NEW RESULTS FROM MINOS

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Outline

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

Mixing Matrix

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

- Neutrinos have mass
- $\nu_e, \nu_\mu, \nu_\tau \leftrightarrow \nu_1, \nu_2, \nu_3$
  - Flavor states—creation and detection
  - Mass states—propagation
- Neutrinos born as one flavor can later be detected as another flavor
- PMNS matrix relates the two bases

Mixing Matrix

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

- Neutrinos have mass
- $\nu_e, \nu_\mu, \nu_\tau \leftrightarrow \nu_1, \nu_2, \nu_3$
  - Flavor states—creation and detection
  - Mass states—propagation
- Neutrinos born as one flavor can later be detected as another flavor
- PMNS matrix relates the two bases

Mixing Matrix

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

$$\times \mathrm{diag}(1, e^{i\alpha}, e^{i\beta})$$

α, β —Majorana phases
not observable in oscillation expts.

- Neutrinos have mass
- $\nu_e, \nu_\mu, \nu_\tau \leftrightarrow \nu_1, \nu_2, \nu_3$
  - Flavor states—creation and detection
  - Mass states—propagation
- Neutrinos born as one flavor can later be detected as another flavor
- PMNS matrix relates the two bases

Pontecorvo, Maki, Nakagawa, Sakata

Mixing Matrix

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

- Factorizes—3 terms, 3 experimental regimes

Mixing Matrix

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- Factorizes—3 terms, 3 experimental regimes
- (12) Sector identified with solar mixing
  - driven by small $\Delta m^2 \sim 8\times10^{-5}$ eV^2
  - Reactor+Solar experiments at L/E~15,000 km/GeV

Mixing Matrix

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

- Factorizes—3 terms, 3 experimental regimes
- (23) Sector identified with atmospheric mixing
  - driven by larger $\Delta m^2 \sim 2\times10^{-3}$ eV^2
  - Atmospheric neutrinos
  - accelerator experiments with L/E~500 km/GeV

Mixing Matrix

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

- Factorizes—3 terms, 3 experimental regimes
- (13) Sector mixing not yet observed
  - θ_{13} is small
  - accelerator experiments L/E~500 km/GeV
  - reactor experiments L/E~500 km/GeV (0.5 km/MeV)

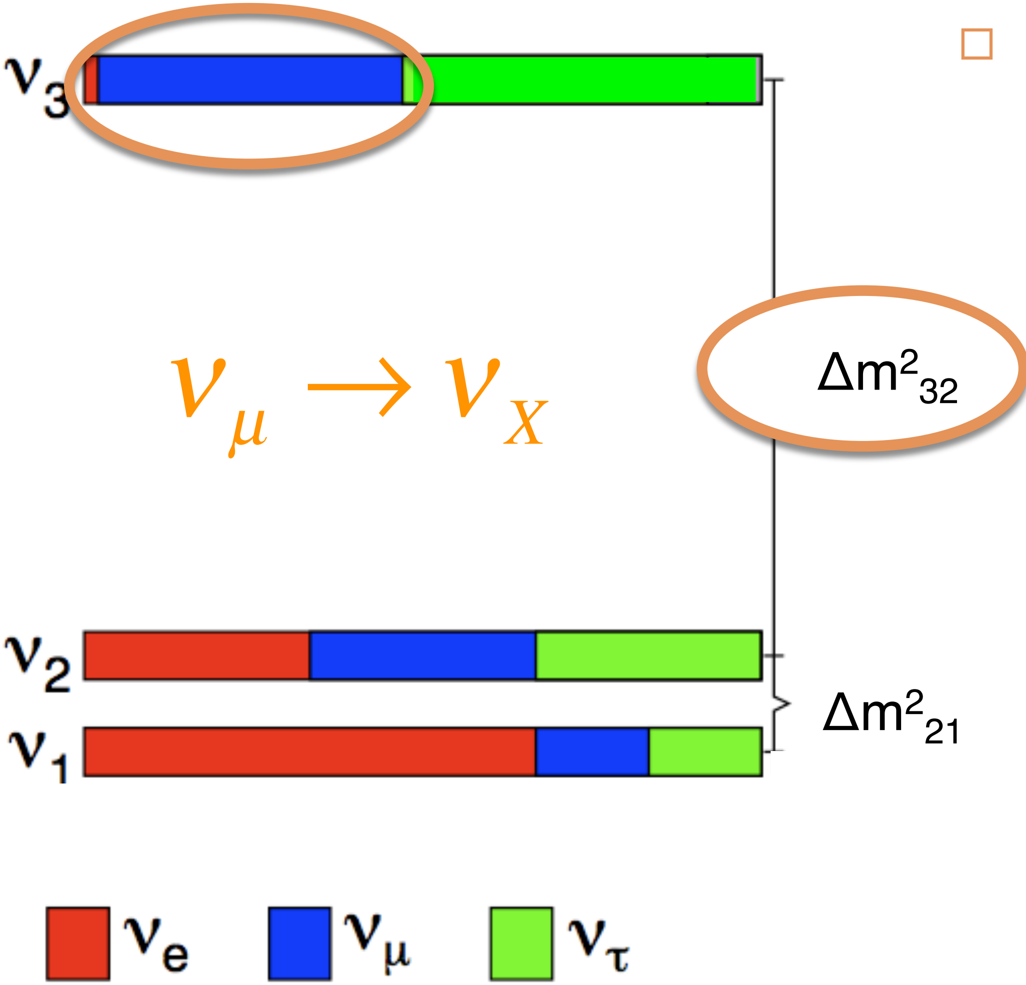
Why measure all these angles?

- Precision measurements provide valuable check that neutrino oscillations are the right solution to neutrino anomalies
- PMNS matrix analogous to CKM matrix governing quark mixing
  - mixing in lepton sector much larger than mixing in quark sector
  - θ_{23} maximal? θ_{12} moderately large—why?
  - θ_{13} small, is it zero?—why?
  - Is there CP violation in the lepton sector? Is it big enough to account for matter vs. antimatter asymmetry in the Universe?

The MINOS Experiment

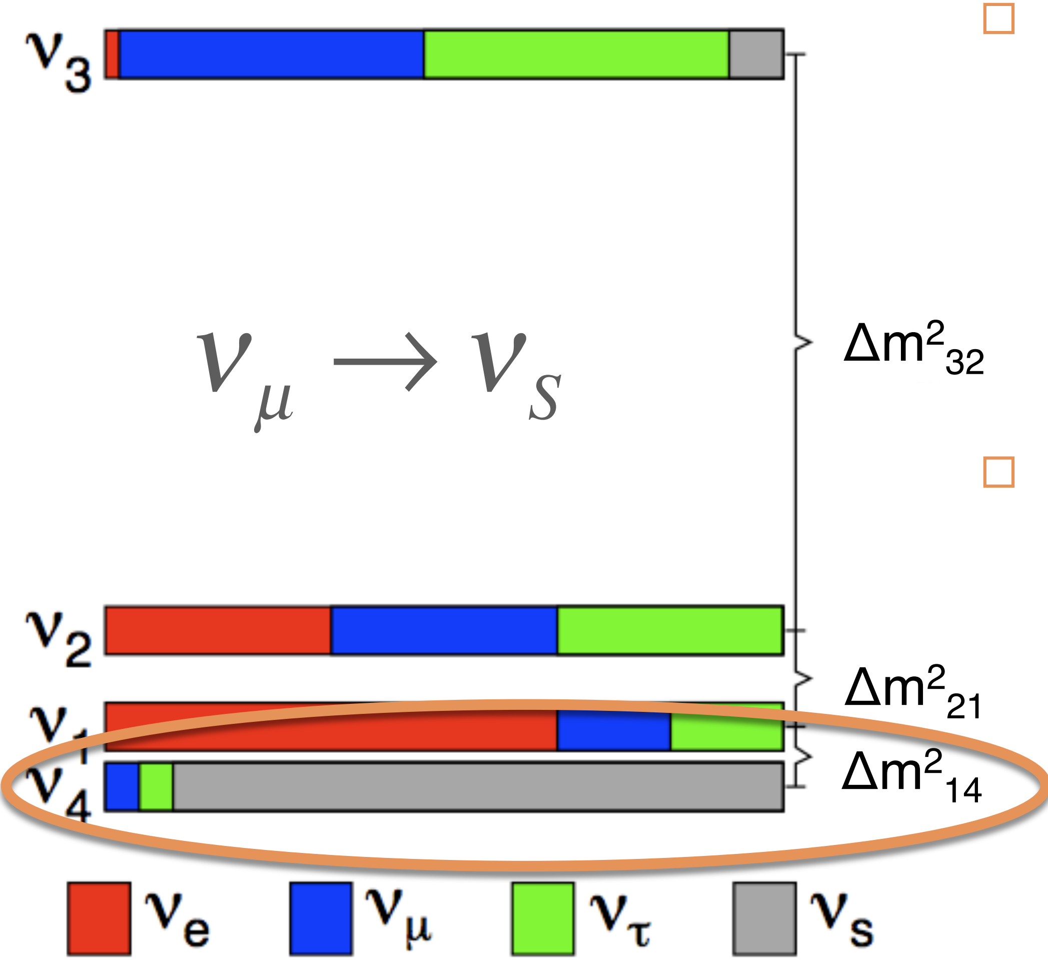
- Long base-line neutrino oscillation experiment
- Neutrinos from NuMI beam line
- L/E ~ 500 km/GeV
  - atmospheric Δm^2
- Two detectors mitigate systematic effects
  - beam flux mis-modeling
  - neutrino interaction uncertainties

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

MINOS Physics Goals



- Measure ν_μ disappearance as a function of energy
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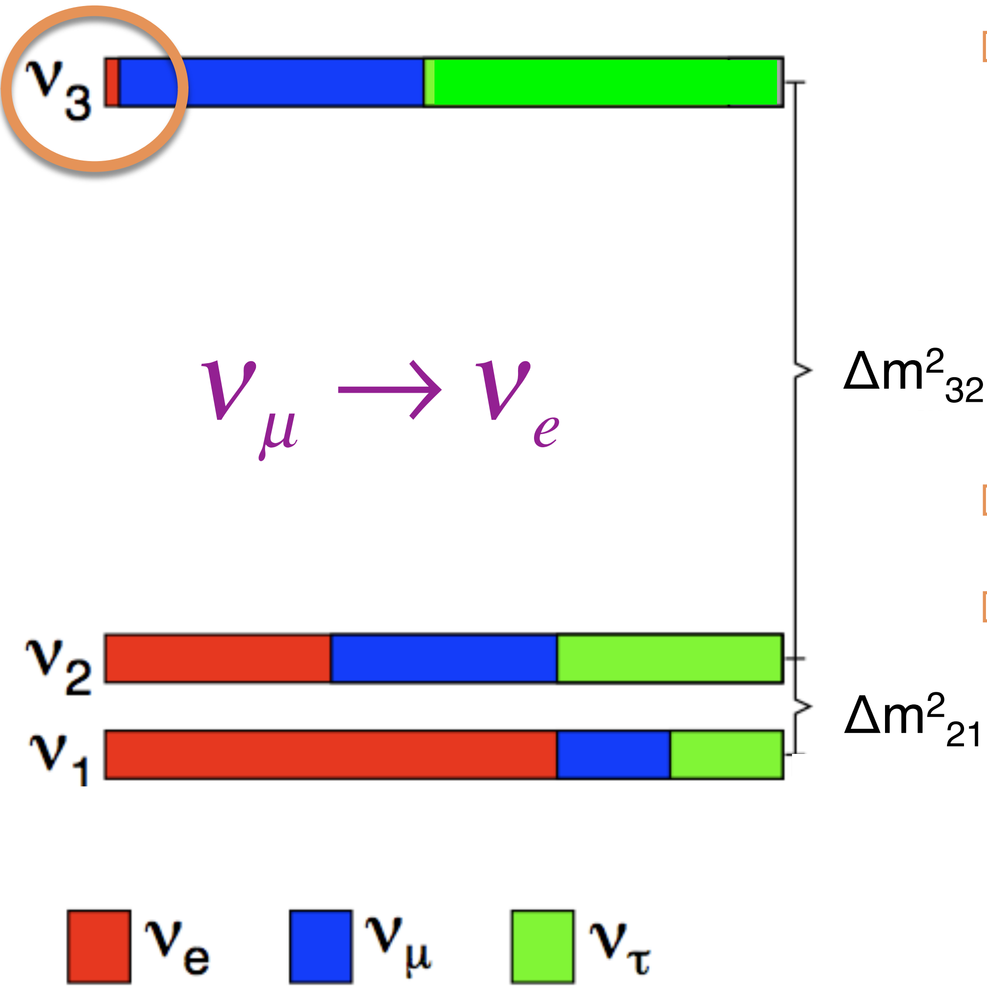
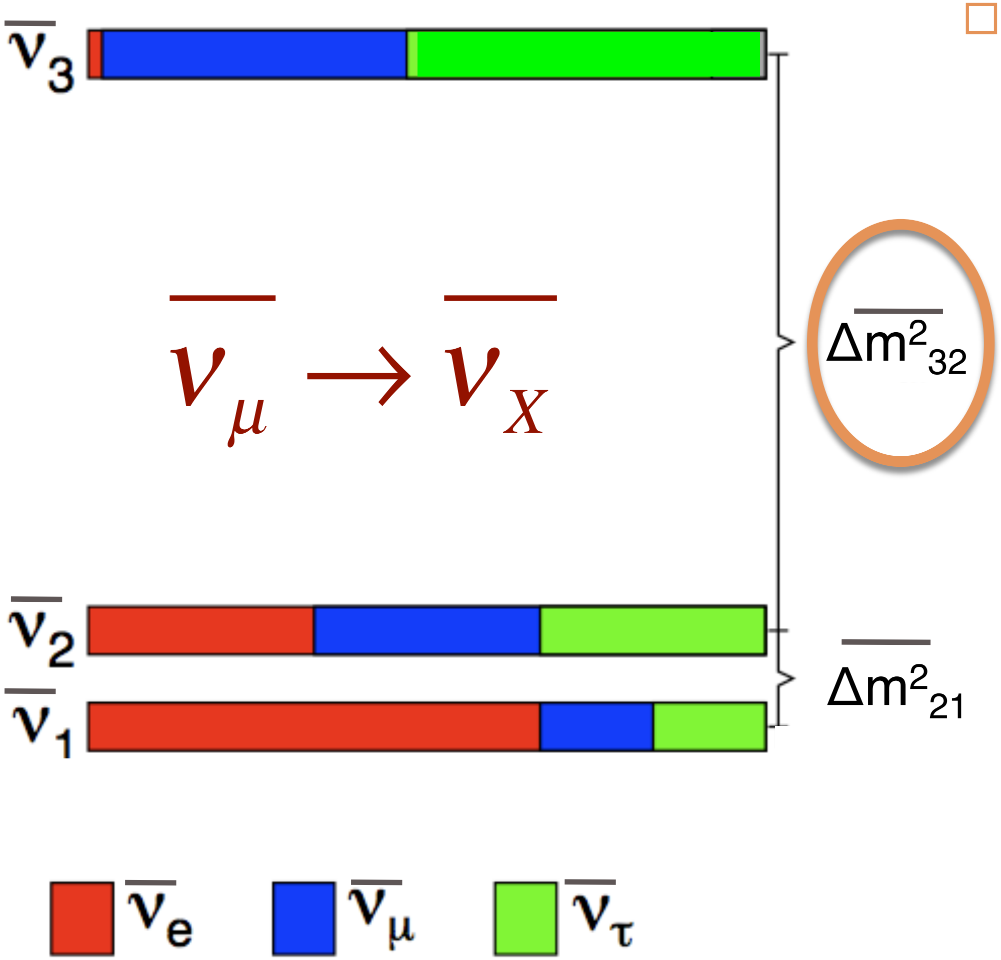
- **Mixing to sterile neutrinos?**

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
- Mixing to sterile neutrinos?
- **Study $\nu_\mu \rightarrow \nu_e$ mixing**
  - measure θ_{13}

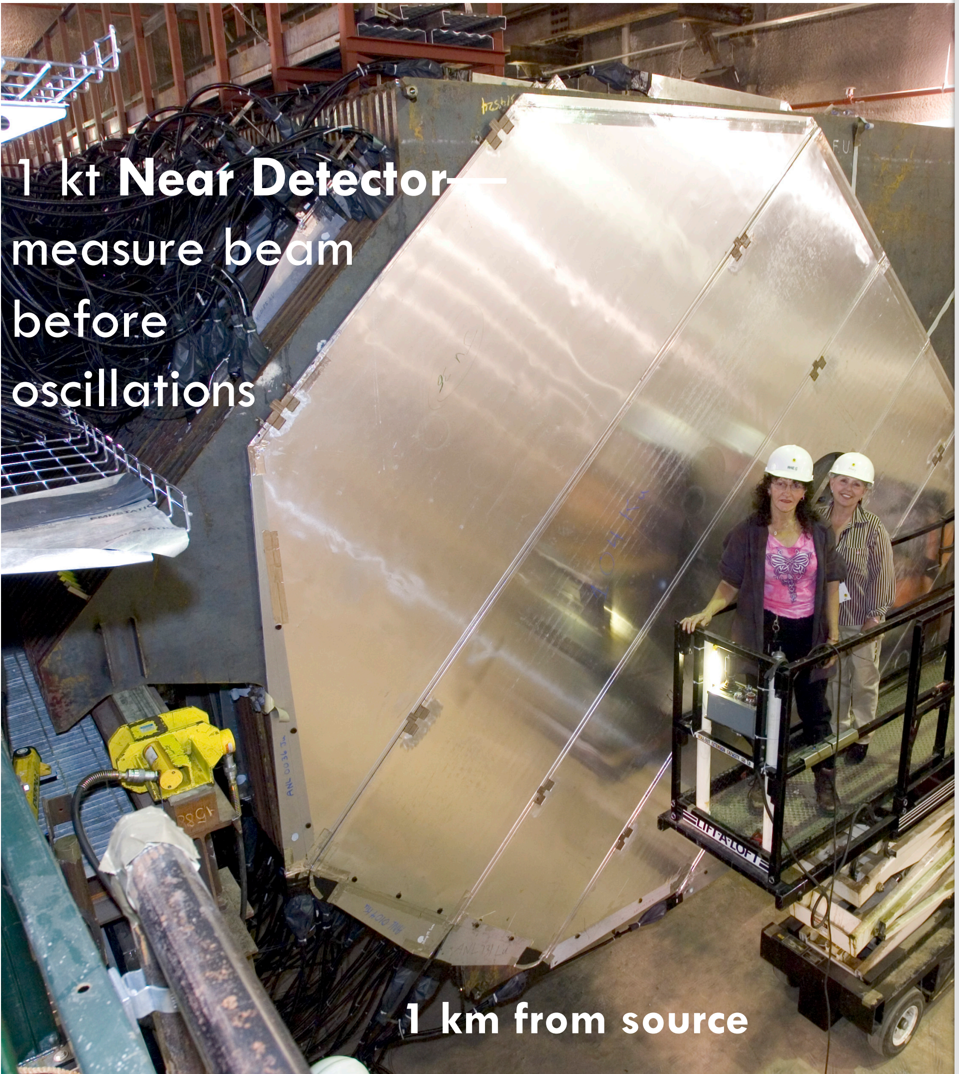
MINOS Physics Goals

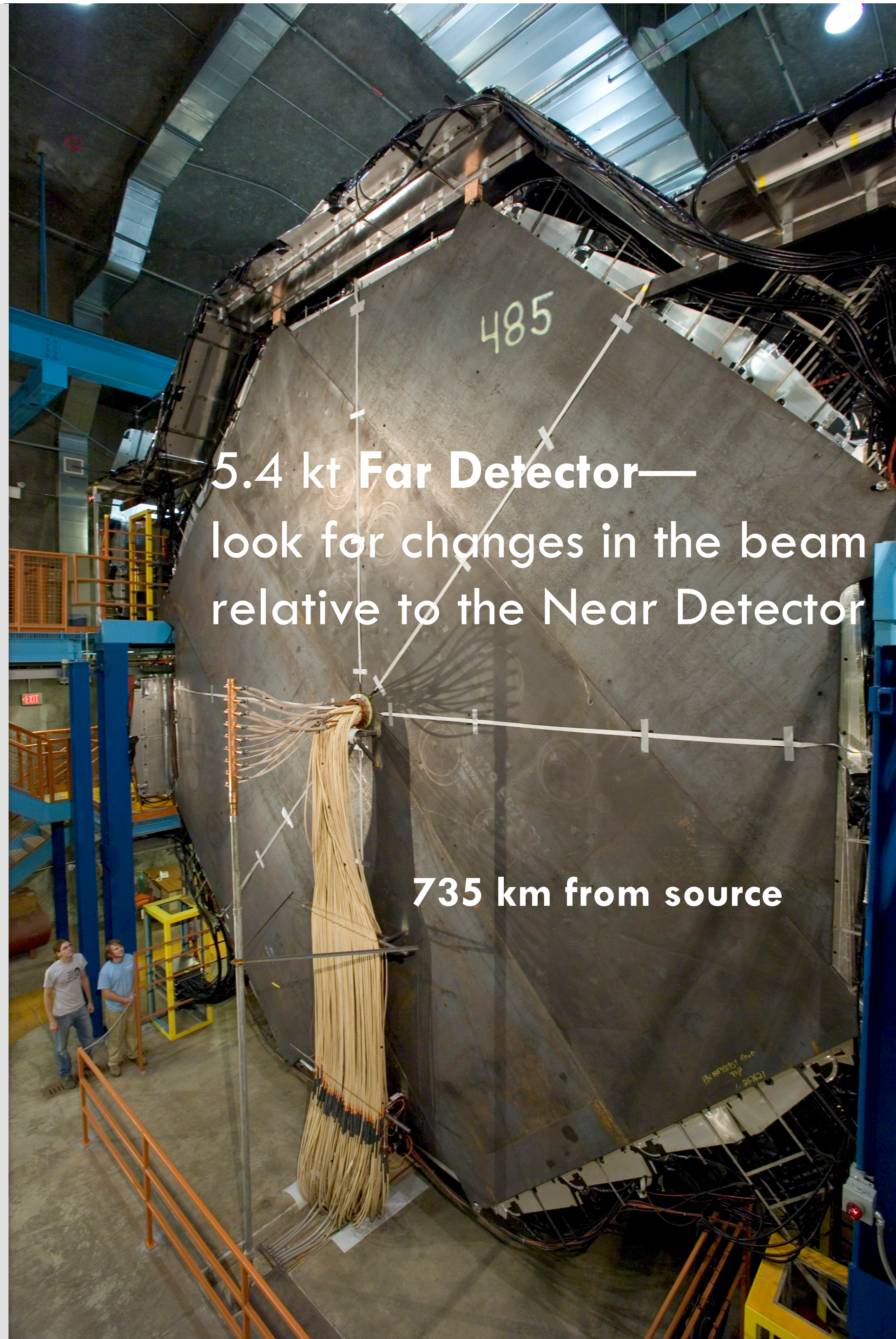


- **Measure $\bar{\nu}_\mu$ disappearance as a function of energy**
  - $\overline{\Delta m^2_{32}}$ and $\sin^2(\overline{2\theta_{23}})$
  - look for differences between neutrino and anti-neutrinos

The Detectors

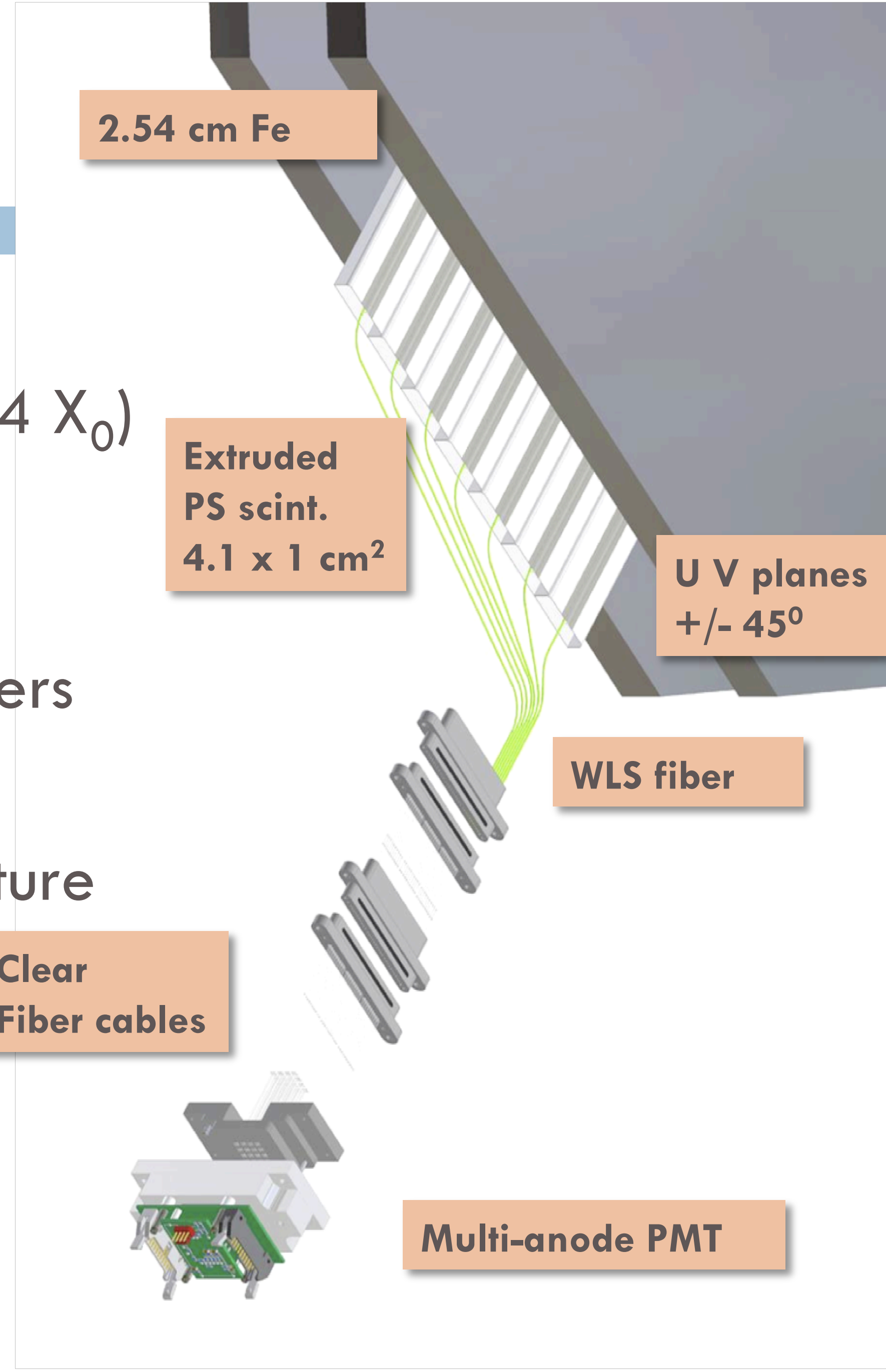
Magnetized, tracking calorimeters



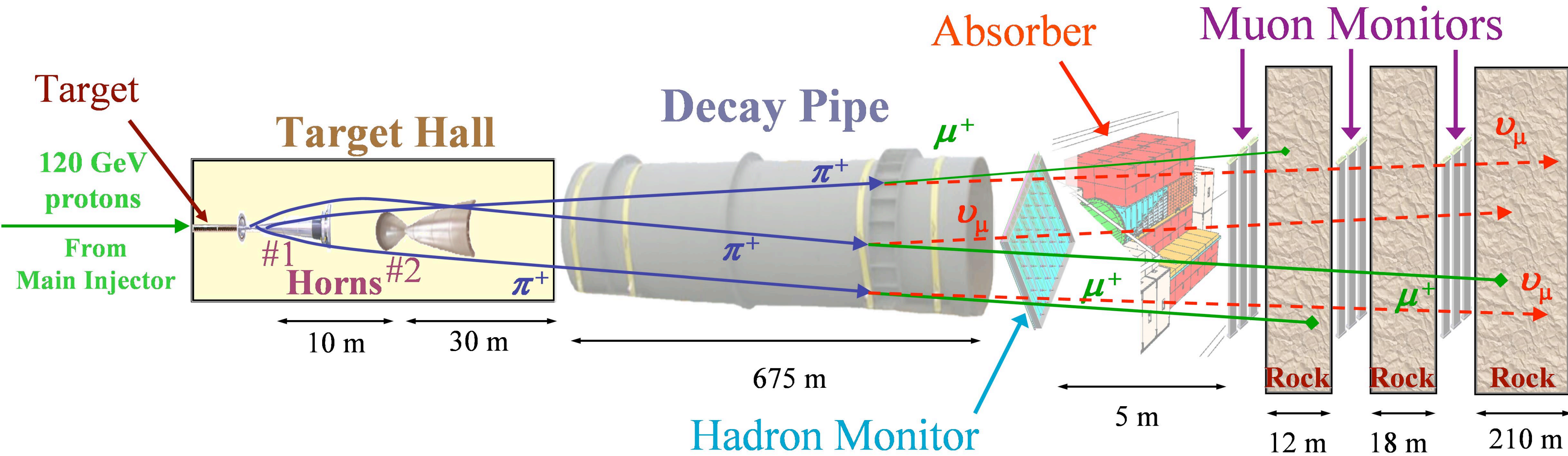


Detector Technology

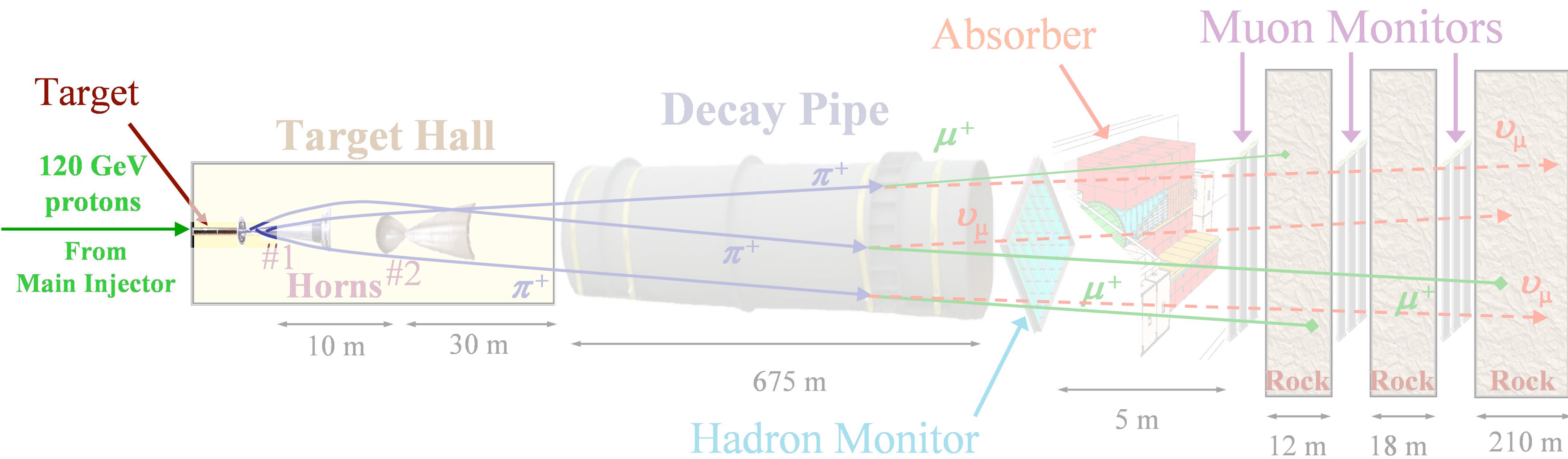
- Tracking sampling calorimeters
  - steel absorber 2.54 cm thick (1.4 X_0)
  - scintillator strips 4.1 cm wide (1.1 Moliere radii)
  - 1 GeV muons penetrate 28 layers
- Magnetized
  - muon energy from range/curvature
  - distinguish μ^+ from μ^-
- Functionally equivalent
  - same segmentation
  - same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



Making a neutrino beam

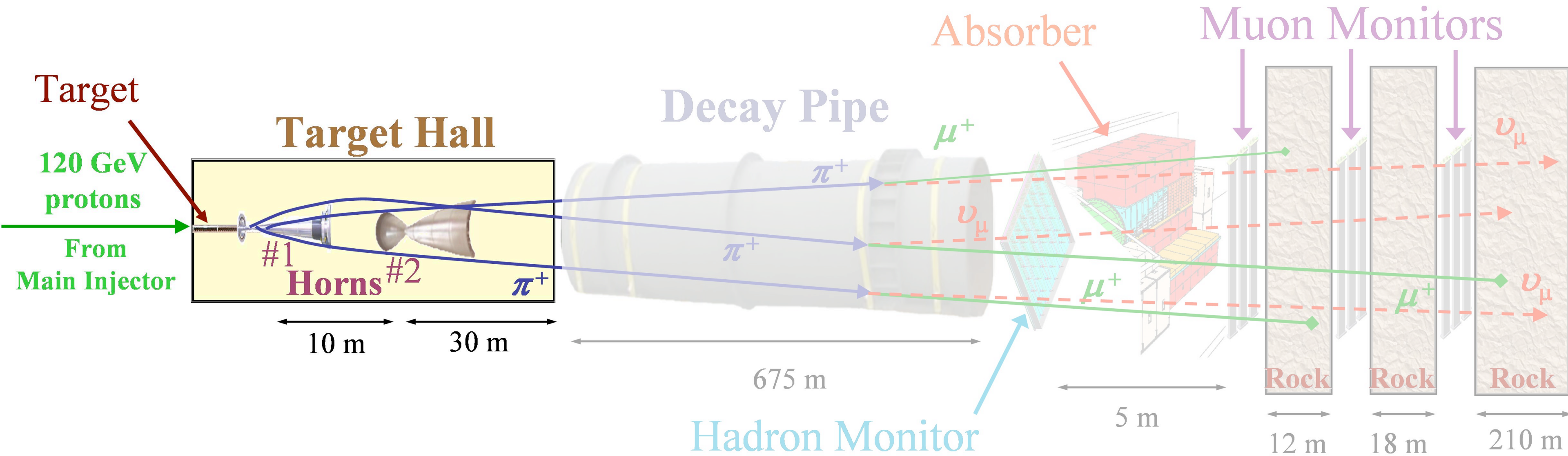


Making a neutrino beam



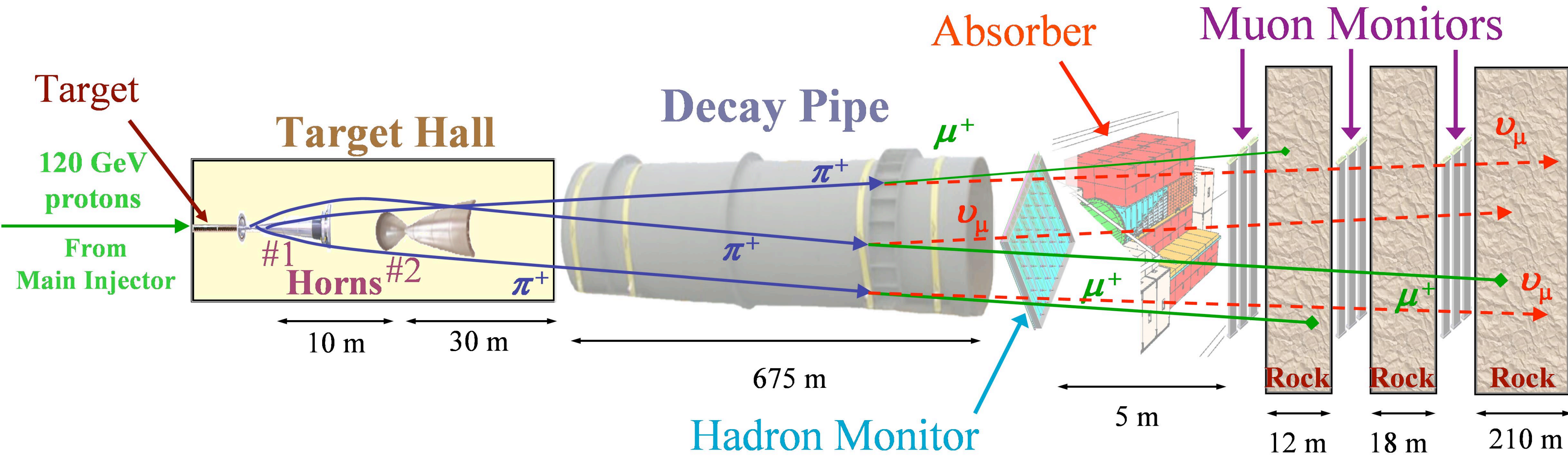
- **Production**
  - bombard graphite target with 120 GeV p^+ from Main Injector
    - 2 interaction lengths
    - 310 kW typical power
  - produce hadrons, mostly π and K

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

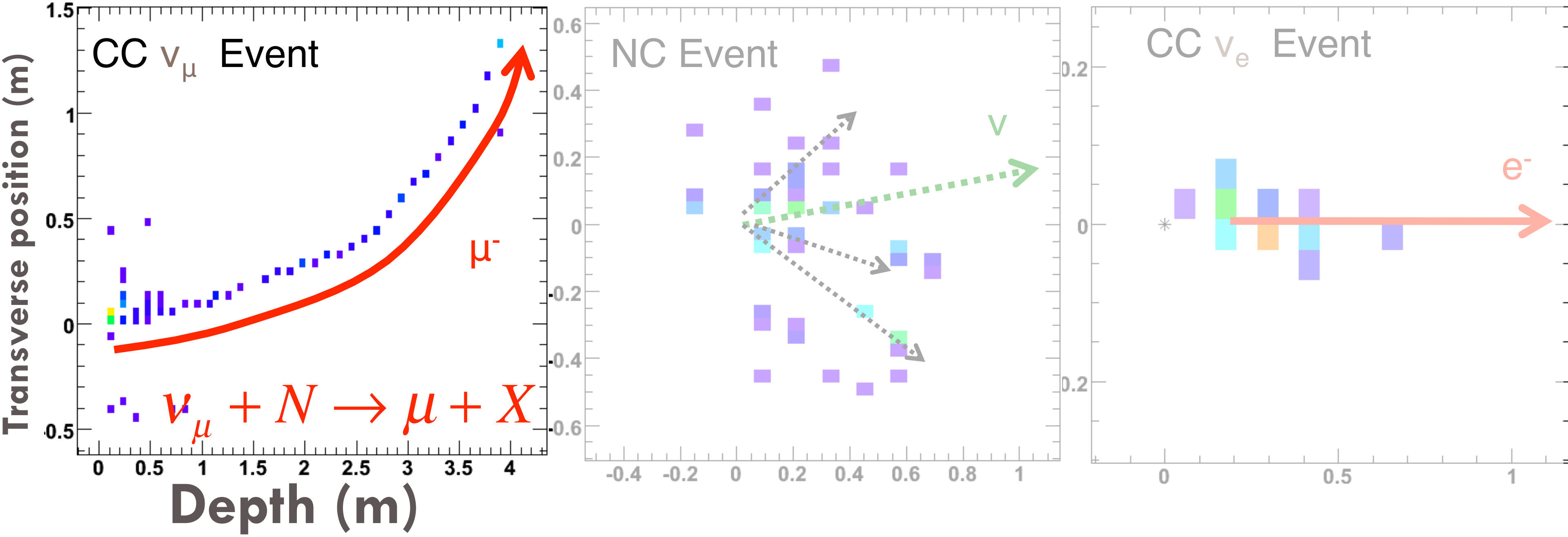
Making a neutrino beam



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

Events in MINOS

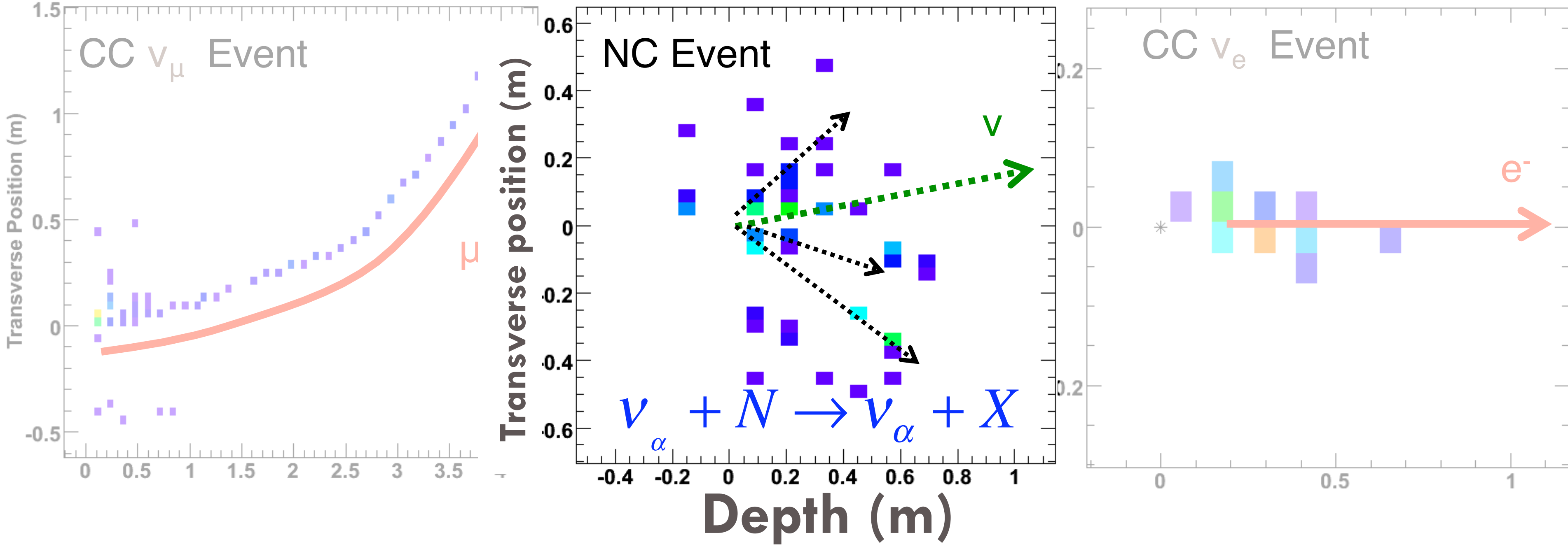
Simulated Events



- 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

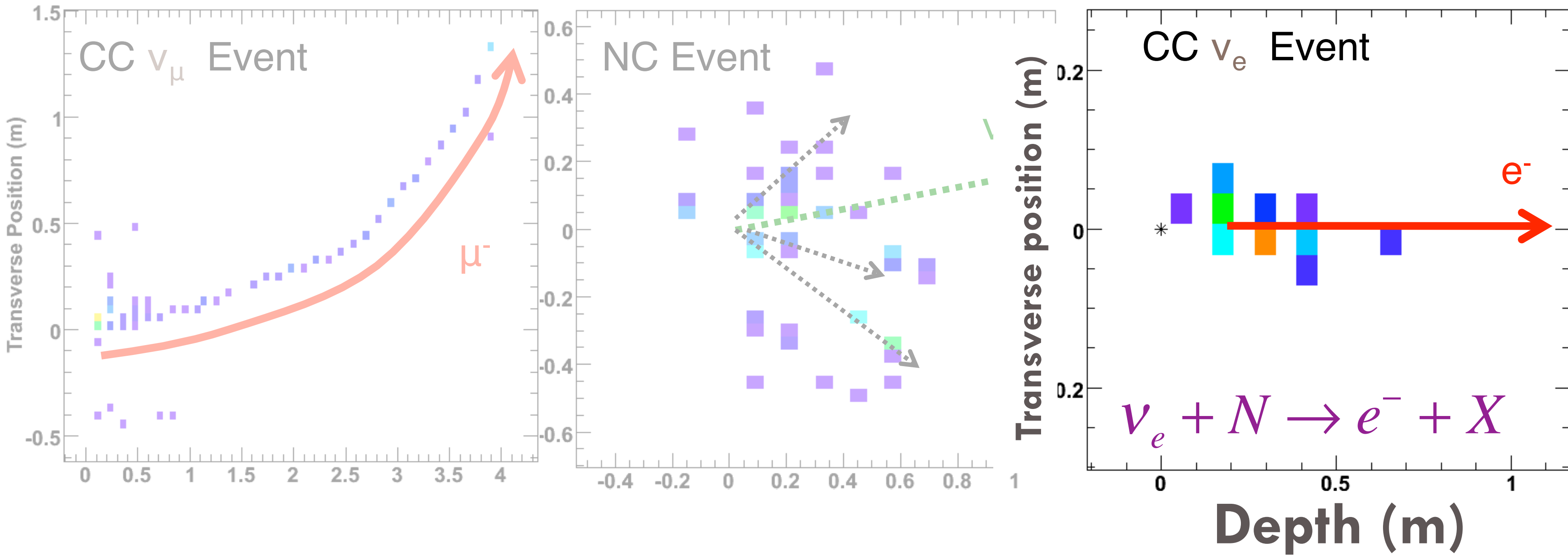
Simulated Events



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

Events in MINOS

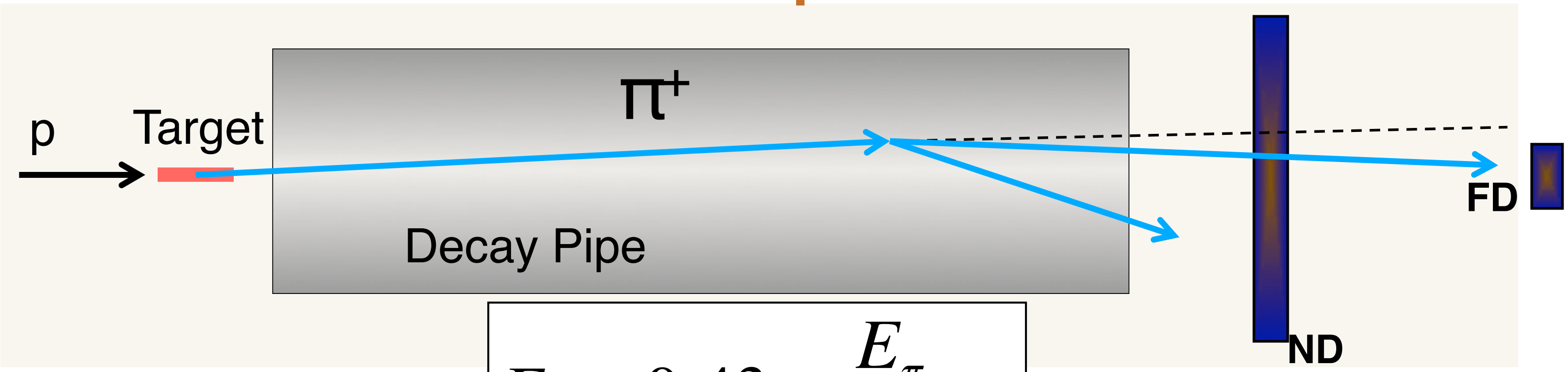
Simulated Events



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

Near to Far

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

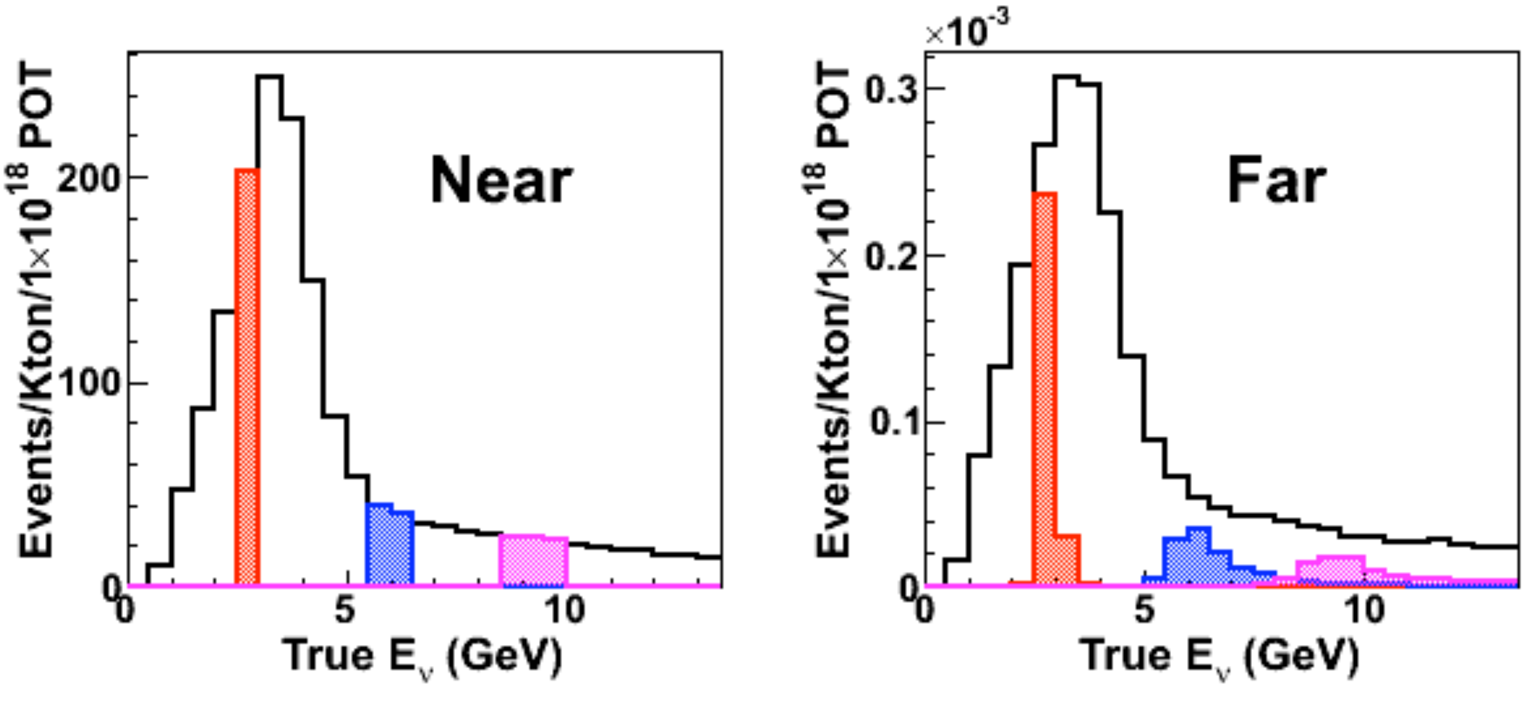


$$E_\nu \approx 0.43 \frac{E_\pi}{1+\gamma^2\theta_\nu^2}$$

- 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

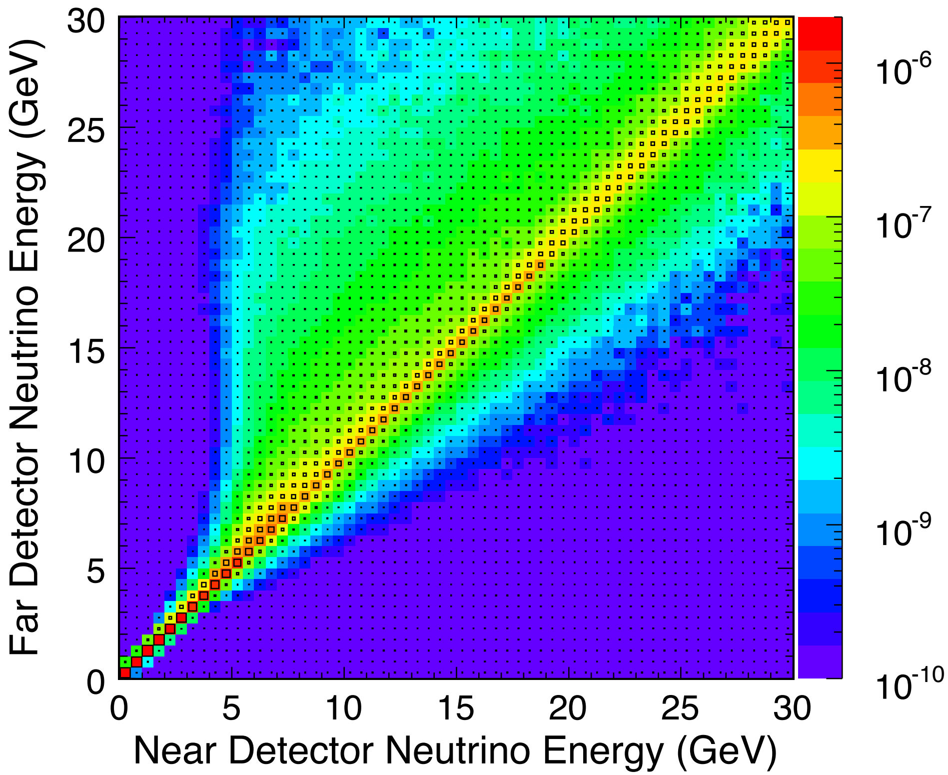
Near to Far

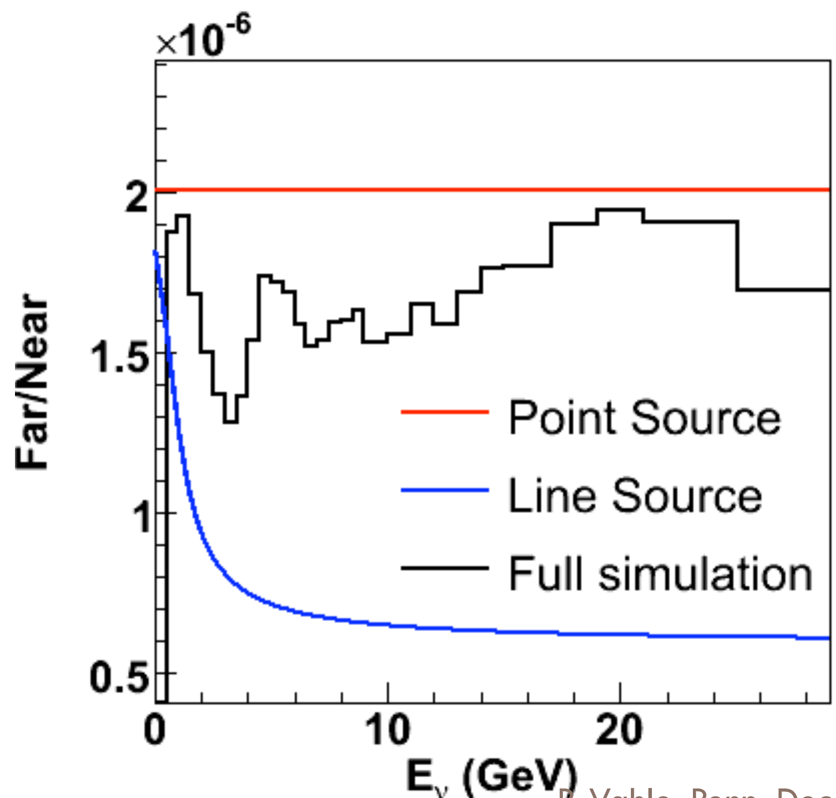
Far spectrum without oscillations is similar, but not identical to the Near spectrum!



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



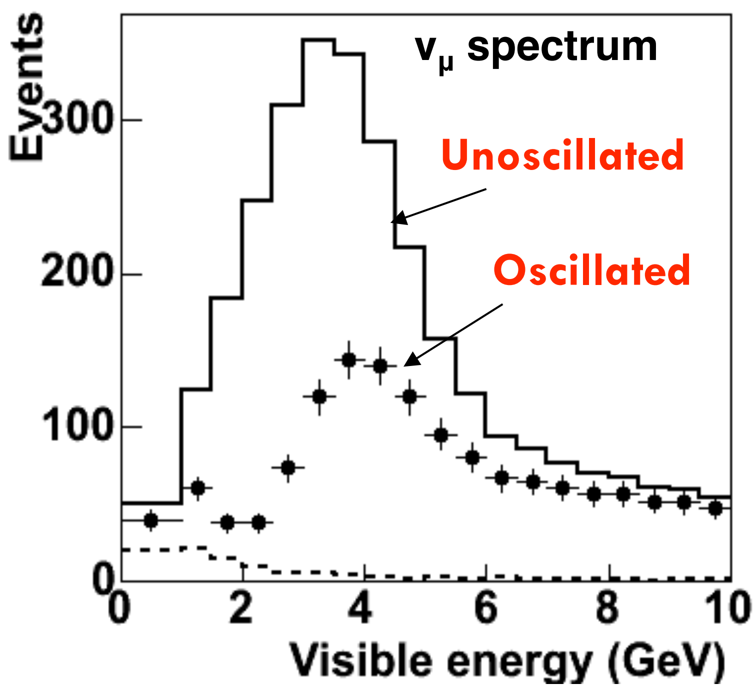


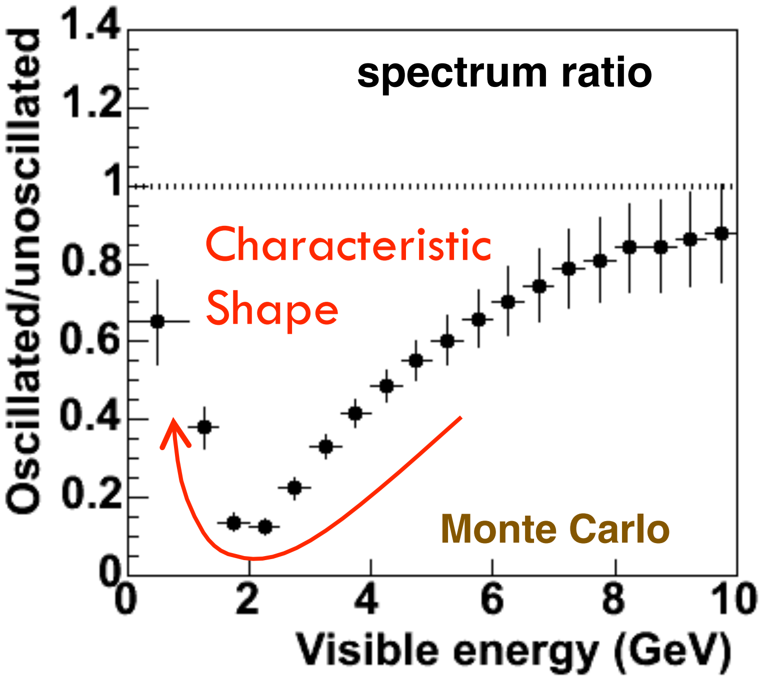
ν_μ Disappearance

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

Monte Carlo

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





ν_μ Disappearance

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

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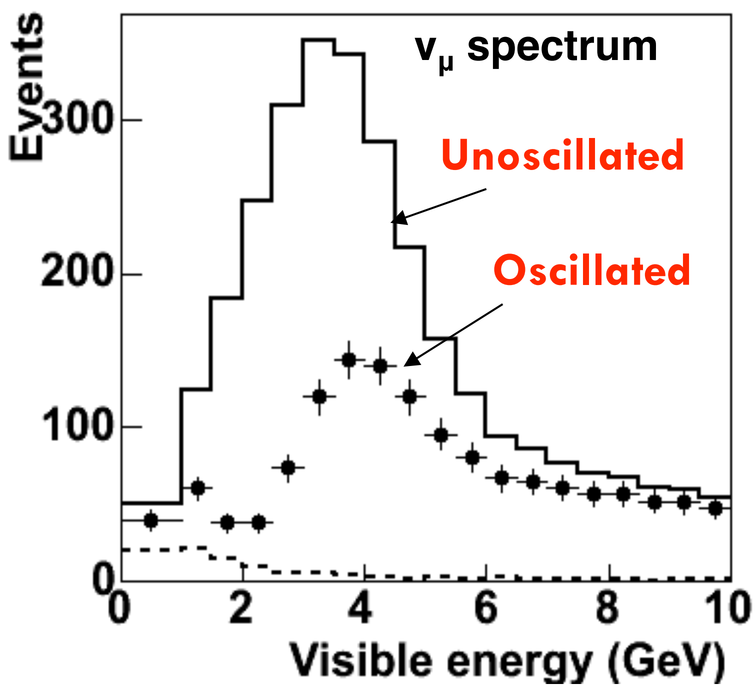

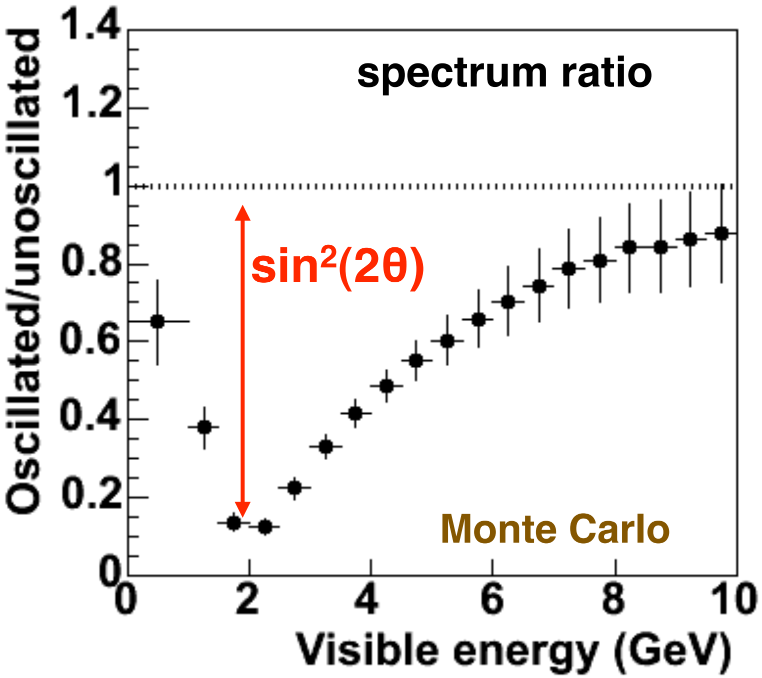

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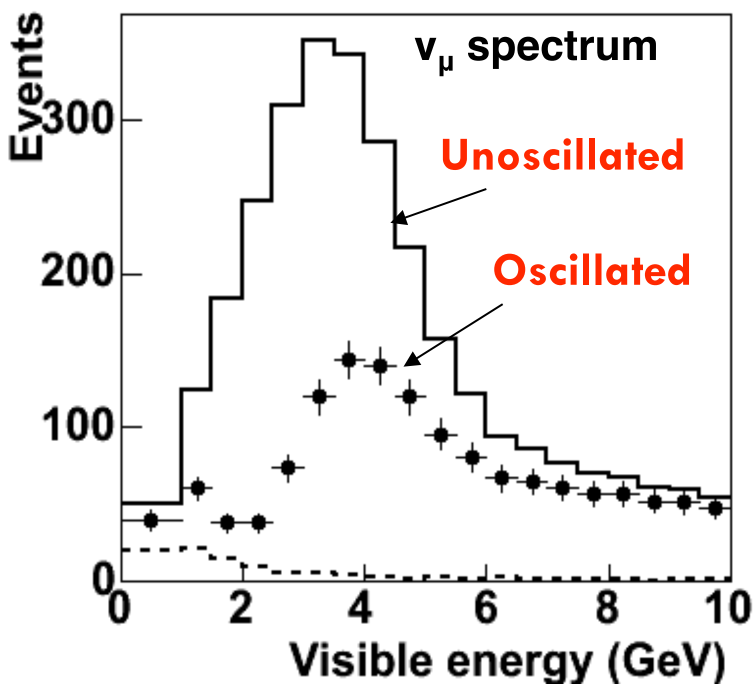
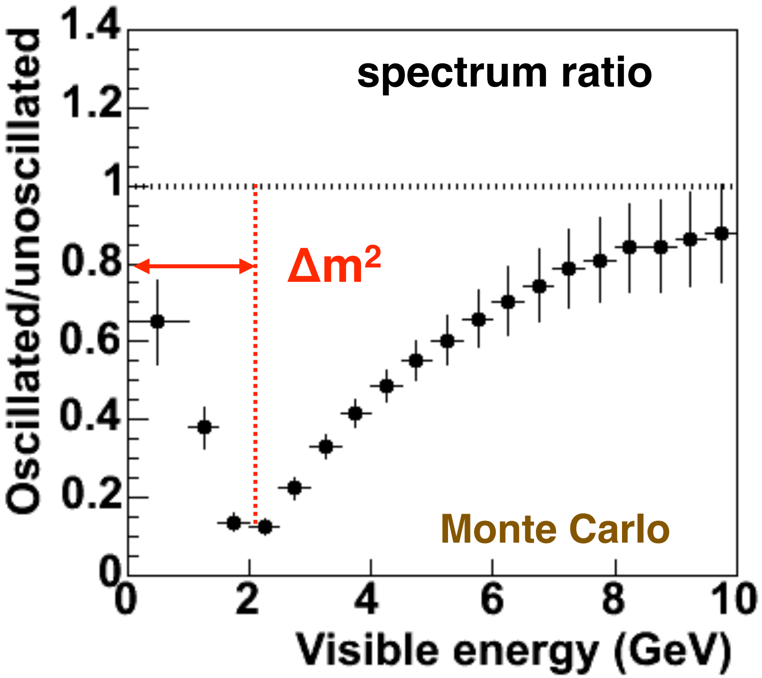
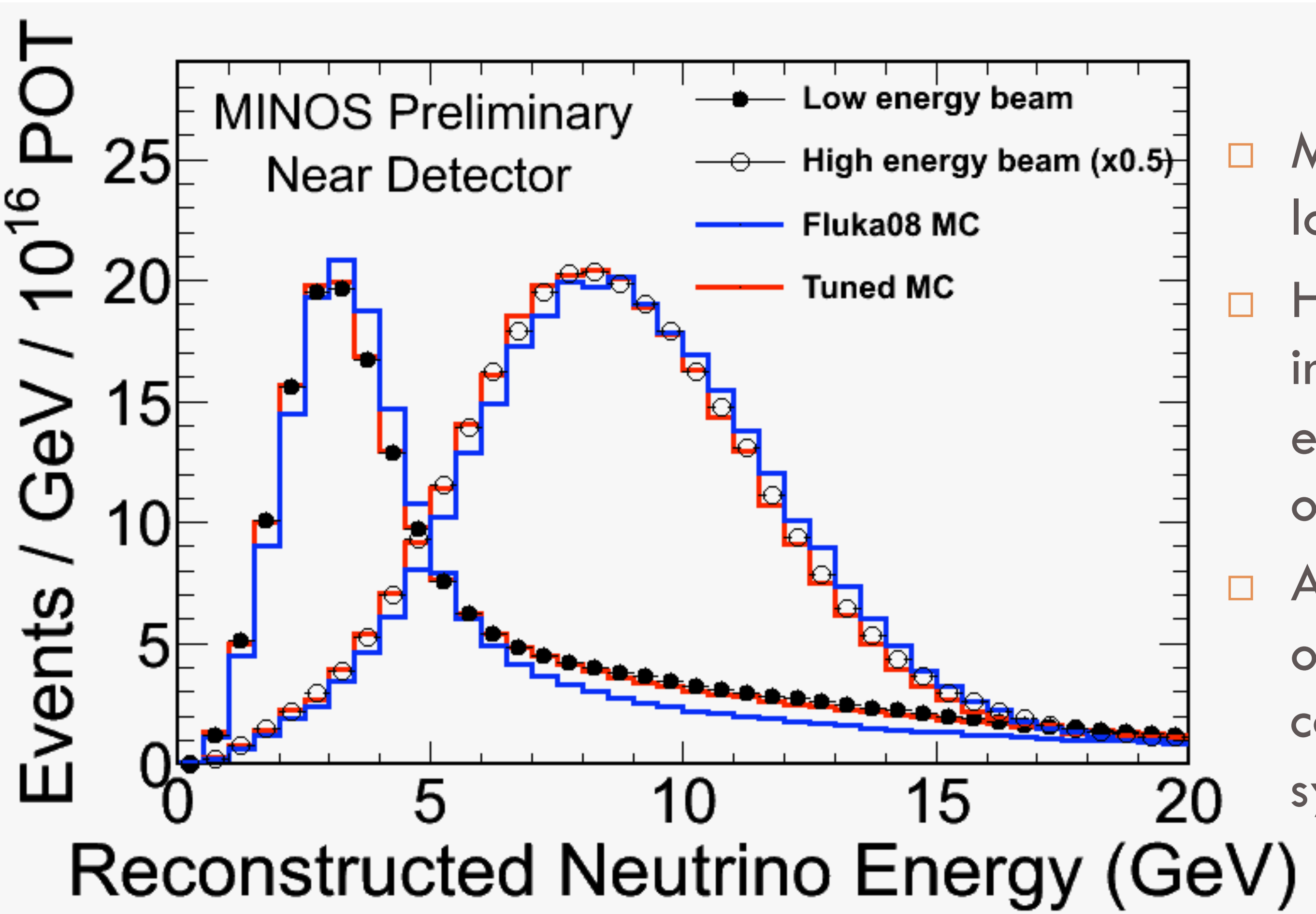


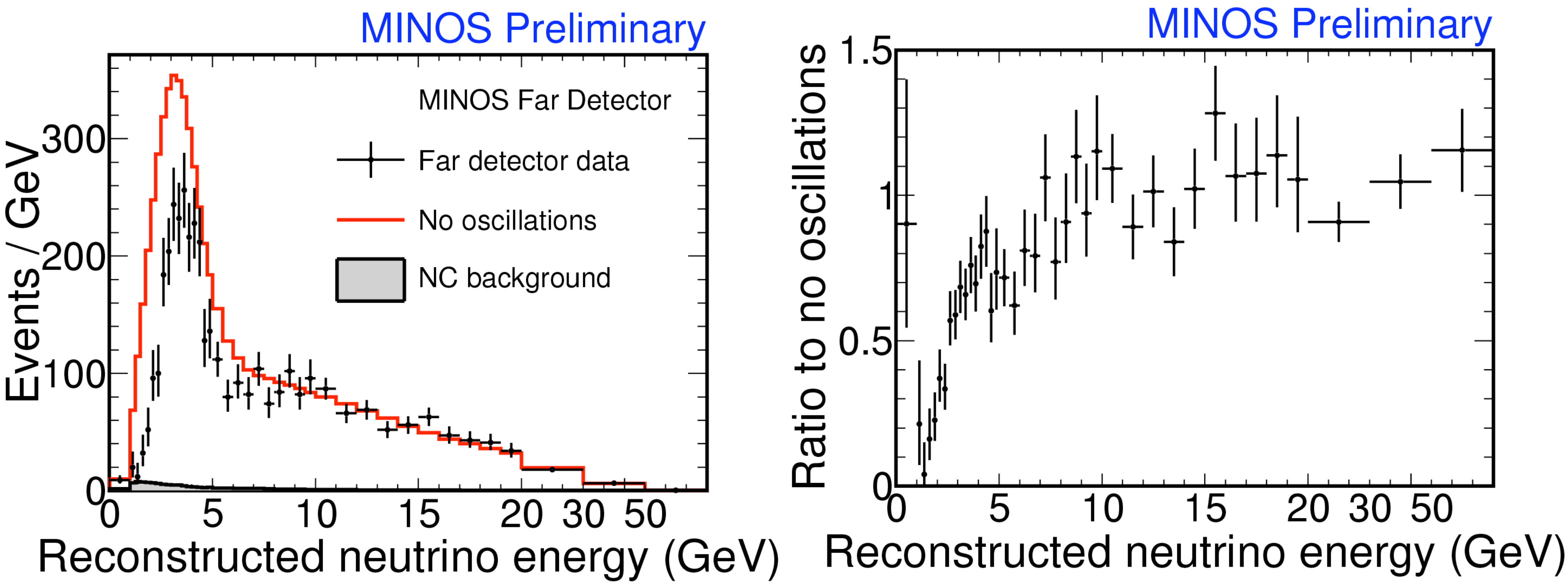


CC events in the Near Detector



- 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

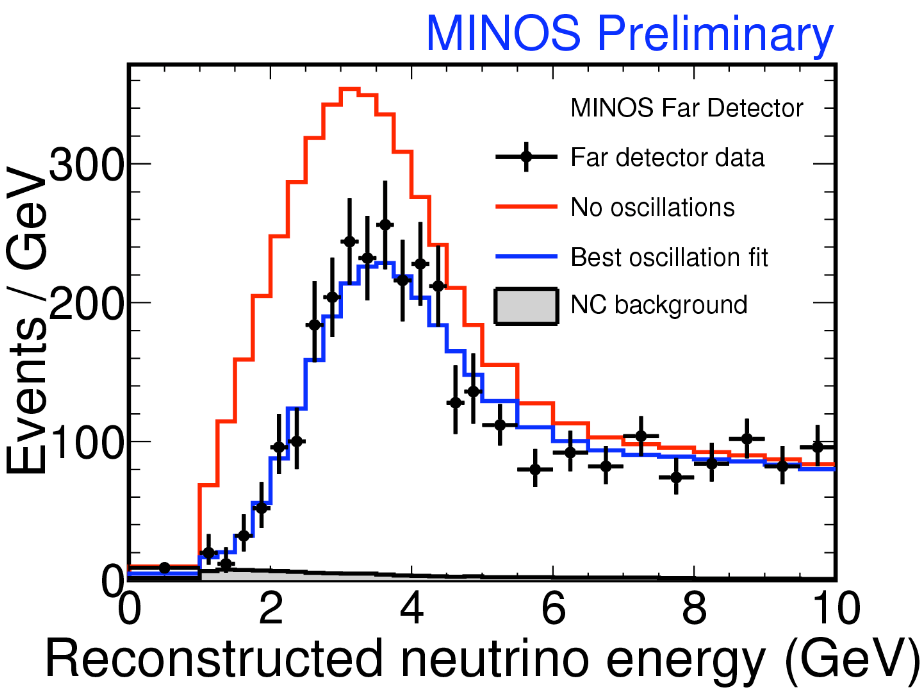
Far Detector Energy Spectrum

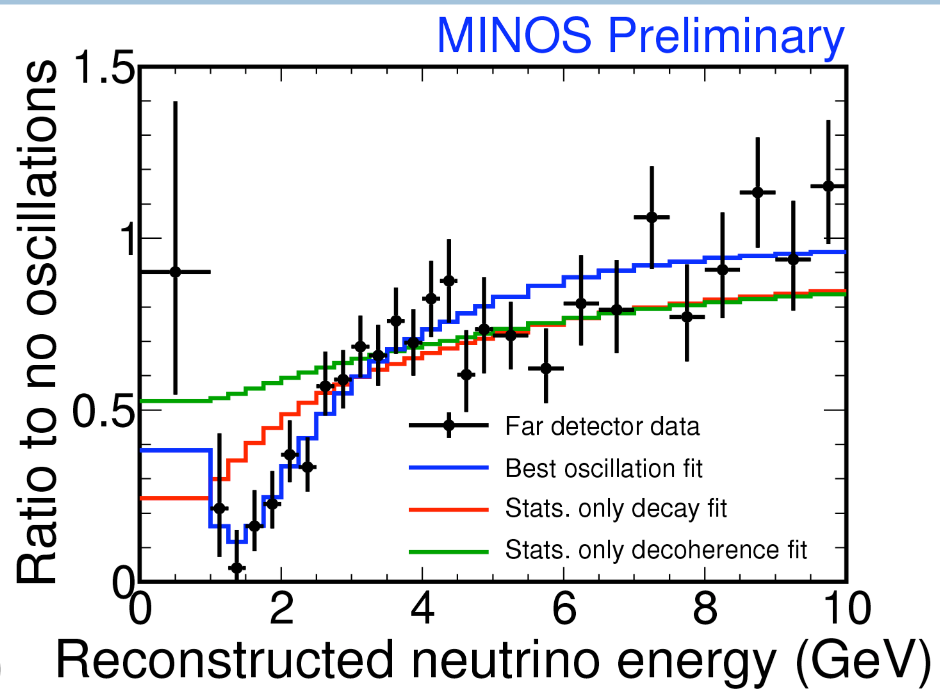


No Oscillations: **2451**

Observation: **1986**

Far Detector Energy Spectrum





- Oscillations fit the data well, 66% of experiments have worse χ^2
- Pure decoherence† disfavored: > **8σ**
- Pure decay‡ disfavored: > **6σ**

(**7.8σ** if NC events included)

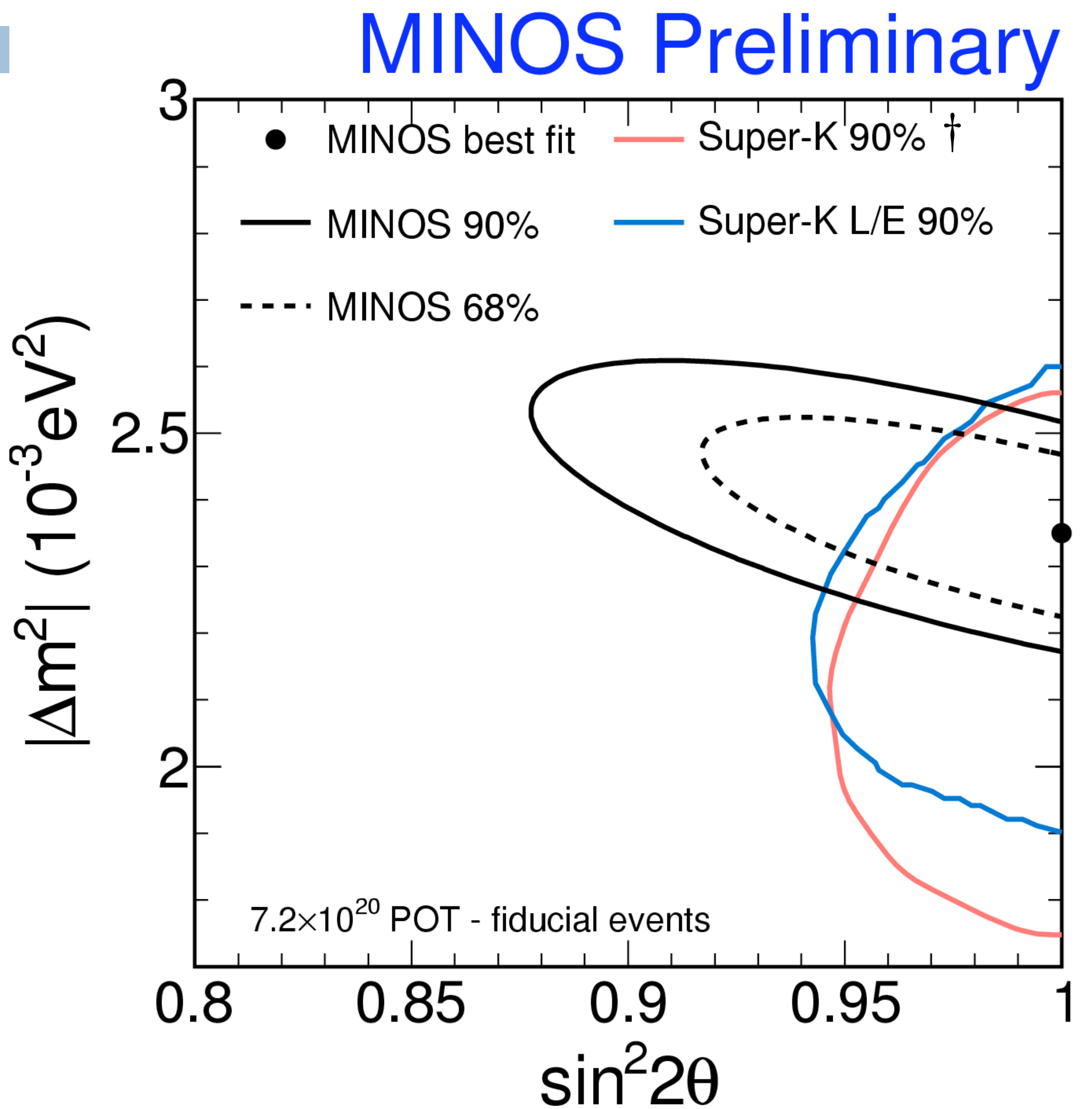
†G.L. Fogli *et al.*, PRD 67:093006 (2003) ‡V. Barger *et al.*,PRL 82:2640 (1999)

Contours

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

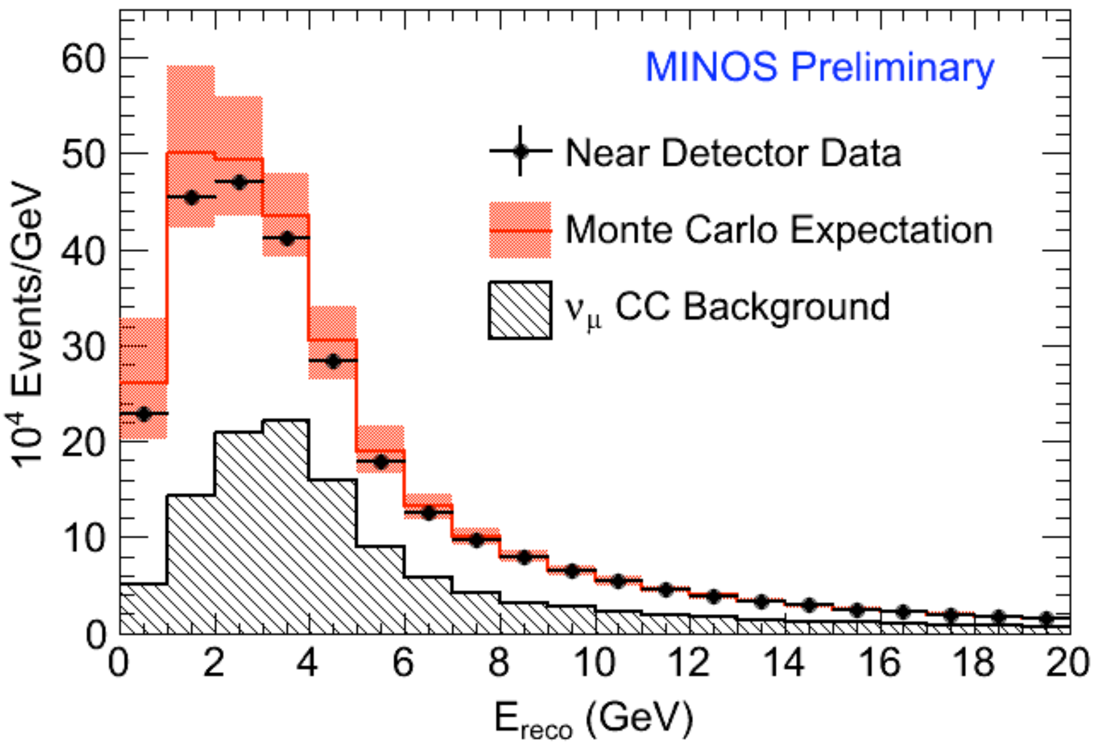
$$\sin^2(2\theta) > 0.91\ (90\%\ \mathrm{C.L.})$$

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



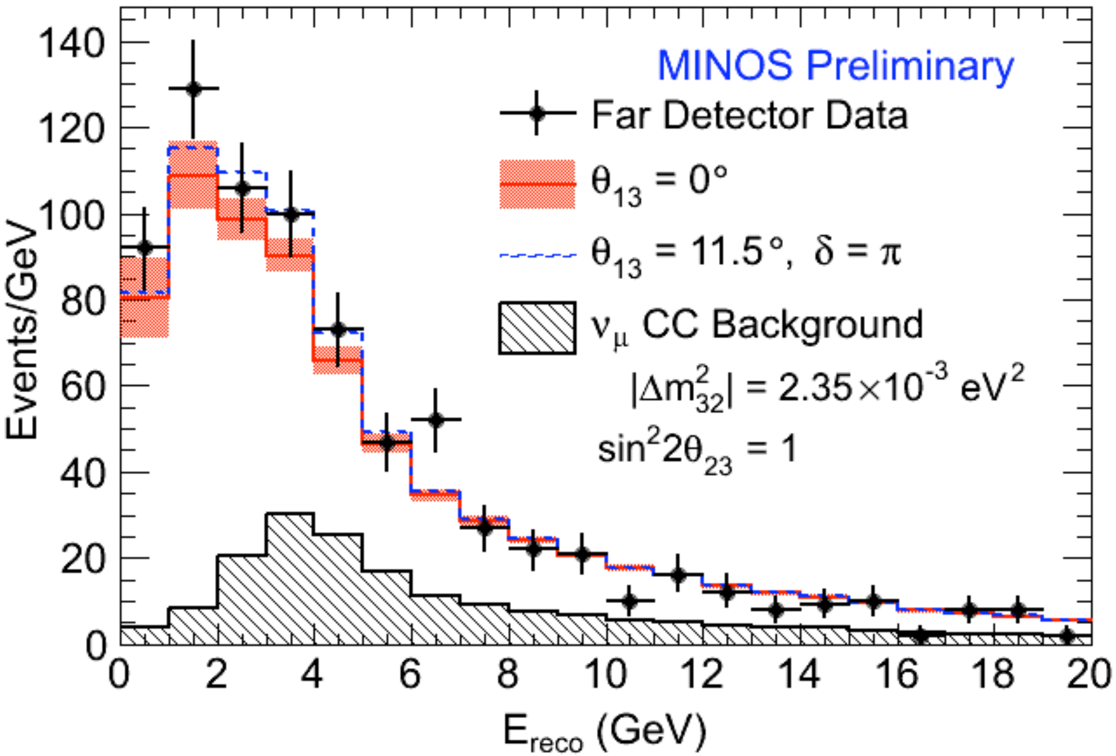
†Super-Kamiokande Collaboration (preliminary)

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)

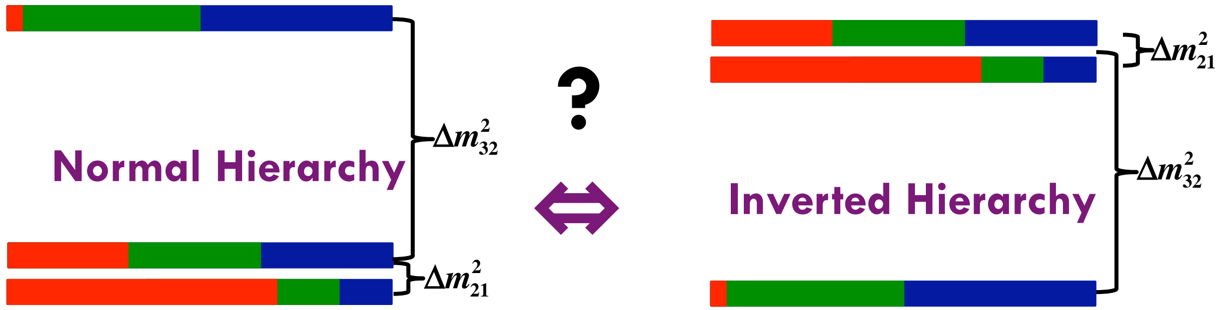
$$f_s \equiv \frac{P_{\nu_\mu \to \nu_s}}{1 - P_{\nu_\mu \to \nu_\mu}} < 0.22\ \ (0.40)\ \text{at } 90\%\ \text{C.L.}$$

no (with) ν_e appearance

ν_e Appearance

- A few percent of the missing ν_μ could change into ν_e depending on value of θ_{13}
- Appearance probability additionally depends on δ_{CP} and mass hierarchy

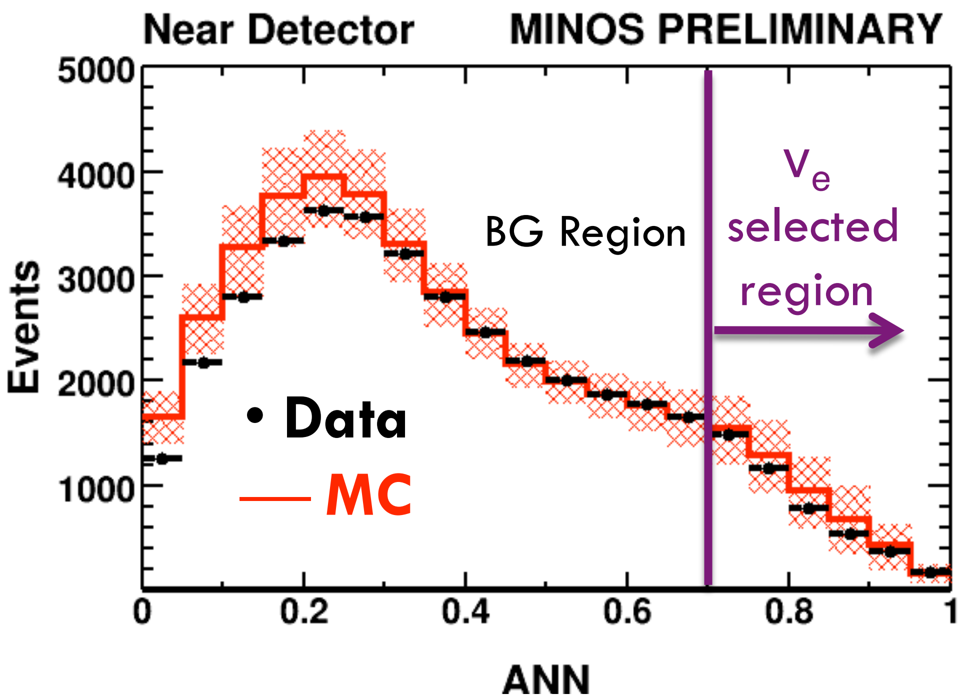
$$P(\nu_\mu \to \nu_e) \approx \sin^2(2\theta_{13})\sin^2(\theta_{23})\sin^2\left(1.27\Delta m^2_{31}\frac{L}{E}\right) +$$
$$\sin^2(2\theta_{12})\cos^2(\theta_{23})\sin^2\left(1.27\Delta m^2_{21}\frac{L}{E}\right) +$$
$$\sin(2\theta_{13})\sin(2\theta_{23})\sin(2\theta_{12})\sin\left(1.27\Delta m^2_{31}\frac{L}{E}\right)\sin\left(1.27\Delta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



P. Vahle, Penn. Dec. 2010

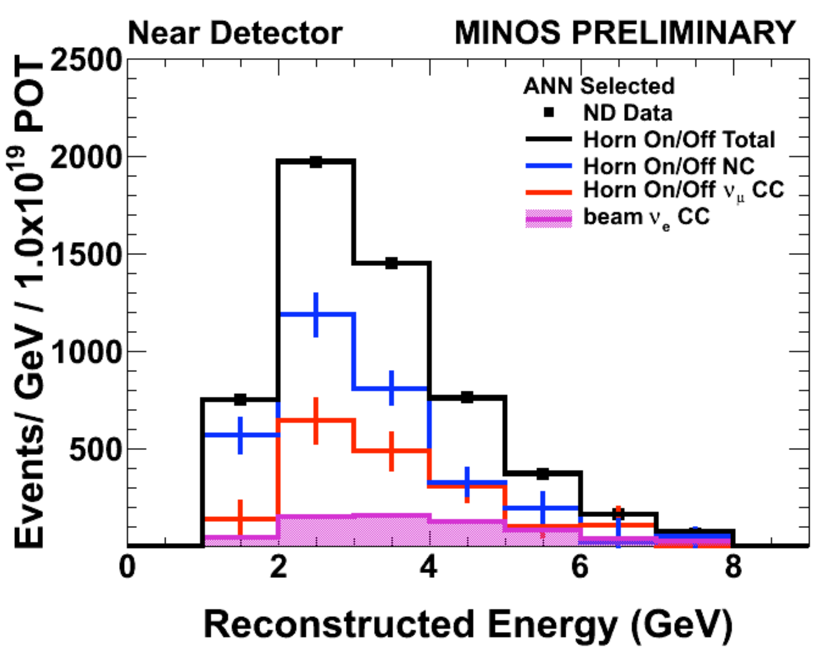
Looking for electron-neutrinos

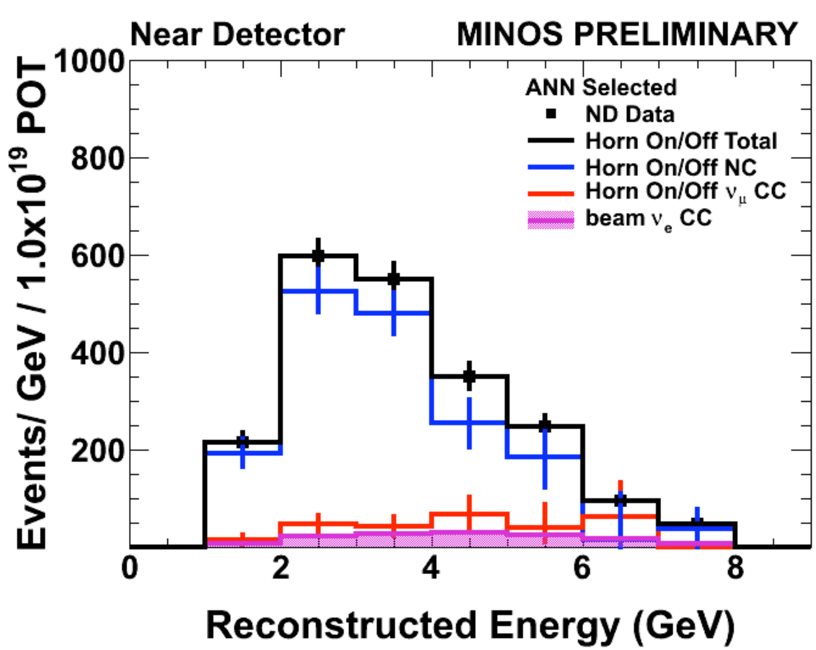
- 11 shape variables in a Neural Net (ANN)
  - characterize longitudinal and transverse energy deposition
- Apply selection to ND data to predict background level in FD
  - NC, CC, beam ν_e each extrapolates differently
  - take advantage of NuMI flexibility to separate background components



Measuring the Background

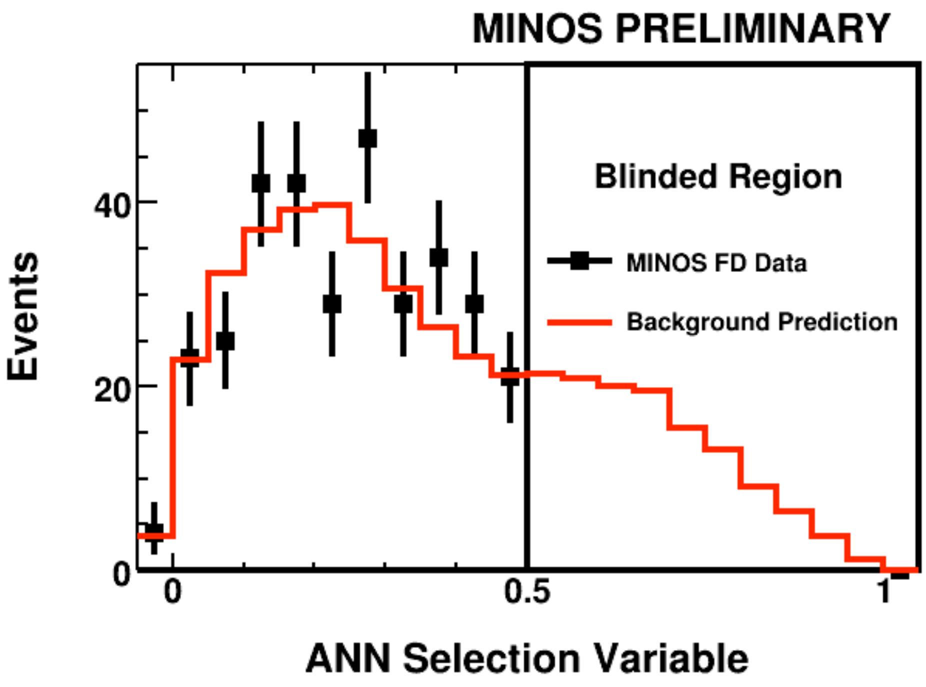
- Turn off the focusing horns—Resulting spectrum is dominated by NC events
- Use ND data in two different configurations to extract relative components of background

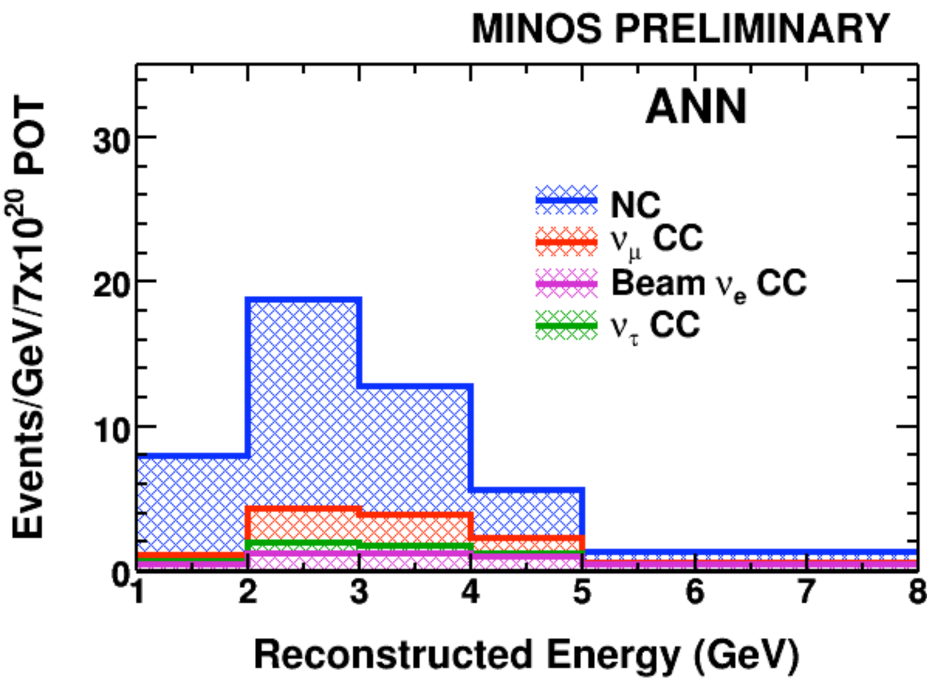




ν_e Appearance Results

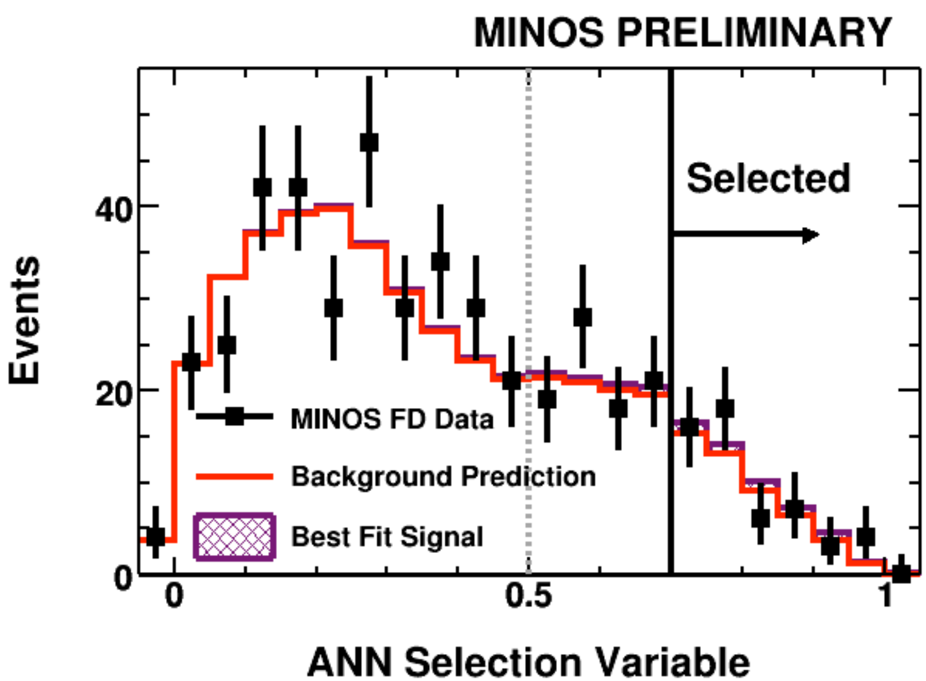
- Based on ND data, expect: **49.1±7.0(stat.)±2.7(syst.)**

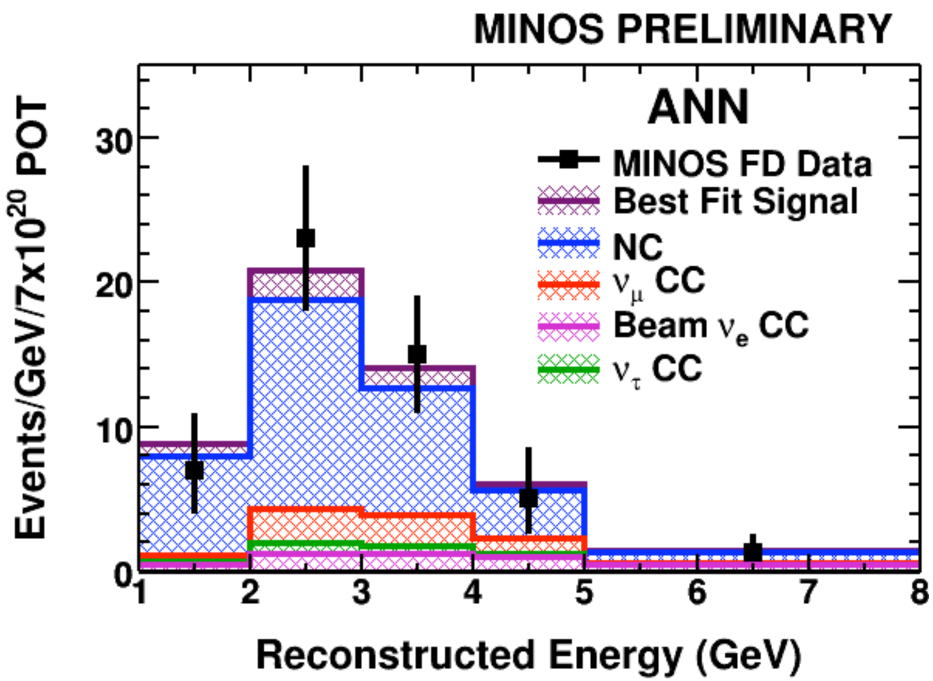




ν_e Appearance Results

- Based on ND data, expect: **49.1±7.0(stat.)±2.7(syst.)**
- Observe: **54** events in the FD, a 0.7σ excess





ν_e Appearance Results

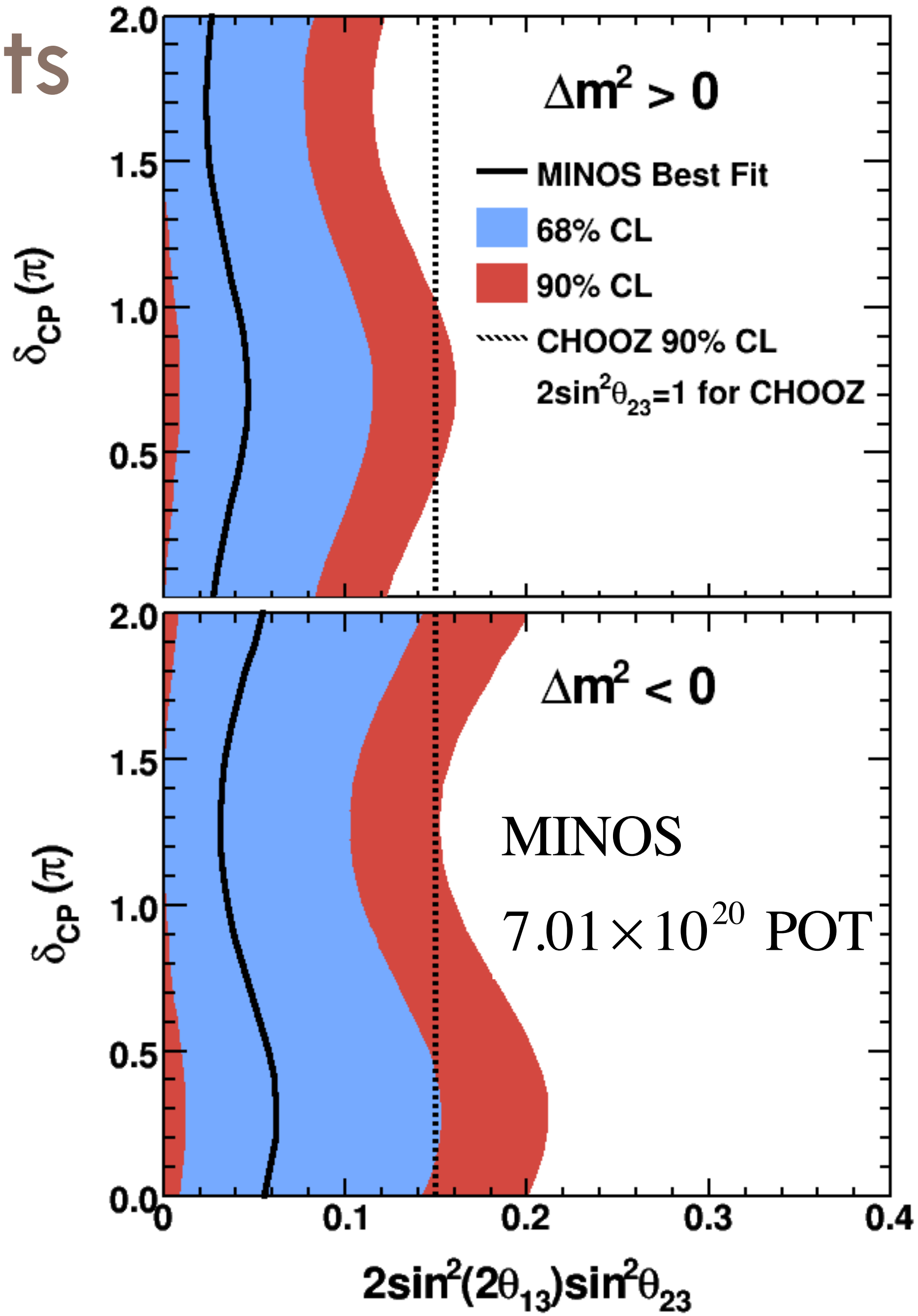
for $\delta_{CP} = 0, \sin^2(2\theta_{23}) = 1,$

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

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

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

at 90% C.L.



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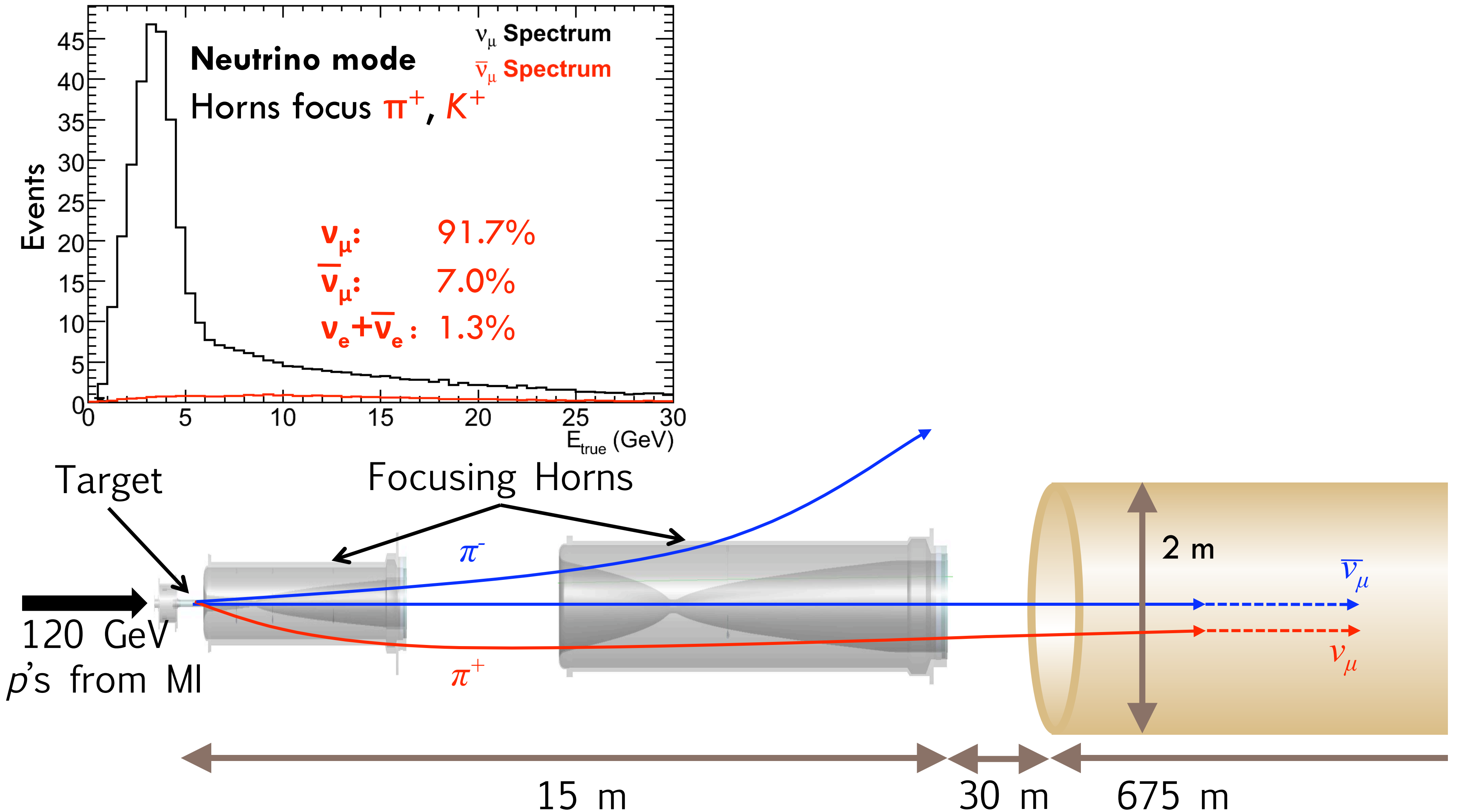
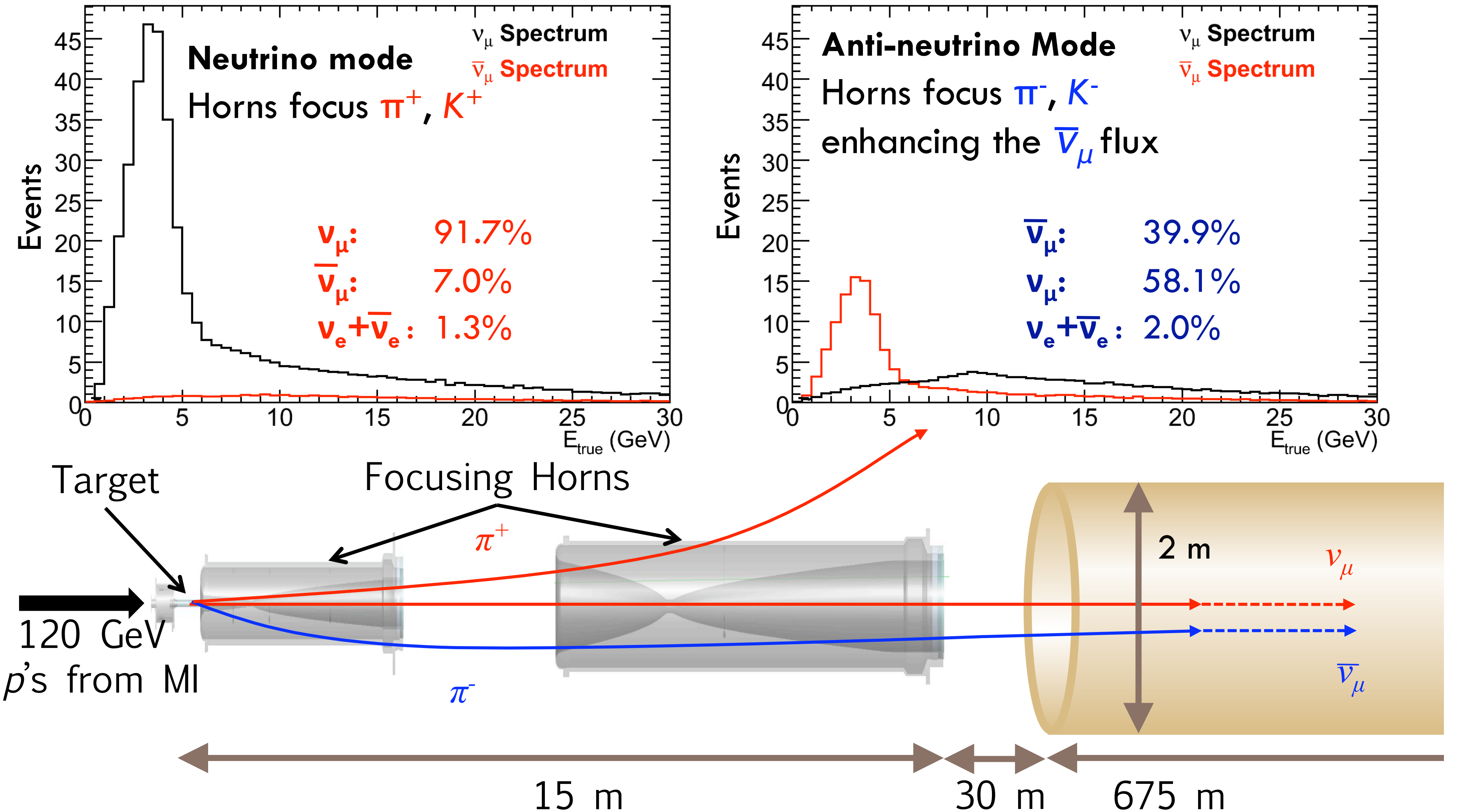
Making an anti-neutrino beam

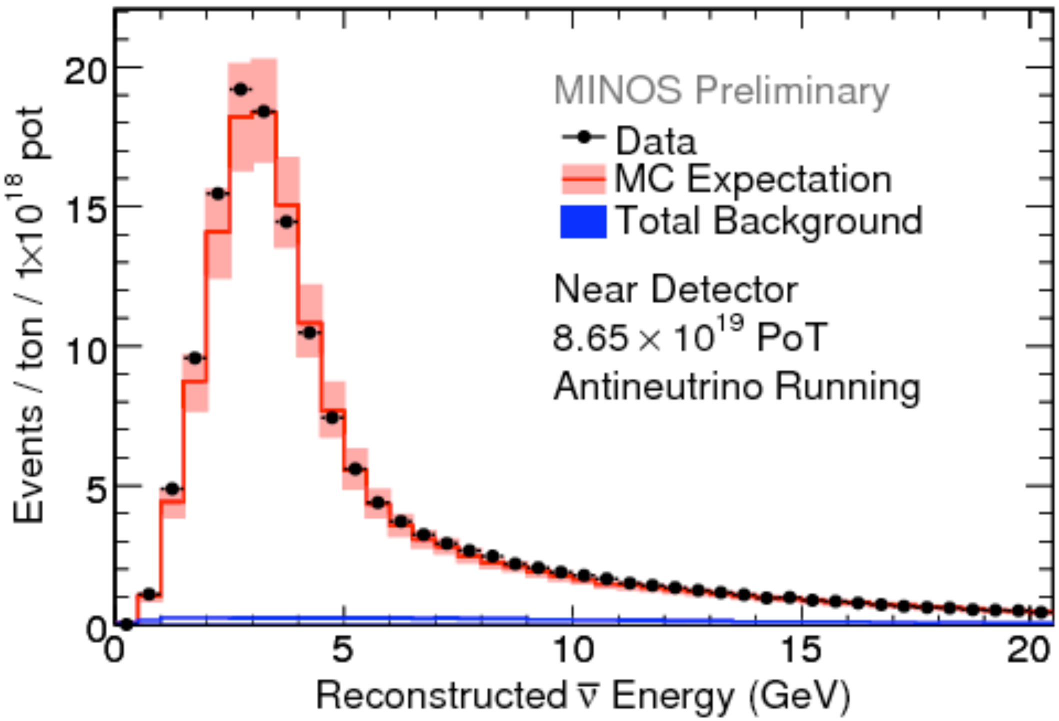


Making an anti-neutrino beam

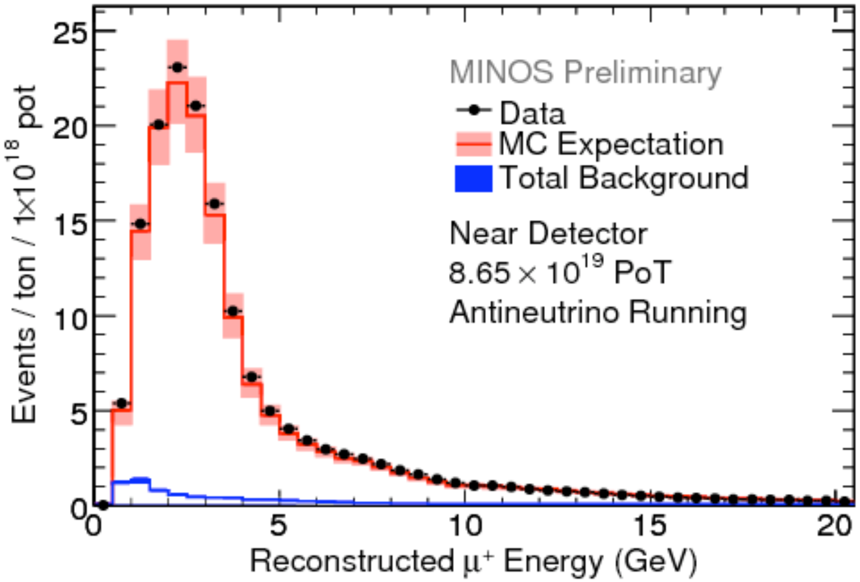


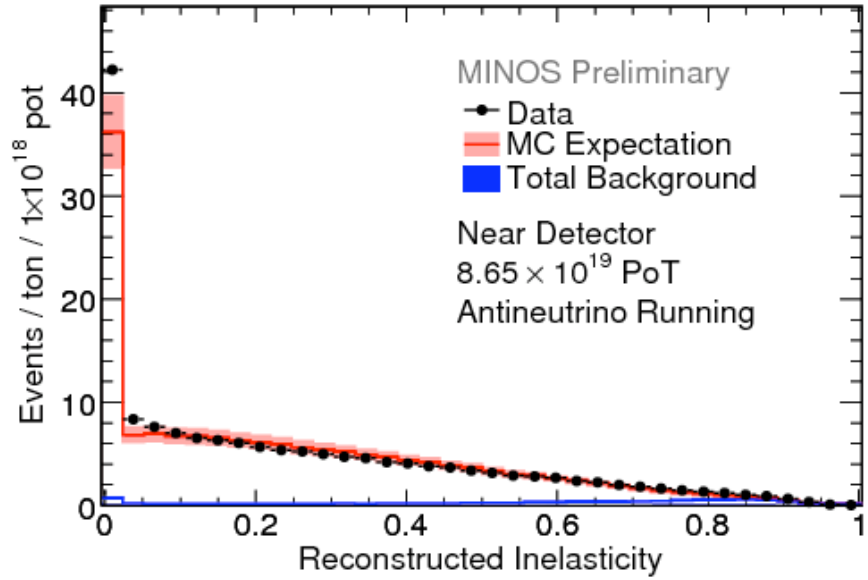
ND Anti-neutrino Data

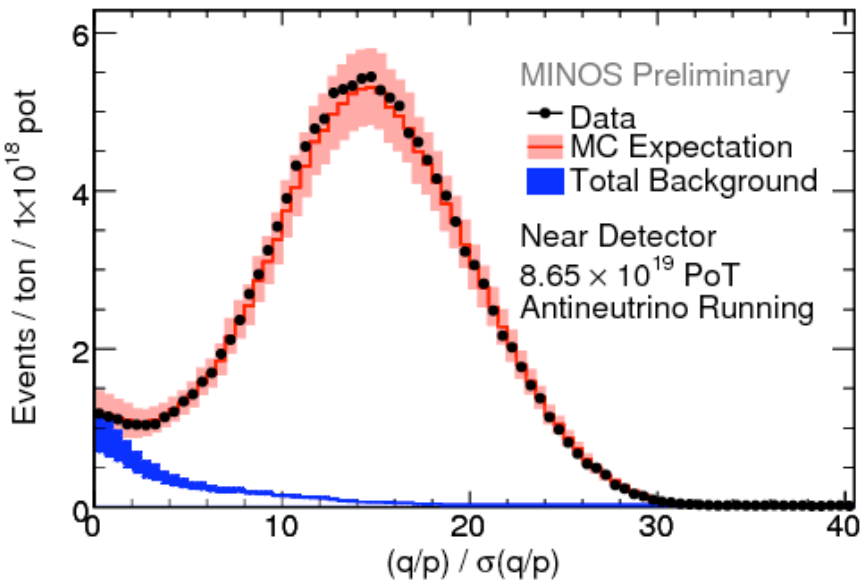
- Focus and select positive muons
  - purity 94.3% after charge sign cut
  - purity 98% < 6GeV
- Analysis proceeds as (2008) neutrino analysis
- Data/MC agreement comparable to neutrino running
  - different average kinematic distributions
  - more forward muons



ND Data

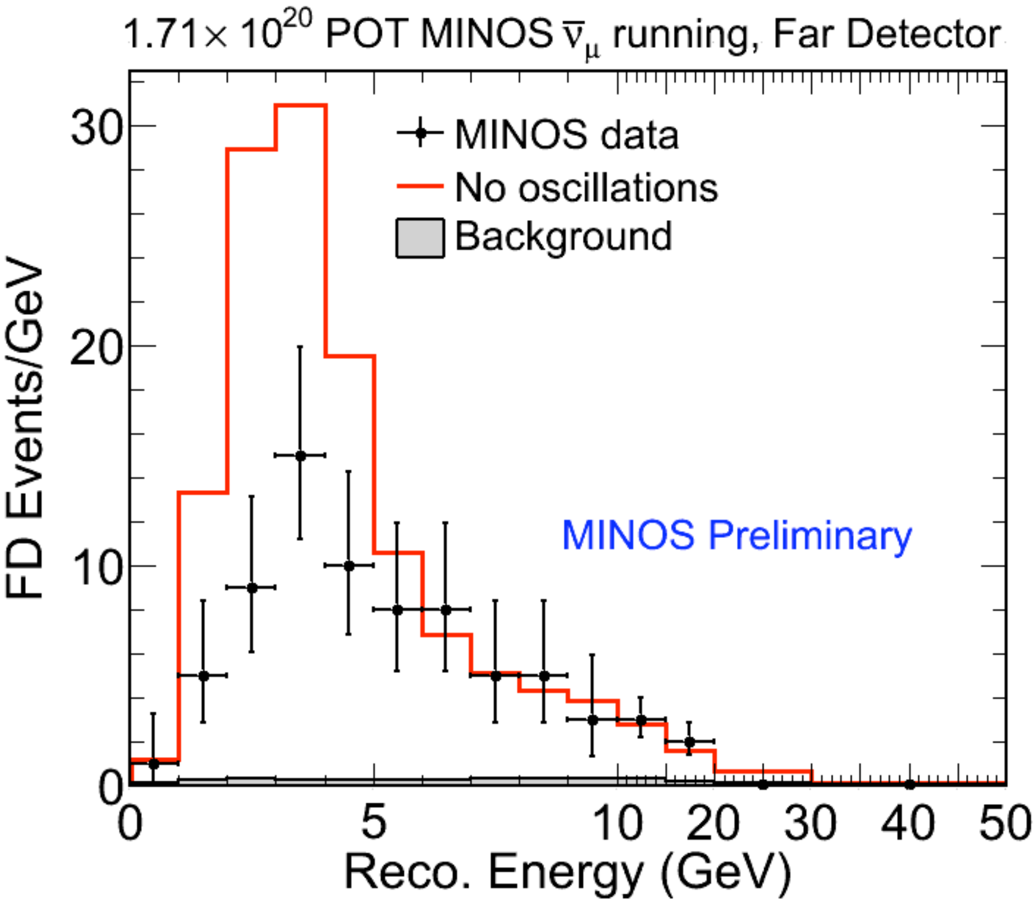






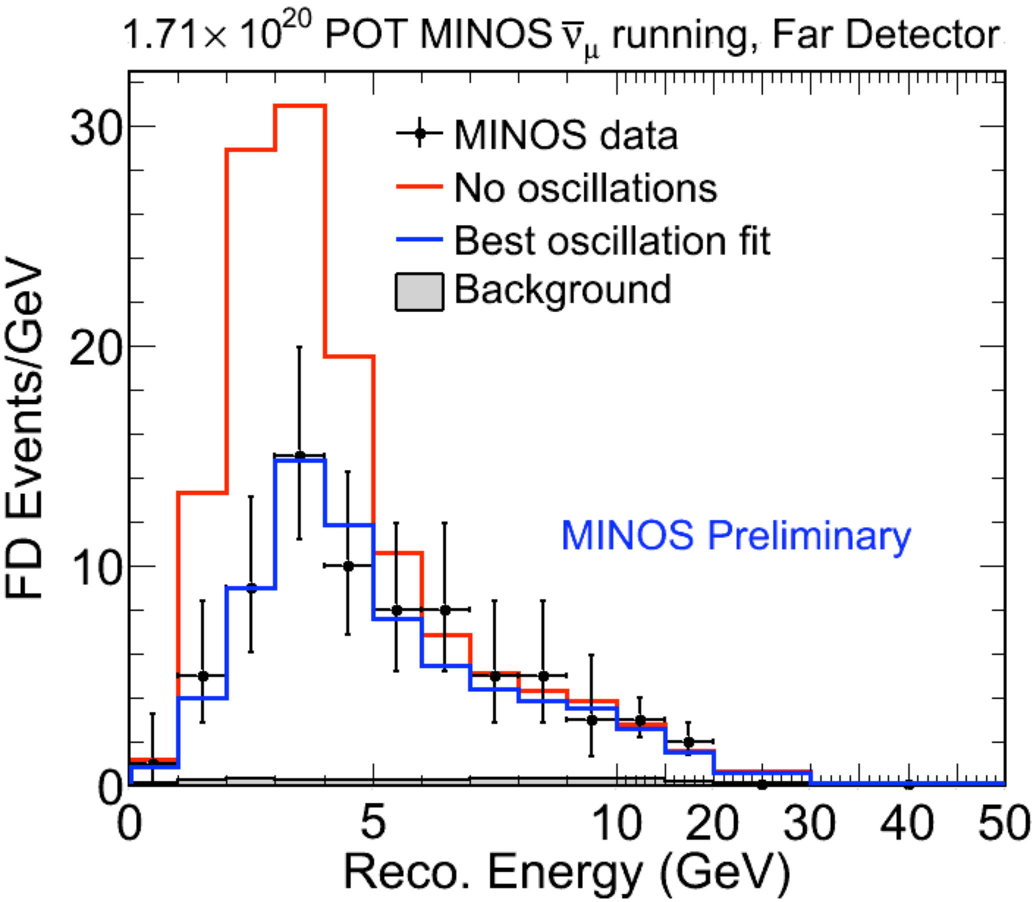
- Data/MC agreement comparable to neutrino running

FD Data



- No oscillation Prediction: **155**
- Observe: **97**
- No oscillations disfavored at 6.3σ

FD Data

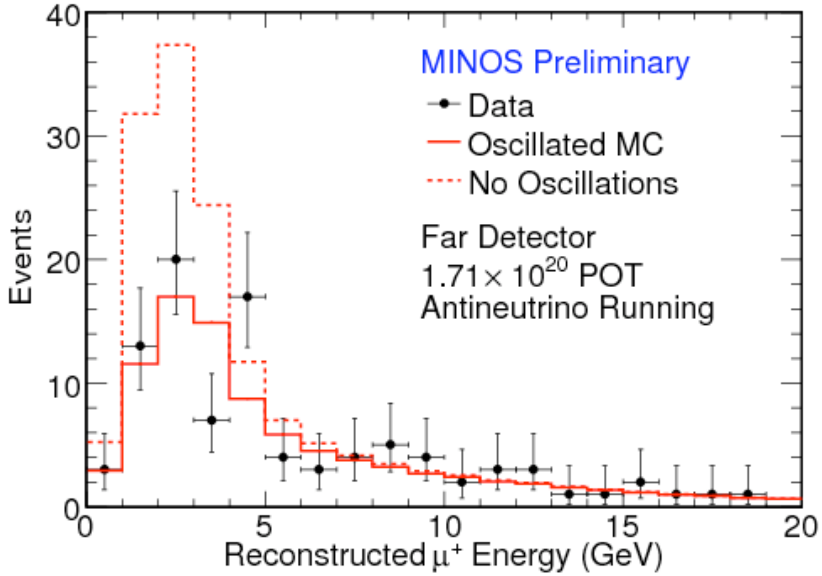


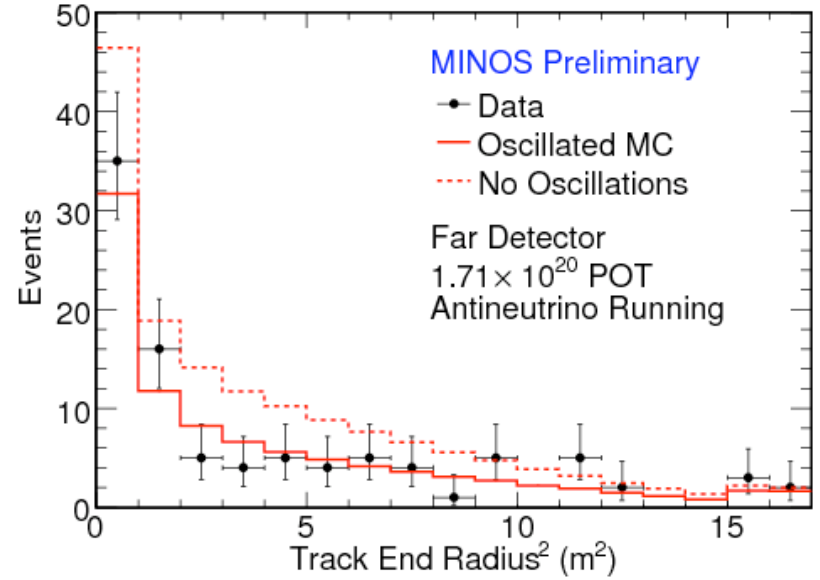
- No oscillation Prediction: **155**
- Observe: **97**
- No oscillations disfavored at 6.3σ

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

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

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
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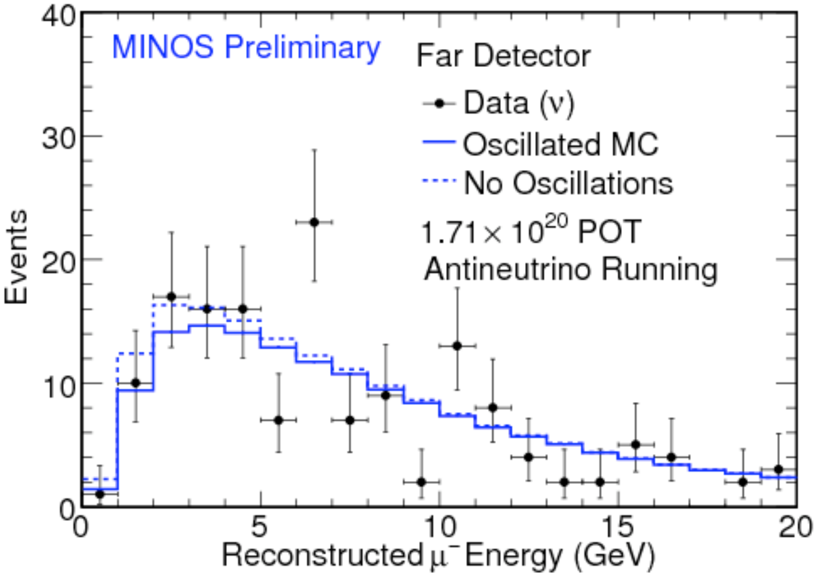
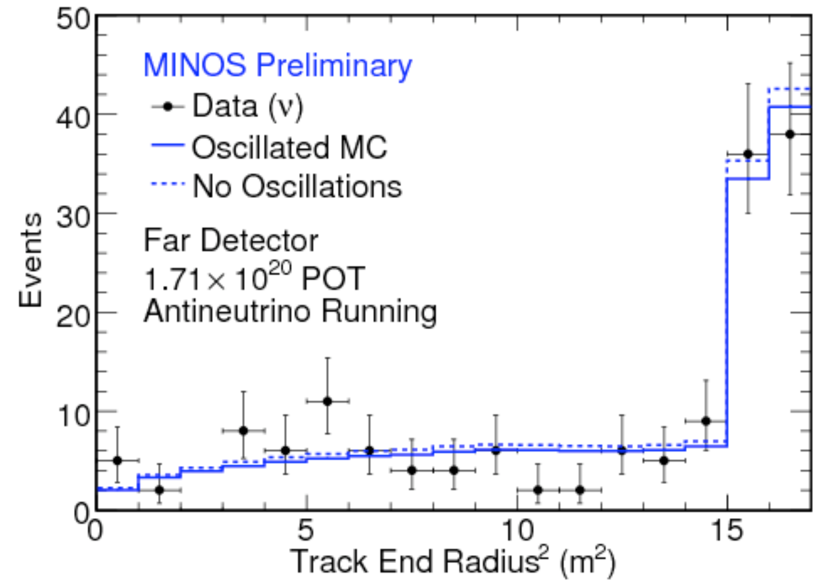
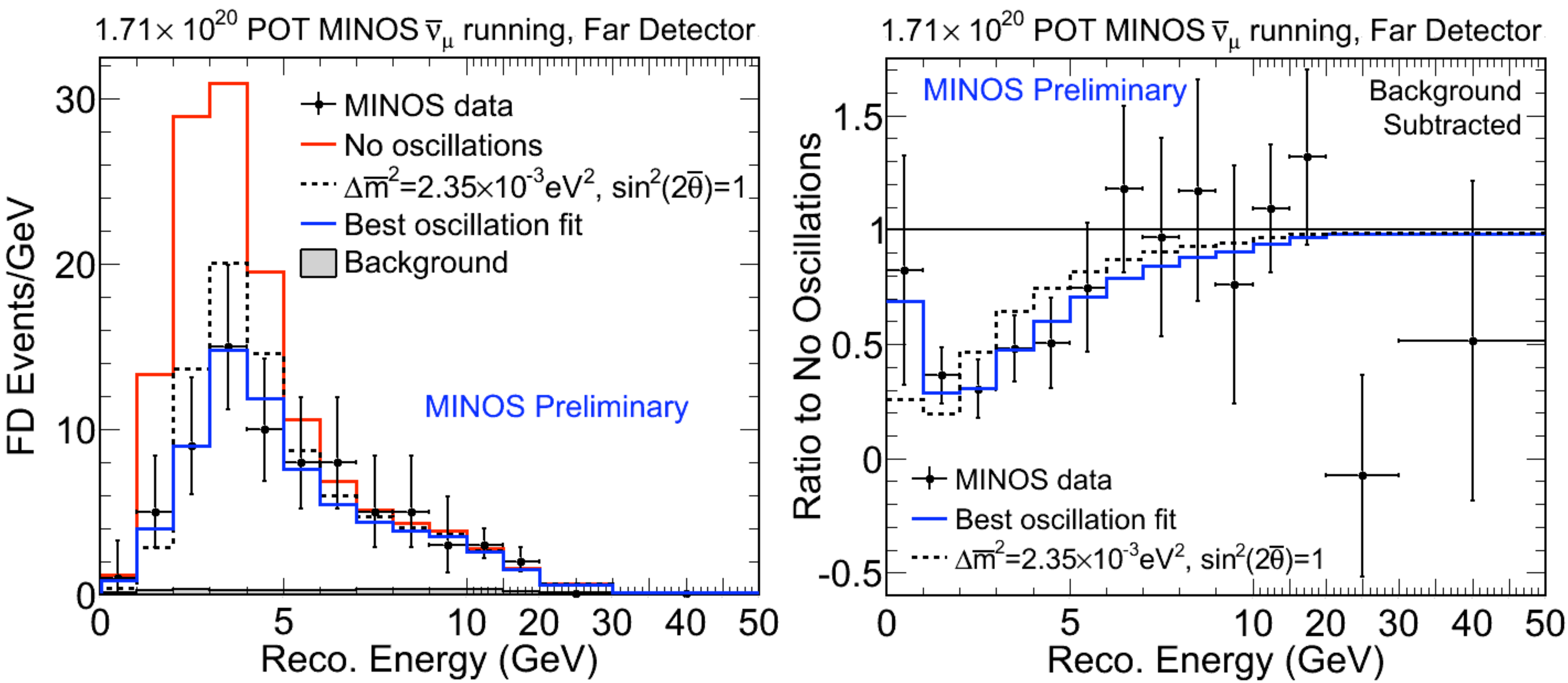
Far Detector
1.71× 10^20 POT
Antineutrino Running
Events
Track End Radius² (m²)

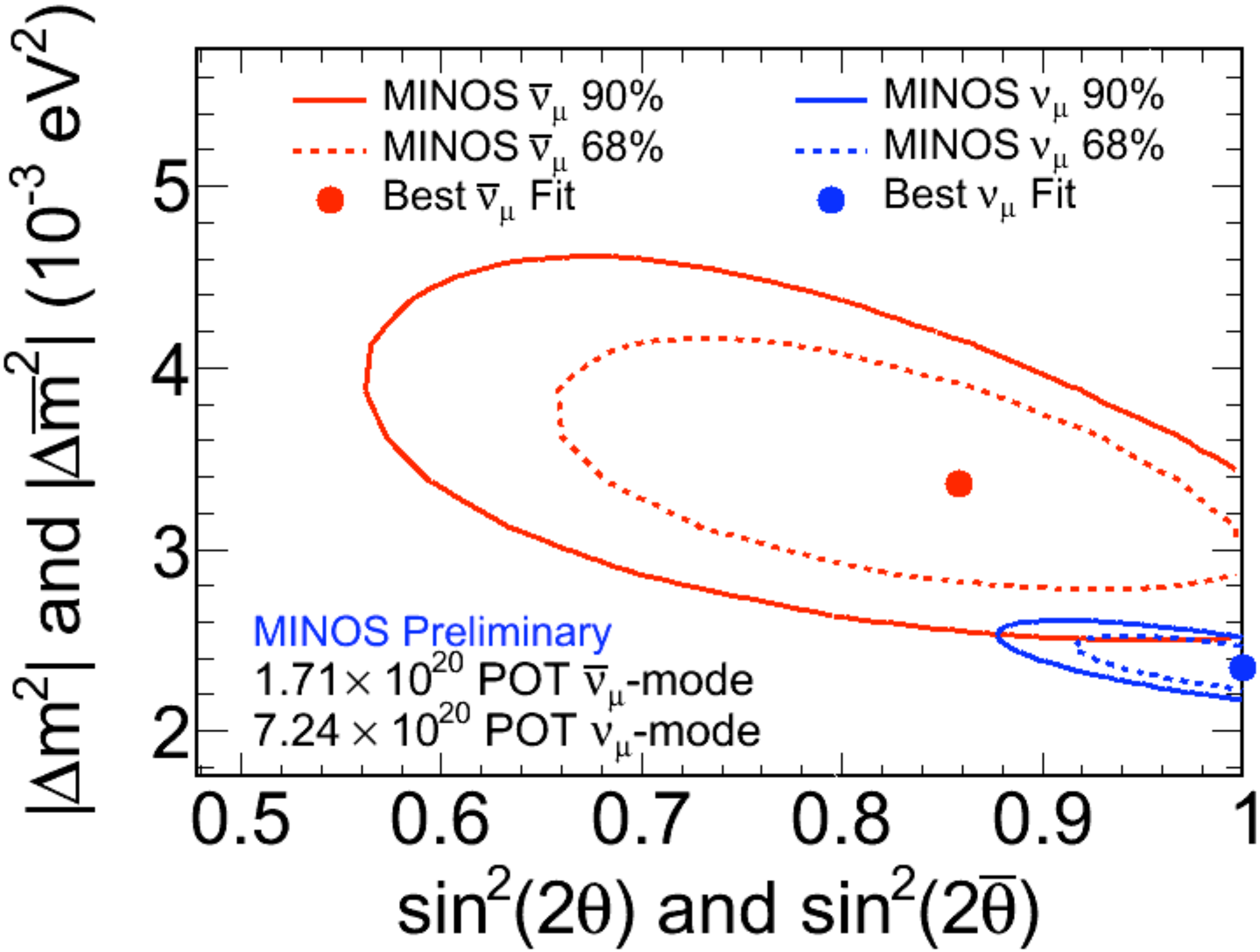

MINOS Preliminary
Far Detector
Data (ν)
Oscillated MC
No Oscillations
1.71× 10^20 POT
Antineutrino Running
Events
Reconstructed μ− Energy (GeV)


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

Comparisons to Neutrinos

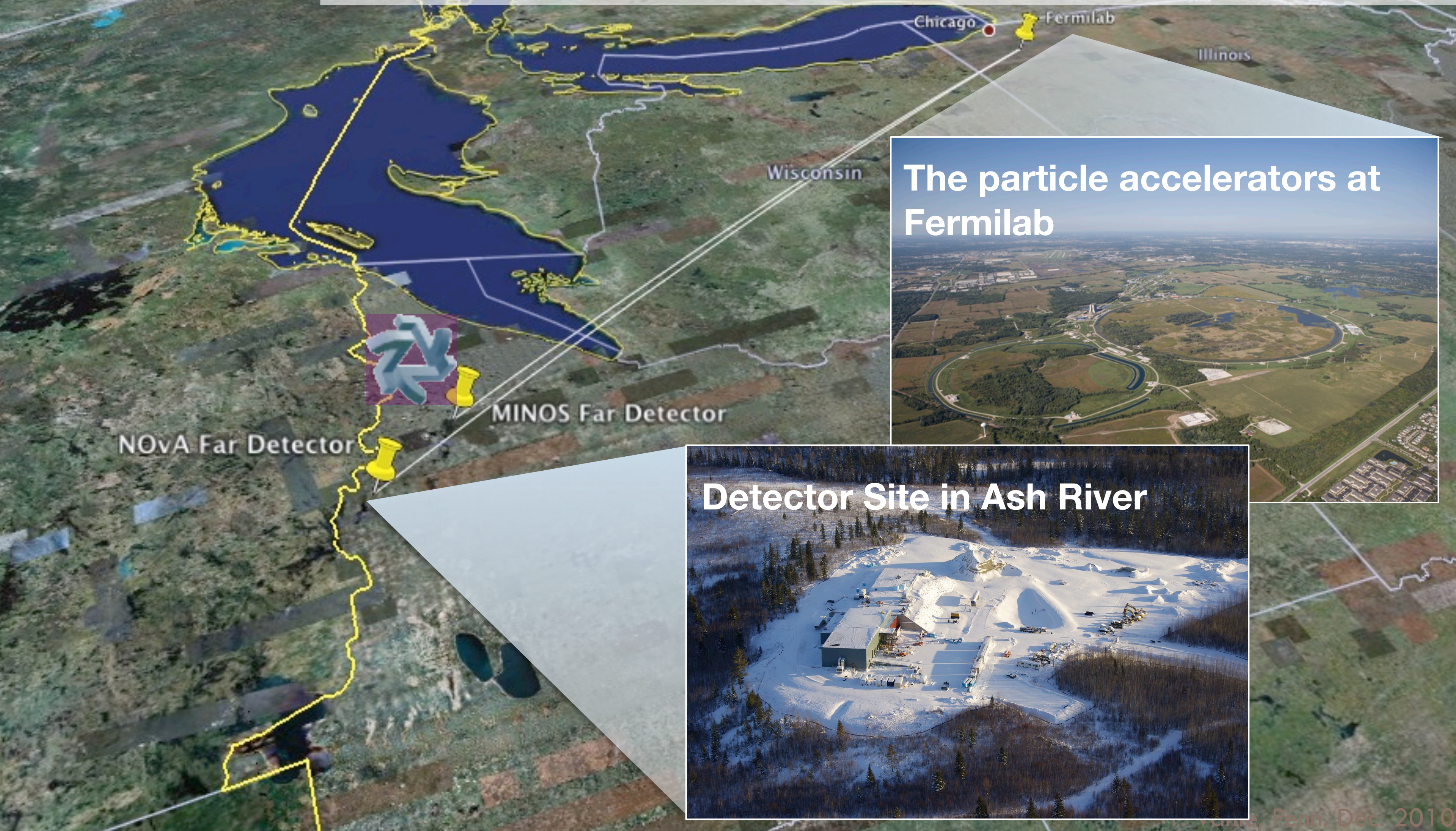


Comparisons to Neutrinos



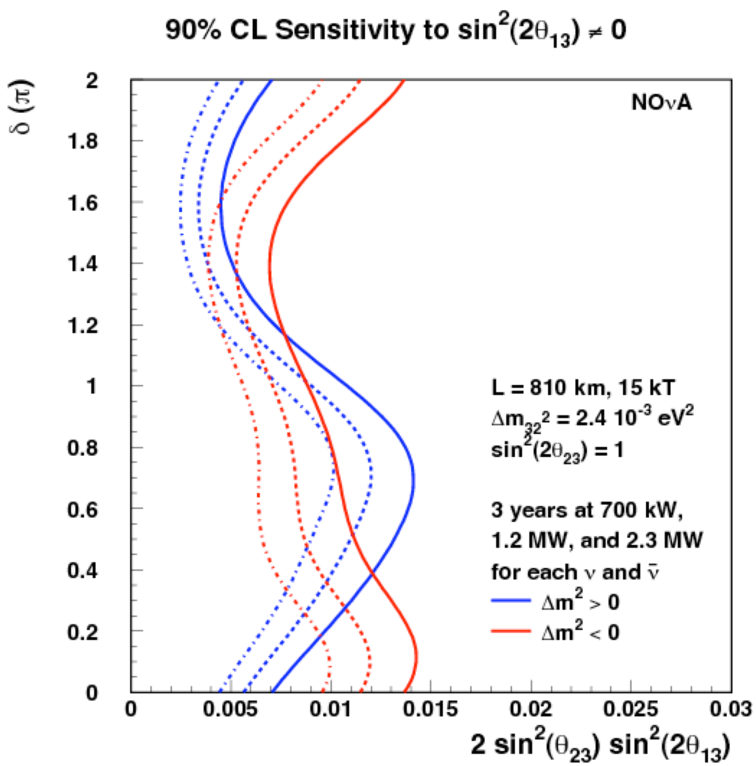
NOvA

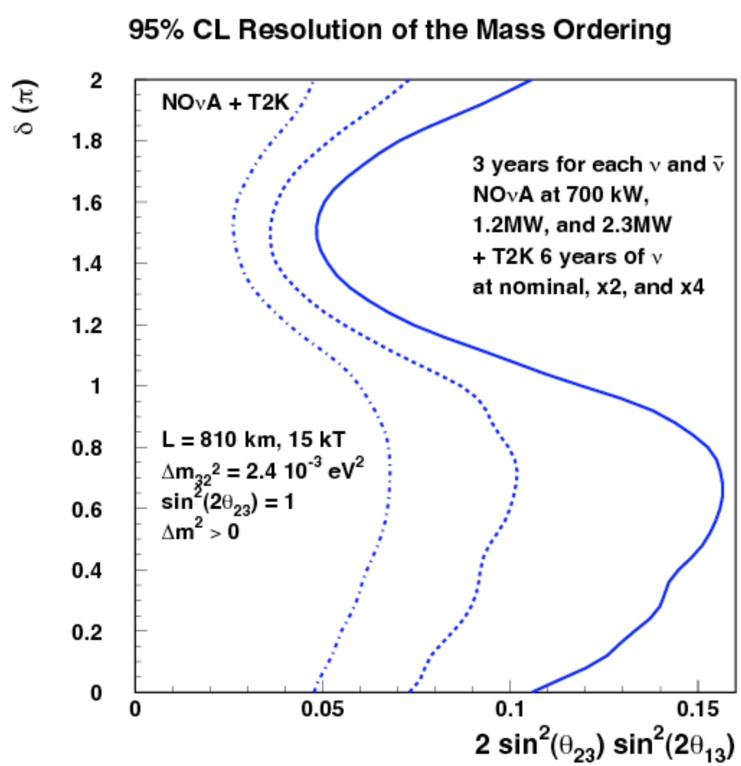
- 2 detector, 810 km baseline off-axis neutrino experiment in upgraded NuMI beam line
- Search for $\nu_\mu \rightarrow \nu_e$ oscillations with an order of magnitude more sensitivity than MINOS



NOvA

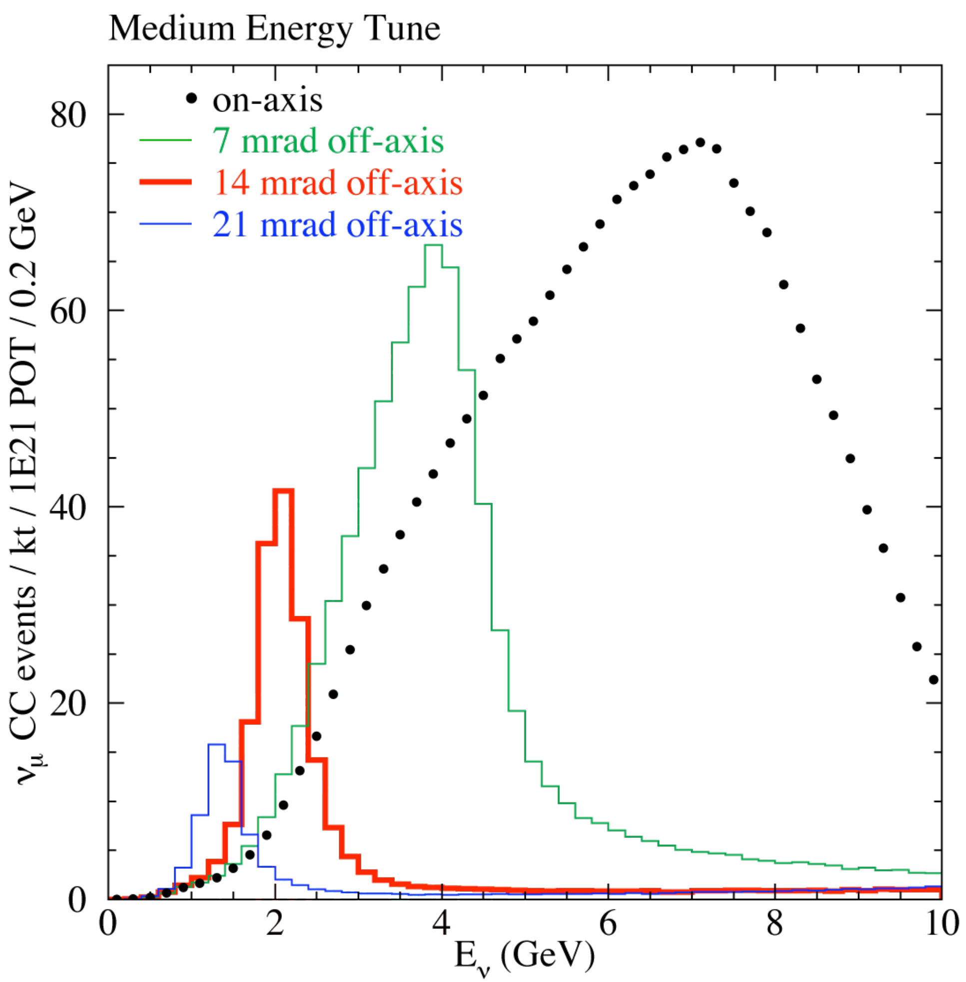
- Physics goals:
  - Measurement of θ_{13}
  - Determining the ordering of mass hierarchy
  - Measure δ_{CP} violating phase



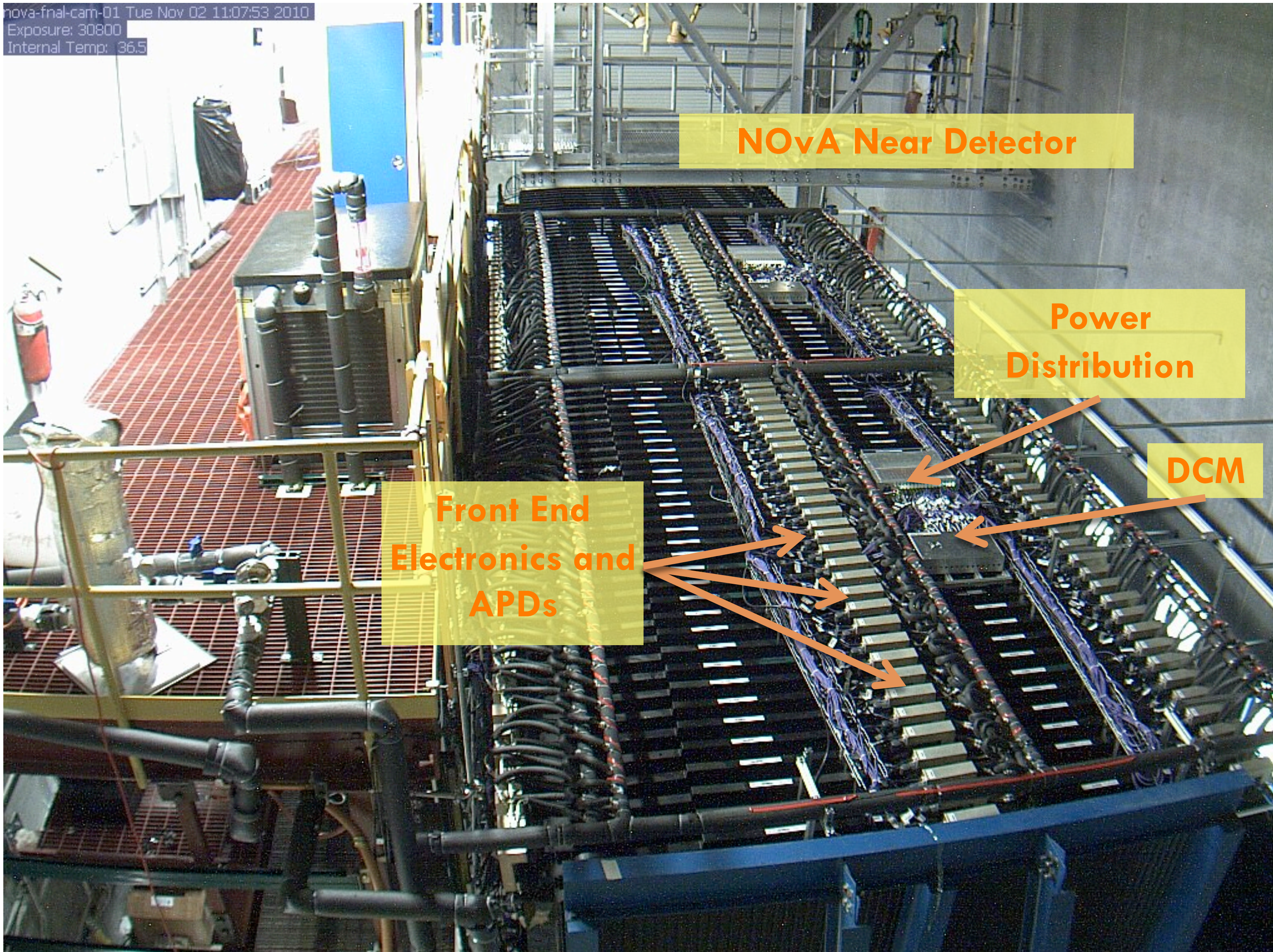


NOvA

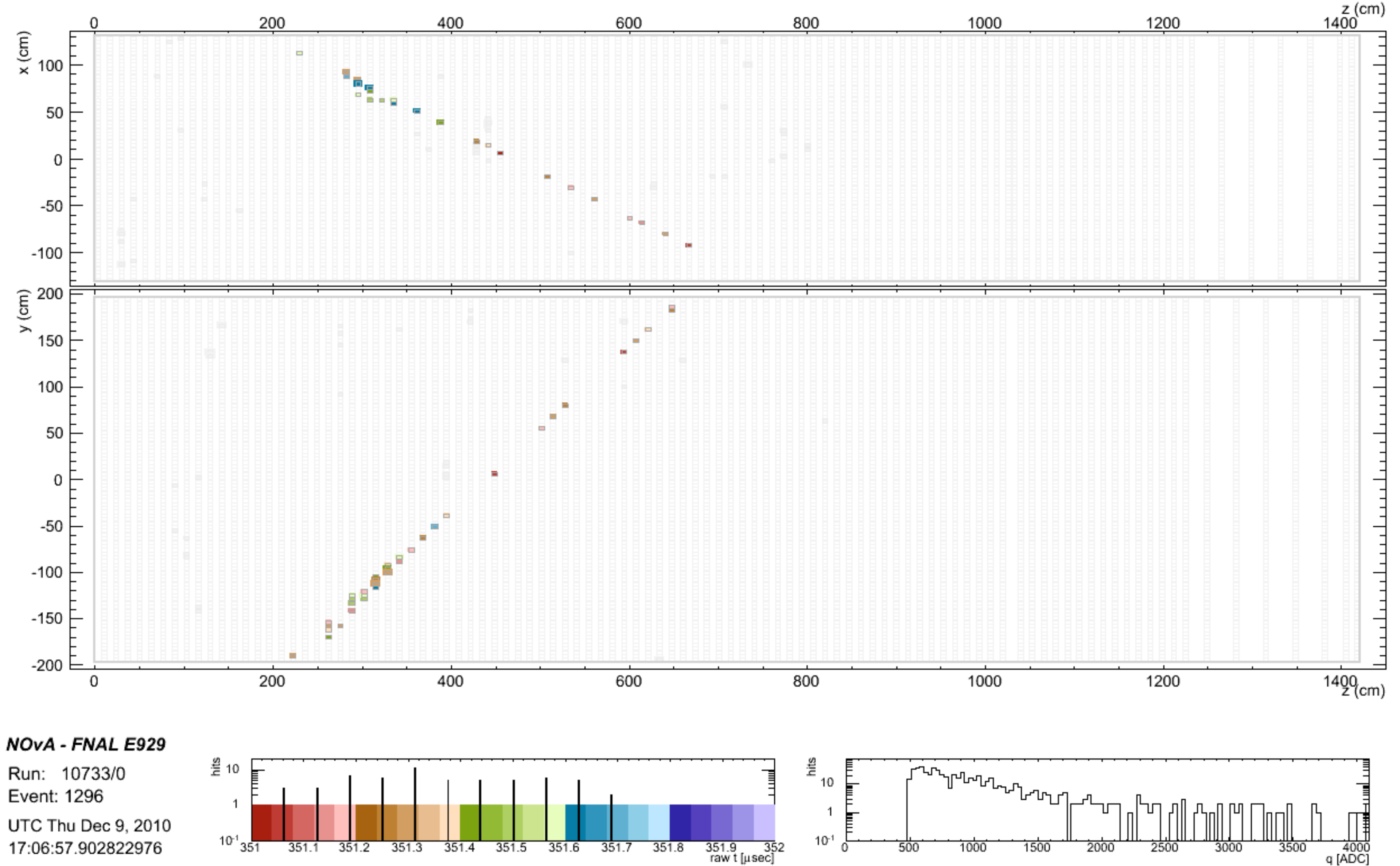
- Big Detector
  - 18 kton
- Higher beam power
- Off Axis design
  - narrow band beam peaked at oscillation max
  - fewer feed down event from high energy NCs
- Improved signal/BG discrimination
- Improved knowledge of cross sections for backgrounds



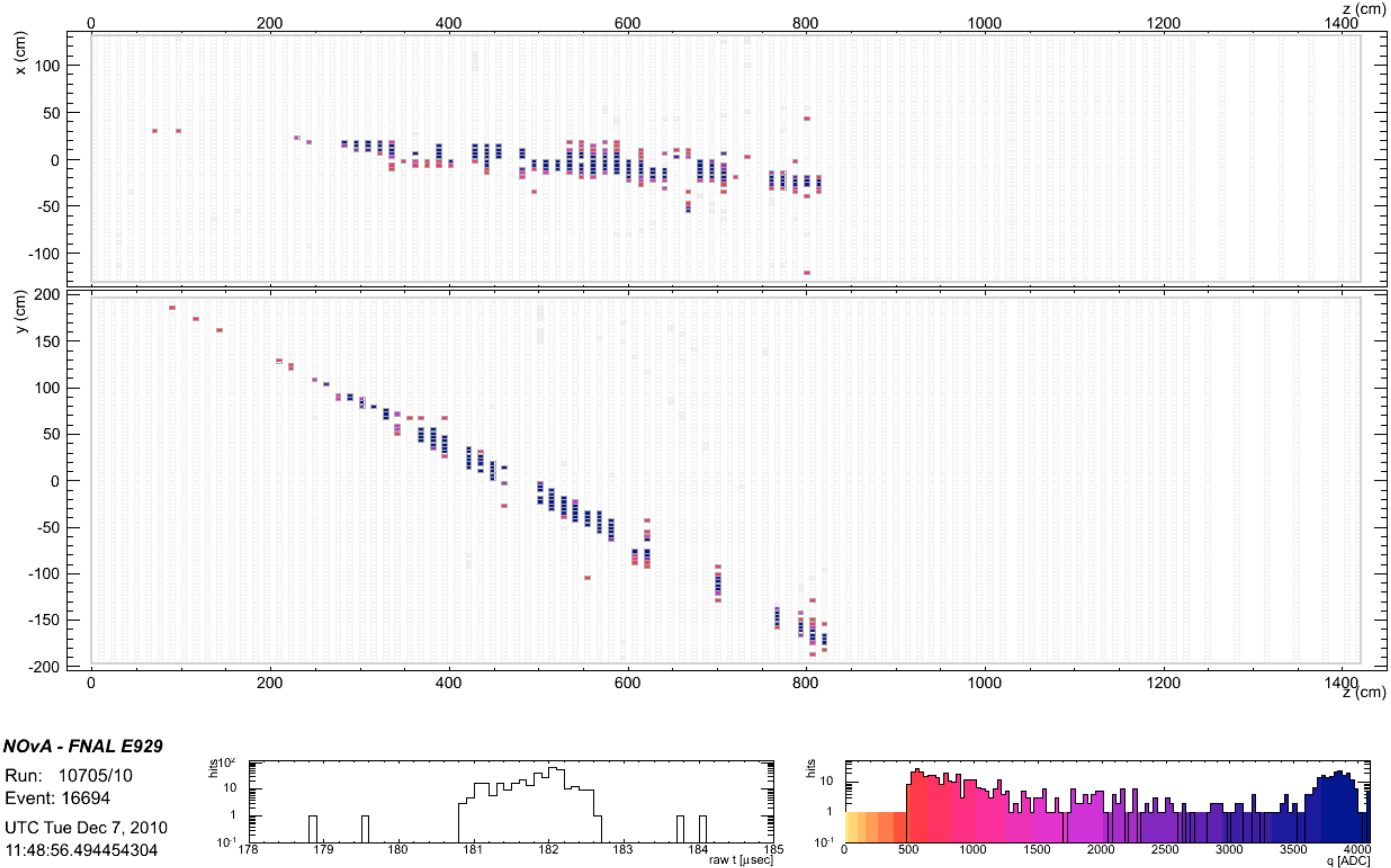
NOvA Near Detector (on the surface)



(real) Cosmics in NOvA

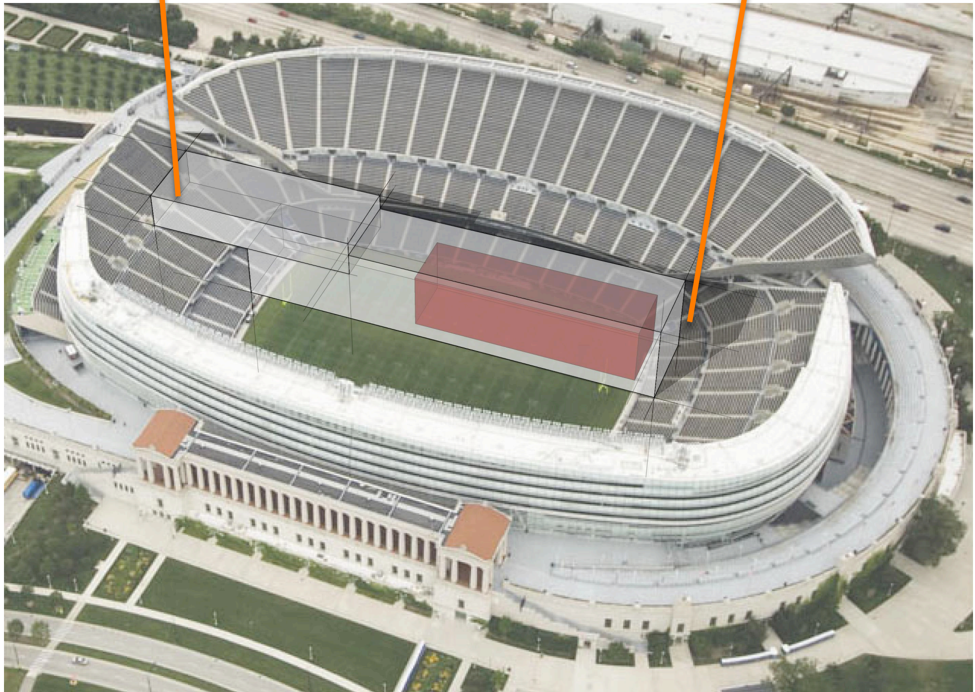


(real) Cosmics in NOvA



NOvA

- Far Detector building under construction
  - Beneficial occupancy, March 2011
  - Half detector ready, Mid 2012
  - Full FD, Fall 2013
- Beam Upgrades, March 2012
  - Recycler/Main Injector upgrades —decrease cycle time, increase intensity 700kW
  - new NuMI horns and target
  - Reconfigure NuMI for ME beam



Summary

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

$$\left|\Delta m^2\right| = 2.35^{+0.11}_{-0.08} \times 10^{-3}\text{eV}^2,$$
$$\sin^2(2\theta) > 0.91\ (90\%\ \text{C.L.})$$

  - NC event rate is not diminished

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

  - electron-neutrino appearance is limited

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

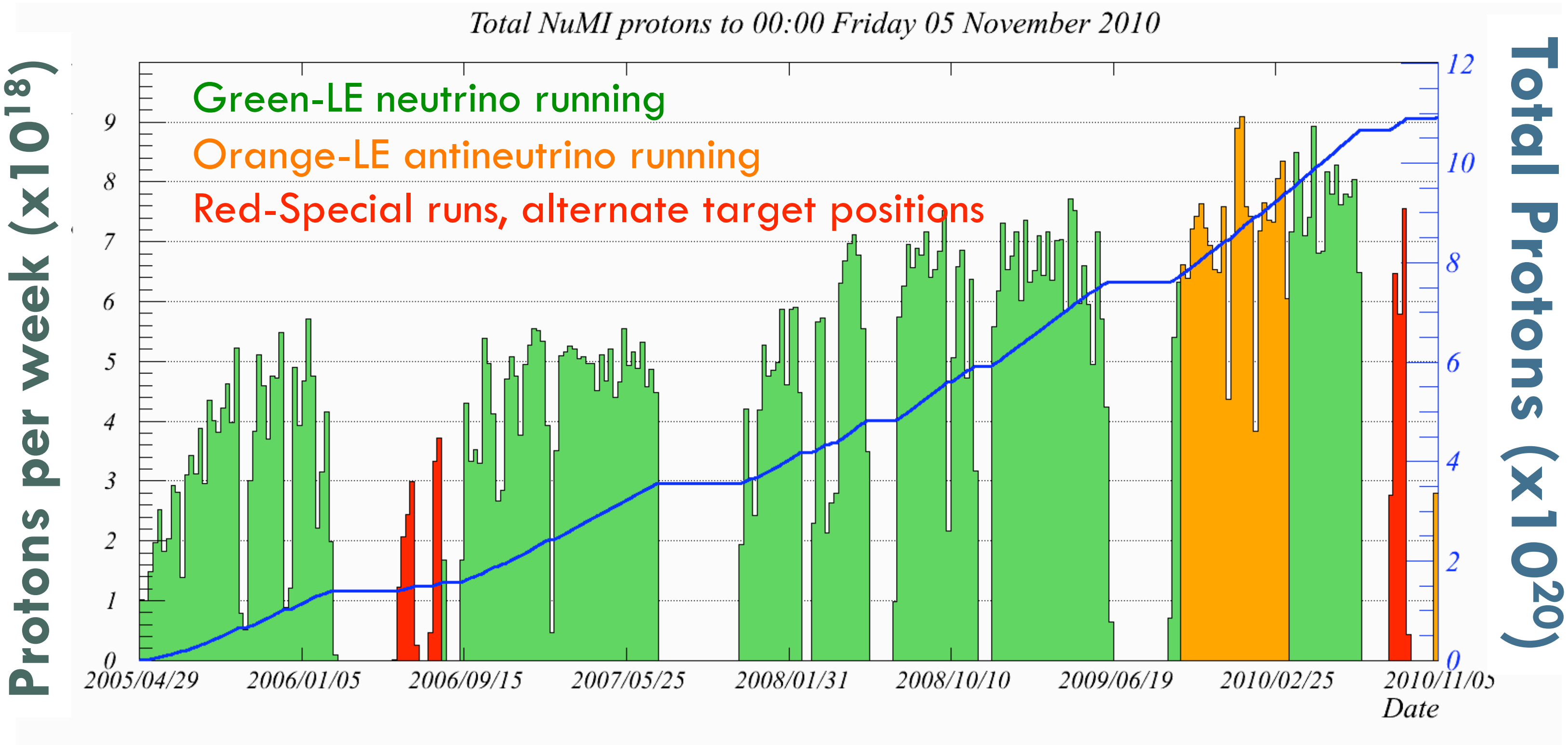
- With $1.71x10^{20}$ POT of anti-neutrino beam
  - muon anti-neutrinos also disappear with

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

  - we look forward to more anti-neutrino beam!
- NOvA is on the horizon
  - Construction of FD underway
  - ND taking data!

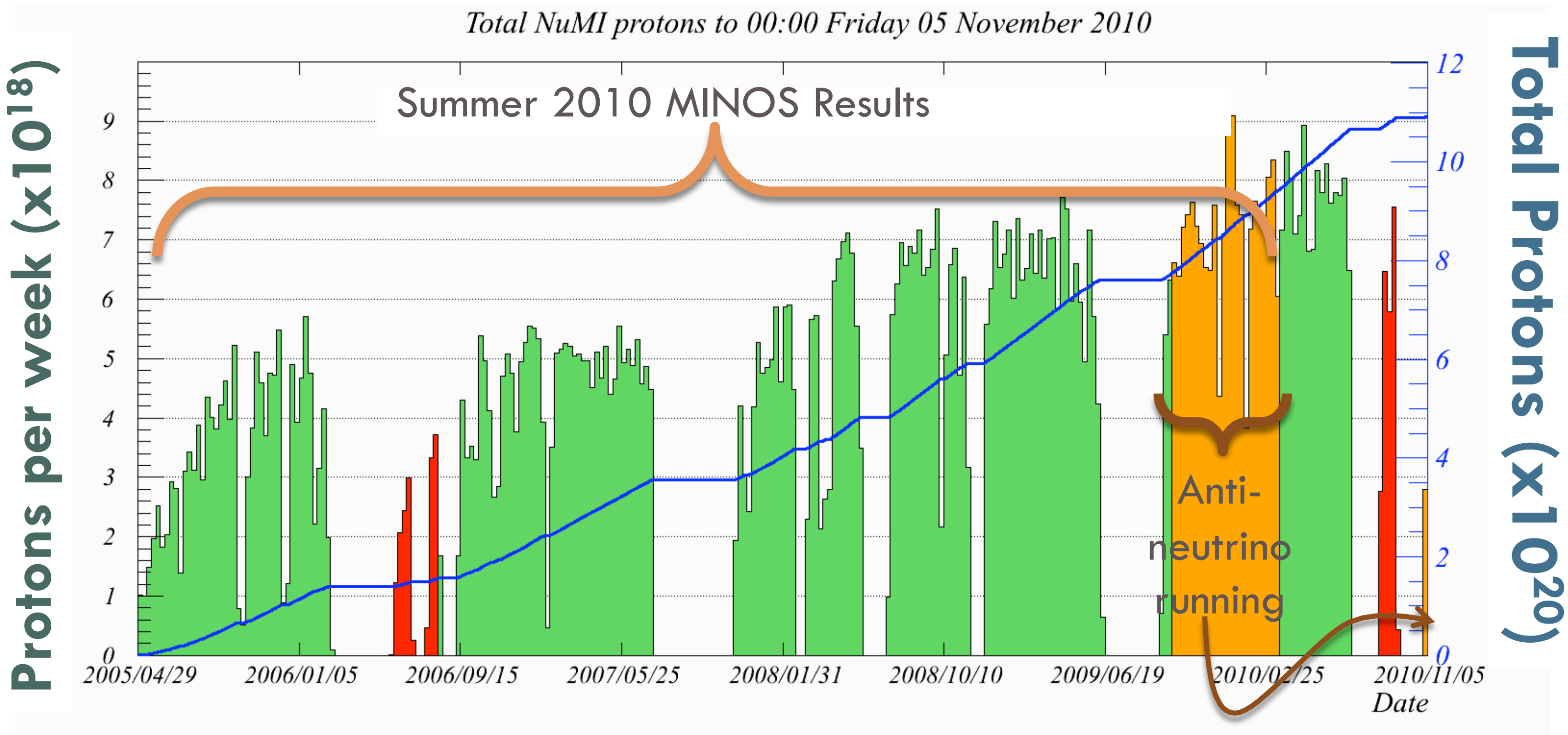
Backup Slides

Beam Performance



- Started data taking 2005
- 1×10^{21} POT milestone achieved Summer 2010

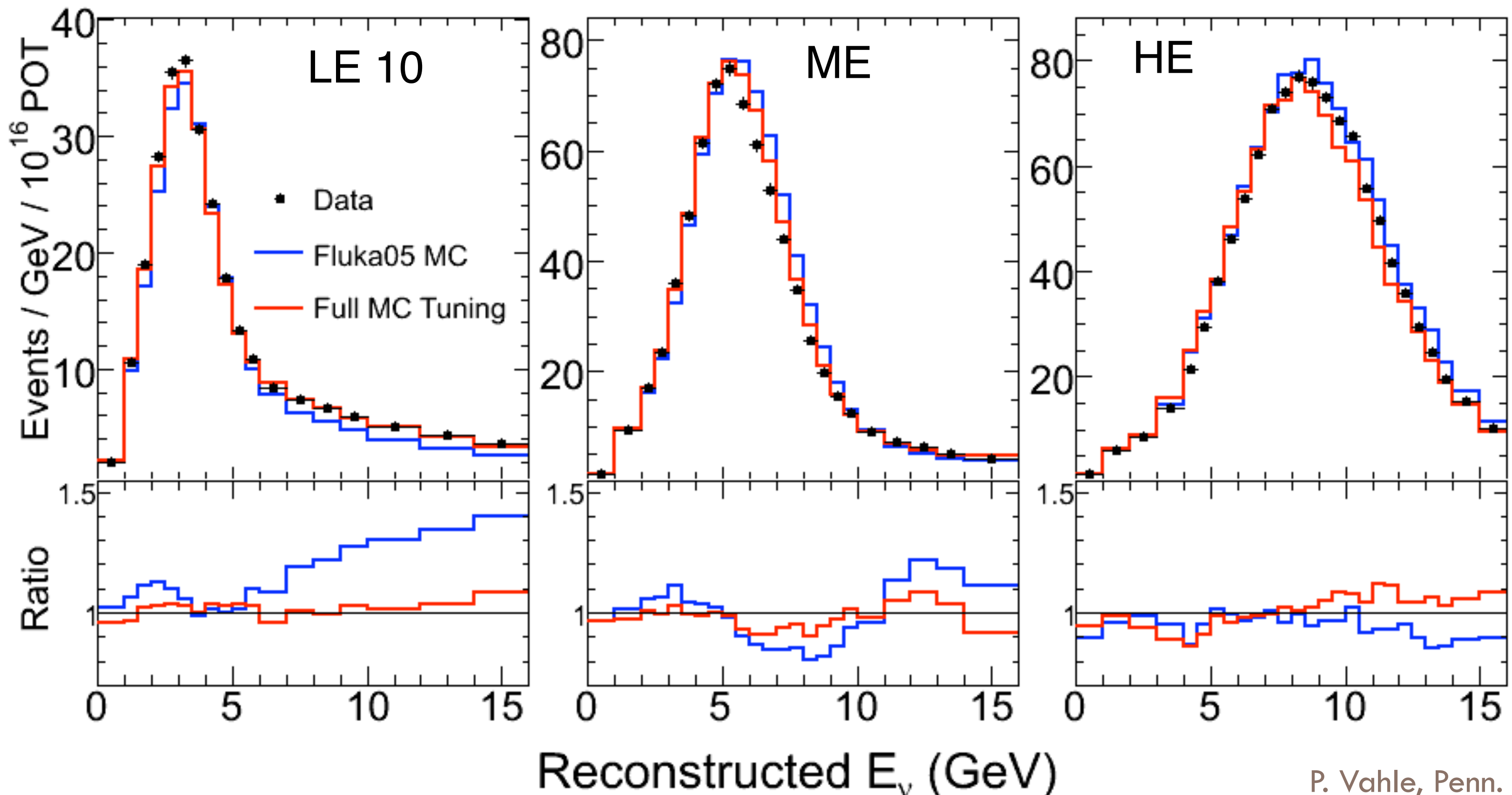
Beam Performance



- 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



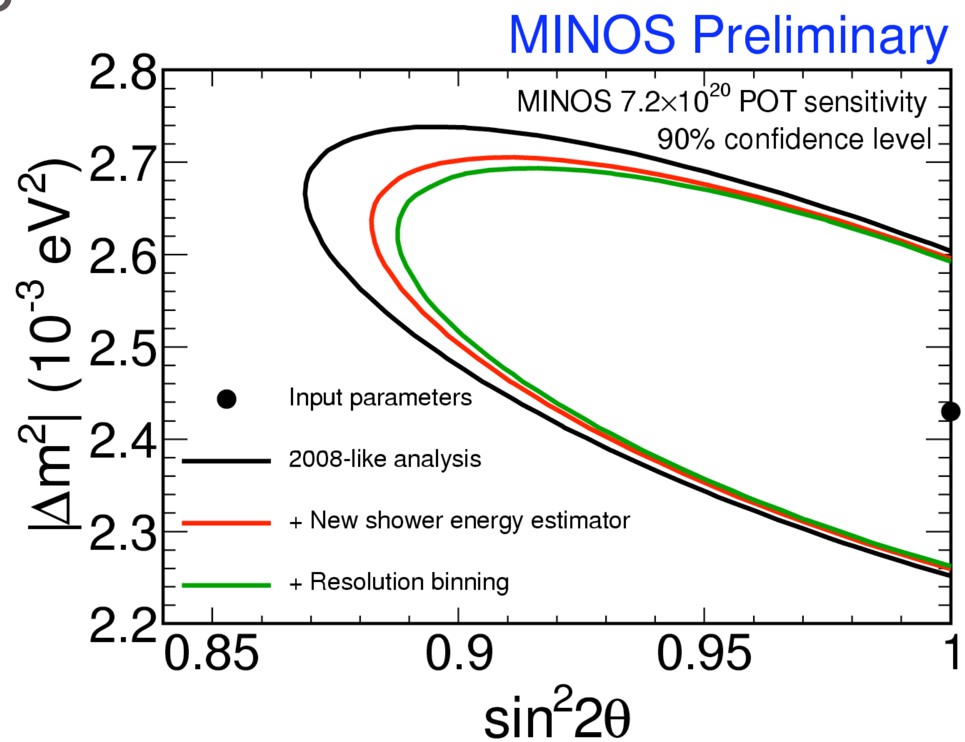
Far/Near differences

- 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

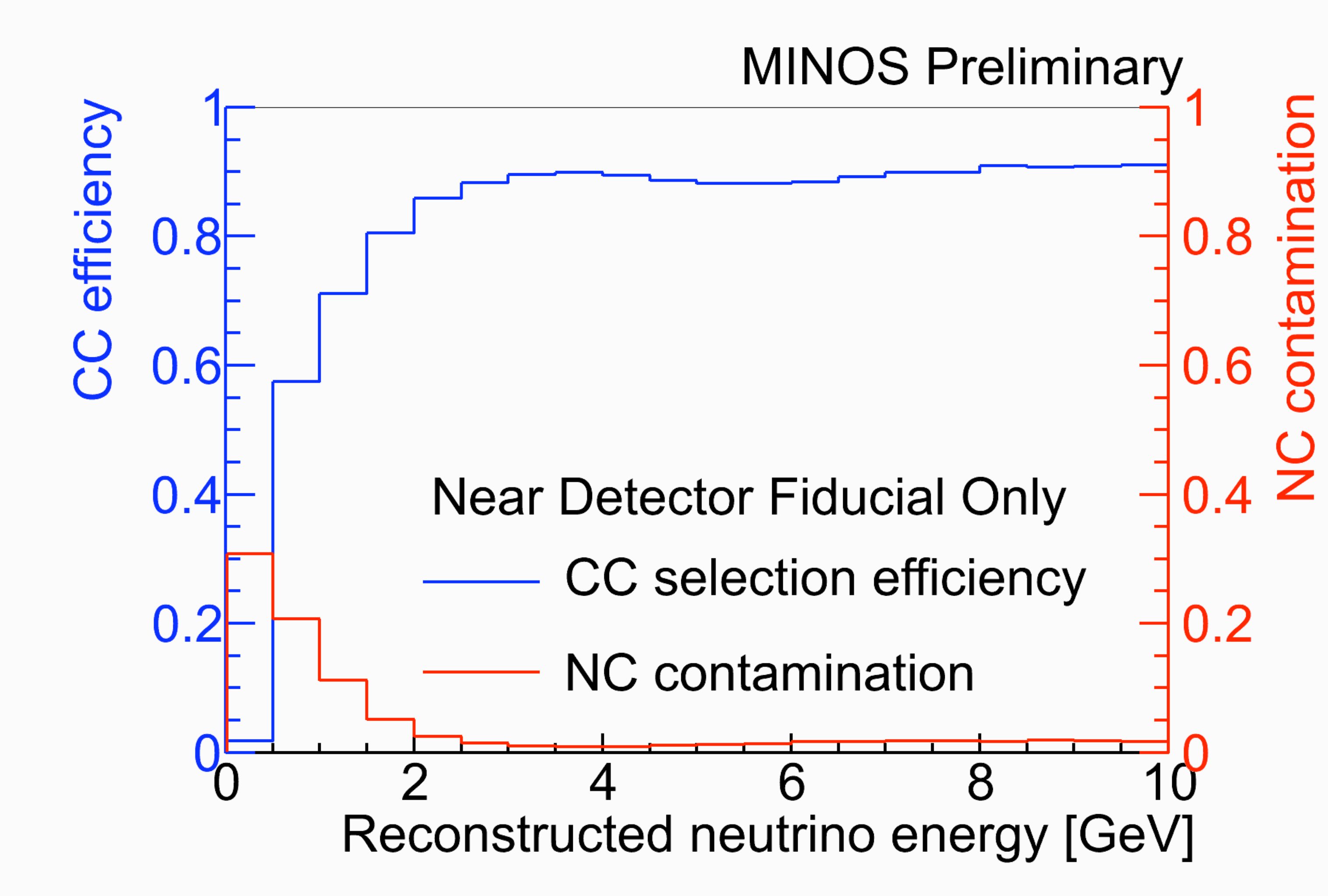
Account for these lower order effects using detailed detector simulation

Analysis Improvements

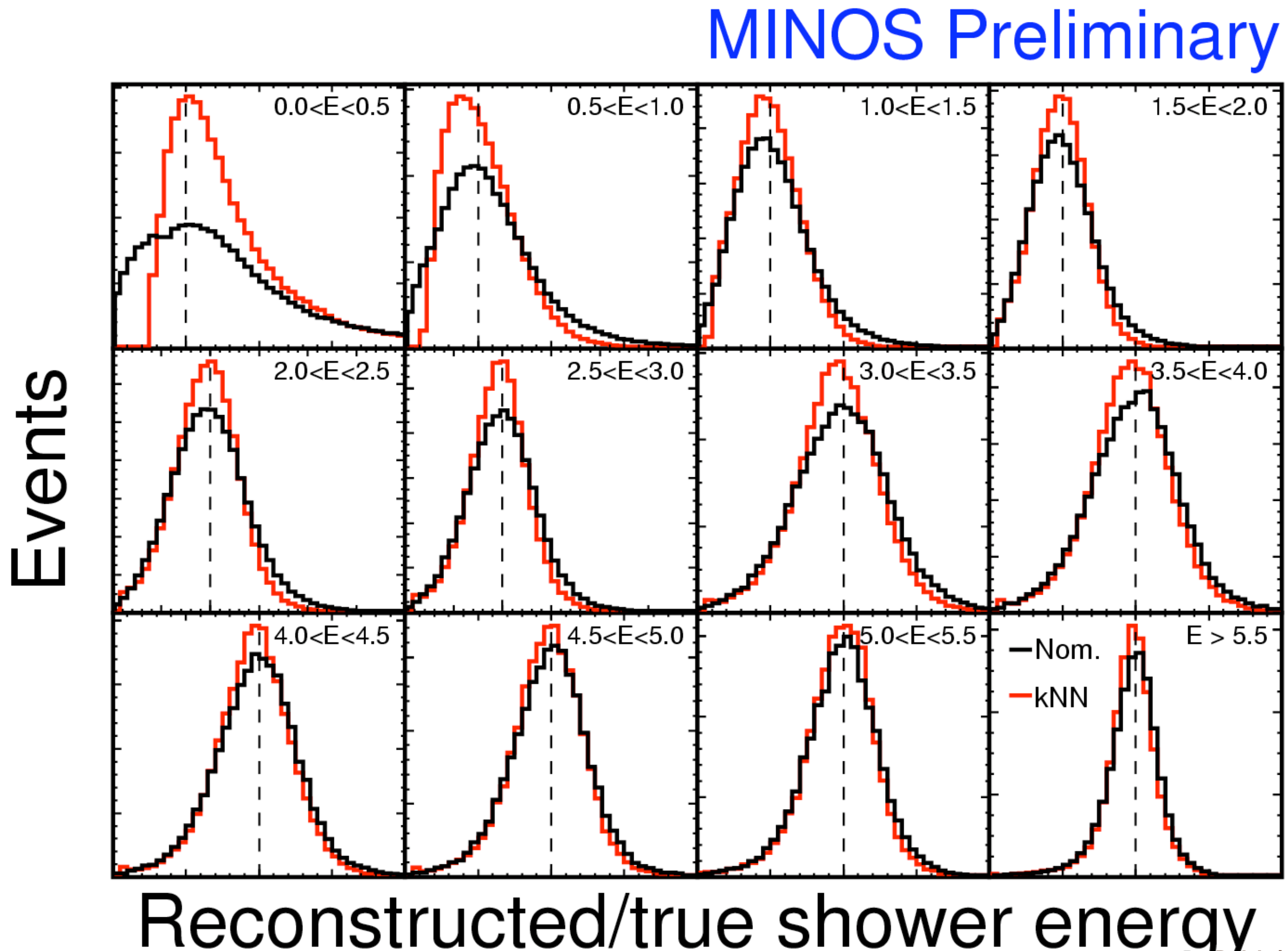
- Since PRL 101:131802, 2008
- Additional data
  - $3.4 \times 10^{20} \rightarrow 7.2 \times 10^{20}$ POT
- Analysis improvements
  - updated reconstruction and simulation
  - new selection with increased efficiency
  - no charge sign cut
  - improved shower energy resolution
  - separate fits in bins of energy resolution
  - smaller systematic uncertainties



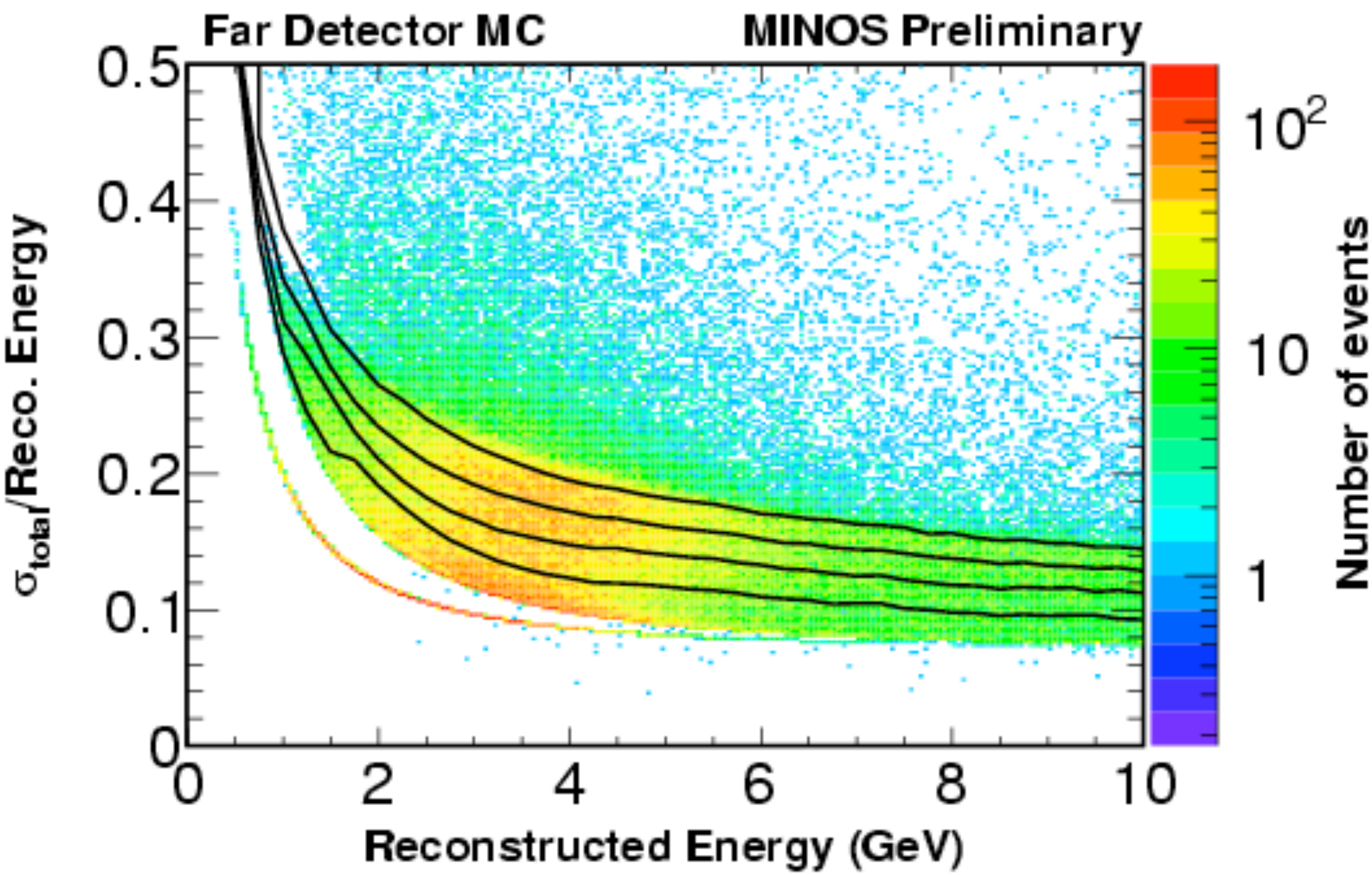
New Muon-neutrino CC Selection



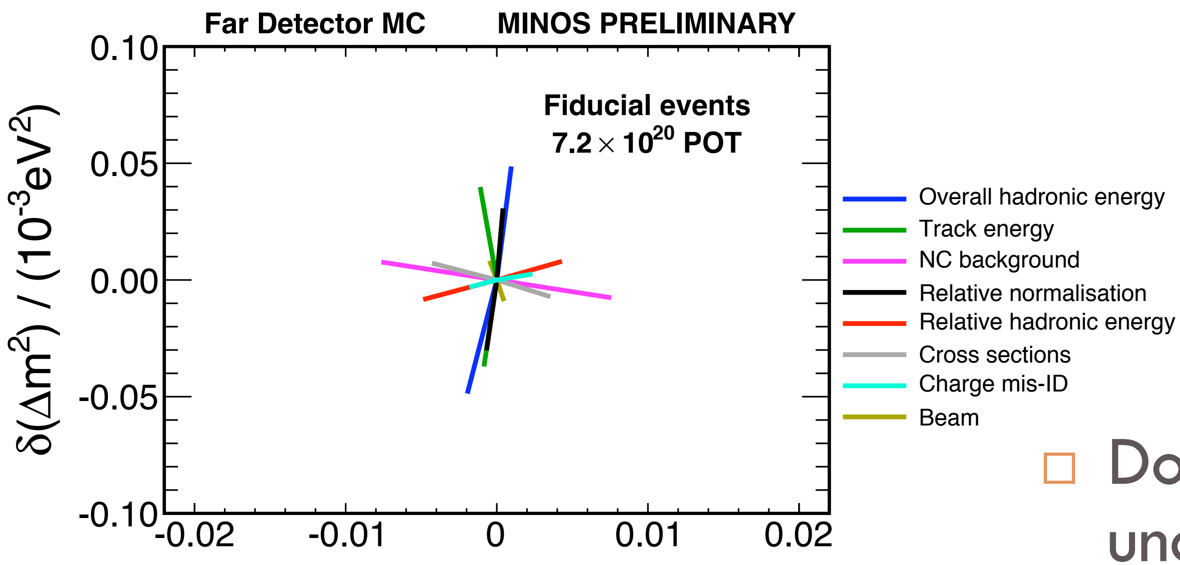
Shower Energy Resolution

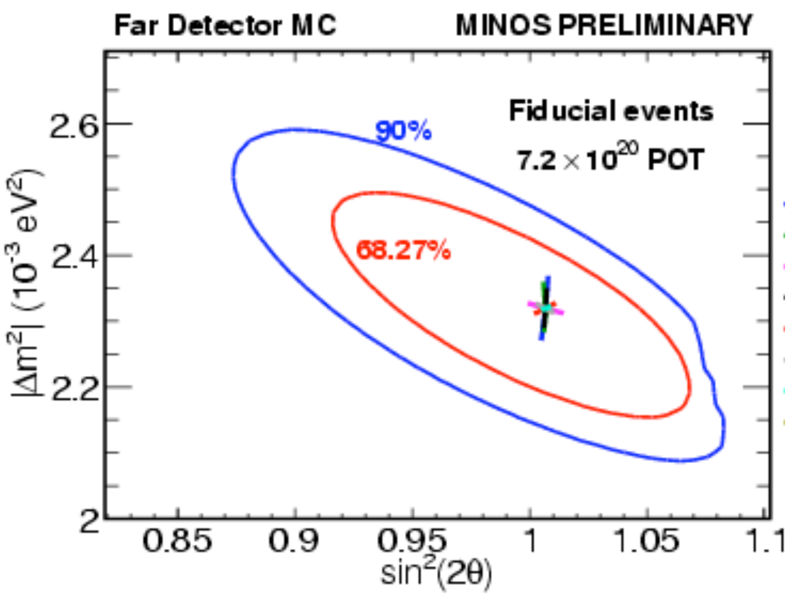


Energy Resolution Binning



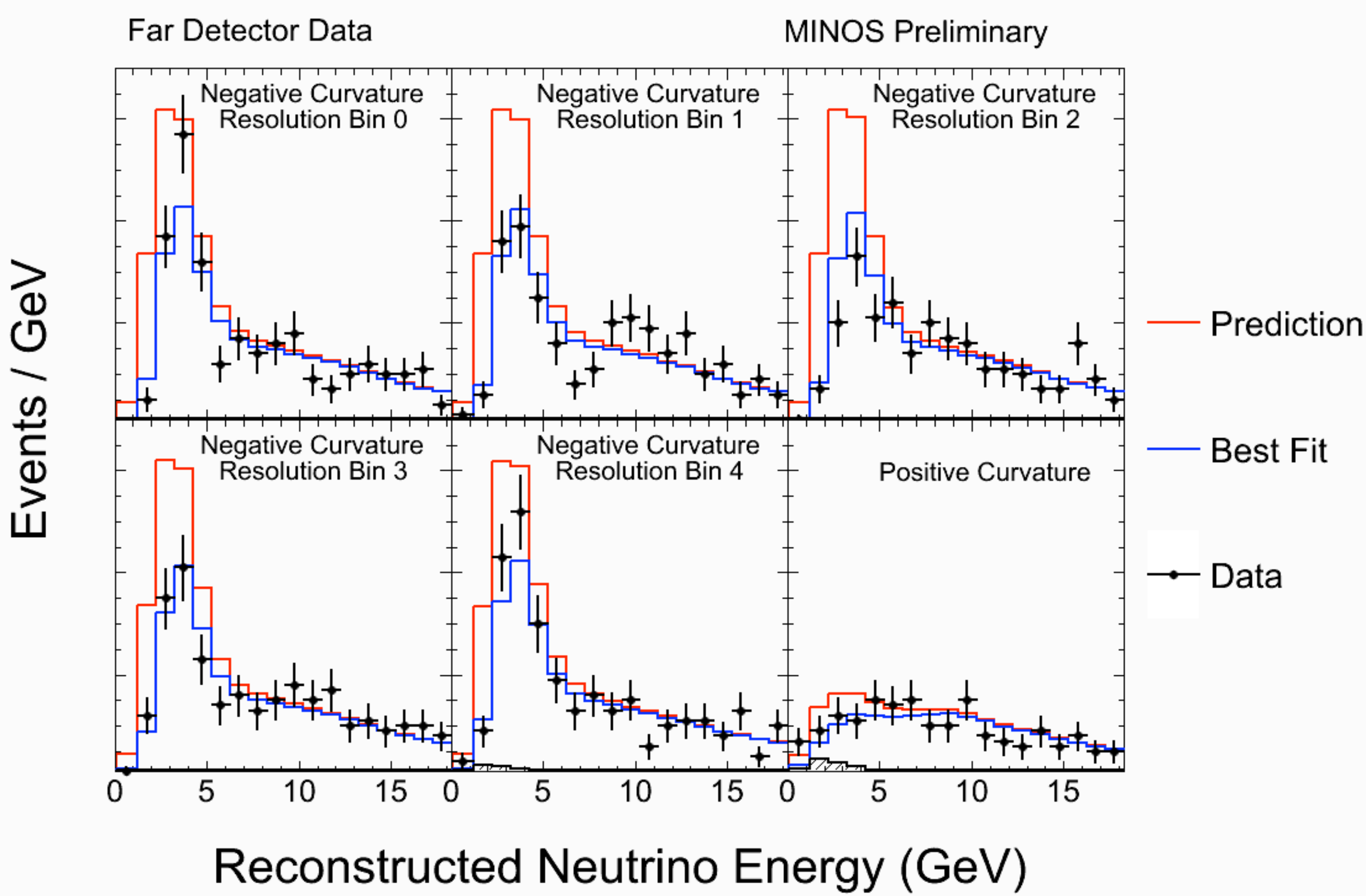
CC Systematic Uncertainties





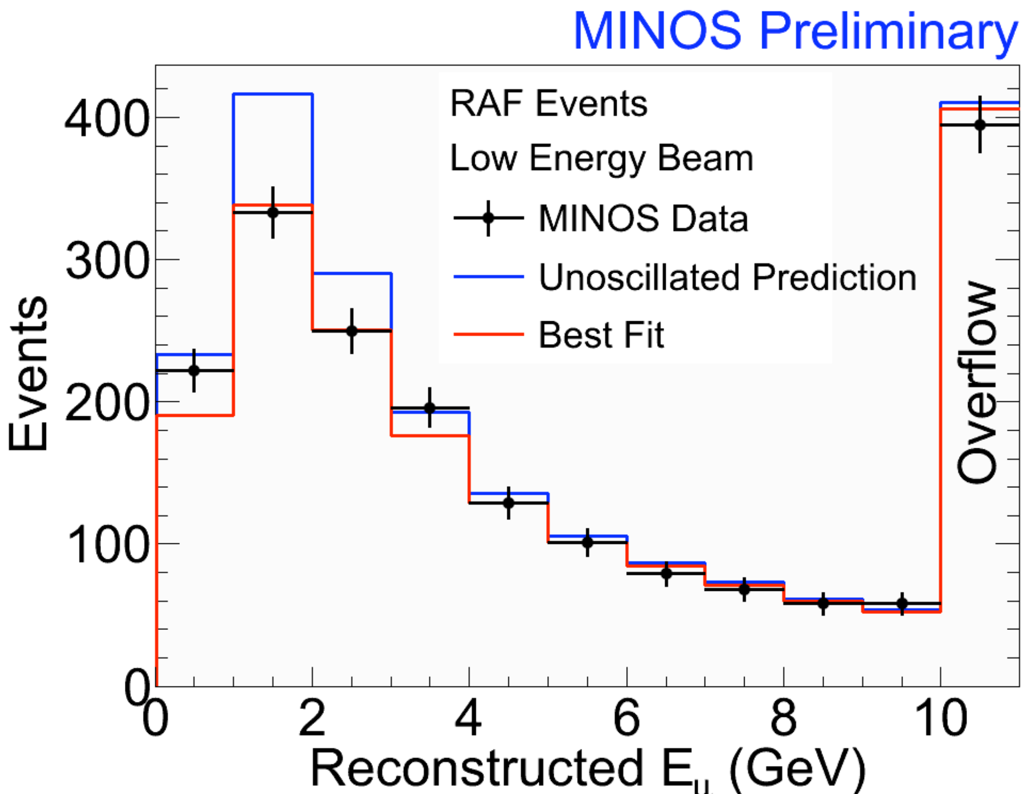
- Dominant systematic uncertainties:
  - hadronic energy calibration
  - track energy calibration
  - NC background
  - relative Near to Far normalization

Resolution Binning



Rock and Anti-fiducial Events

- Neutrinos interact in rock around detector and outside of Fiducial Region
- These events double sample size, events have poorer energy resolution



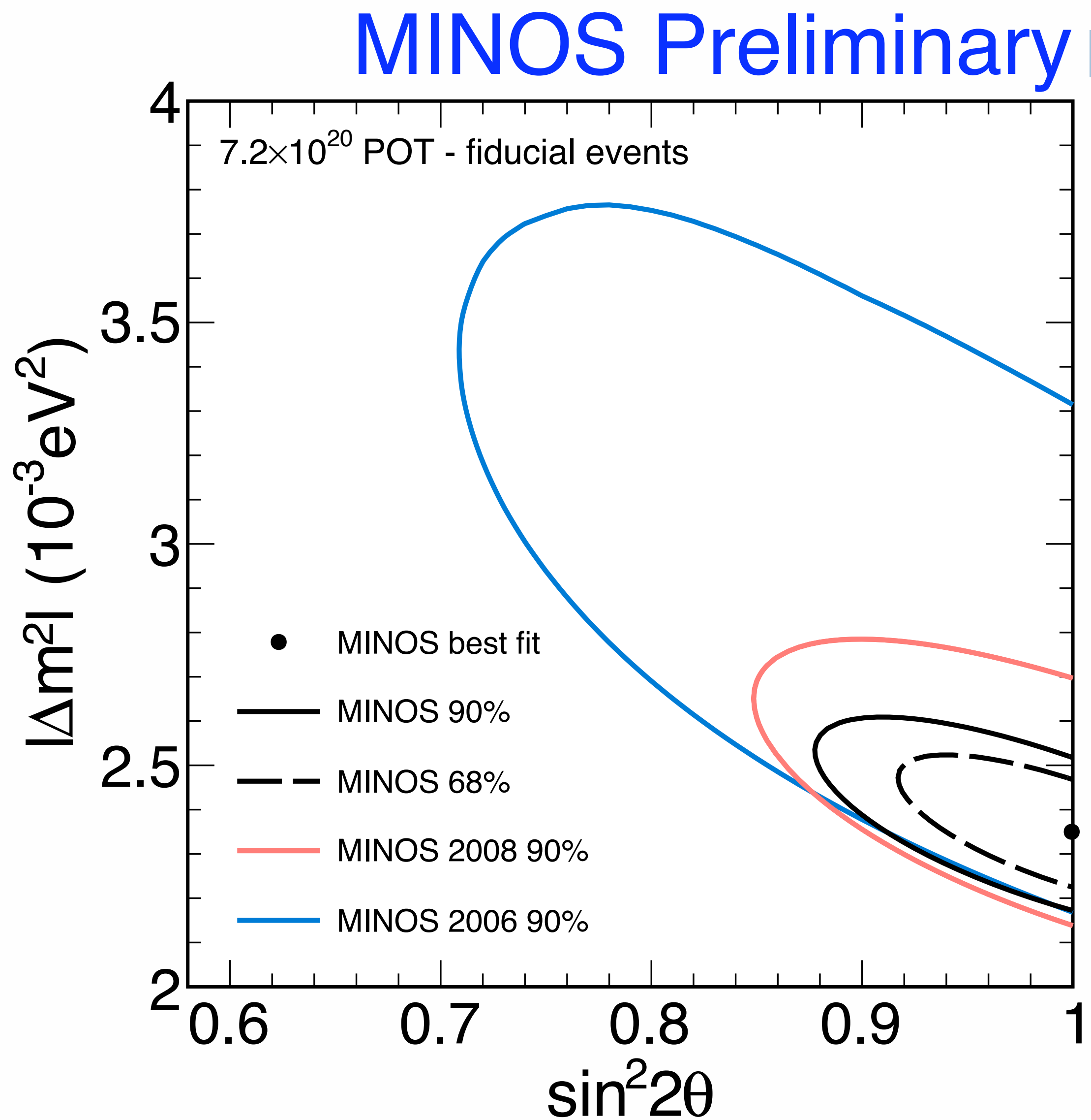
Combined fit coming soon

Contours

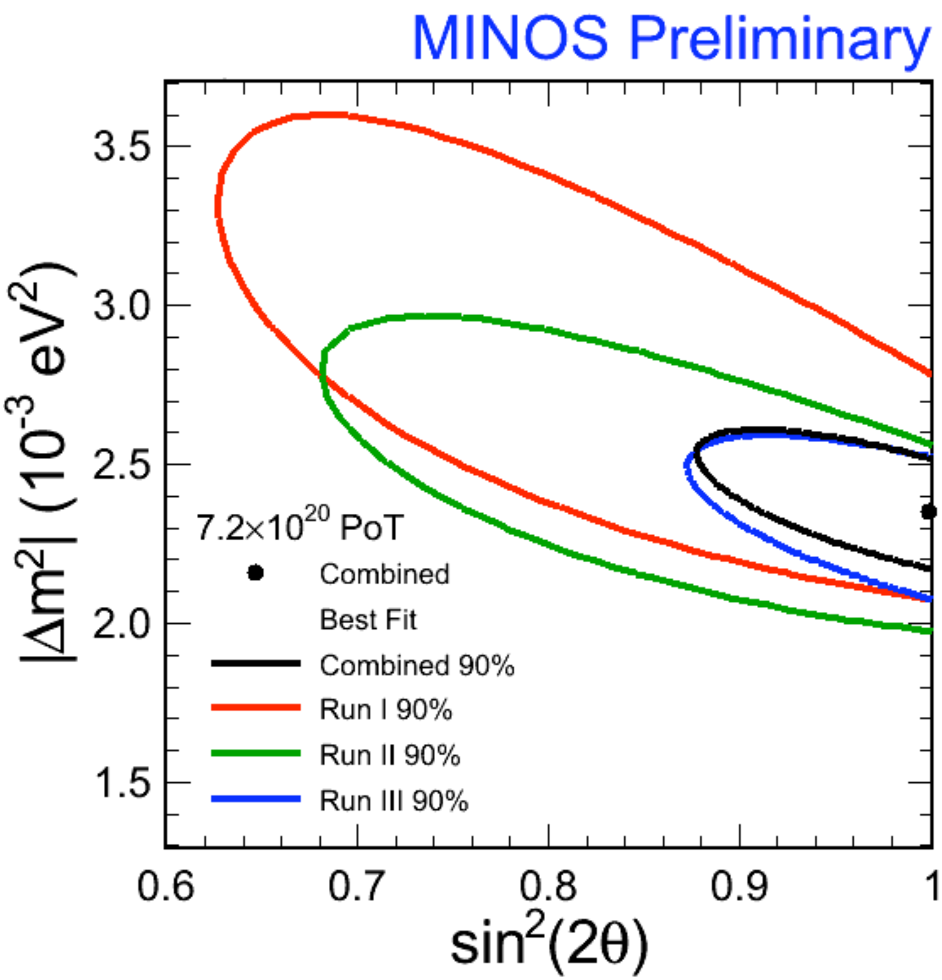
$$\left|\Delta m^2\right| = 2.35^{+0.11}_{-0.08} \times 10^{-3}\,\mathrm{eV}^2$$

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

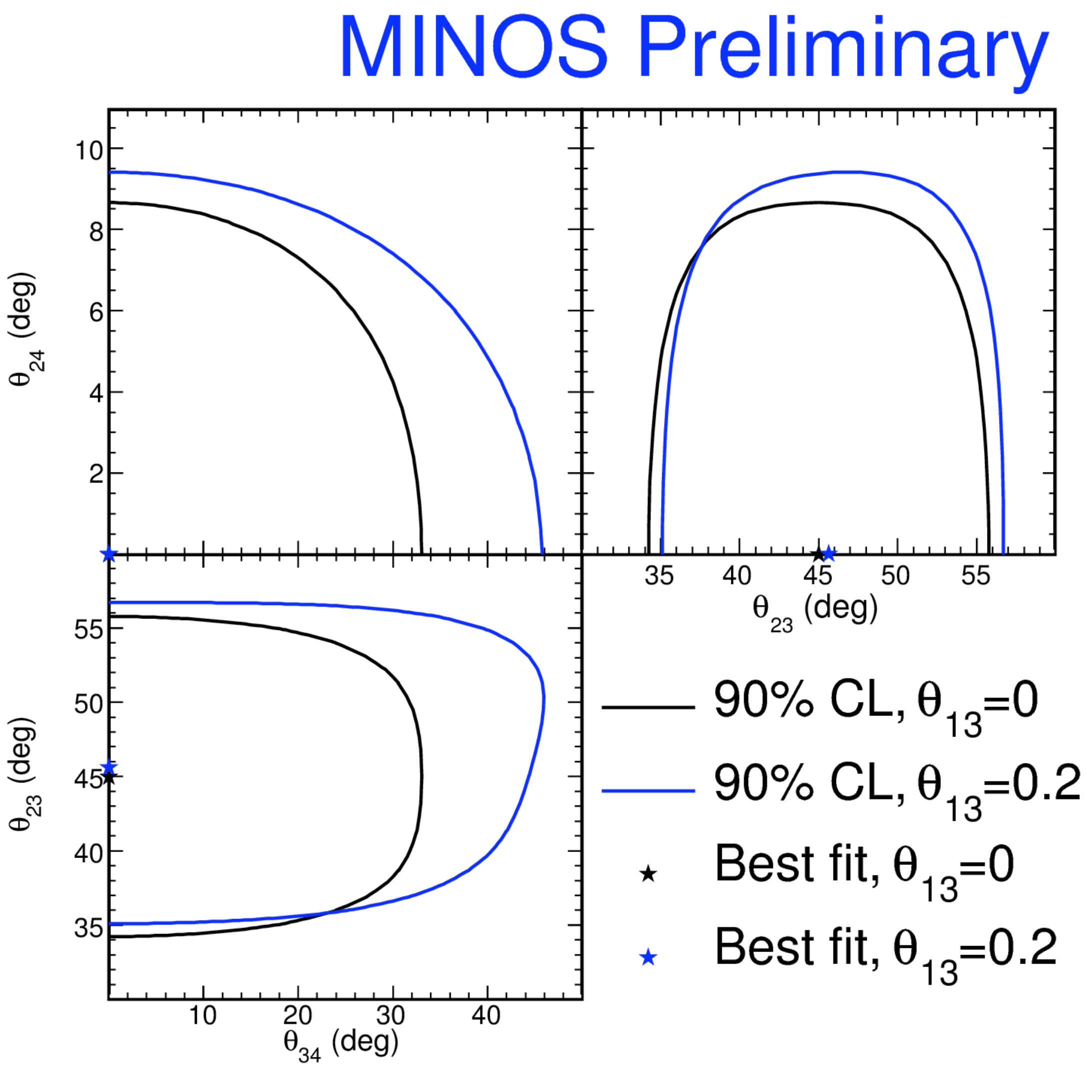
- Contour includes effects of dominant systematic uncertainties
  - normalization
  - NC background
  - shower energy
  - track energy



Contours by Run Period

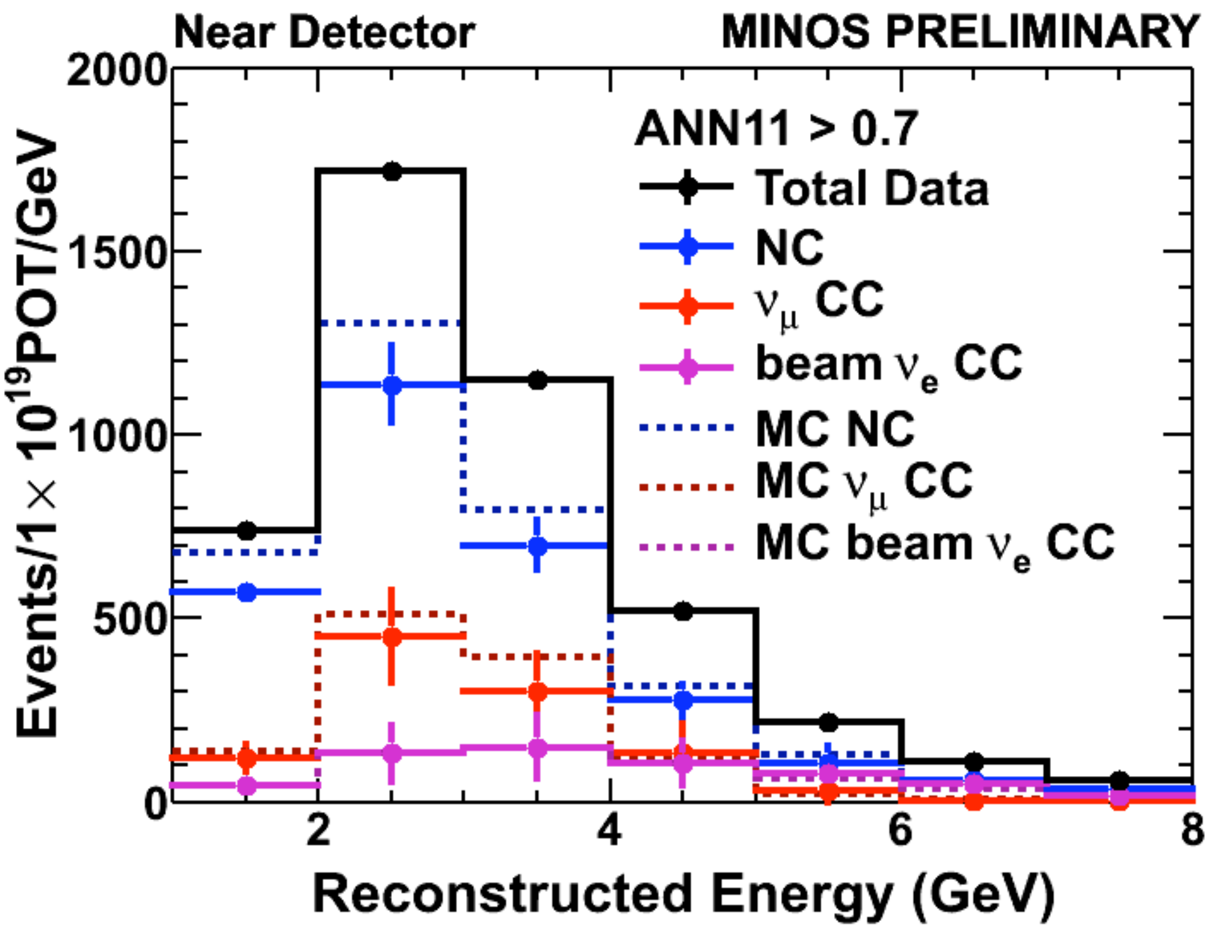


Fits to NC

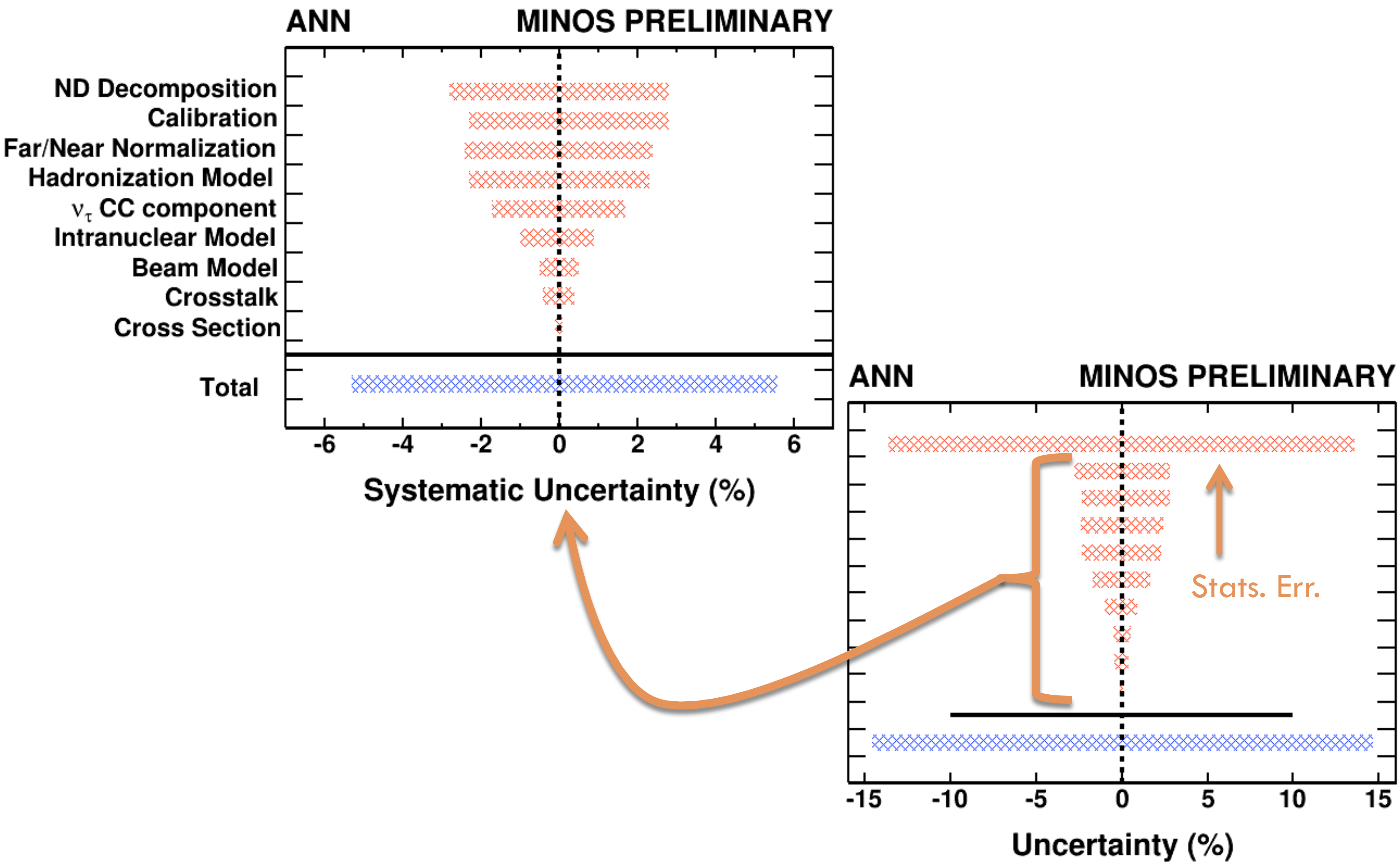


- Fit CC/NC spectra simultaneously with a 4th (sterile) neutrino
- 2 choices for 4th mass eigenvalue
  - $m_4 >> m_3$
  - $m_4 = m_1$

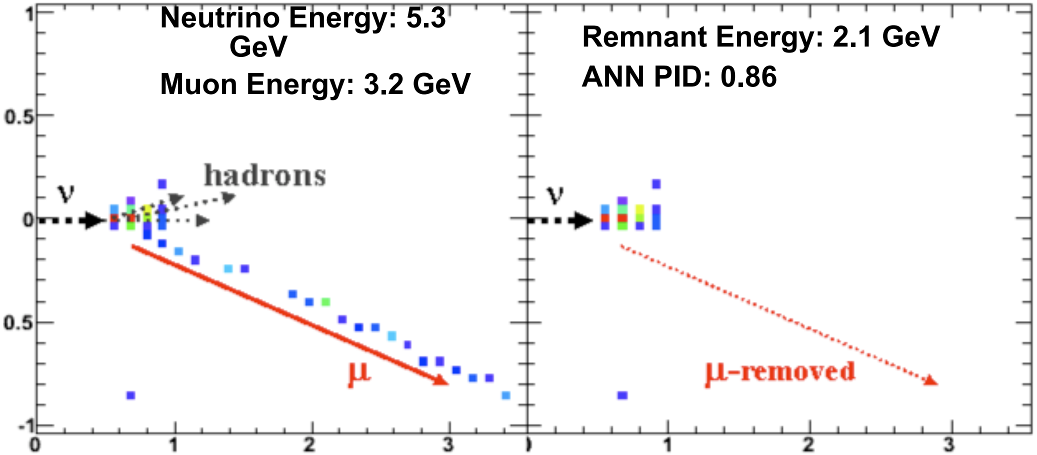
Electron-neutrino Background Decomposition



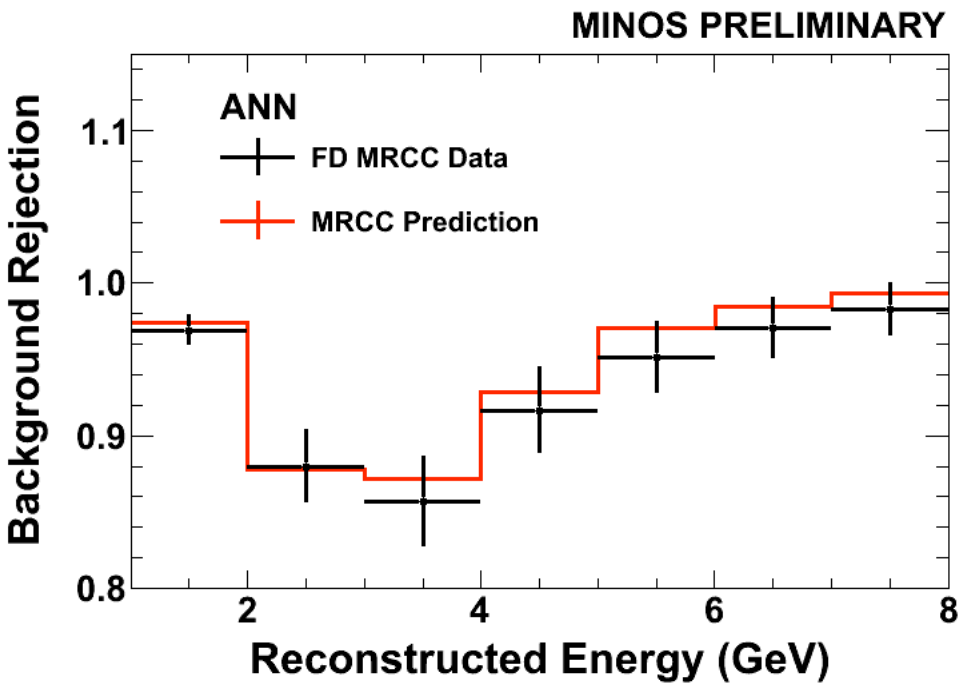
Electron-neutrino Systematics



MRCC Background Rejection Check



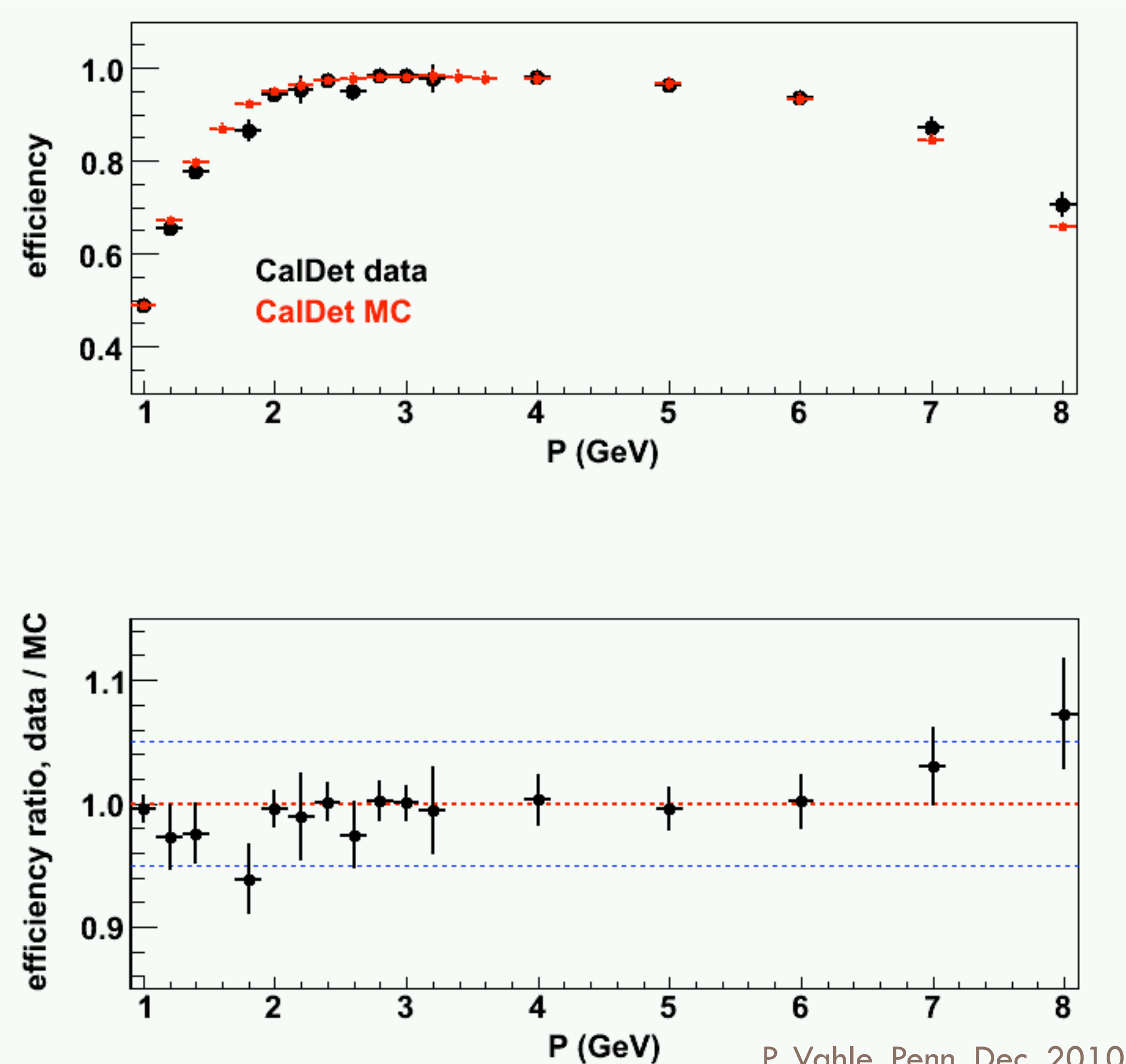
Remove muons, test BG rejection on shower remnants



- Mis-id rate:
  - pred (6.42±0.05)%
  - data (7.2±0.9)%
    - (stats error only)
- Compatible at 0.86 σ

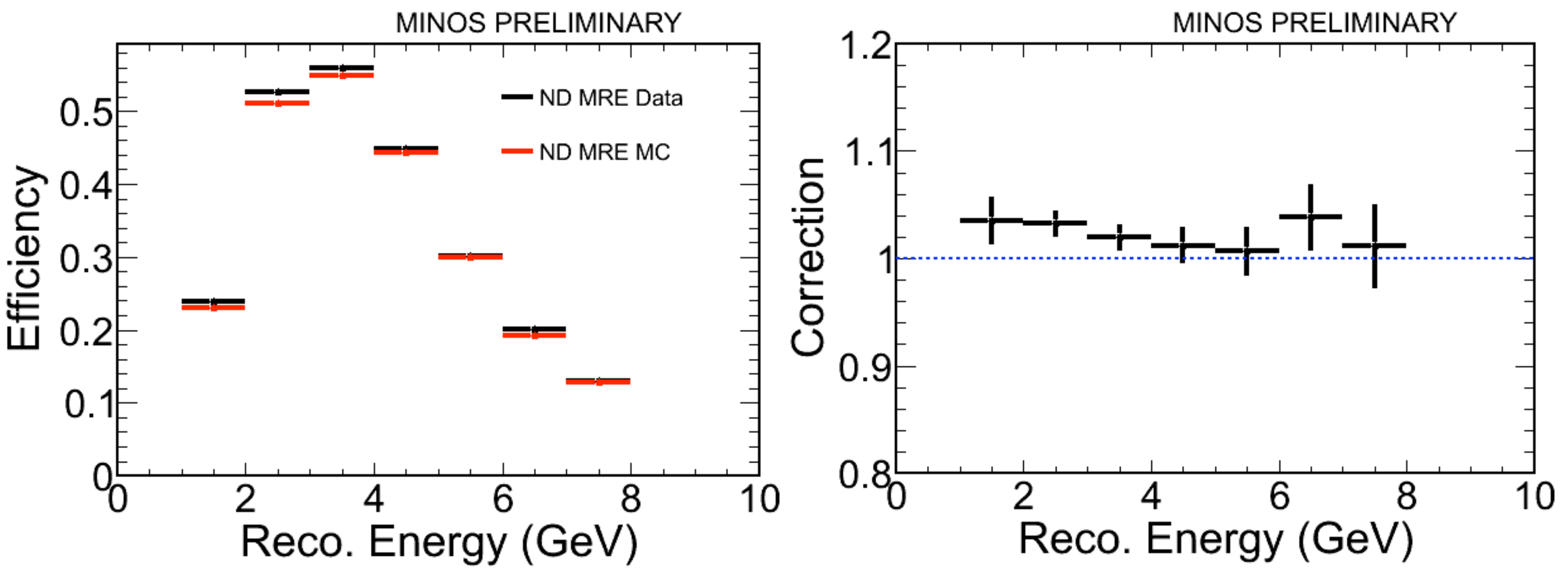
Checking Signal Efficiency

- Test beam measurements demonstrate electrons are well simulated



Checking Signal Efficiency

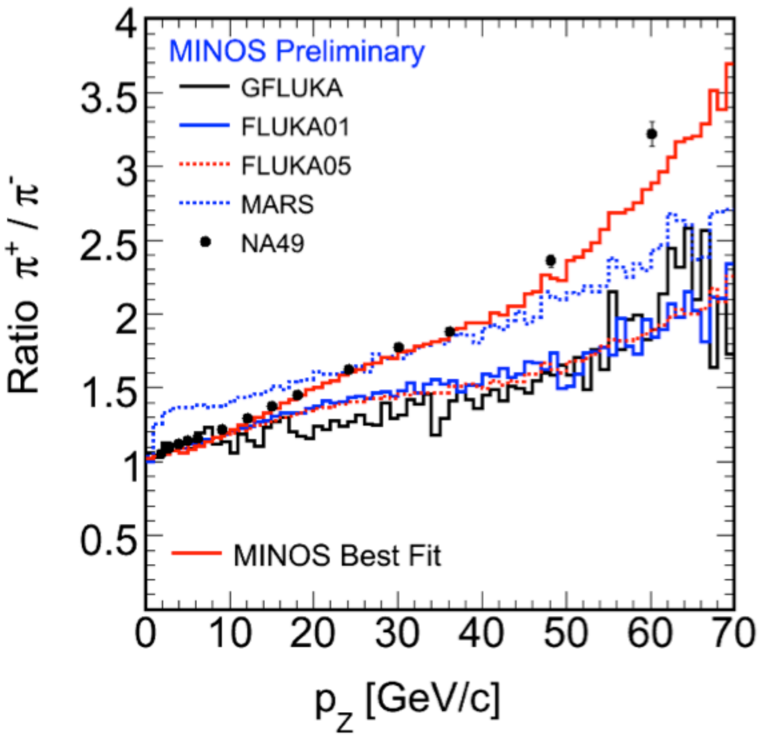
- Check electron neutrino selection efficiency by removing muons, add a simulated electron

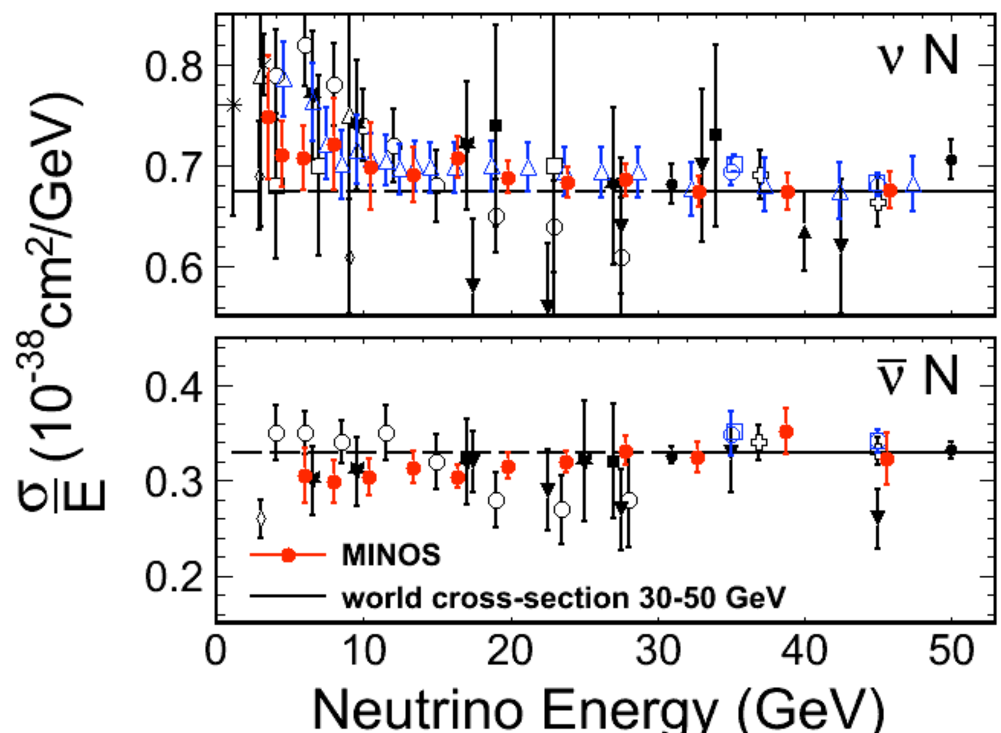


Making an antineutrino beam

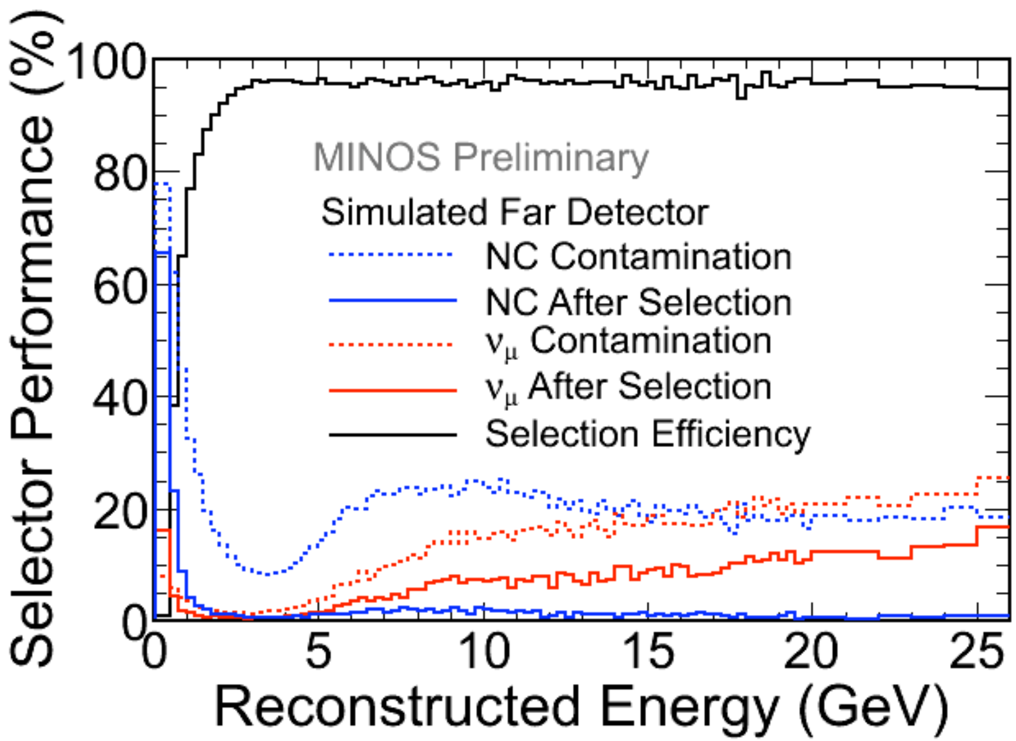
- Hadron production and cross sections conspire to change the shape and normalization of energy spectrum

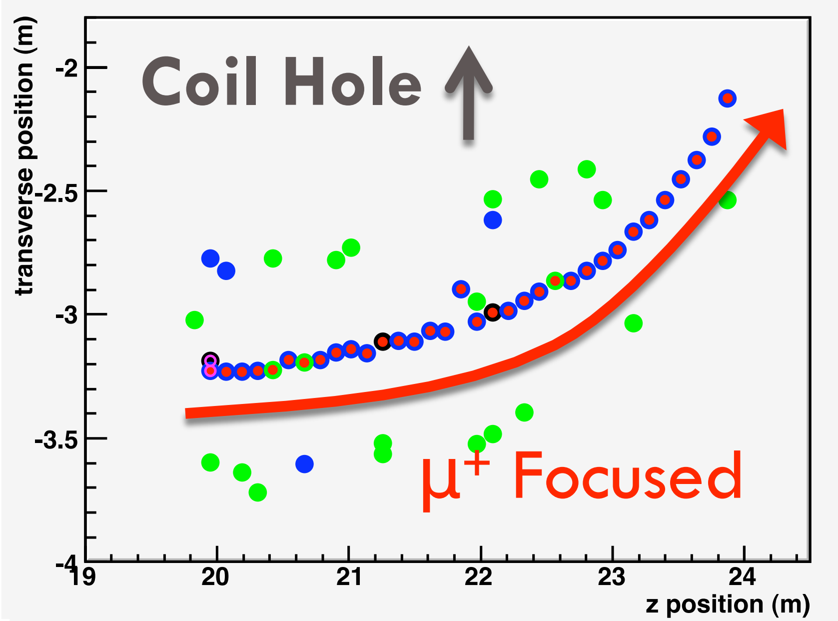
~3x fewer antineutrinos for the same exposure

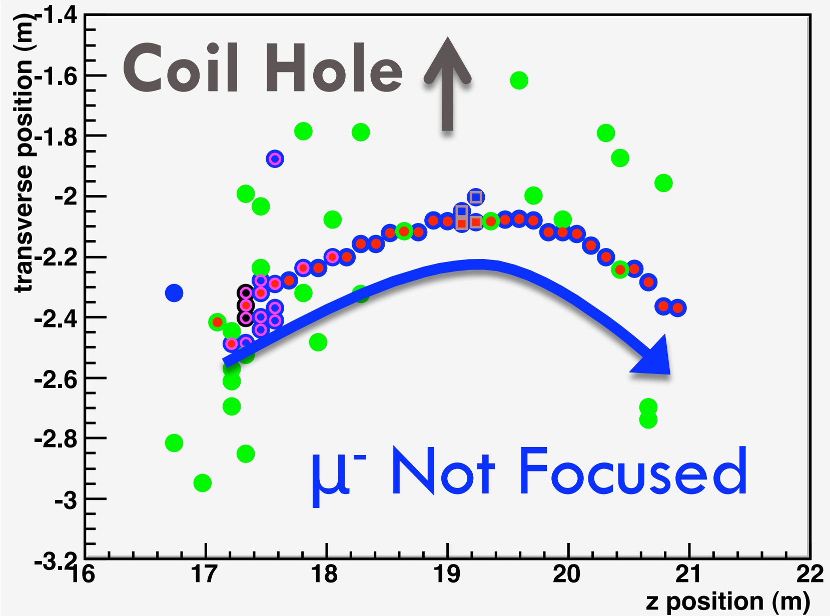




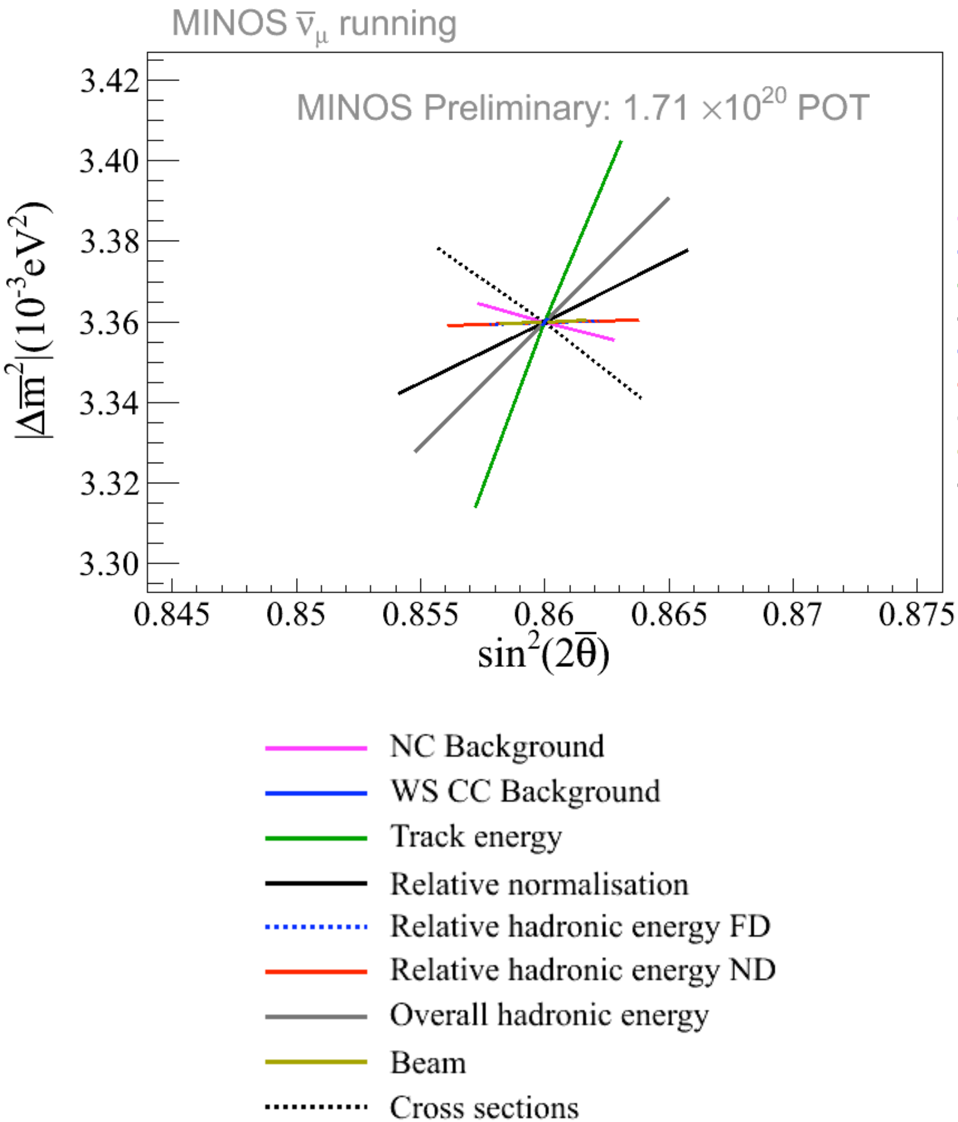
Anti-neutrino Selection

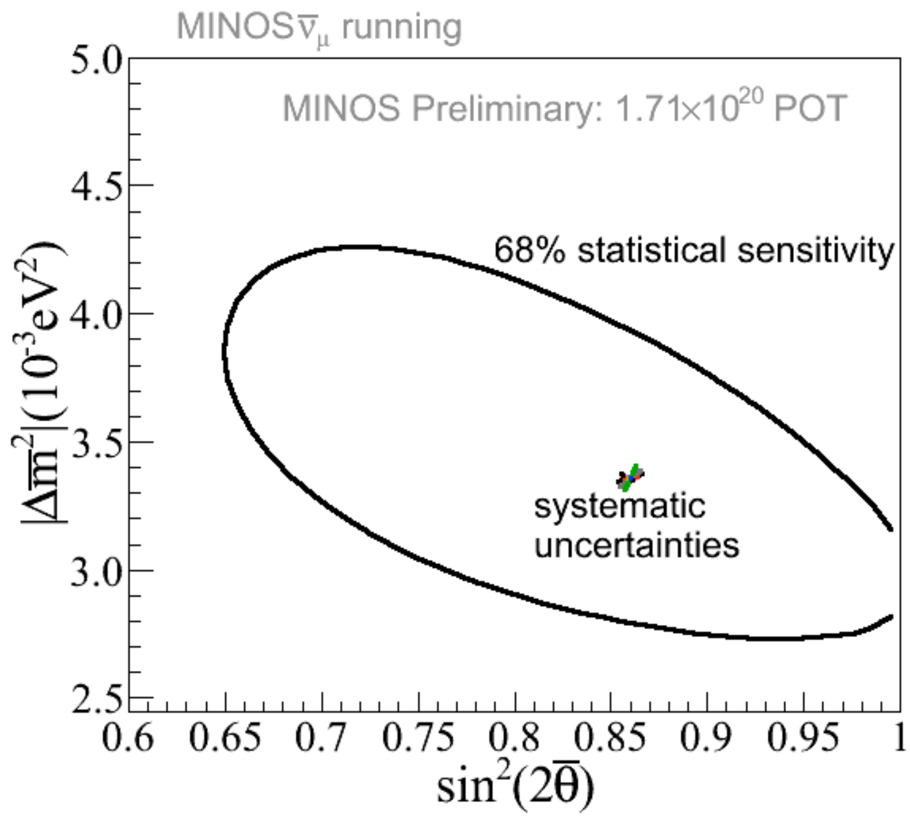




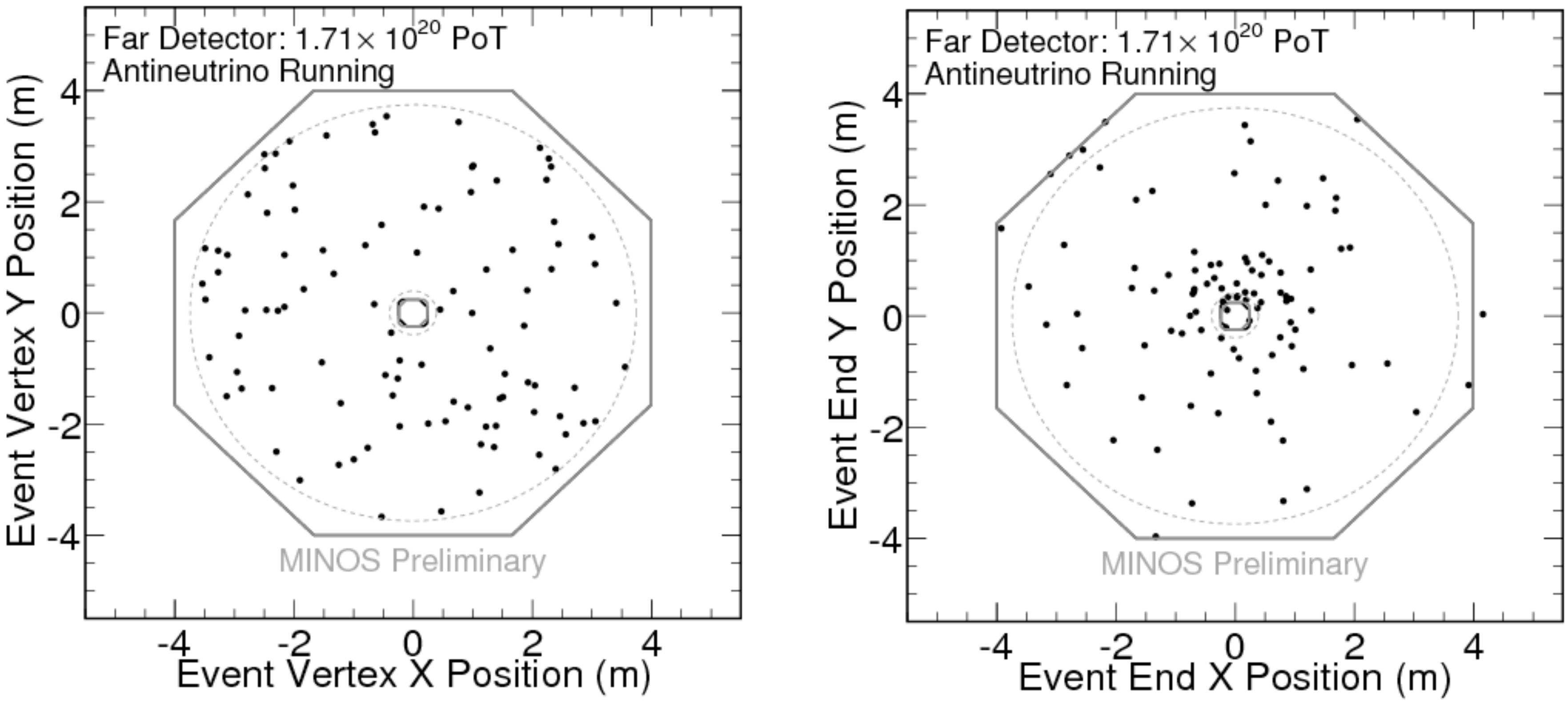


Anti-neutrino Systematics



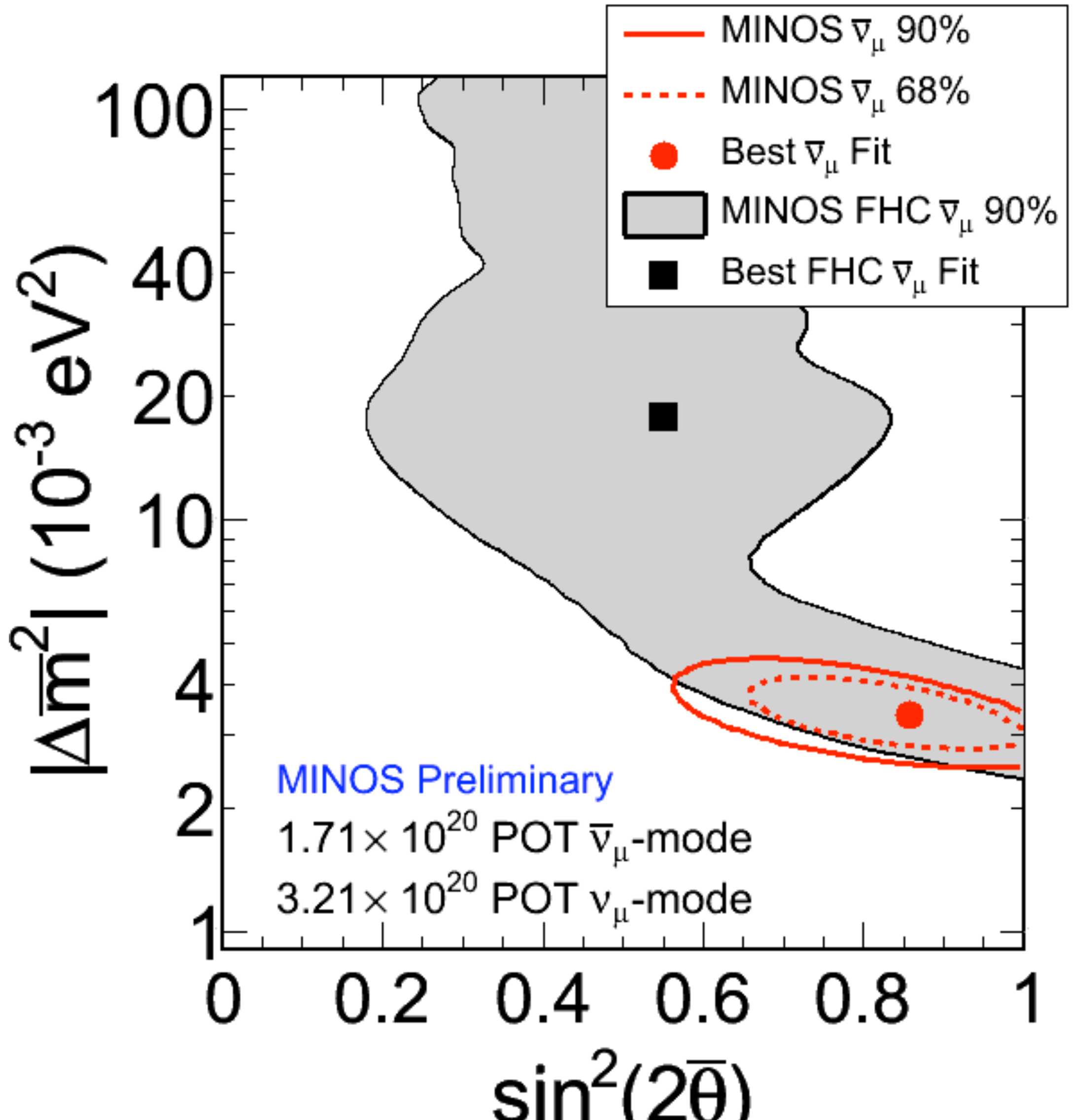


FD Anti-neutrino Data



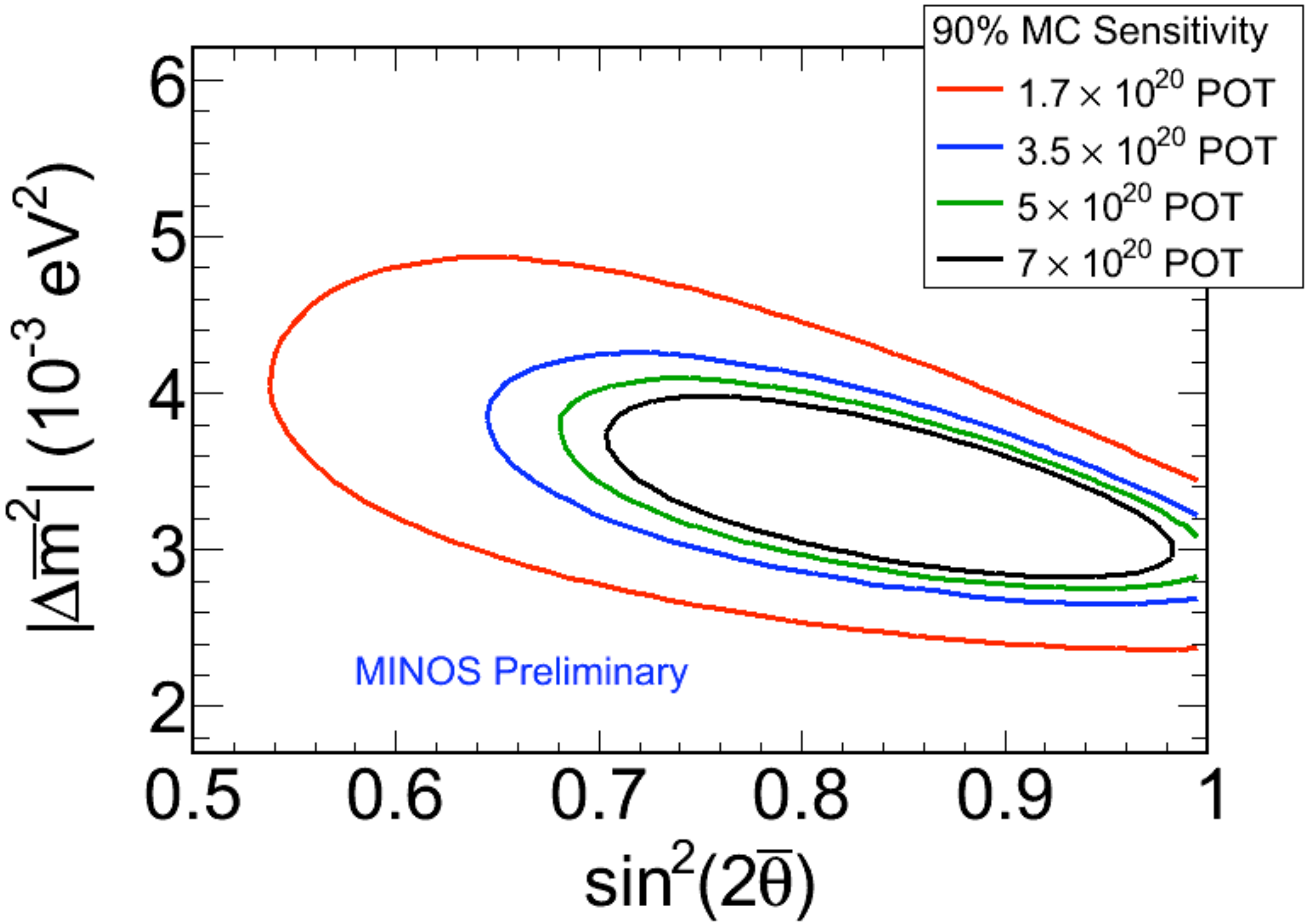
- Vertices uniformly distributed
- Track ends clustered around coil hole

Previous Anti-neutrino Results

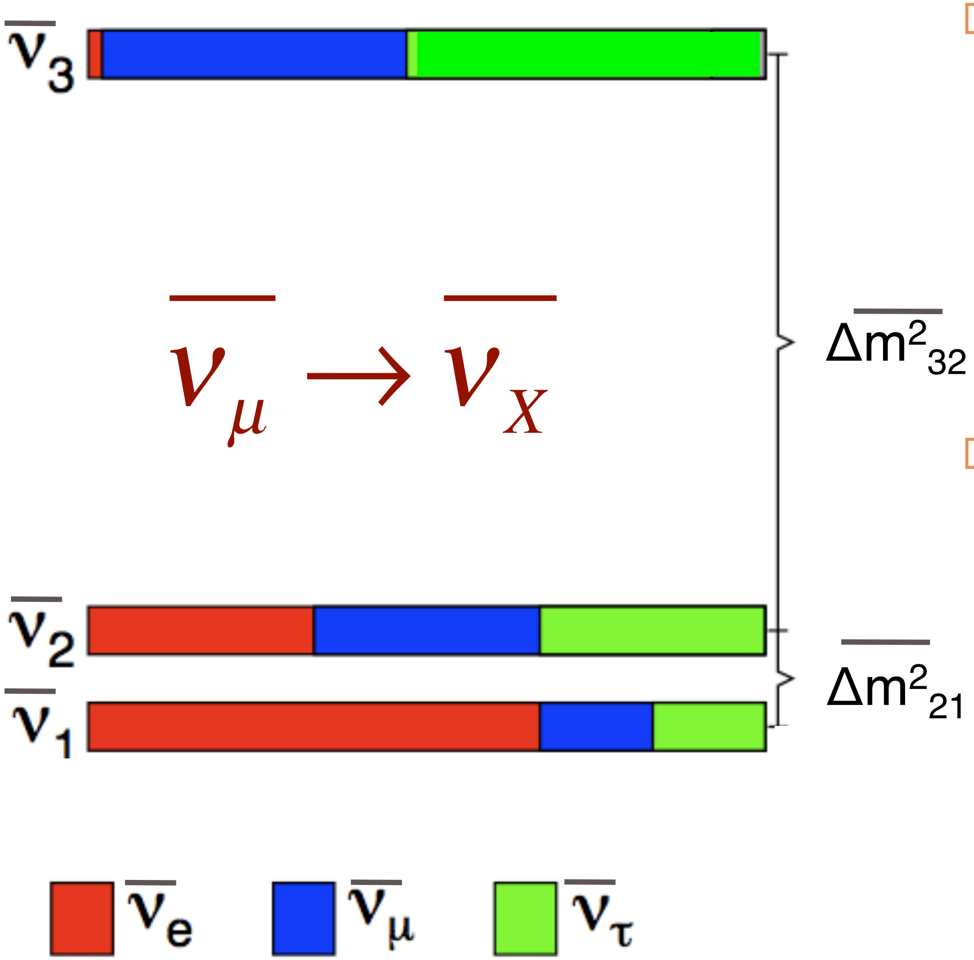


- Results consistent with (less sensitive) analysis of anti-neutrinos in the neutrino beam
  - anti-neutrinos from unfocused beam component
  - mostly high energy antineutrinos
- Analysis of larger exposure on going

Future Anti-neutrino Sensitivity

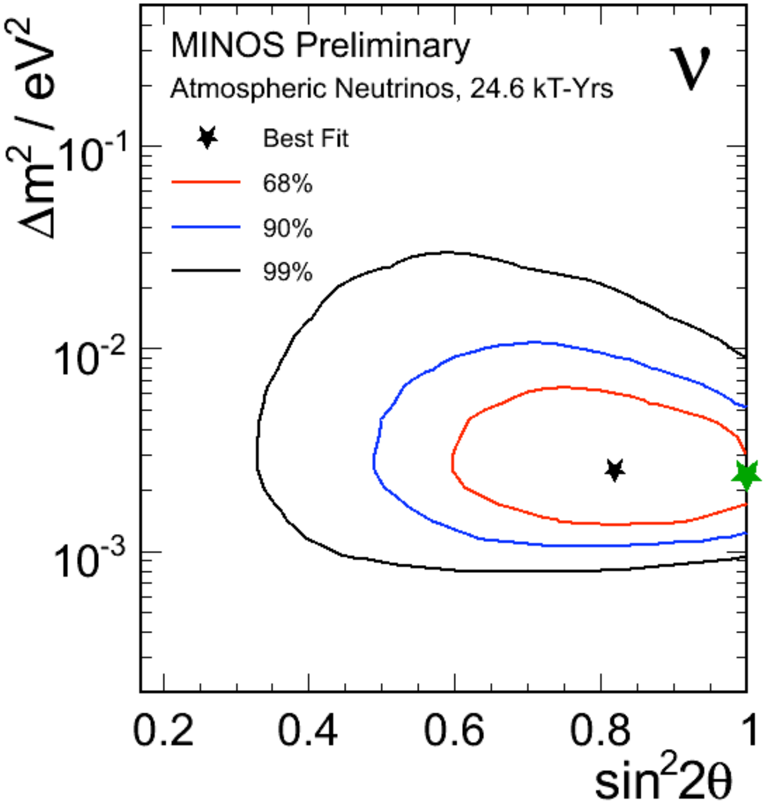


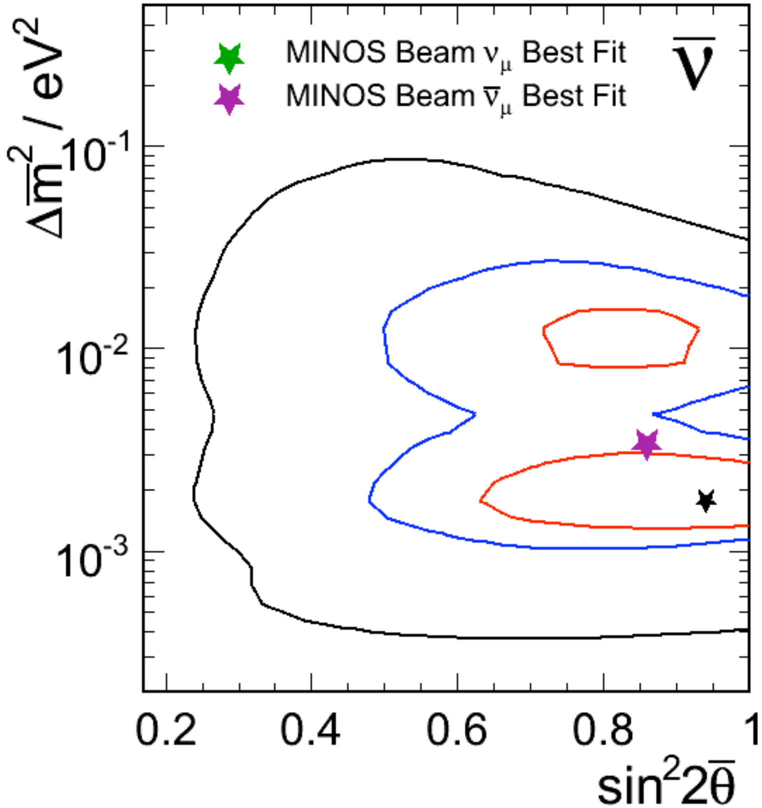
MINOS Physics Goals



- **Measure $\bar{\nu}_\mu$ disappearance as a function of energy**
  - $\overline{\Delta m^2_{32}}$ and $\sin^2(\overline{2\theta}_{23})$
  - look for differences between neutrino and anti-neutrinos
- **More MINOS analyses:**
  - atmospheric neutrinos
  - cross section measurements
  - Lorentz invariance tests
  - cosmic rays

Atmospheric Neutrinos





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

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