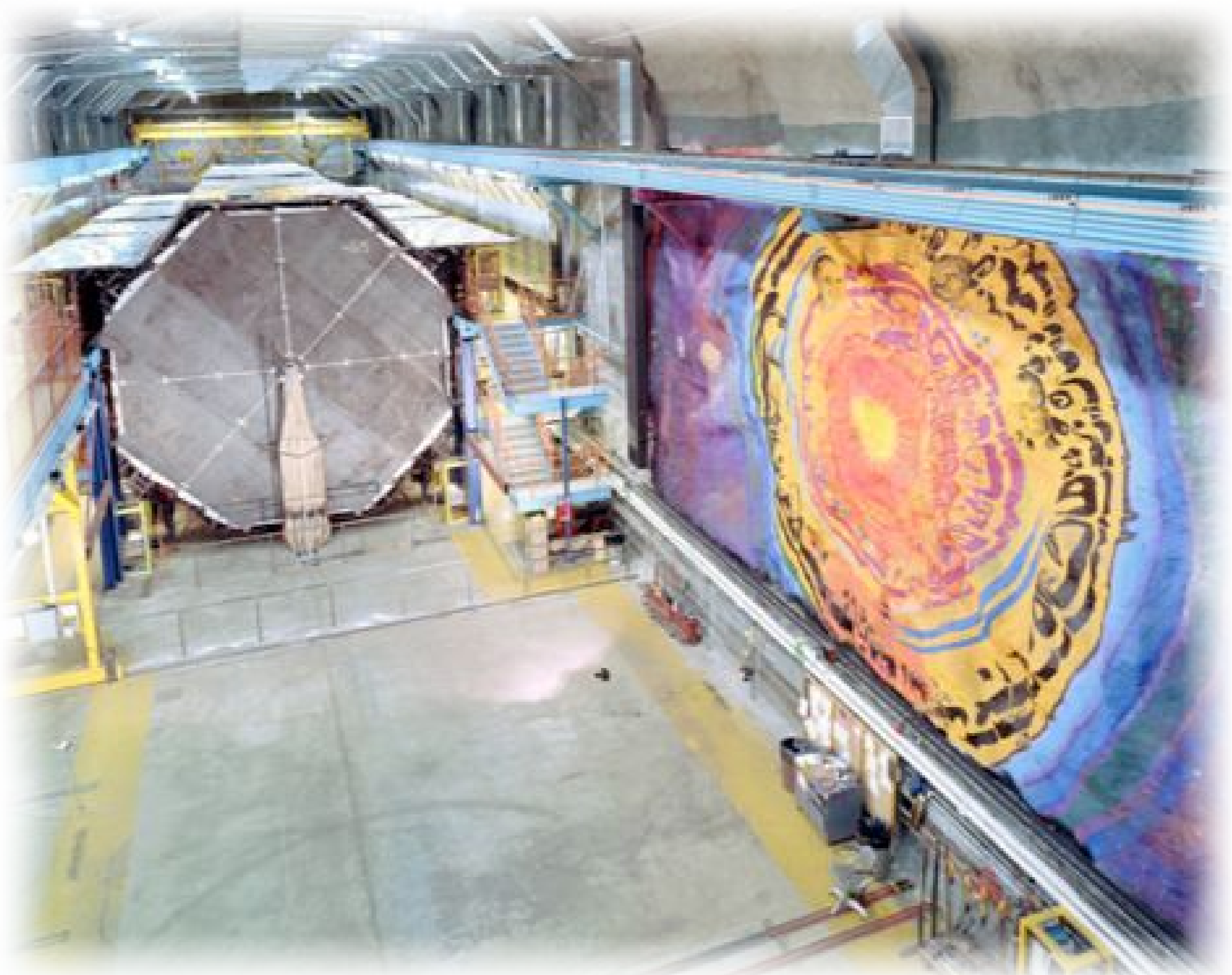
MINOS Search for Sterile Neutrinos



Adam Aurisano
University of Cincinnati
for the MINOS Collaboration

DPF 2013
Santa Cruz, California
08/16/2013

MINOS Overview

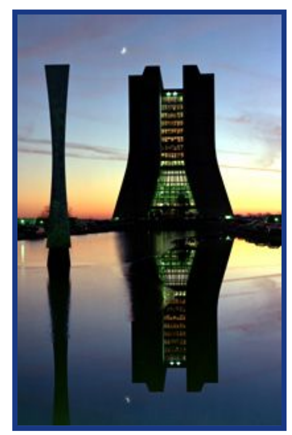
• **MINOS (Main Injector Neutrino Oscillation Search)**

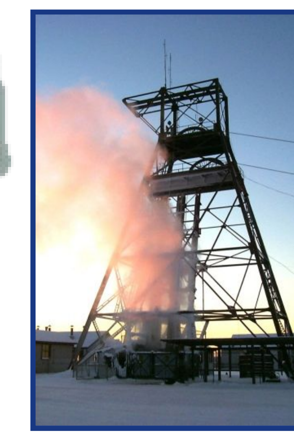
• ~320 kW NuMI neutrino beam from 120 GeV Main Injector-accelerated protons

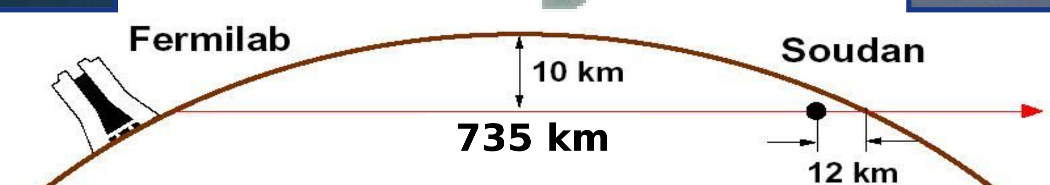
• Neutrino energy spectrum measured with two functionally identical iron-scintillator tracking calorimeters:

- Near Detector at Fermilab
  - 1km away from target
  - 1 kton mass
- Far Detector, deep underground in the Soudan mine
  - 735 km away
  - 5.4 kton mass

• Compare Far Detector observations with extrapolation of Near Detector measurement to study neutrino oscillations

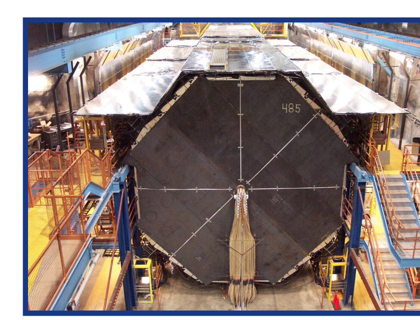






Near

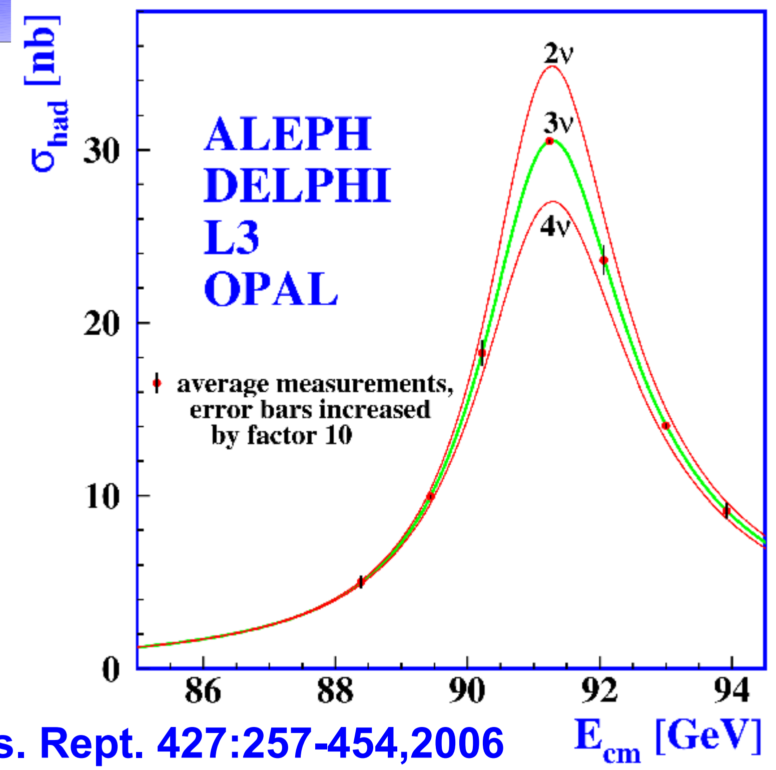
Far



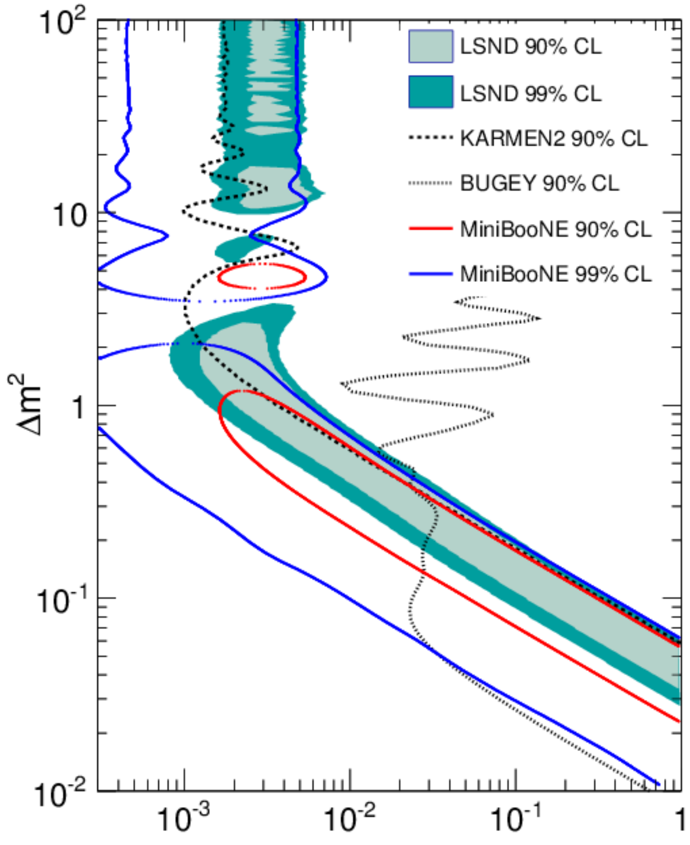
Sterile Neutrinos

- Preferred explanation for ν_μ CC disappearance is ν_μ oscillating into ν_τ
  - θ_{13} is nonzero, so a small fraction oscillates into ν_e
- Oscillations into a new fourth neutrino flavor are not excluded, but:
- Measurements of Z^0 width at LEP => only 3 light active neutrinos → 4th neutrino flavor has no weak interactions

  =>Sterile neutrino (ν_s)
- Short-baseline experiments, like LSND and MiniBooNE are consistent with a large mass splitting (Δm^2~1 eV^2), and therefore additional neutrino flavors



Phys. Rept. 427:257-454,2006

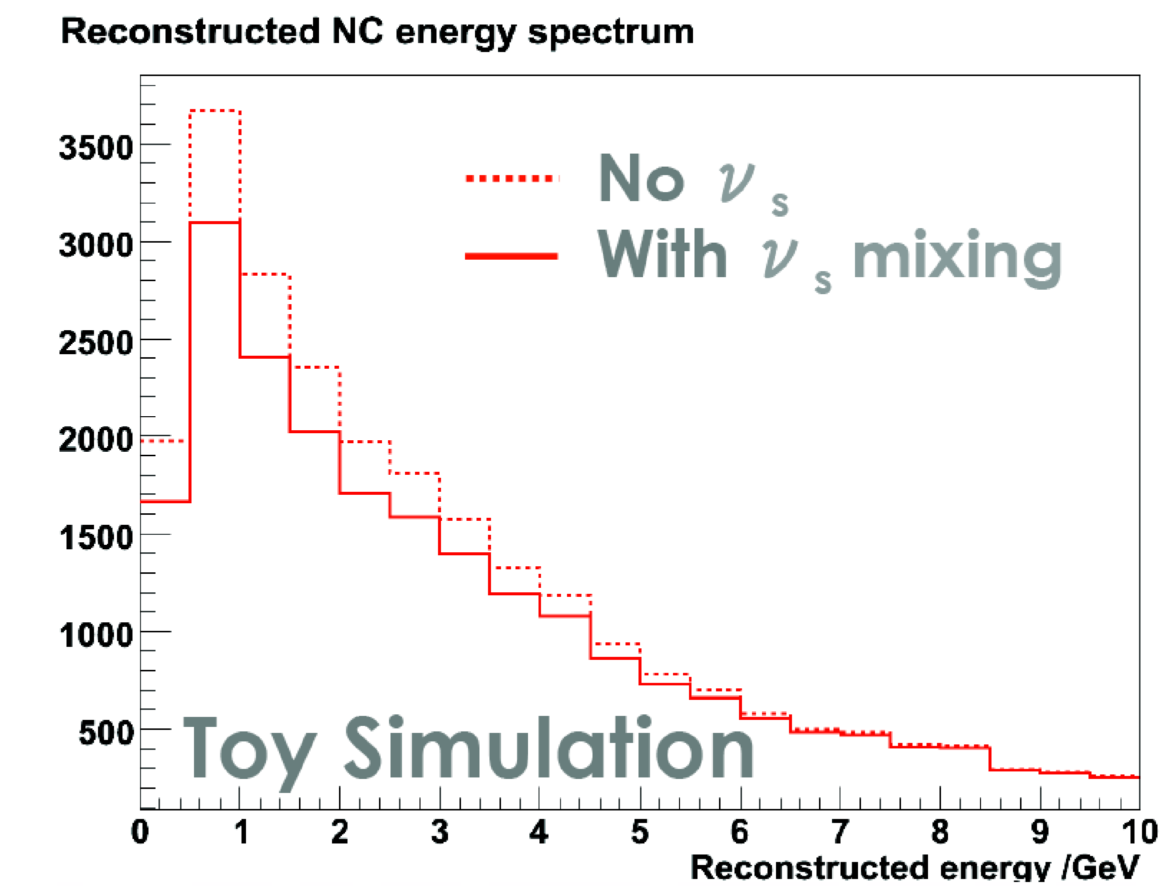


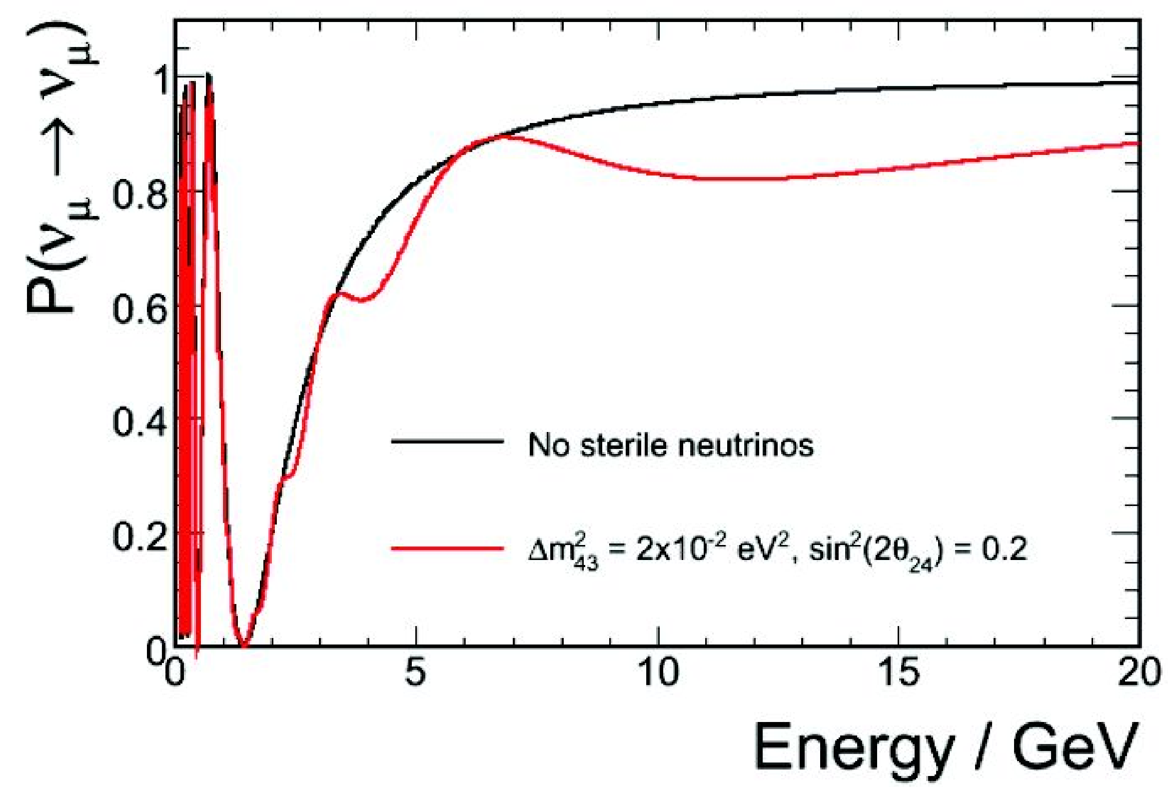
Phys. Rev. Lett. 110 161801 (2013)

Looking for Sterile Neutrinos

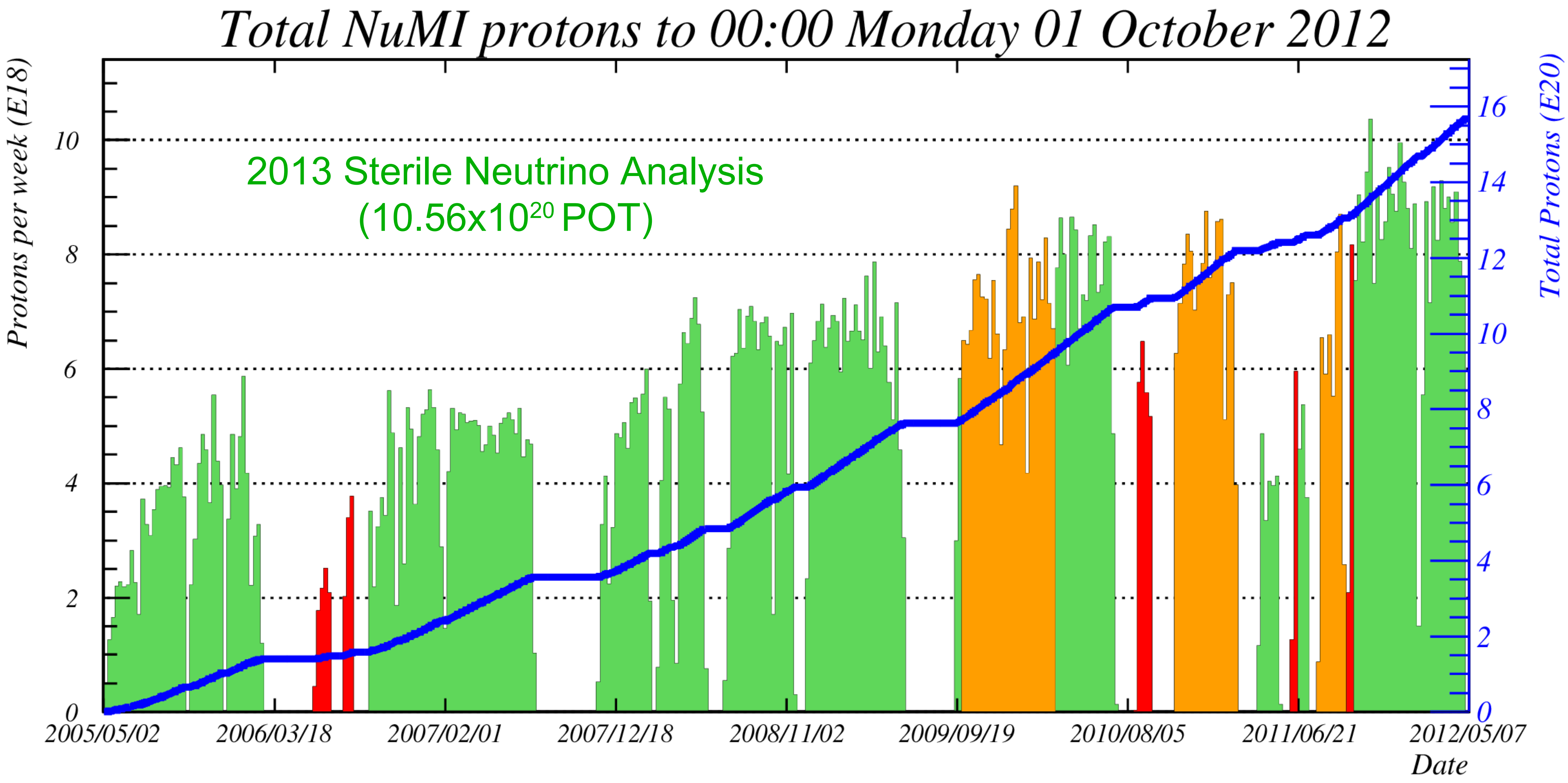
Strategy 1:
- Neutral current interaction rate is the same for the three active flavors → standard oscillations do not change NC rate
- $\nu_\mu \rightarrow \nu_s$ oscillations reduce the NC rate as ν_s do not interact in the detector
- Look for NC disappearance relative to 3-flavor predictions
- Model independent

Strategy 2:
- Sterile oscillations add modulations to standard 3-flavor picture, even in CC interactions
- Fit both NC and CC spectra to the 4-flavor model
- Constrain sterile mixing parameters





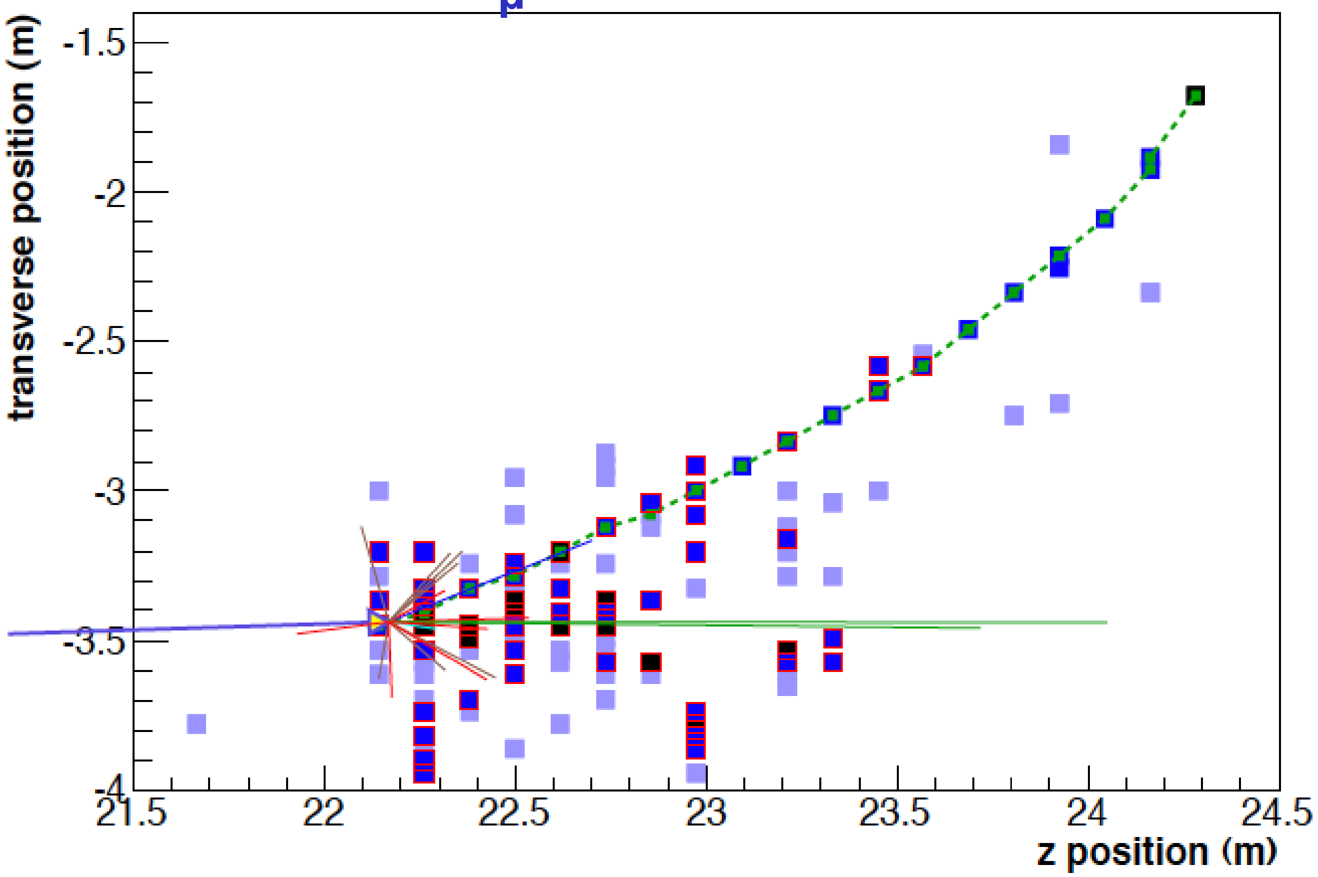
Accumulated Beam Data



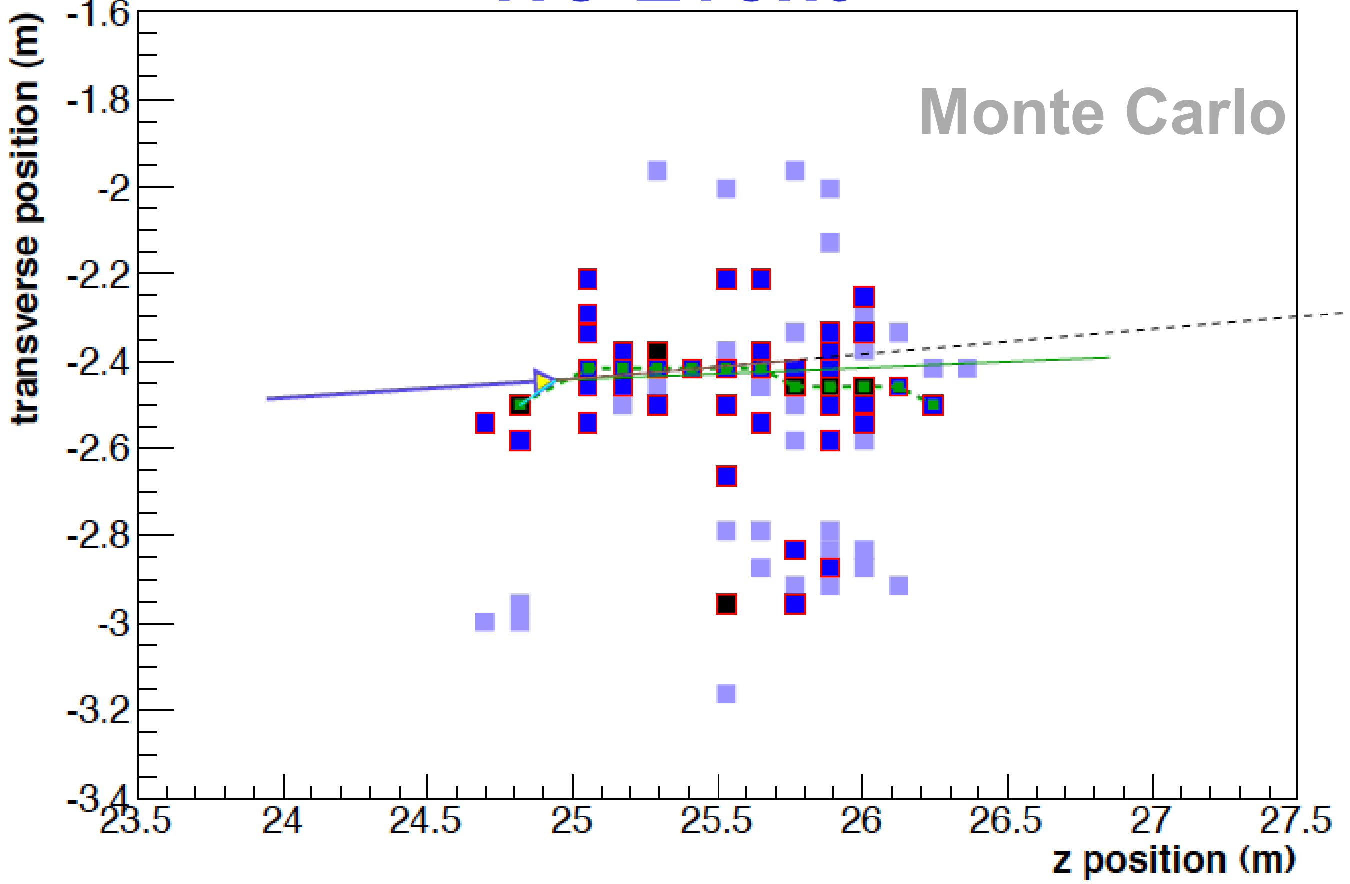
Neutrino Running   Higher Energy Neutrino Running   Antineutrino Running

Event Topologies

ν_μ CC Event



NC Event



Charged Current ν_μ events

- long μ track, hadronic activity near event vertex
- neutrino energy from sum of muon energy (range or curvature) and shower energy

$$\frac{\sigma(E)}{E} \approx 5\%(\text{range}),\ 10\%(\text{curvature})$$

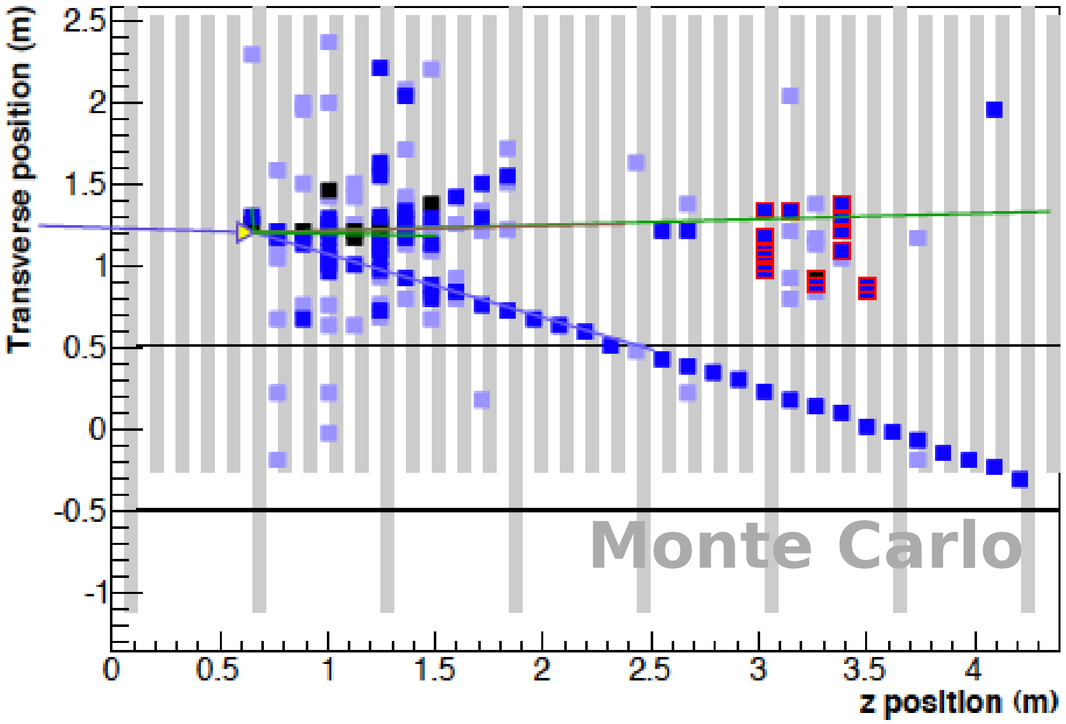
Neutral Current events

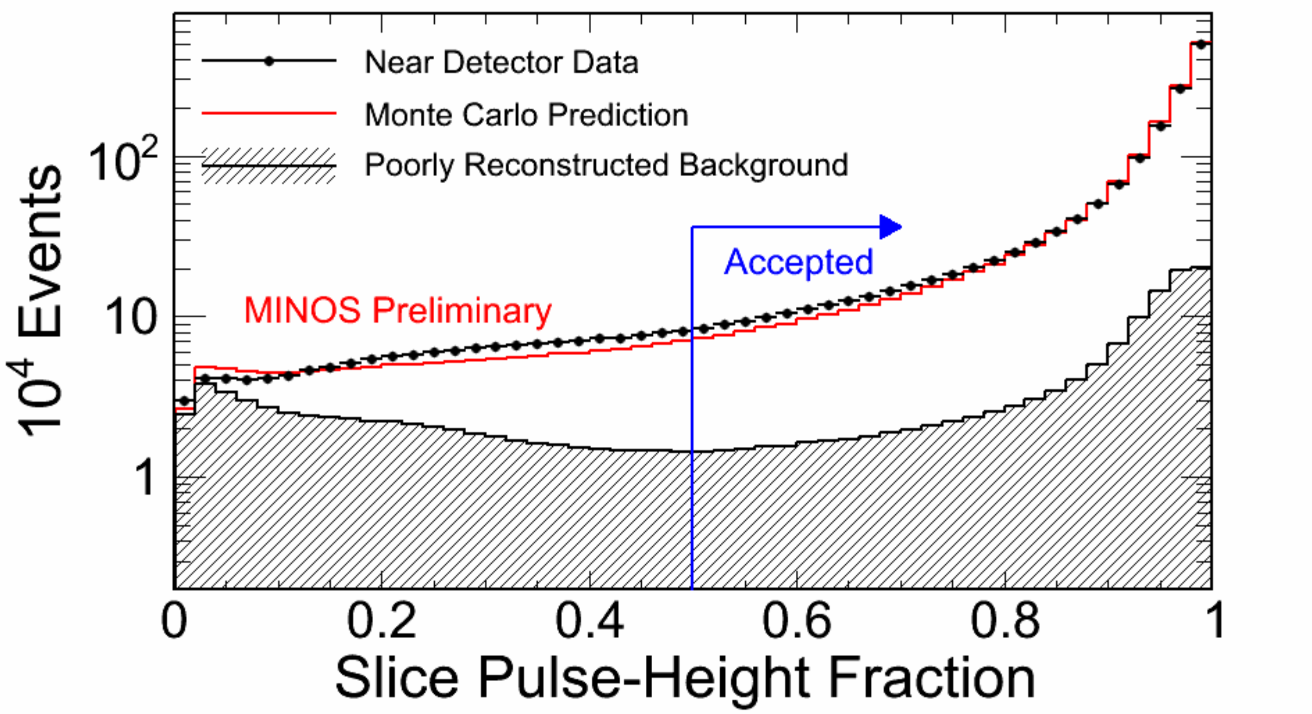
- short diffuse showers
- shower energy from calorimetric response

$$\frac{\sigma(E)}{E} \approx \frac{56\%}{\sqrt{E}}$$

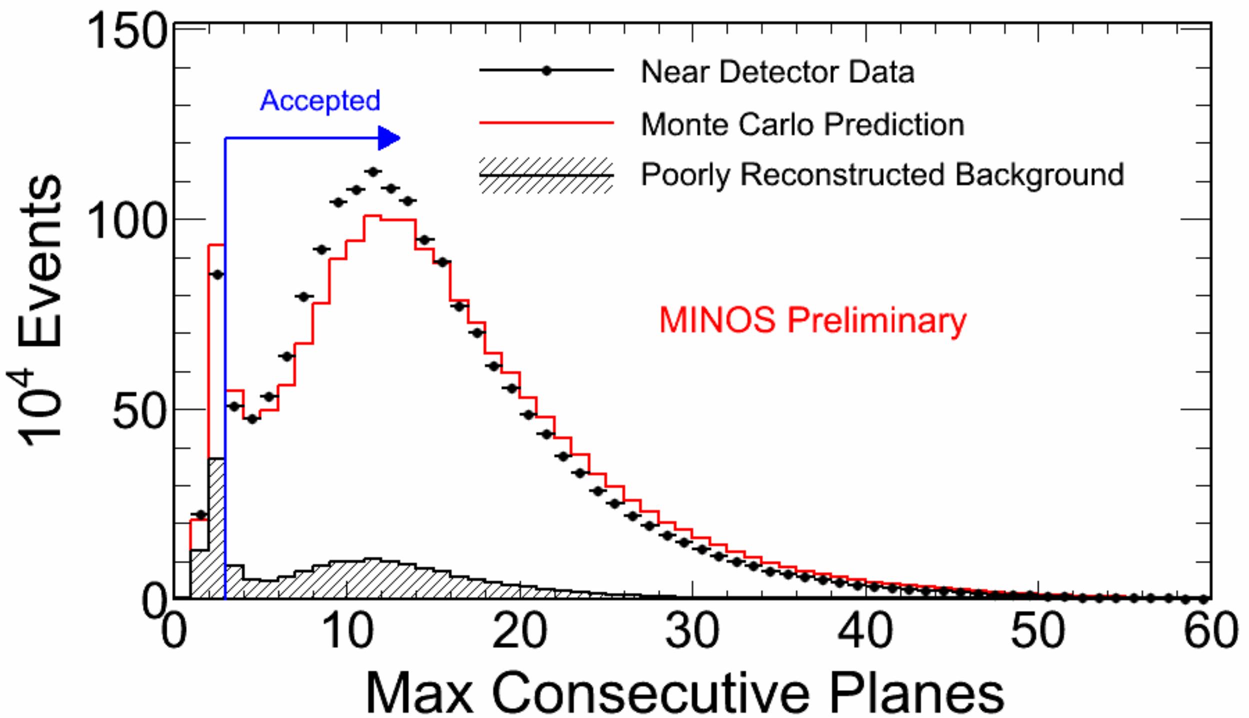
ND Pre-Selection

- High event rate in Near Detector requires time and spatial slicing, and may cause split events



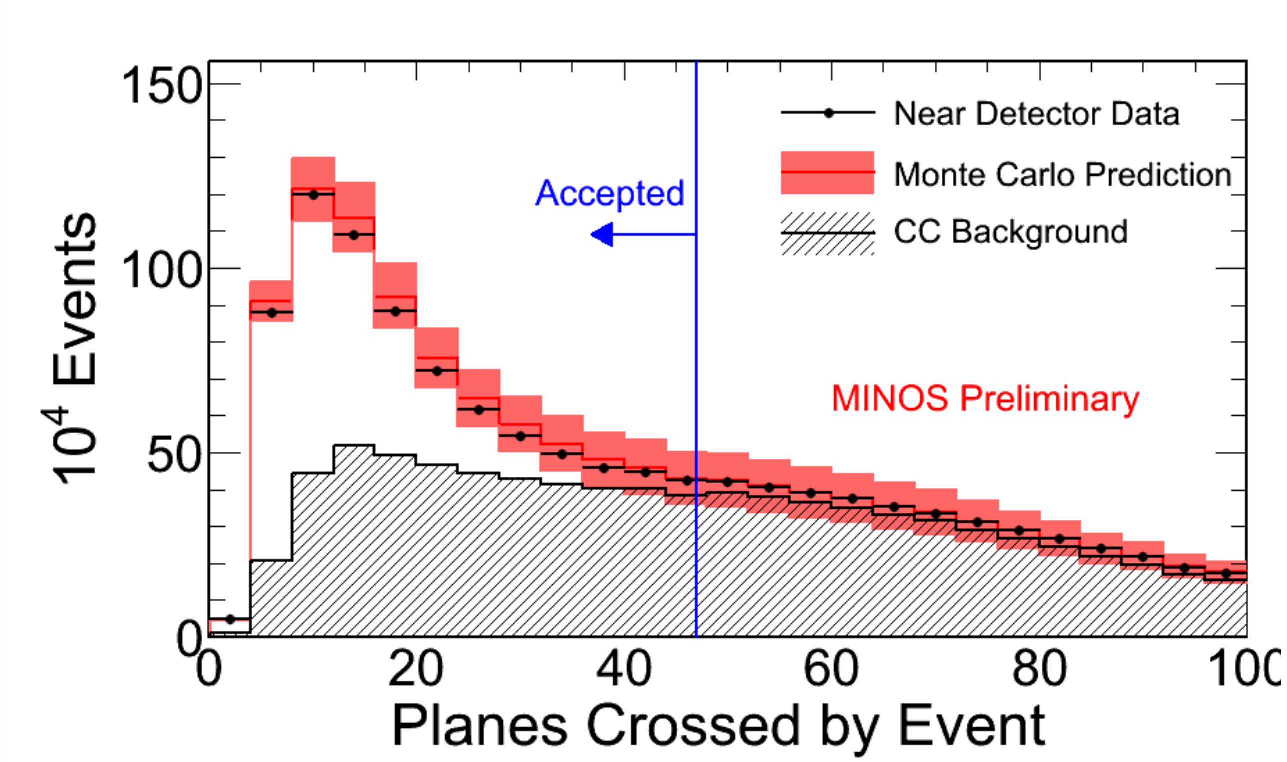


- Mitigated in the analysis by applying pre-selection cuts:
  - Fraction of pulse height in slice > 50%
  - Activity in > 3 consecutive planes
- Reduces poorly reconstructed background ($E_{shw\_reco}/E_{shw\_true} < 0.3$) with $E_{reco} < 1$ GeV

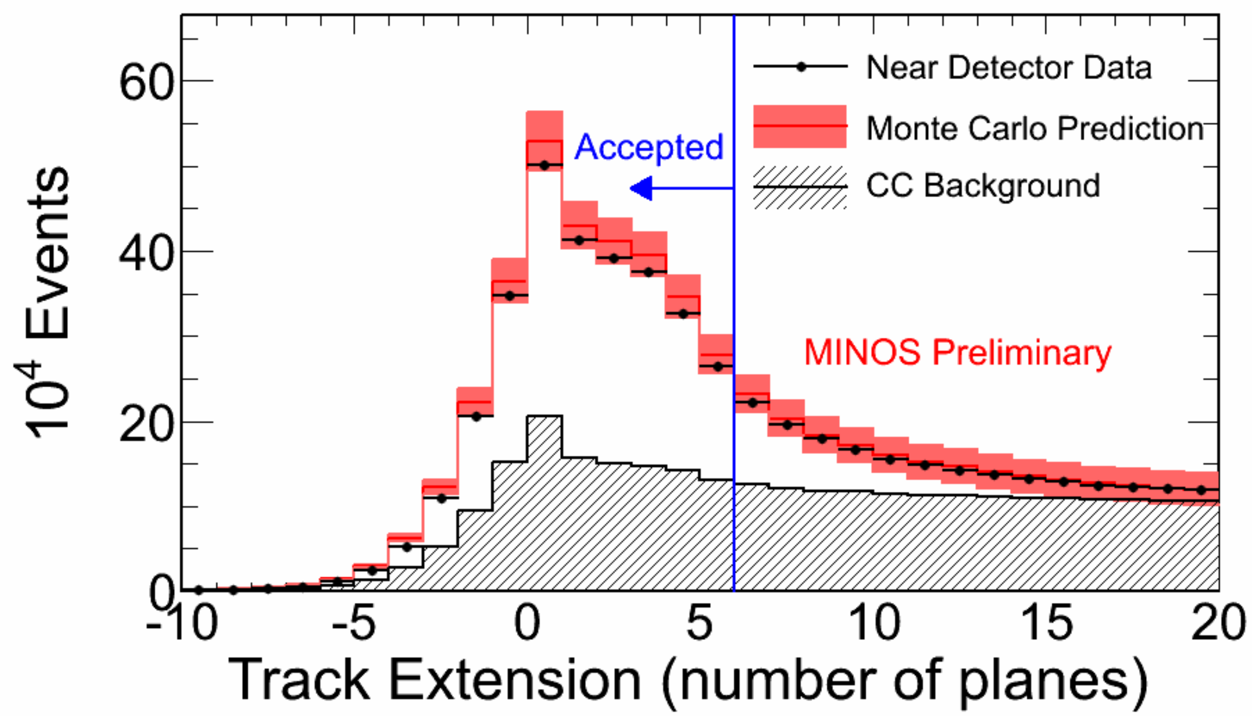


NC Event Selection

NC/CC event separation achieved via cuts on topological variables



Discard events with length > 47 planes

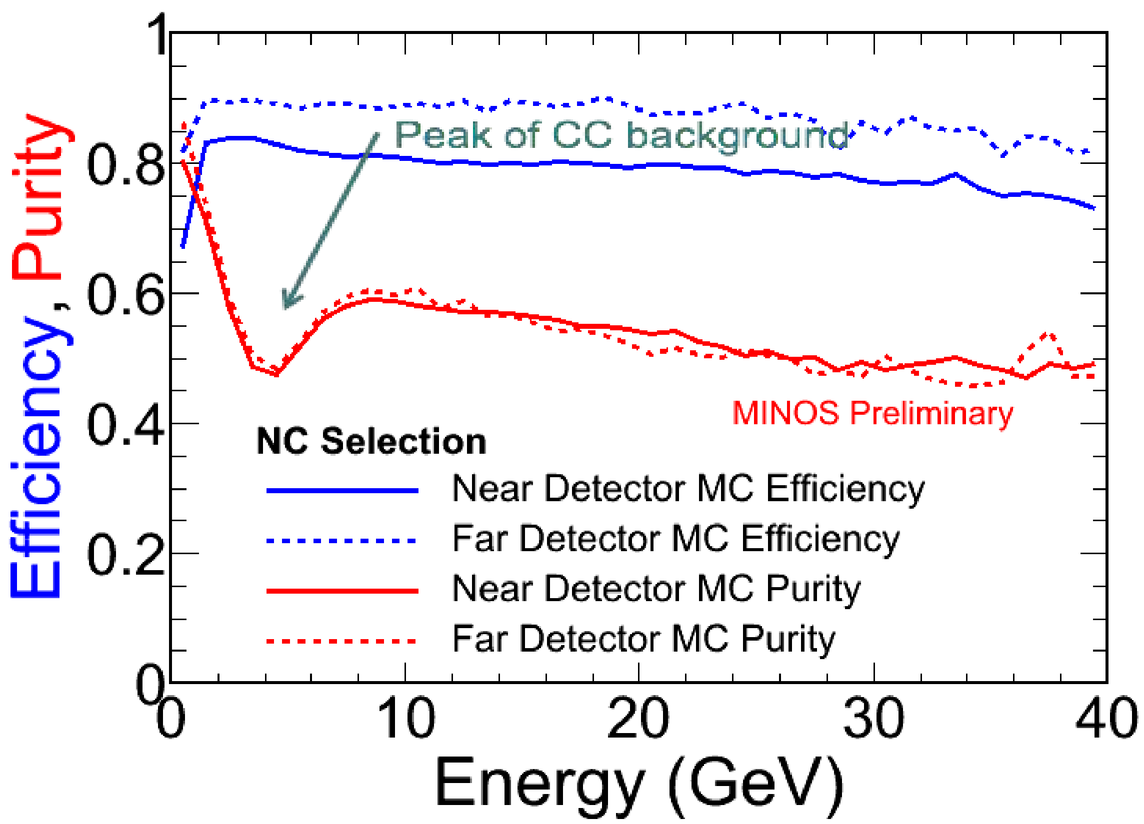


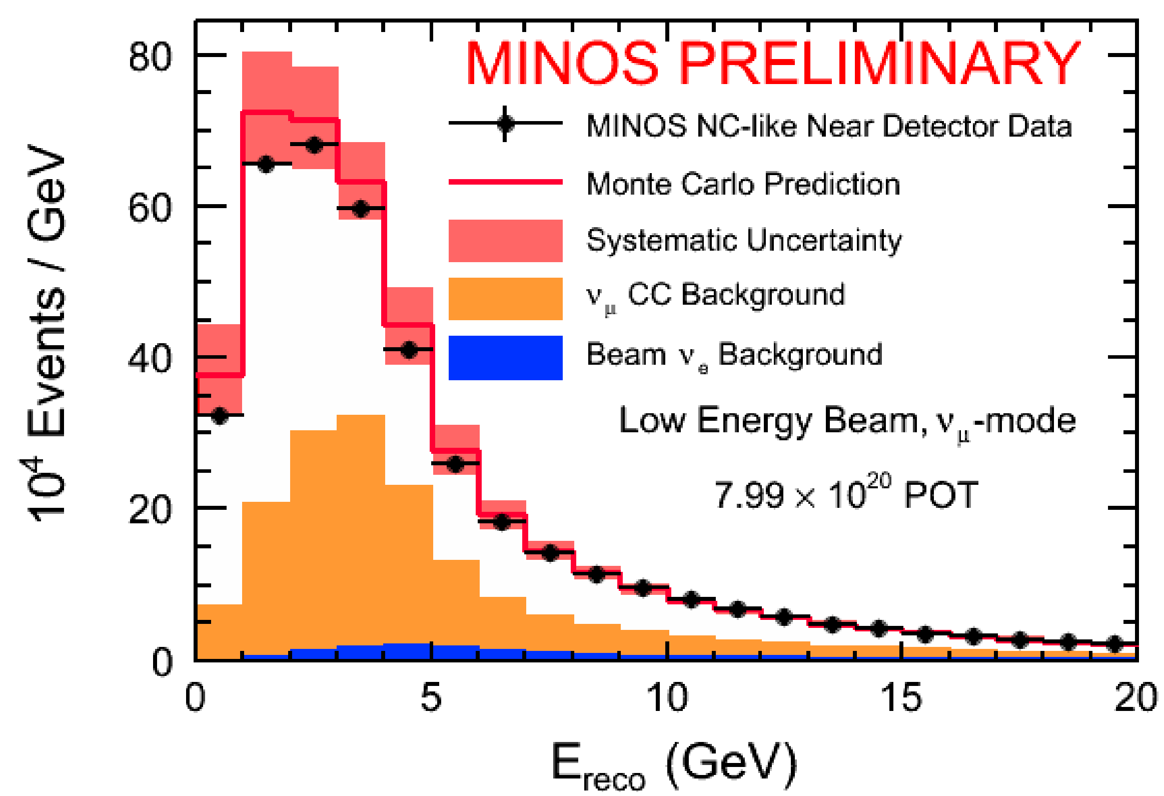
Discard events with a track > 6 planes longer than the shower

- Same selection applied to data and MC in Far Detector
- CC events are selected from events failing NC selection
- CC selection criteria are the same as in the standard ν_μ disappearance analysis – see A. Radovic's talk

ND NC Energy Spectrum

Main background originates from inelastic (high-y) ν_μ CC events





NC events selected with 88% efficiency and 62% purity in FD

Data and MC differences smaller than systematic uncertainties

97% of ν_e CC events are classified as NC

Far/Near Extrapolation

- The measured Near Detector energy spectrum is used to predict the Far Detector spectrum via the **Far/Near Ratio** method

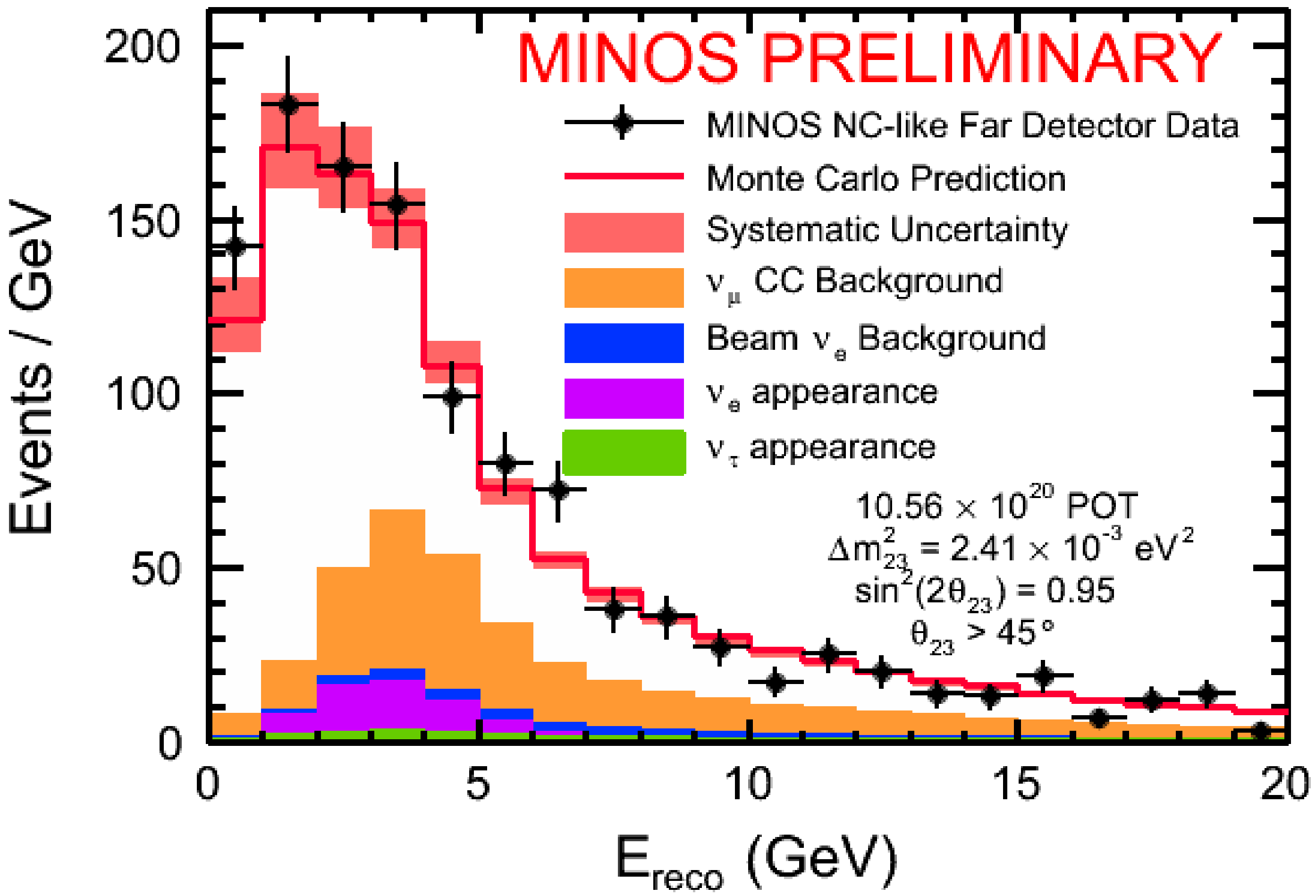
- The method uses the ND data without relying on a specific parameterization

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

- Correct each energy bin in the FD MC using the ND data/MC differences as a scale factor
- Simple, robust to most systematic uncertainties
- FD data spectrum blinded until analysis procedures defined to avoid prediction biases

FD Energy Spectrum

- CC background in FD prediction is oscillated at the 2012 MINOS ν_μ CC disappearance best fit values for Δm^2_{32} and $\sin^2(2\theta_{23})$
  - Both upper and lower octant values of θ_{23} are considered (upper shown here)
- θ_{13} = 9° and δ = 0



No depletion of neutral current events observed

Observed: 1221 events
Expected: 1183 ± 34(stat) ± 36(syst) events

Comparison to 3-Flavor Predictions

Compare the NC energy spectrum in FD data (10.56 x10^{20} POT exposure) with the expectation from standard 3-flavor neutrino oscillation physics using the *R* statistic

$$R = \frac{N_{data} - \sum B_{CC}}{S_{NC}}$$

Predicted CC background from all flavors

Predicted NC interaction signal

No NC disappearance ⇒ $R = 1$

FD predictions are obtained using the Far/Near ratio extrapolation method and assuming:

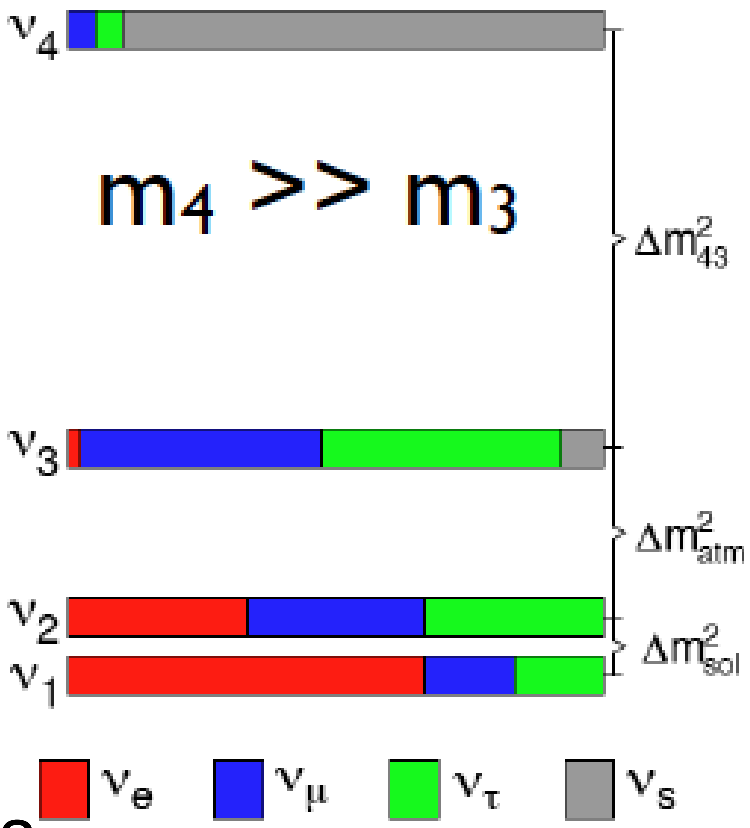
$\Delta m^2_{32} = 2.41\times10^{-3}$ eV^2 $\theta_{23} = 51°$ (upper octant) $\theta_{13} = 9°$

$\Delta m^2_{21} = 7.59\times10^{-5}$ eV^2 $\theta_{12} = 35°$ $\delta_{CP} = 0°$ Normal mass hierarchy

E_{reco} (GeV)	R ± stat ± syst	NC	ν_μ CC	ν_τ CC	Beam ν_e CC	ν_e App. CC	Data
0-200	1.05 ± 0.05 ± 0.06	771	289	18	50	55	1221
3-200	1.01 ± 0.07 ± 0.07	397	237	12	46	34	731
0-3	1.09 ± 0.06 ± 0.08	374	52	5	4	21	490

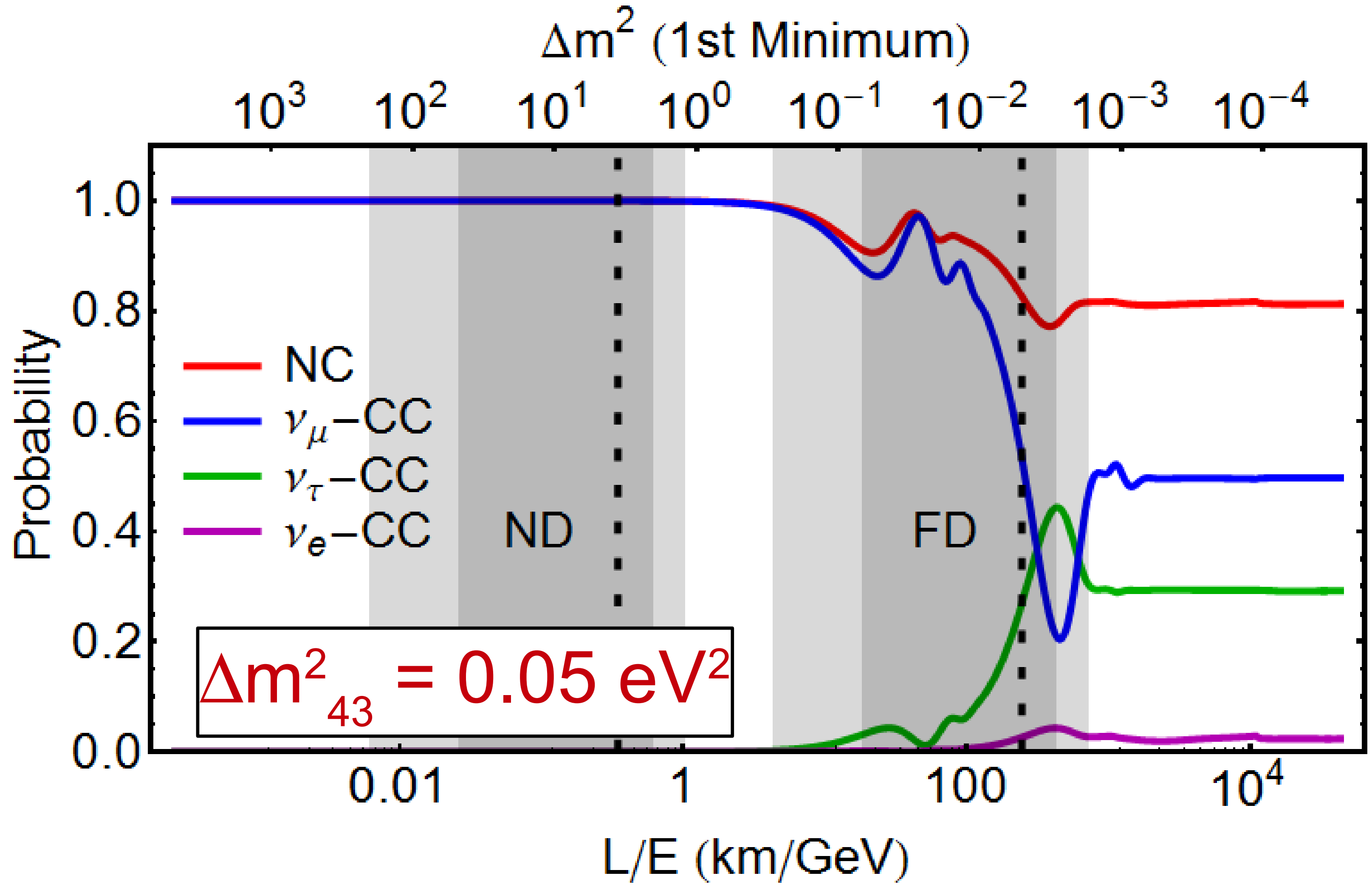
4-Flavor Analysis

- Assume 3+1 model
  - one additional sterile neutrino and an additional neutrino mass scale
  - Extend mixing matrix with extra angles and phases
- For simplicity, fix parameters MINOS is not senstive to, δ_1, δ_2, δ_3, and θ_{14}, to zero
  - θ_{23}, θ_{24}, θ_{34}, and Δm^2_{32} are varied
- Fit both the NC and CC spectra to determine sterile mixing parameters
- Δm^2_{43} requires extra consideration → unlike 3-flavor oscillations, depending on the value of Δm^2_{43}, oscillations can be significant in the near detector
  - Can break down into a small, medium and large Δm^2_{43} regimes



Small Δm^2_{43} Oscillations

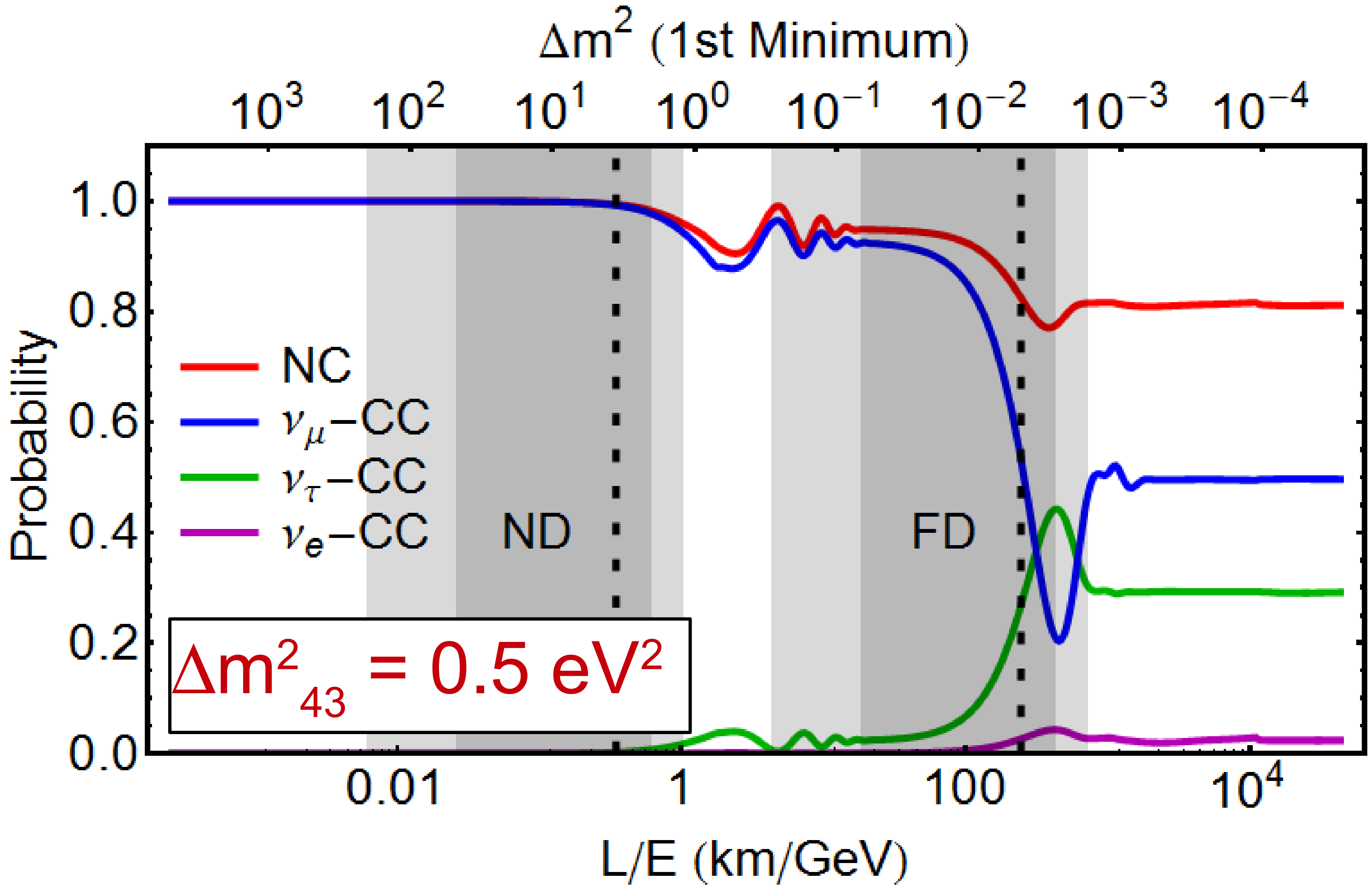
At small Δm^2_{43}, oscillations occur in the far detector at high energies (but not in the near detector). The largest effect is visible where beam flux uncertainties are least well known.



Requires more work to understand beam flux uncertainties at high energies

Medium Δm^2_{43} Oscillations

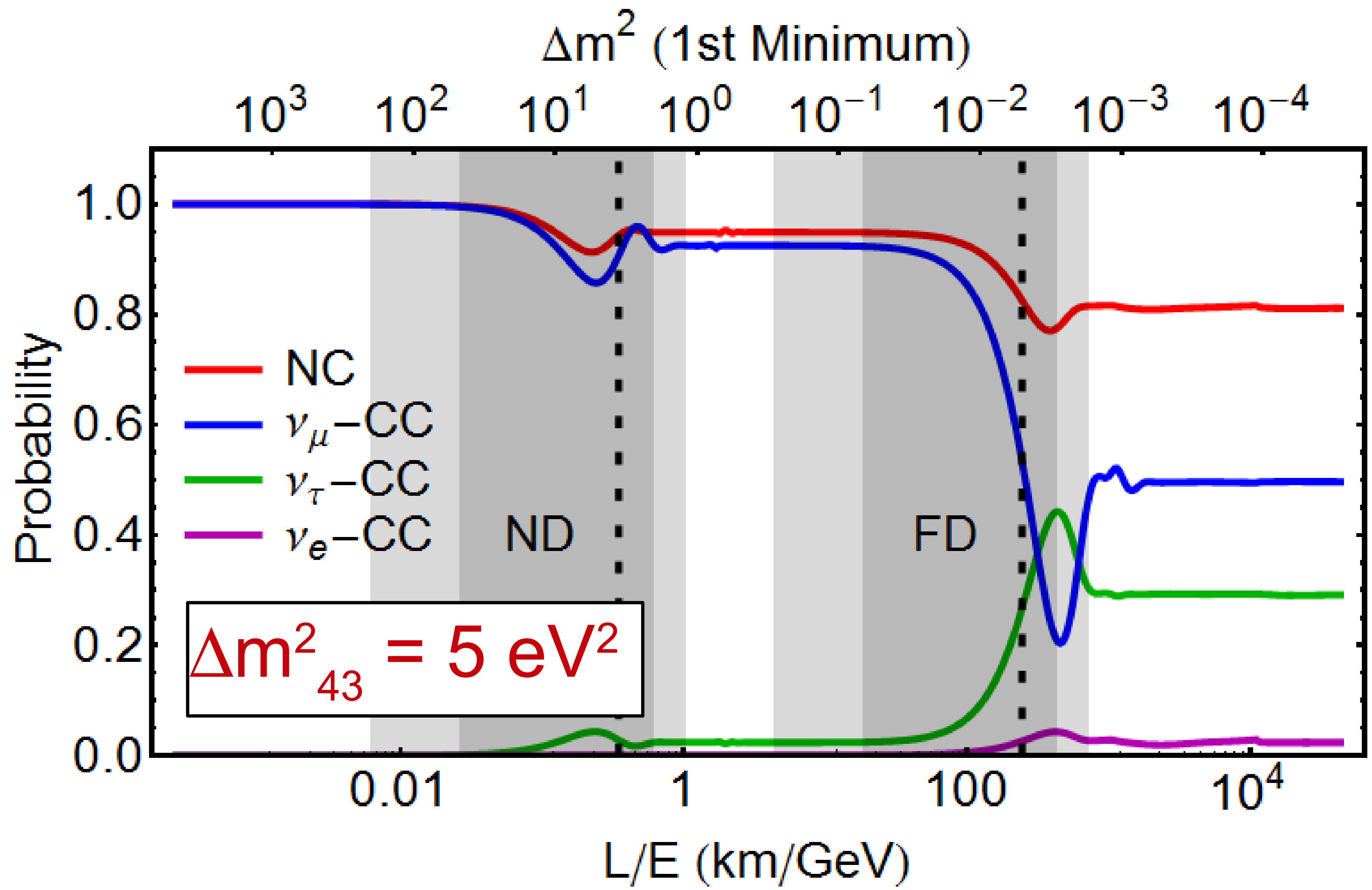
At medium Δm^2_{43}, there are no oscillations at the near detector, but those in the far detector are rapid. The effect averages out creating an overall deficit → effectively a counting experiment



For the following results, we fix Δm^2_{43} = 0.5 eV^2 to remain in the "counting experiment" regime

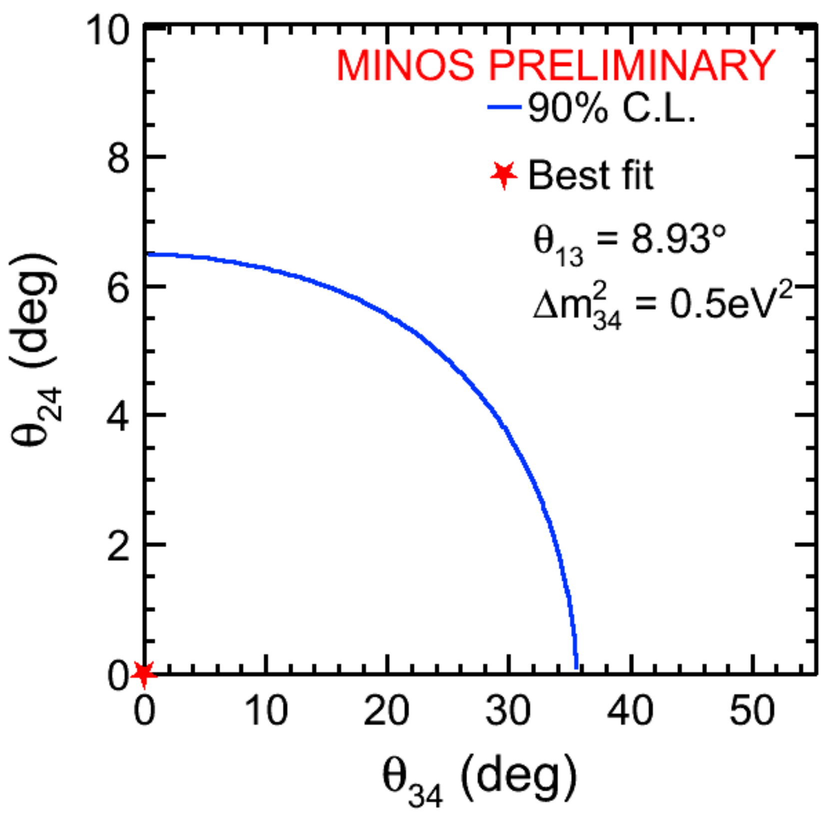
Large Δm^2_{43} Oscillations

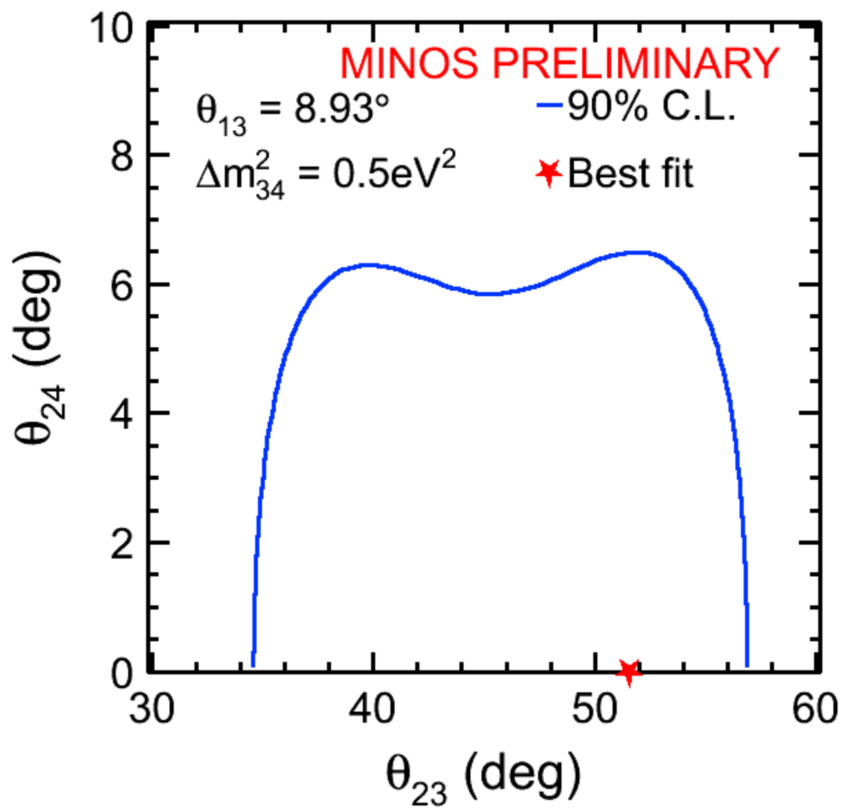
At large Δm^2_{43}, there are significant oscillations in the near detector and a constant deficit in the far detector

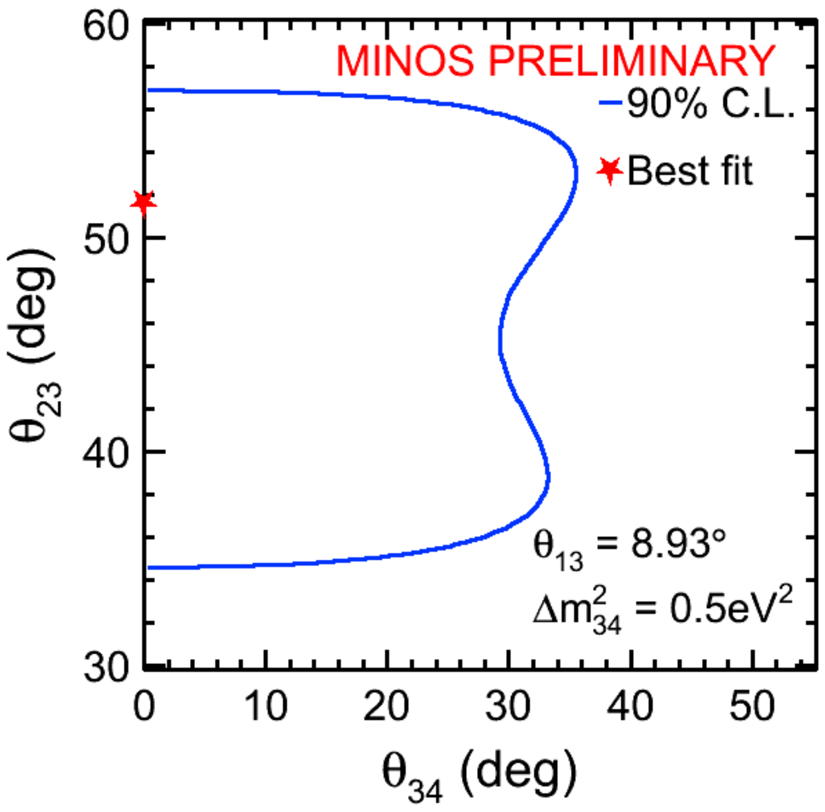


Requires more work to incorporate near detector oscillations and varying pion decay position into the F/N ratio

4-Flavor Results





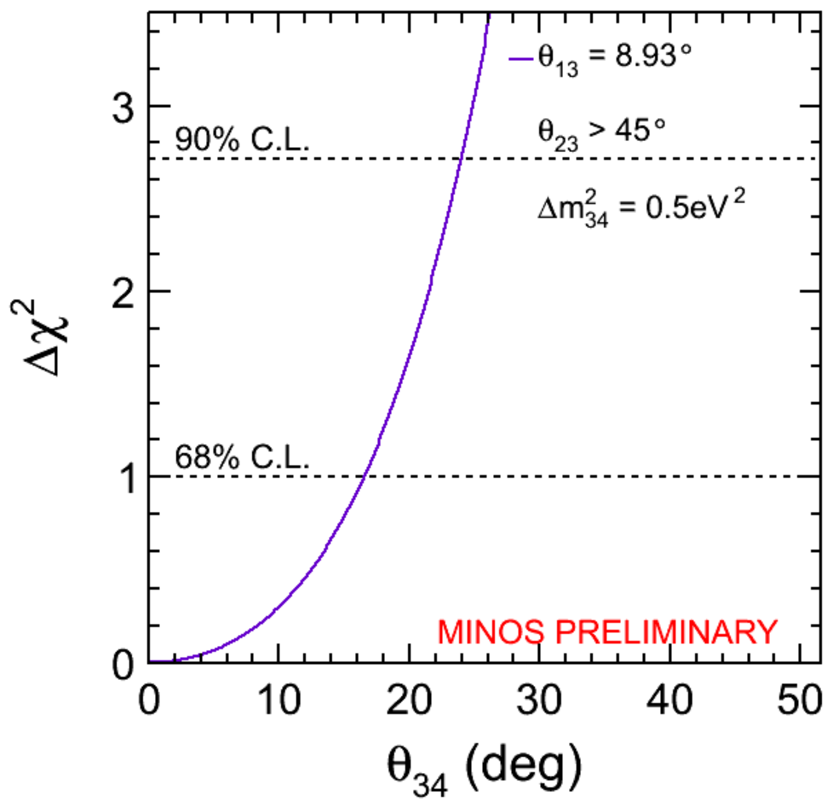


Best fit at no sterile mixing → set limits

Slight preference for upper octant

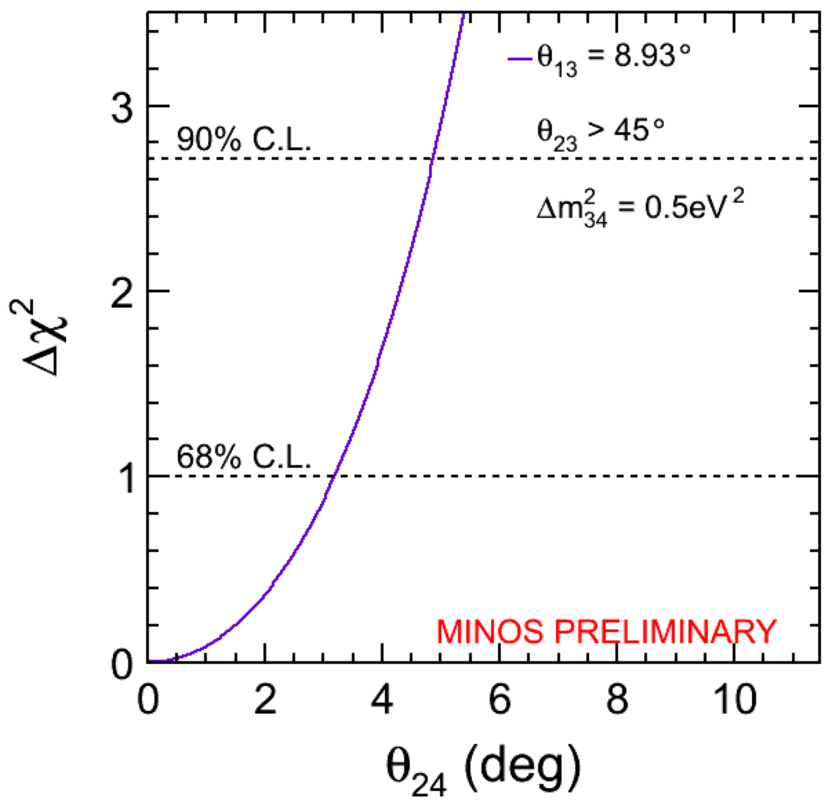
- 90% confidence level allowed regions for ν_s mixing
- Fit only at Δm^2_{43} = 0.5 eV^2 to avoid near detector oscillations

4-Flavor Results: 1D Limits



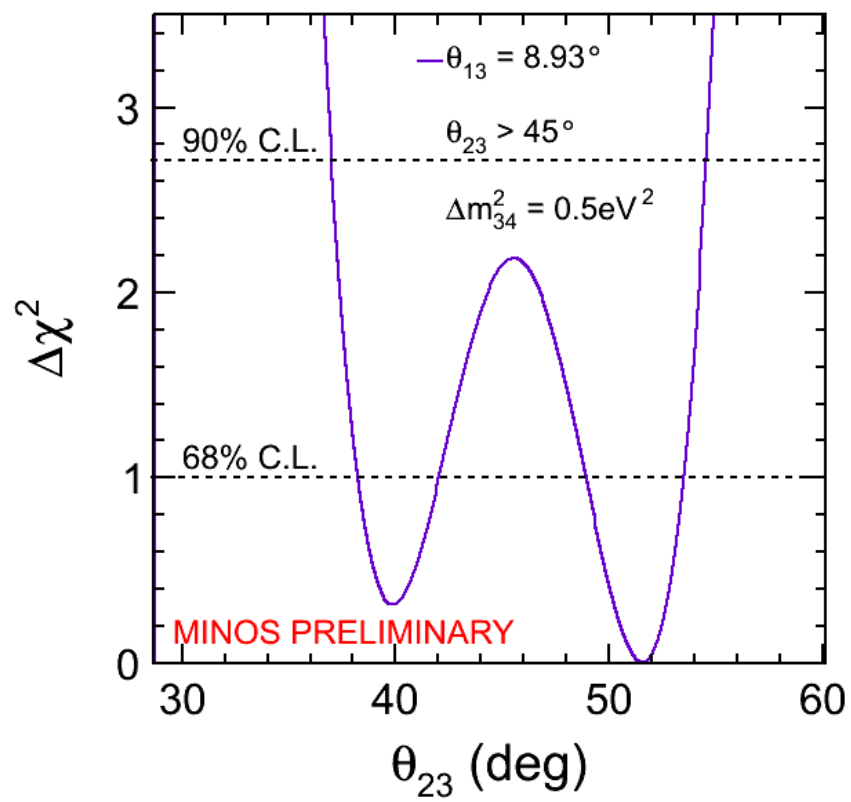
$\theta_{34} < 24°$ at 90% CL

$\sin^2\theta_{34} < 0.17$



$\theta_{24} < 5°$ at 90% CL

$\sin^2\theta_{24} < 0.007$



$37° < \theta_{23} < 54°$ at 90% CL

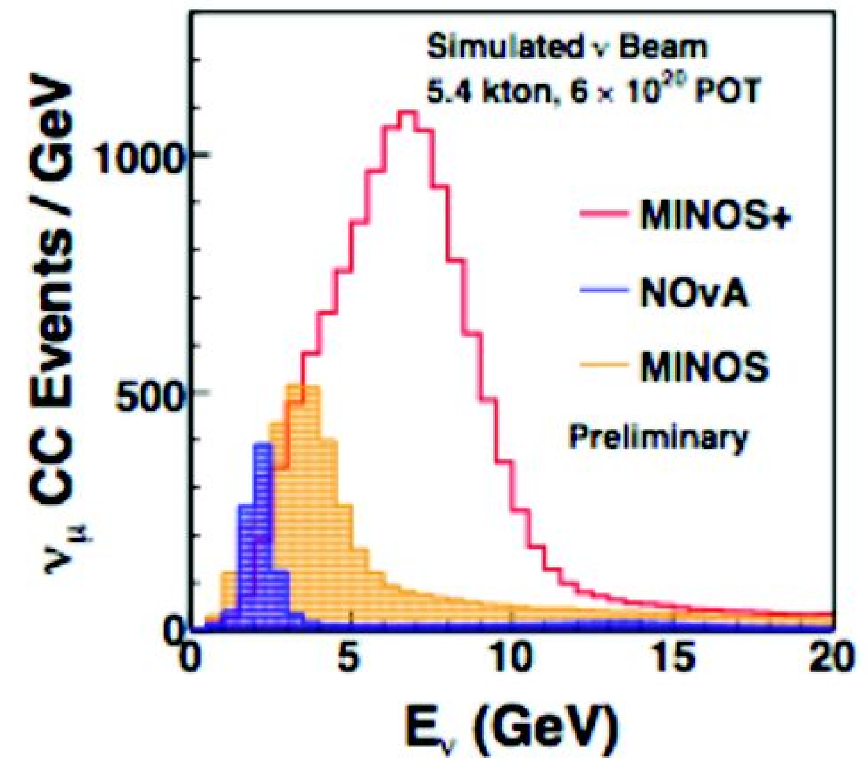
$0.42 < \sin^2\theta_{23} < 0.90$

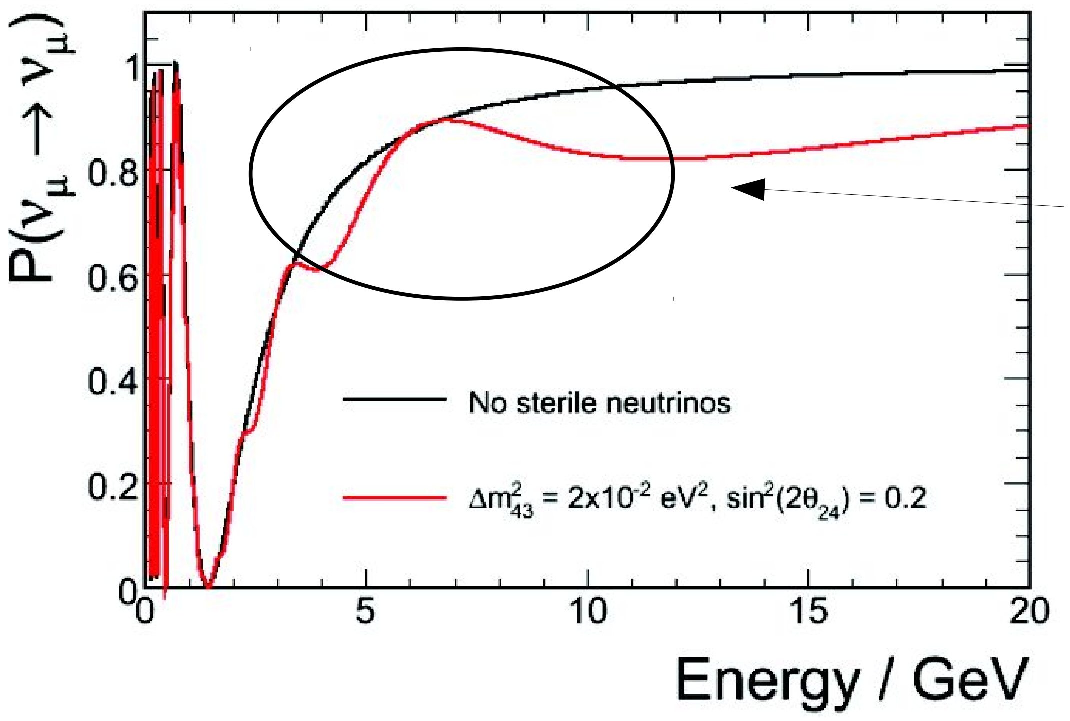
- 90% confidence level limits from 1D $\Delta\chi^2$ projections
- Fit only at Δm^2_{43} = 0.5 eV^2 to avoid near detector oscillations

MINOS+

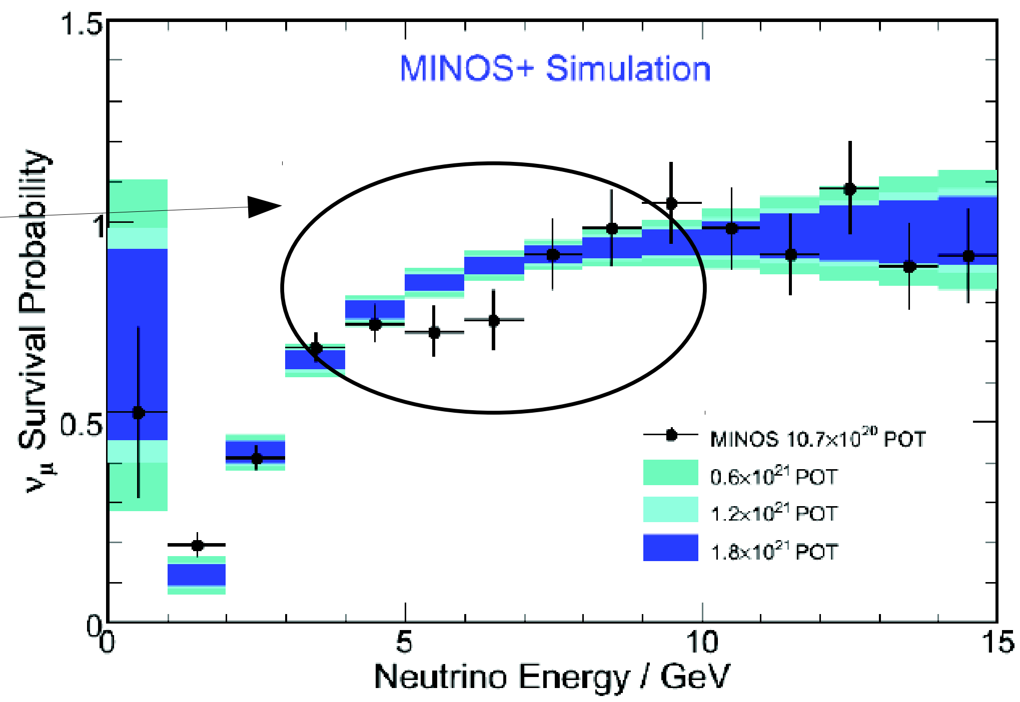
In addition to analysis improvements and the incorporation of antineutrino running MINOS data, the MINOS detectors will continue to operate in the NOνA beam.

MINOS+ will enhance the high energy tail, where sterile neutrino searches have most statistical power.





Will reduce the statistical uncertainties at this region where sterile oscillation effects would be pronounced

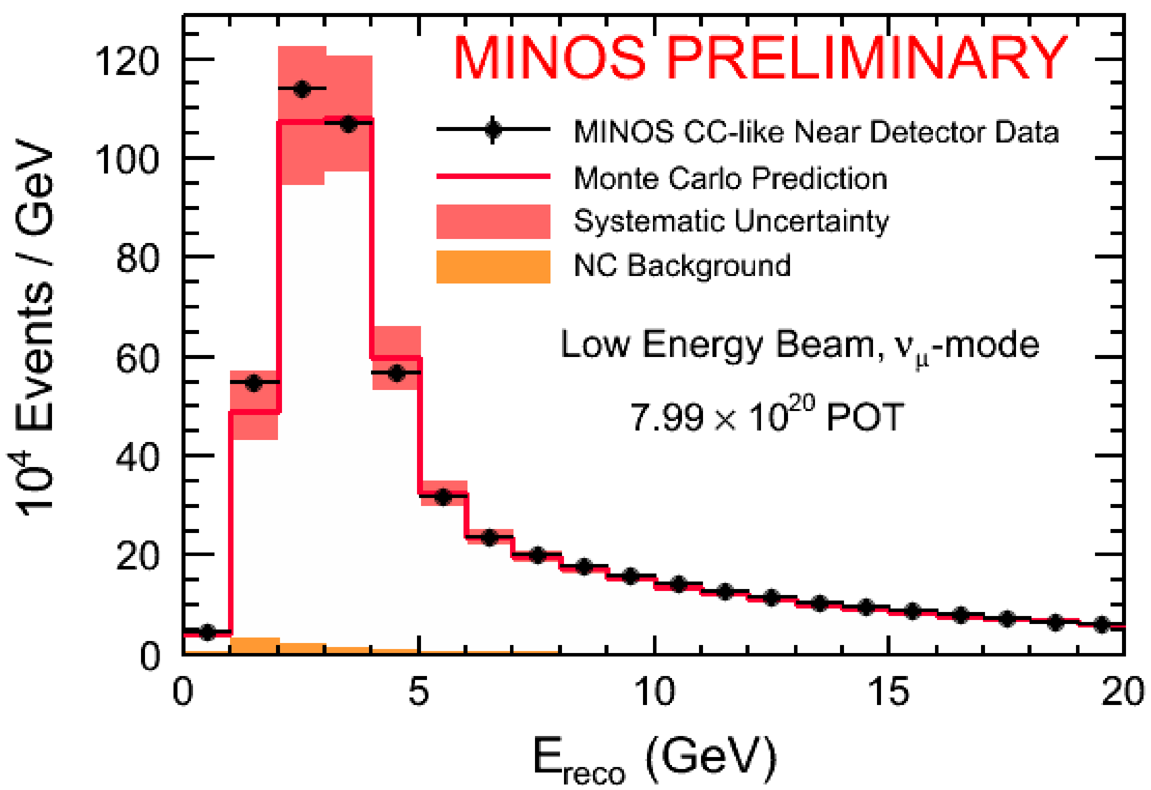


Conclusions

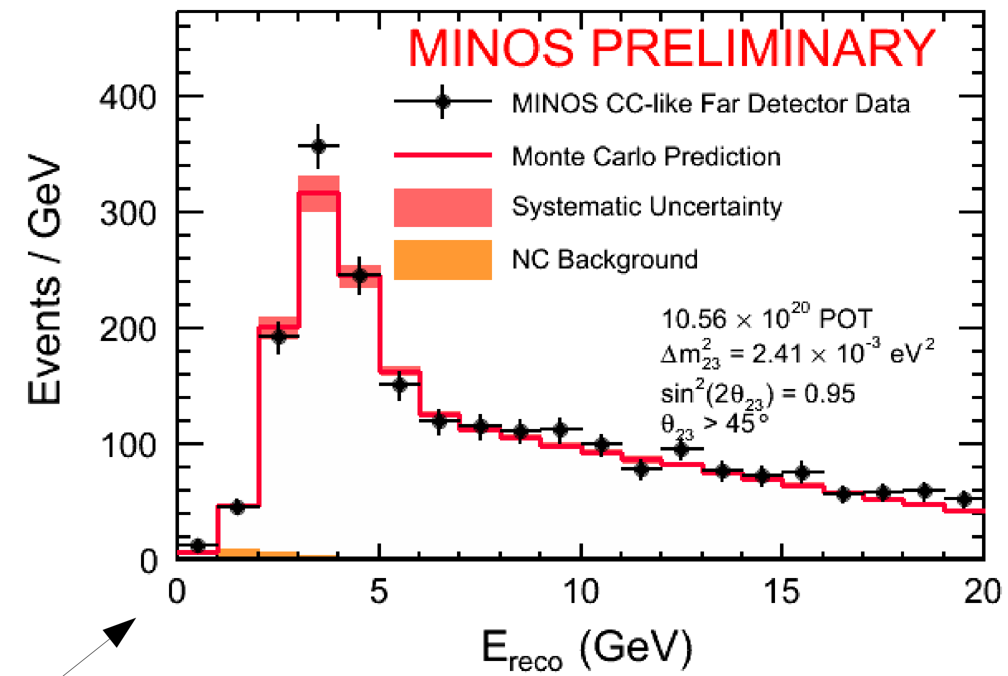
- MINOS is making very important contributions to the body of knowledge on sterile neutrinos
- From measurement of the neutral current rate in a sample of 10.56×10^{20} POT of NuMI neutrino running, MINOS finds:
  - $R = 1.05 \pm 0.05(\text{stat}) \pm 0.06(\text{syst})$ (Upper octant: 0-200 GeV)
  - $R = 1.07 \pm 0.05(\text{stat}) \pm 0.06(\text{syst})$ (Lower octant: 0-200 GeV)
  - Results consistent with no oscillation into sterile neutrinos
- Using a four-flavor shape analysis of neutral current and charged current samples, MINOS sets limits on sterile mixing angles (limits valid at $\Delta m^2_{43} = 0.5\ \text{eV}^2$):
  - $\theta_{34} < 24°$ at 90% CL
  - $\theta_{24} < 5°$ at 90% CL
  - $37° < \theta_{23} < 54°$ at 90% CL
- Actively working to incorporate ND oscillations and varying baseline in formalism
- MINOS+ will improve the search by enhancing the high-energy tail → stay tuned!

BACKUP

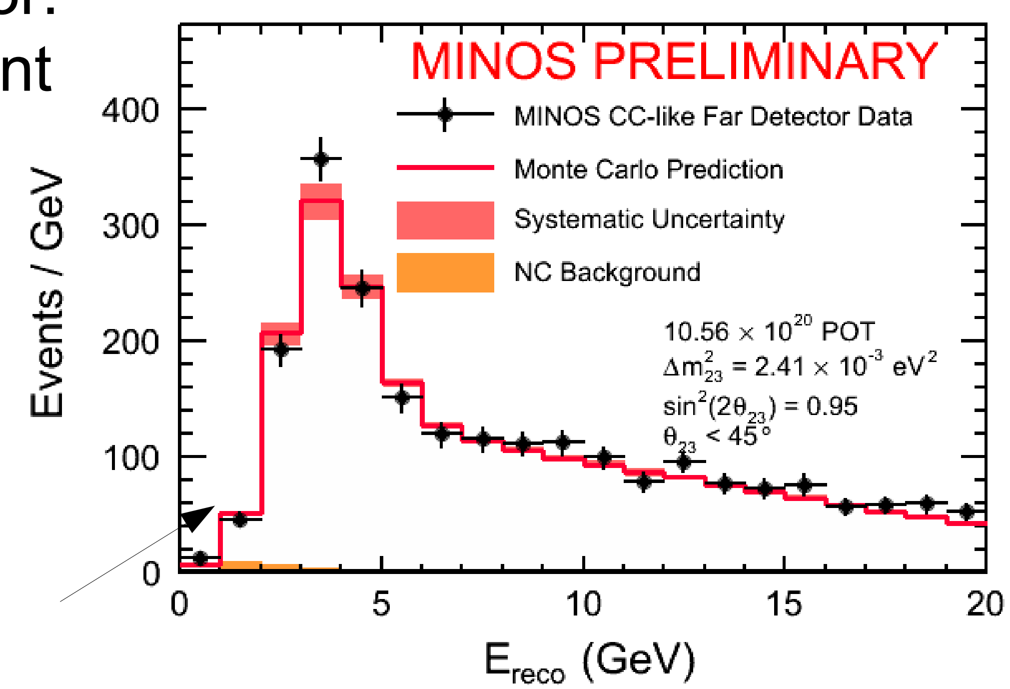
CC Spectra



Near Detector



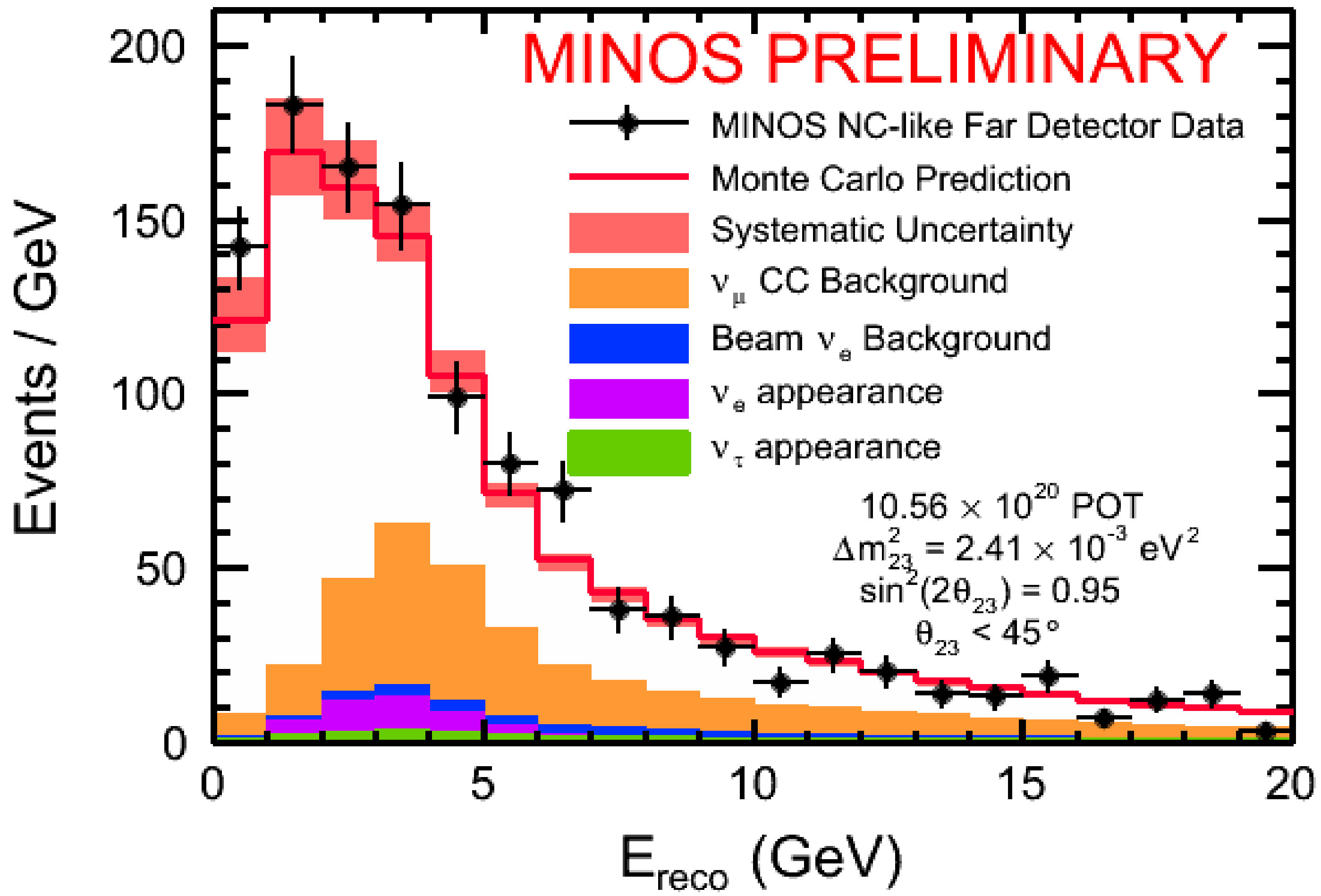
Far detector: upper octant



Far detector: lower octant

FD Energy Spectrum: Lower Octant

- CC background in FD prediction is oscillated at the 2012 MINOS ν_μ CC disappearance best fit values for Δm^2_{32} and $\sin^2(2\theta_{23})$
  - Both upper and lower octant values of θ_{23} are considered (upper shown here)
- θ_{13} = 9° and δ = 0



No depletion of neutral current events observed

Observed: 1221 events
Expected: 1168.48 ± 34.18(stat) ± 36.13(syst) events

3-Flavor Analysis: Lower Octant

Compare the NC energy spectrum in FD data (10.56 x10^{20} POT exposure) with the expectation from standard 3-flavor neutrino oscillation physics using the *R* statistic

Predicted CC background from all flavors

$$R = \frac{N_{data} - \sum B_{CC}}{S_{NC}}$$

Predicted NC interaction signal

FD predictions are obtained using the Far/Near ratio extrapolation method and assuming:

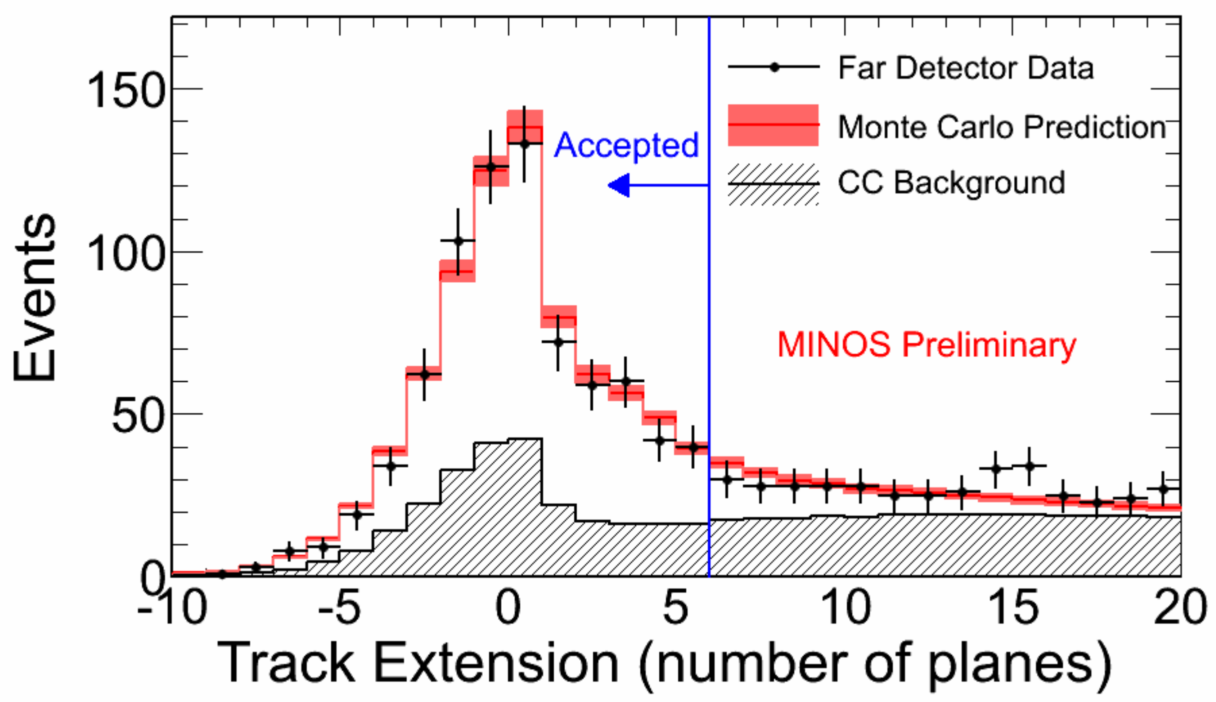
$\Delta m^2_{32} = 2.41\times10^{-3}$ eV^2 θ_{23} = 38° (upper octant) $\Delta m^2_{21} = 7.59\times10^{-5}$ eV^2 θ_{12} = 35°

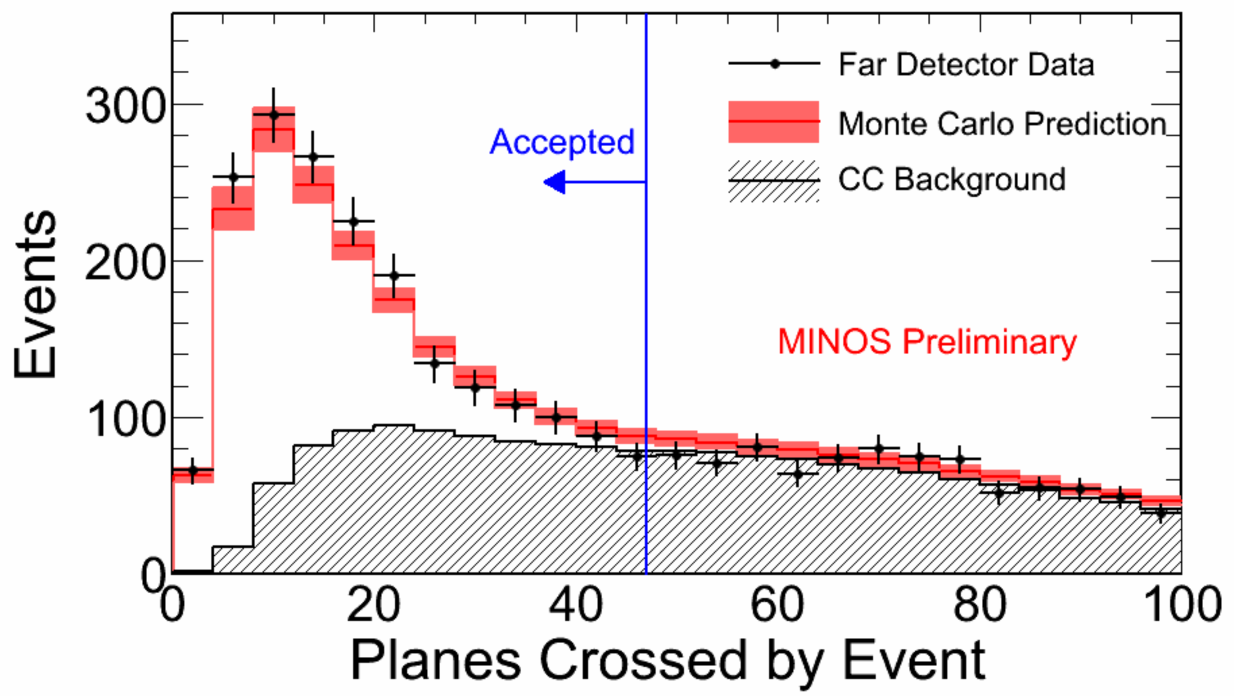
θ_{13} = 9° δ_{CP} = 0° Normal mass hierarchy

E_{reco} (GeV)	R ± stat ± syst	NC	ν_μ CC	ν_τ CC	Beam ν_e CC	ν_e App. CC	Data
0-200	1.07 ± 0.05 ± 0.06	771	292	18	50	37	1221
3-200	1.03 ± 0.07 ± 0.07	397	238	14	46	23	731
0-3	1.11 ± 0.06 ± 0.08	374	54	5	4	14	490

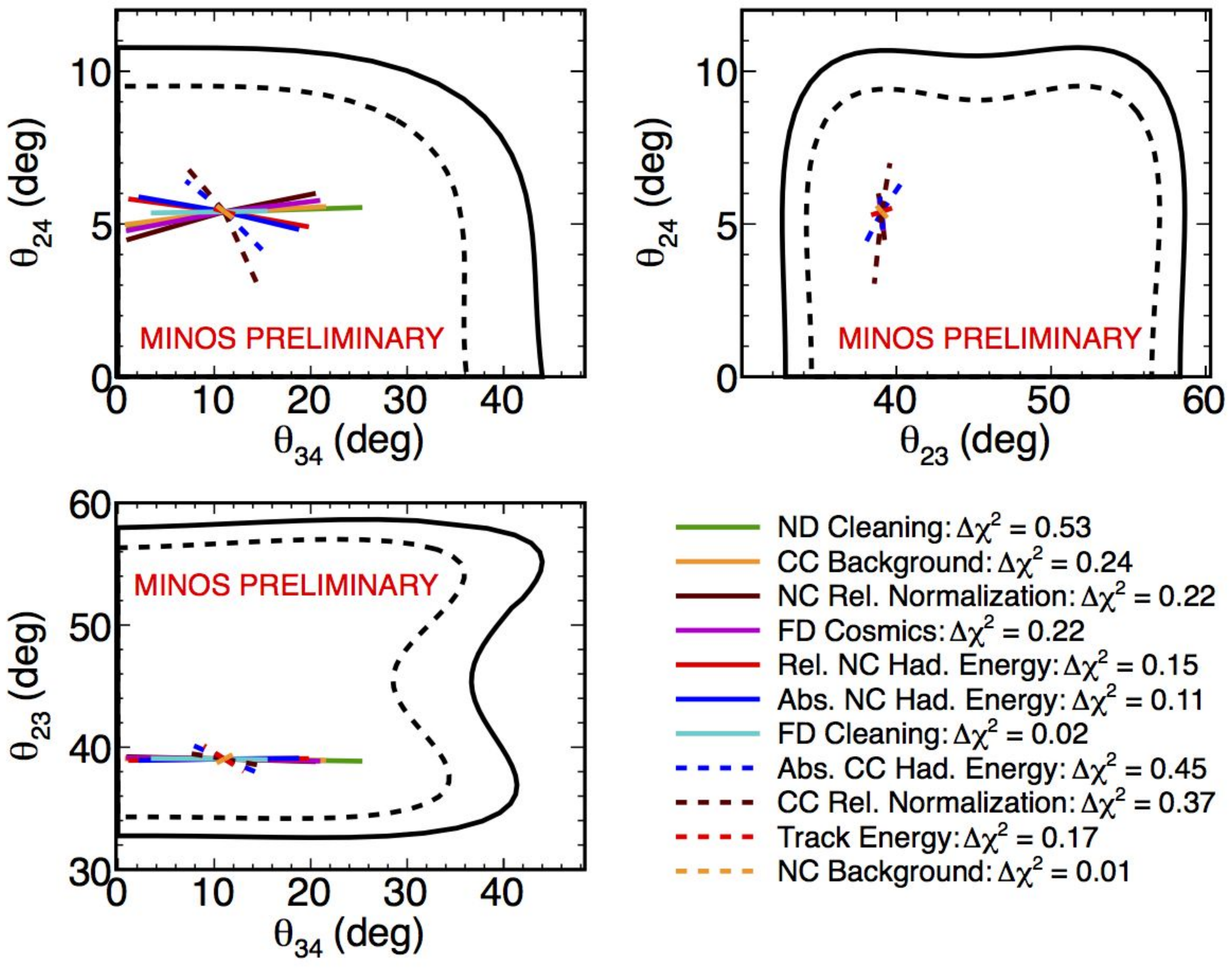
No NC disappearance ⇒ *R*=1

FD NC Selection Variables



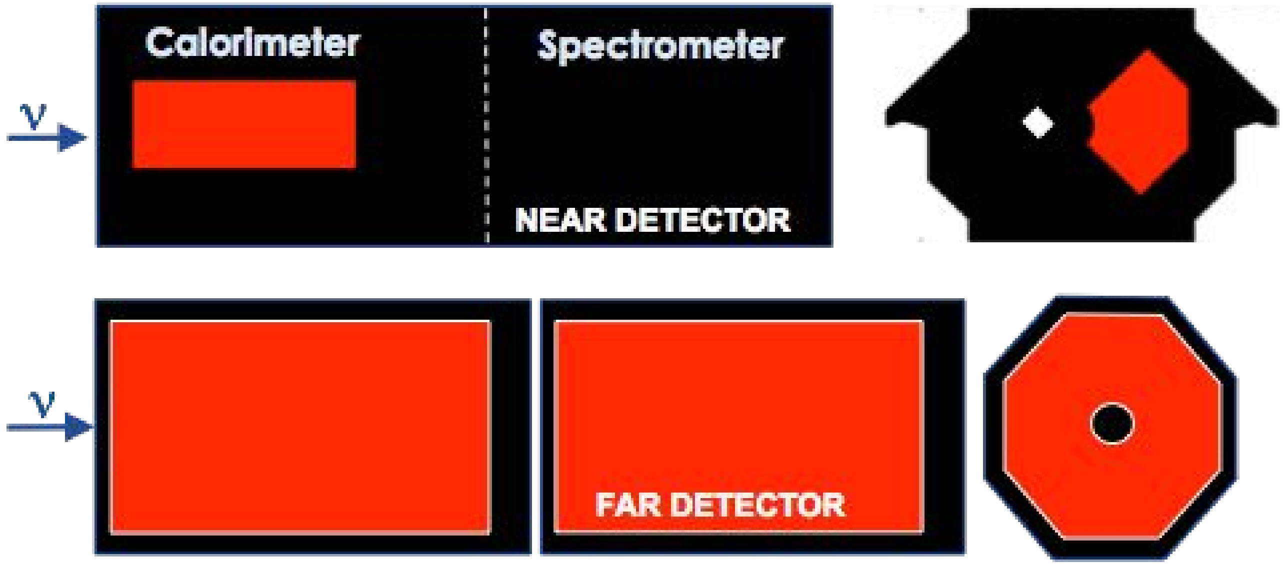


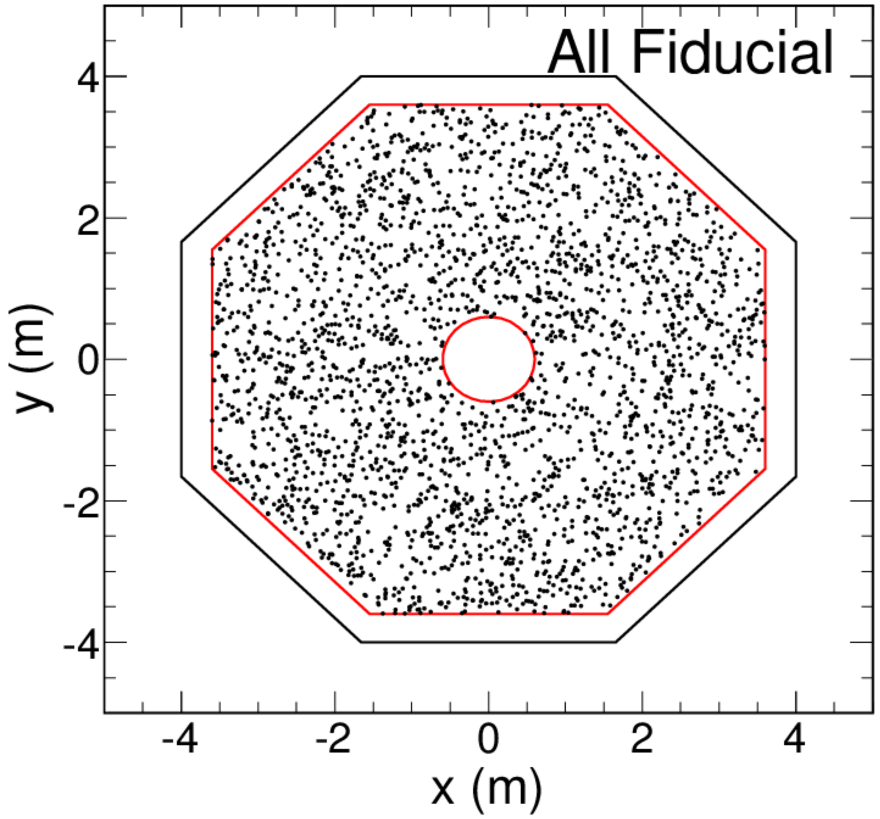
Systematic Uncertainties



Pre-Selection

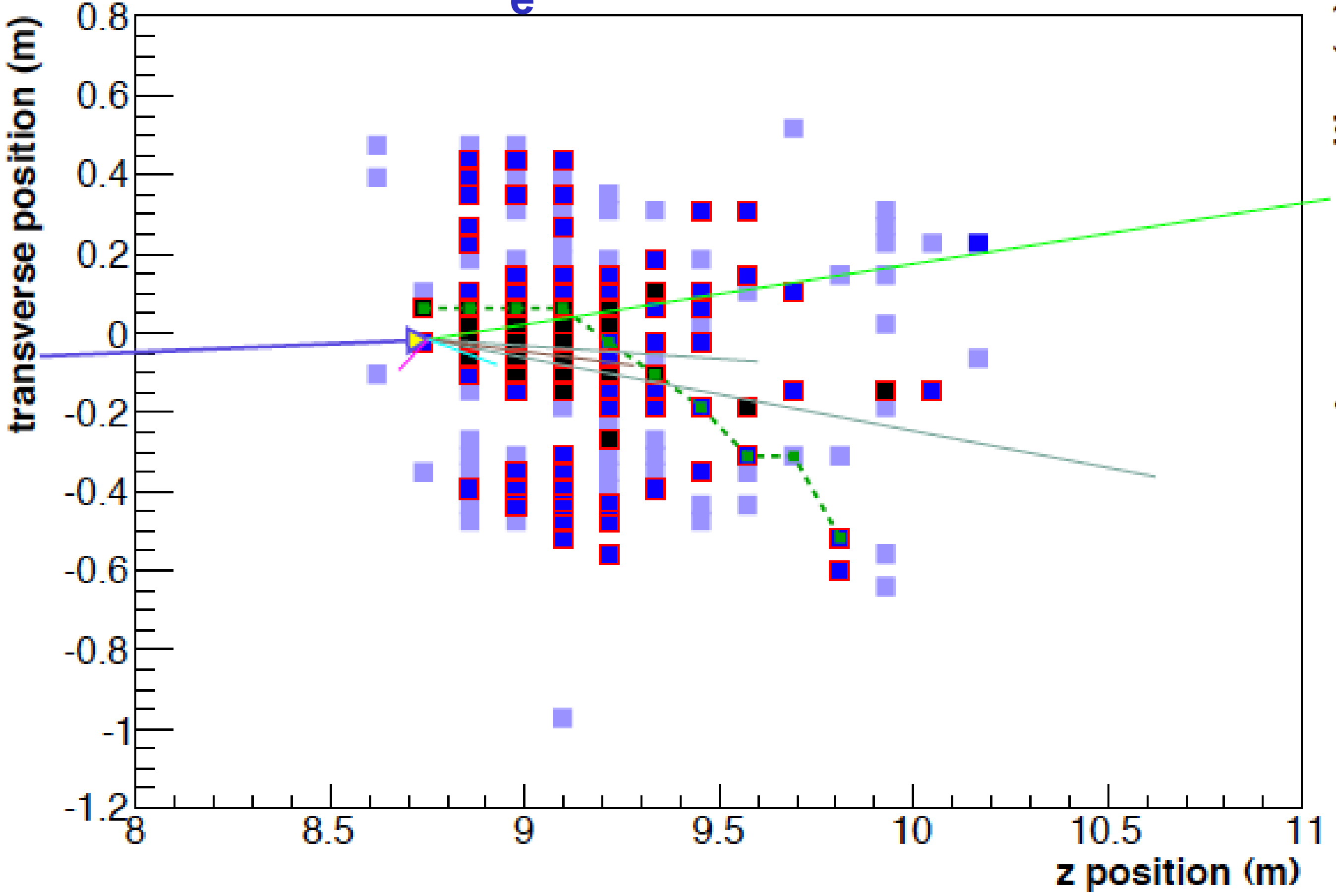
- Beam quality and detector quality cuts
  - Beam positioning, magnetic horns energized, detectors running within operational parameters
  - Cosmics removed using timing and steepness
- Event vertex reconstructed within the fiducial volume of the detectors
  - Fiducial volume optimized for containment of hadronic showers



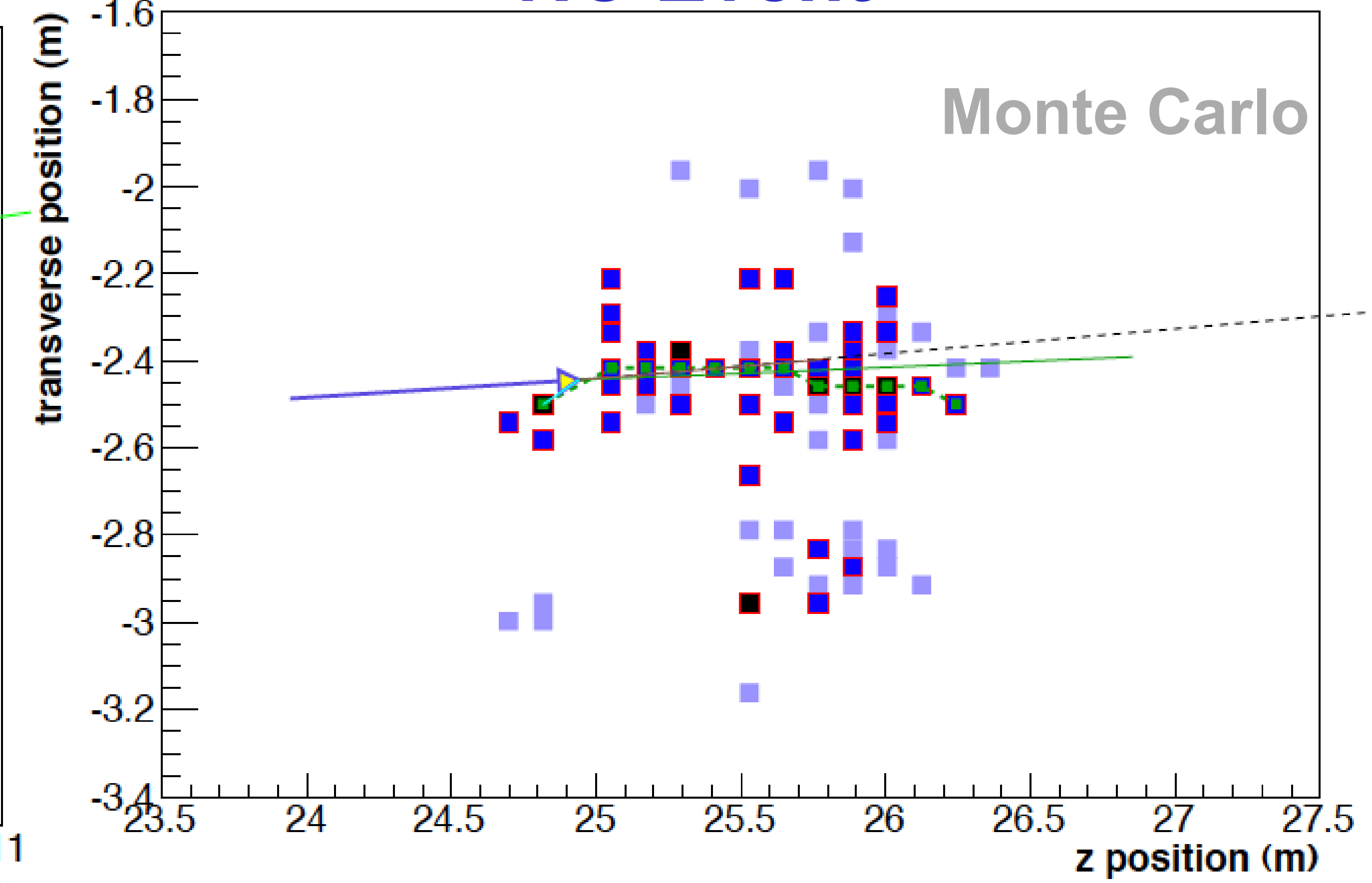


Event Topologies

ν_e CC Event



NC Event



Charged Current ν_e events

- compact shower event with typical electromagnetic profile
- shower energy from calorimetric response

Neutral Current events

- short diffuse showers
- shower energy from calorimetric response

$$\frac{\sigma(\mathrm{E})}{E} \approx \frac{22\%}{\sqrt{\mathrm{E}}}$$

$$\frac{\sigma(\mathrm{E})}{E} \approx \frac{56\%}{\sqrt{\mathrm{E}}}$$