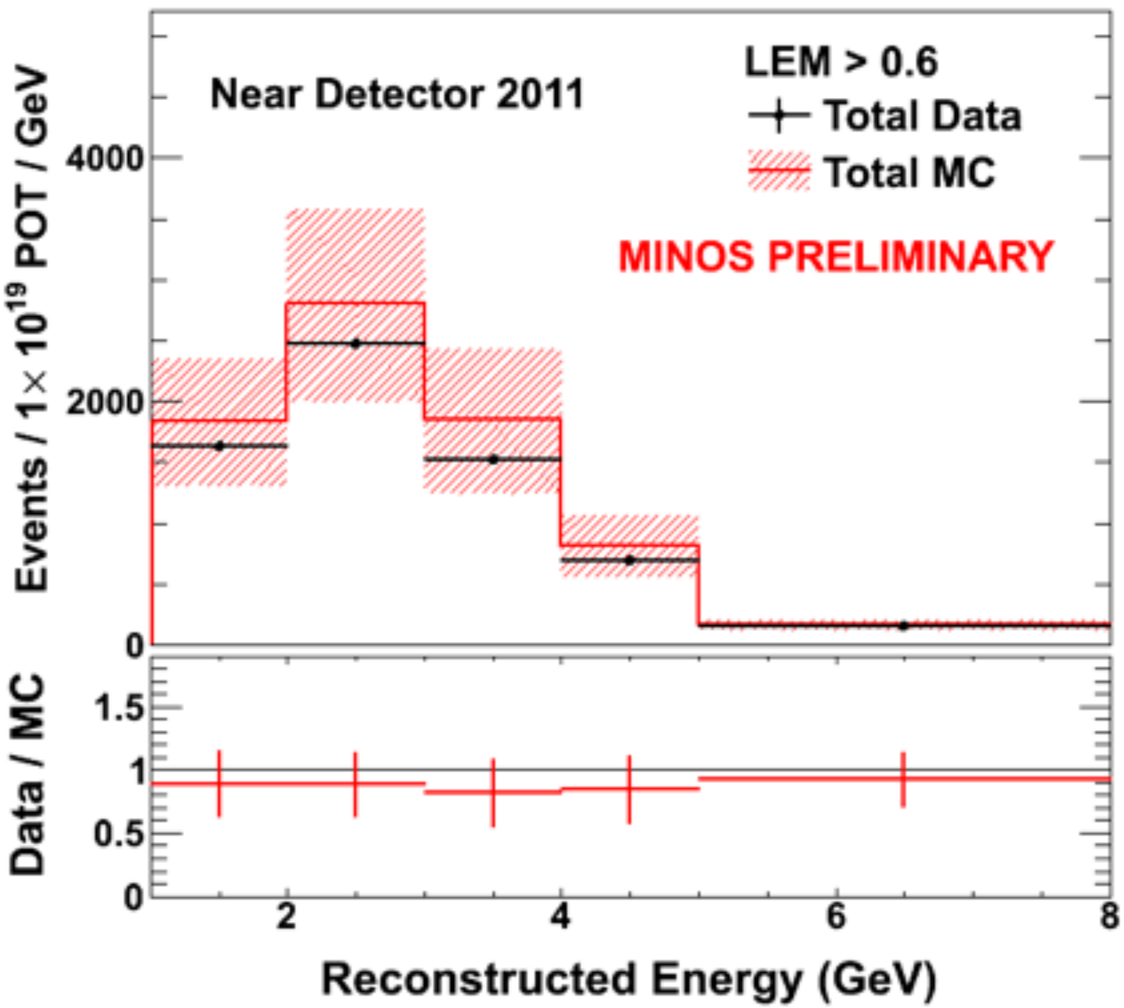
Compute variables using information from best N matches

Discriminating Variables

- Three discriminating variables combined in neural net
- Achieve ~40% signal efficiency, ~98% BG rejection



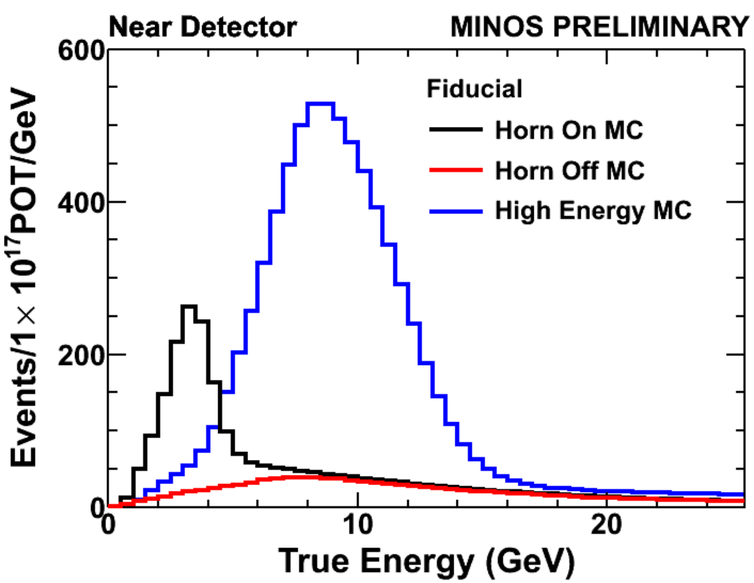
Near Detector Data

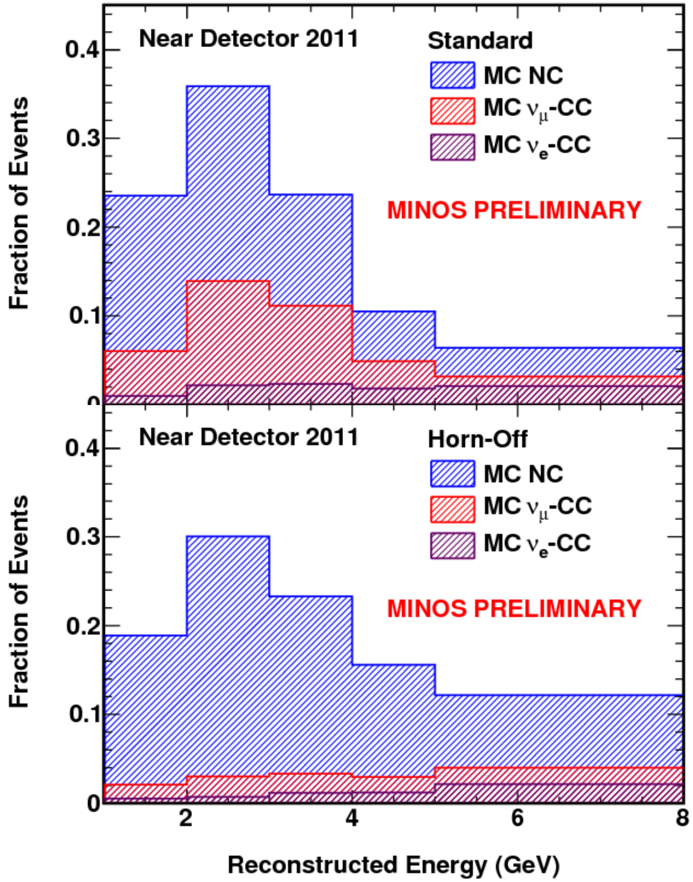


- ND data sample comprised of NC, ν_μ CC, beam ν_e CC interactions.
- Each propagates to the FD in a different manner
- Must determine relative composition of ND spectrum

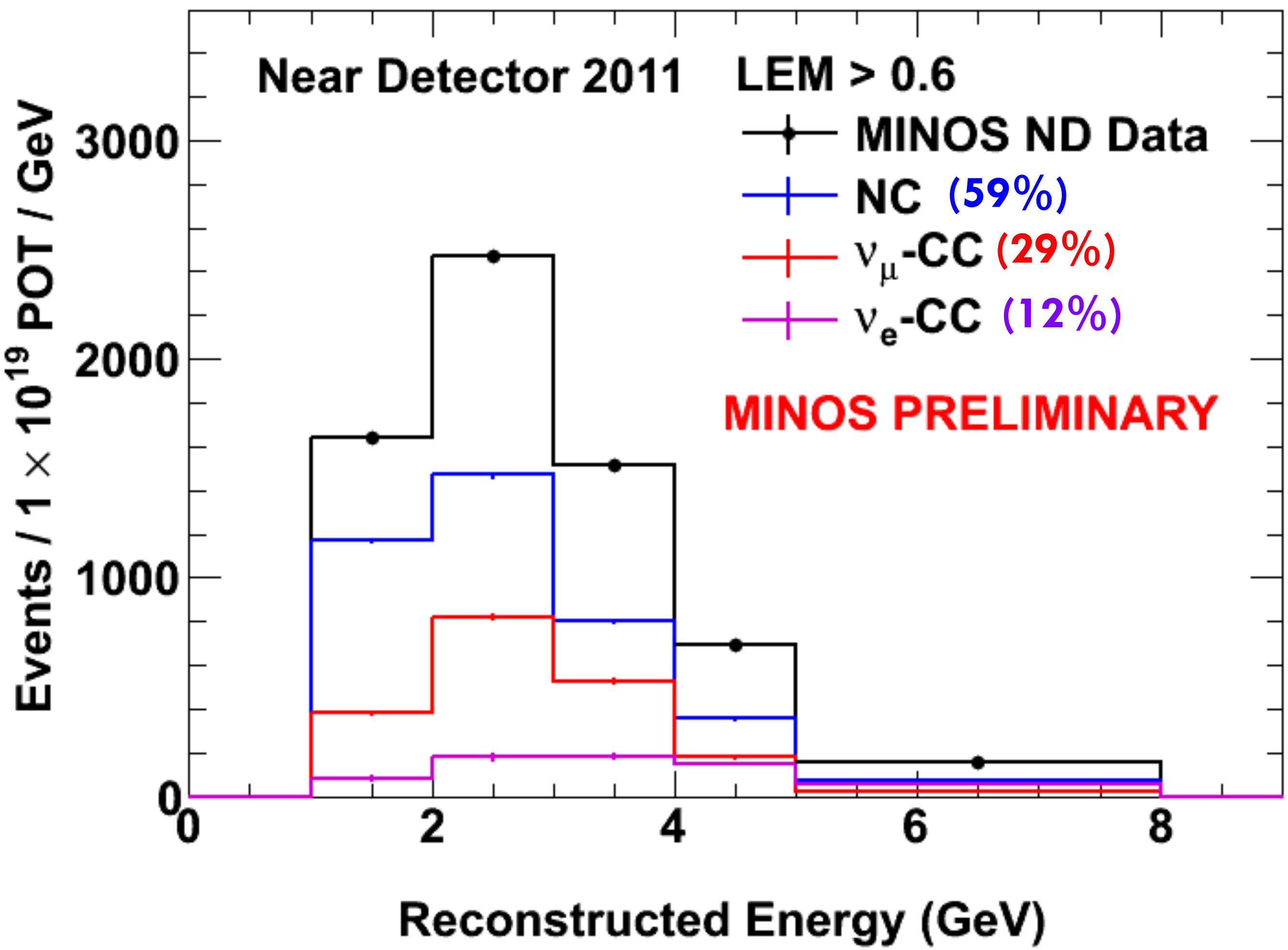
Measuring the Background

- Use ND data in different configurations to extract relative components of background
- Selected event spectrum has different relative components of each background type





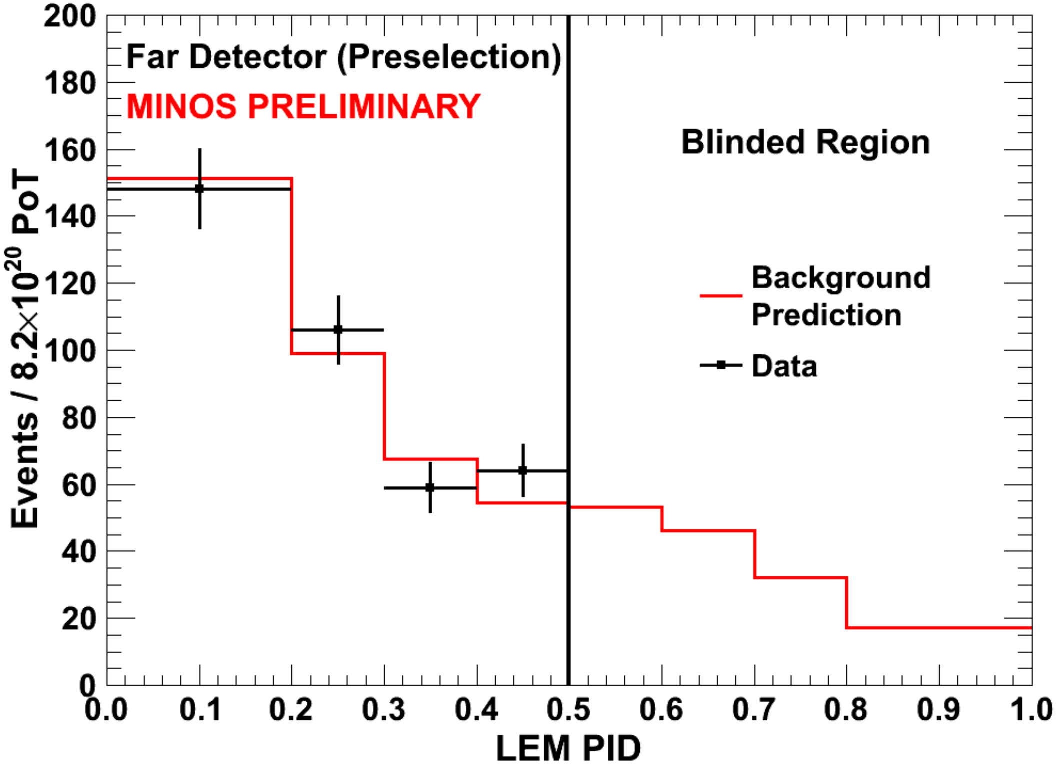
Decomposition



P. Vahle, INFO 2011

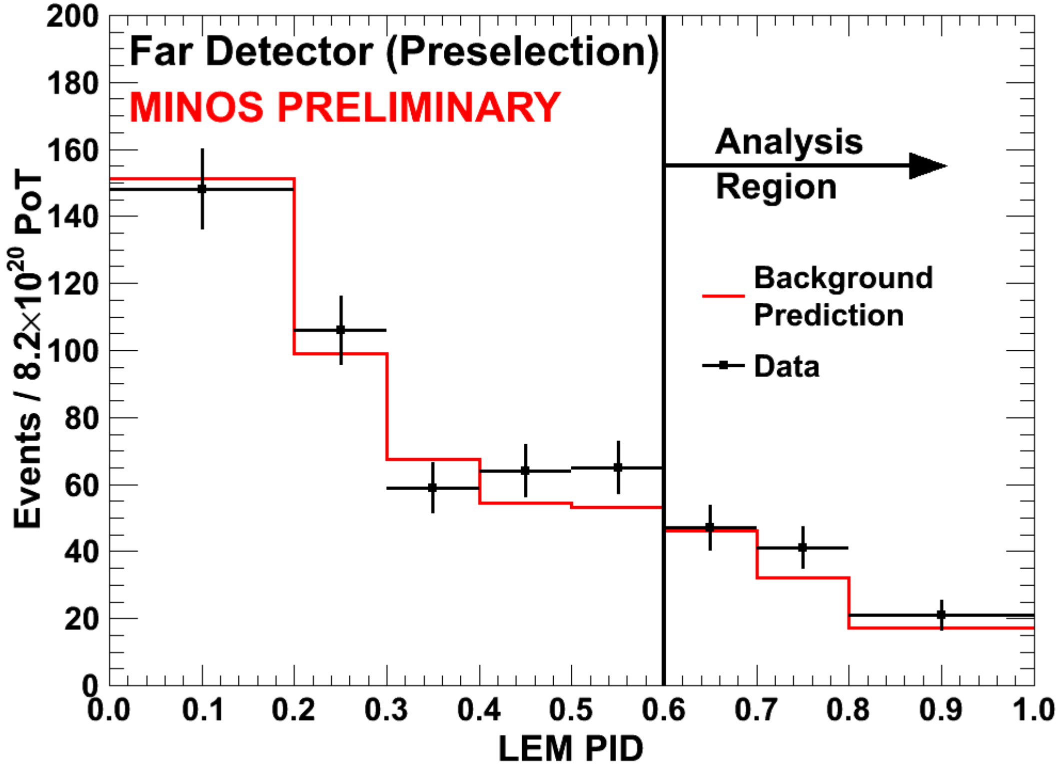
ν_e Appearance Results

- In signal enhanced region, based on ND data, expect: **49.5±7.0(stat.)±2.8(syst.)**

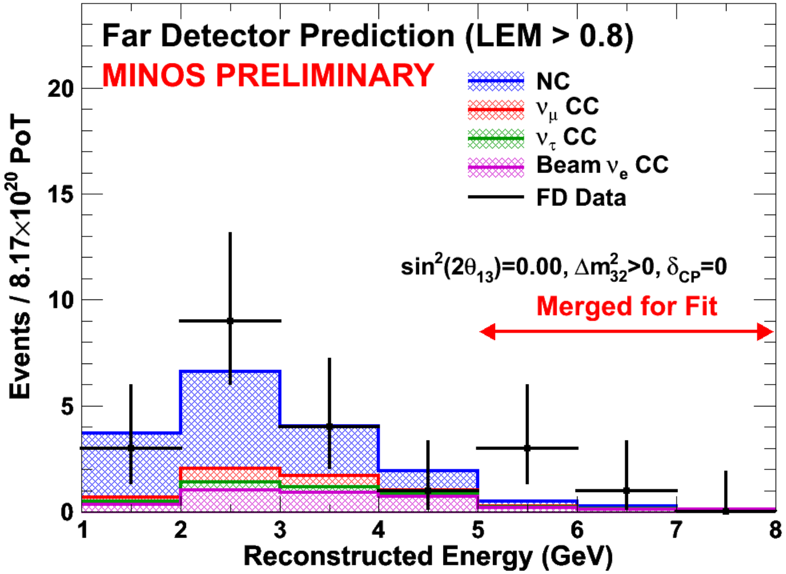


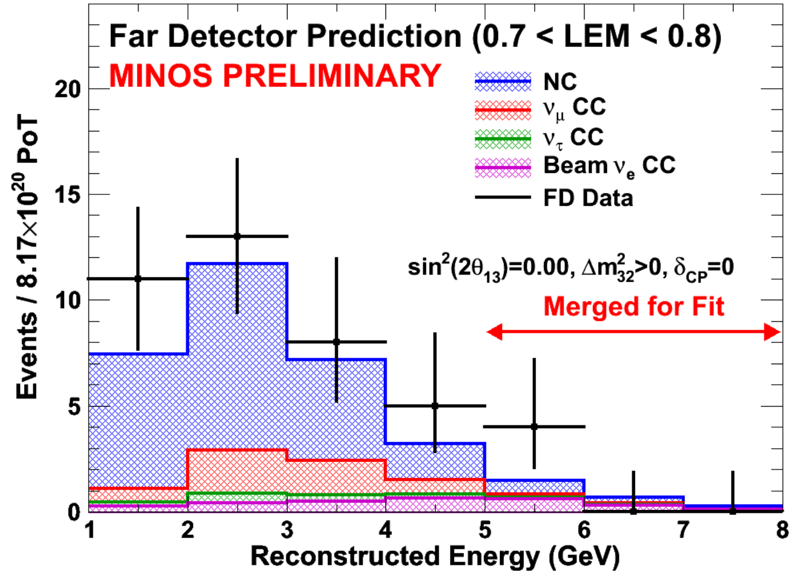
ν_e Appearance Results

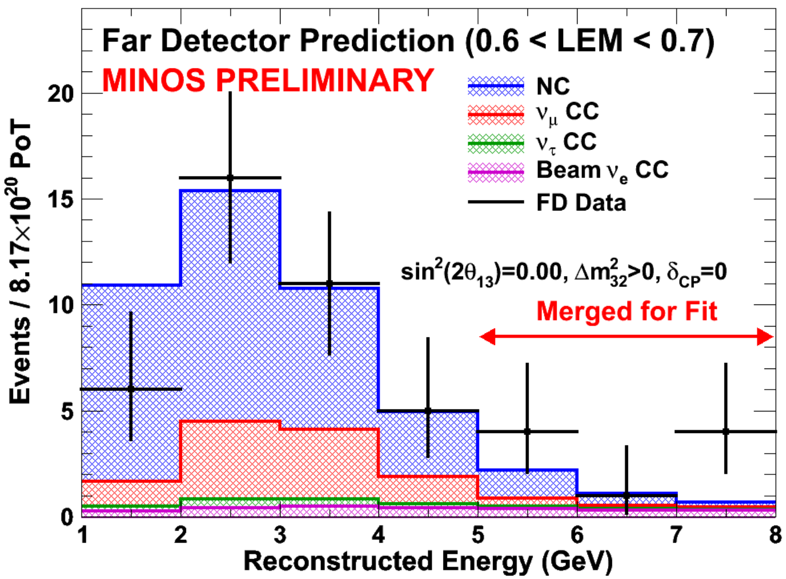
- In signal enhanced region, based on ND data, expect: **49.5±7.0(stat.)±2.8(syst.)**
- Observe: **62** events in the FD



Fitting to Oscillations

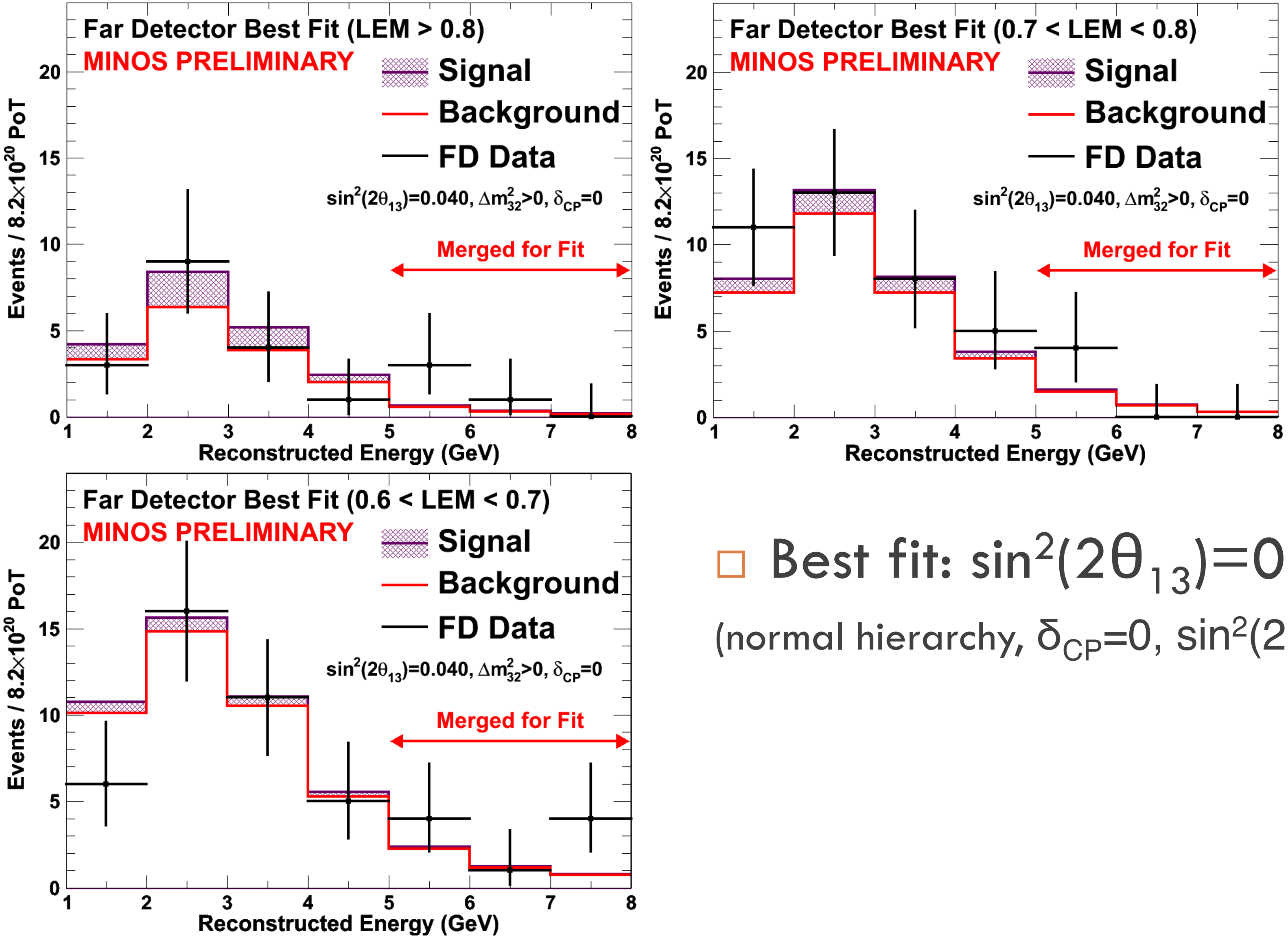






- Oscillation parameters extracted from a full 3 flavor fit to energy spectrum in 3 bins of PID

Fitting to Oscillations

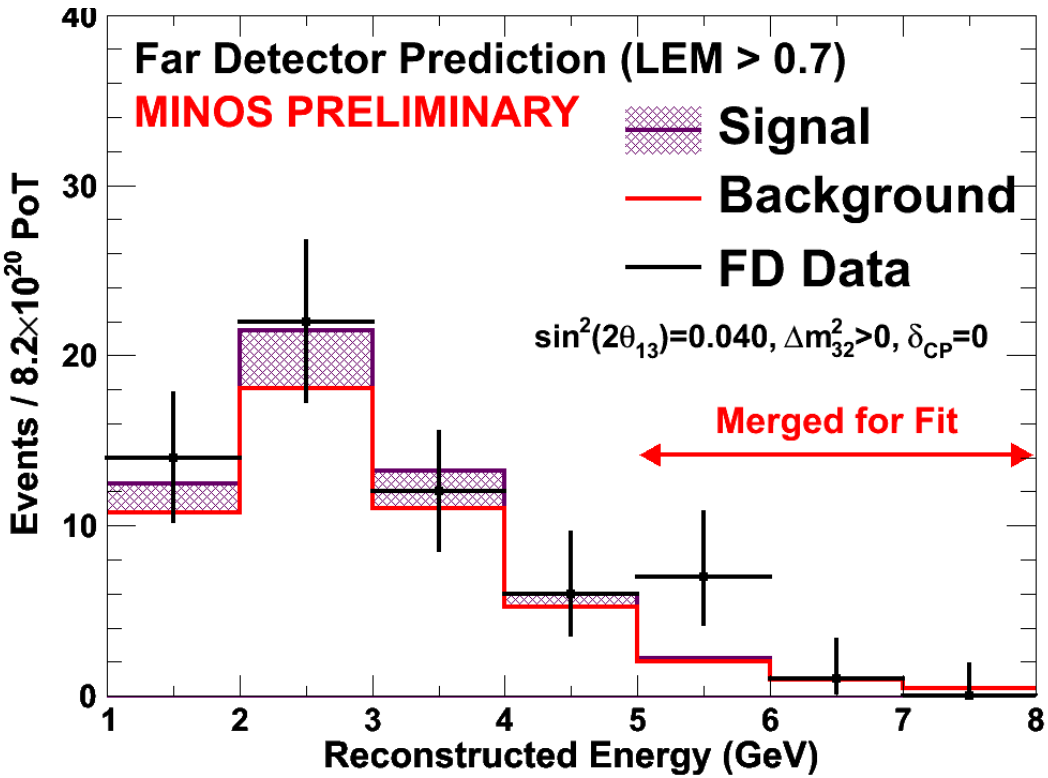


- Best fit: $\sin^2(2\theta_{13})=0.040$

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

FD Data

- Energy spectrum for signal enhanced region



ν_e Appearance Results

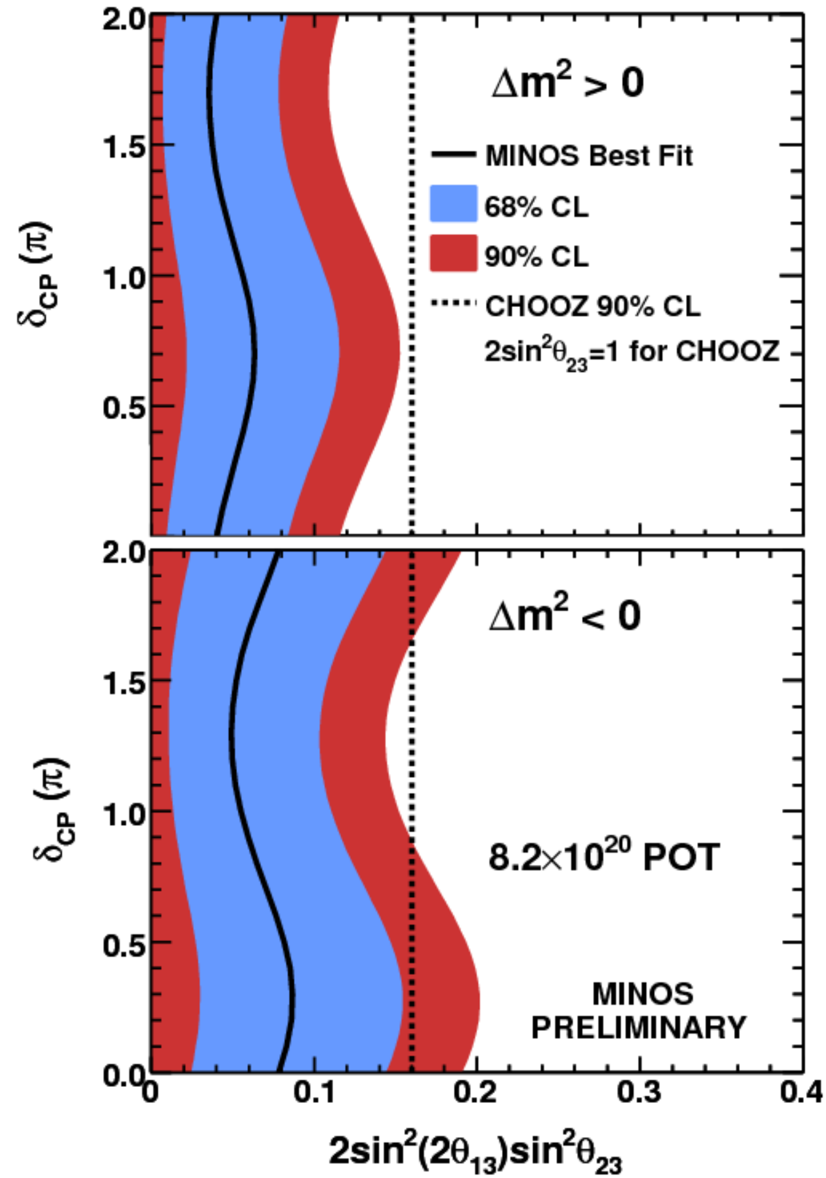
for $\delta_{CP} = 0, \sin^2(2\theta_{23}) = 1,$

$|\Delta m^2_{32}| = 2.32 \times 10^{-3}\ \mathrm{eV}^2$

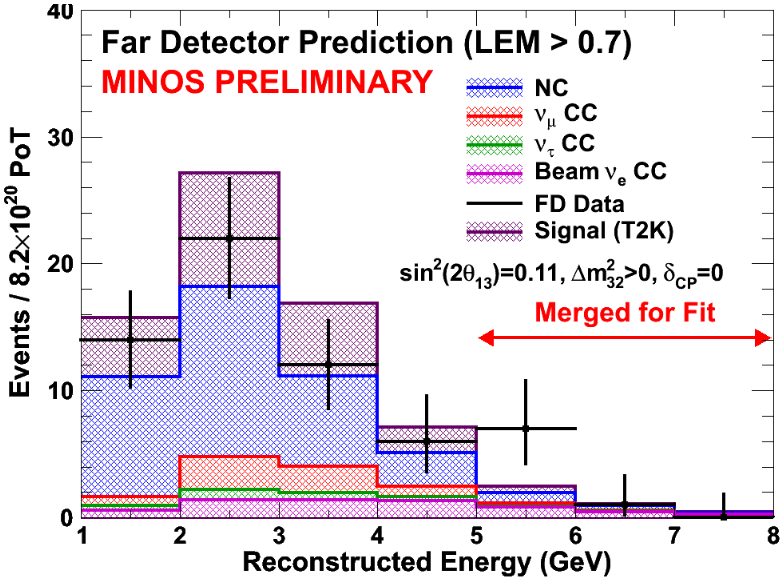
$\sin^2(2\theta_{13}) = 0.04\ \ (0.08)$ at best fit

$\sin^2(2\theta_{13}) < 0.12\ \ (0.19)$ at 90% C.L.

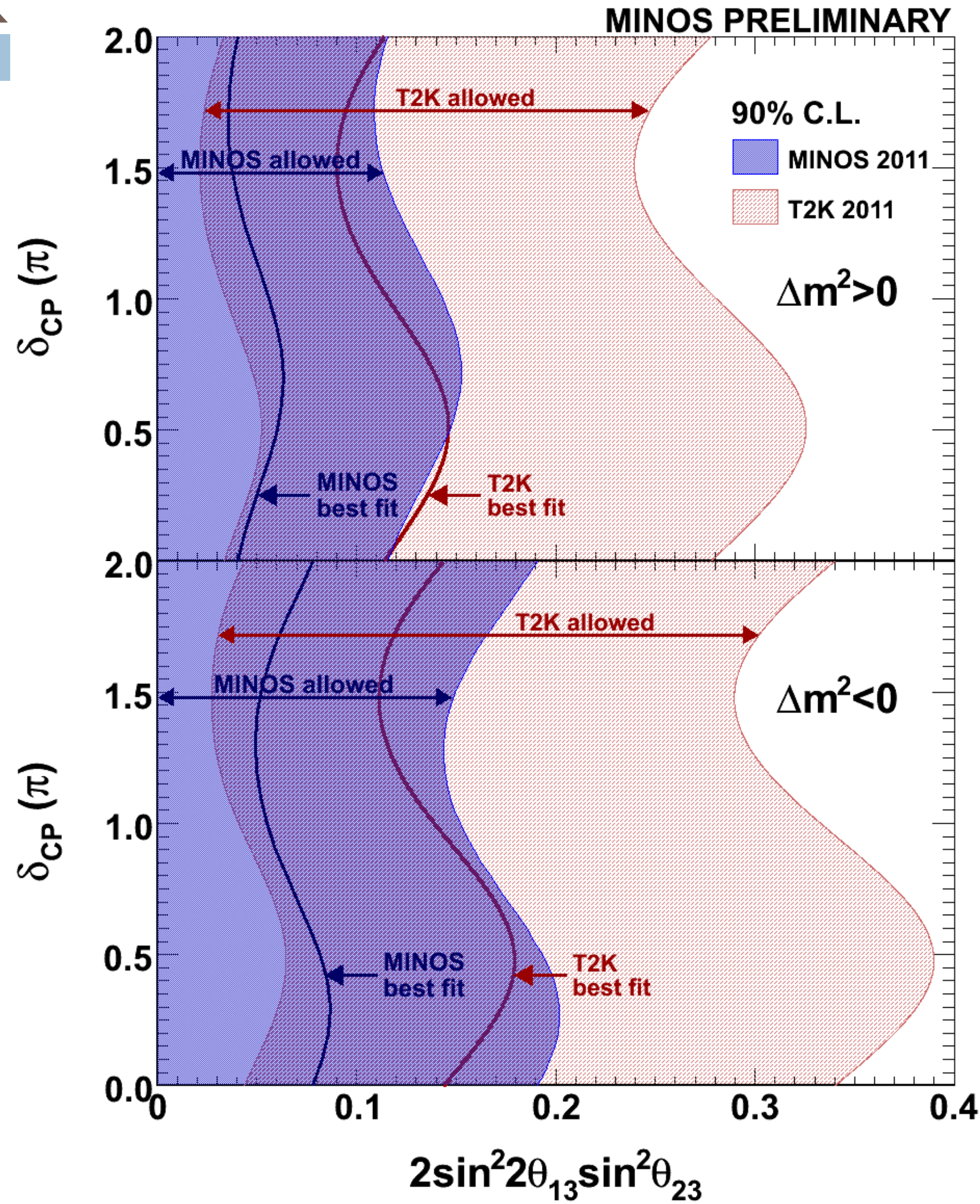
$\sin^2(2\theta_{13}) = 0$ excluded at 89%



Comparing to T2K

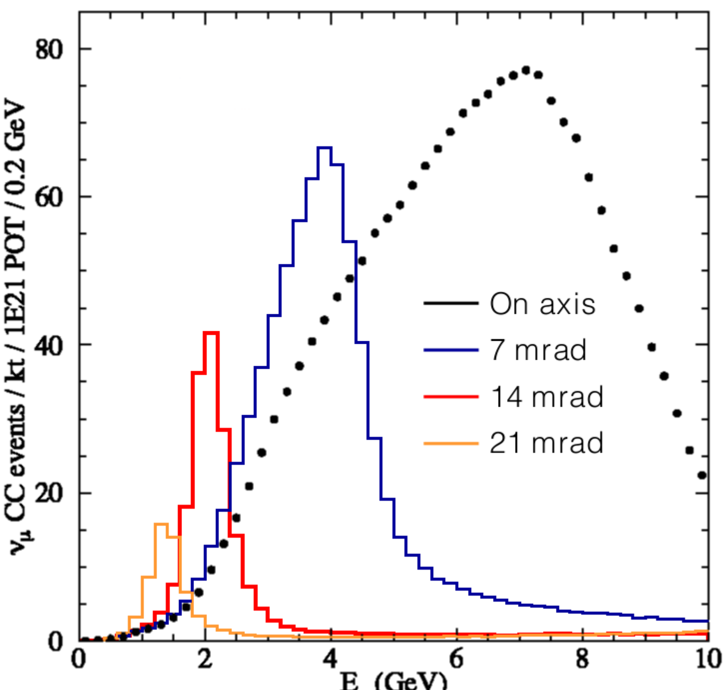


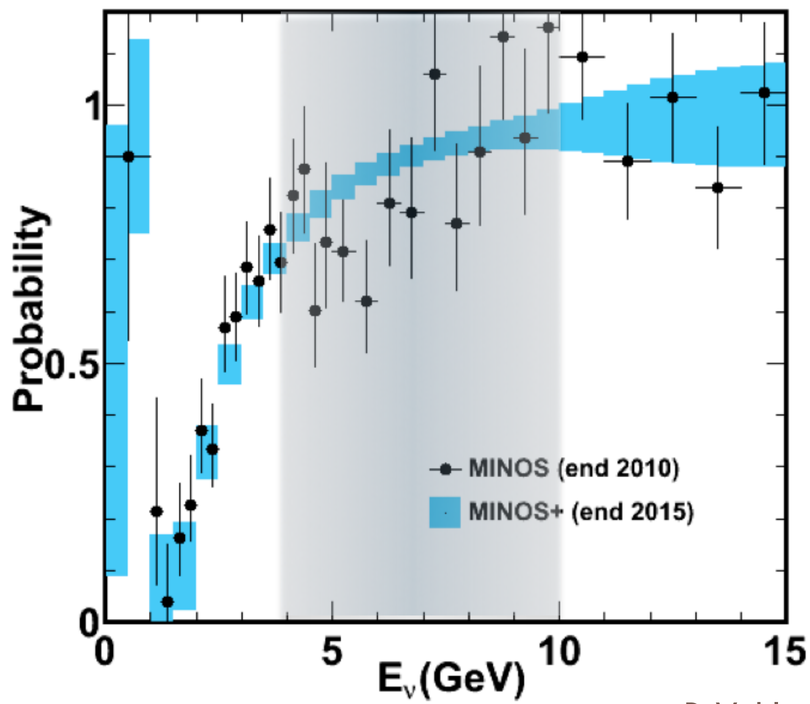
- We have more data on tape and will continue to run until next winter



MINOS+

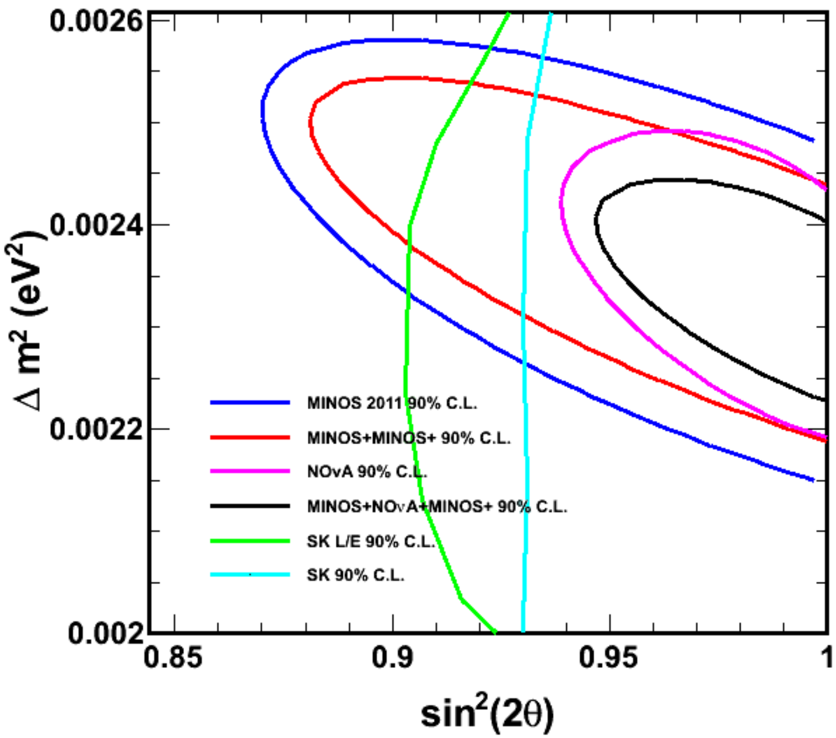
- In the NOvA era, the MINOS detectors will be exposed to a high intensity beam peaked at 7 GeV
- Above the oscillation sweet spot, but in a region that currently suffers from poor statistics

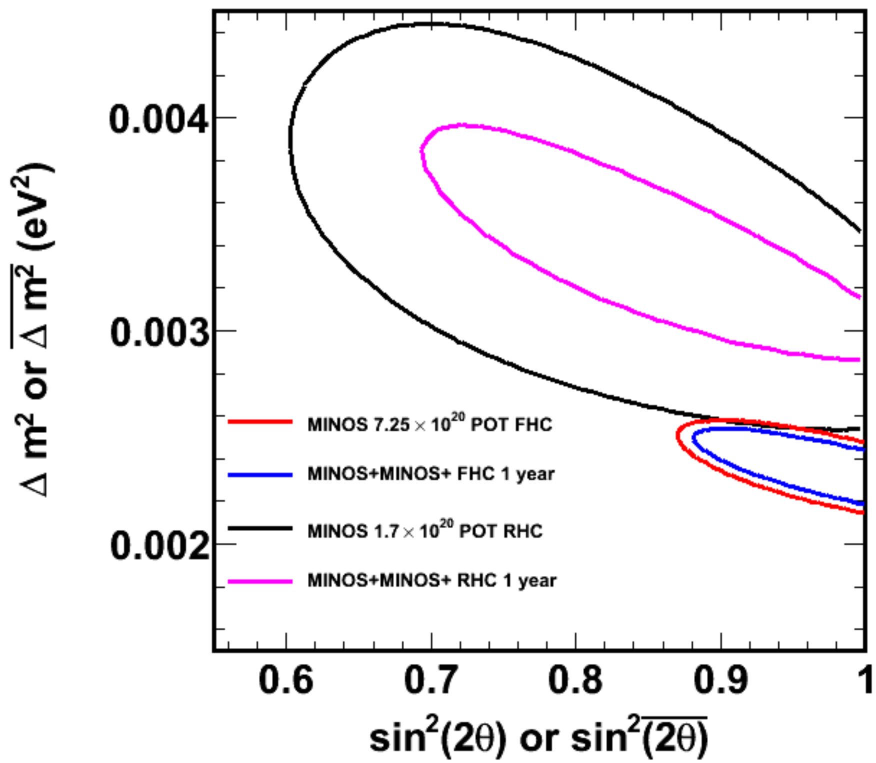




P. Vahle, INFO 2011

MINOS+

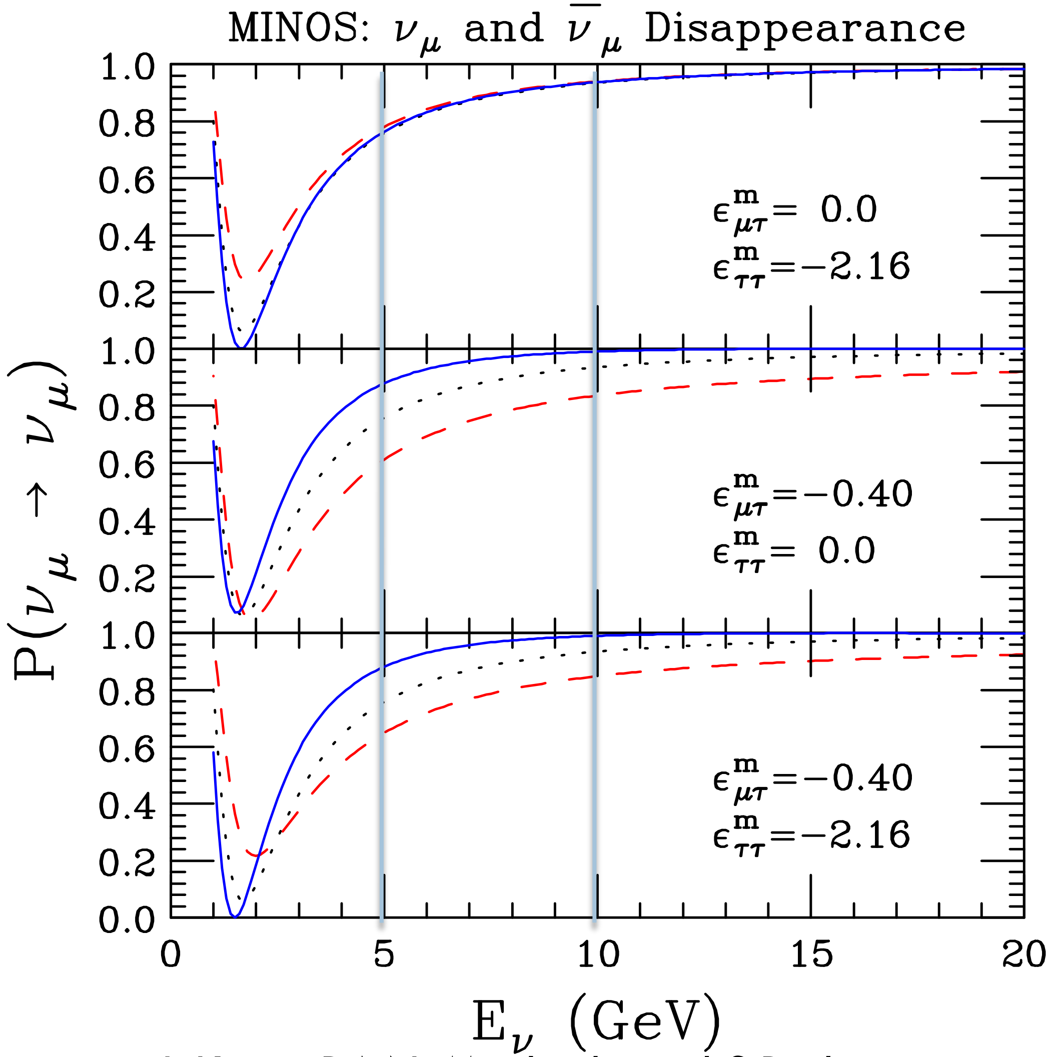




- Continue to contribute to oscillation parameter measurements, but with different systematics

Non Standard Interactions in MINOS+

- High energy behavior can constrain models, for example NSI
  - NSI has a measurable effect in neutrinos as well as antineutrinos
  - Comparison of low energy to high energy behavior could disentangle this without anti-nu running



J. Kopp, P.A.N. Machado and S.Parke, Phys.Rev.D82:113002 (2010).

Summary

- With 7x10^{20} POT of neutrino beam, MINOS finds
  - muon-neutrinos disappear

$$\left|\Delta m^2\right| = 2.32^{+0.12}_{-0.08} \times 10^{-3}\,\mathrm{eV}^2,$$
$$\sin^2(2\theta) > 0.90 \ (90\%\ \mathrm{C.L.})$$

  - NC event rate is not diminished

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

- Updated electron-neutrino appearance results:

$$\sin^2(2\theta_{13}) < 0.12\ (0.19) \text{ at } 90\%\ \mathrm{C.L.}$$
$$\sin^2(2\theta_{13}) = 0 \text{ excluded at } 89\%$$

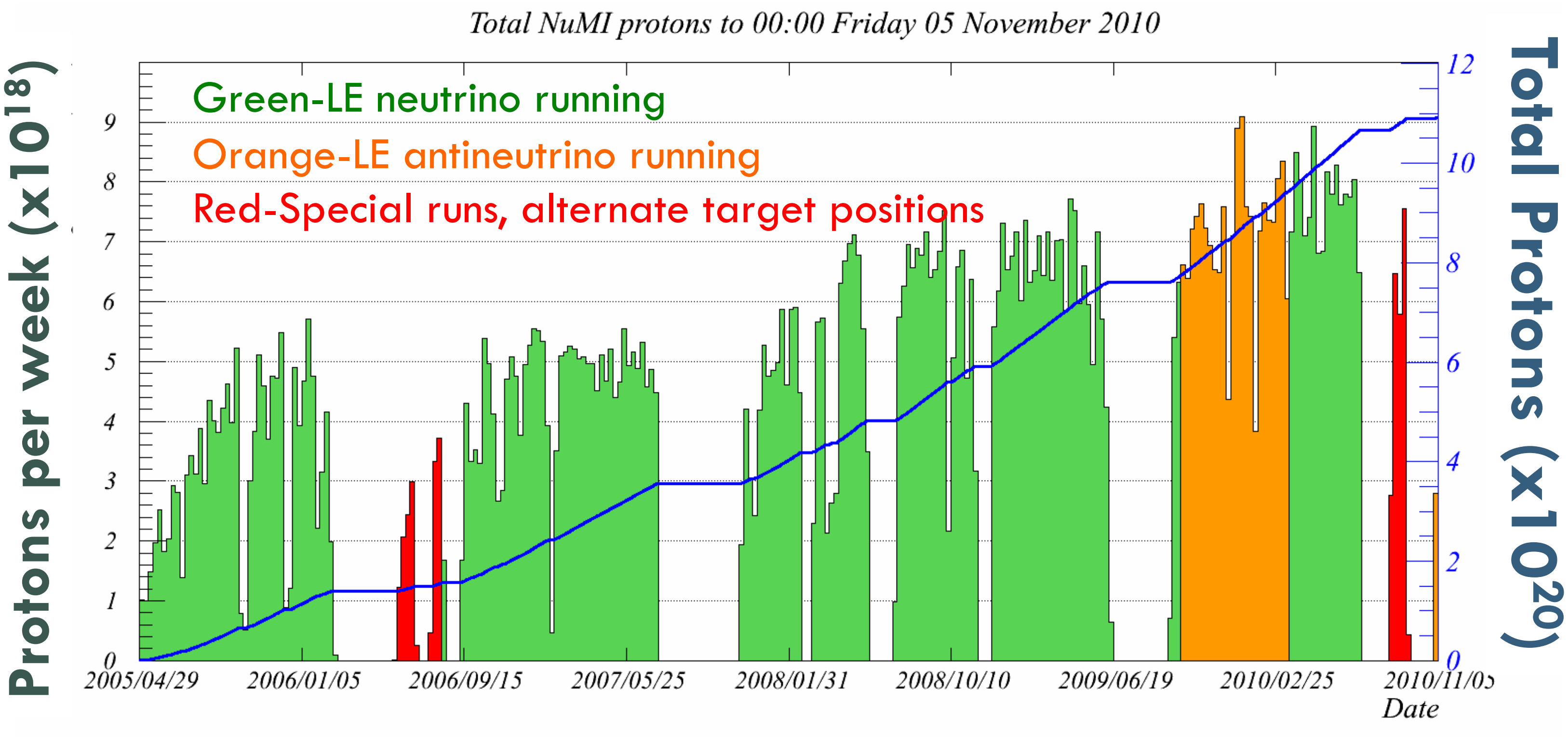
- With 1.71x10^{20} POT of anti-neutrino beam

$$\left|\overline{\Delta m^2}\right| = 3.36^{+0.46}_{-0.40} \times 10^{-3}\,\mathrm{eV}^2,$$
$$\sin^2(2\overline{\theta}) = 0.86^{+0.11}_{-0.12}$$

MINOS+ is on the horizon!

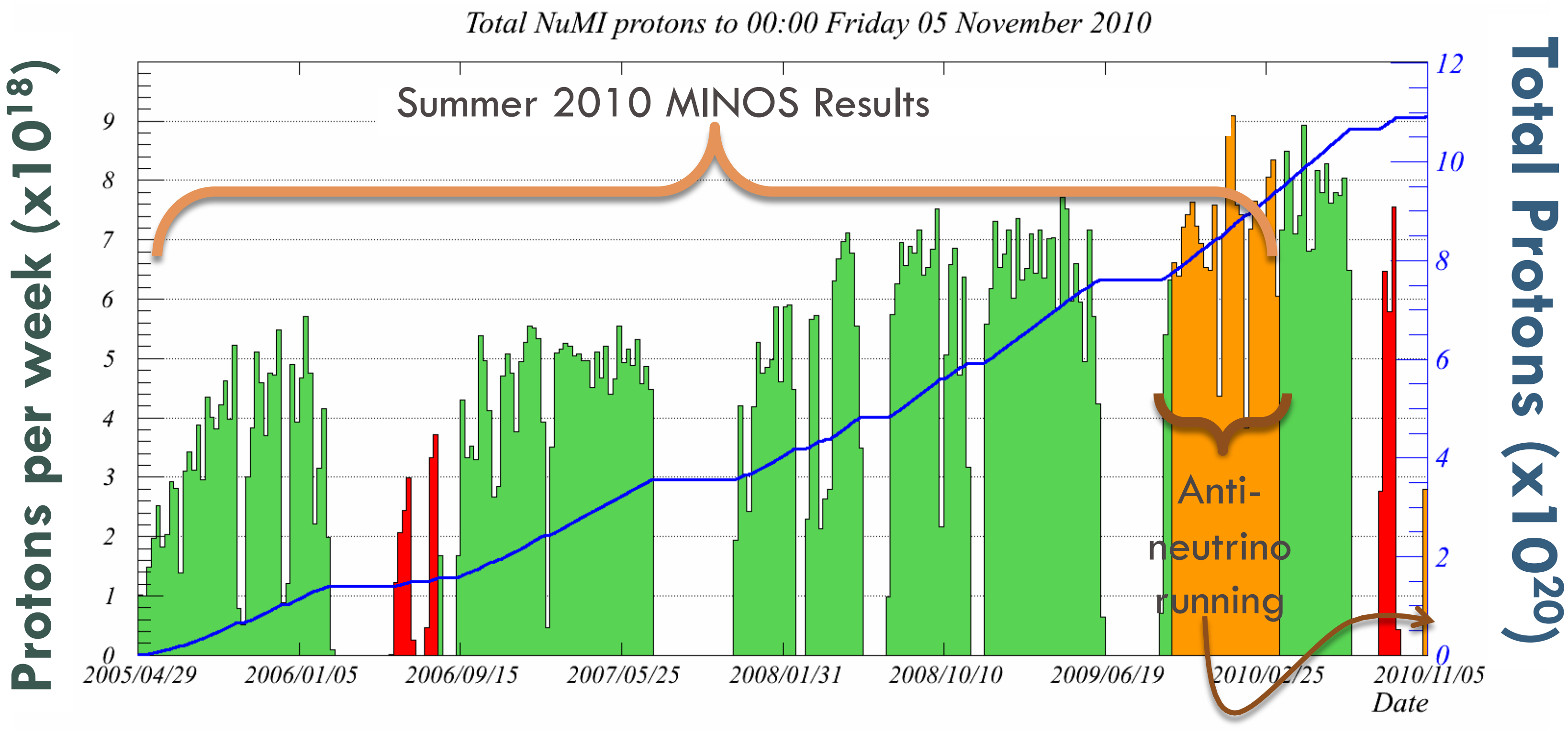
Backup Slides

Beam Performance



- Started data taking 2005
- $1\text{x}10^{21}$ POT milestone achieved Summer 2010

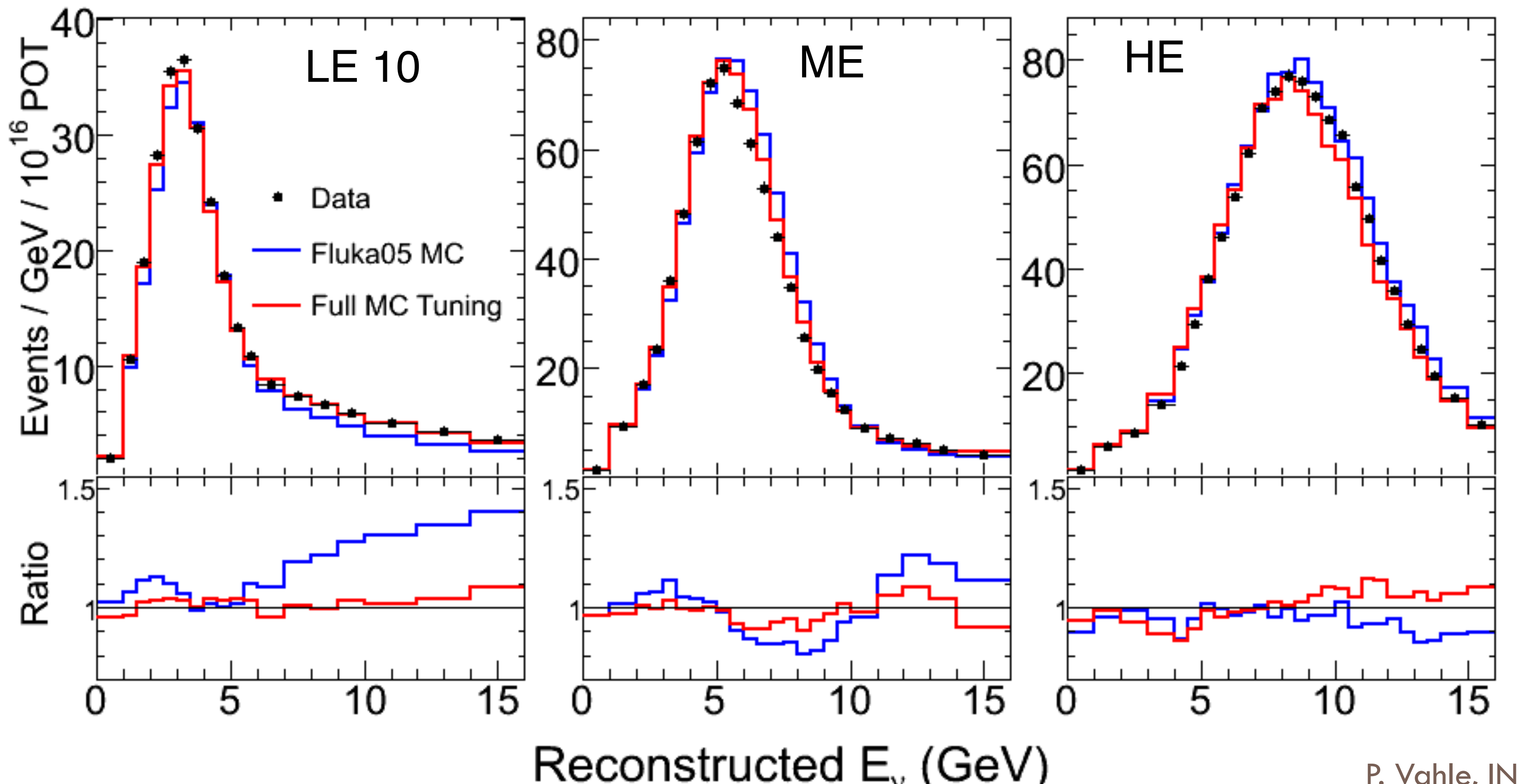
Beam Performance



- 7×10^{20} POT low energy neutrino mode
- 1.71×10^{20} POT antineutrino mode

Neutrino Spectrum

- Use flexibility of beam line to constrain hadron production, reduce uncertainties due to neutrino flux



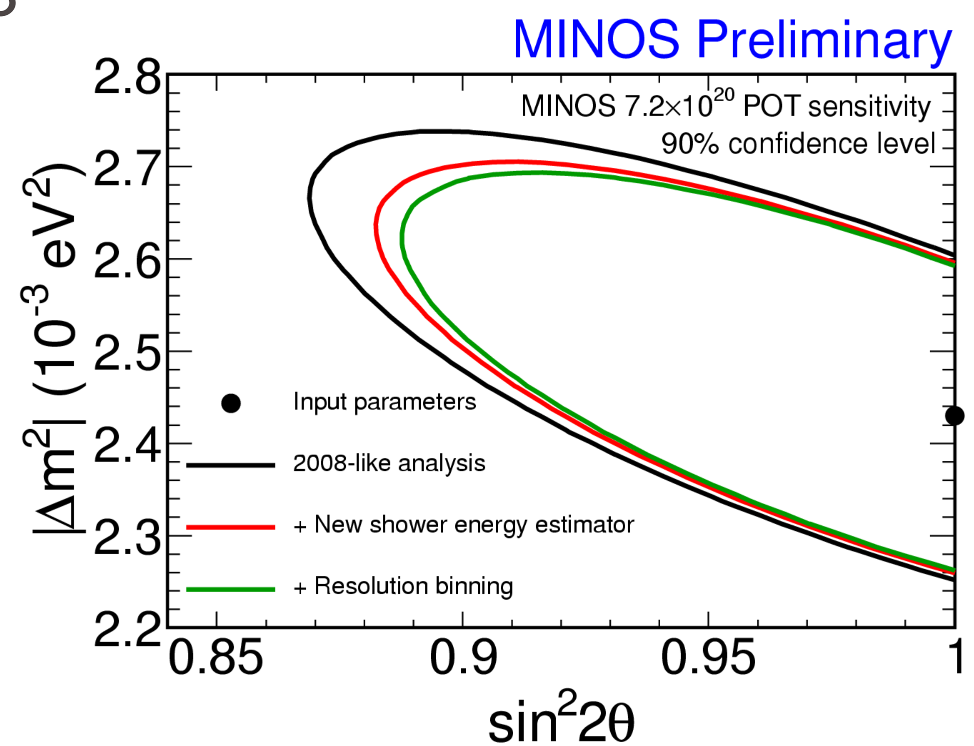
Far/Near differences

- ν_μ CC events oscillate away
- Event topology
  - Light level differences (differences in fiber lengths)
  - Multiplexing in Far (8 fibers per PMT pixel)
  - Single ended readout in Near
- PMTs (M64 in Near Detector, M16 in Far):
  - Different gains/front end electronics
  - Different crosstalk patterns
- Neutrino intensity
- Relative energy calibration/energy resolution

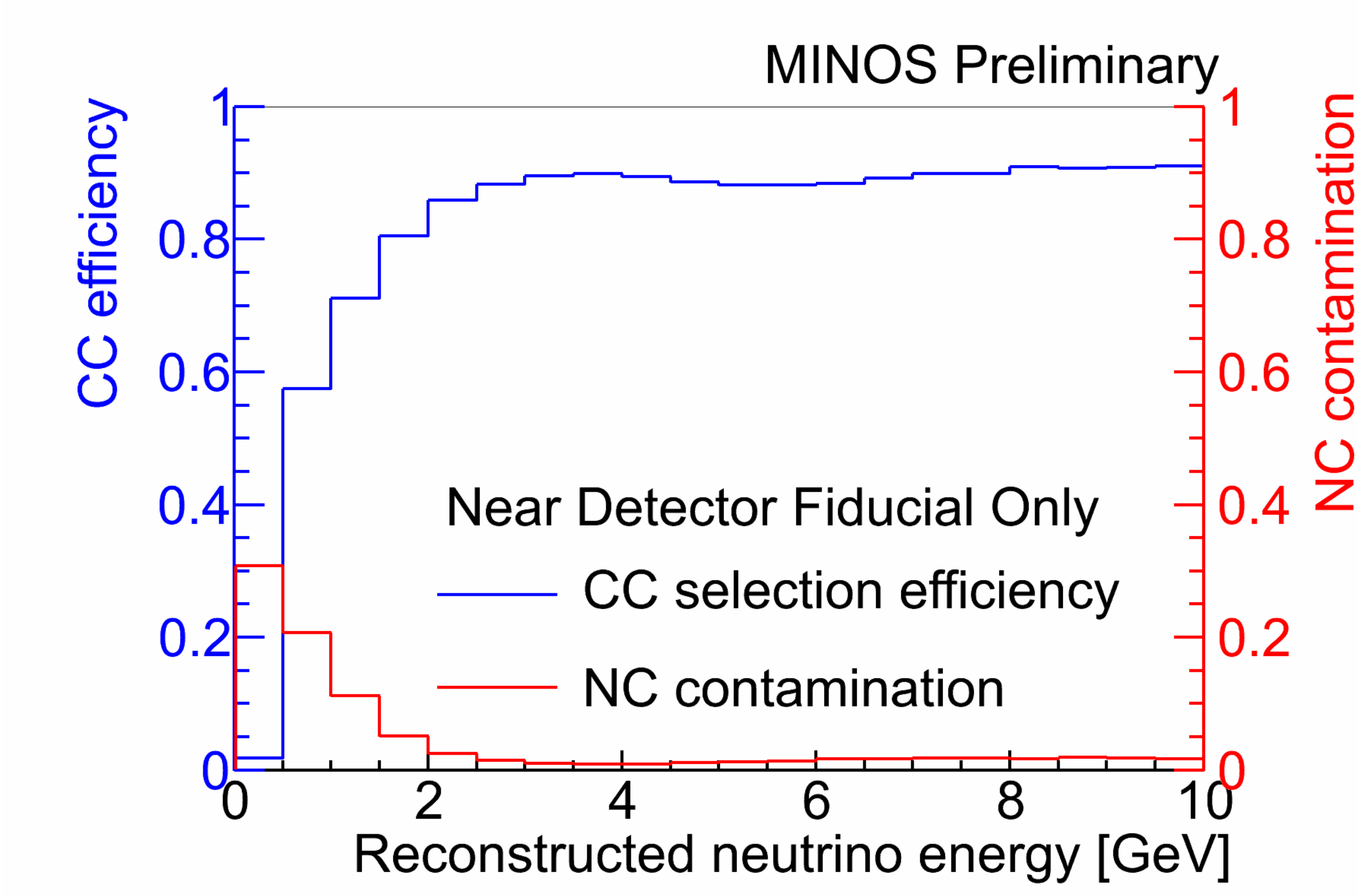
Account for these lower order effects using detailed detector simulation

Analysis Improvements

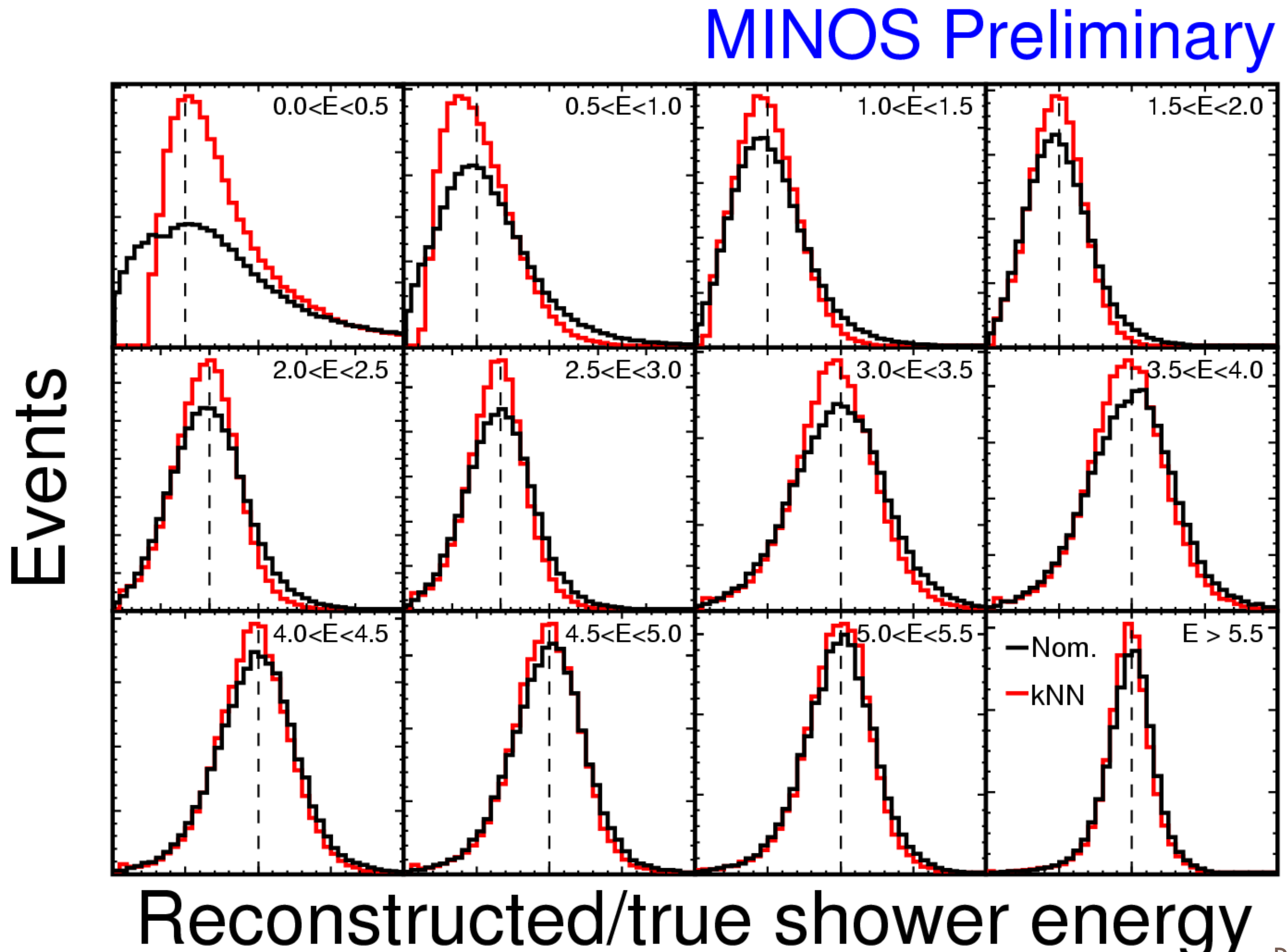
- Since PRL 101:131802, 2008
- Additional data
  - $3.4\times10^{20} \rightarrow 7.2\times10^{20}$ POT
- Analysis improvements
  - updated reconstruction and simulation
  - new selection with increased efficiency
  - no charge sign cut
  - improved shower energy resolution
  - separate fits in bins of energy resolution
  - smaller systematic uncertainties



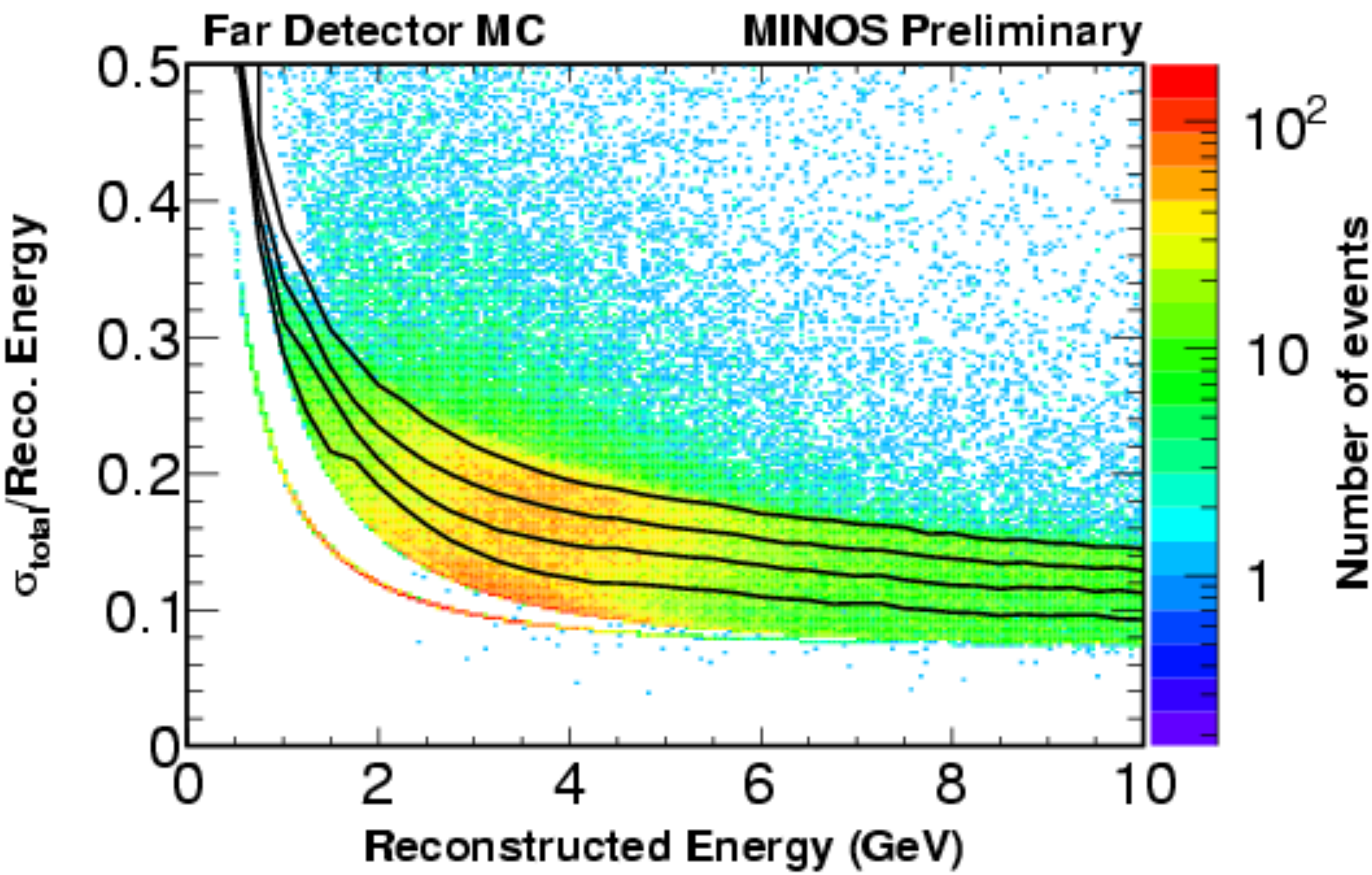
New Muon-neutrino CC Selection



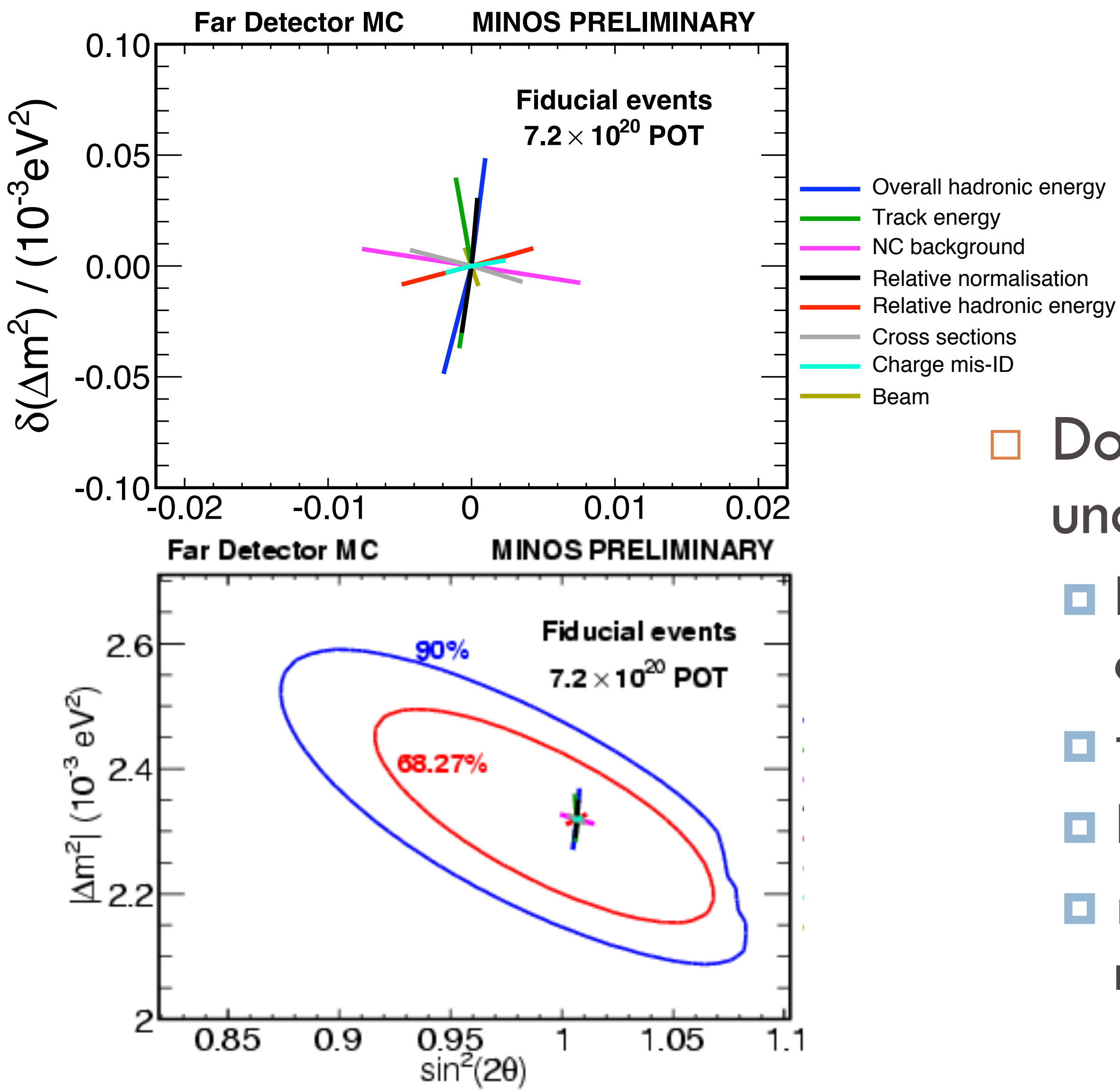
Shower Energy Resolution



Energy Resolution Binning

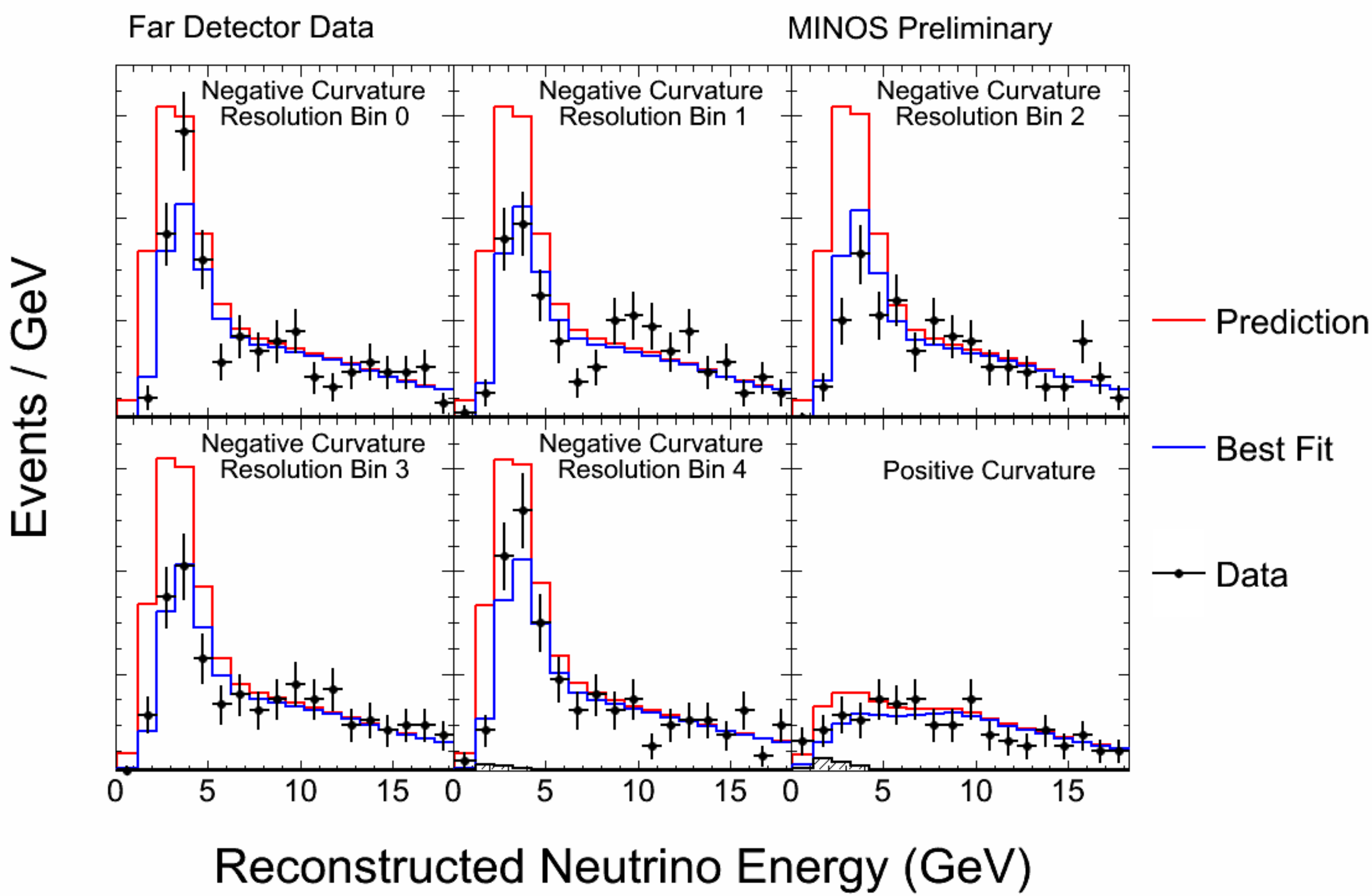


CC Systematic Uncertainties



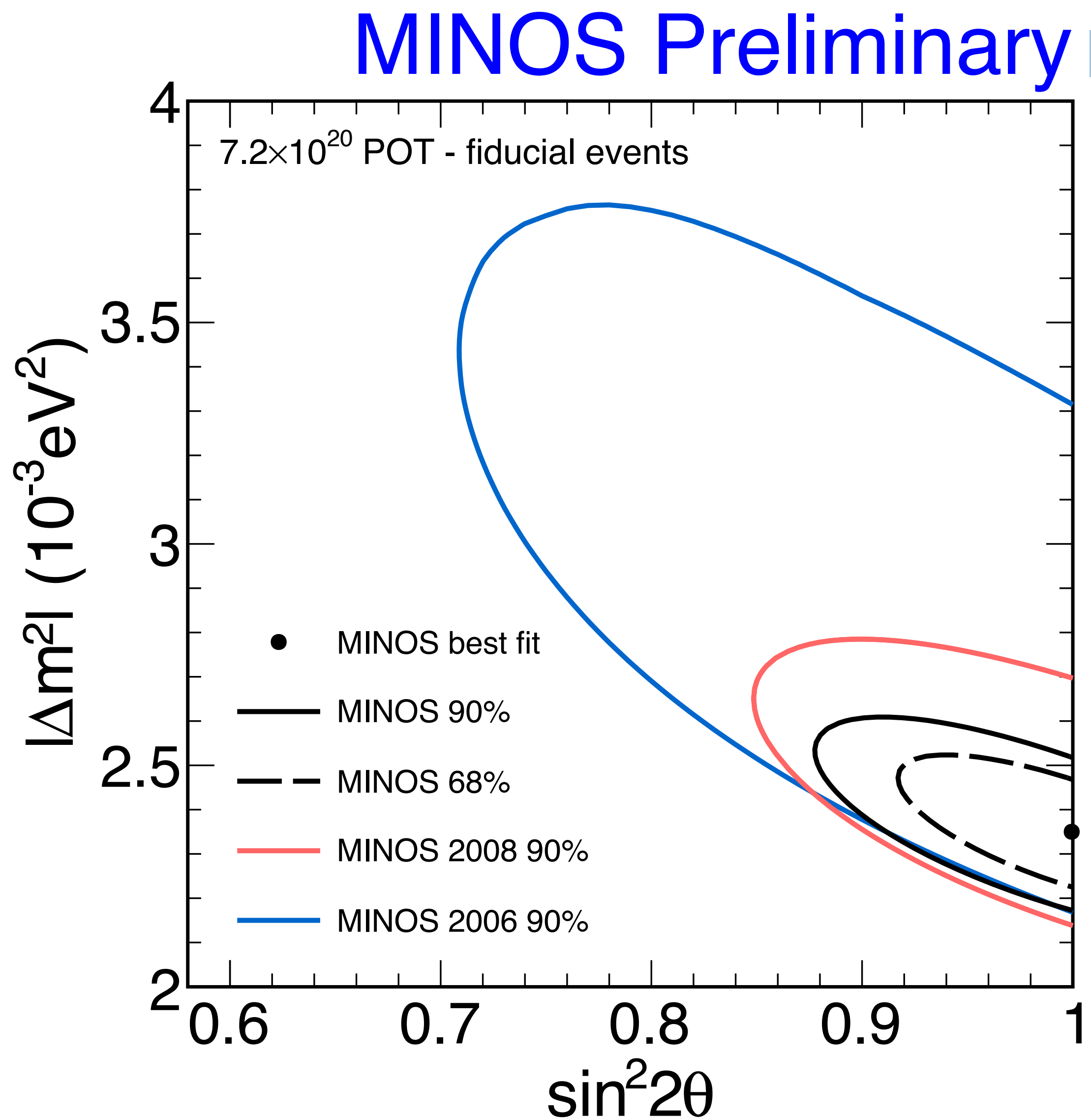
- Dominant systematic uncertainties:
  - hadronic energy calibration
  - track energy calibration
  - NC background
  - relative Near to Far normalization

Resolution Binning

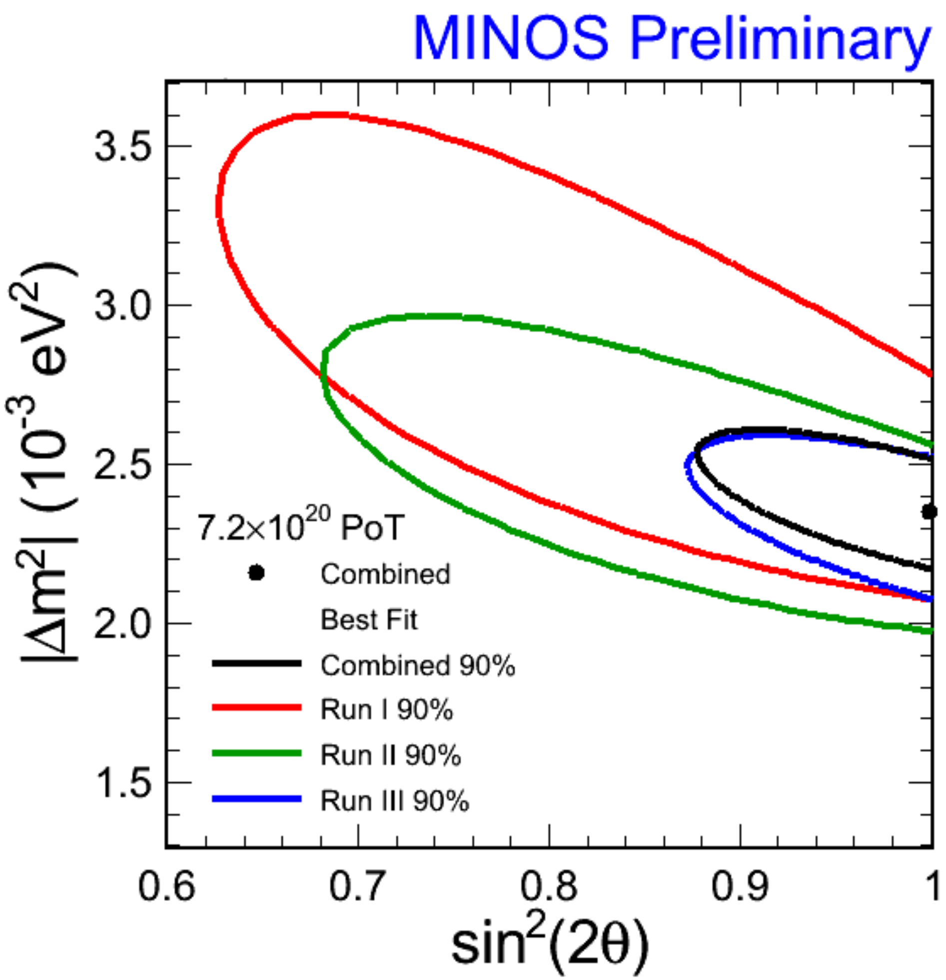


Contours

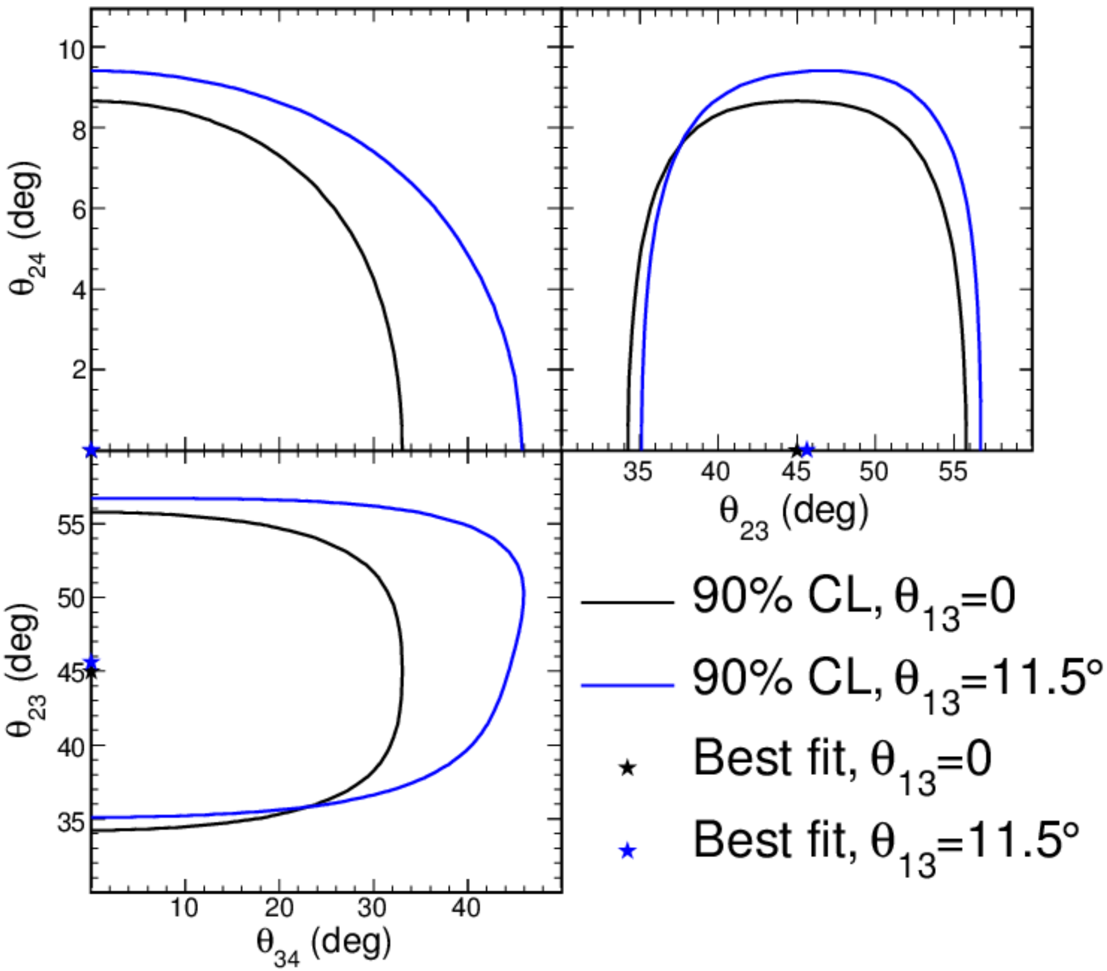
- Contour includes effects of dominant systematic uncertainties
  - normalization
  - NC background
  - shower energy
  - track energy



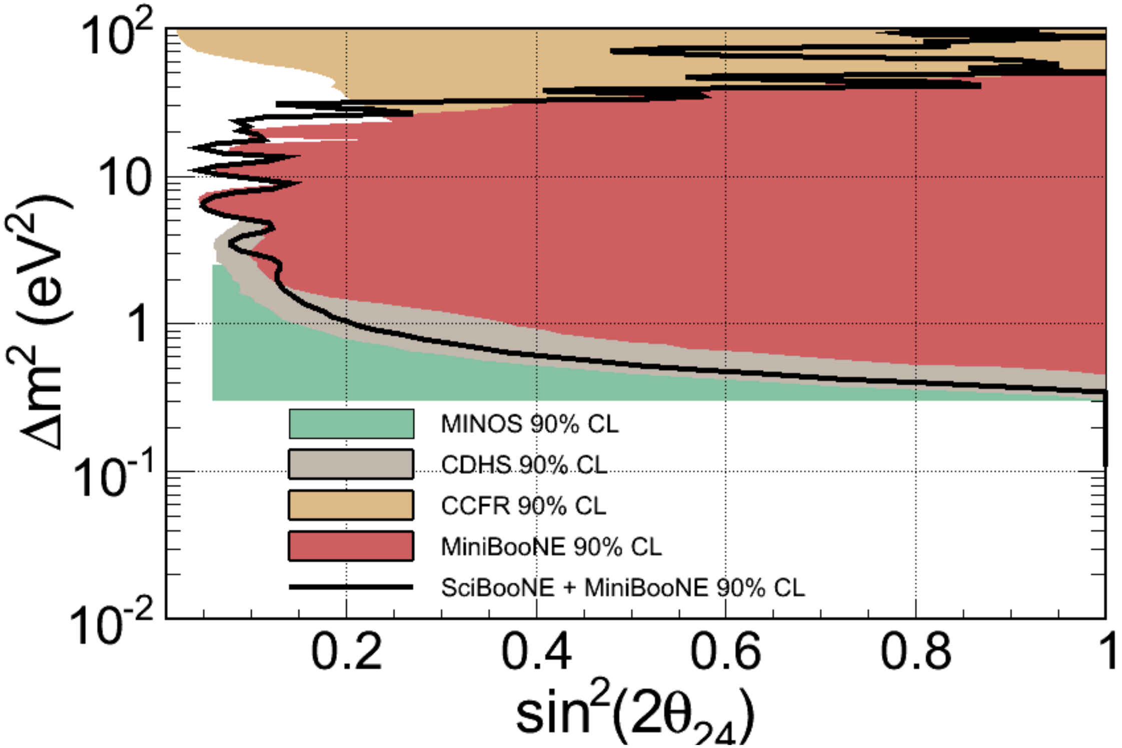
Contours by Run Period



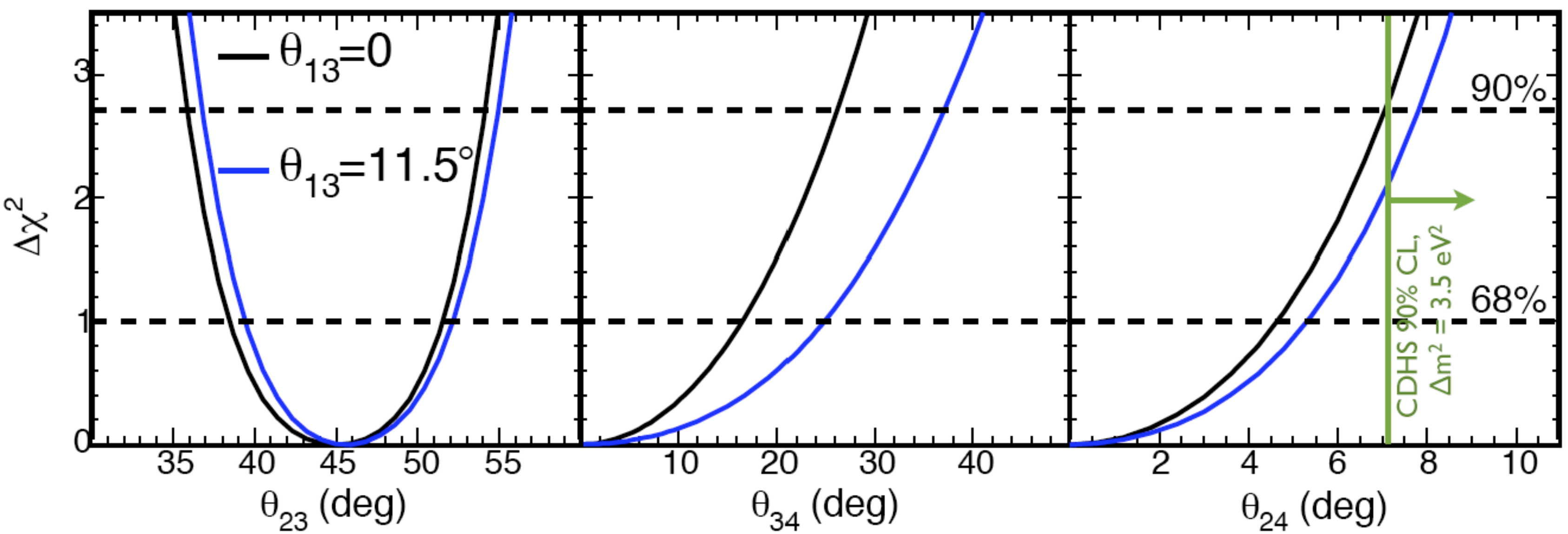
Fits to NC



- Fit CC/NC spectra simultaneously with a 4th (sterile) neutrino
- 2 choices for 4th mass eigenvalue
  - $m_4 >> m_3$
  - $m_4 = m_1$



10^2
10
1
10^{-1}
10^{-2}
Δm^2 (eV^2)
0.2
0.4
0.6
0.8
1
$\sin^2(2\theta_{24})$
MINOS 90% CL
CDHS 90% CL
CCFR 90% CL
MiniBooNE 90% CL
SciBooNE + MiniBooNE 90% CL



$\Delta\chi^2$
0
1
2
3
θ_{13}=0
θ_{13}=11.5°
35
40
45
50
55
θ_{23} (deg)
10
20
30
40
θ_{34} (deg)
2
4
6
8
10
θ_{24} (deg)
90%
68%
CDHS 90% CL,
Δm^2 = 3.5 eV^2

Electron-neutrino Systematics

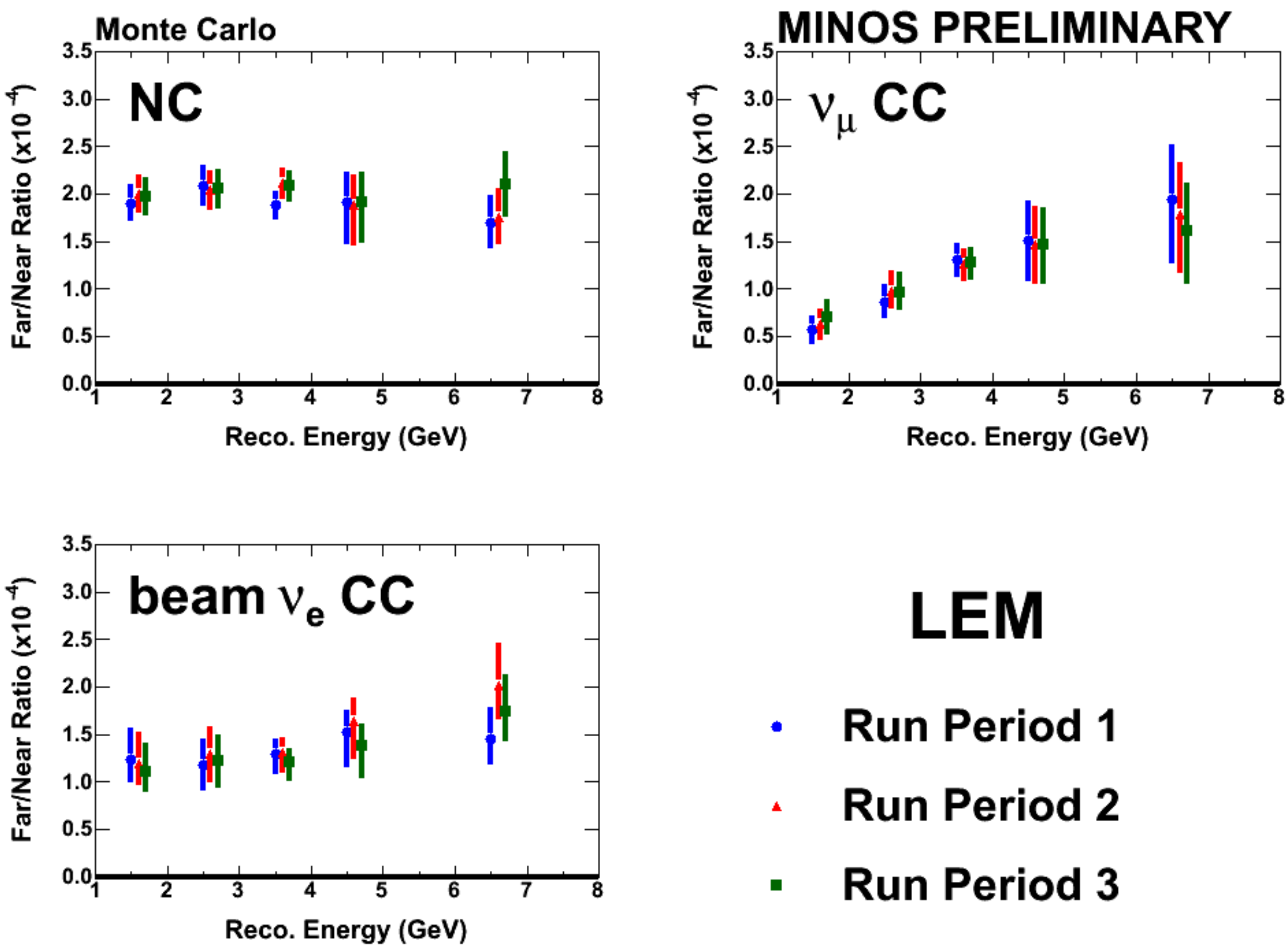
- Systematics evaluated using modified MC
- Effect of systematics on each bin added in quadrature
- Systematics in each bin included in fit as nuisance parameters

Systematic	
Calibration	$\pm 4.2\%$
Hadronic Errors	$\pm 0.8\%$
Cross Section and Intranuclear Model	$\pm 0.7\%$
Normalization	$\pm 1.9\%$
Beam Model	$\pm 0.7\%$
Crosstalk	$\pm 2.0\%$
Total Far/Near Ratio	$\pm 5.3\%$
ν_τ CC Component Uncertainties	$\pm 2.1\%$
ND Decomposition Error	$\pm 0.3\%$
Total Systematic Uncertainty	$\pm 5.7\%$
Preliminary	

Electron-neutrino prediction in FD

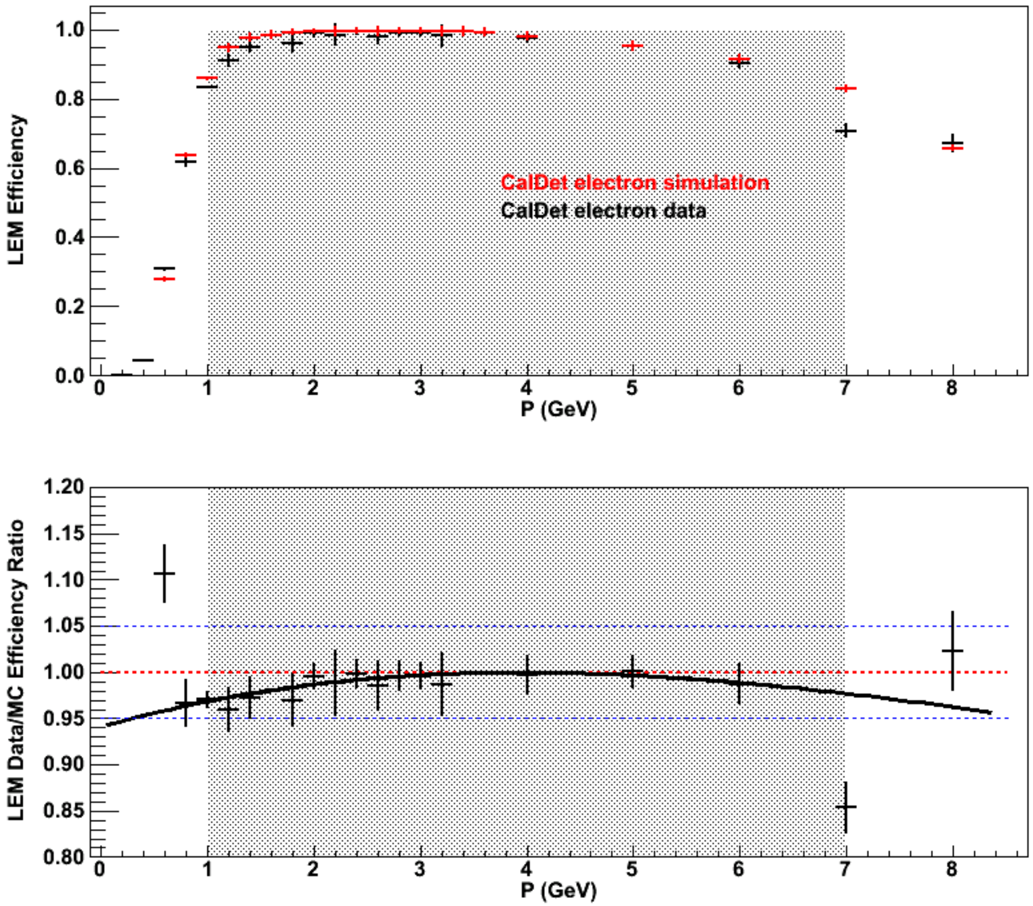
Total BG:	49
NC:	34
Muon-neutrino CC:	7
beam electron-neutrinos:	6
tau-neutrino CC:	2
Signal at CHOOZ limit:	30

Electron-neutrino F/N ratios



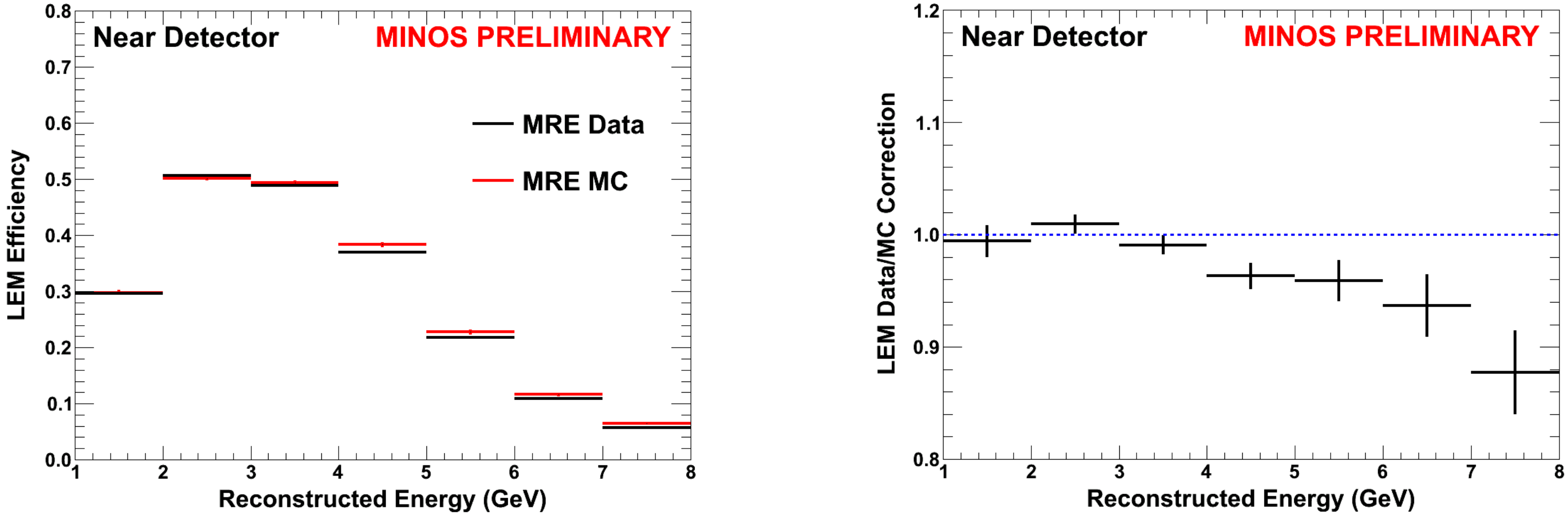
Checking Signal Efficiency

- Test beam measurements demonstrate electrons are well simulated

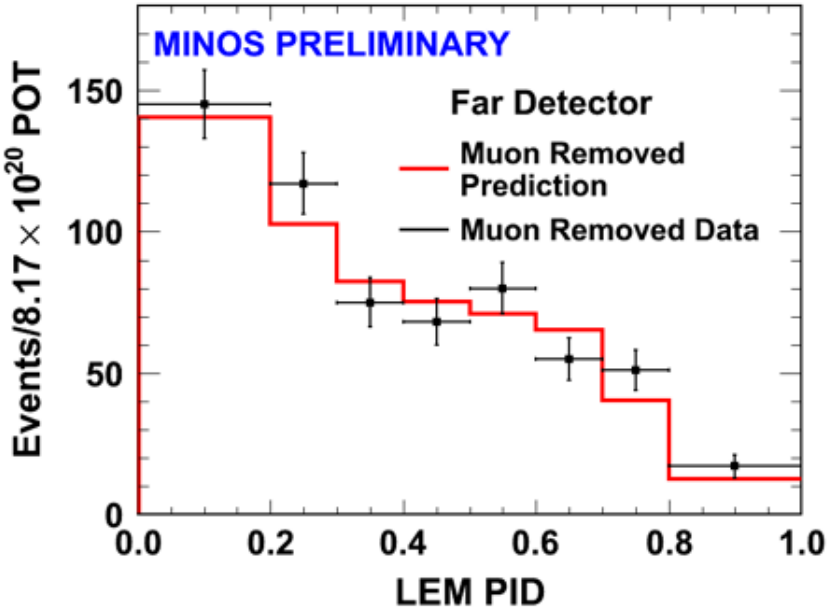


Checking Signal Efficiency

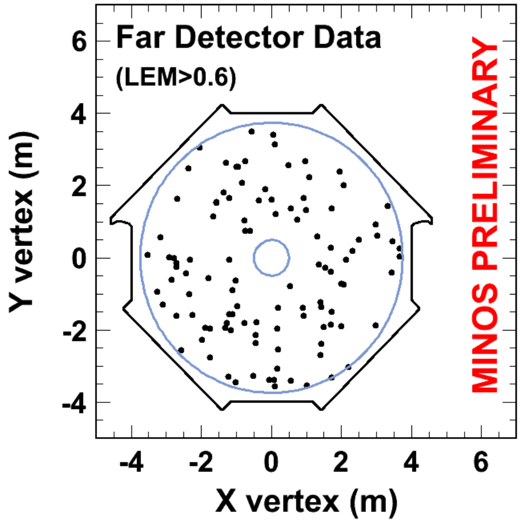
- Check electron neutrino selection efficiency by removing muons, add a simulated electron

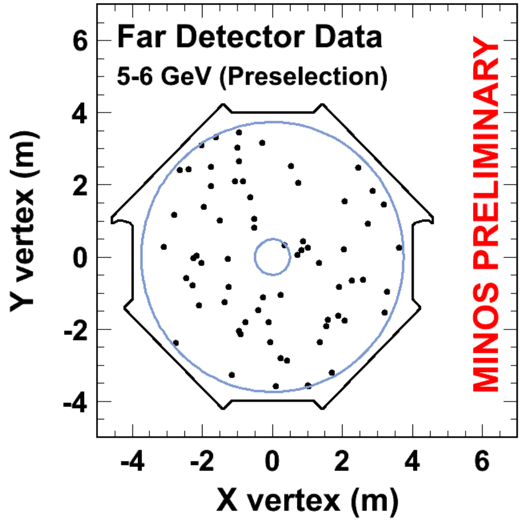


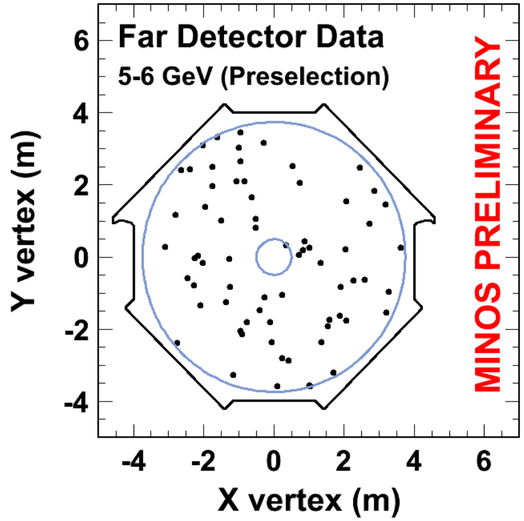
Muon Removed Sample



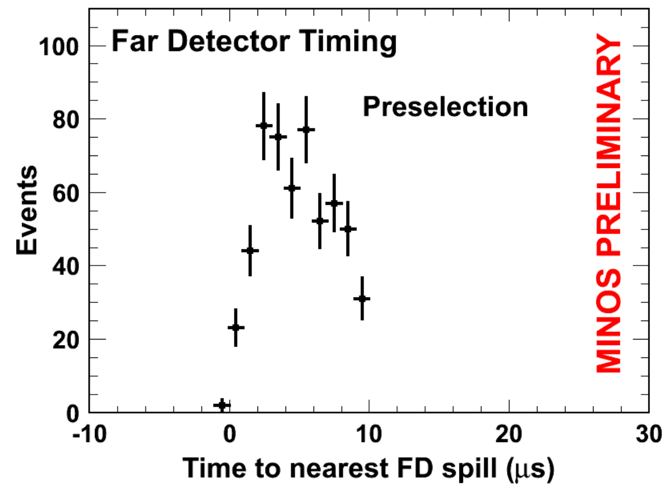
FD Electron-neutrinos Vertices

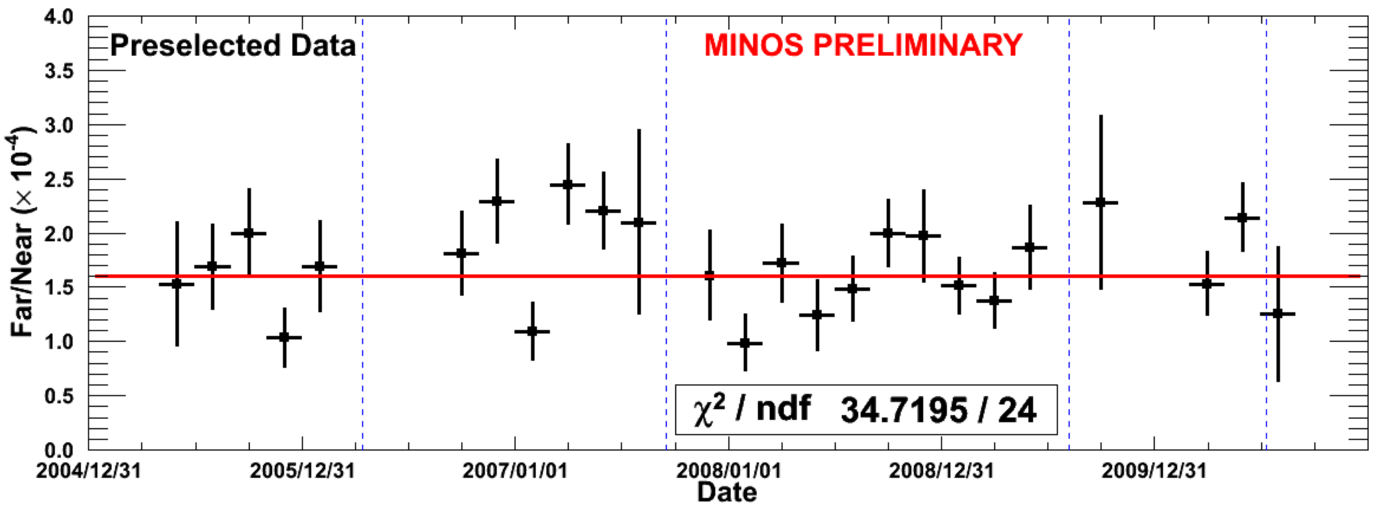




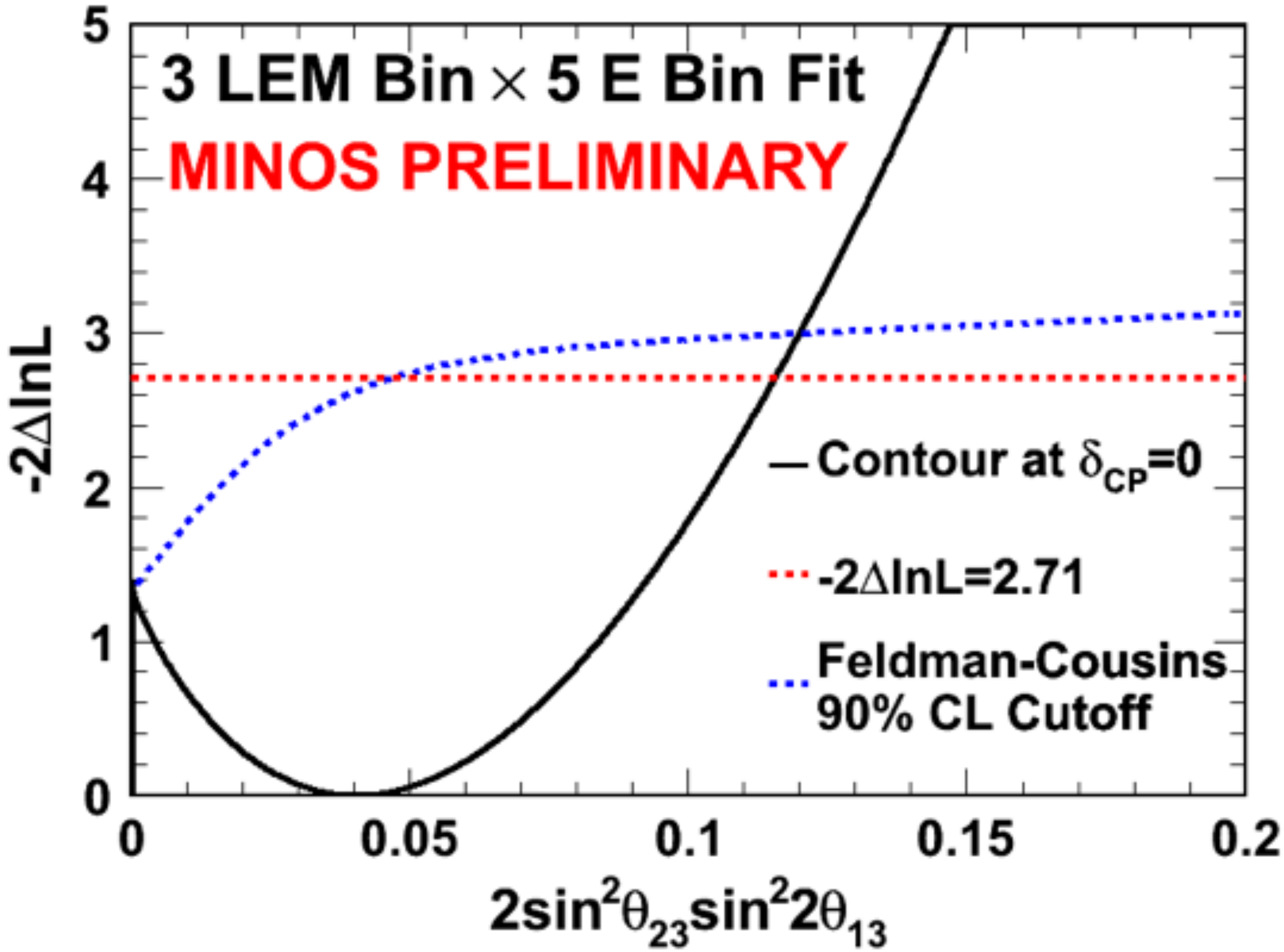


Electron-neutrino Event Rate





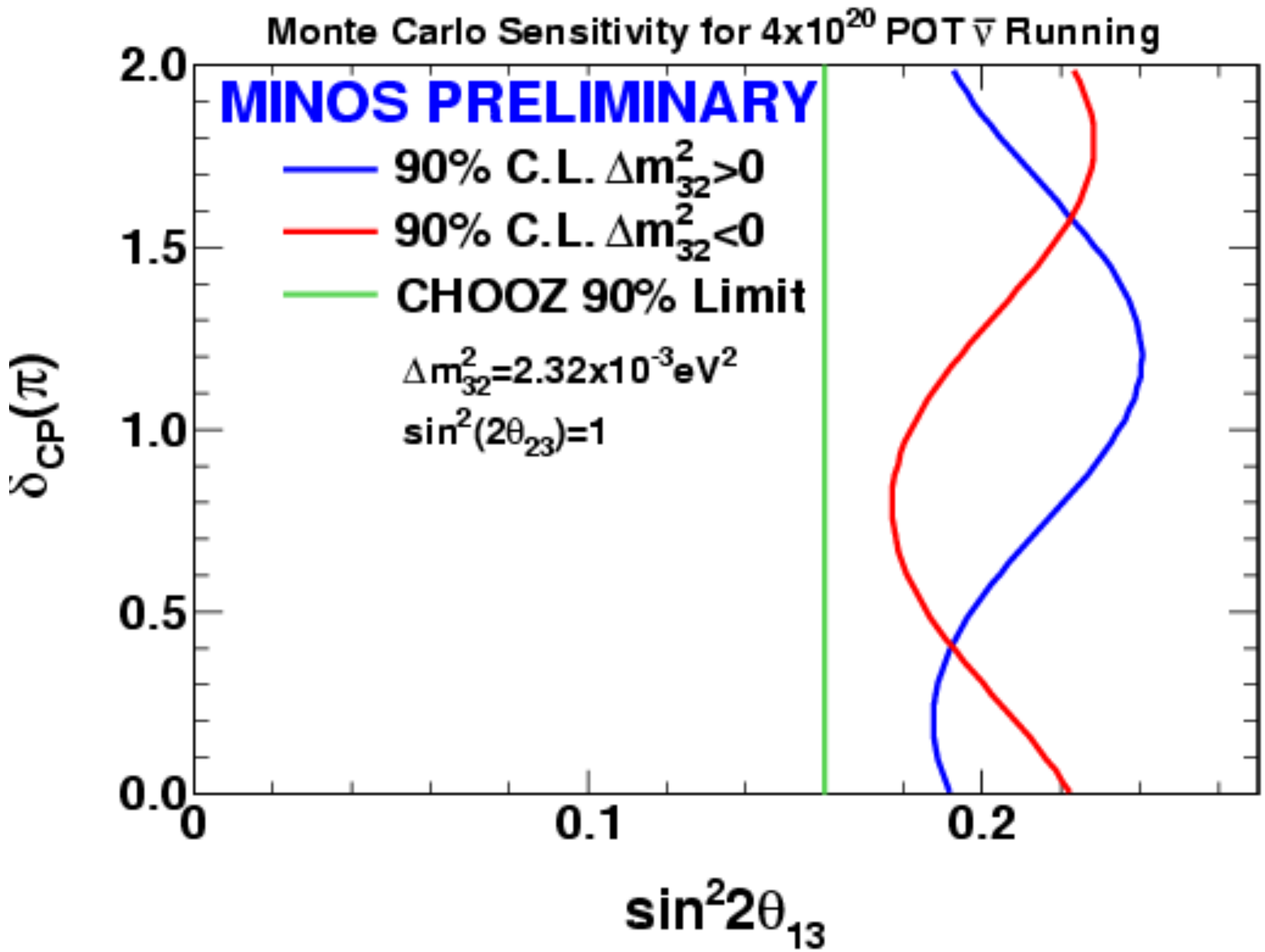
Feldman-Cousins Effect



Cross Check Fits

OFFICIAL FIT	**0.040**	**0.115**
LEM energy shape fit < 5 GeV	0.021	0.089
ANN energy shape fit	0.046	0.135
ANN energy shape fit < 5 GeV	0.045	0.136
2010-style analysis (ANN rate-only)	0.041	0.130
LEM rate-only	0.064	0.147
LEM shape fit	0.046	0.121
Official fit excluding new data	0.057	0.144

electron anti-neutrino appearance



P. Vahle, INFO 2011

Combined fits

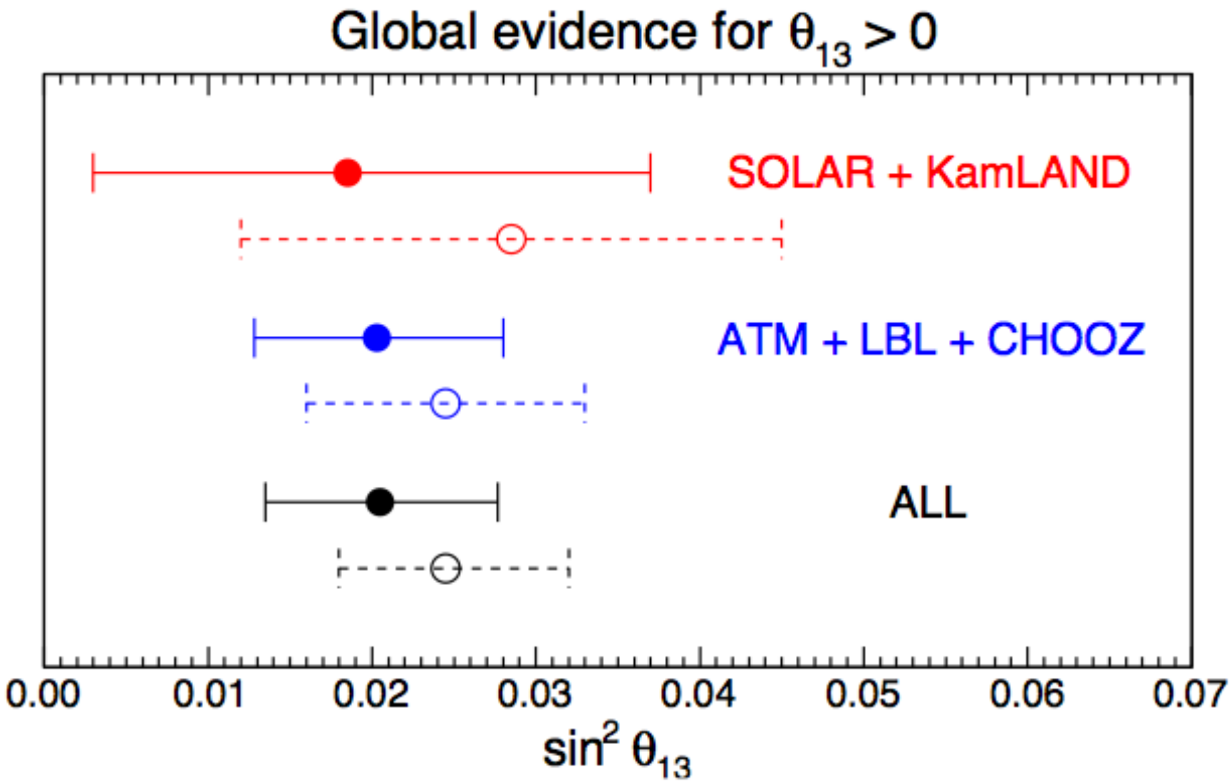


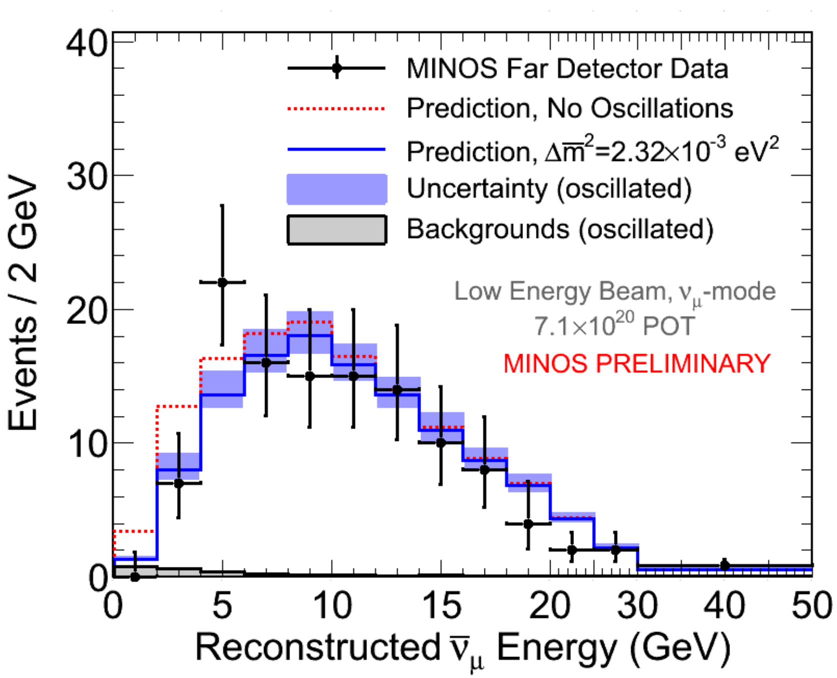
FIG. 3: Global 3ν analysis. Preferred $\pm 1\sigma$ ranges for the mixing parameter $\sin^2\theta_{13}$ from partial and global data sets. Solid and dashed error bars refer to old and new reactor neutrino fluxes, respectively.

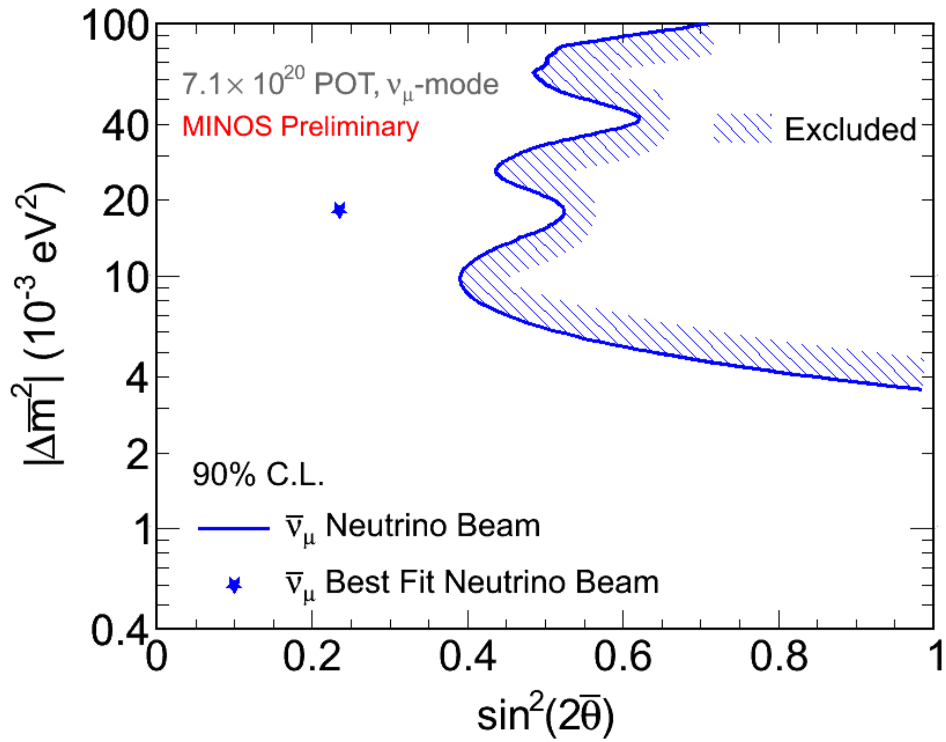
Combined Fits

TABLE I: Results of the global 3ν oscillation analysis, in terms of best-fit values and allowed 1, 2 and 3σ ranges for the mass-mixing parameters, assuming old reactor neutrino fluxes. By using new reactor fluxes, the corresponding best fits and ranges for $\sin^2\theta_{12}$ and $\sin^2\theta_{13}$ (in parentheses) are basically shifted by about +0.006 and +0.004, respectively, while the other parameters are essentially unchanged.

Parameter	$\delta m^2/10^{-5}$ eV^2	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$	$\Delta m^2/10^{-3}$ eV^2
Best fit	7.58	0.306	0.021	0.42	2.35
		(0.312)	(0.025)		
1σ range	7.32 – 7.80	0.291 – 0.324	0.013 – 0.028	0.39 – 0.50	2.26 – 2.47
		(0.296 – 0.329)	(0.018 – 0.032)		
2σ range	7.16 – 7.99	0.275 – 0.342	0.008 – 0.036	0.36 – 0.60	2.17 – 2.57
		(0.280 – 0.347)	(0.012 – 0.041)		
3σ range	6.99 – 8.18	0.259 – 0.359	0.001 – 0.044	0.34 – 0.64	2.06 – 2.67
		(0.265 – 0.364)	(0.005 – 0.050)		

Anti-neutrino Disappearance



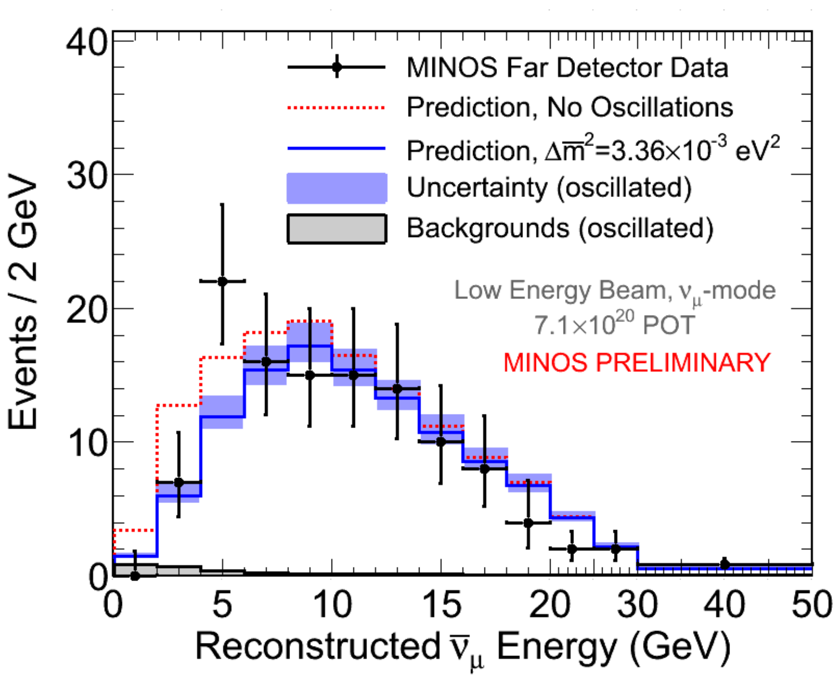


No Oscillations:	$150.3^{+16.3}_{-18.2}$
With Oscillations:	$136.4^{+15.2}_{-14.9}$
Observed:	130

at $\sin^2(2\bar{\theta}_{23}) = 1$

$$\left|\Delta\bar{m}^2\right| < 3.37 \times 10^{-3}\ \mathrm{eV}^2\ (90\%\ \mathrm{C.L.})$$

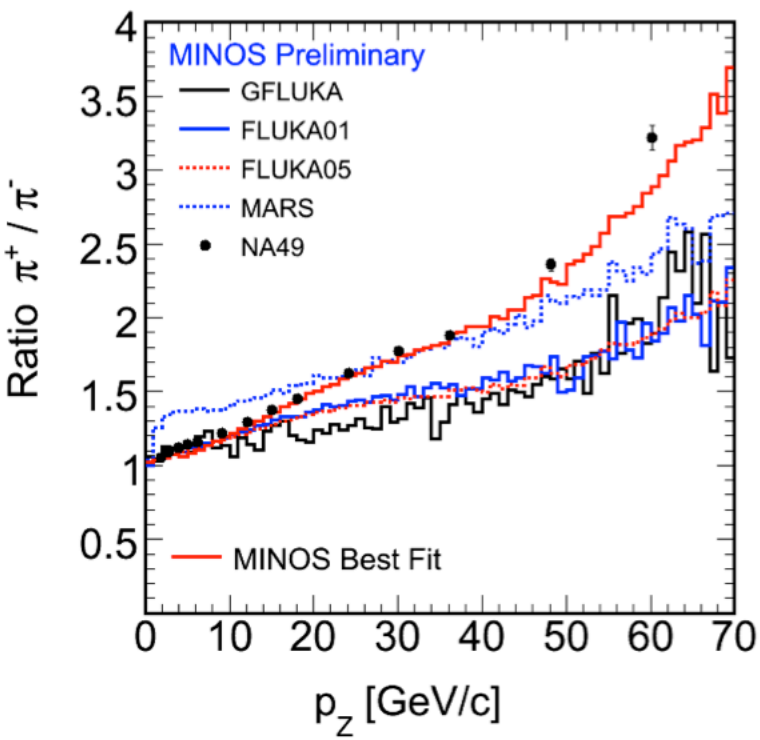
Anti-neutrino Disappearance

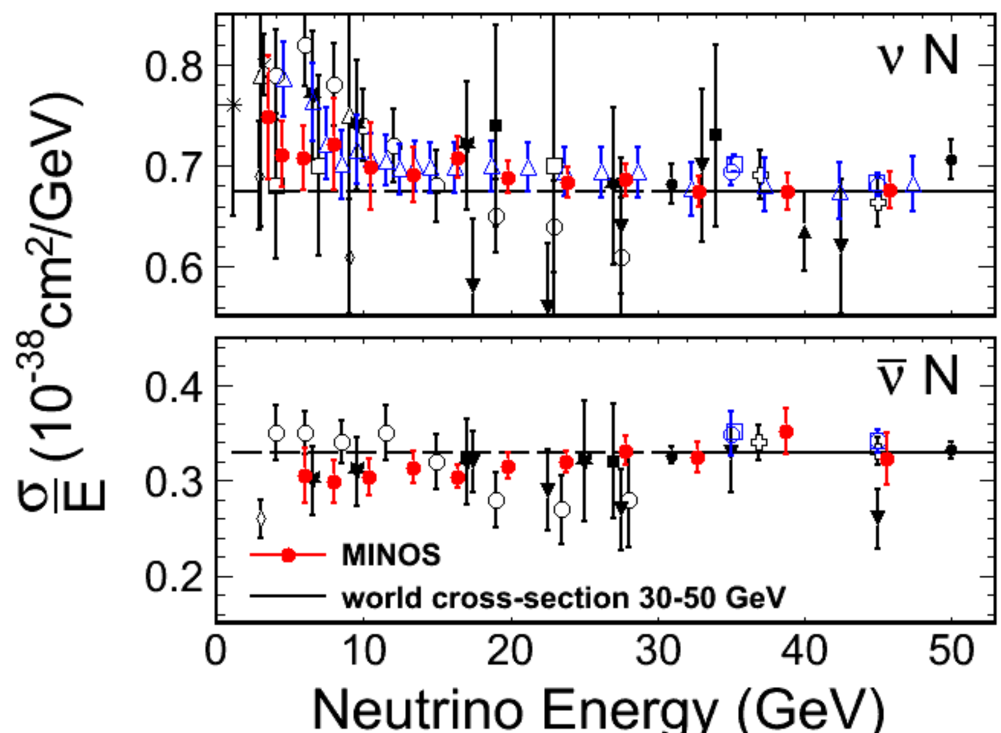


Making an antineutrino beam

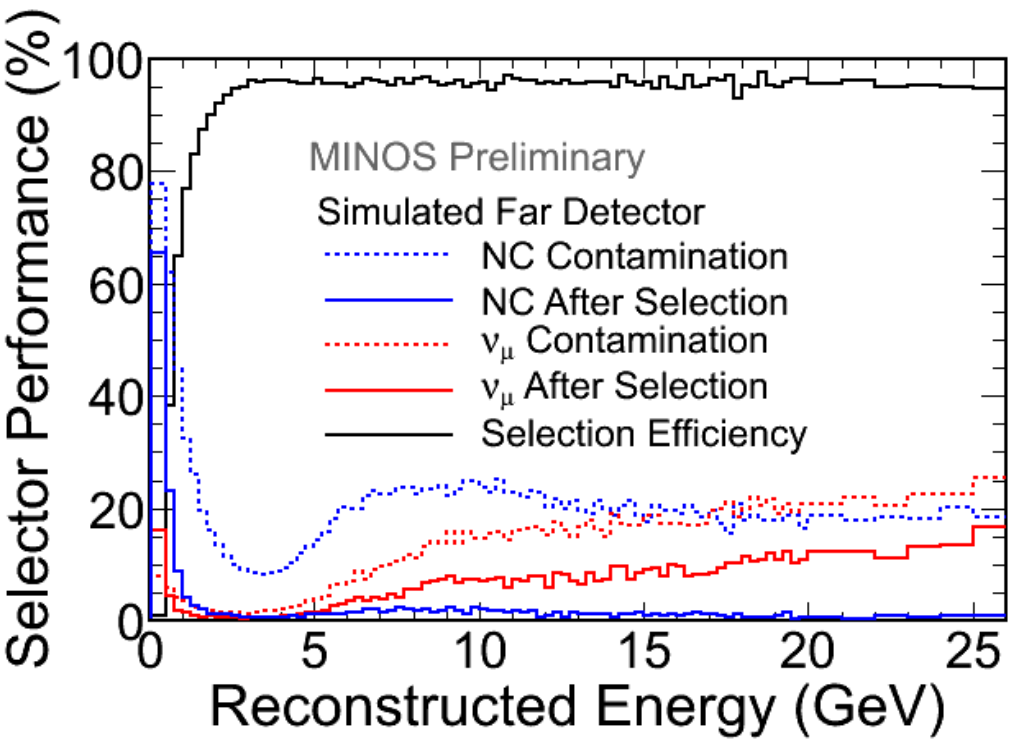
- Hadron production and cross sections conspire to change the shape and normalization of energy spectrum

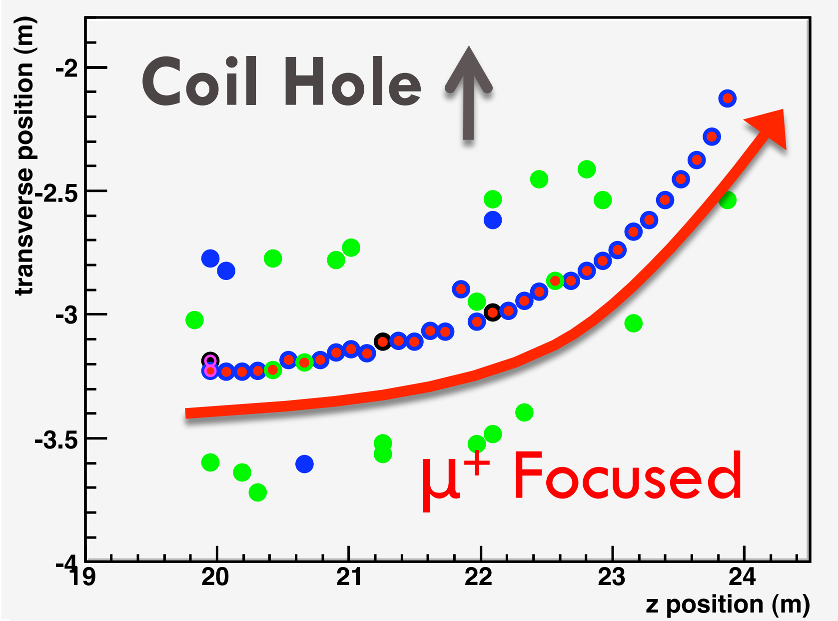
~3x fewer antineutrinos for the same exposure

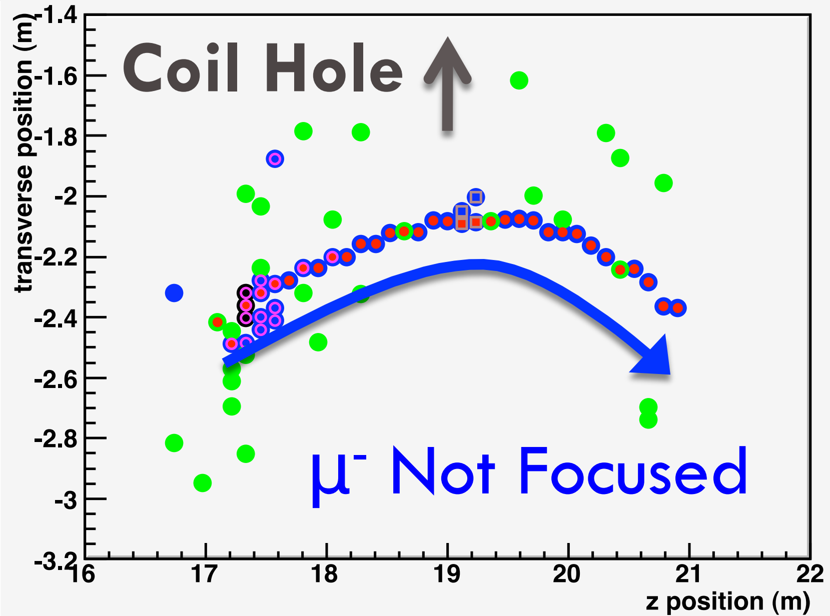




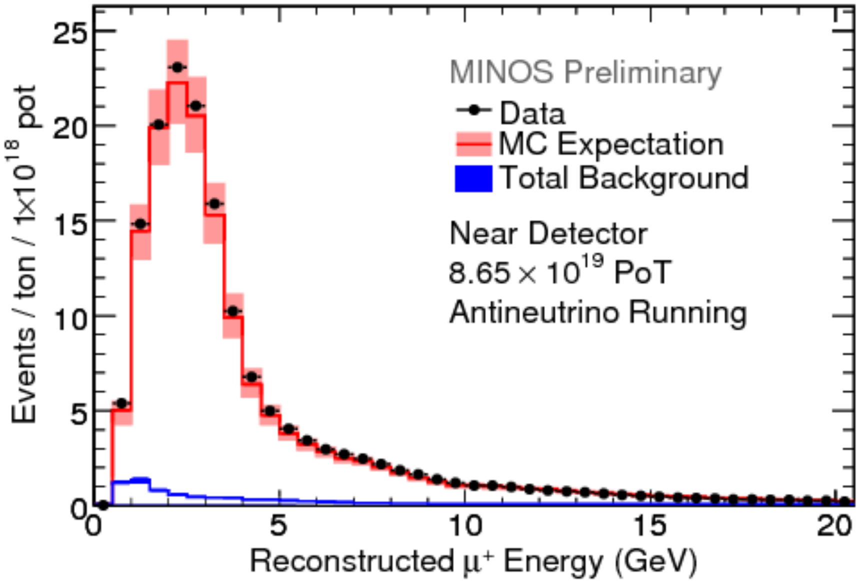
Anti-neutrino Selection

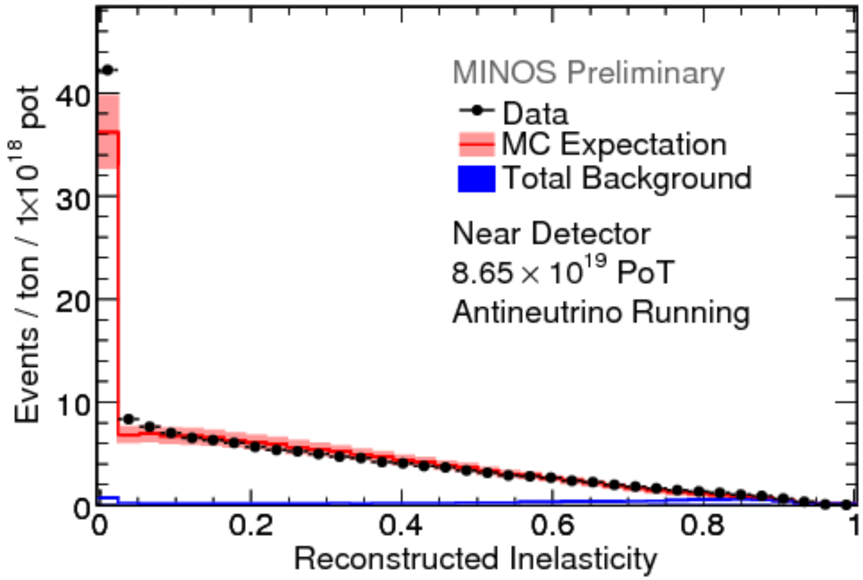


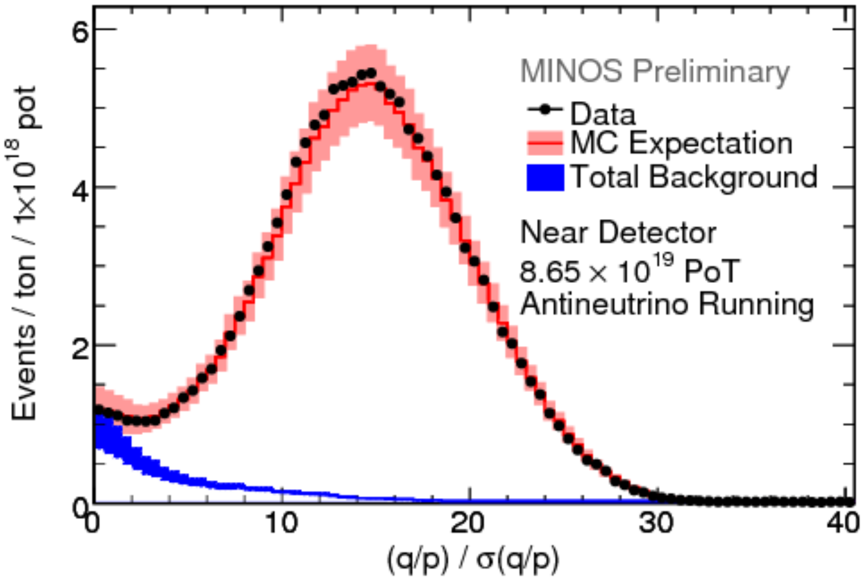




ND Data

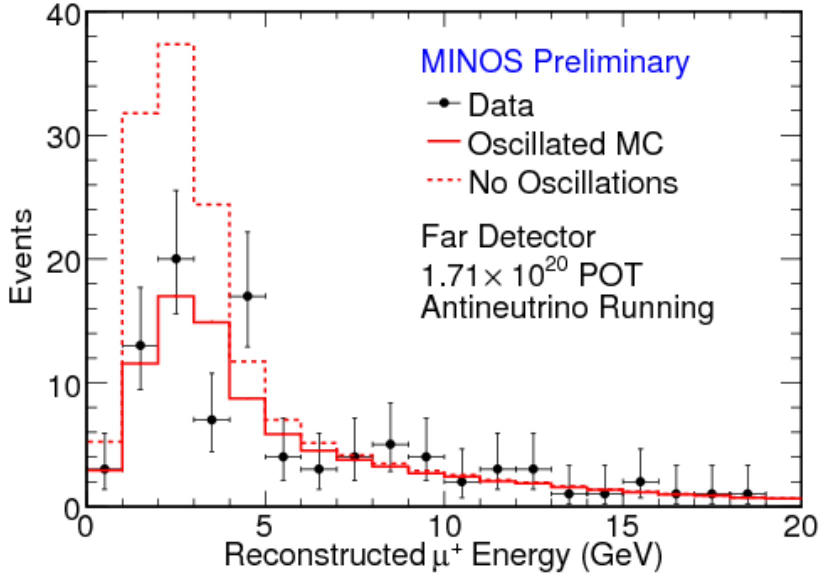




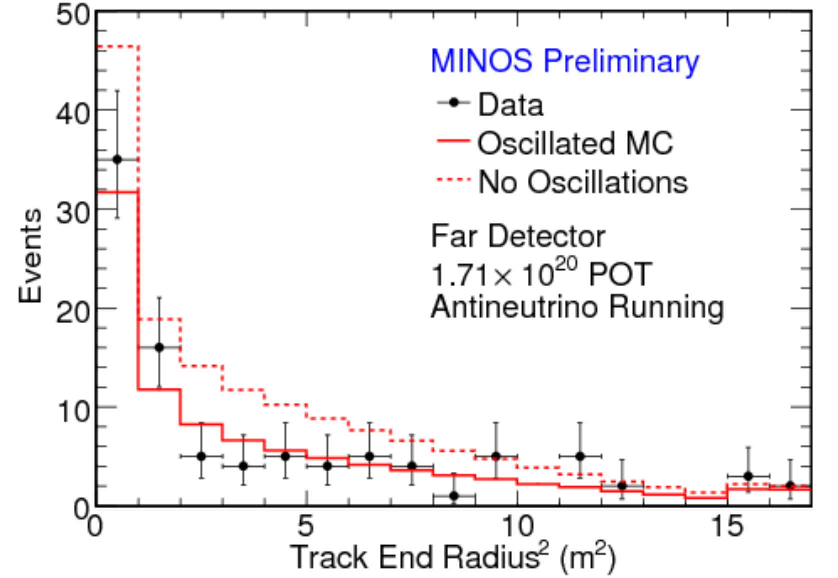


- Data/MC agreement comparable to neutrino running

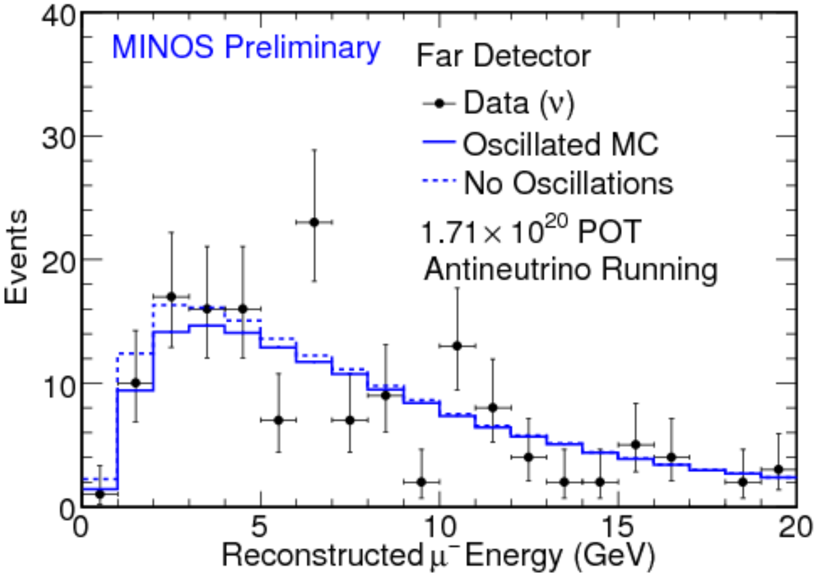
FD Data



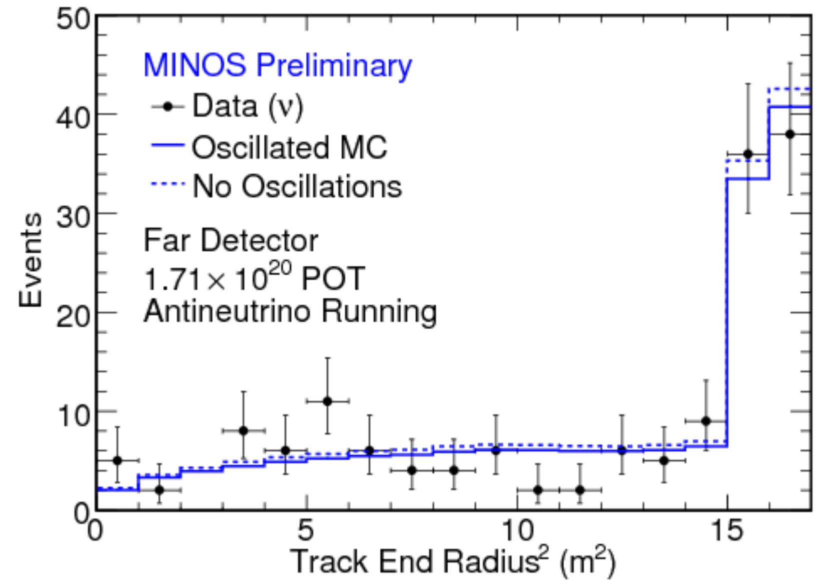
MINOS Preliminary
Data
Oscillated MC
No Oscillations
Far Detector
1.71× 10^20 POT
Antineutrino Running
Events
Reconstructed μ+ Energy (GeV)



MINOS Preliminary
Data
Oscillated MC
No Oscillations
Far Detector
1.71× 10^20 POT
Antineutrino Running
Events
Track End Radius² (m²)

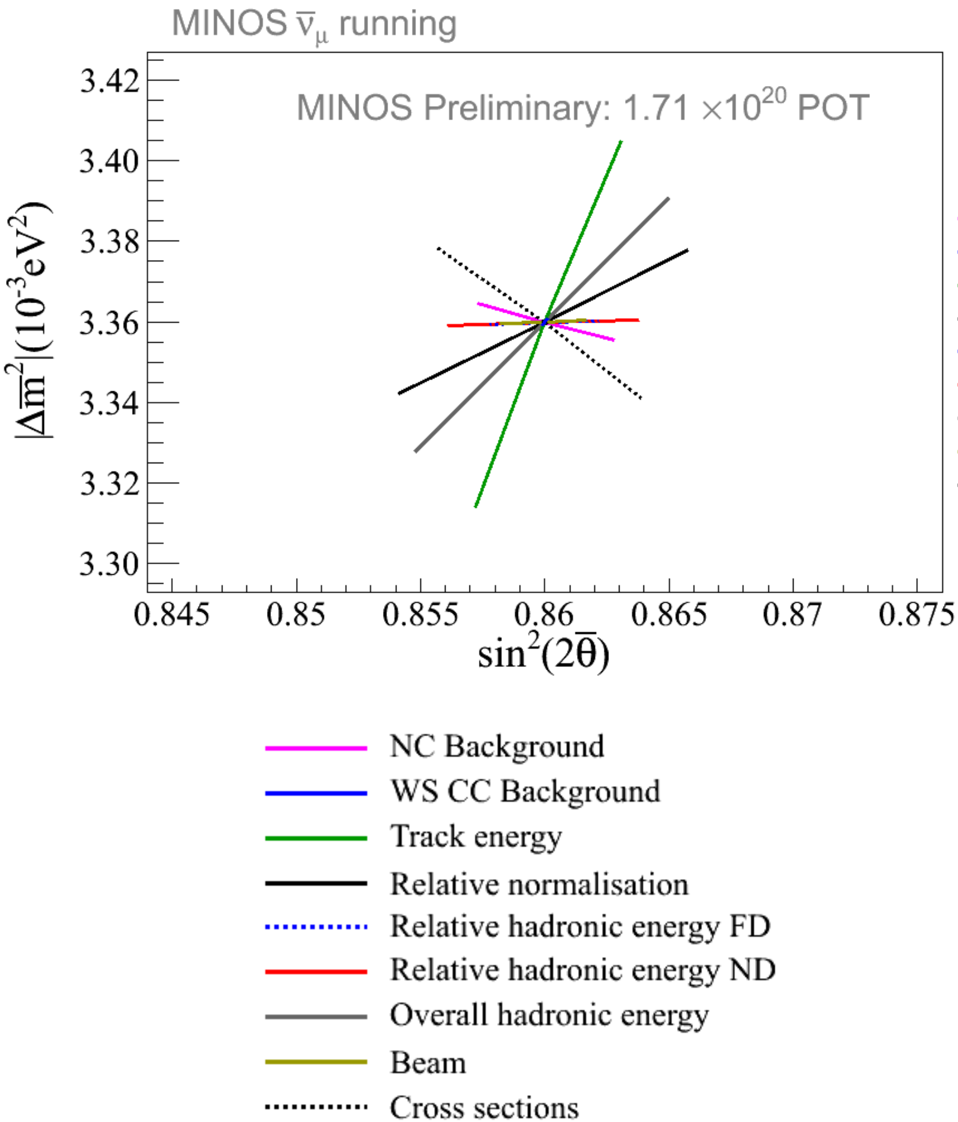


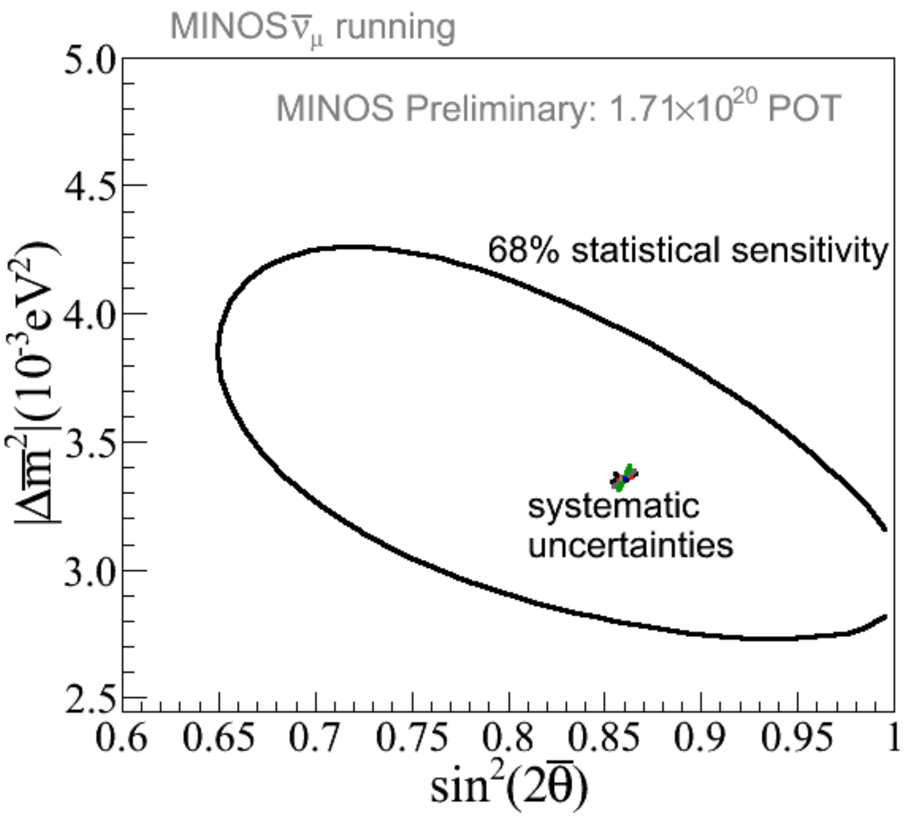
MINOS Preliminary
Far Detector
Data (ν)
Oscillated MC
No Oscillations
1.71× 10^20 POT
Antineutrino Running
Events
Reconstructed μ− Energy (GeV)



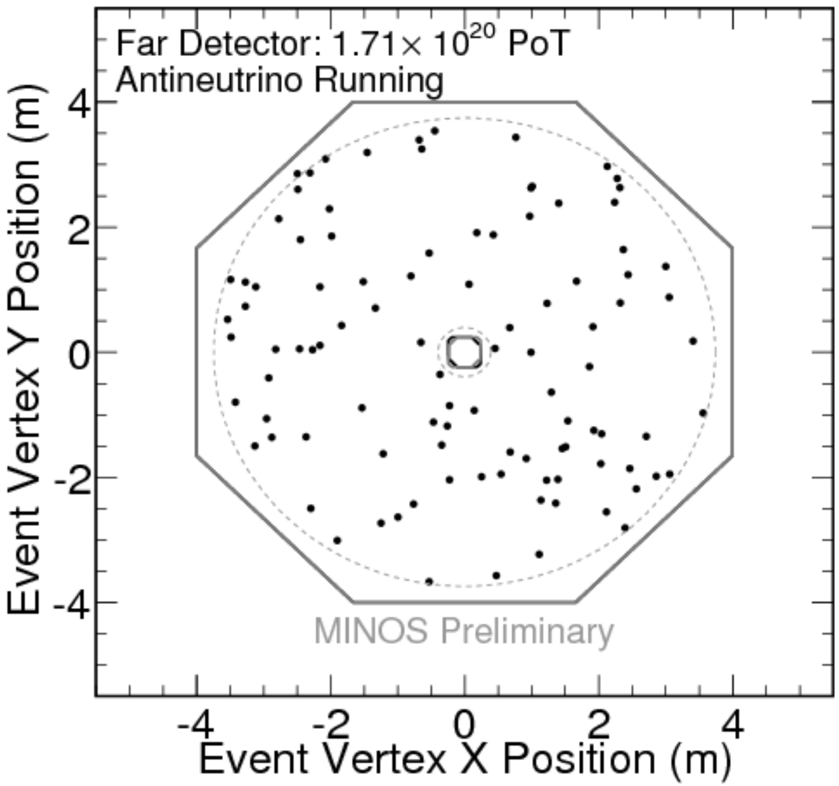
MINOS Preliminary
Data (ν)
Oscillated MC
No Oscillations
Far Detector
1.71× 10^20 POT
Antineutrino Running
Events
Track End Radius² (m²)

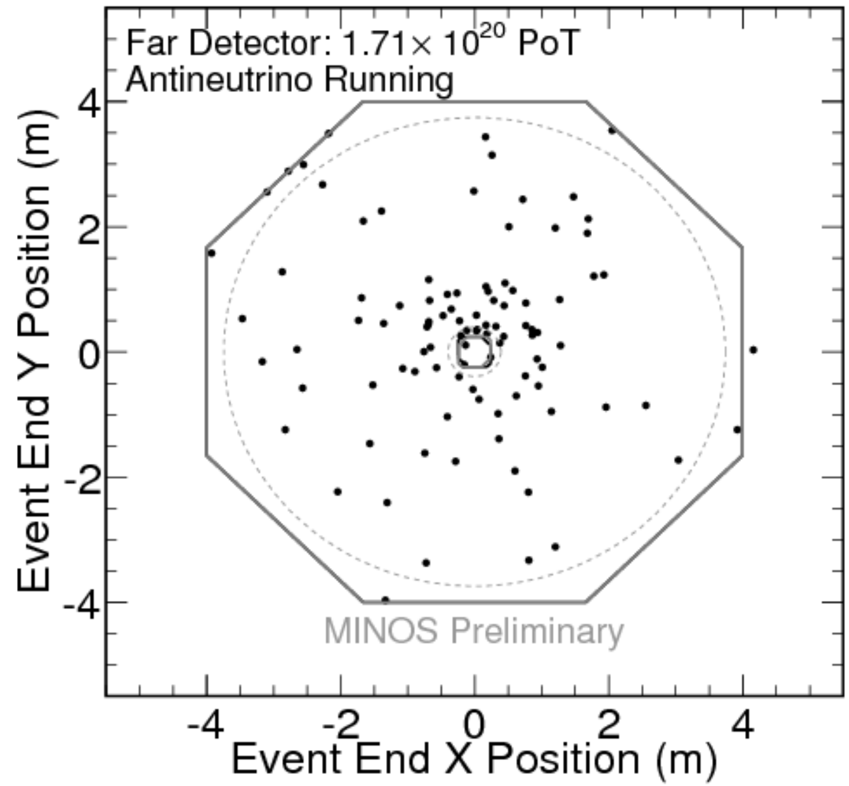
Anti-neutrino Systematics





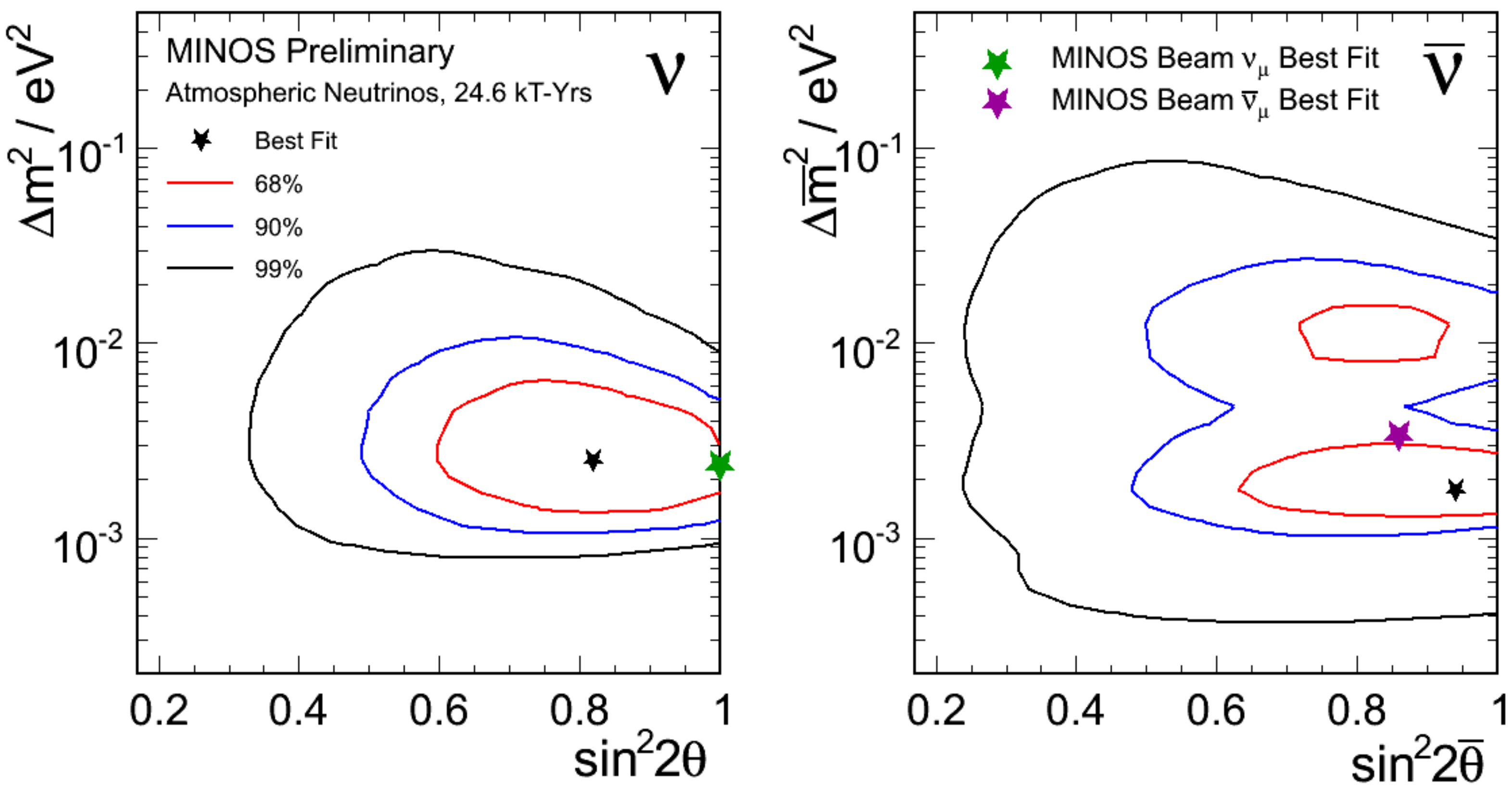
FD Anti-neutrino Data





- Vertices uniformly distributed
- Track ends clustered around coil hole

Atmospheric Neutrinos

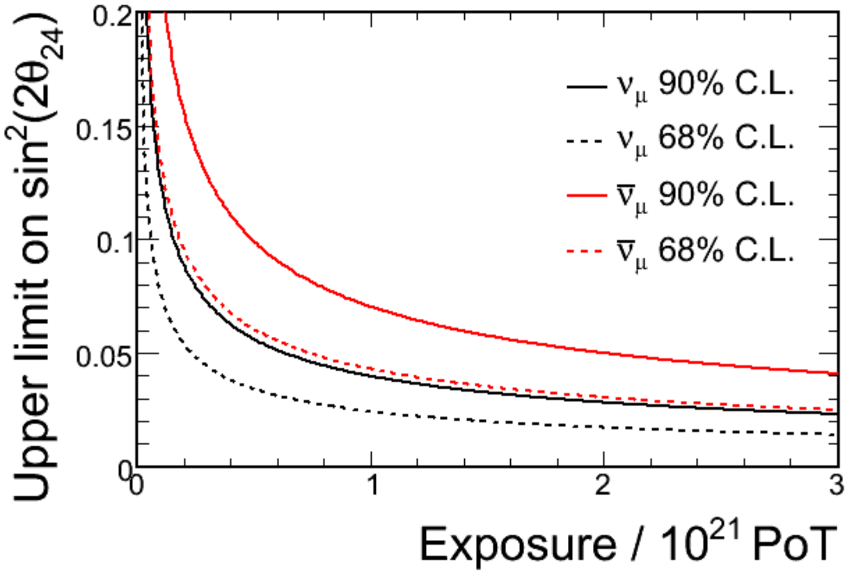


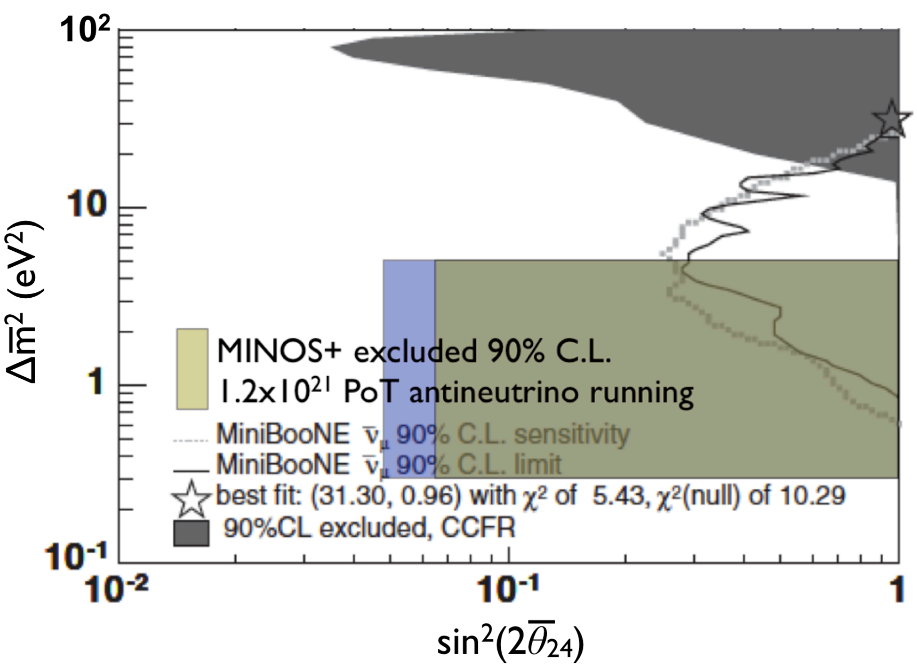
$$R^{data}_{\bar{\nu}/\nu} \;/\; R^{MC}_{\bar{\nu}/\nu} = 1.04^{+0.11}_{-0.10} \pm 0.10$$

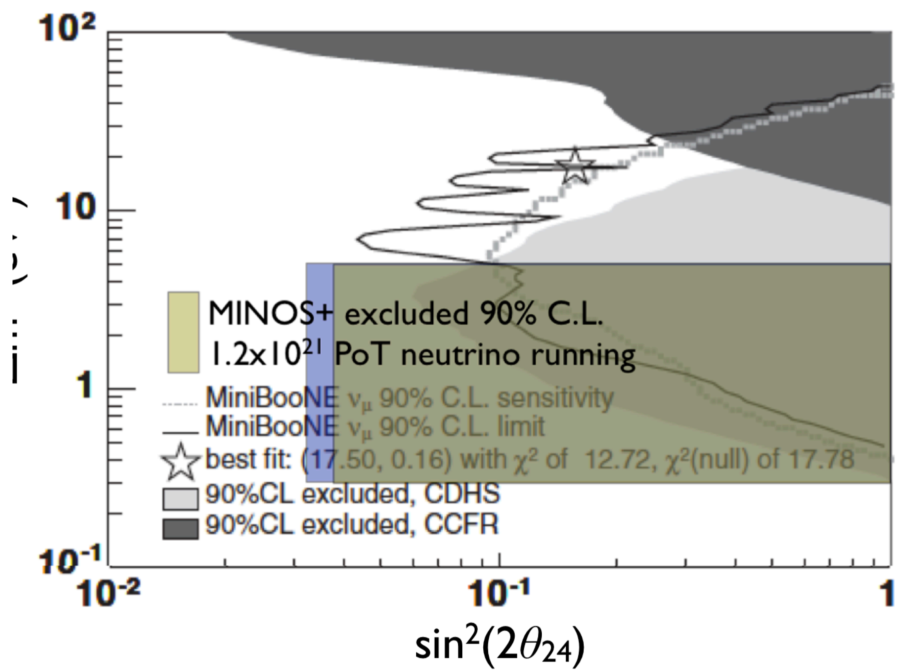
$$\left|\Delta m^2\right| - \left|\overline{\Delta m^2}\right| = 0.4^{+2.5}_{-1.2} \times 10^{-3}\,\mathrm{eV}^2$$

MINOS+

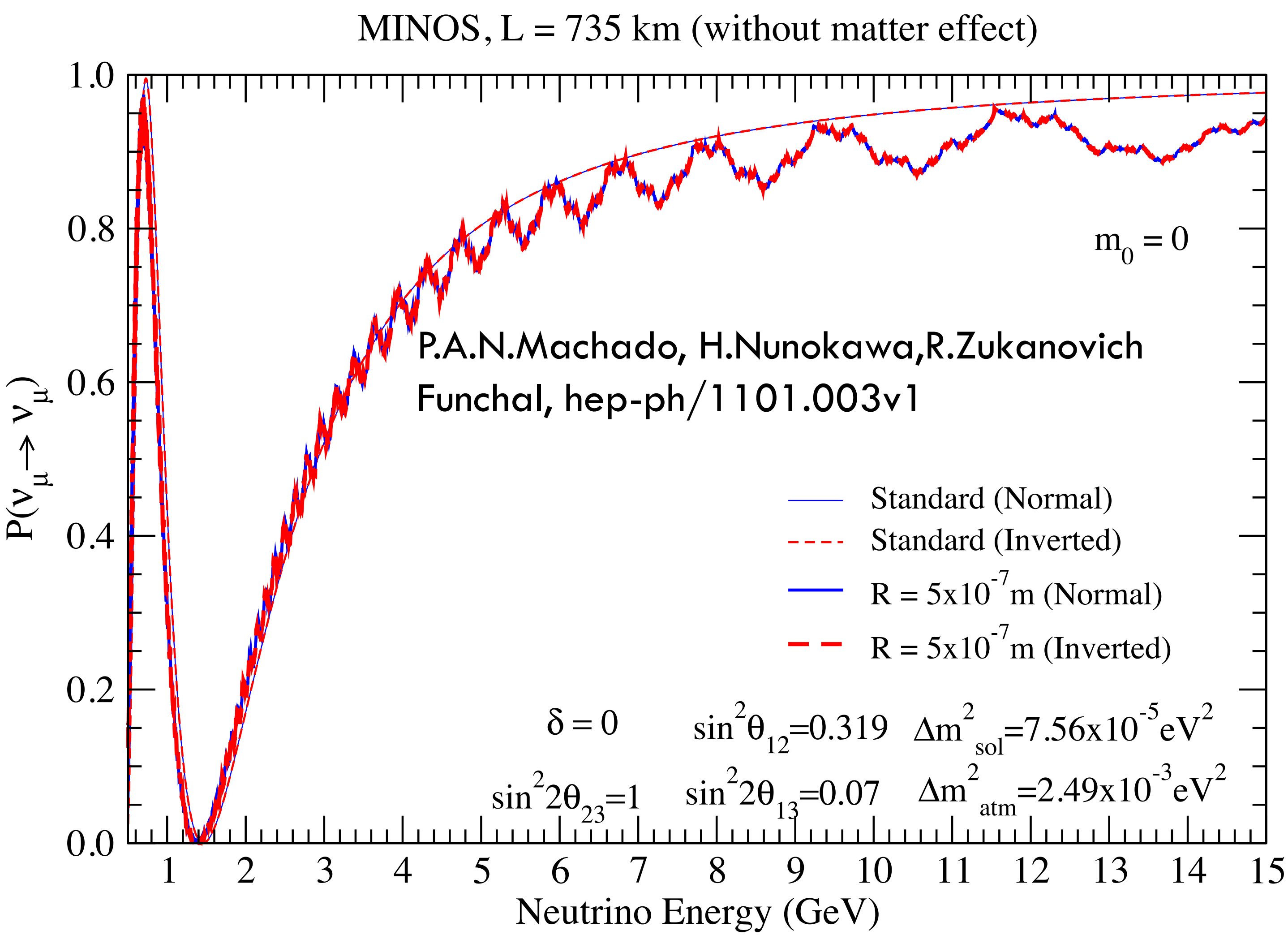
- Sterile neutrino reach
- Use CC disappearance (brown)
- NC rate (purple)





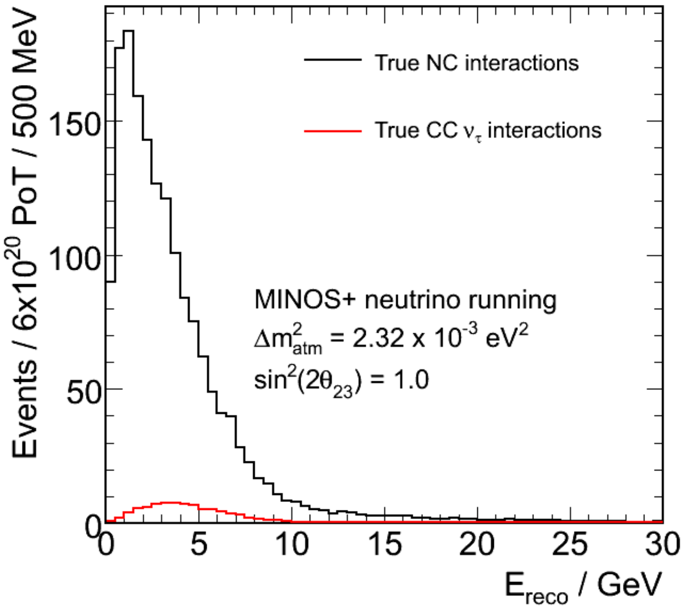


Extra Dimensions

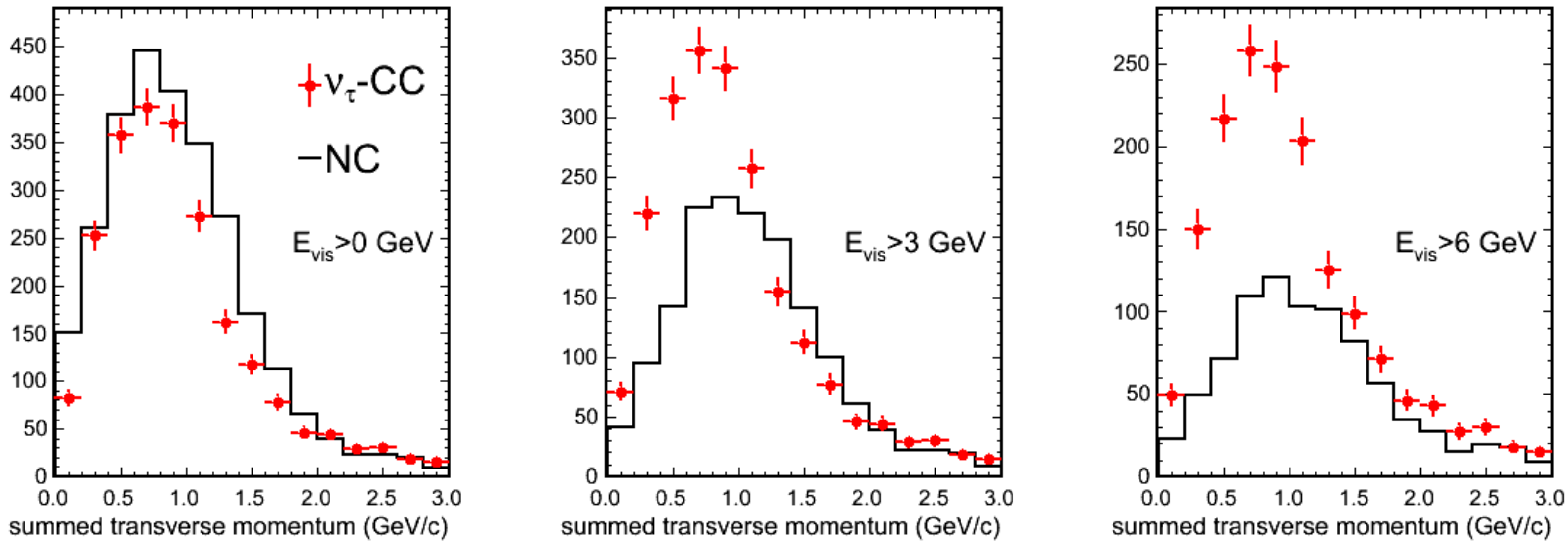


Assumes heavy RH (sterile) neutrino + extra dimensions!

Tau Neutrinos



- There are 80 tau events/ 1000 NC
- With some work it *might* be possible to see a signal but its hard!
- OPERA have 1 tau event so far…



Seasonal Muon Variation

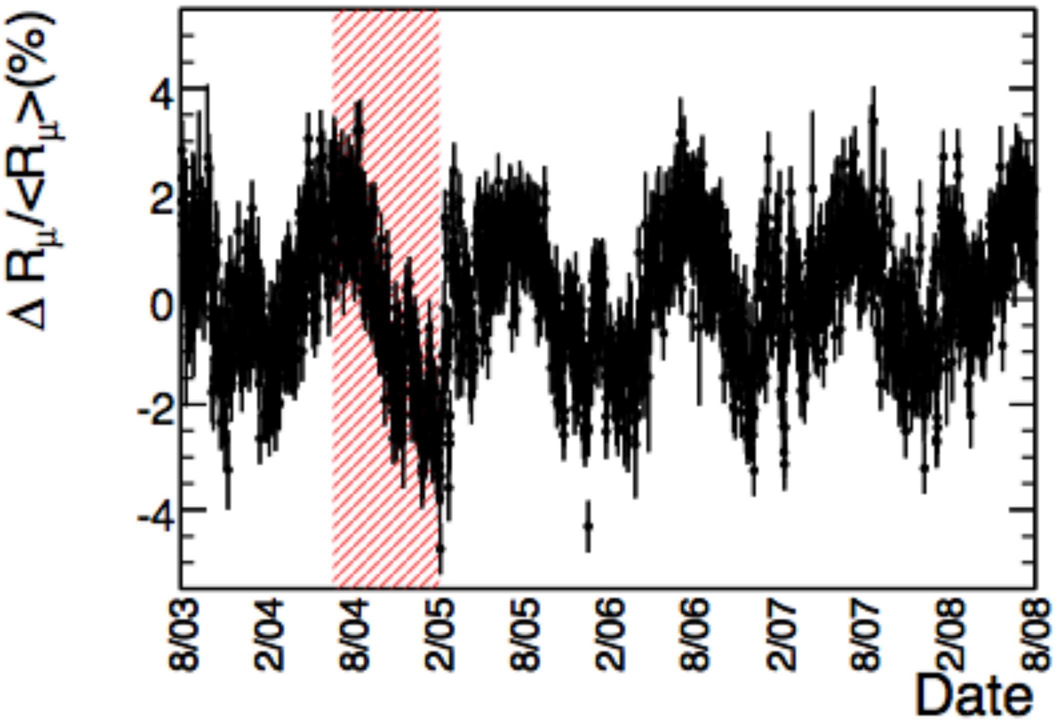


FIG. 4: The daily deviation from the mean rate of cosmic ray muon arrivals from 8/03-8/08, shown here with statistical error bars. The periodic fluctuations have the expected maxima in August, minima in February. The hatched region indicates the period of time when the detector ran with the magnetic field reversed from the normal configuration.

Near to Far

Far spectrum without oscillations is similar, but not identical to the Near spectrum!