MINOS AND NOVA

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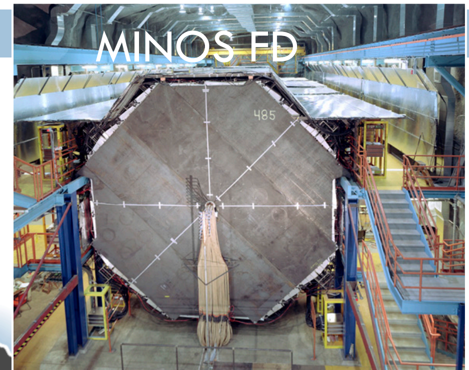
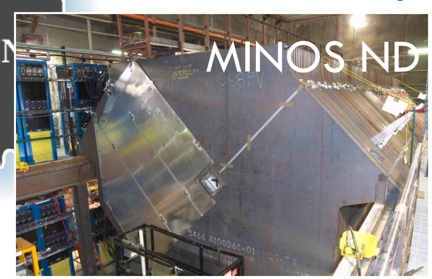
The NuMI Long-baseline Experiments



- MINOS
  - Running since 2005
  - FD on beam axis
  - Optimized for ν_μ ID

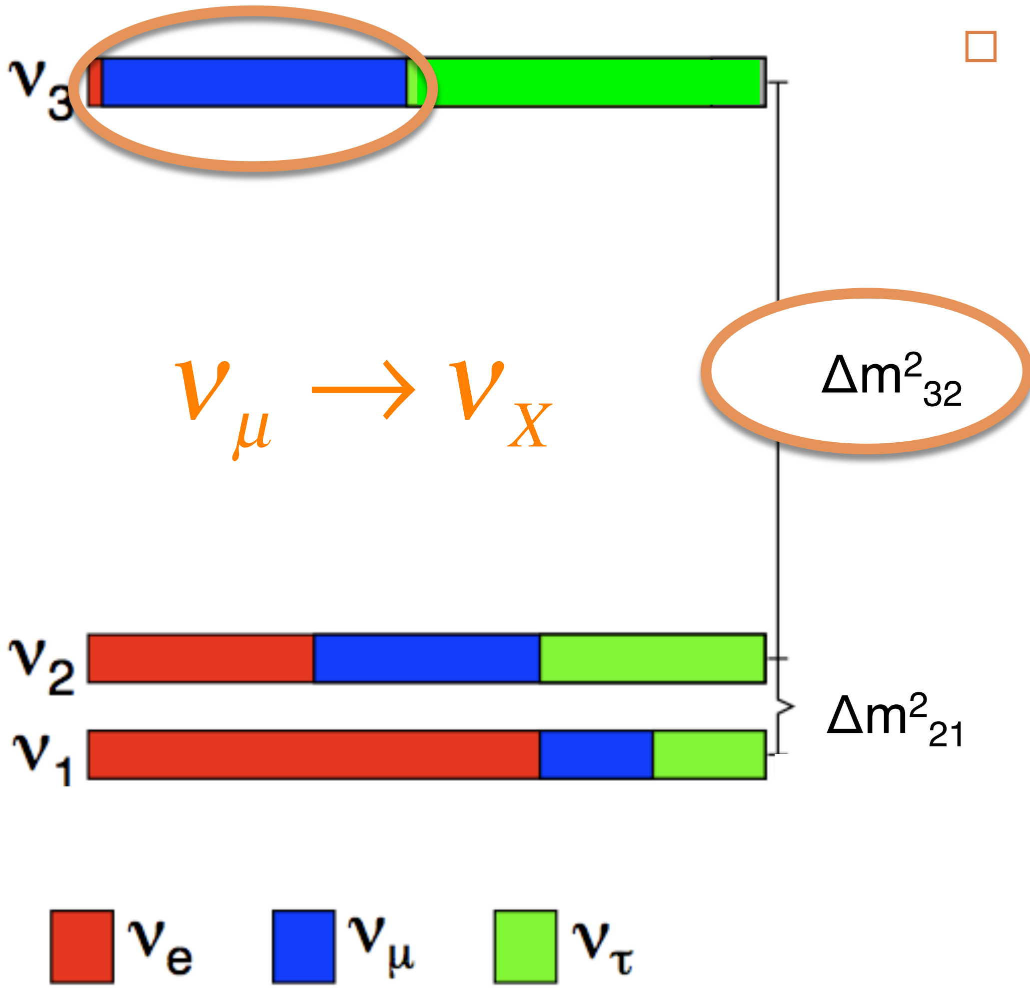
- NOvA
  - Under construction
  - FD placed off-axis
  - Optimized for ν_e ID

- Use NuMI beam line from Fermilab
- L/E ~ 500 km/GeV
  - atmospheric Δm^2



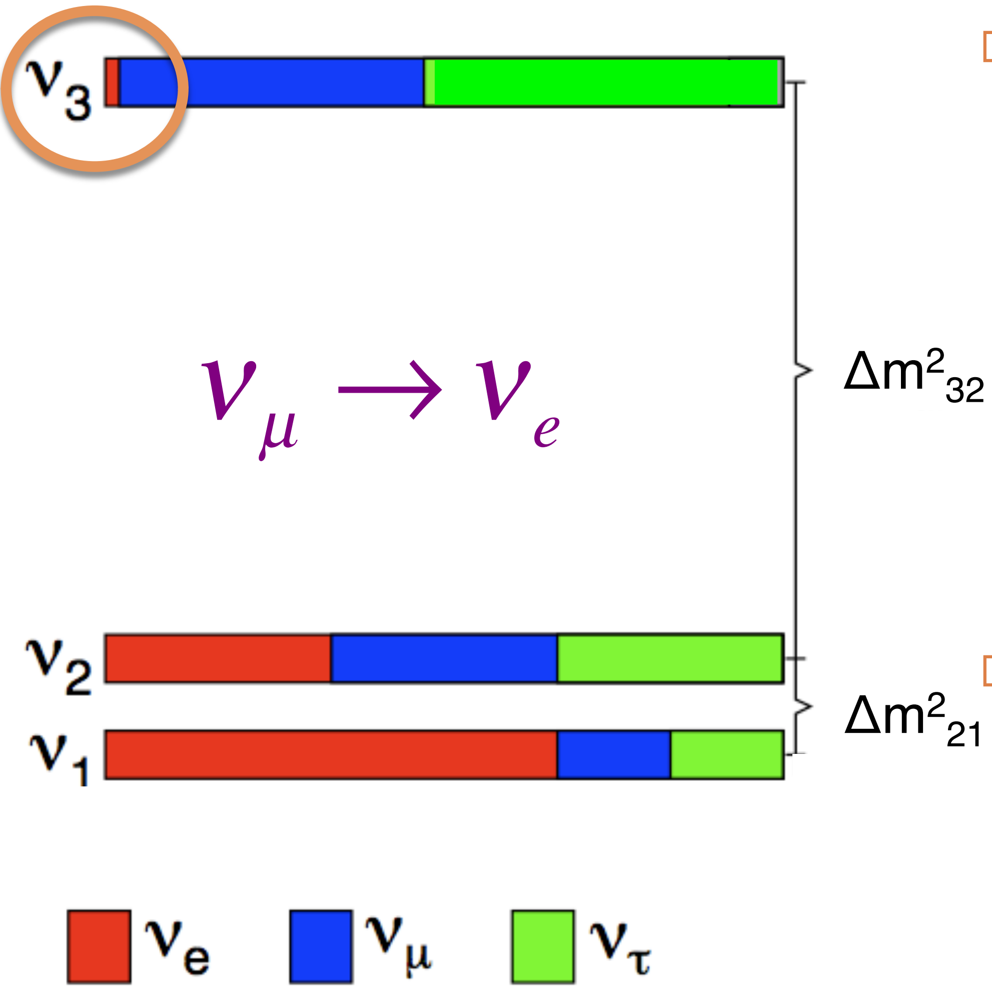
- Two detectors mitigate systematic effects
  - beam flux mismodeling
  - neutrino interaction uncertainties

Physics Goals



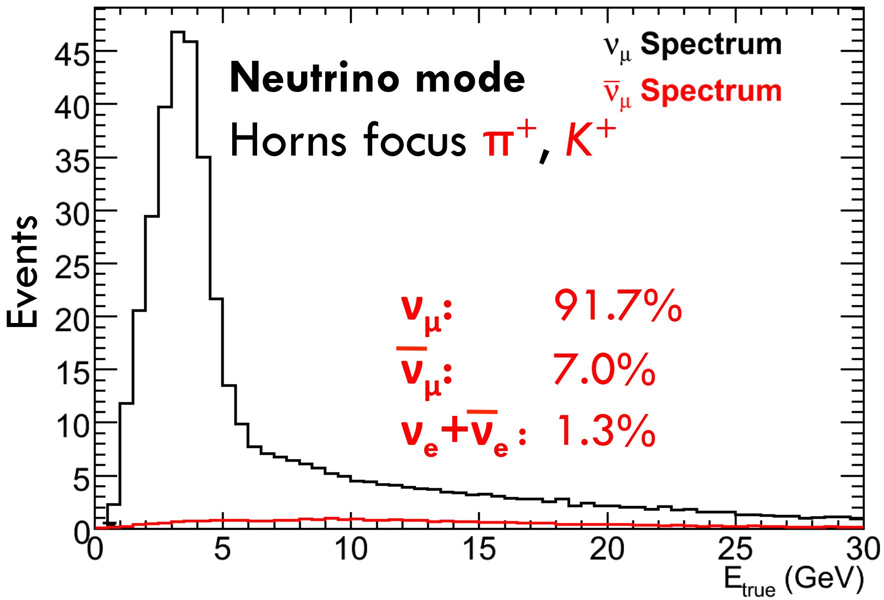
- **Measure ν_μ disappearance as a function of energy**
  - Δm^2_{32} and $\sin^2(2\theta_{23})$
  - test oscillations vs. decay/ decoherence
  - look for differences between neutrino and anti-neutrinos

Physics Goals

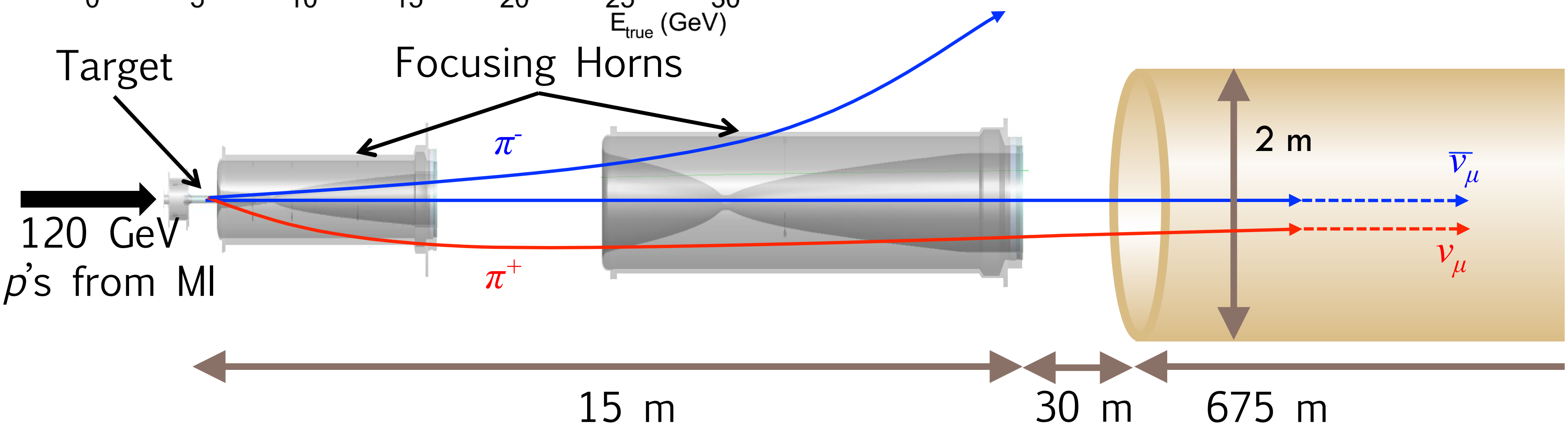


- Measure ν_μ disappearance as a function of energy
  - Δm^2_{32} and $\sin^2(2\theta_{23})$
  - test oscillations vs. decay/ decoherence
  - look for differences between neutrino and anti-neutrinos
- **Study $\nu_\mu \rightarrow \nu_e$ mixing**
  - measure θ_{13}
  - Mass hierarchy
  - Delta CP

Making a Neutrino Beam



- Production: 120 GeV p^+ on 2 interaction length C target
- Focusing: π/K focused/sign selected by two horns
- Decay: π/K decay in 2m diameter decay pipe to ν_μ with wide range of energies



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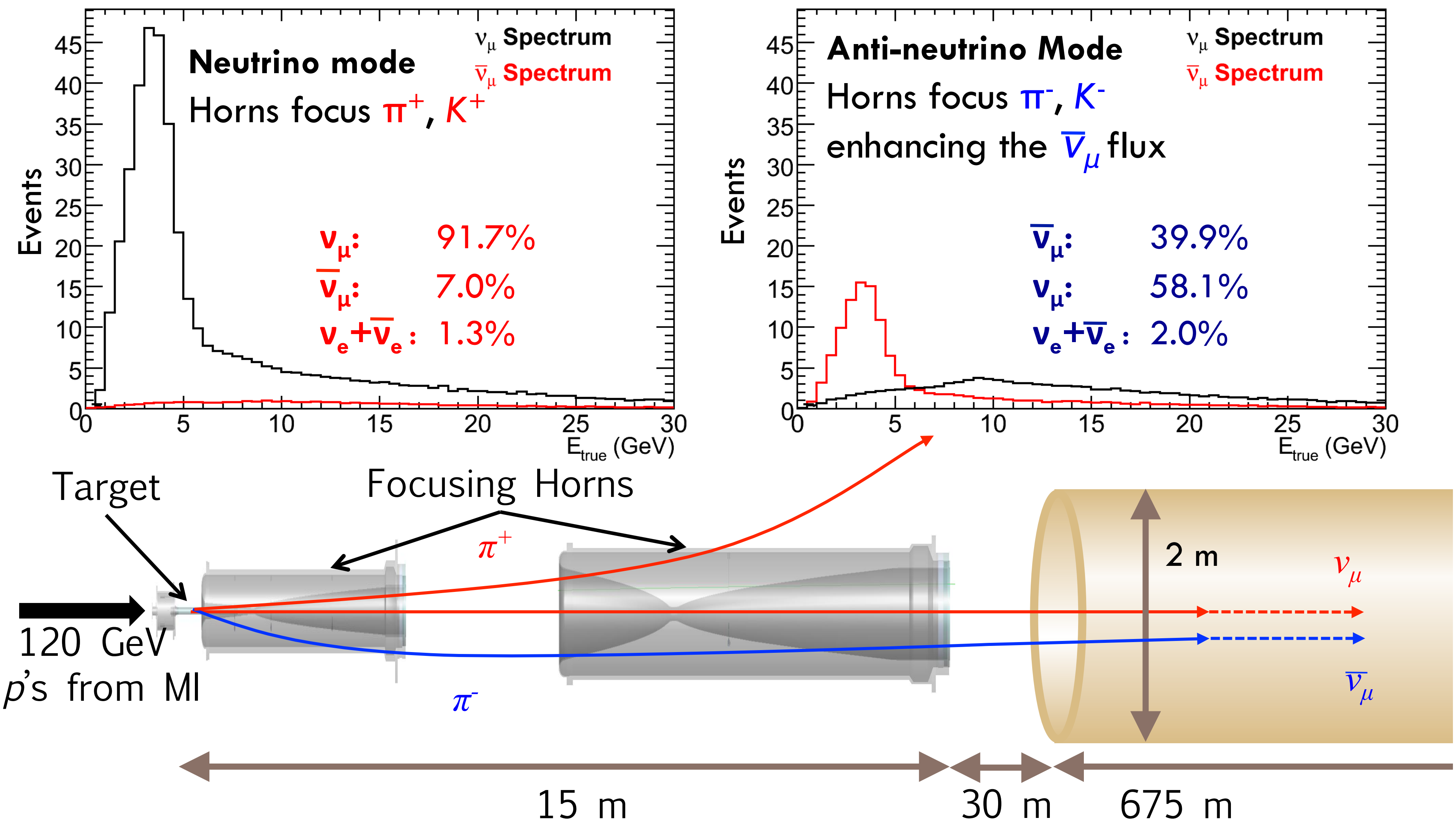
Making an Anti-neutrino Beam



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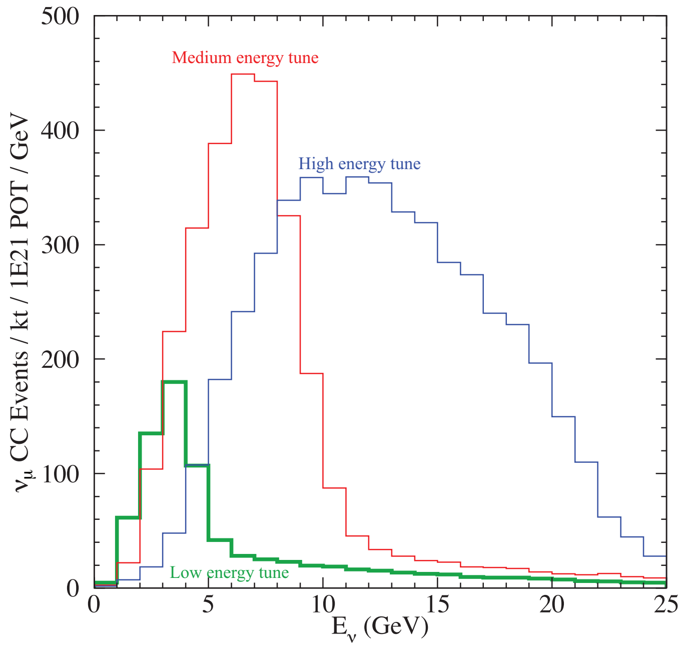
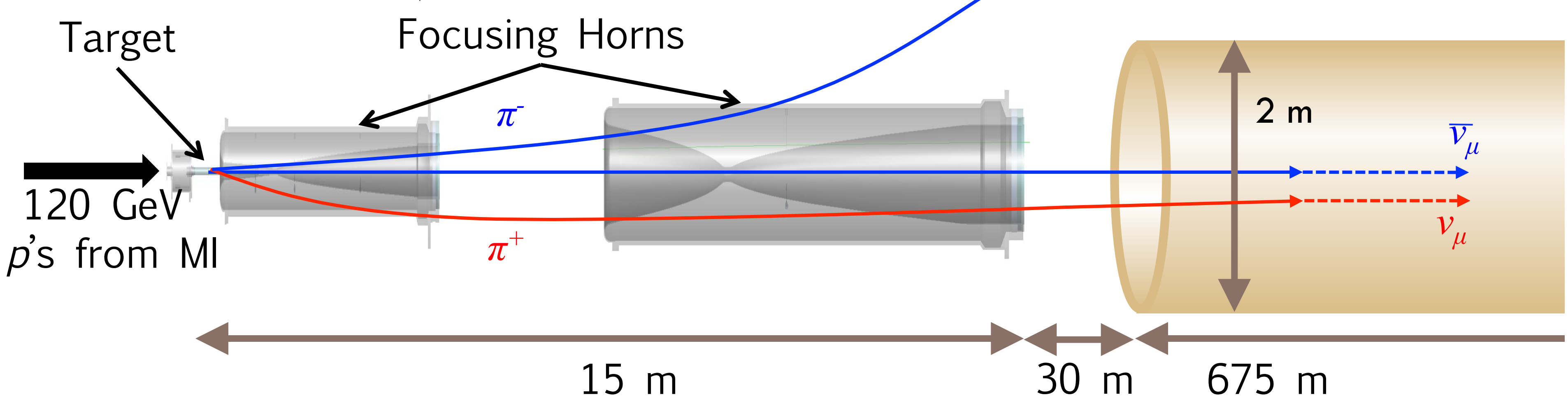
Making the NOvA Neutrino Beam

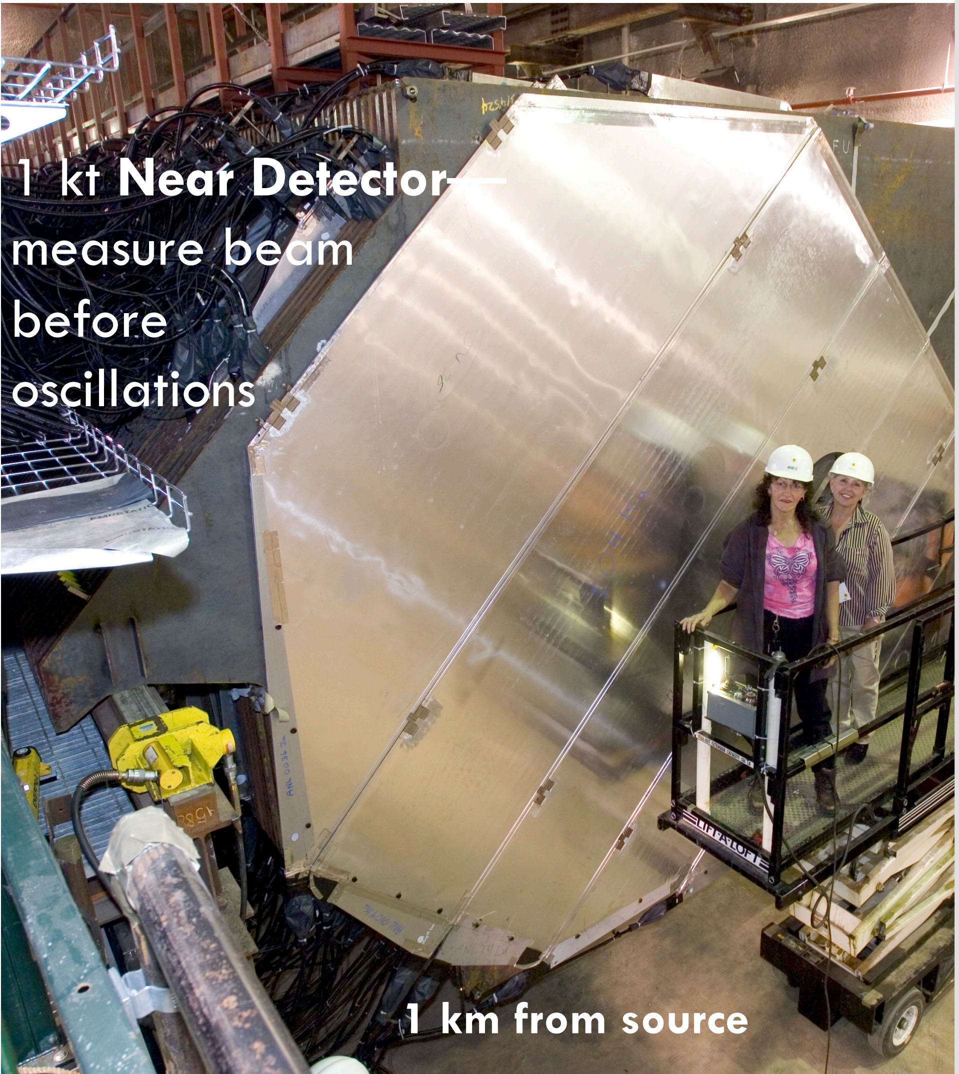


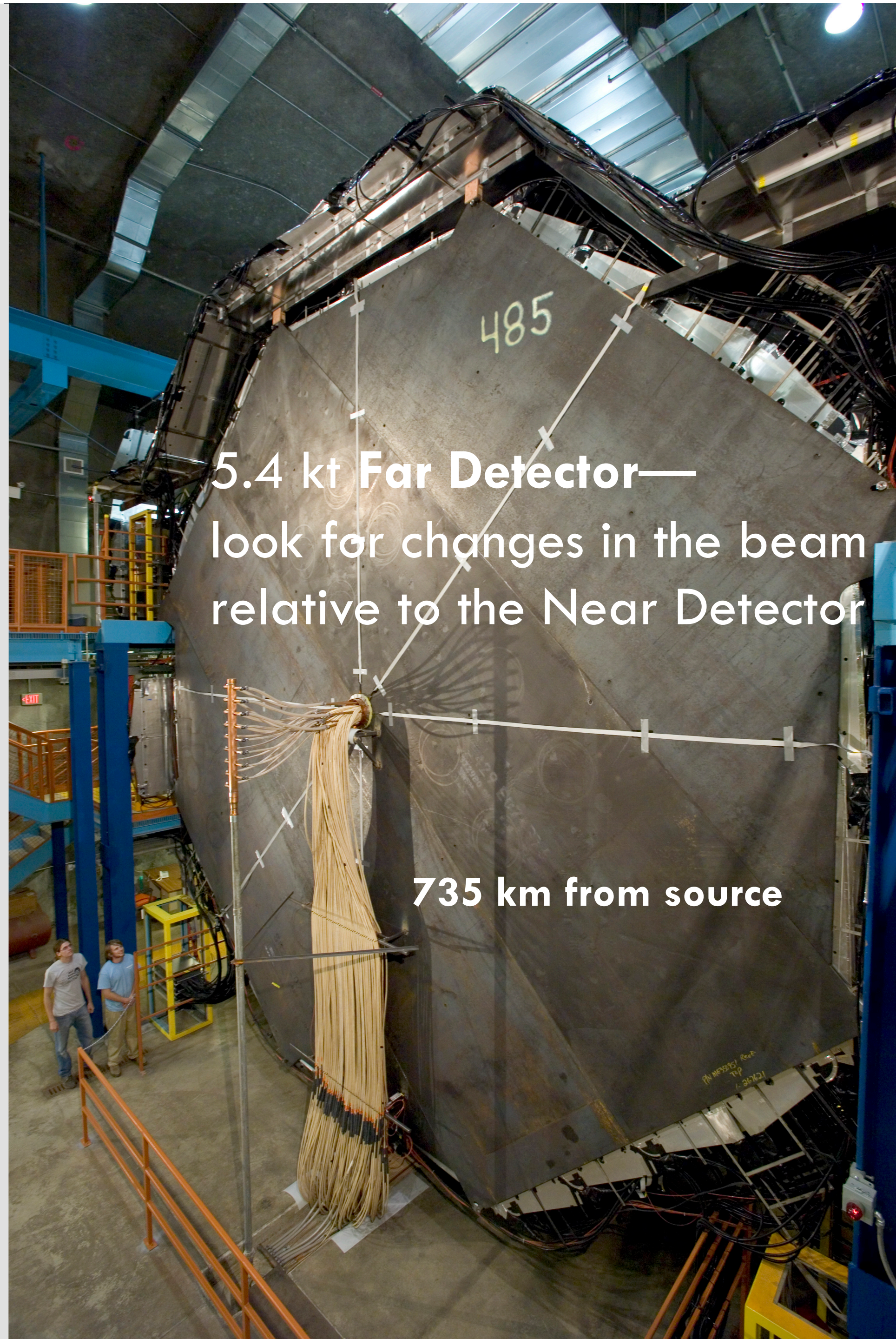
- **Enhanced 700kW NuMI beam line**
  - Increased intensity and faster rep rate
  - New high power target and horns
  - Target/horns reconfigured for higher energy on-axis beam



The MINOS Detectors

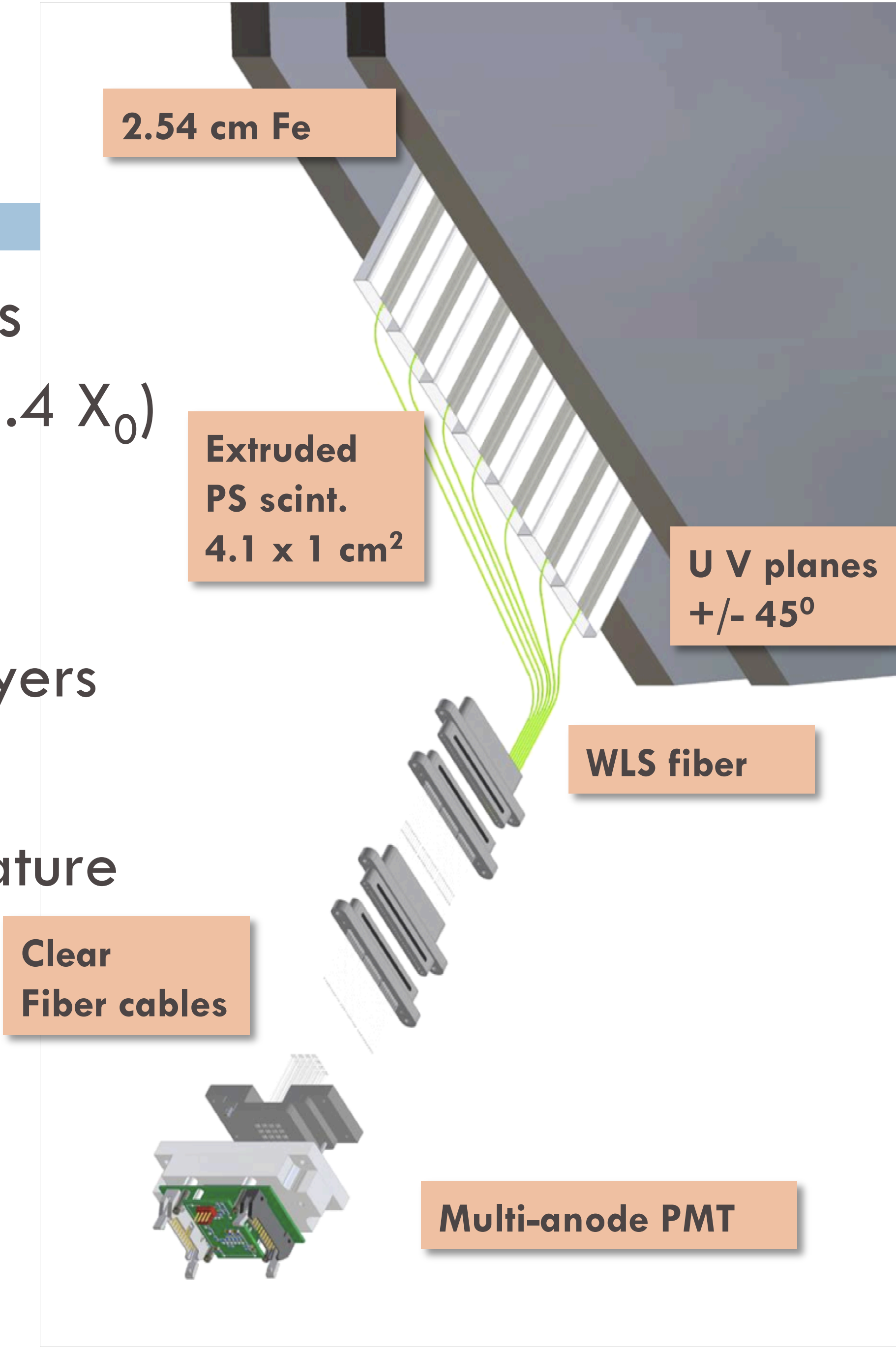
Magnetized, tracking calorimeters





Detector Technology

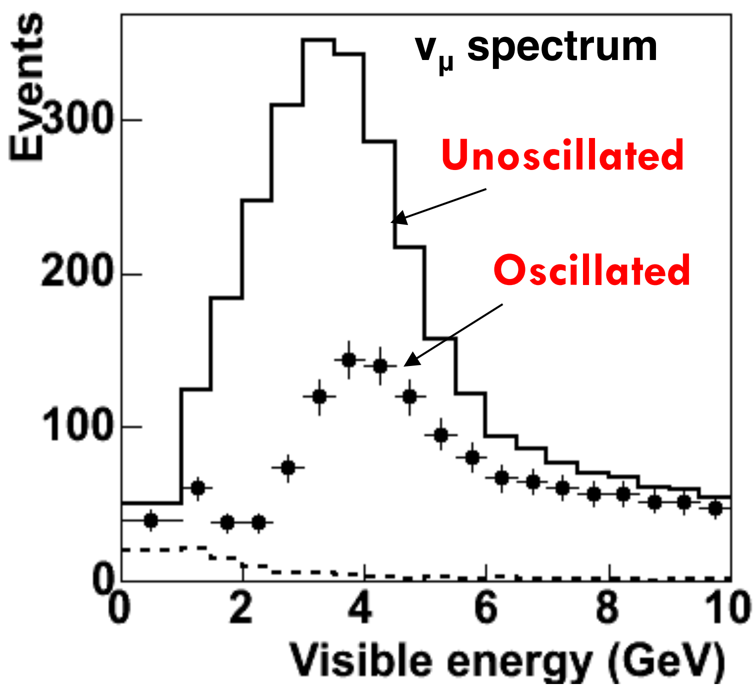
- Tracking sampling calorimeters
  - steel absorber 2.54 cm thick (1.4 X_0)
  - scintillator strips 4.1 cm wide (1.1 Moliere radii)
  - 1 GeV muons penetrate 28 layers
- Magnetized
  - muon energy from range/curvature
  - distinguish μ^+ from μ^-
- Functionally equivalent
  - same segmentation
  - same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

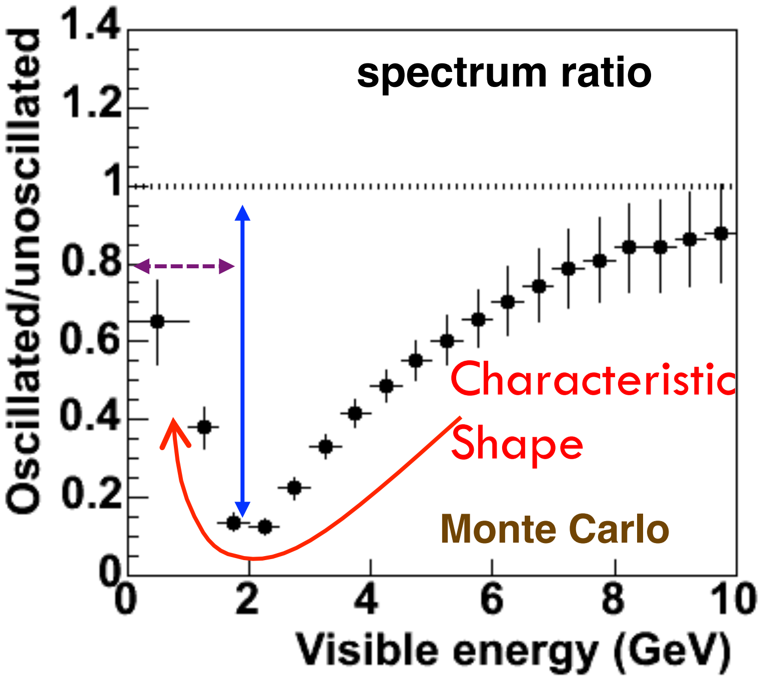


ν_μ Disappearance

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

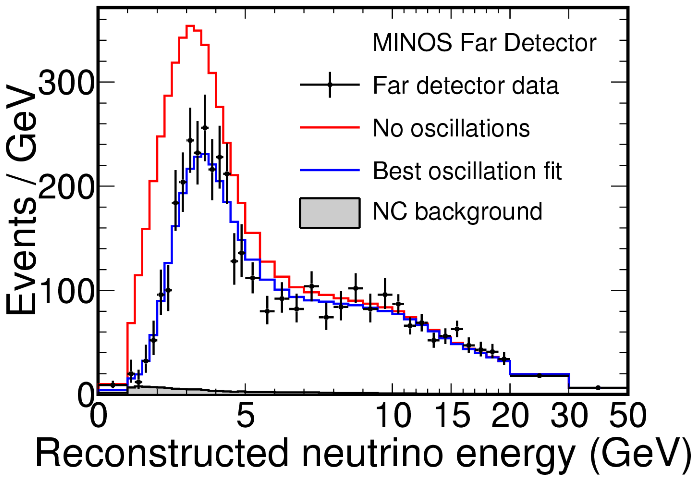
Monte Carlo
(Input parameters: $\sin^2 2\theta = 1.0$, $\Delta m^2 = 3.35\times10^{-3}$ eV^2)

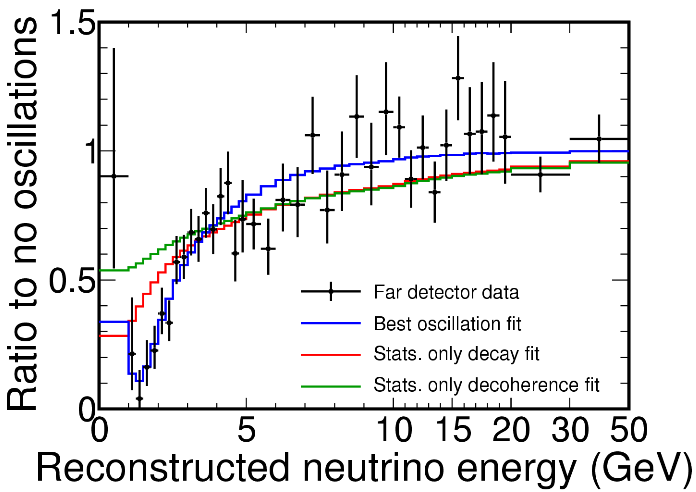




ν_μ Disappearance

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





- No oscillations: 2451
- Observe: 1986

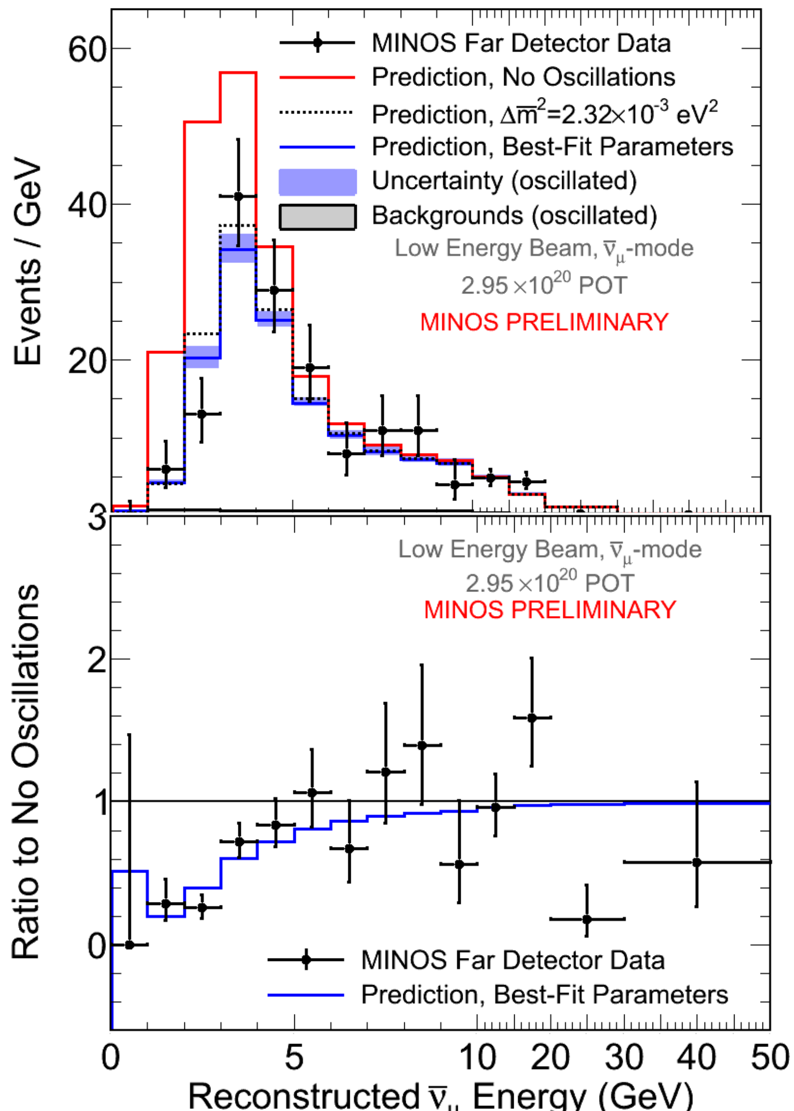
$$\left|\Delta m^2\right| = 2.32^{+0.12}_{-0.08} \times 10^{-3}\,\mathrm{eV}^2$$

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

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

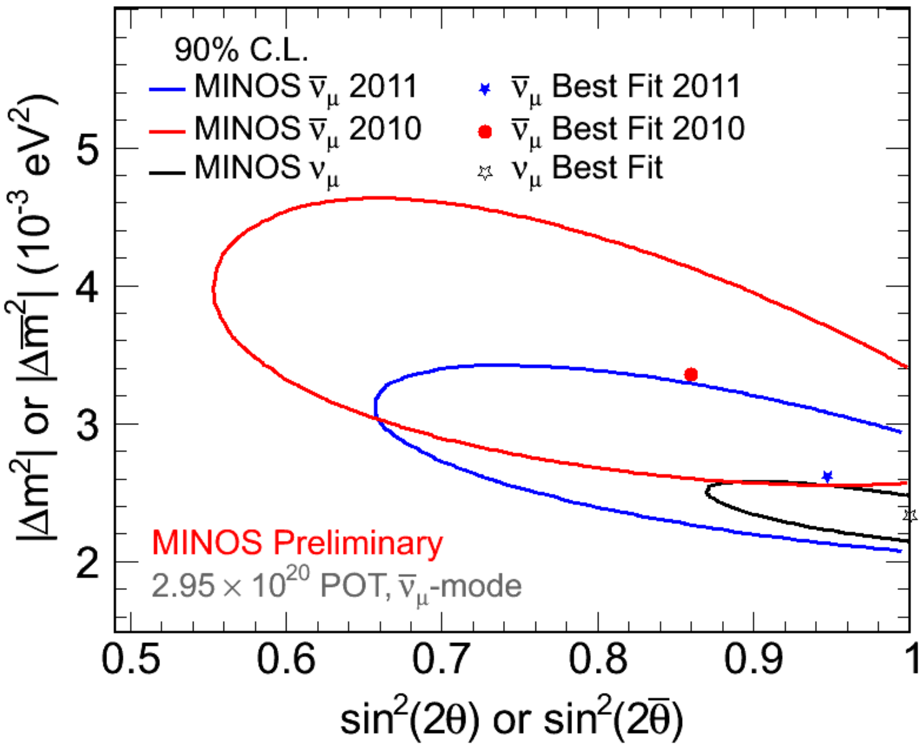


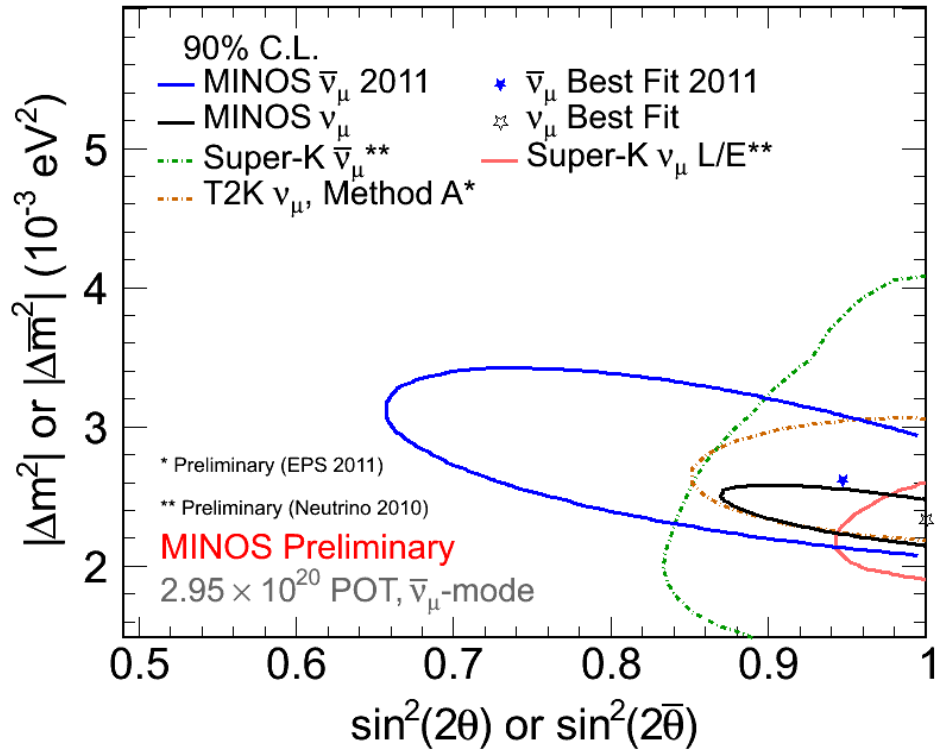
- No oscillations: 276
- Oscillated Prediction: 196
- Observe: 197
- No oscillations disfavored at 7.3σ

$$\left|\overline{\Delta m^2}\right| = (2.62^{+0.31}_{-0.28}\ (\text{stat.}) \pm 0.09\ (\text{syst.})) \times 10^{-3}\,\text{eV}^2$$

$$\sin^2(2\bar{\theta}) > 0.75\ (90\%\ \text{C.L.})$$

Comparisons

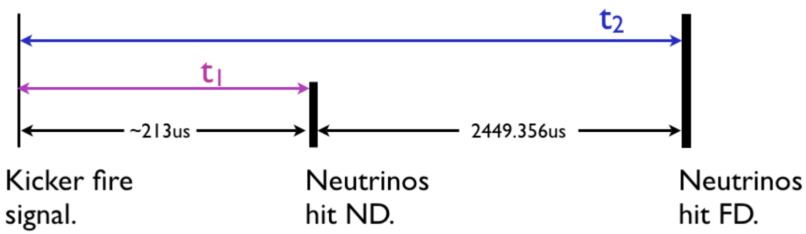




- Assuming identical underlying oscillation parameters, the neutrino and antineutrino measurements are consistent at the 42% C.L. (compared to 2% in 2010)

Neutrino Time of Flight

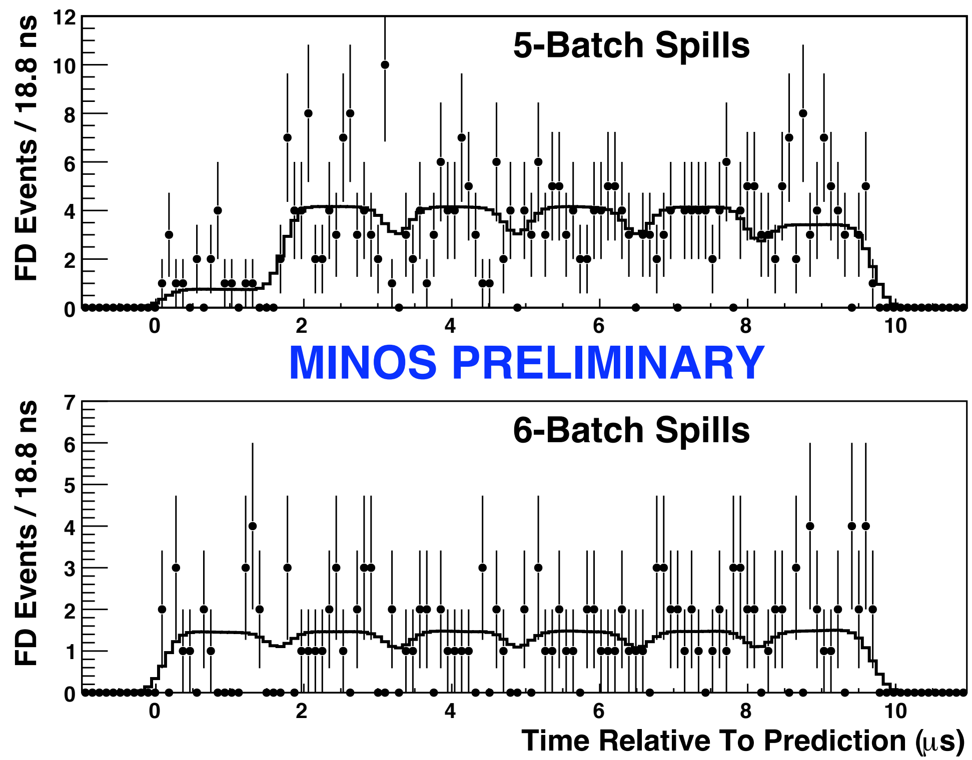
Phys.Rev. D76 (2007) 072005



Measure time of flight as t_1 - t_2

	Description	Uncertainty (68% C.L.)
A	Distance between detectors	2 ns
B	ND Antenna fiber length	27 ns
C	ND electronics latencies	32 ns
D	FD Antenna fiber length	46 ns
E	FD electronics latencies	3 ns
F	GPS and transceivers	12 ns
G	Detector readout differences	9 ns
	Total (Sum in quadrature)	64 ns

TABLE II: Sources of uncertainty in ν relative time measurement.



Neutrinos arrive 126 ± 32 (stat.) ± 64(syst.) ns before expected

$-2.4\times10^{-5} < (v-c)/c < 12.6\times10^{-5}$ (99% C.L.)

Efforts to improve systematics and timing system are underway

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

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

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

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

"Atmospheric" Term

Depends on Δm^2 and unknown θ_{13}

"Solar" Term

<1% for current accelerator experiments

Interference Term

depends on δ_{CP}

- for neutrinos, + for antineutrinos

ν_e Appearance

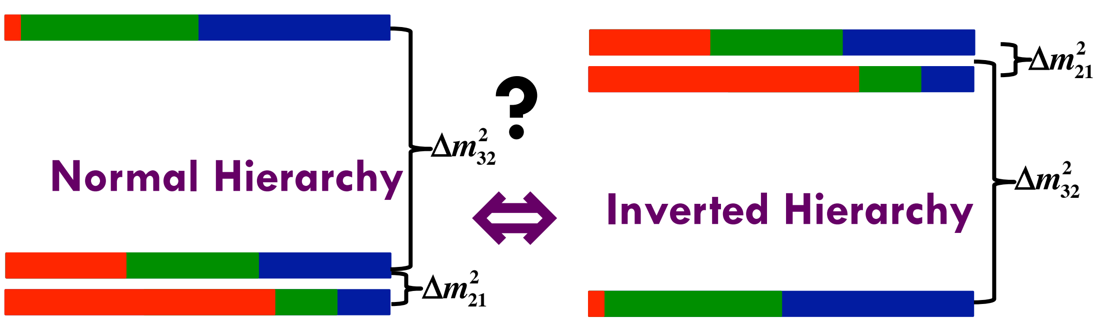
- At L/E~500 km/GeV, dominant oscillation mode is $\nu_\mu \to \nu_\tau$
- A few percent of the missing ν_μ could change into ν_e

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

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

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

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



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

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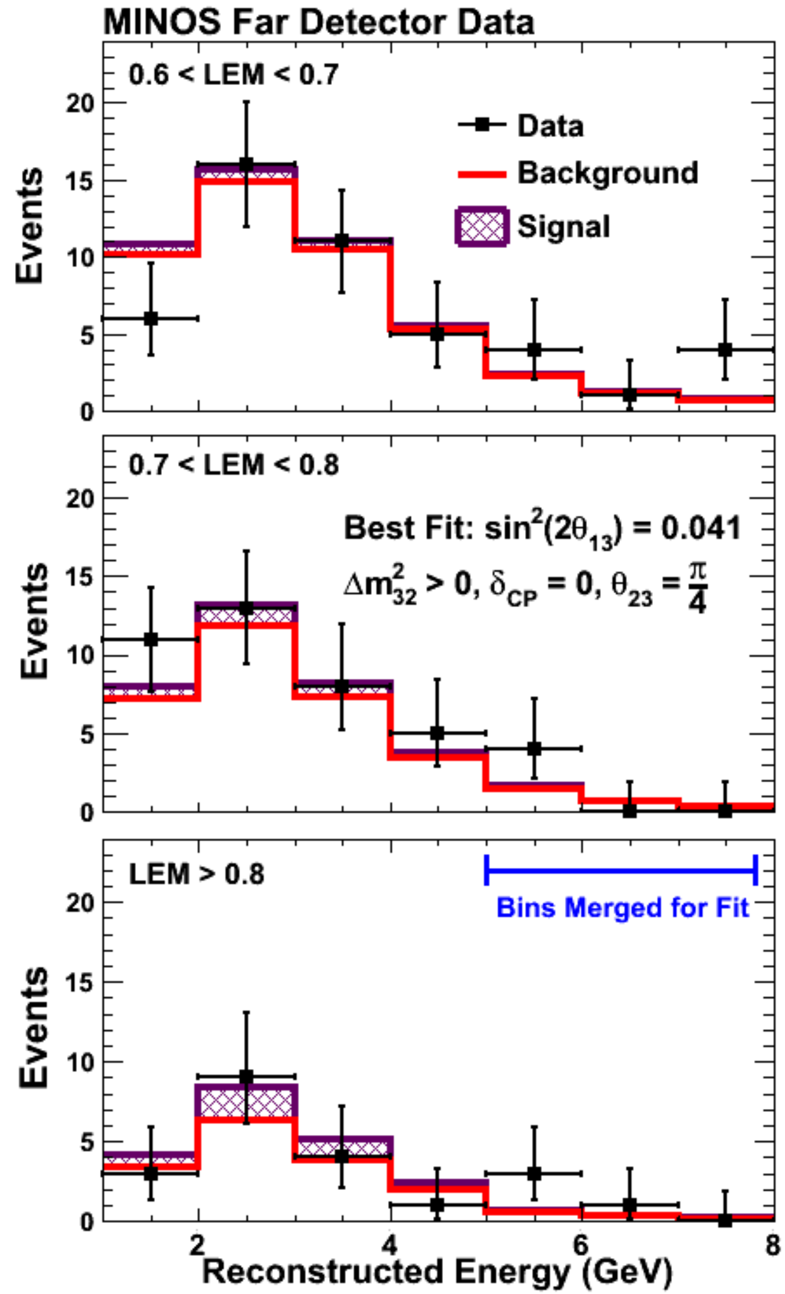
hep-ex:1108.0015

Fitting to Oscillations

- Expect: **49.6±7.0(stat.)±2.7(syst.)**
  (in signal enhanced region)
- Observe: **62** events in the FD
- Best fit: $\sin^2(2\theta_{13})=0.041$
  (normal hierarchy, $\delta_{CP}=0$, $\sin^2(2\theta_{23})=1$)



ν_e Appearance Results

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

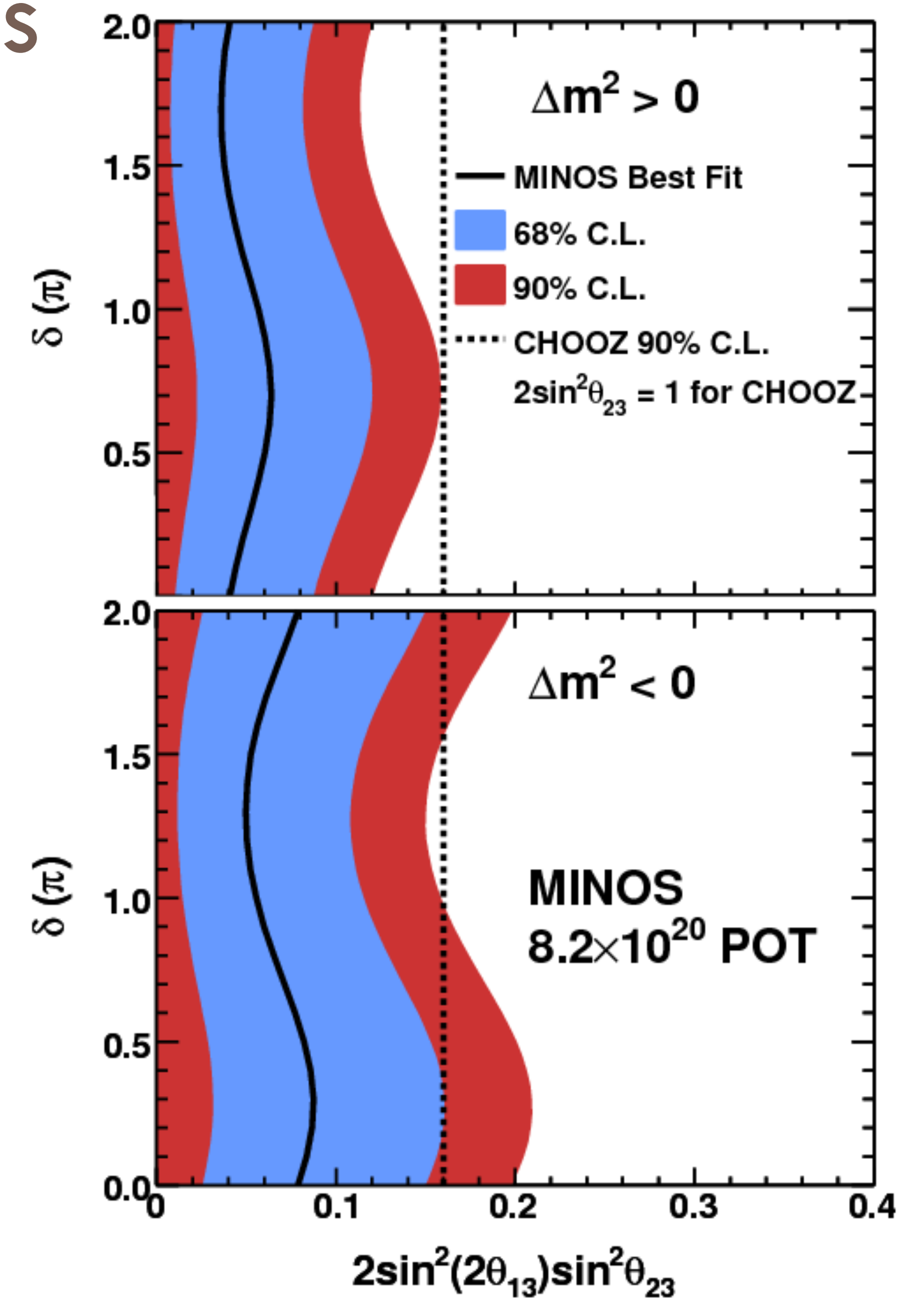
$|\Delta m^2_{32}| = 2.32 \times 10^{-3}\ \text{eV}^2$

$\sin^2(2\theta_{13}) = 0.041\ \ (0.079)$ at best fit

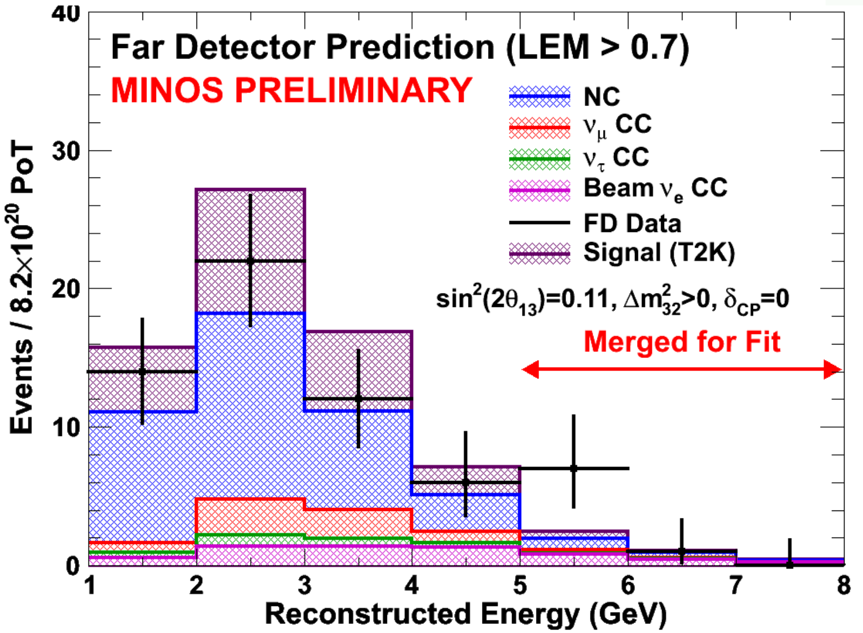
$\sin^2(2\theta_{13}) < 0.12\ \ (0.20)$ at 90% C.L.

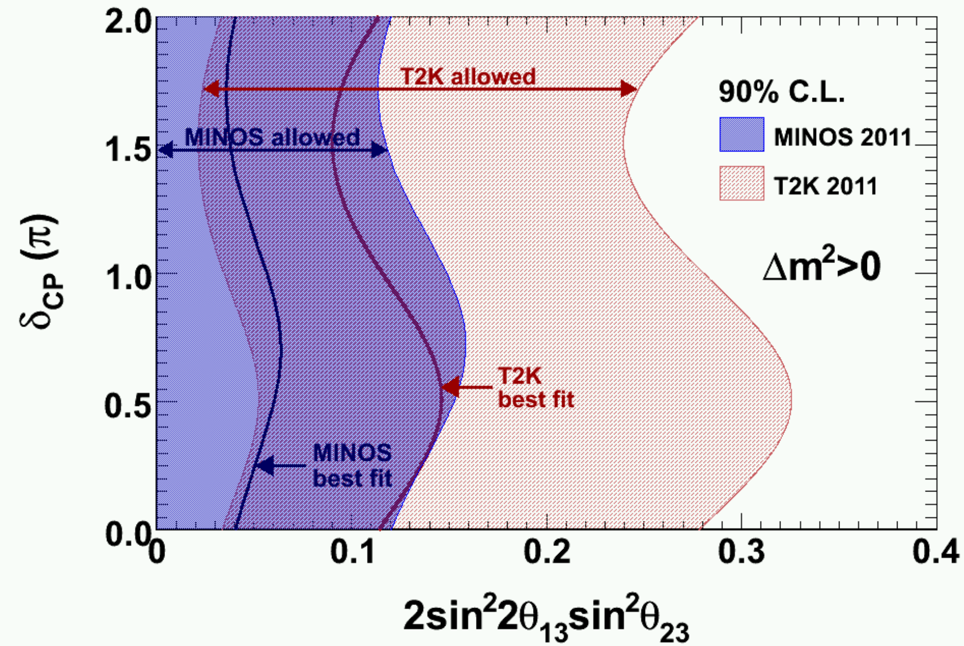
$\sin^2(2\theta_{13}) = 0$ excluded at 89%

hep-ex:1108.0015



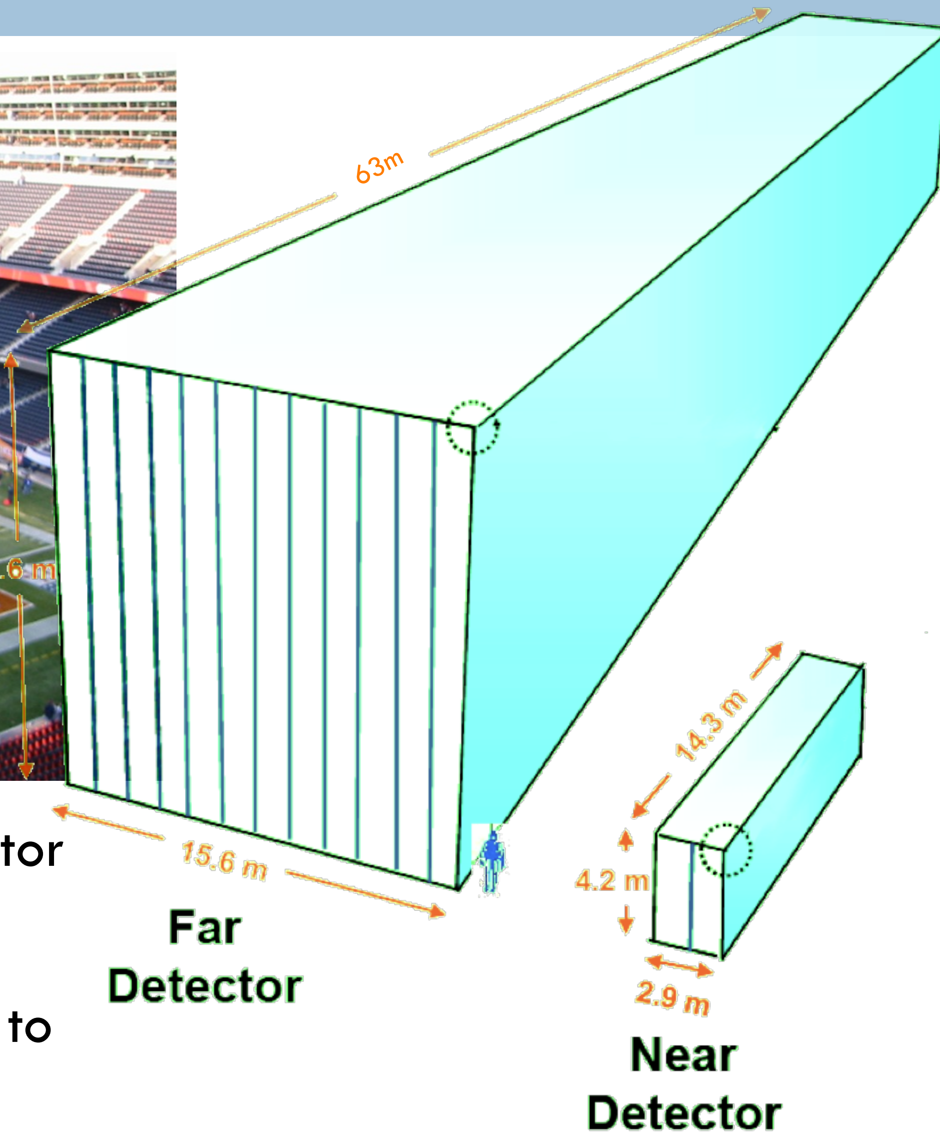
Comparing to T2K





- We have more data on tape and are still running

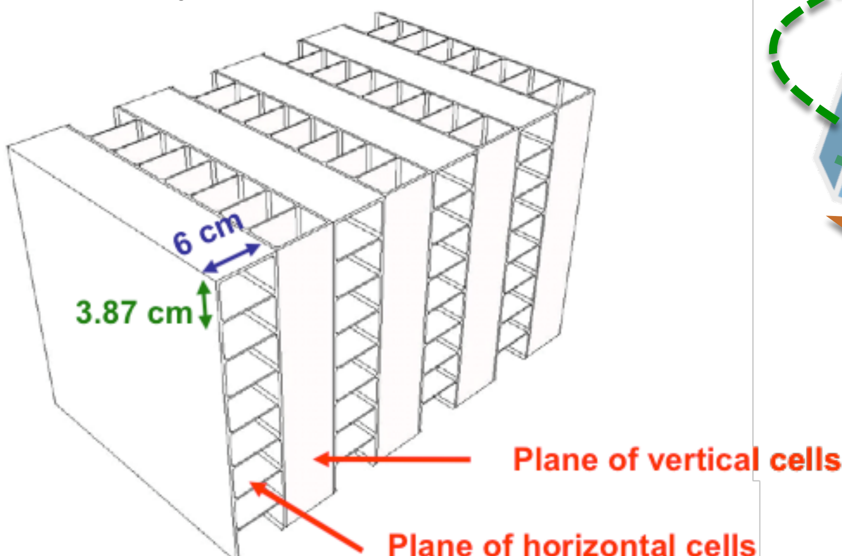
The NOvA Detectors

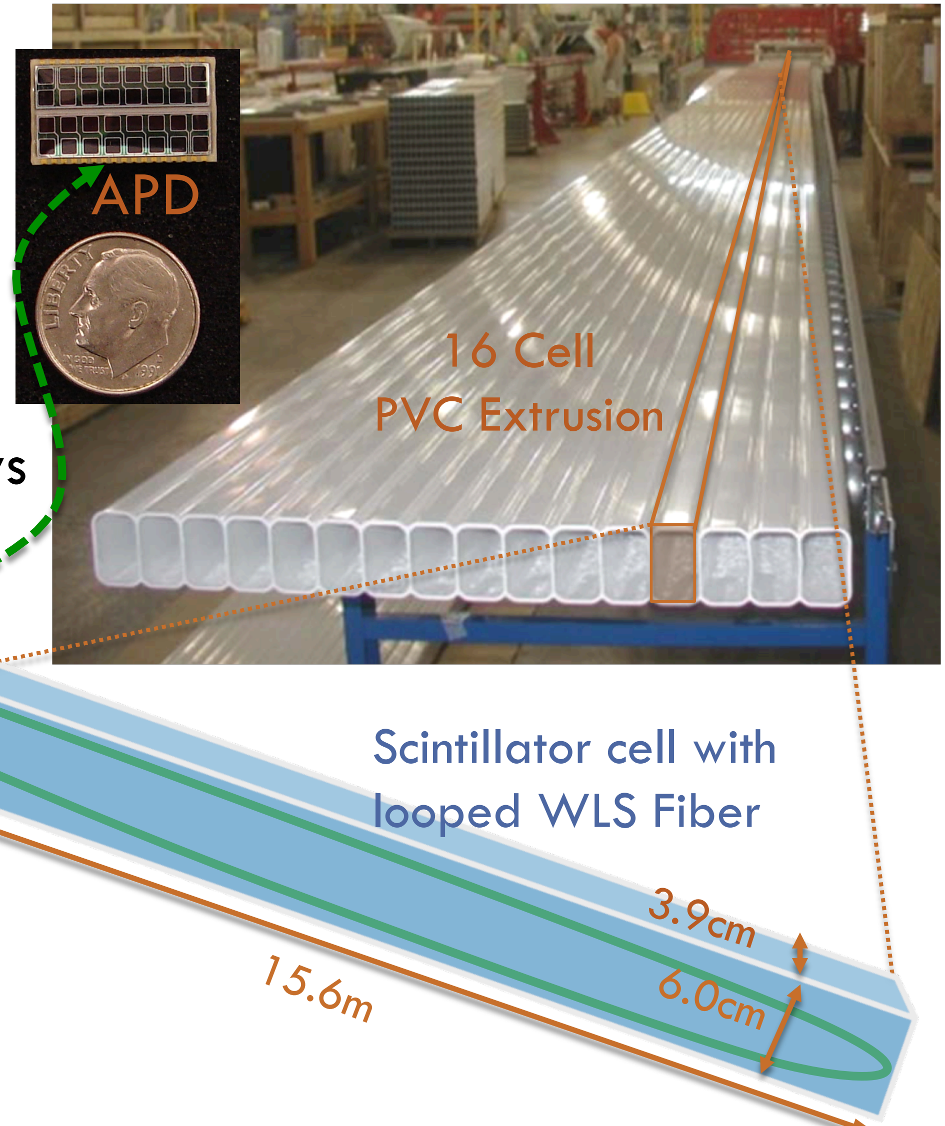


- Massive, Low-Z, 65% active Far Detector
  - 15 kton, 810 km from source
- Functionally equivalent Near Detector to mitigate systematic uncertainties
  - 220 ton Near Detector, 1 km from source

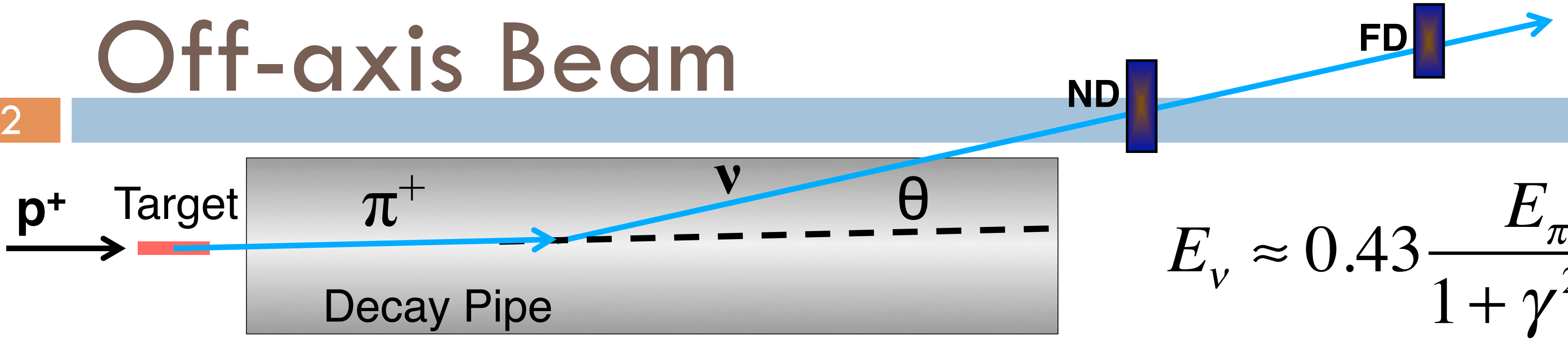
Detector Technology

- PVC extrusion + Liquid Scintillator
  - mineral oil + 5% pseudocumene
- Read out via WLS fiber to APD
  - muon crossing far end=38 PE
- Layered planes of orthogonal views
- 0.15 X_0 per layer



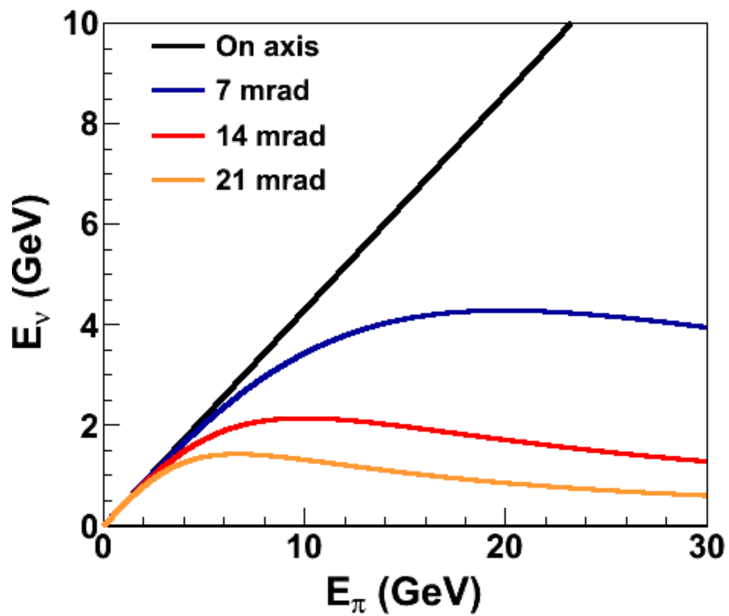


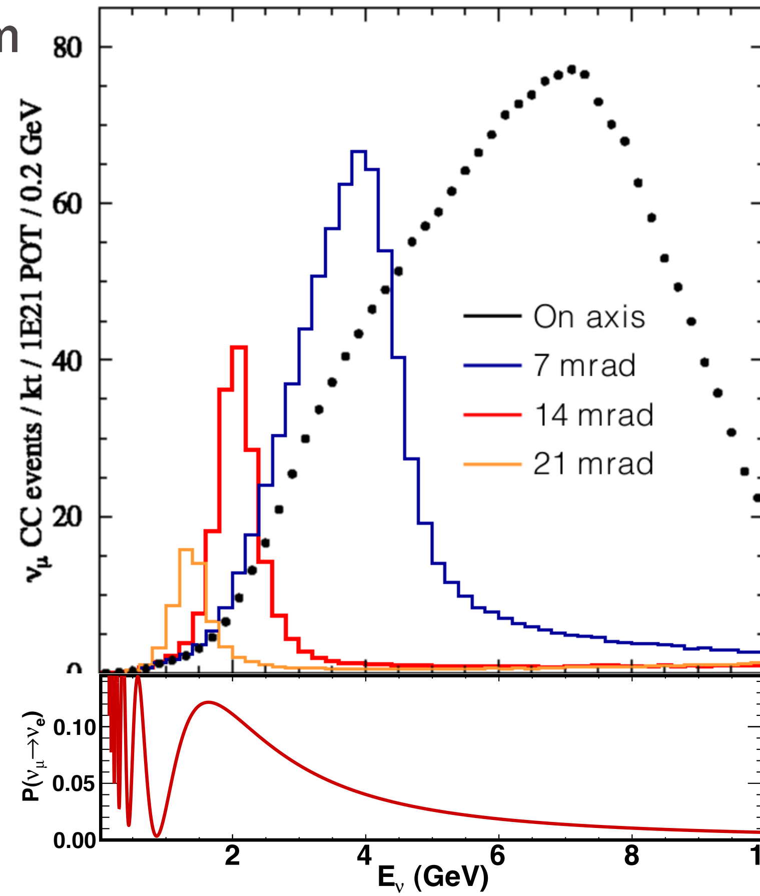
Off-axis Beam



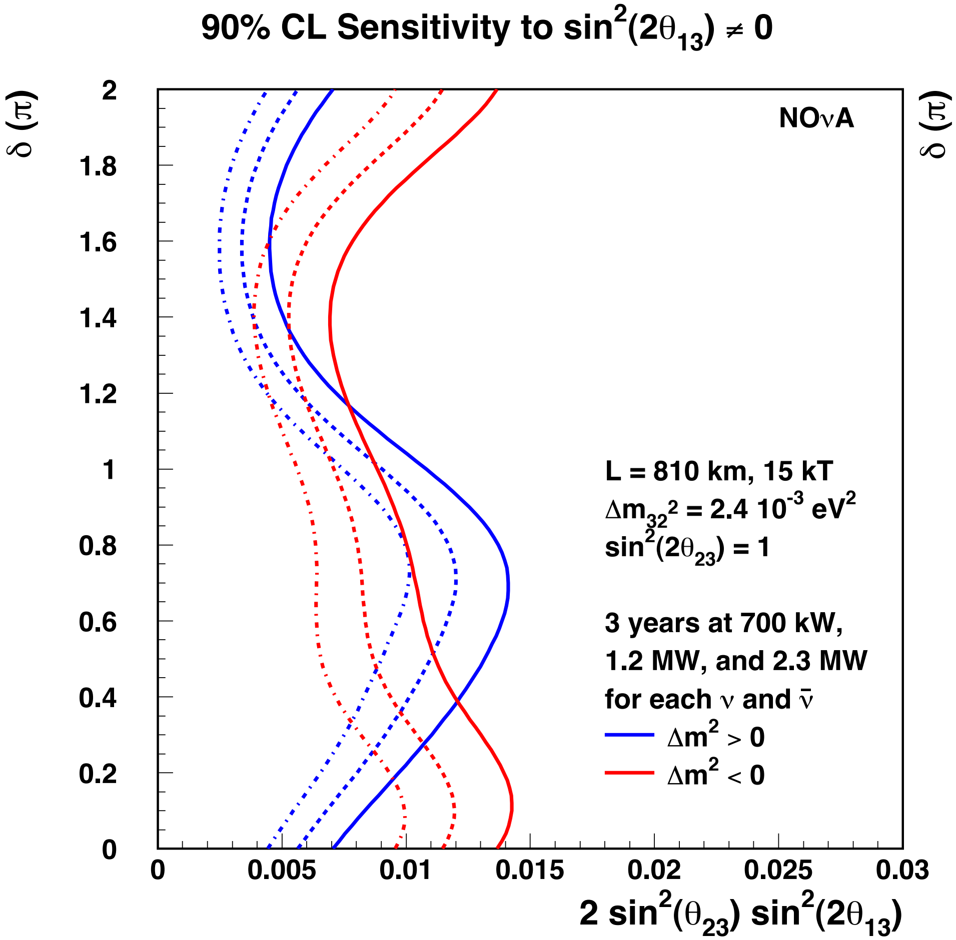
$$E_\nu \approx 0.43 \frac{E_\pi}{1+\gamma^2\theta_\nu^2}$$

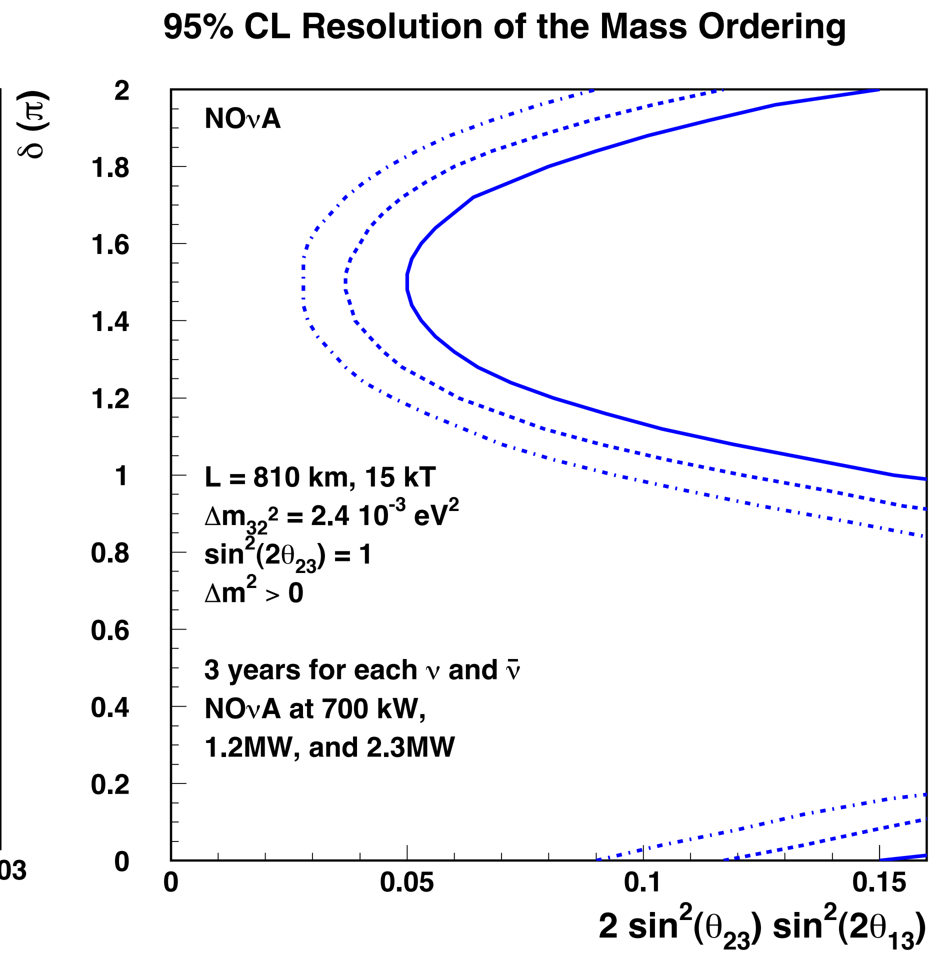
- At 14 mrad off-axis, narrow band beam peaked at 2 GeV
  - Near oscillation maximum
  - Few high energy NC background events





Sensitivity





- Sensitivity to $\sin^2(2\theta_{13})$ after 3 years each of neutrino beam and antineutrino beam
- Sensitivity to mass hierarchy

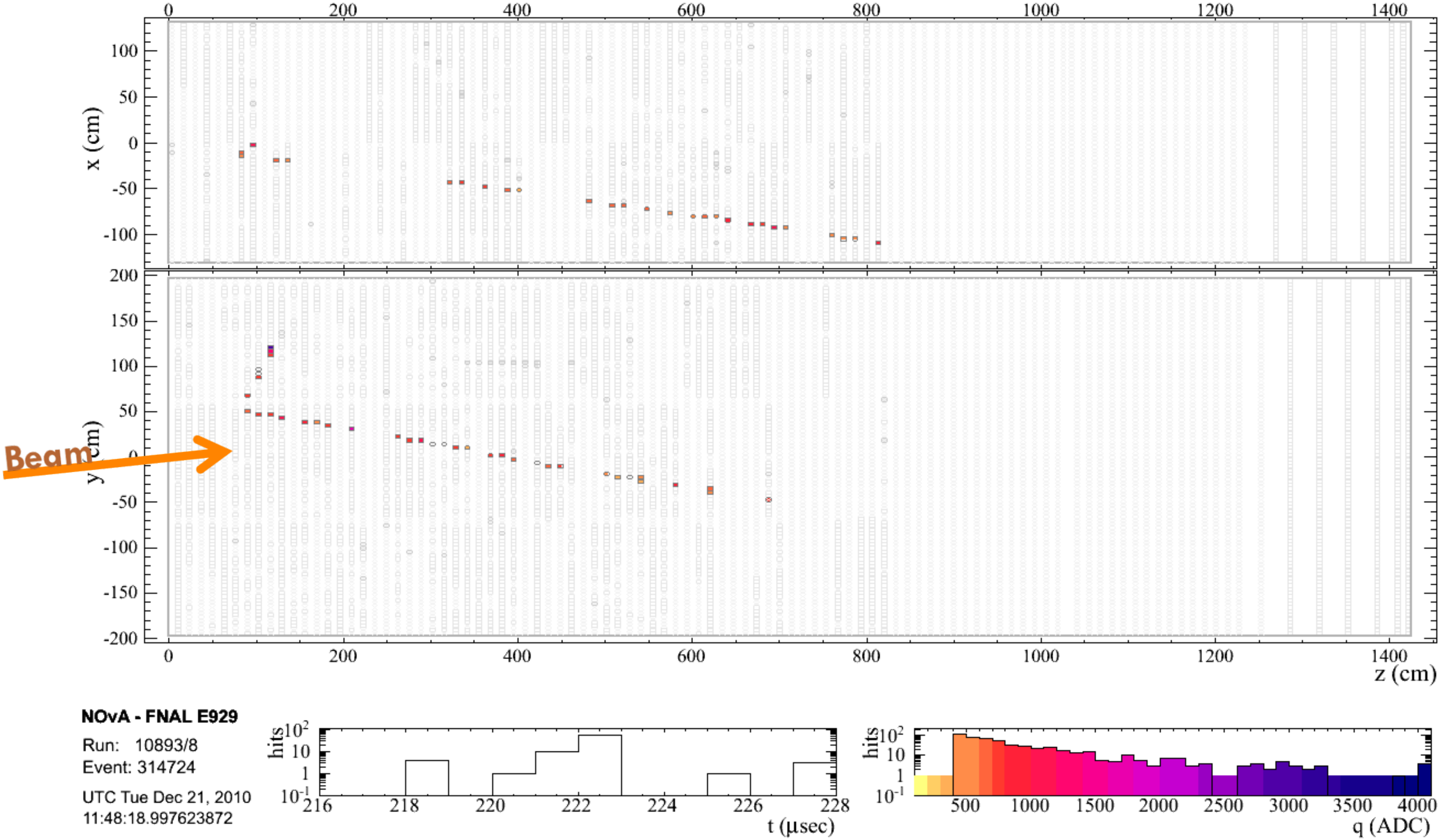
Project Timeline

- Beam:
  - Accelerator shutdown to install upgrades for 700kW beam: March 2012
- FD:
  - Start construction: Jan 2012
  - 50% detector by end of shutdown
  - Complete by early 2014
- ND:
  - Cavern excavation during shutdown
  - Prototype in operation at FNAL on the surface

NDOS

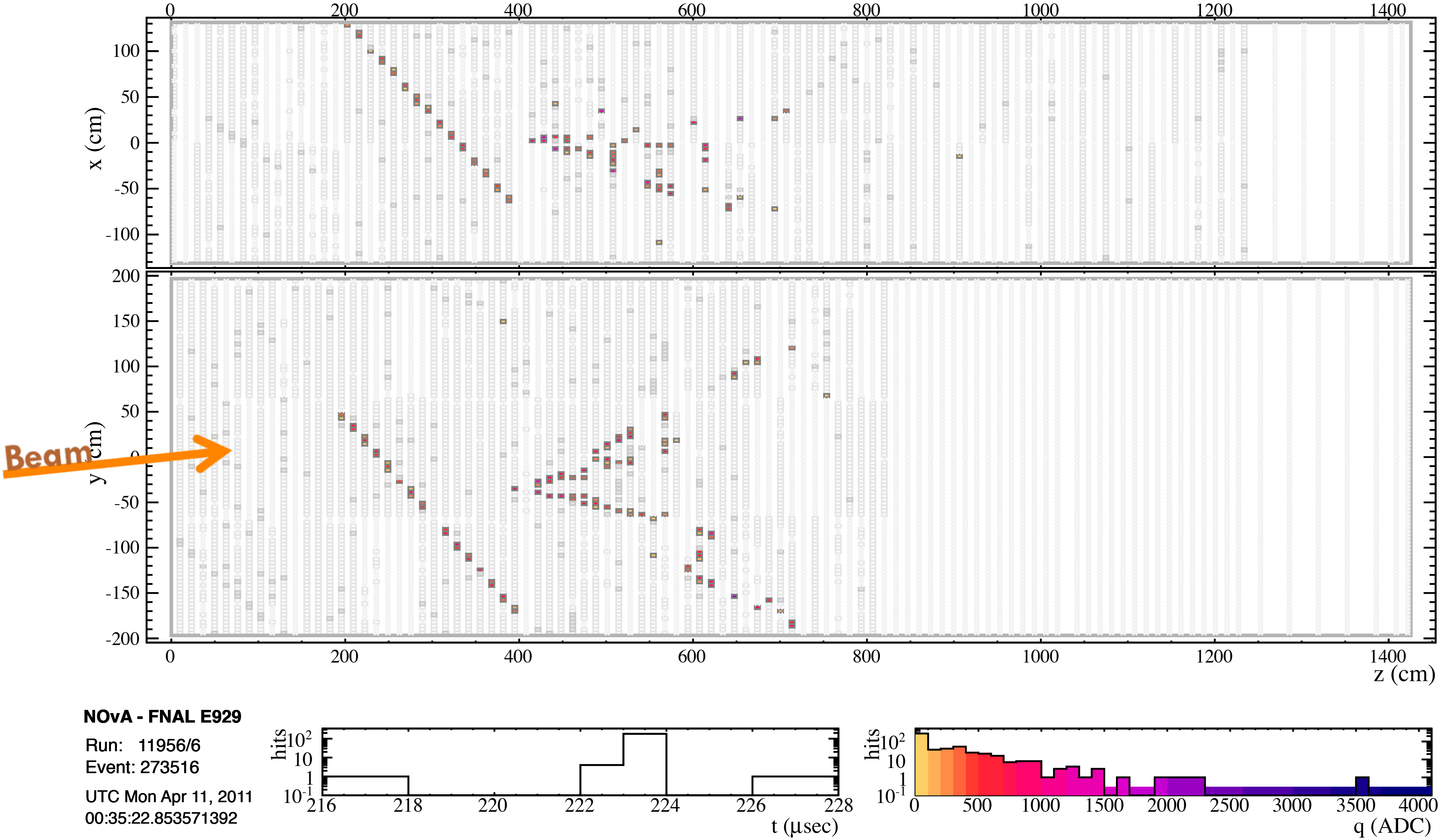
- At the intersection of the NuMI and Booster beams
- Run Goals:
  - Test detector design and installation procedures
  - Exercise calibration scheme
  - Verify cosmic background suppression
  - Benchmark MC

Neutrinos



Beam
x (cm)
y (cm)
z (cm)
NOvA - FNAL E929
Run: 10893/8
Event: 314724
UTC Tue Dec 21, 2010
11:48:18.997623872
hits
t (μsec)
q (ADC)

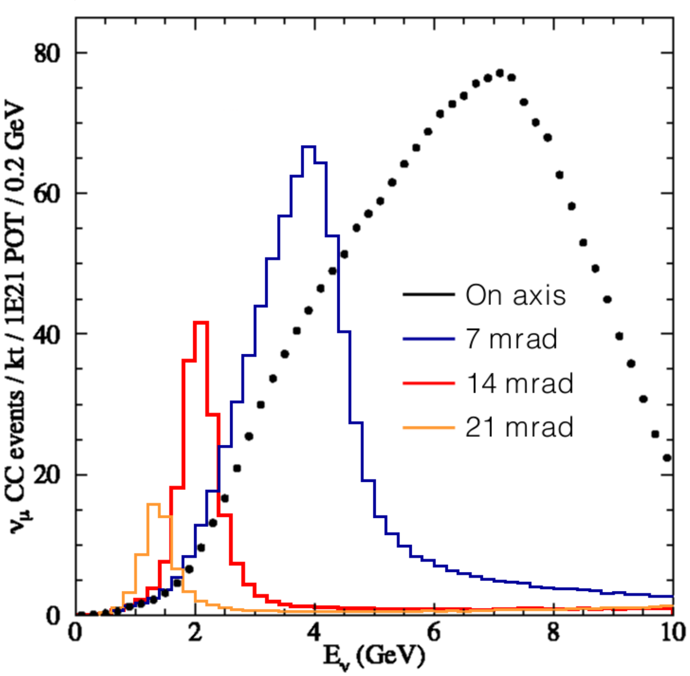
Neutrinos

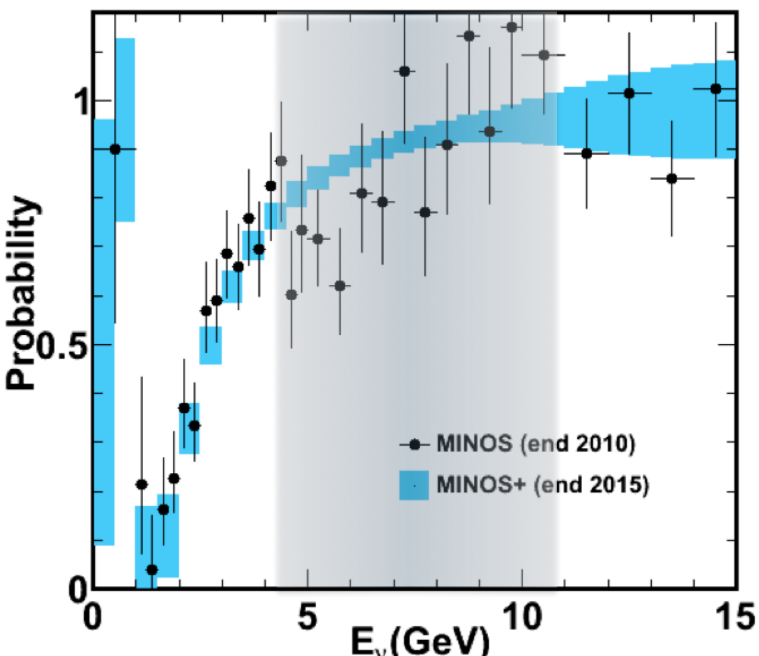


x (cm)
y (cm)
z (cm)
Beam
NOvA - FNAL E929
Run: 11956/6
Event: 273516
UTC Mon Apr 11, 2011
00:35:22.853571392
hits
t (μsec)
q (ADC)

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
- Plans for upgraded TOF measurement





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Summary

- With 7×10^{20} POT of neutrino beam, MINOS finds
  - muon-neutrinos disappear

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

  - So Do antineutrinos

$$|\Delta \overline{m}^2| = (2.62^{+0.31}_{-0.28} \pm 0.09) \times 10^{-3}\,\text{eV}^2,$$
$$\sin^2(2\overline{\theta}) > 0.75 \text{ (90\% C.L.)}$$

- Updated electron neutrino appearance results

$$\sin^2(2\theta_{13}) < 0.12 \text{ (0.20) at 90\% C.L.}$$
$$\sin^2(2\theta_{13}) = 0 \text{ excluded at 89\%}$$

NOvA and MINOS+ on the horizon!

Backup Slides

Neutrinos Have Mass!

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = U^\dagger \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix} \qquad P(\nu_\alpha \to \nu_\beta) = \left| \sum_j U^*_{\beta j} e^{-i\frac{m_j^2 L}{2E}} U_{\alpha j} \right|^2$$

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

- 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 ($U_{\alpha j}$)

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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

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

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

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

- (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 Numbers?

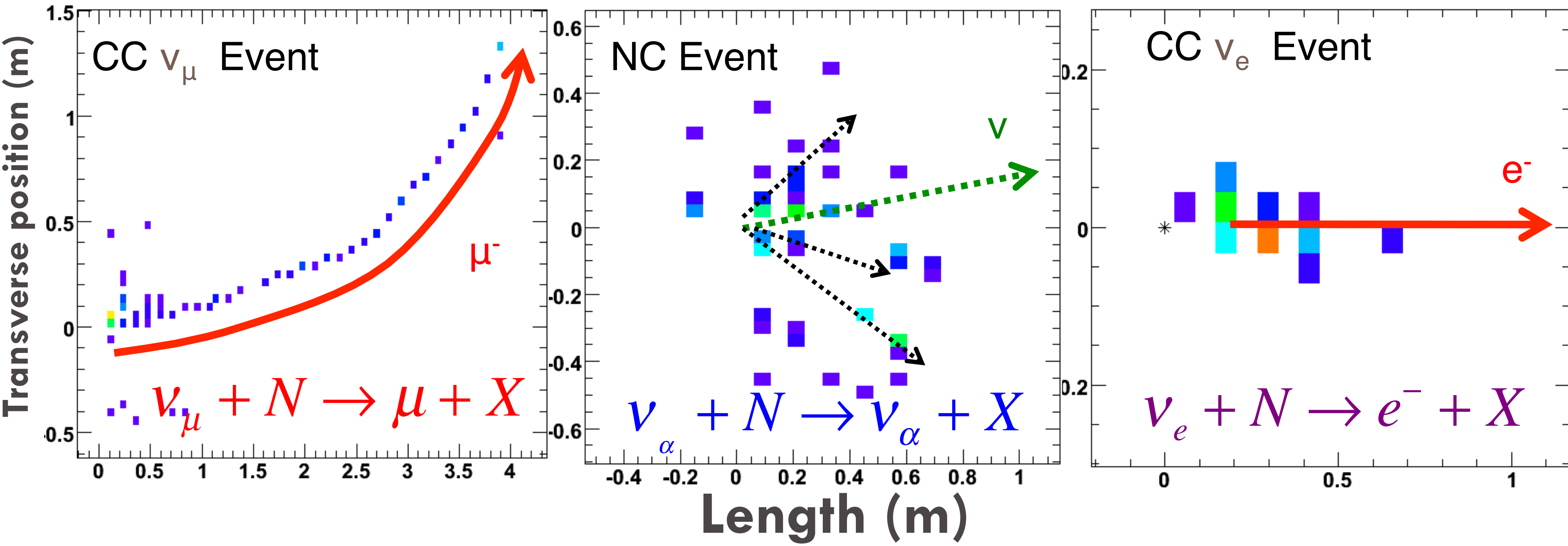
- Precision measurements provide a valuable check that neutrino oscillations are the solution to neutrino anomalies
- PMNS matrix analogous to CKM matrix
  - lepton sector mixing much larger than quark sector mixing
  - θ_{23} maximal, θ_{12} moderately large, θ_{13} small, zero? why?
  - Is there CP 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!

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

Events in MINOS

Simulated Events



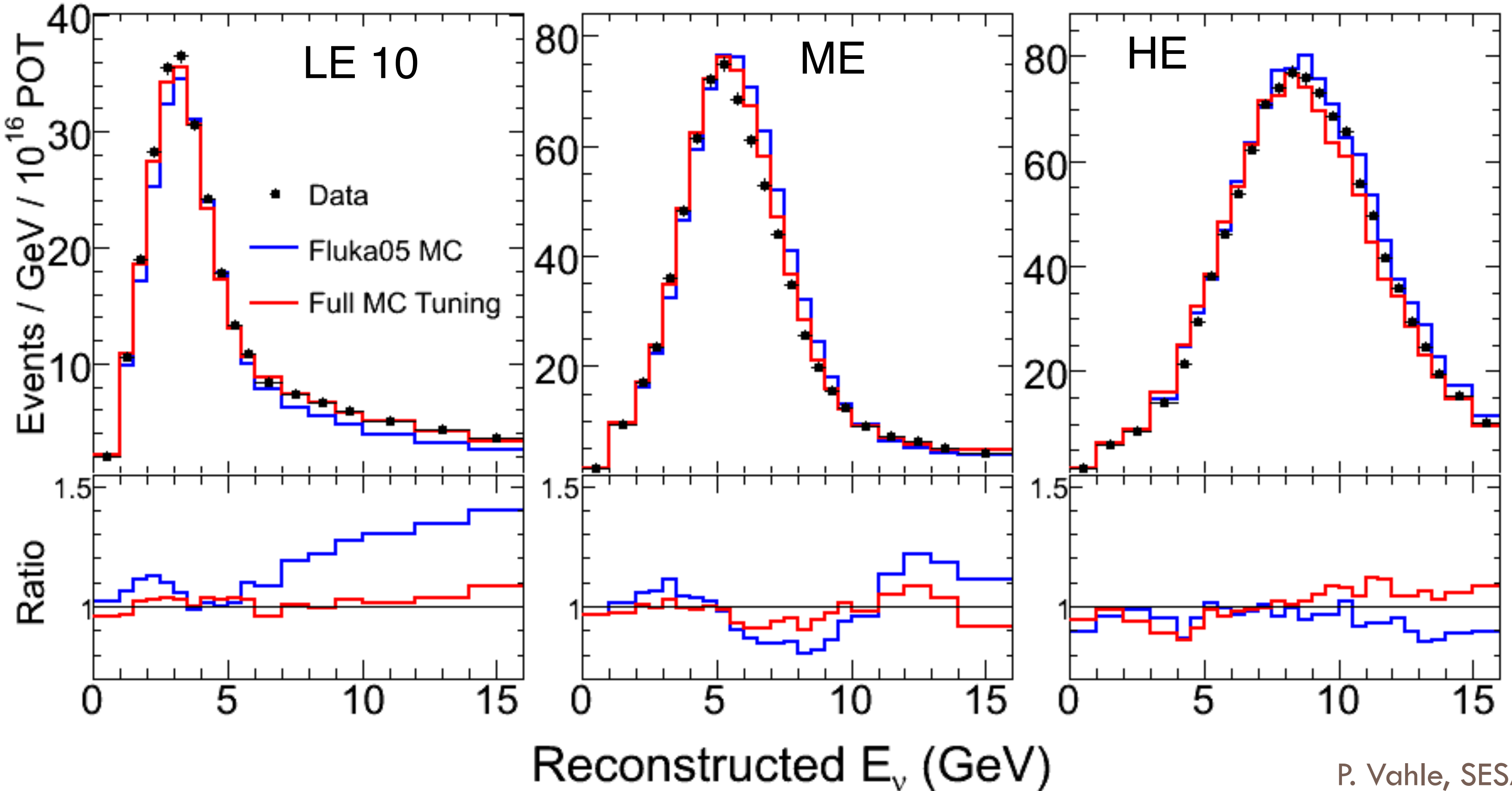
- long μ track, hadronic activity at vertex
- energy sum of muon energy (range or curvature) and shower energy

- short, diffuse shower
- energy from calorimetric response

- compact shower with EM core
- energy from calorimetric response

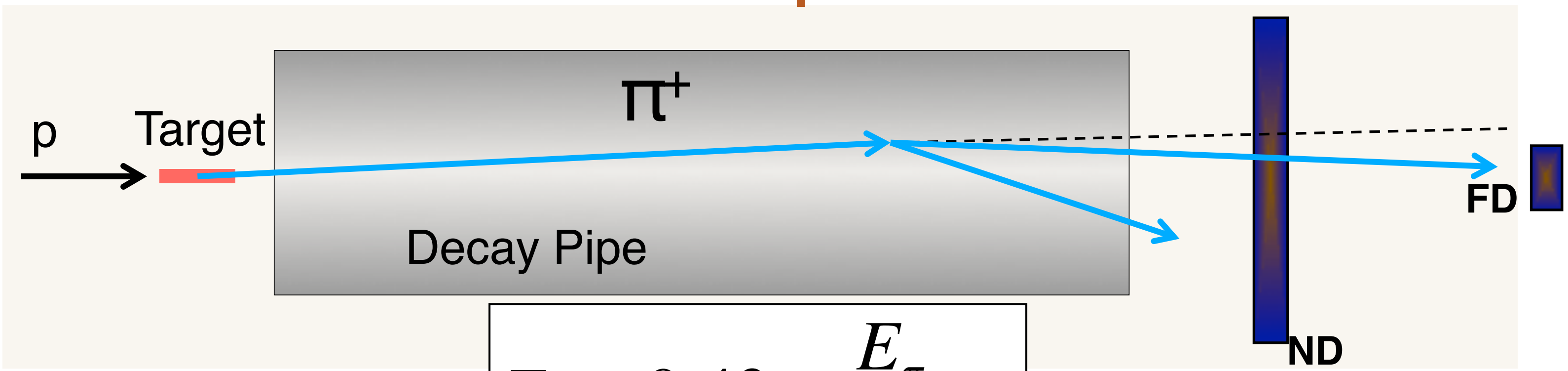
Neutrino Spectrum

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



Near to Far

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

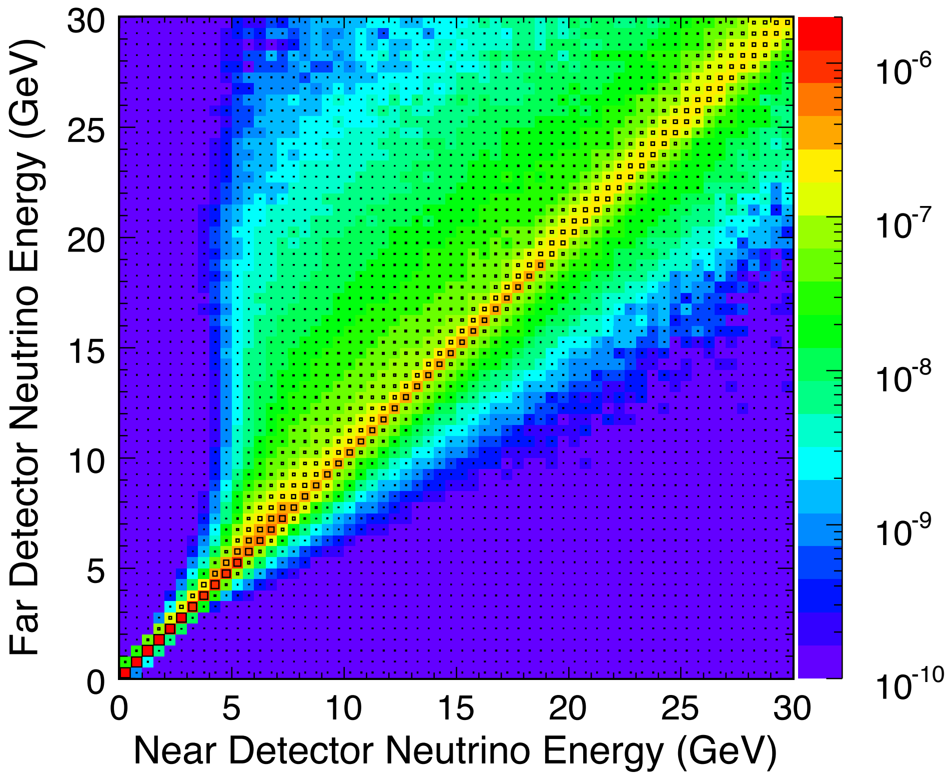


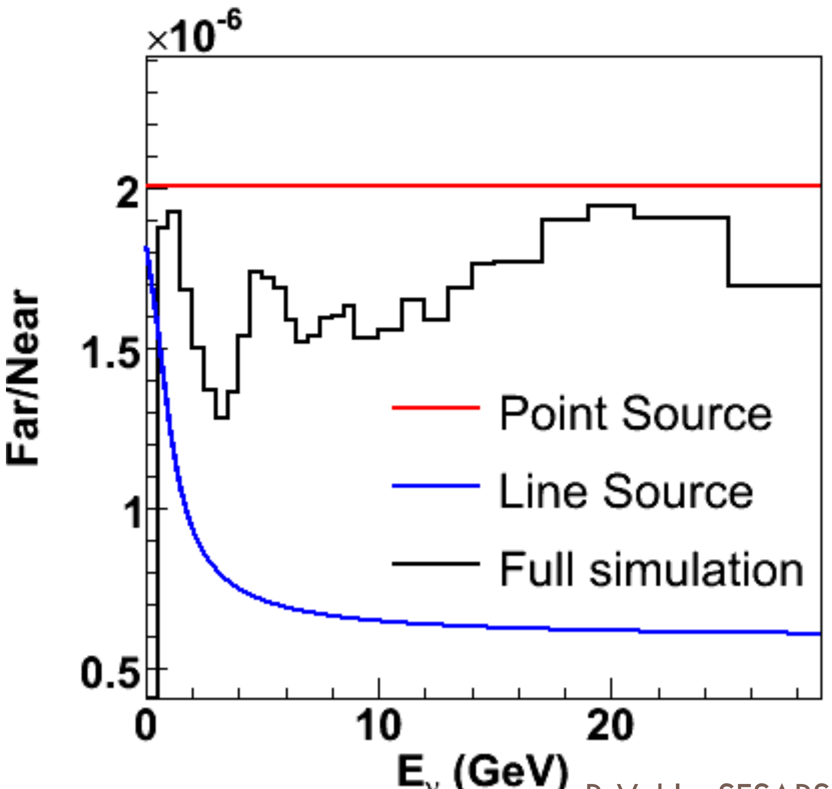
$$E_\nu \approx 0.43 \frac{E_\pi}{1+\gamma^2\theta_\nu^2}$$

- 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





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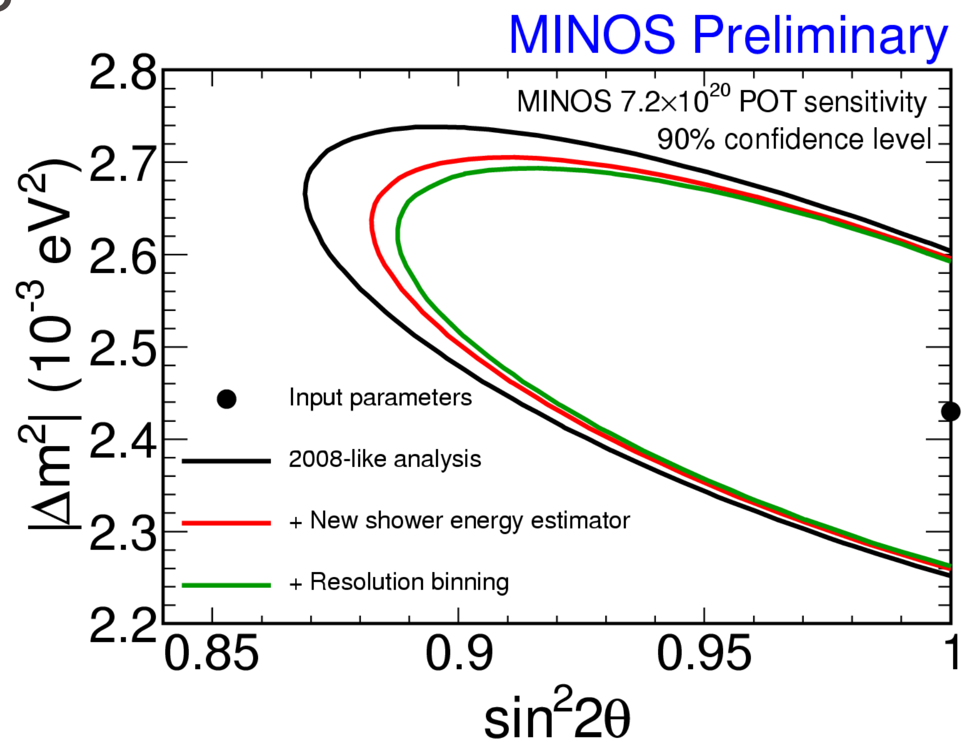
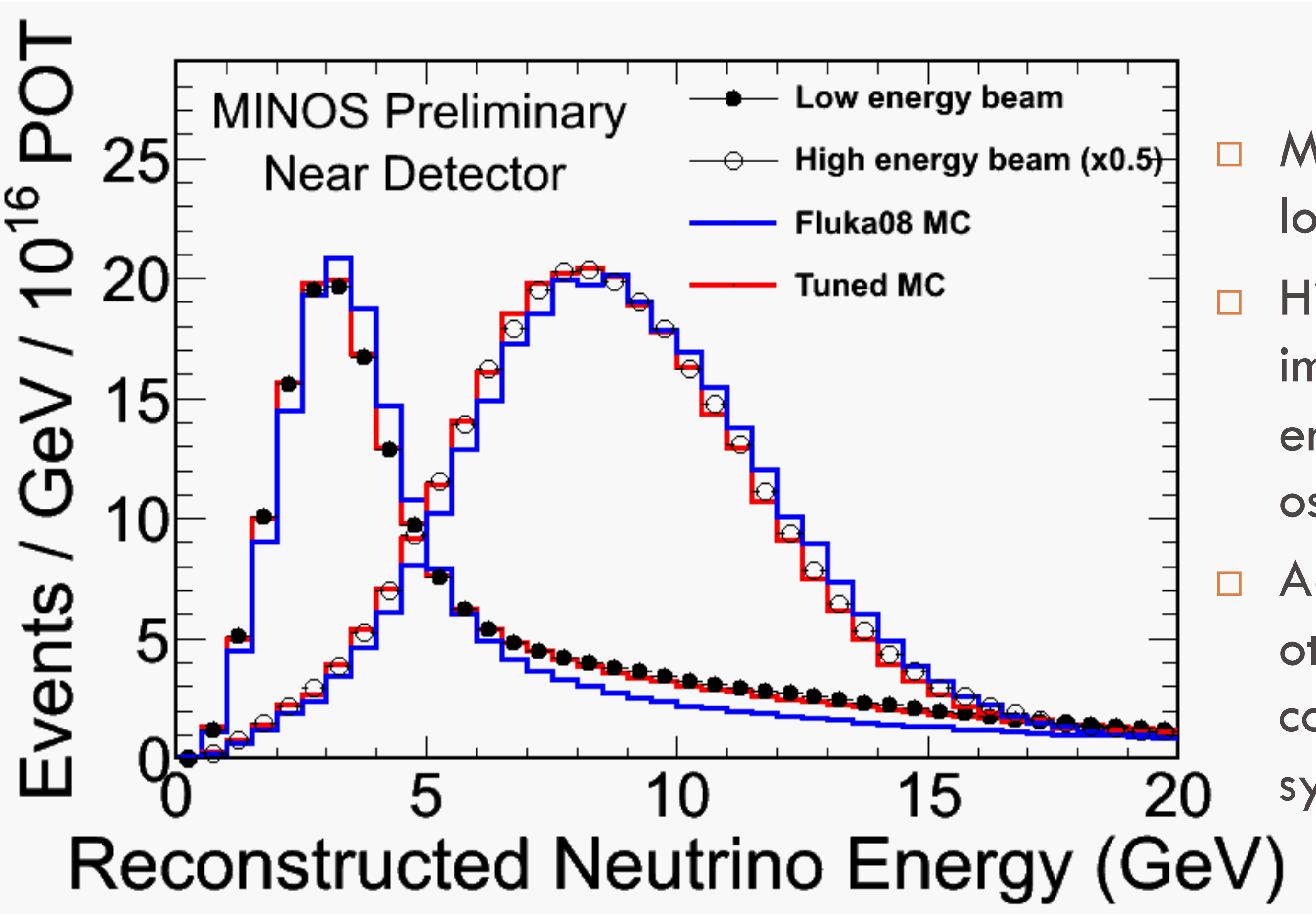
CCAnalysis Improvements

- Since PRL 101:131802, 2008
- Additional data
  - $3.4 \times 10^{20} \rightarrow 7.2 \times 10^{20}$ 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



CC events in the Near Detector



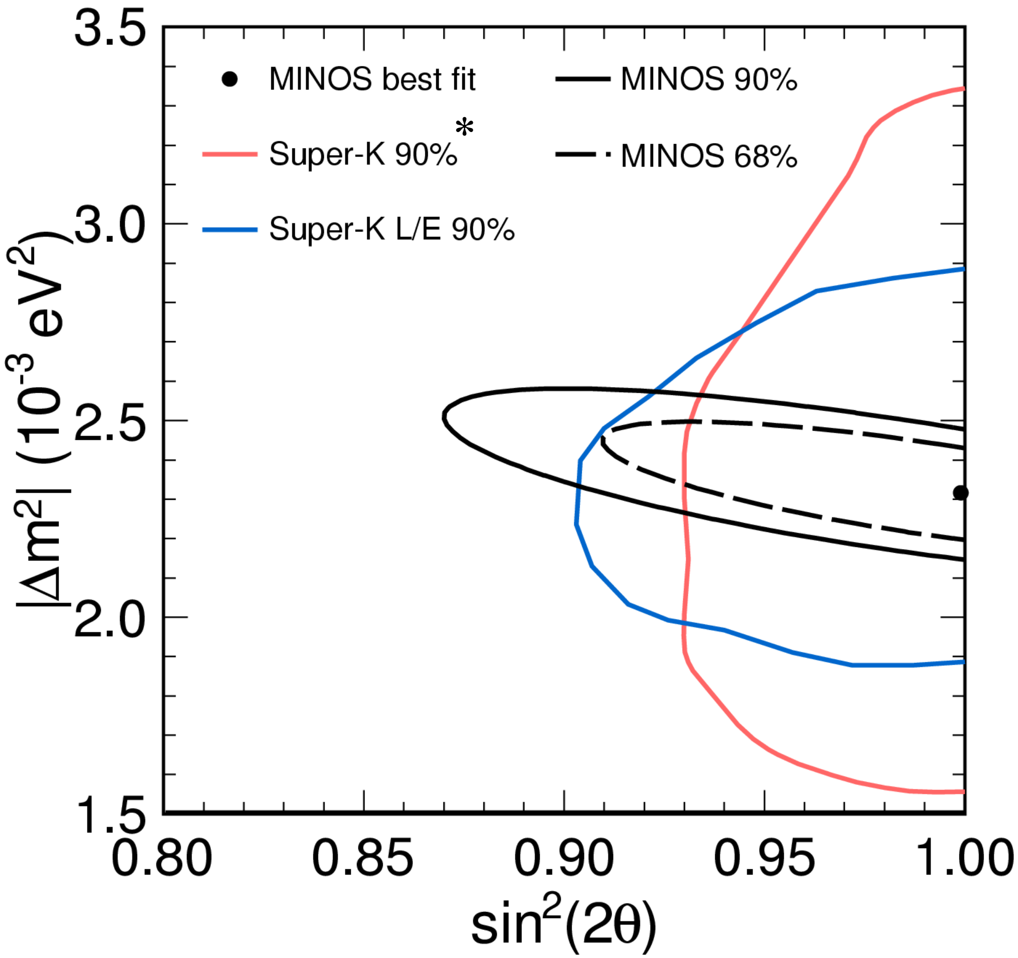
- Majority of data from low energy beam
- High energy beam improves statistics in energy range above oscillation dip
- Additional exposure in other configurations for commissioning and systematics studies

Contours

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

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

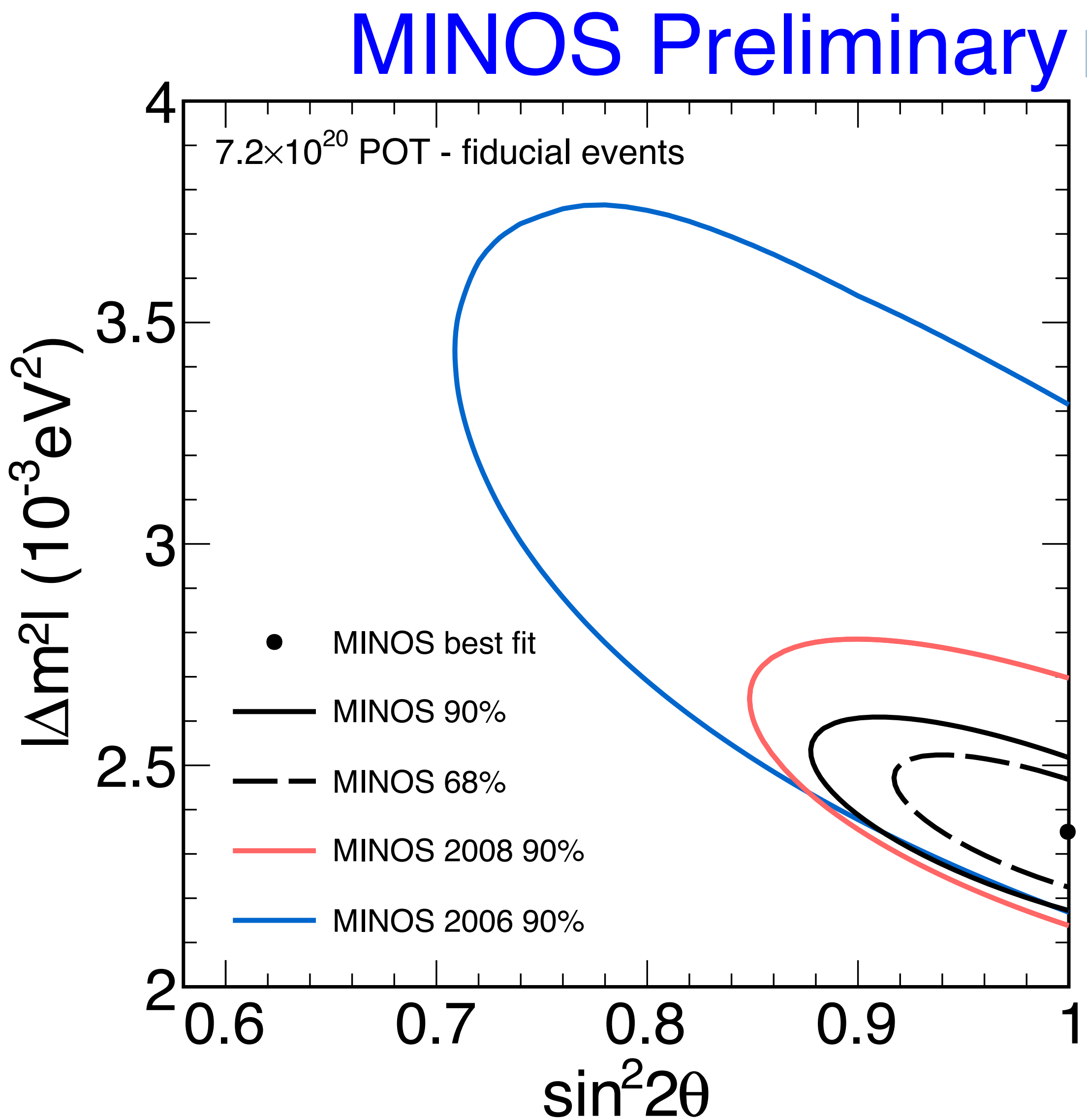
- Pure decoherence† disfavored at **9σ**
- Pure decay‡ disfavored at **7σ**



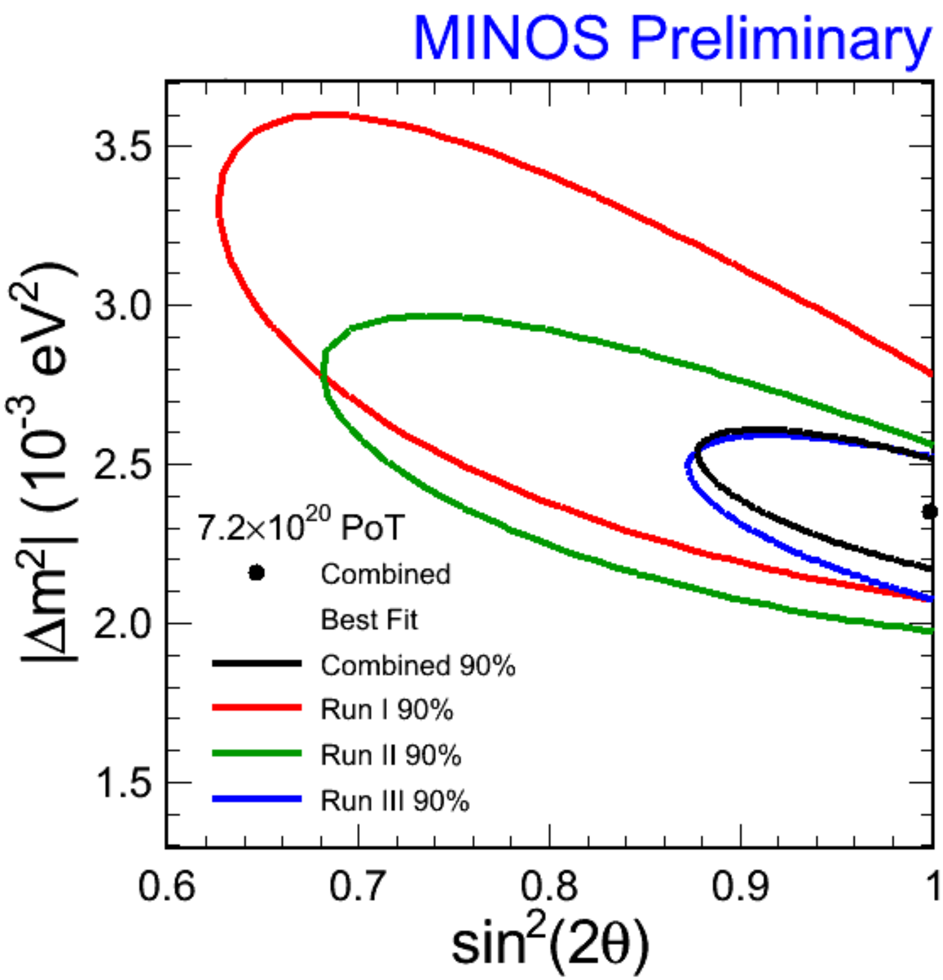
†G.L. Fogli *et al.*, PRD 67:093006 (2003)
‡V. Barger *et al.*, PRL 82:2640 (1999)
*J. Hosaka et al., Phys. Rev. D 74, 032002 (2006)

Contours

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

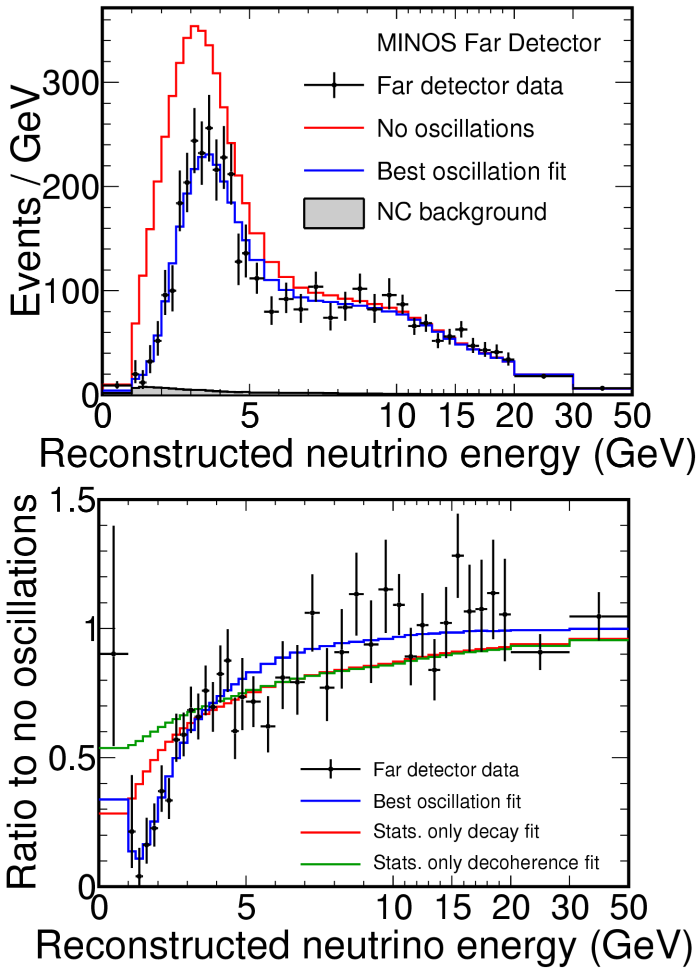


Contours by Run Period



ν_μ Disappearance

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



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

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

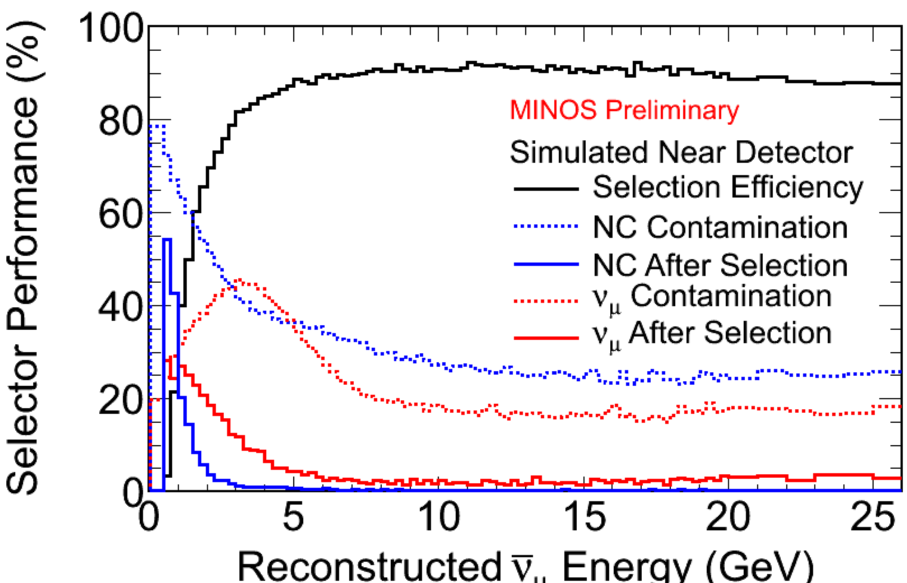
$$\sin^2(2\theta) > 0.90\ (90\%\ \mathrm{C.L.})$$

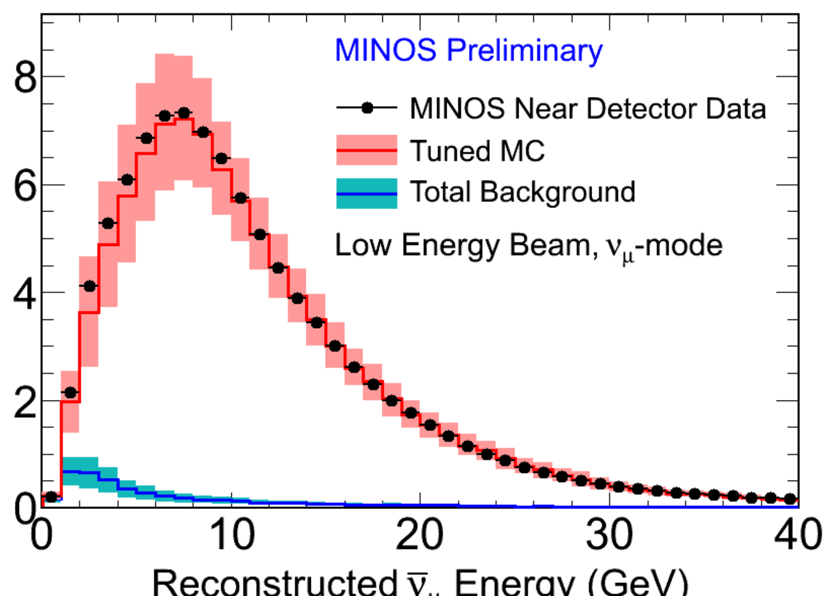
- Oscillations fit the data well, 66% of experiments have worse χ^2
- Pure decoherence† disfavored at **9σ**
- Pure decay‡ disfavored at **7σ**

†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)

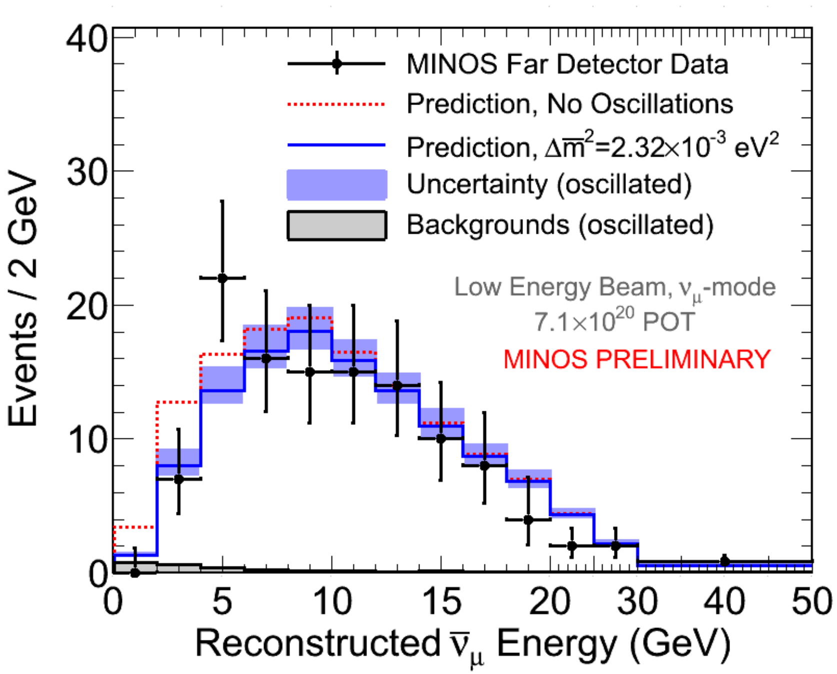
Anti-neutrino Disappearance

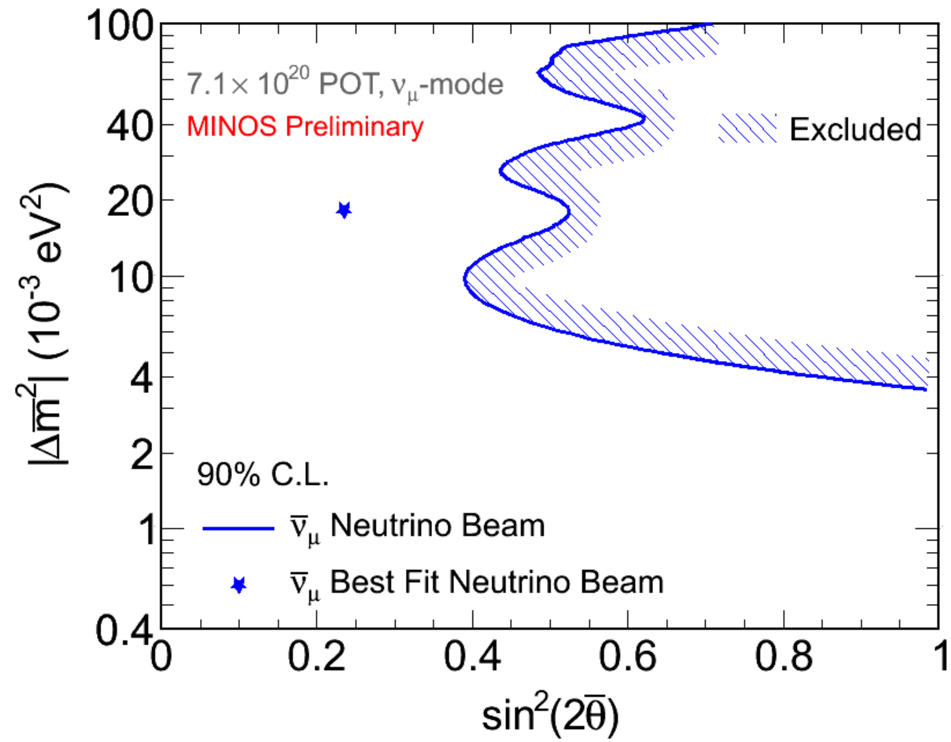
- Measure oscillations using 7% anti-neutrino component of the neutrino beam
- Peaked at higher energies
- Selection efficiency 90%, purity 95%





Anti-neutrino Disappearance



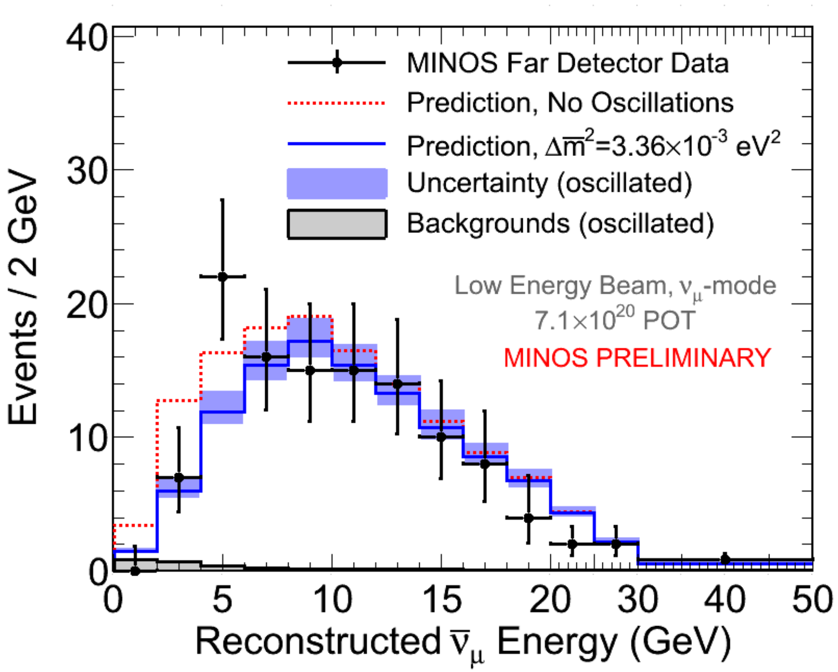


No Oscillations:	$150.3^{+16.3}_{-18.2}$
With Oscillations:	$136.4^{+15.2}_{-14.9}$
Observed:	130

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

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

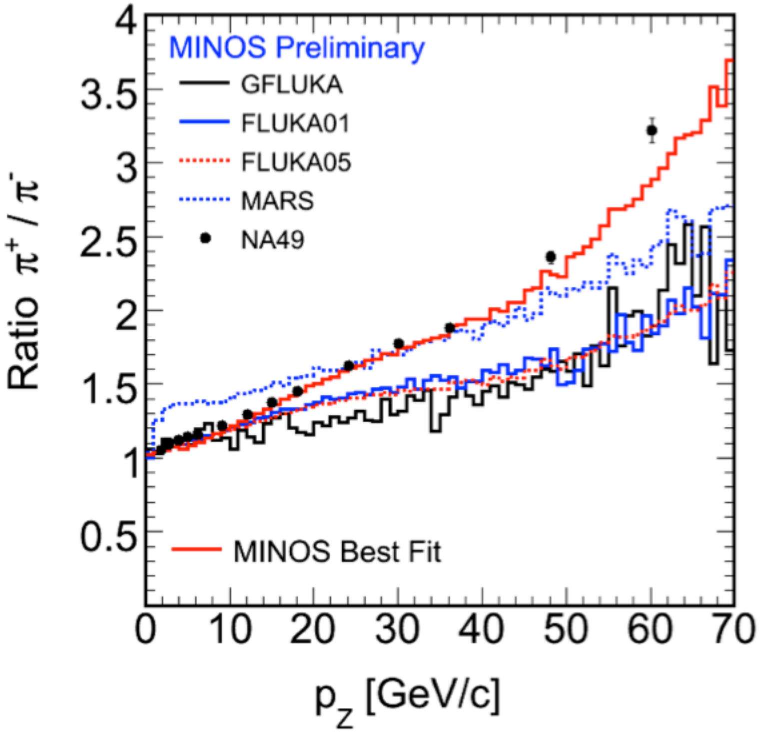
Anti-neutrino Disappearance

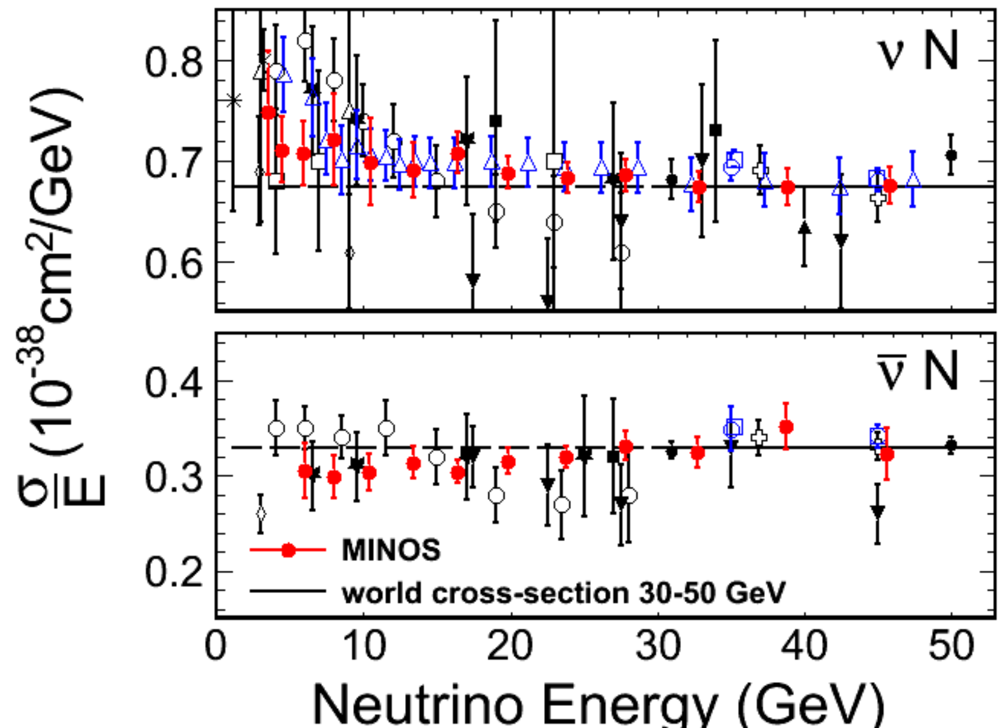


Making an antineutrino beam

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

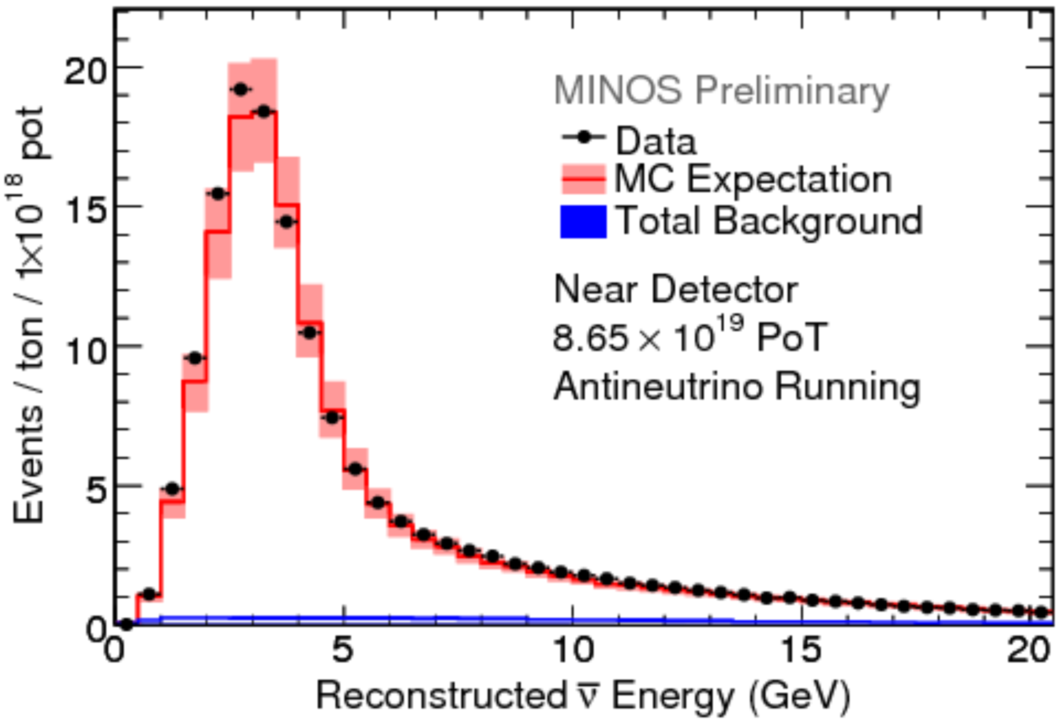
~3x fewer antineutrinos for the same exposure



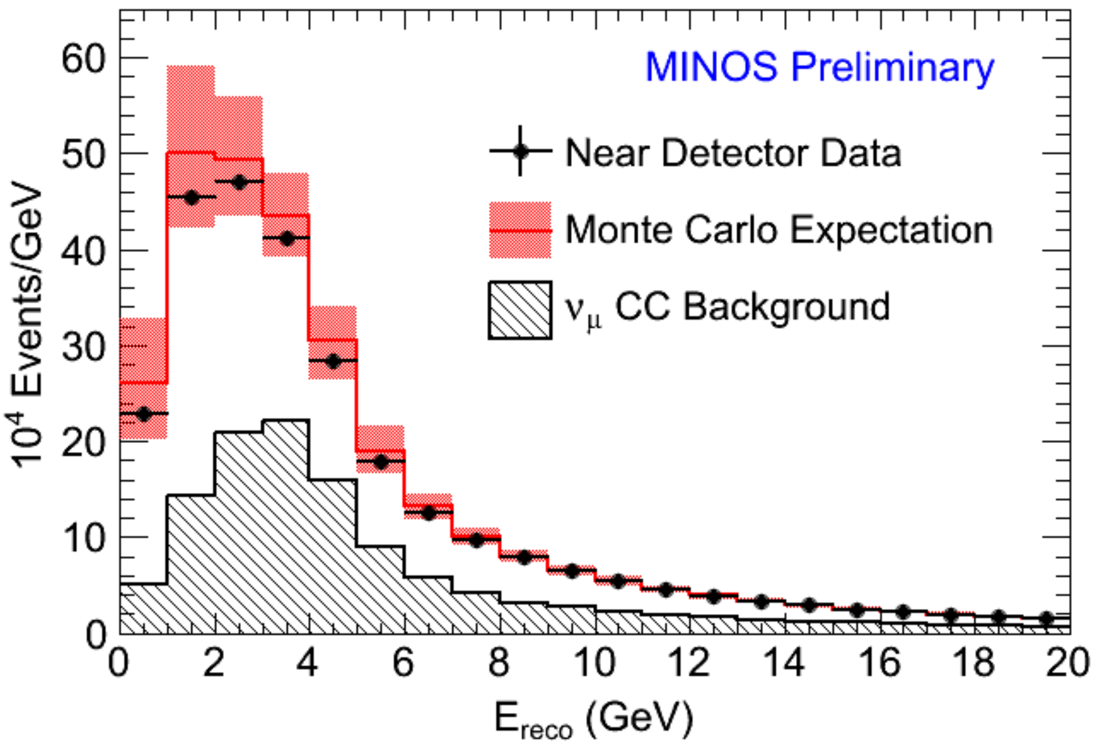


ND Anti-neutrino Data

- 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



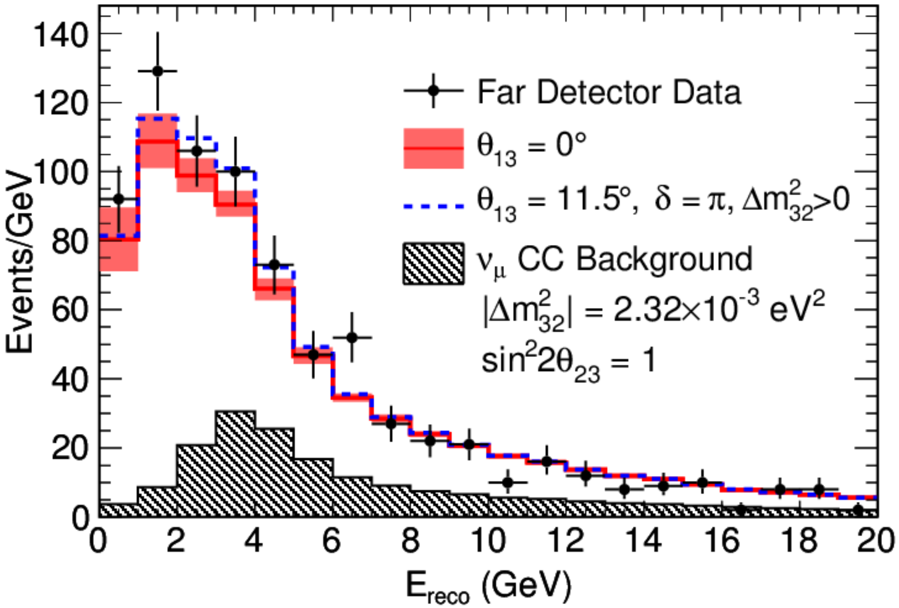
Neutral Current Near Event Rates



- 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

- Neutral Current event rate should not change in standard 3 flavor oscillations

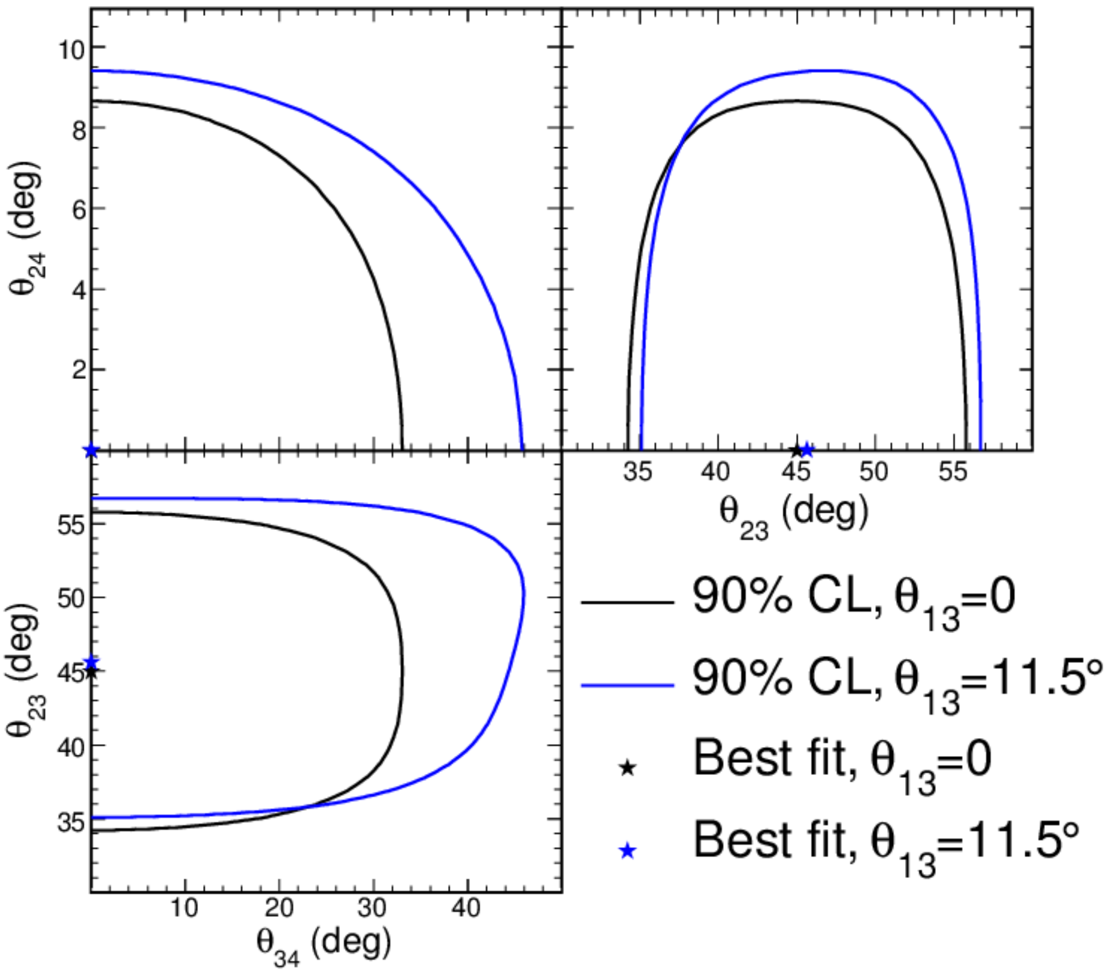


- Expect: **757** events
- Observe: **802** events
- No deficit of NC events

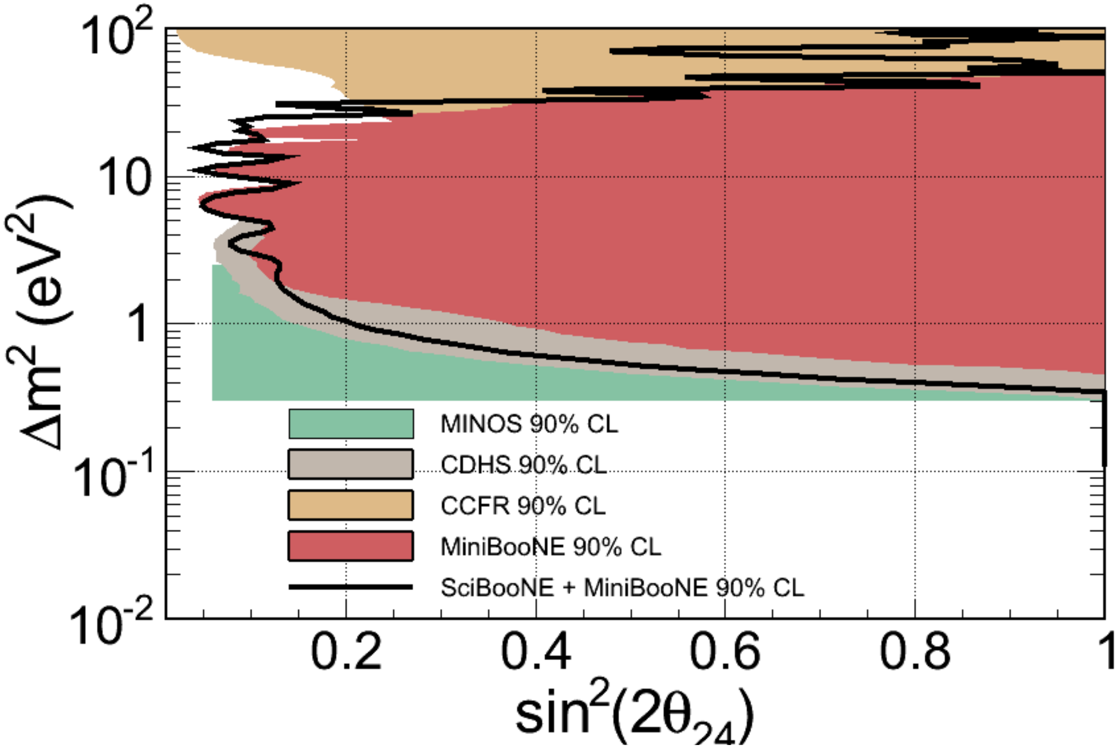
$$f_s \equiv \frac{P_{\nu_\mu \to \nu_s}}{1 - P_{\nu_\mu \to \nu_\mu}} < 0.22\ \ (0.40)\text{ at }90\%\text{ C.L.}$$

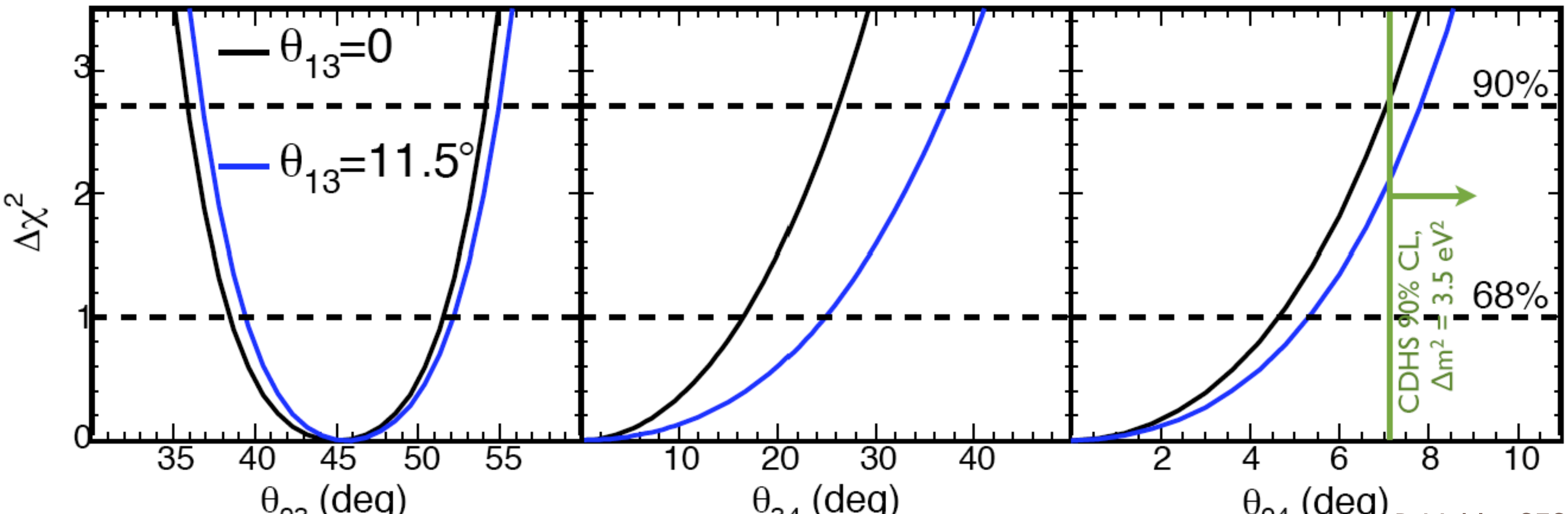
no (with) ν_e appearance

Fits to NC



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





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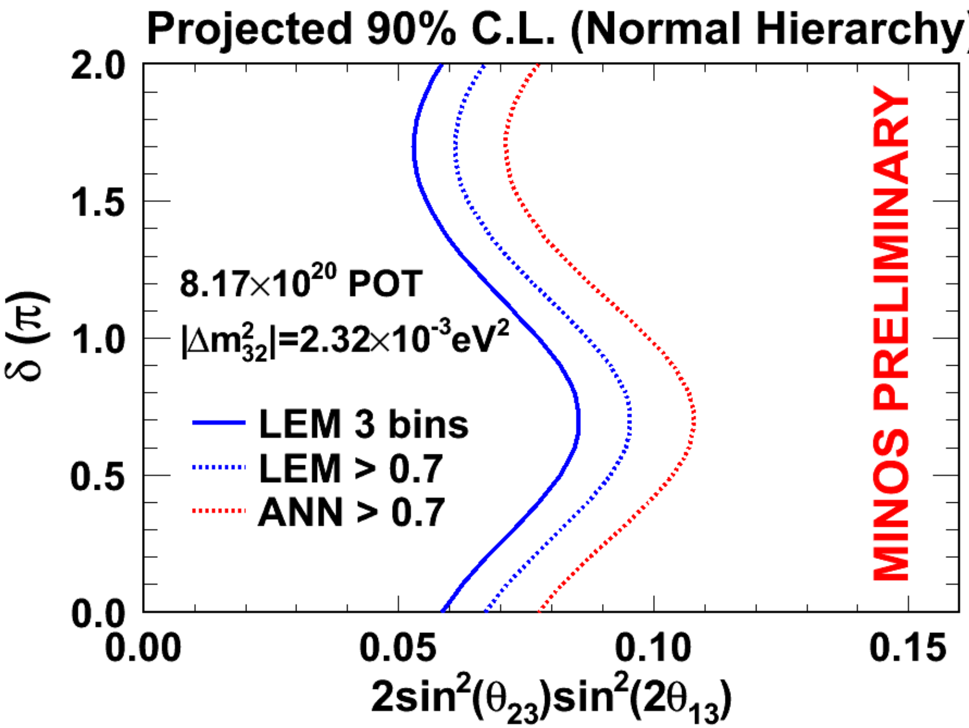
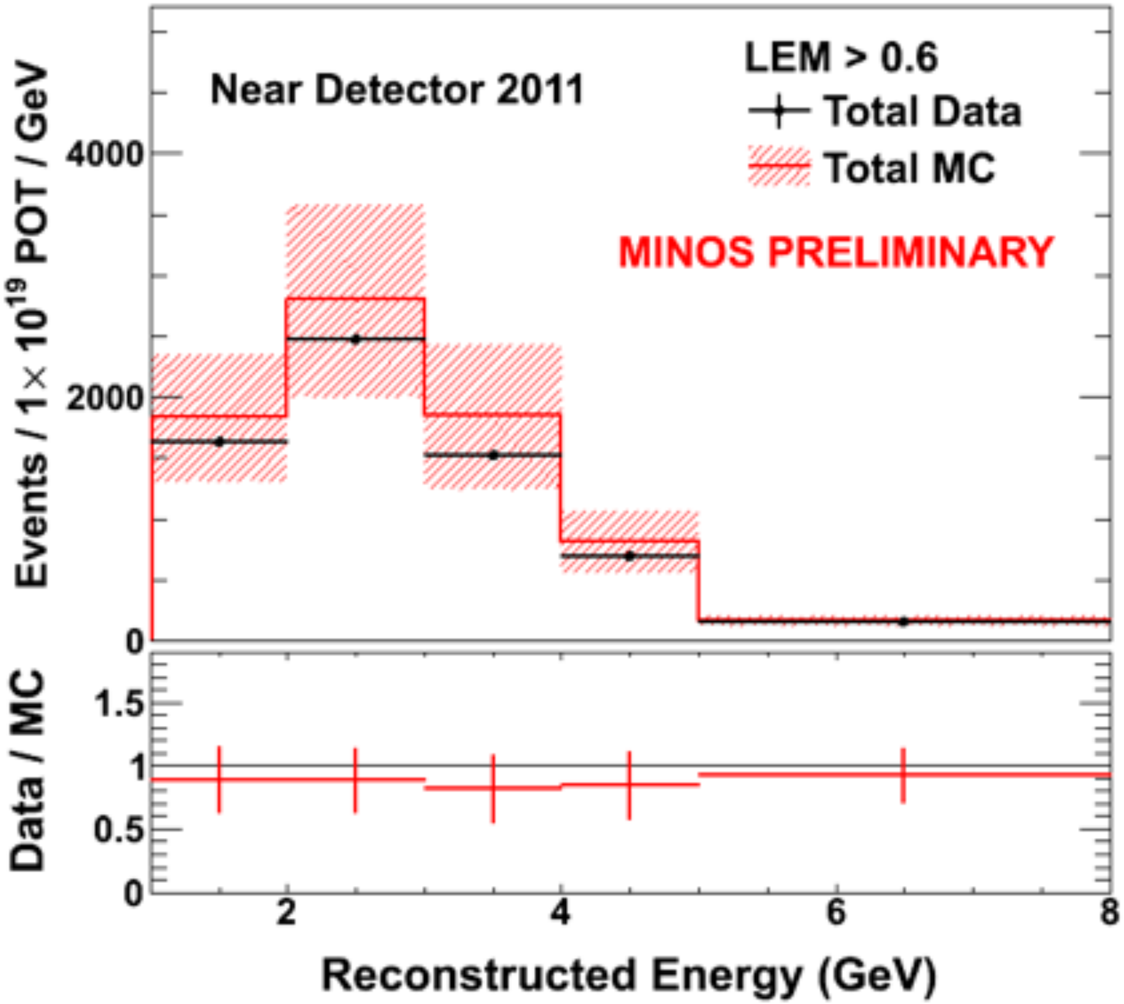
The Updated Analysis

- 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



Near Detector Data

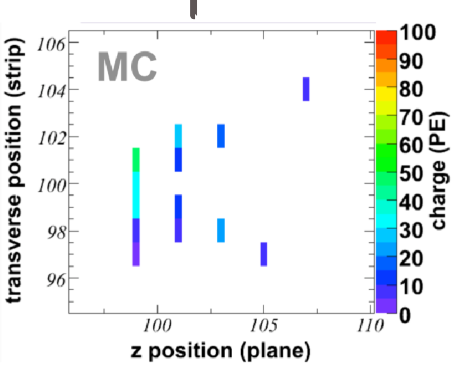


- ND data sample comprised of NC, ν_μ CC, beam ν_e CC interactions.
- Each propagates to the FD in a different manner
- Must determine relative composition of ND spectrum

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)

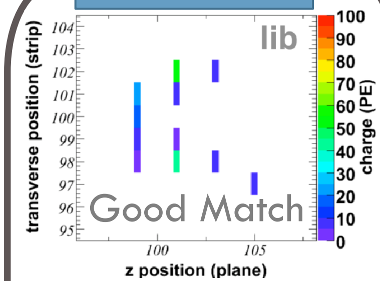


Compare to MC Library

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

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

Library Event #1

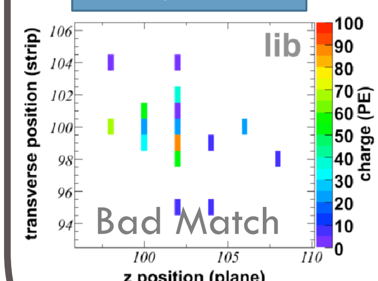


Library Event #2

Library Event #3

. . .

Library Event #k



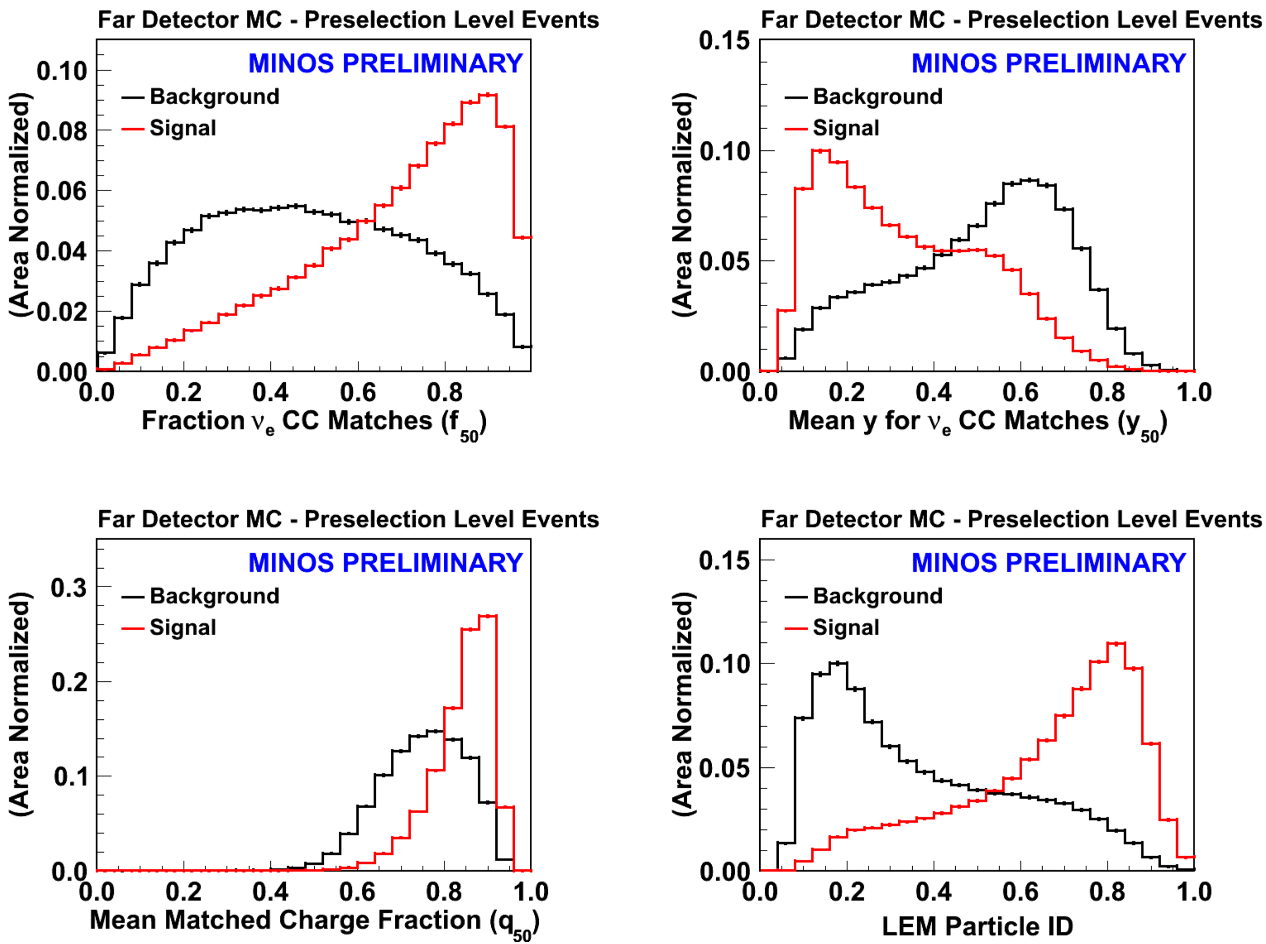
. . .

Library Event #30M

Compute variables using information from best N matches

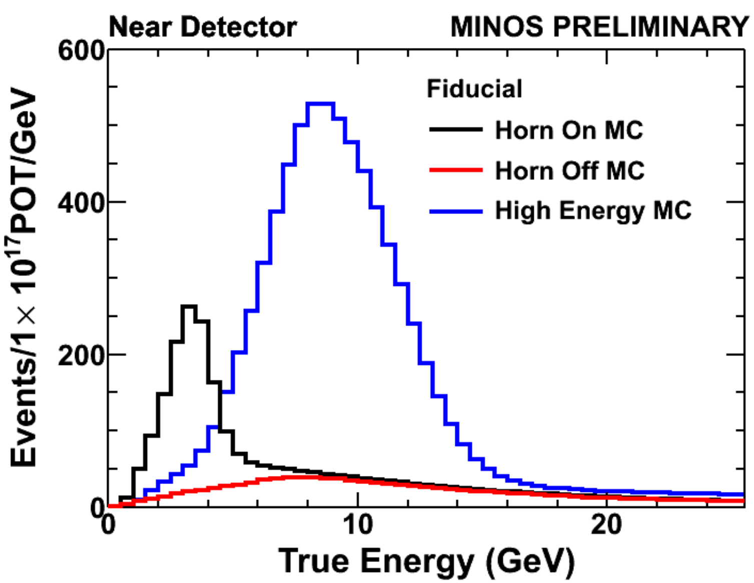
Discriminating Variables

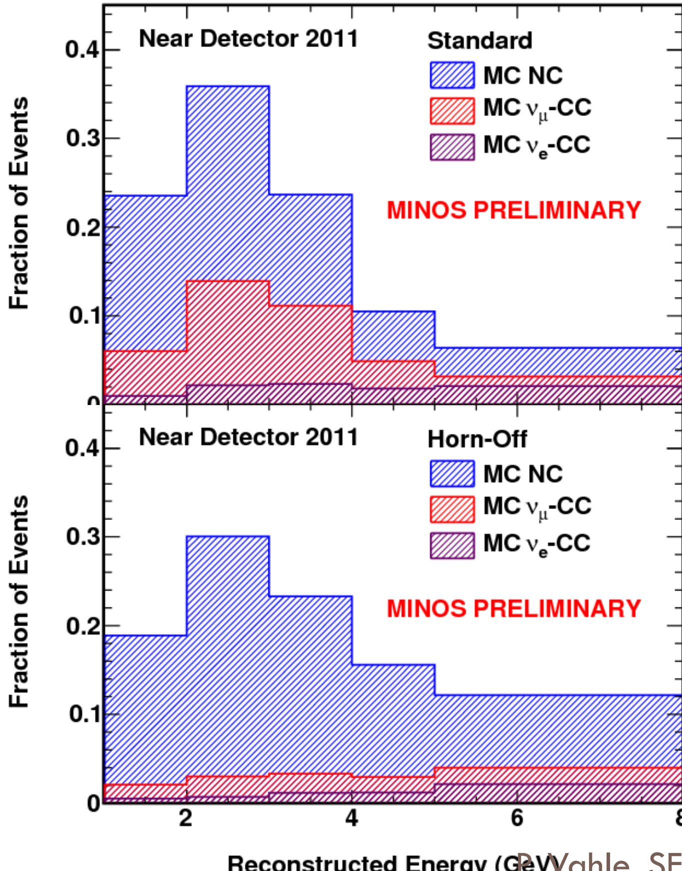
- Three discriminating variables combined in neural net
- Achieve ~40% signal efficiency, ~98% BG rejection



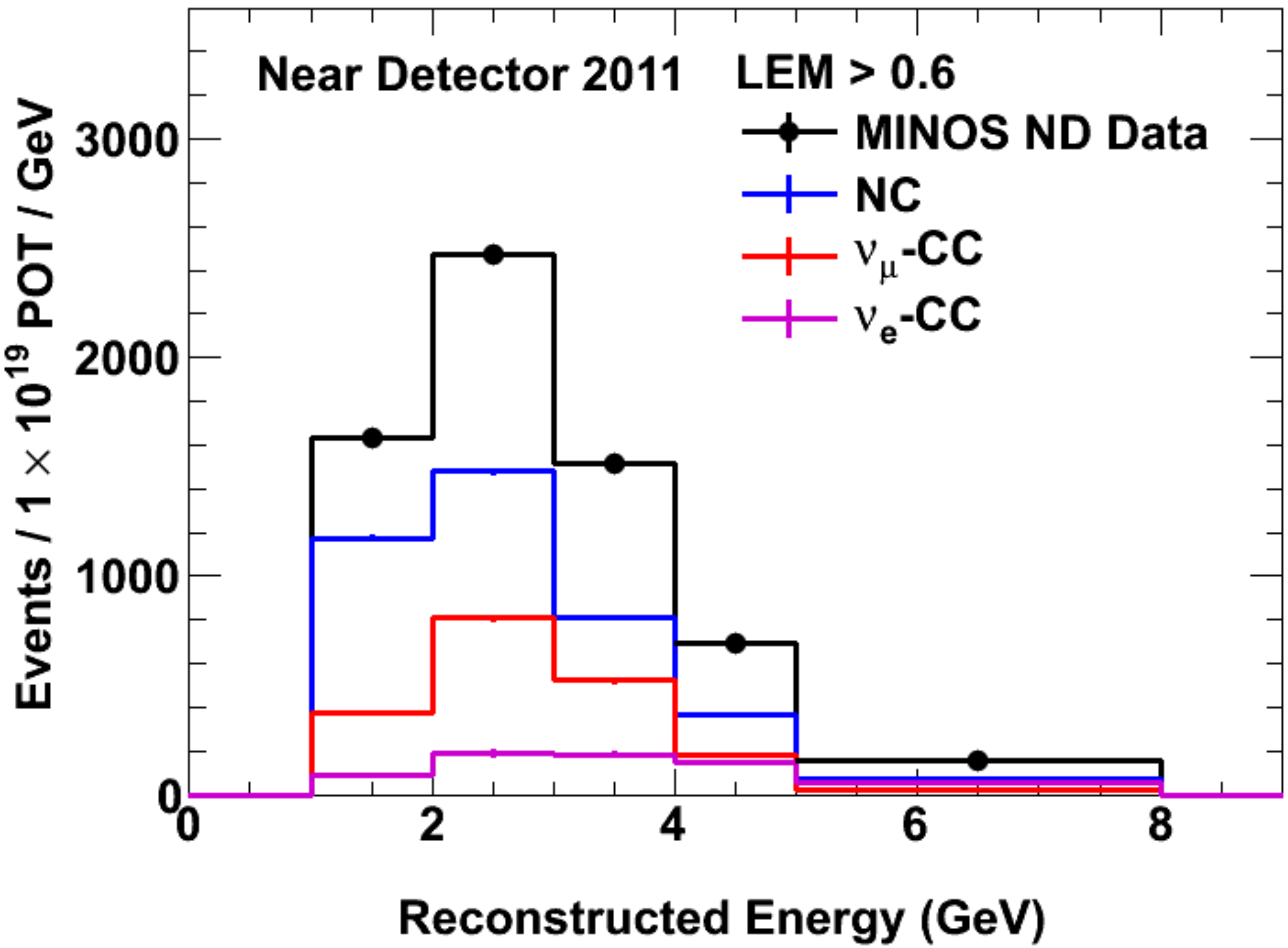
Measuring the Background

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



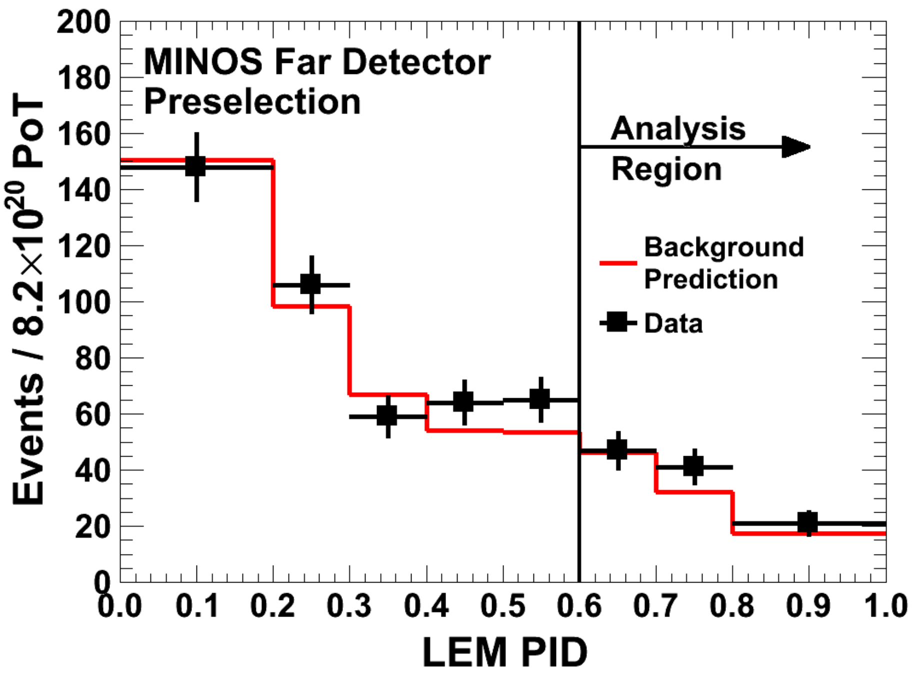


Decomposition



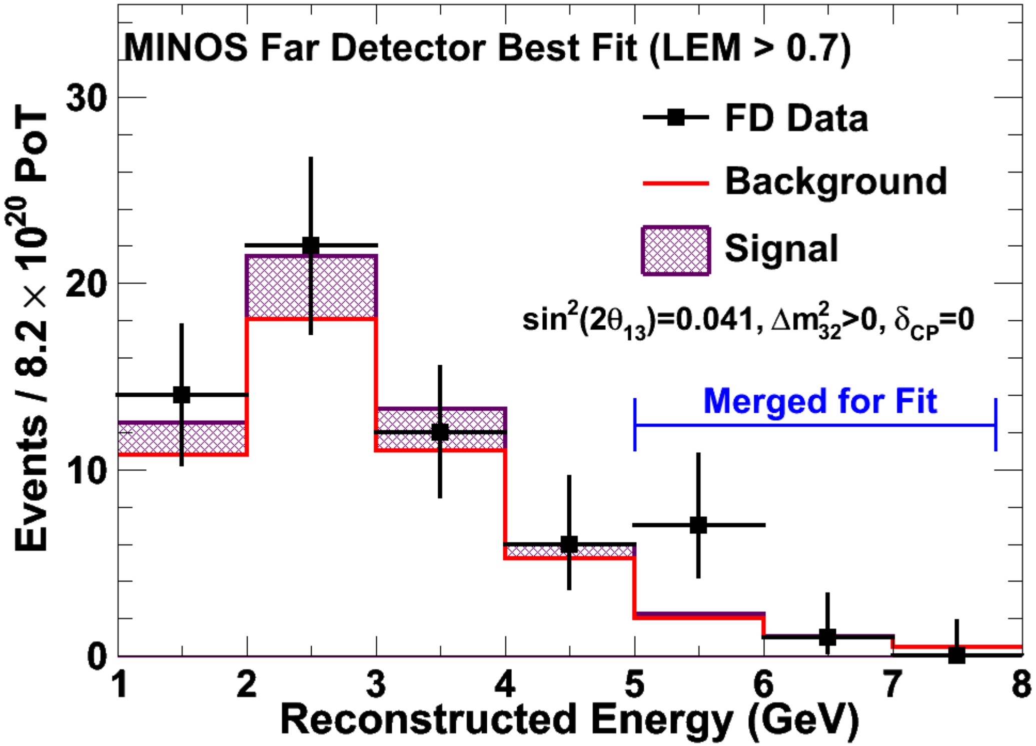
ν_e Appearance Results

- In signal enhanced region, based on ND data, expect: **49.6±7.0(stat.)±2.7(syst.)**
- Observe: **62** events in the FD



FD Data

- Energy spectrum for signal enhanced region



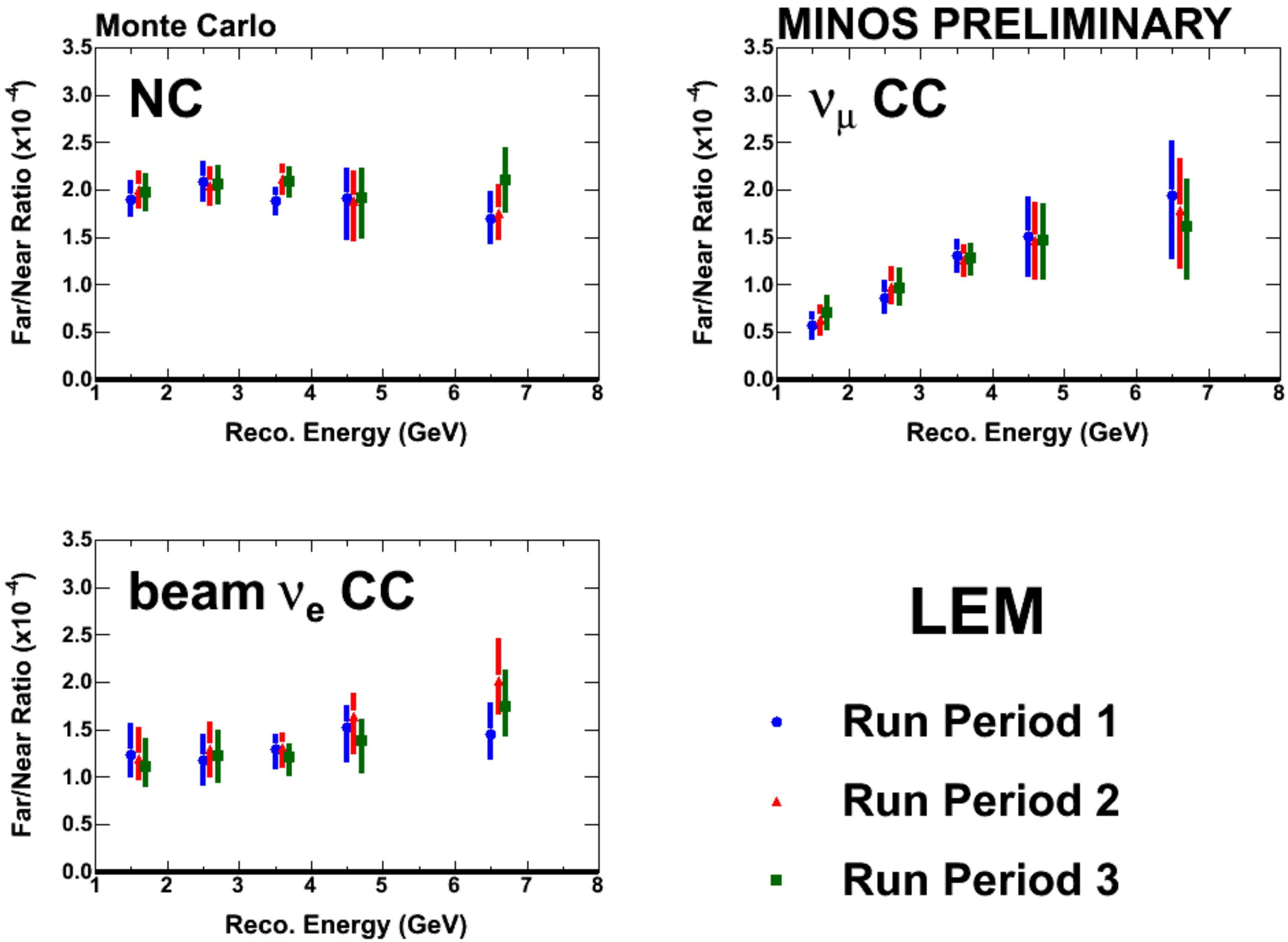
Electron-neutrino Systematics

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

Uncertainty source	Uncertainty on background events
Event energy scale	4.0%
ν_τ background	2.1%
Relative FD/ND rate	1.9%
Hadronic shower model	1.1%
All others	2.0%
Total	5.4%

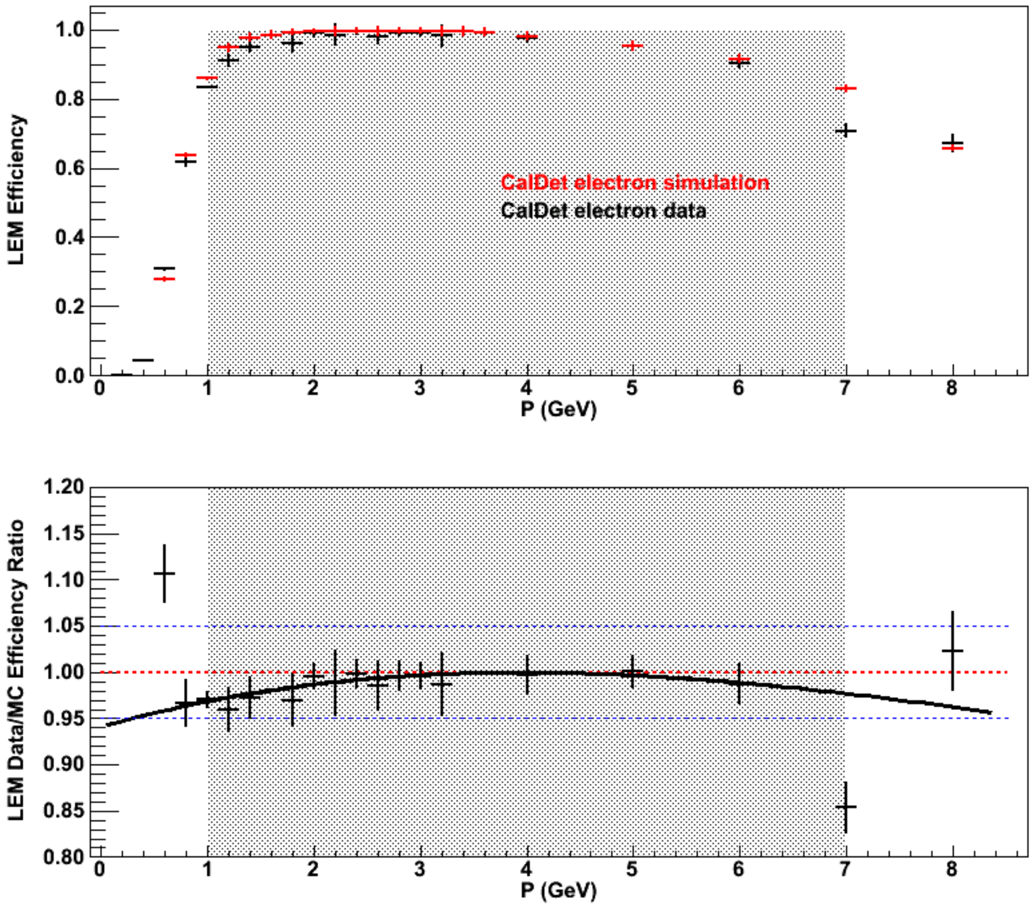
TABLE I: Systematic uncertainties on the number of predicted background events in the FD in the signal region, defined by LEM>0.7. The final θ_{13} measurement uses multiple LEM and reconstructed energy bins and thus uses a full systematics covariance matrix. These uncertainties, which are small compared to the statistical errors, lead to a 7.0% loss in sensitivity to $\sin^2(2\theta_{13})$. The "All others" category includes uncertainties relating to the neutrino flux, cross sections, detector modeling, and background decomposition.

Electron-neutrino F/N ratios



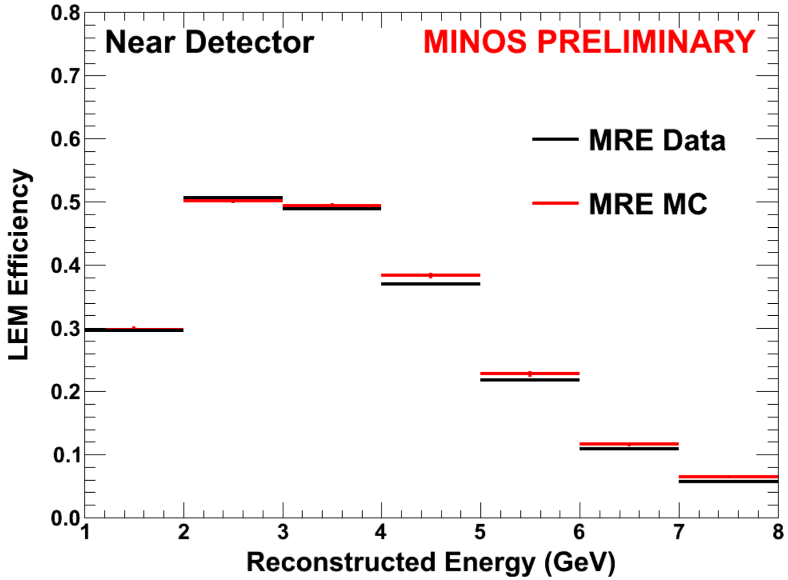
Checking Signal Efficiency

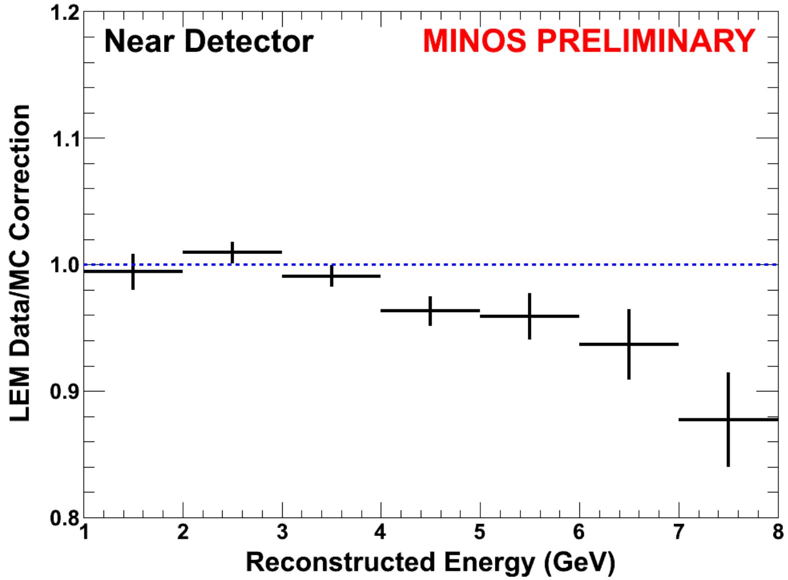
- Test beam measurements demonstrate electrons are well simulated



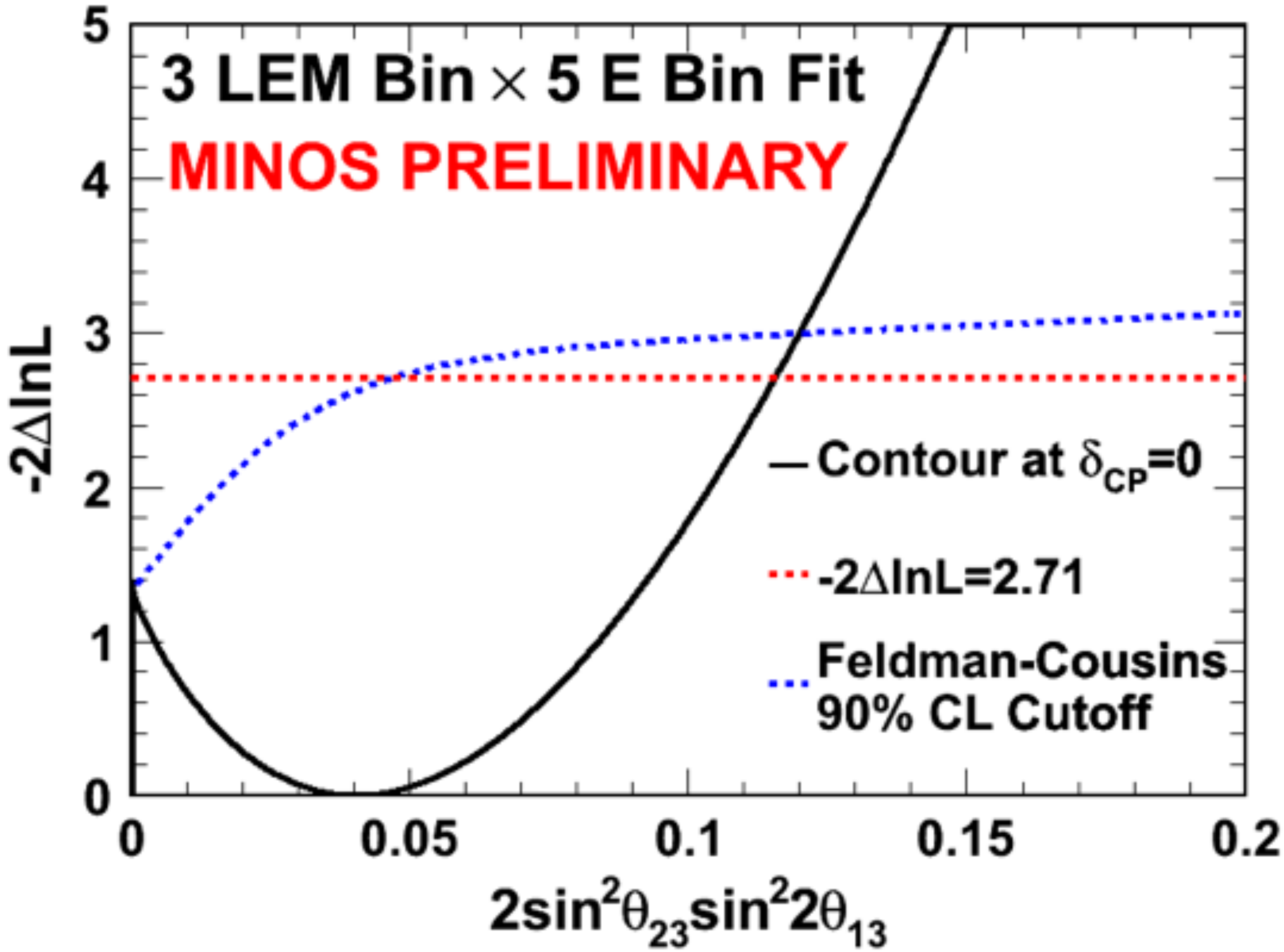
Checking Signal Efficiency

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

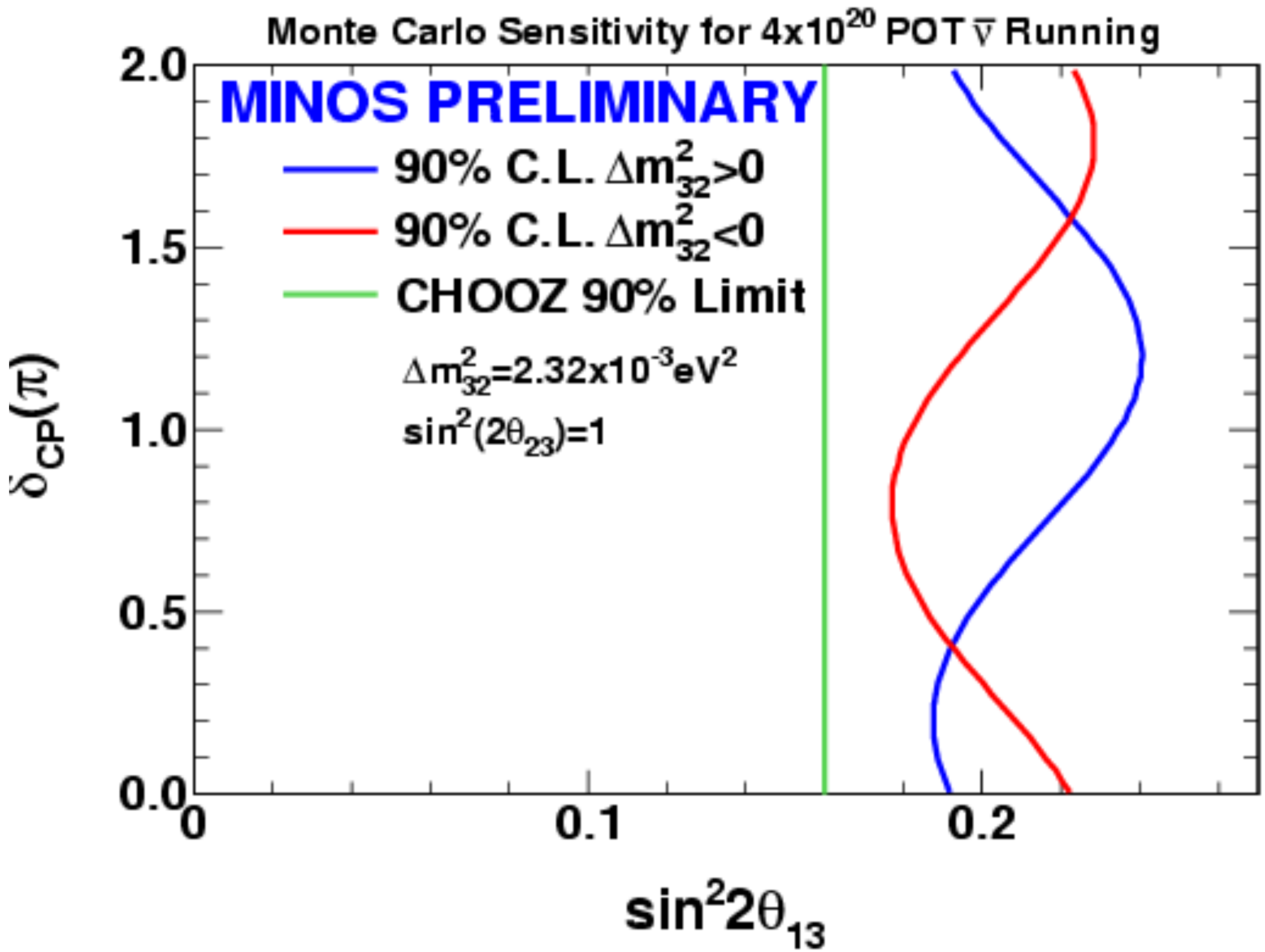




Feldman-Cousins Effect



electron anti-neutrino appearance



Combined fits

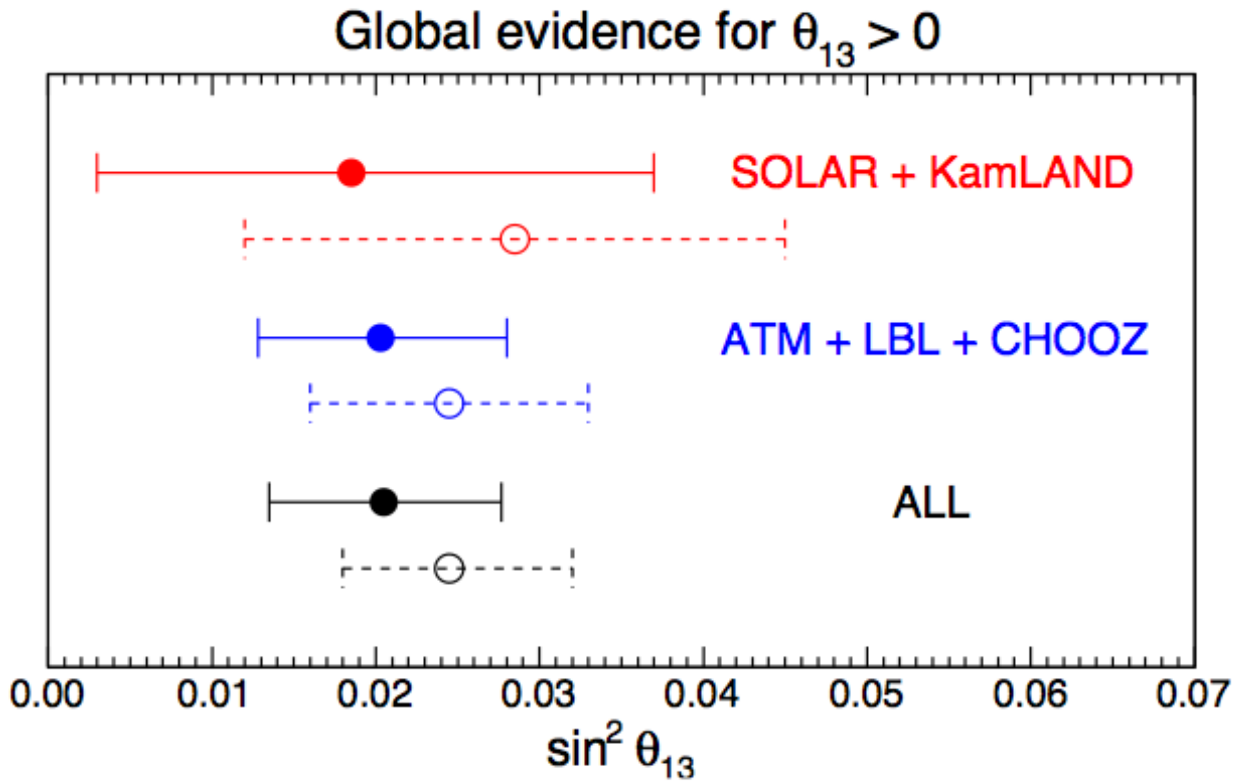


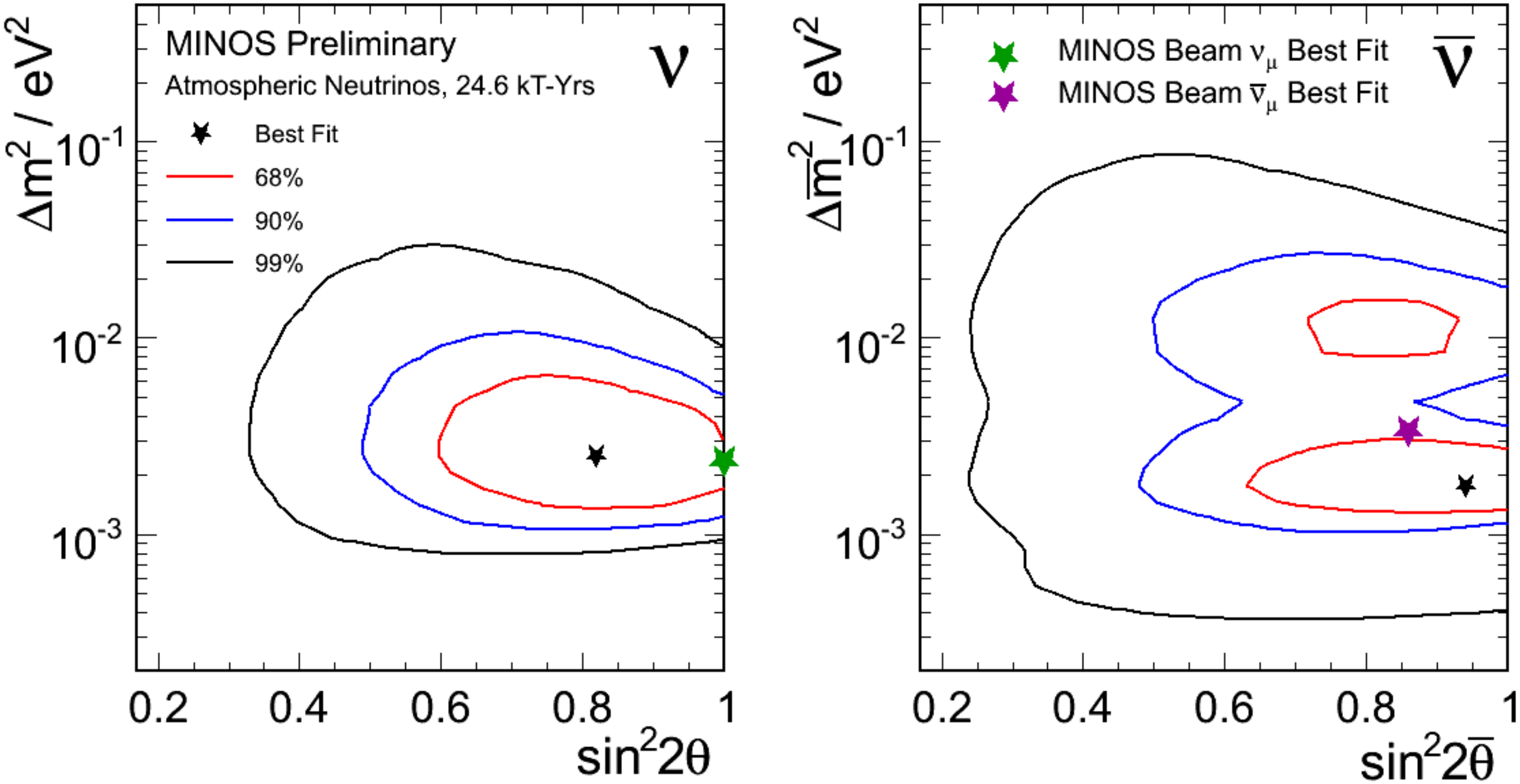
FIG. 3: Global 3ν analysis. Preferred $\pm 1\sigma$ ranges for the mixing parameter $\sin^2\theta_{13}$ from partial and global data sets. Solid and dashed error bars refer to old and new reactor neutrino fluxes, respectively.

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)		

Atmospheric Neutrinos



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

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

Seasonal Muon Variation

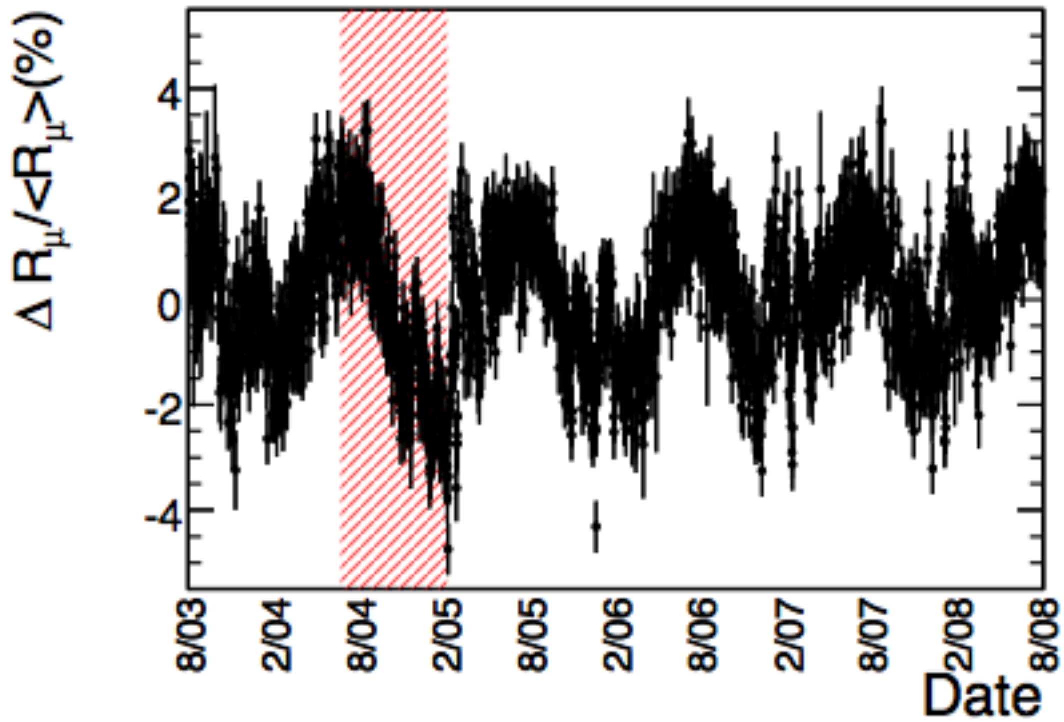
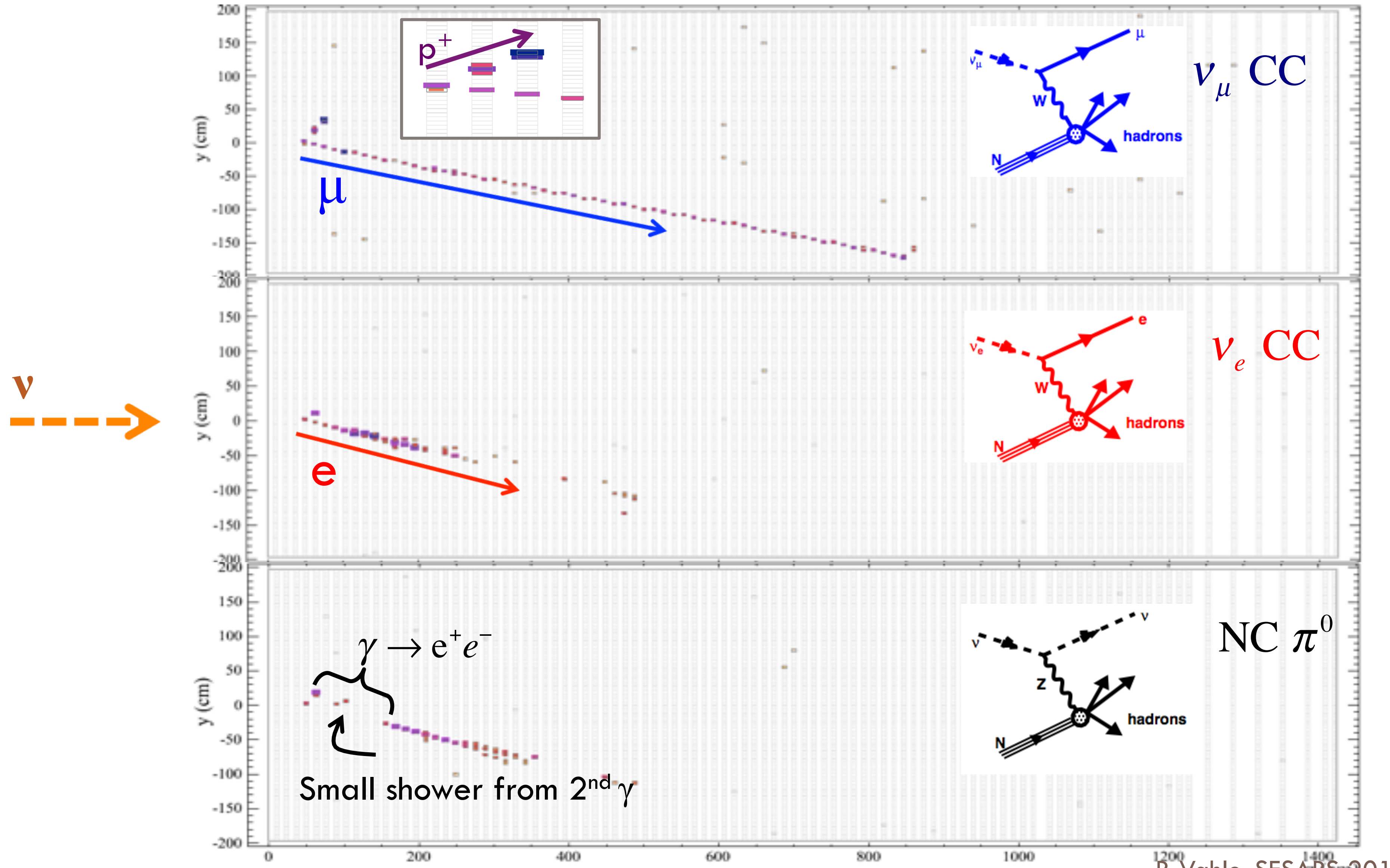


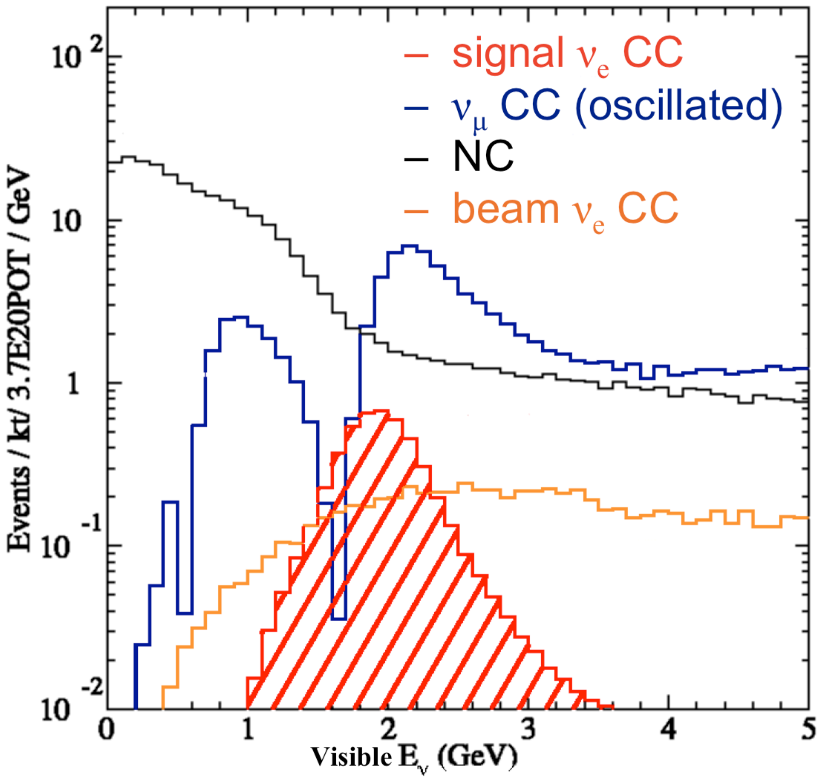
FIG. 4: The daily deviation from the mean rate of cosmic ray muon arrivals from 8/03-8/08, shown here with statistical error bars. The periodic fluctuations have the expected maxima in August, minima in February. The hatched region indicates the period of time when the detector ran with the magnetic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

NOvA backup

MC Events in NOvA



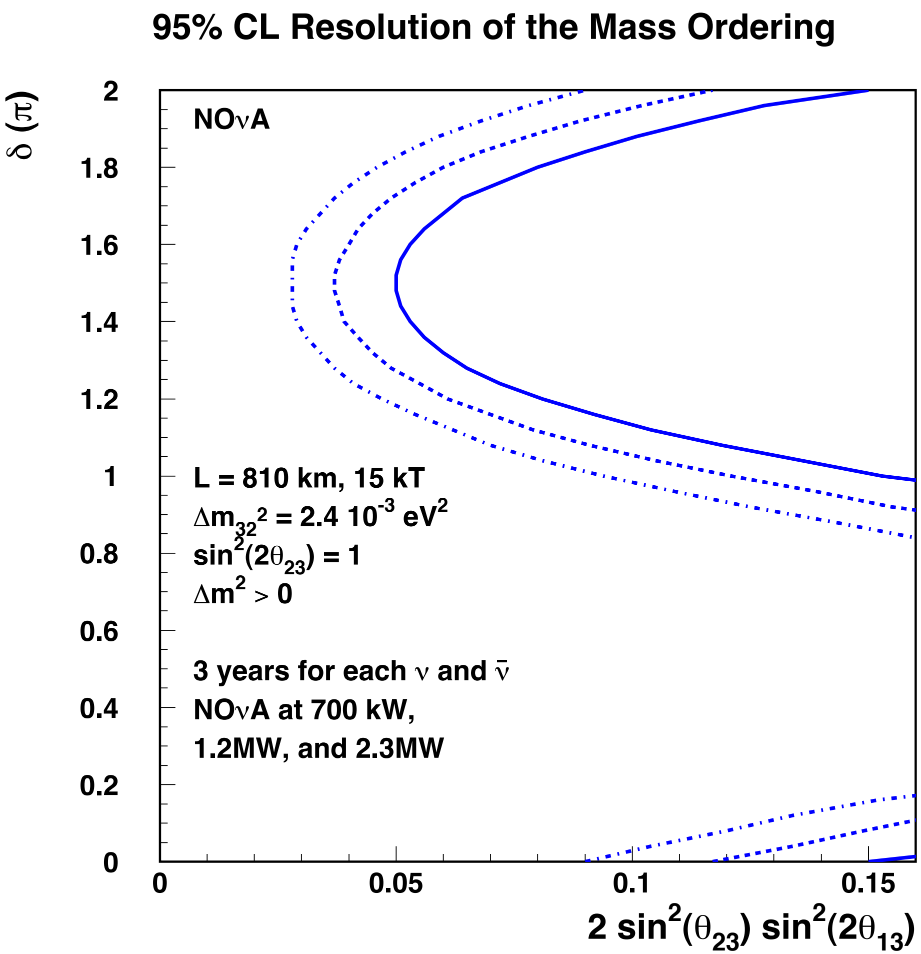
Case Study

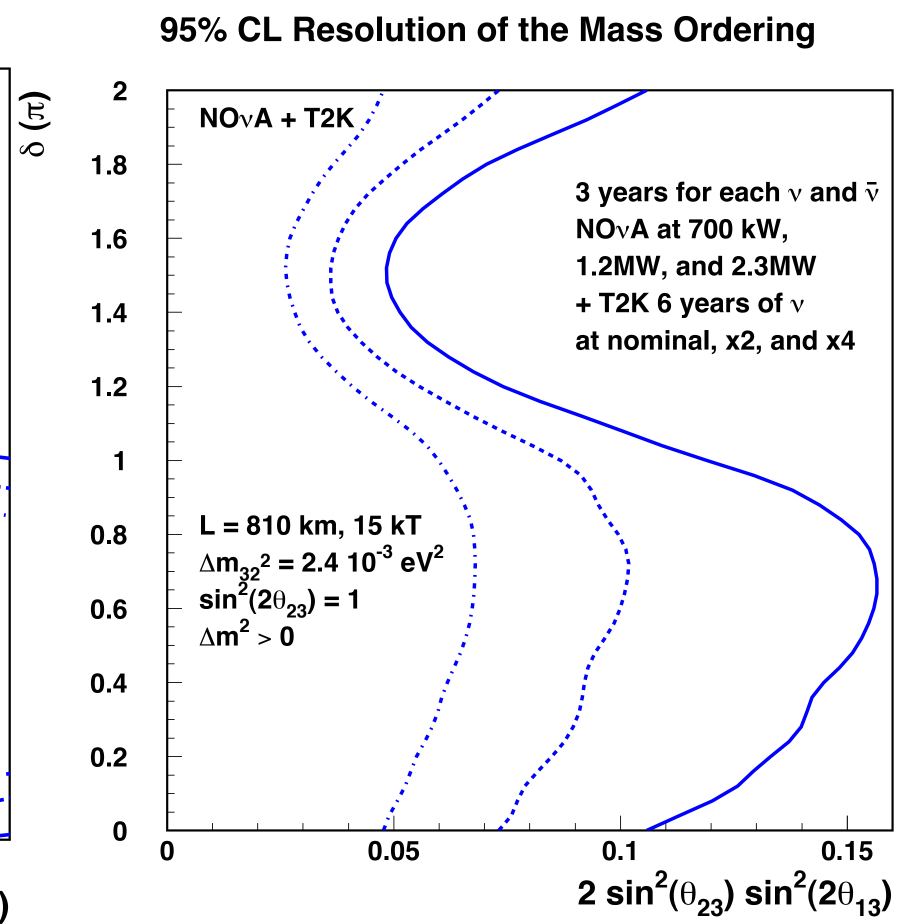


Interaction Type	Events in 3 years
ν_μ CC	2500
NC	2200
ν_e CC beam	120
ν_e CC signal	270

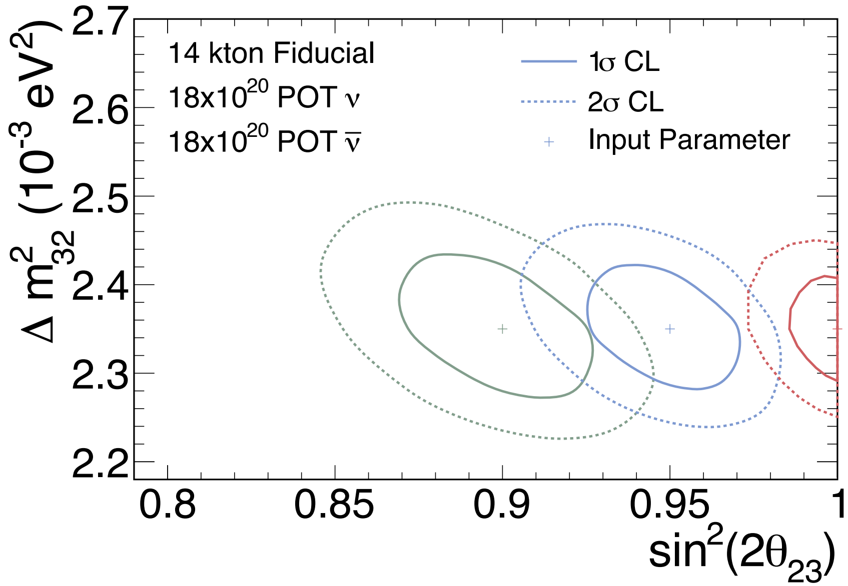
- Consider ν_e appearance at the CHOOZ limit:
  - Before cuts, signal is 4σ above background
  - Cuts on summed event pulse height, event length: 7σ
  - Sophisticated selection based on event topology: 18σ
  - Compare to ~4σ of MINOS analysis

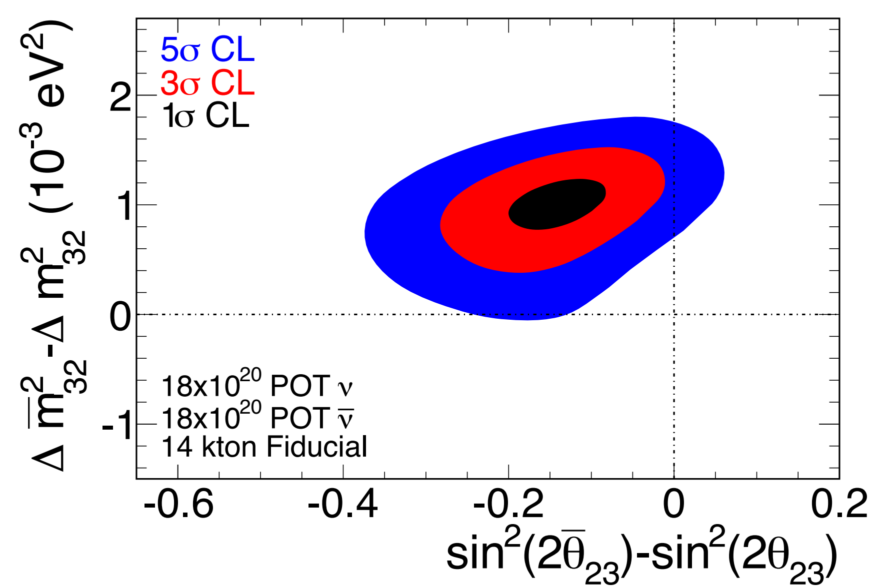
Mass Hierarchy





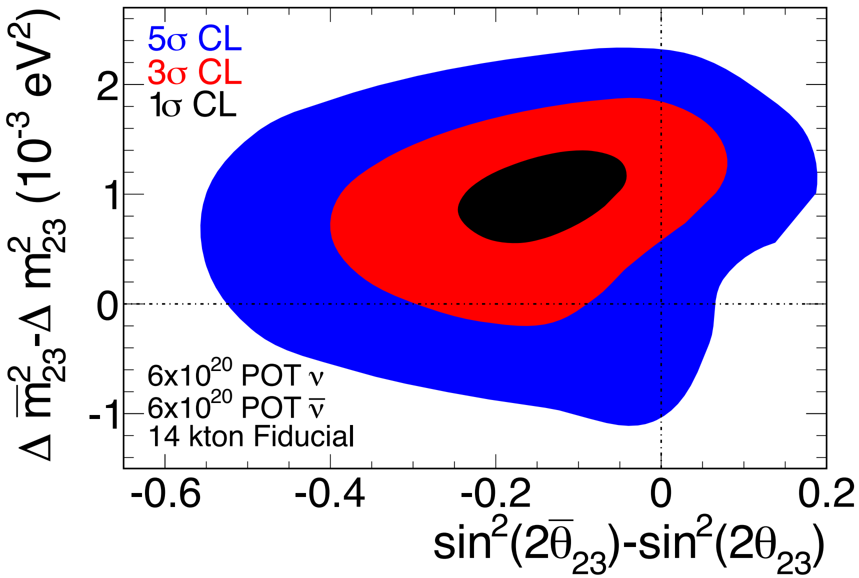
Muon Neutrino Disappearance





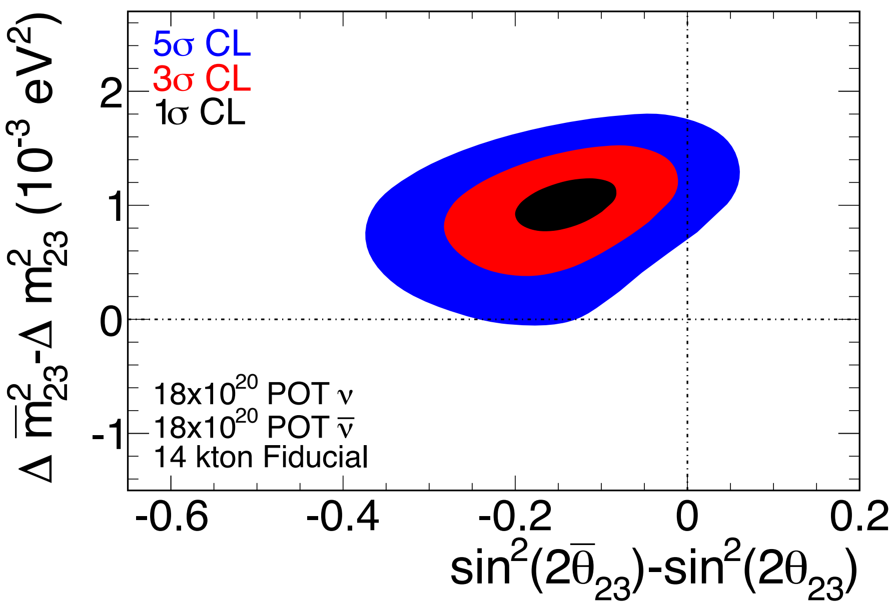
- Sensitivity to (Δm^2, $\sin 2(2\theta_{23})$) after 3 years each of neutrino beam and antineutrino beam
- If tension in MINOS neutrino/ antineutrino results persists, the difference in the neutrino and antineutrino parameters measured by nova

Muon Neutrino/Antineutrino Disappearance

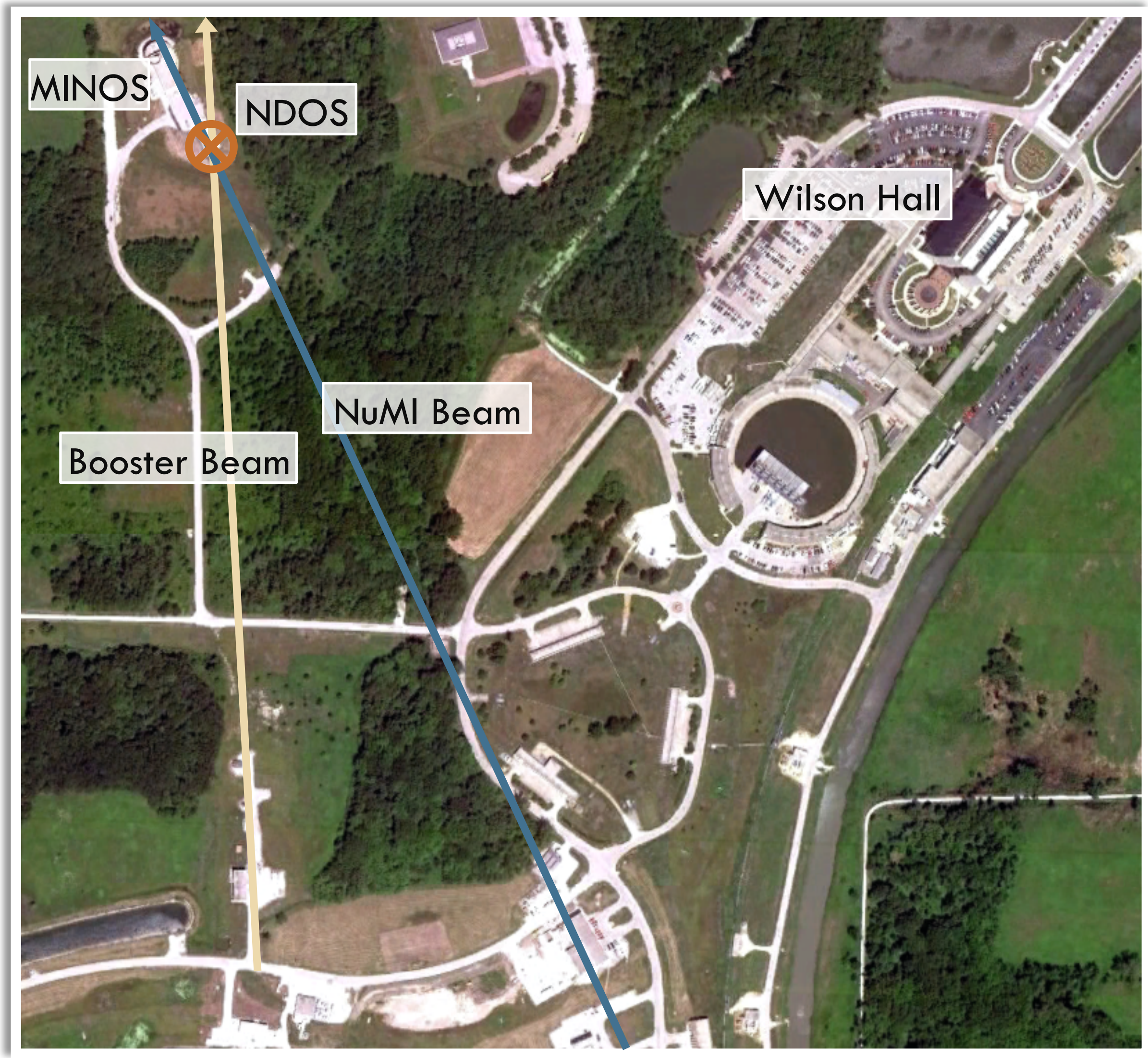


1 Year Each

3 Years Each

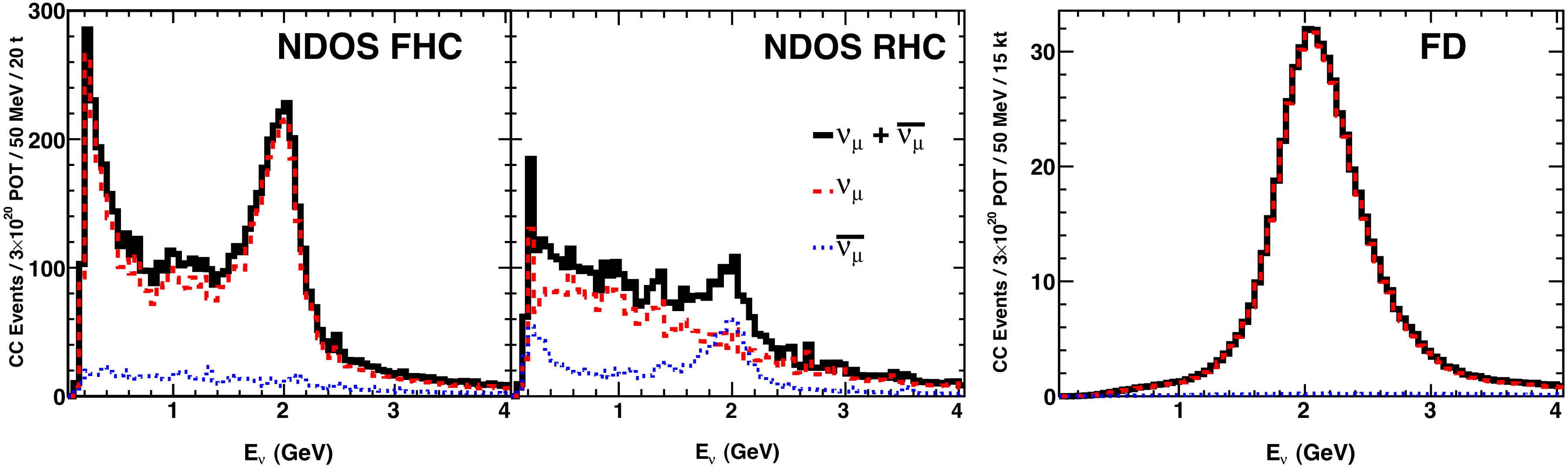


Near Detector On the Surface



- Exposed to Booster and NuMI neutrino beams
- 110 mrad off NuMI axis
- Nearly on Booster Axis (det. rotated wrt beam)

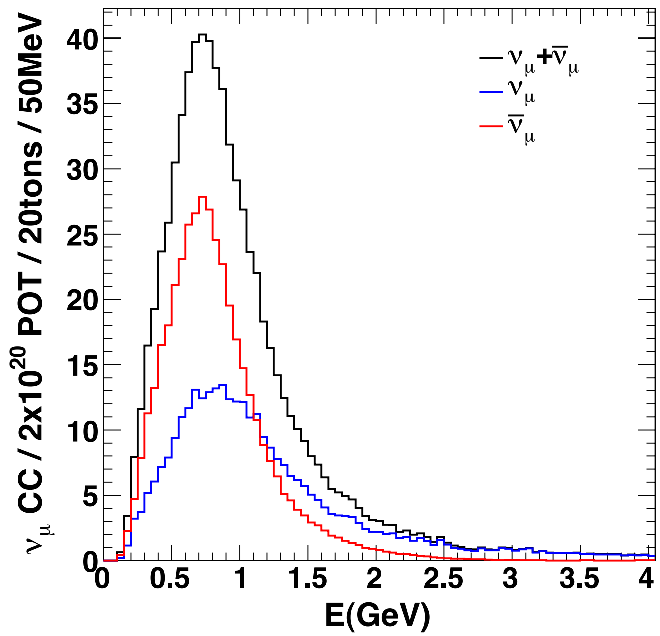
NDOS Energy Spectrum — NuMI



	FHC	RHC
$\nu_\mu + \overline{\nu_\mu}$ CC Events (1.6 – 2.4 GeV)	5200 (1800)	3900 (900)
$\nu_\mu + \overline{\nu_\mu}$ QE CC Events (1.6 – 2.4 GeV)	2600 (500)	2000 (300)
$\nu_e + \overline{\nu_e}$ CC Events	250	190
NC Events	2300	1900

Event counts for 1×10^{20} POT, 46 ton fiducial mass, no inefficiency

NDOS Energy Spectrum — Booster



	Booster Antineutrino Mode
$\nu_\mu + \overline{\nu_\mu}$ CC Events	820
$\nu_e + \overline{\nu_e}$ CC Events	10
NC	450

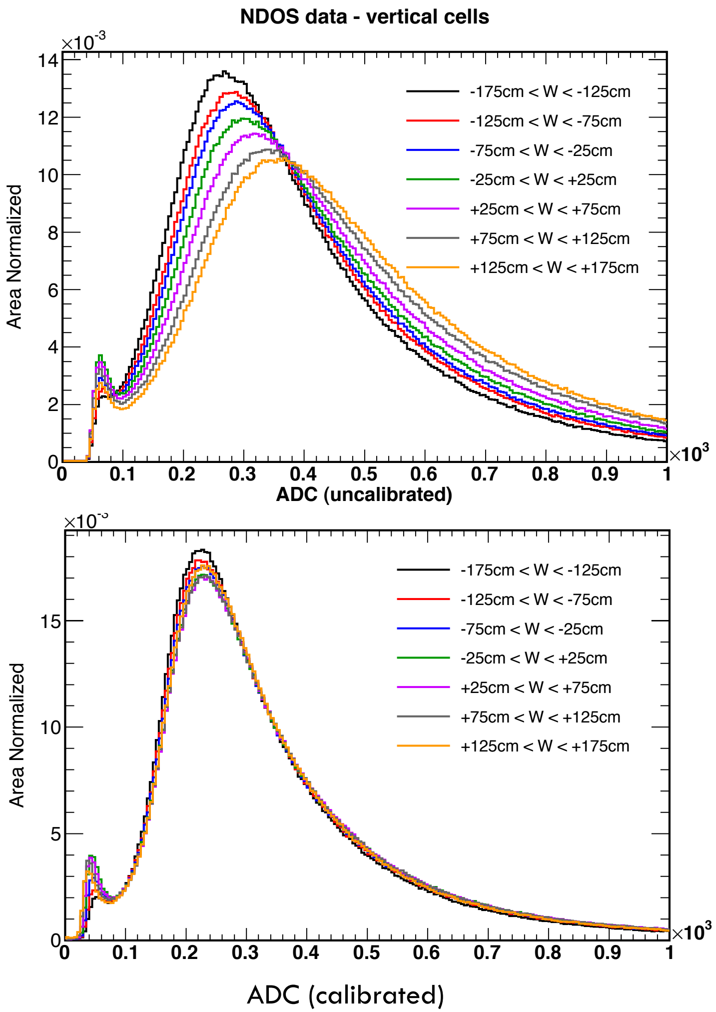
Event counts for 1x10^{20} POT, 46 ton fiducial mass, no inefficiency

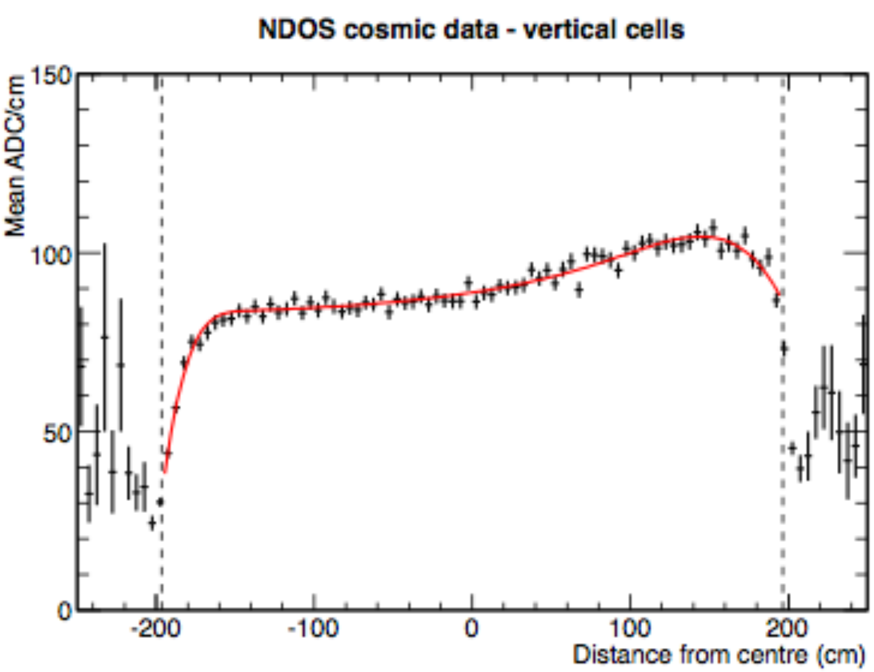
Lessons Learned

- 22% of module manifolds developed cracks during detector installation
  - "Splints" to fix NDOS
  - Changes to pressure testing
  - Redesign of manifolds
- APDs and oil do not mix
  - plan to coat APDs with epoxy
  - revamped procedures to ensure cleanliness is maintained during industrial scale installation

Calibration

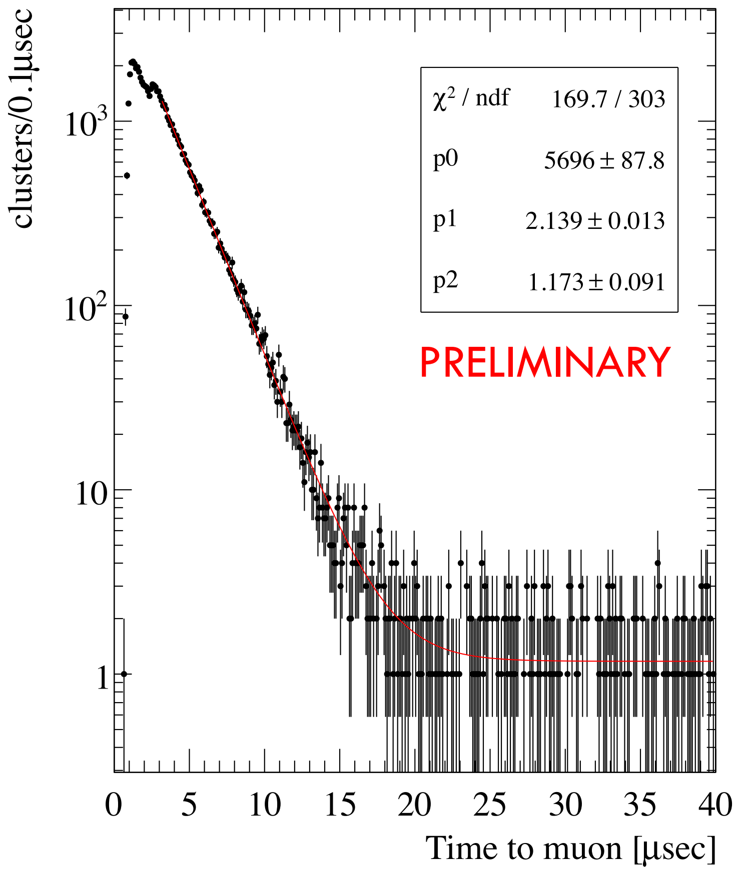
- Cosmic muons provide intra-detector calibration source

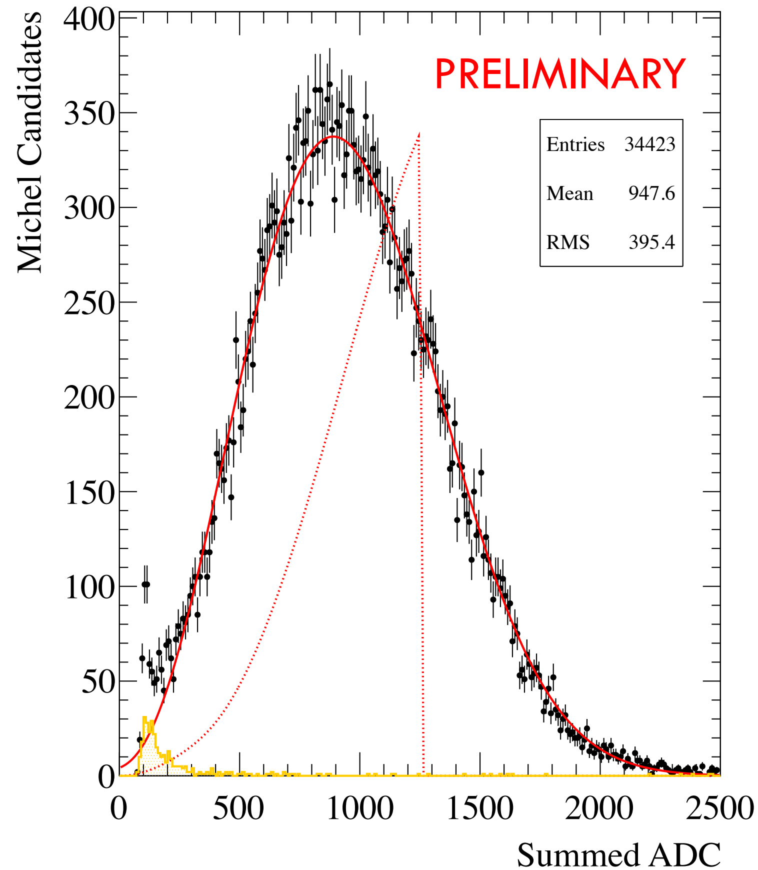




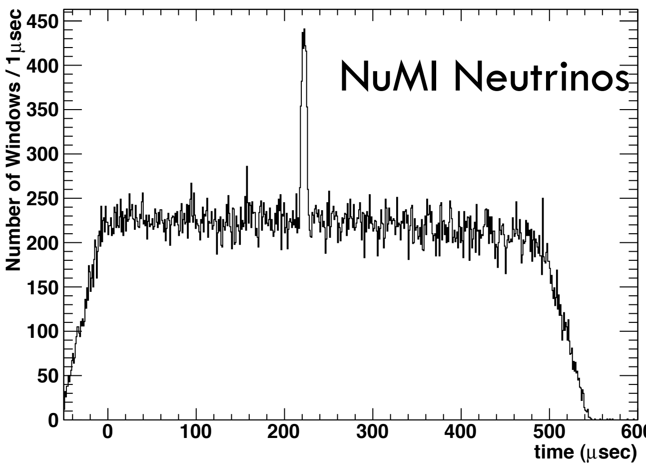
Michel Electrons

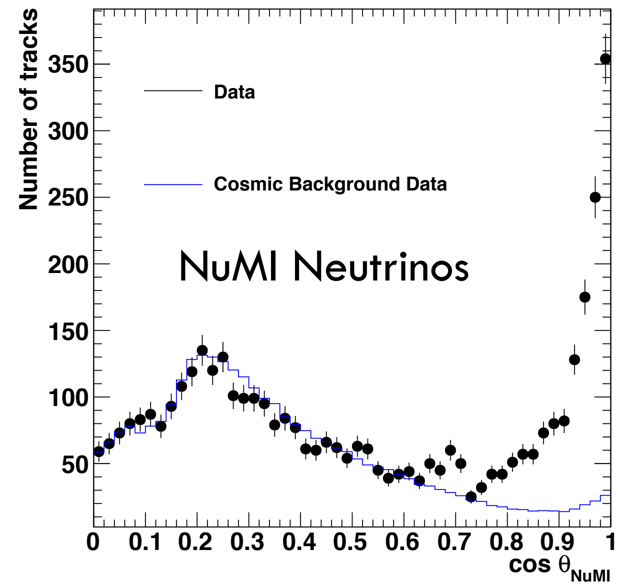
- Use Michel electrons for electro-magnetic energy calibration

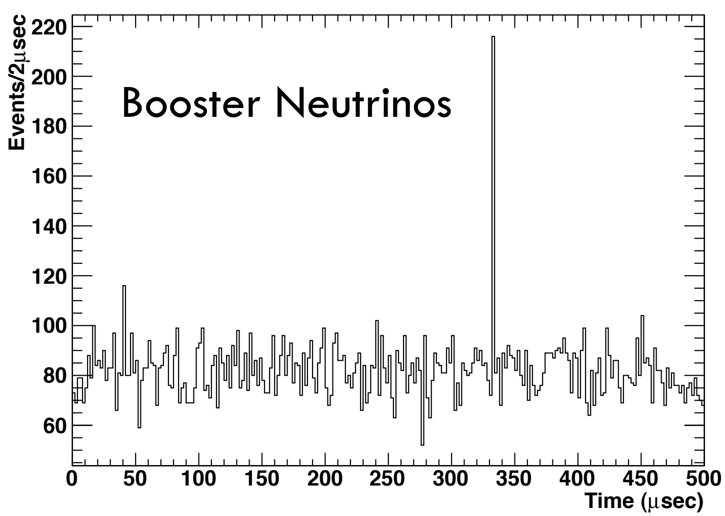


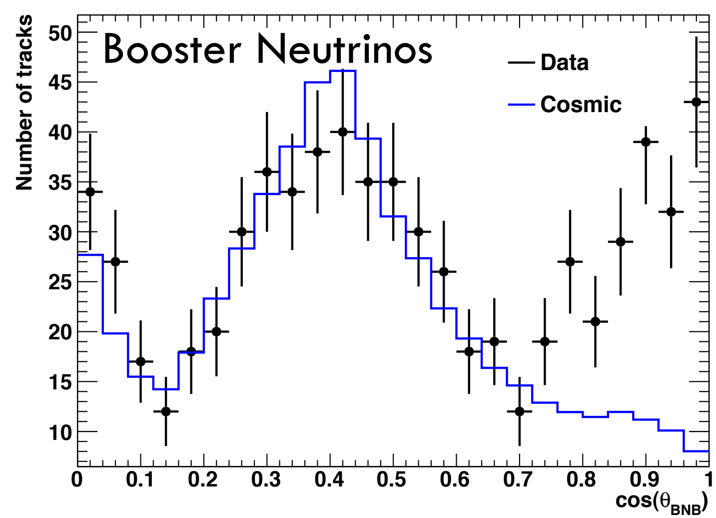


Finding Neutrinos

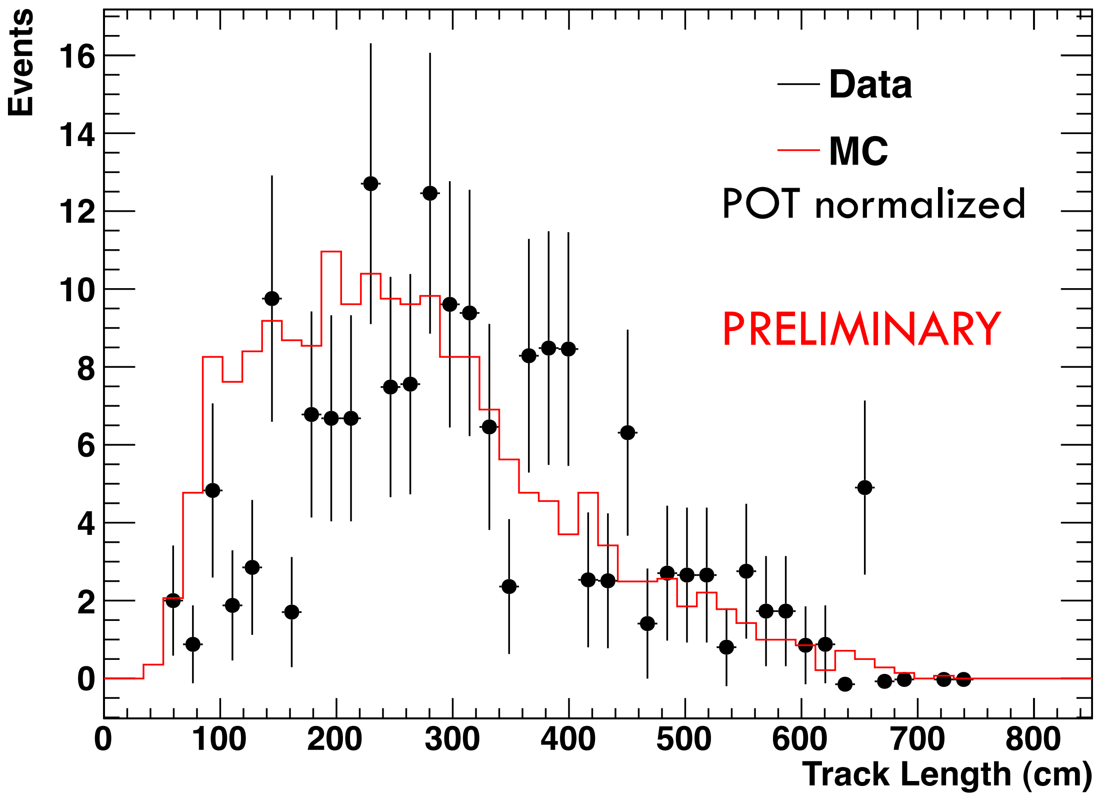






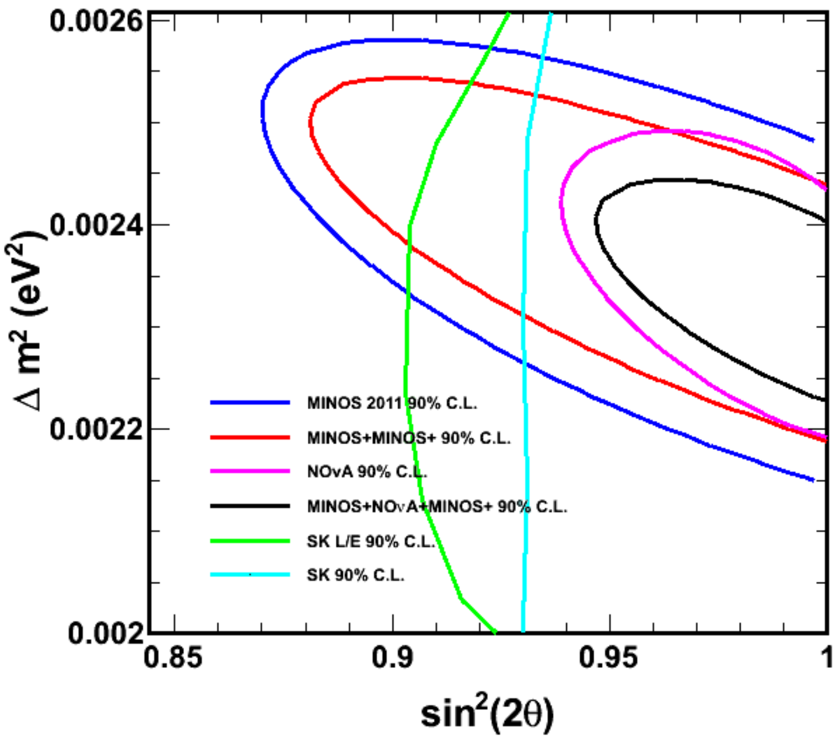


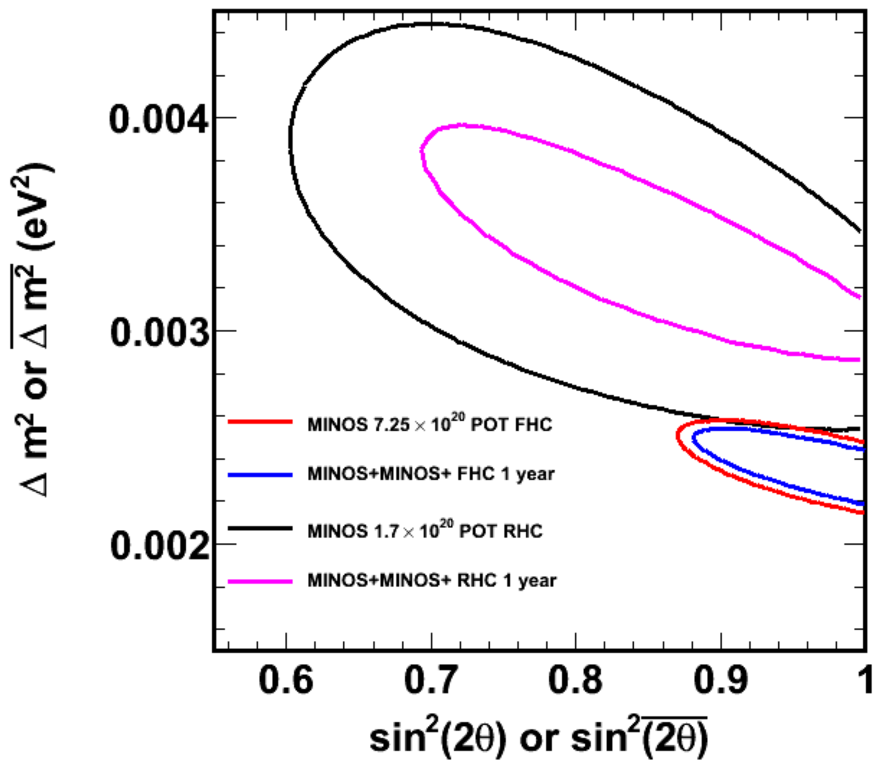
Comparisons to MC



- Early look at contained events indicates NuMI MC event rate agrees with data

MINOS+

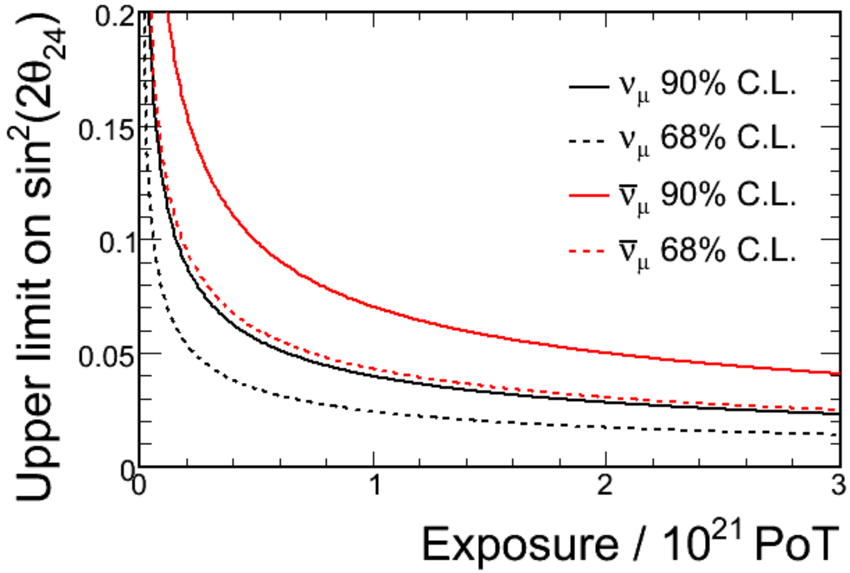


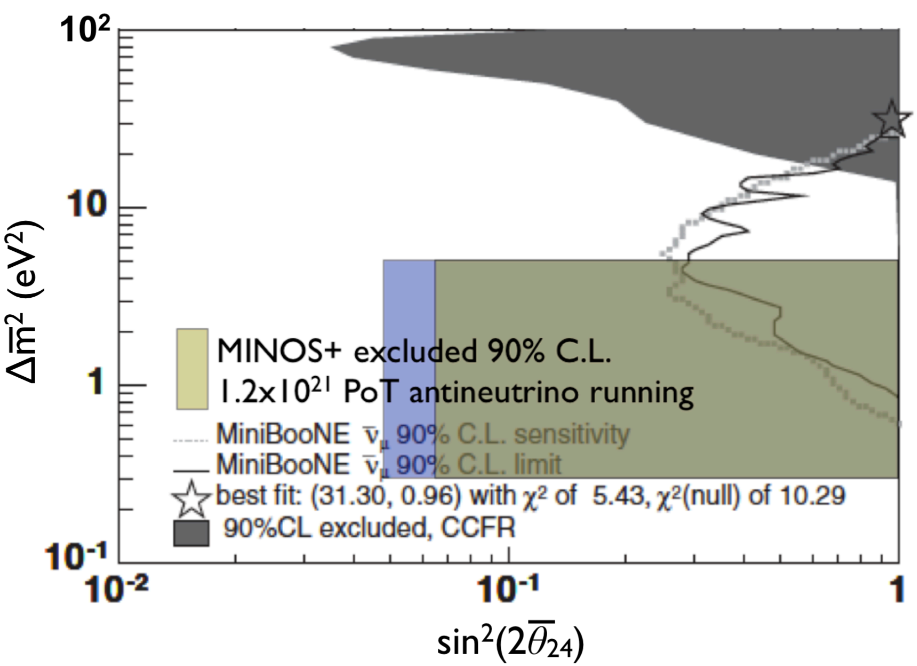


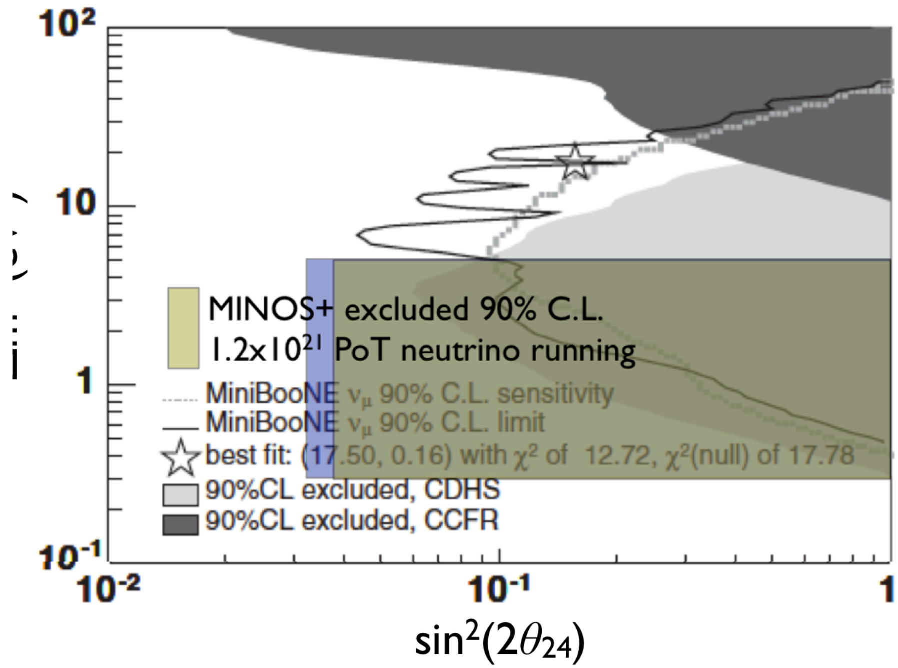
- Continue to contribute to oscillation parameter measurements, but with different systematics

MINOS+

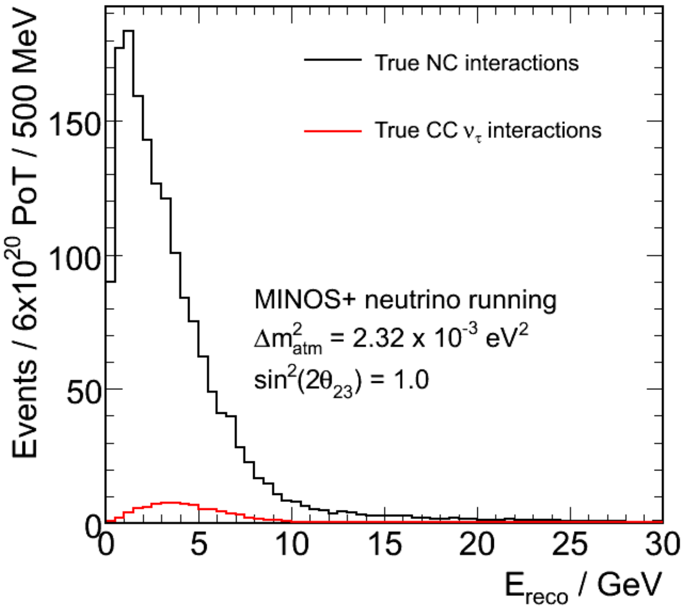
- Sterile neutrino reach
- Use CC disappearance (brown)
- NC rate (purple)







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…