A Search for Sterile Neutrinos at MINOS and MINOS+

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Outline

- MINOS and MINOS+
- *New:* Final Three-flavor oscillations results
  - ν_μ and ν_μ beam samples
    - **Update:** final year of beam data
  - Atmospheric samples
    - **Update:** final three years of atmospheric data
- *New:* Sterile Neutrino Search
  - Two-detector simultaneous fit
  - ν_μ-CC and NC disappearance
    - Full MINOS ν_μ beam sample
    - First two years of MINOS+
- Summary

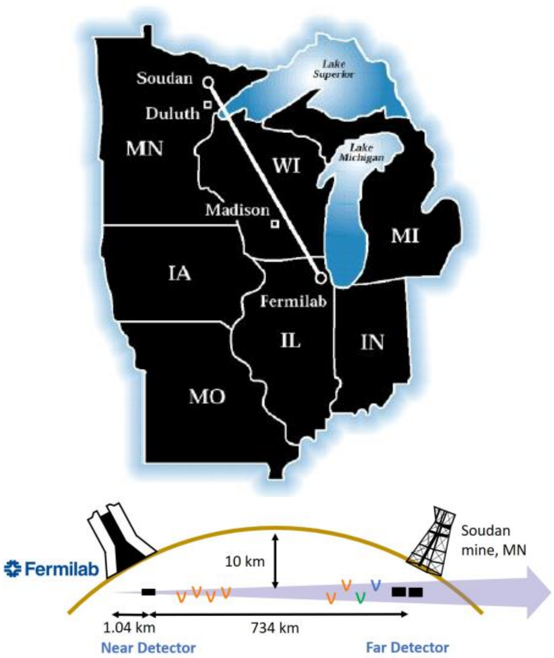
Argonne ▪ Athens ▪ Brookhaven ▪ Caltech ▪ Cambridge ▪ Campinas ▪ Cincinnati ▪ Fermilab ▪ Goiás ▪ Harvard ▪ Holy Cross ▪ Houston ▪ IIT ▪ Indiana ▪ Iowa State ▪ Lancaster ▪ Manchester ▪ Minnesota-Twin Cities ▪ Minnesota-Duluth ▪ Otterbein ▪ Oxford ▪ Pittsburgh ▪ Rutherford ▪ São Paulo ▪ South Carolina ▪ Stanford ▪ Sussex ▪ Texas A&M ▪ Texas-Austin ▪ Tufts ▪ UCL ▪ Warsaw ▪ William & Mary

MINOS and MINOS+

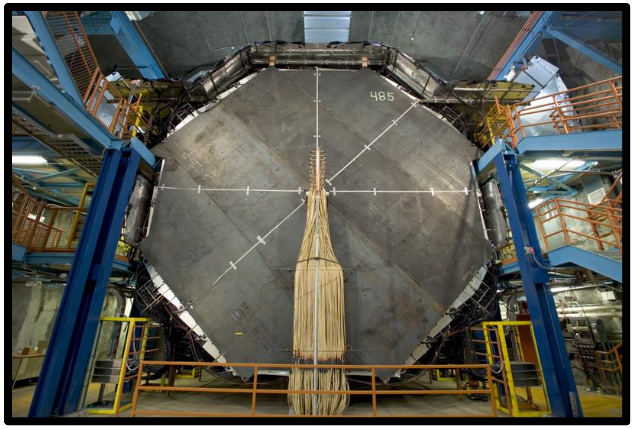
MINOS and MINOS+

- Observed neutrino oscillations over a long-baseline using two functionally identical detectors
  - Iron-scintillator tracking calorimeters – muon track containment
  - Magnetized – charge determination and energy estimation
  - Numerous systematic uncertainties cancel to first order
- Detectors sample the NuMI beam on axis

Near Detector
- Location: Fermilab
- Mass: 1 kton
- Baseline: 1 km



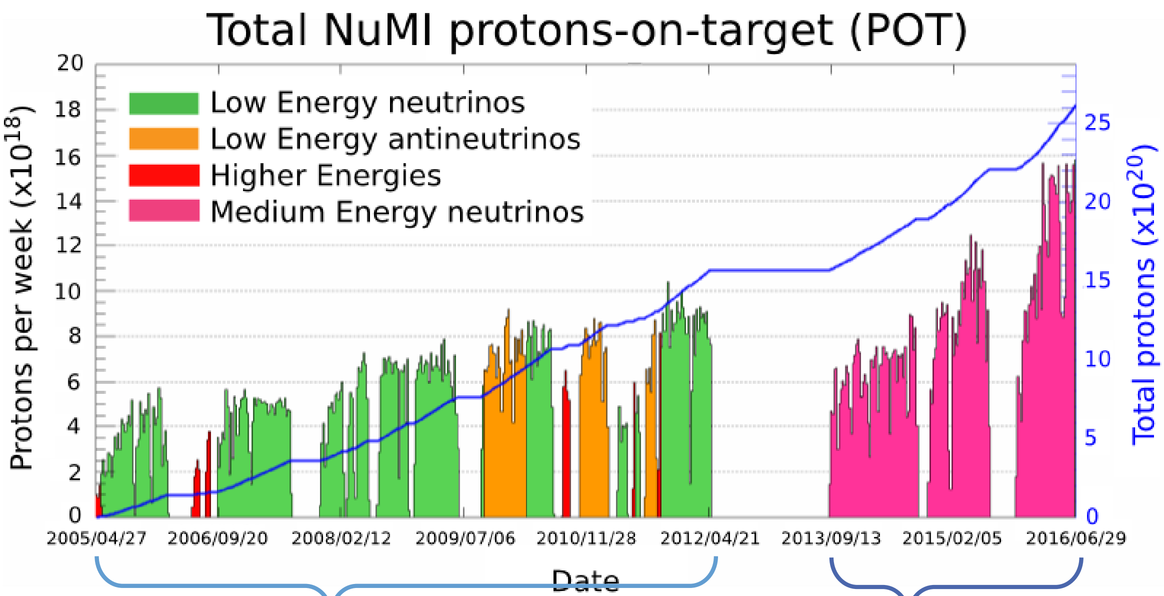
Far Detector
- Location: Soudan Undergound Laboratory
- 5.4 kton mass
- 735 km baseline

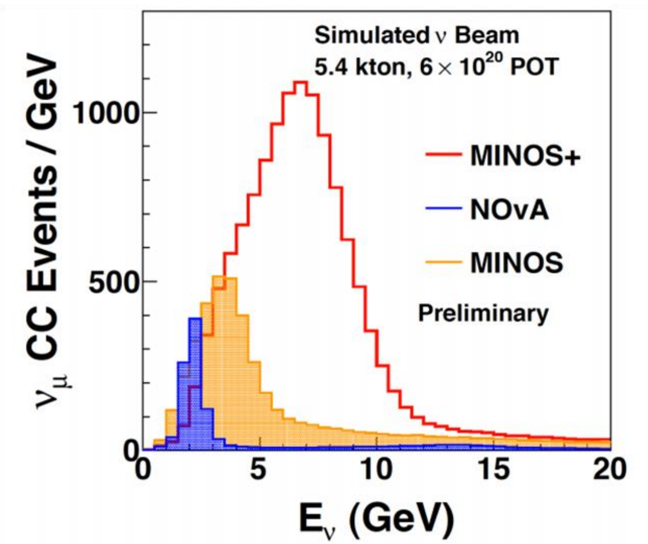


The NuMI Beam

- MINOS
  - Peak Energy: ~3 GeV
  - Optimized for atmospheric frequency oscillations

- MINOS+
  - Peak Energy: ~7 GeV
  - Constrain deviations from 3-flavor paradigm



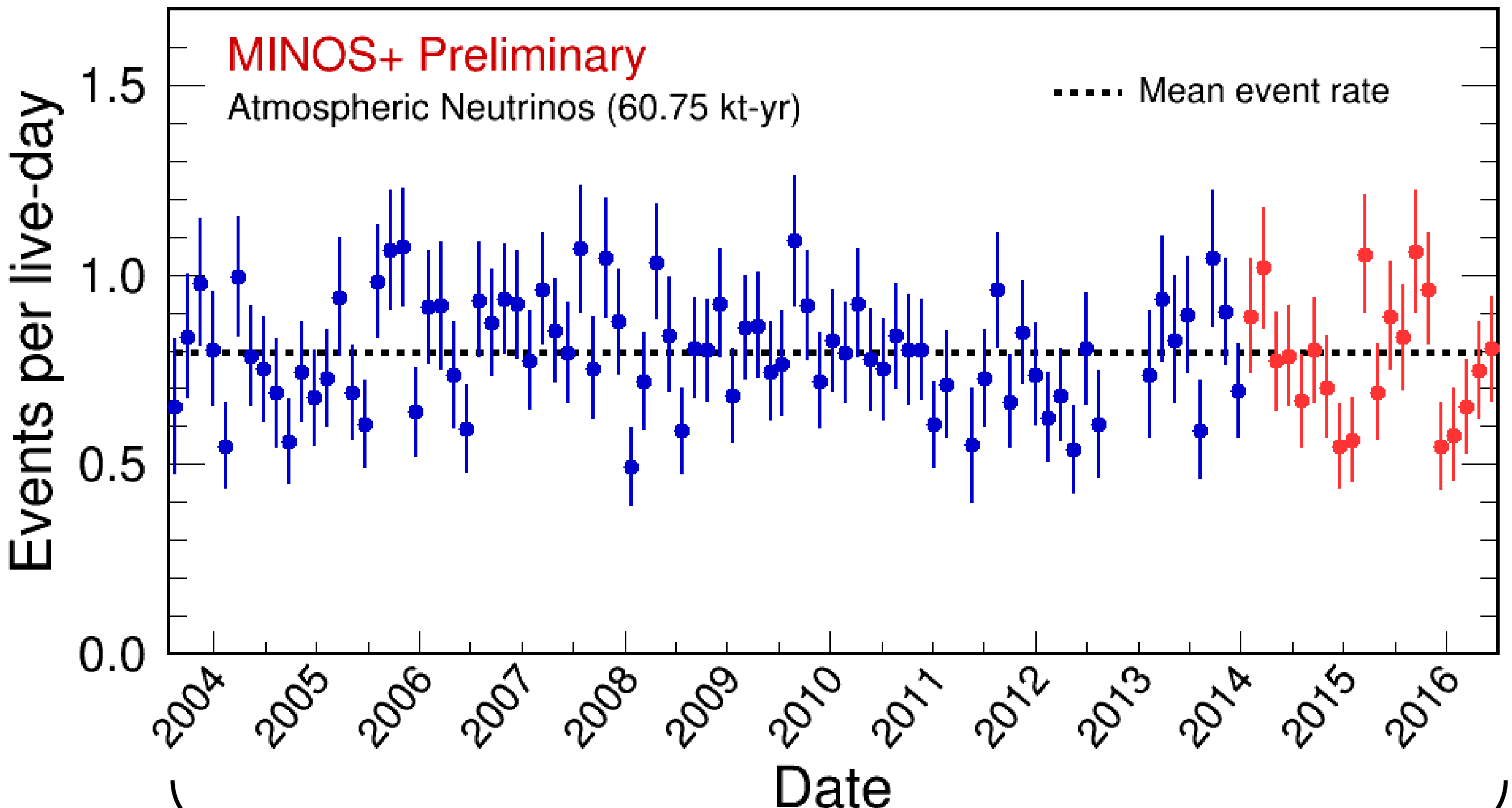


MINOS:
- 10.56×10^{20} POT (ν_μ-mode)
- 3.36×10^{20} POT ($\bar{\nu}_\mu$-mode)

MINOS+:
- 9.69×10^{20} POT (ν_μ-mode)

MINOS & MINOS+
- ~25×10^{20} POT in 11 years of running

MINOS & MINOS+ Atmospheric Neutrinos

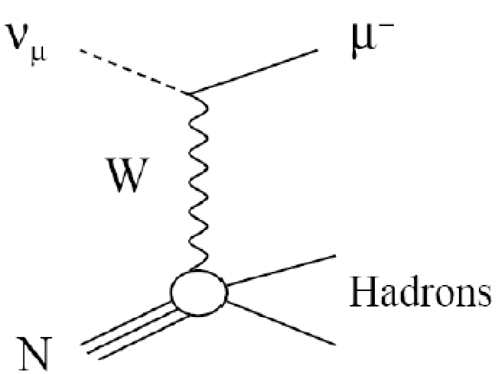


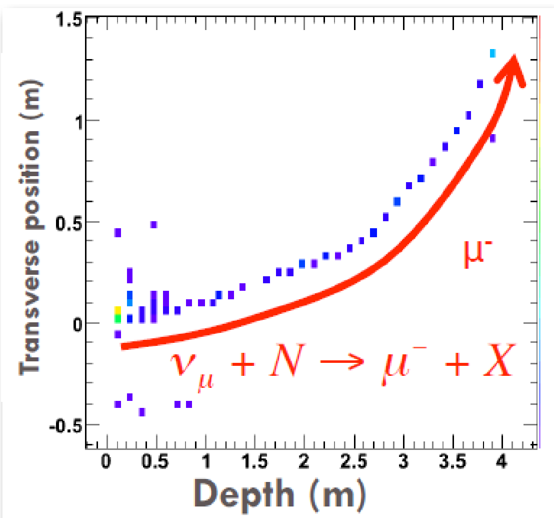
Full dataset (2003 – 2016): 60.8 kt-yr

Update: 12.1 kt-yr (25% more data)

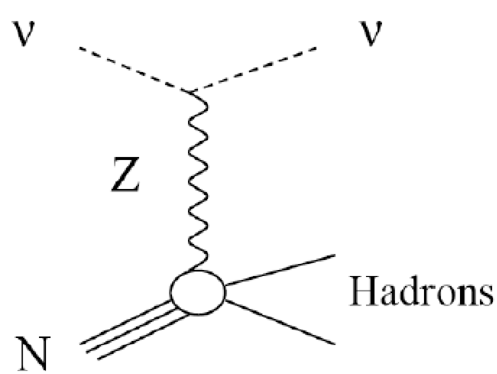
Event Topologies

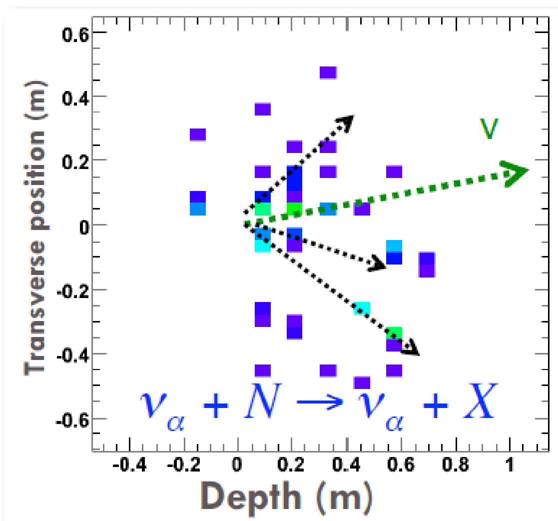
ν_μ CC Event



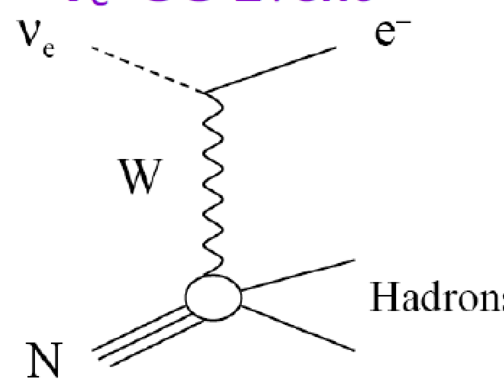


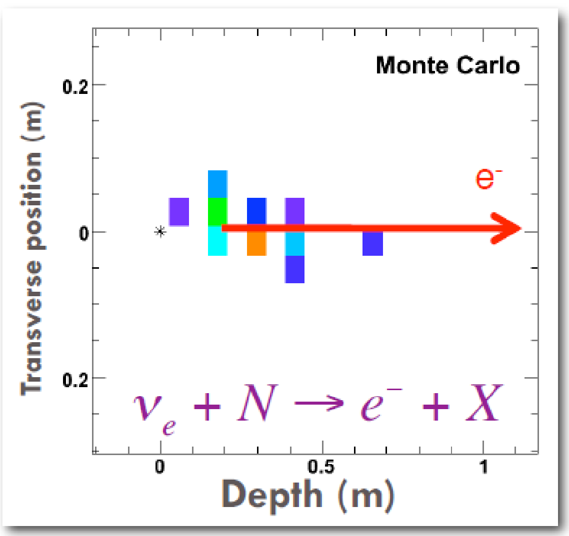
NC Event



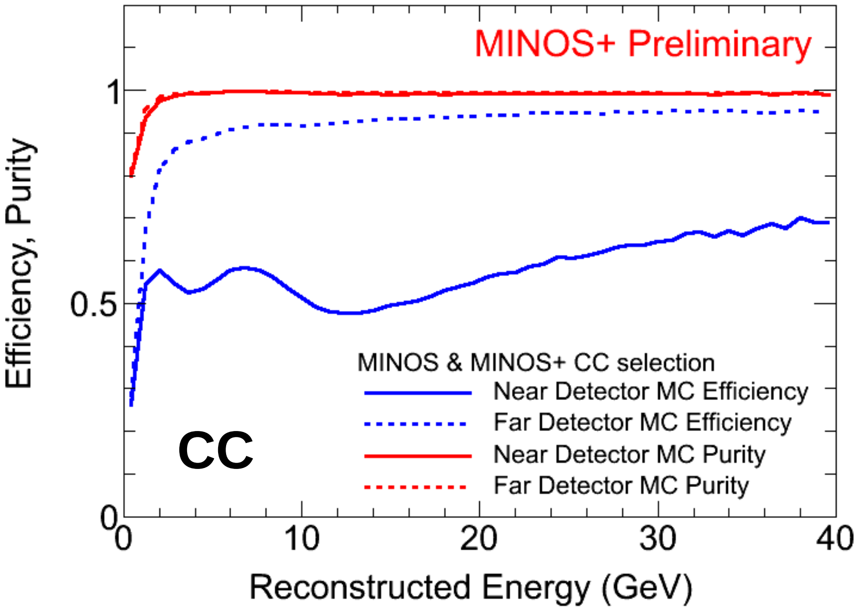


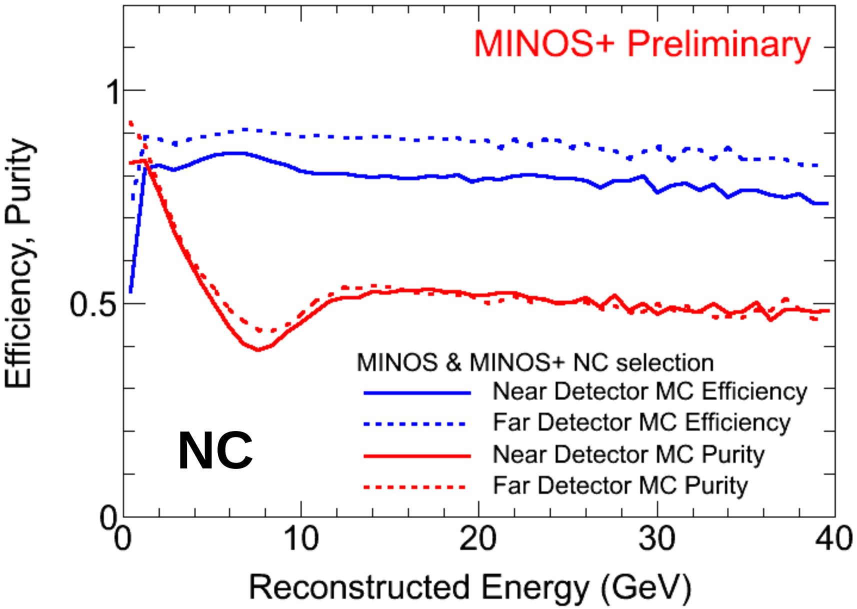
ν_e CC Event





Event Selection

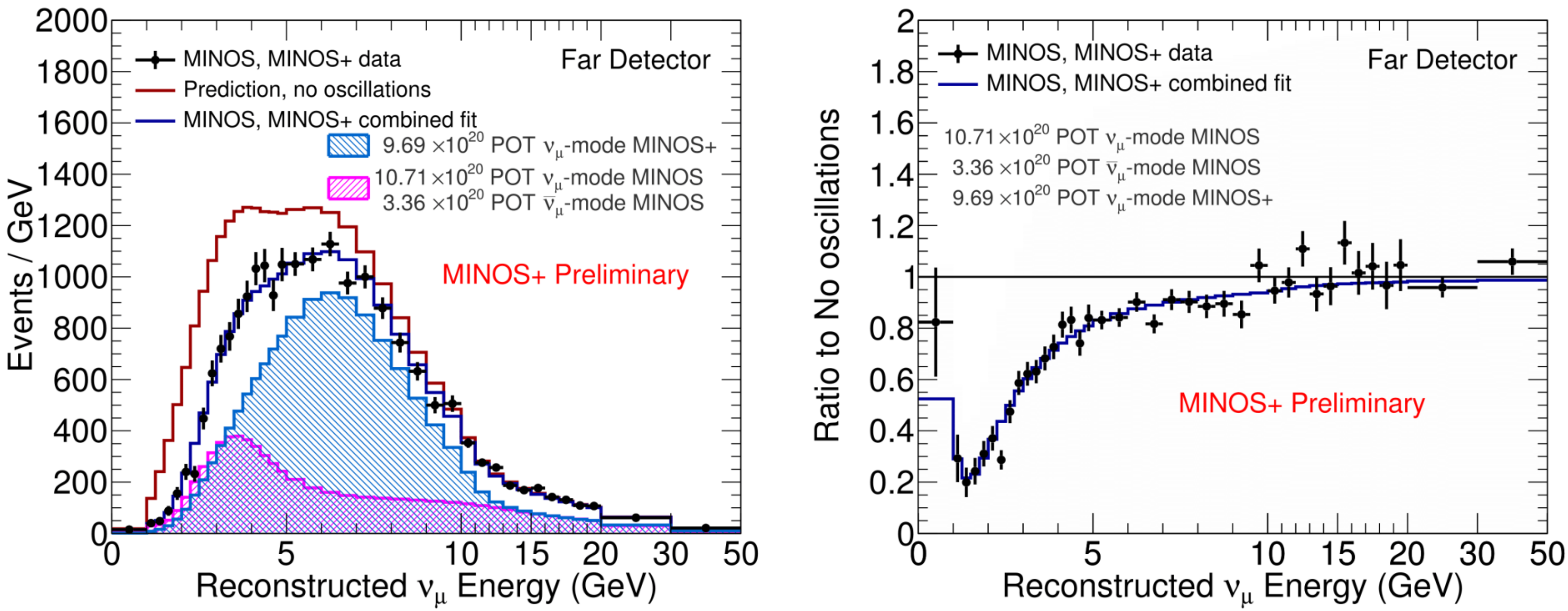




- ν_μ charged current selection
  - Use 4 variable kNN designed to distinguish muon from pion tracks
  - Applied to events failing NC selection
  - 86% efficiency, 99% purity at the FD
- Neutral current selection
  - Selection based on topological quantities
    - Require compact events
    - No long tracks extending out of shower
  - 89% efficiency and 61% purity at FD
  - Primary background is inelastic ν_μ
  - 97% of ν_e CC pass selection

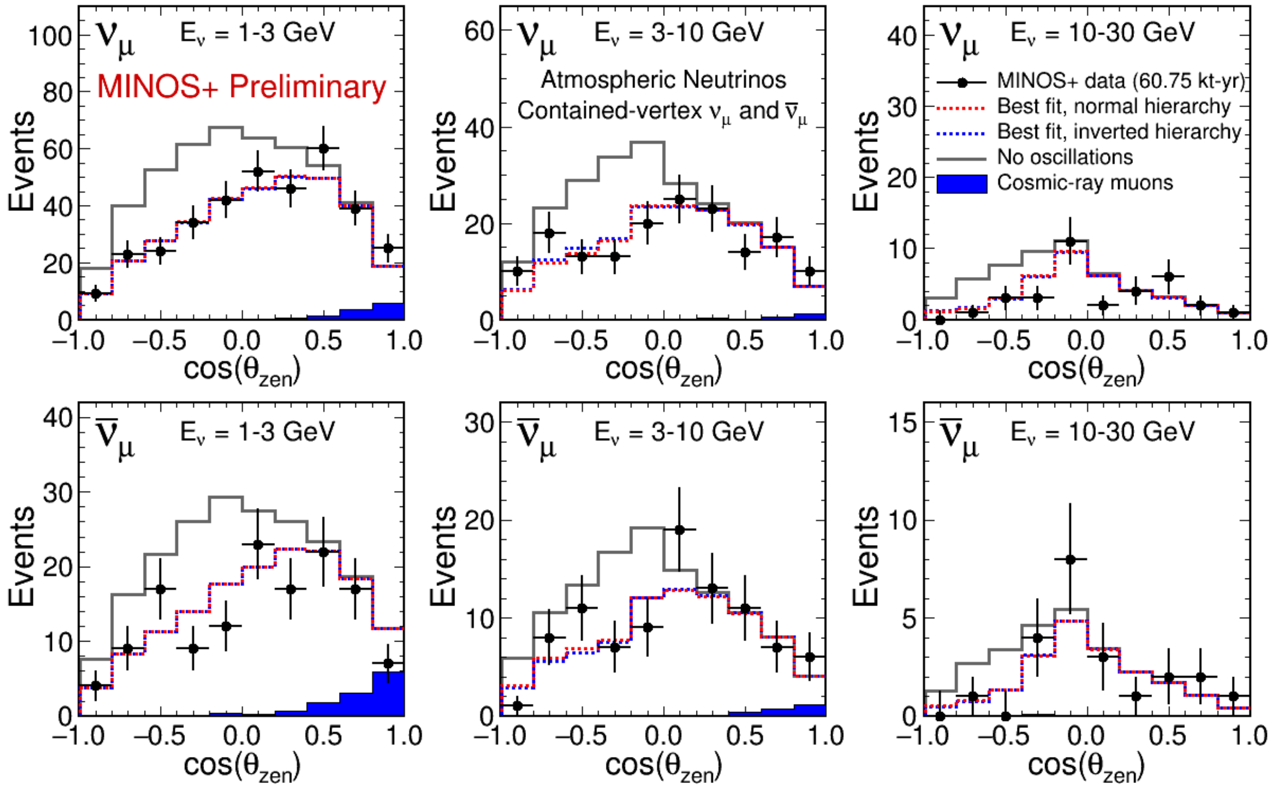
Three-Flavor Oscillations Analysis

Far Detector Beam Data



- MINOS and MINOS+ sample muon-neutrino disappearance over a broad range of energies
- Data agrees strongly with three flavor prediction
  - Oscillations beyond three flavors are tightly constrained

Far Detector Atmospheric Data



- Fit in bins of $\cos(\theta_{zen})$ and energy
- Magnetic field permits separate neutrino and antineutrino samples for mass ordering discrimination
- Complements beam neutrino sample

Combined Fit Results

Best Fit

$\Delta m^2_{32} = 2.42 \times 10^{-3}\ eV^2$

$\sin^2\theta_{23} = 0.42$

Confidence Intervals

Mass Splitting ($\times 10^{-3}\ eV^2$)

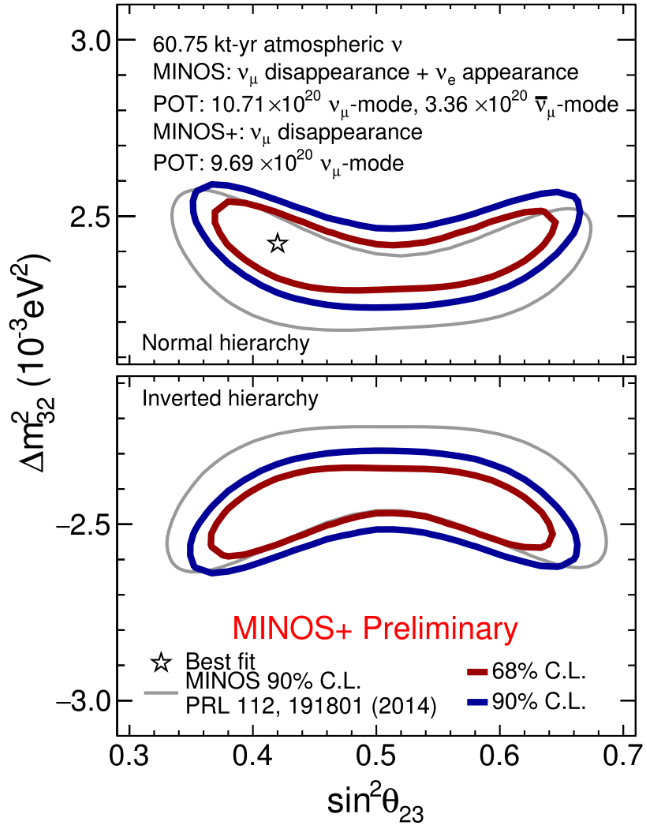
NH: $2.33 < \Delta m^2_{32} < 2.50$

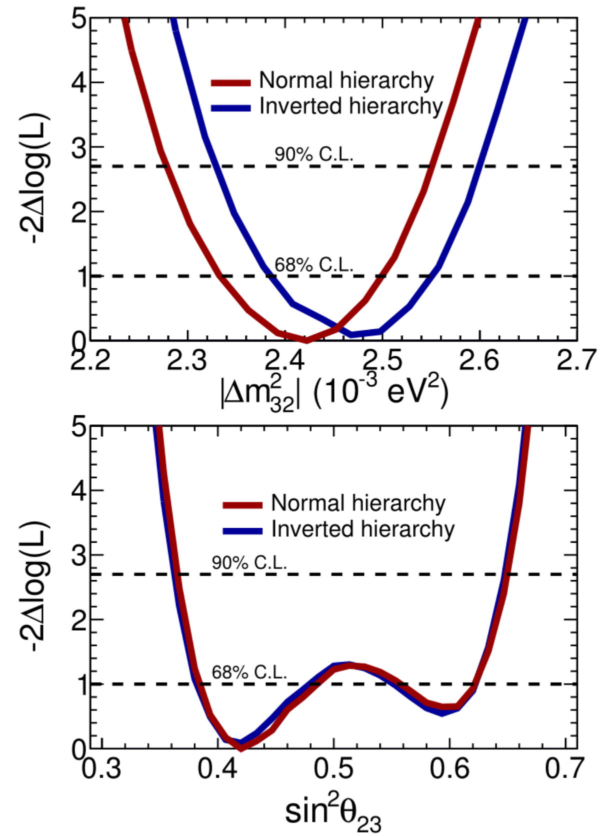
IH: $-2.38 > \Delta m^2_{32} > -2.55$

Mixing Angle

NH: $0.37 < \sin^2\theta_{23} < 0.65$

IH: $0.36 < \sin^2\theta_{23} < 0.65$





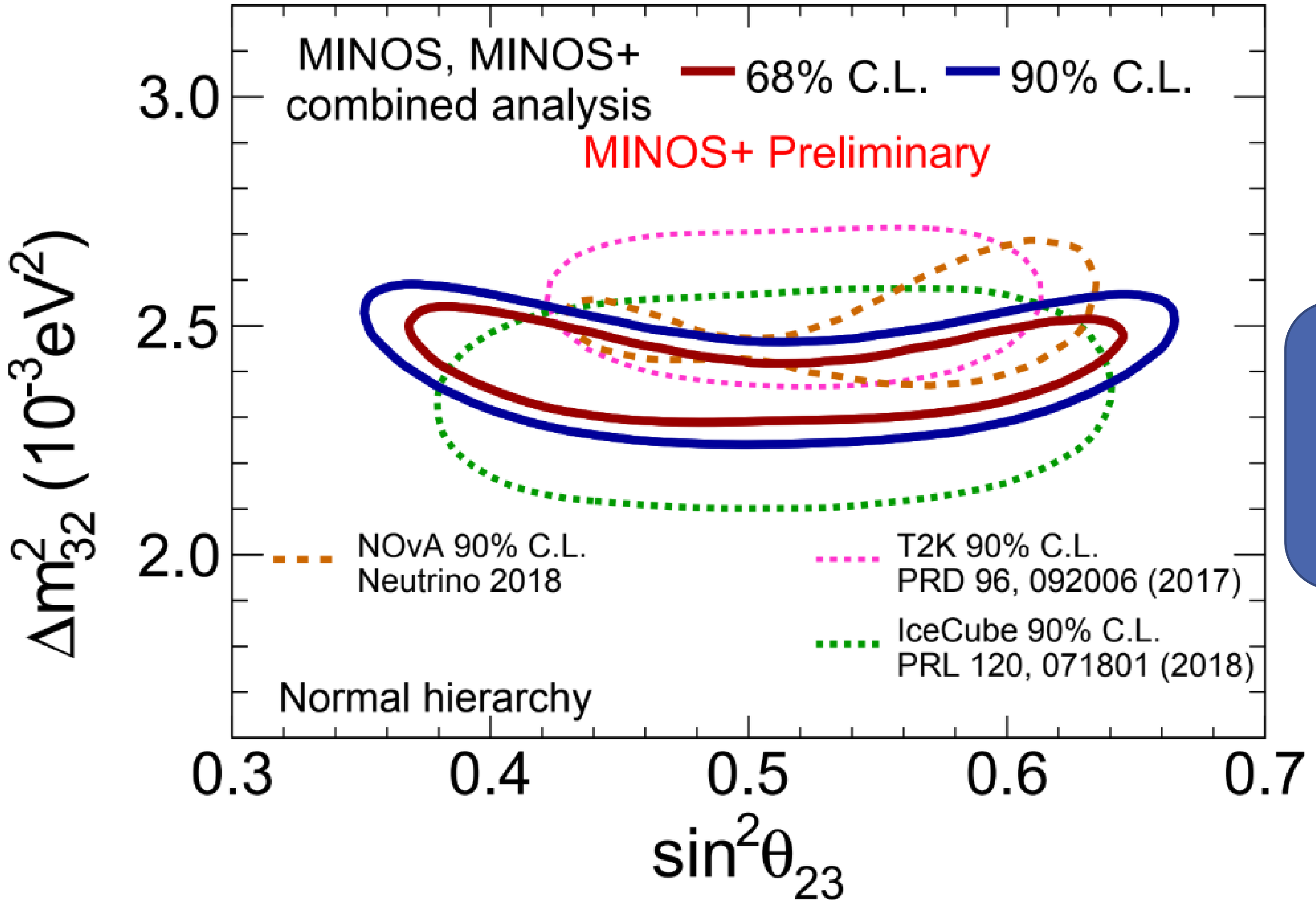
Data Preferences ($\Delta\chi^2$)

Normal Hierarchy: 0.06

Lower Octant θ_{23}: 0.65

Non-Maximal Mixing: 1.27

Comparison with Other Experiments



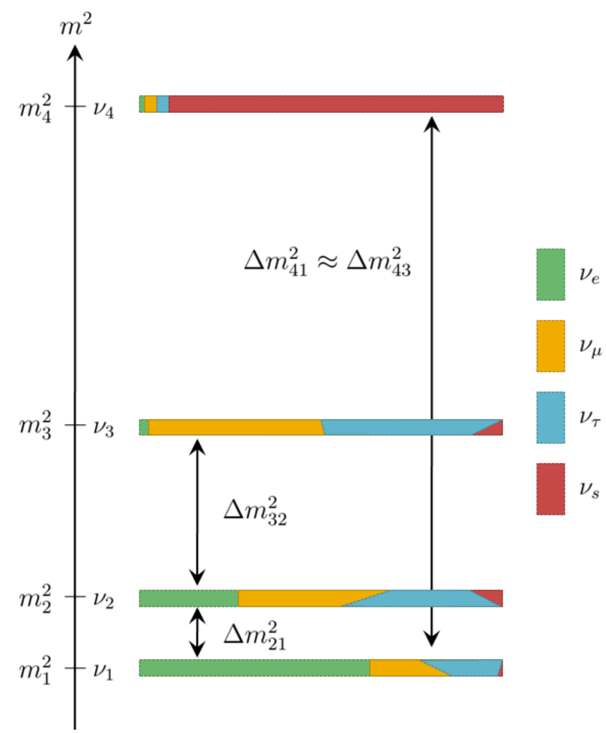
Measurement of Δm^2_{32} to 3.5% at 68% C.L.

Sterile Neutrino Search

3+1 Model

- Short-baseline electron-(anti)neutrino appearance results consistent with new mass state and new sterile flavor
  - No weak interaction
- Expand PMNS matrix from 3x3 to 4x4
- 6 new parameters
  - New mass scale (Δm^2_{41})
  - Three mixing angles (θ_{14}, θ_{24}, θ_{34})
  - Two CP-violating phases (δ_{14}, δ_{24})
- Search for two signals
  - Neutral current disappearance
    - NC events independent of 3-flavor oscillations
    - Sterile neutrinos would deplete interactions
    - Sensitive to Δm^2_{41}, θ_{24}, θ_{34}
  - ν_μ-charged current disappearance
    - Sterile neutrinos cause modulations with differing frequency to 3-flavor oscillations
    - Sensitive to Δm^2_{41} and θ_{24}

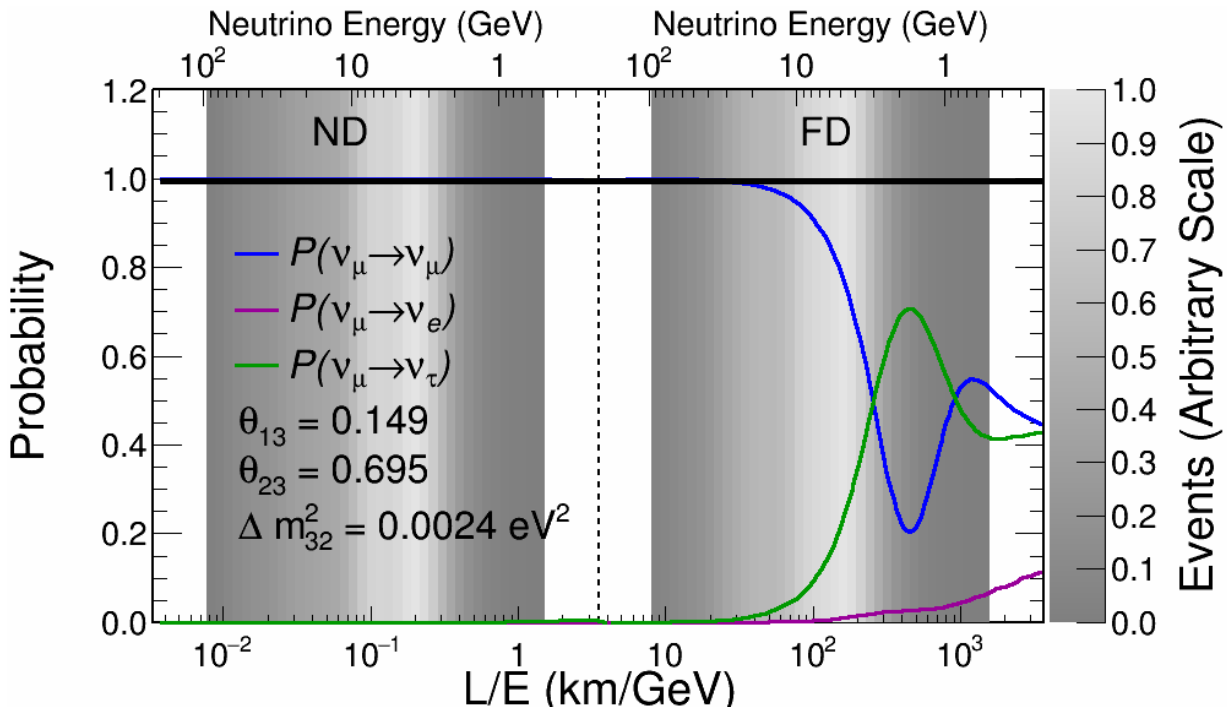
$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$



Standard (3-flavor) Oscillations

$\Delta m^2_{41} = 0\ eV^2$

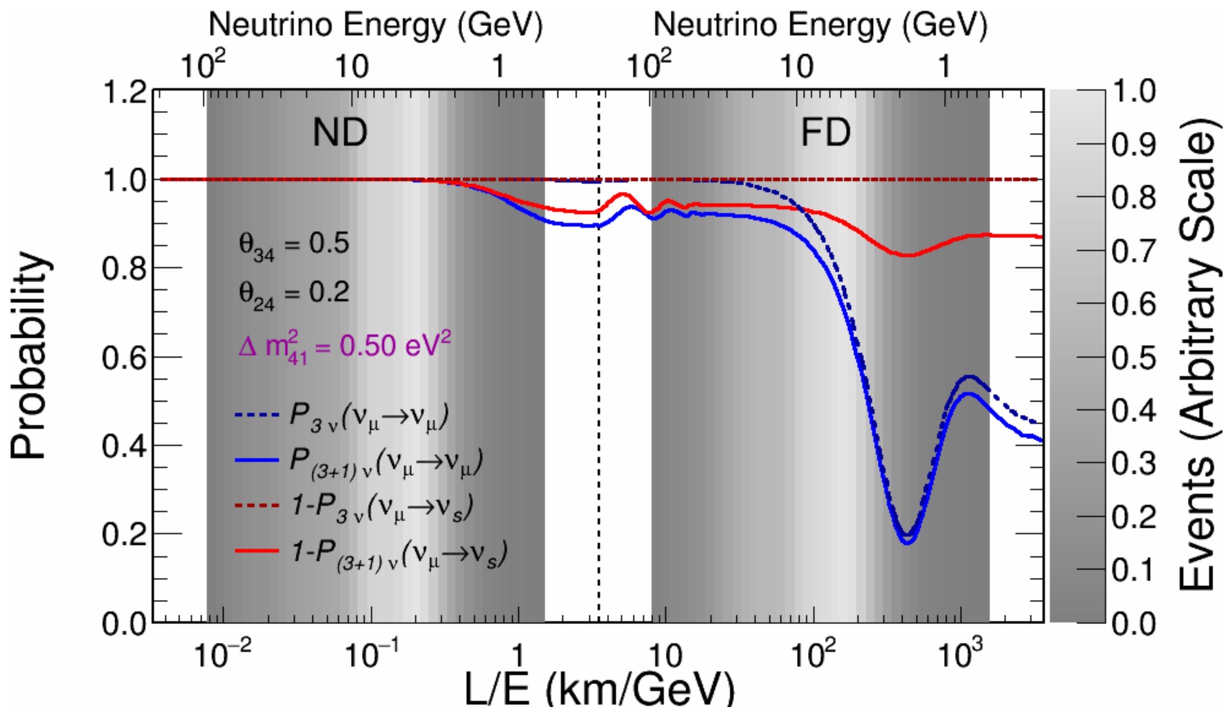
- **Far Detector oscillations *only***
  - CC signal – single pronounced oscillation maximum
  - NC signal – no oscillations observed
- **Near Detector observes no oscillations**
  - Constrains beam
  - Cancels systematic uncertainties



(3+1)-flavor Oscillations

$\Delta m^2_{41} = 0.5\ eV^2$

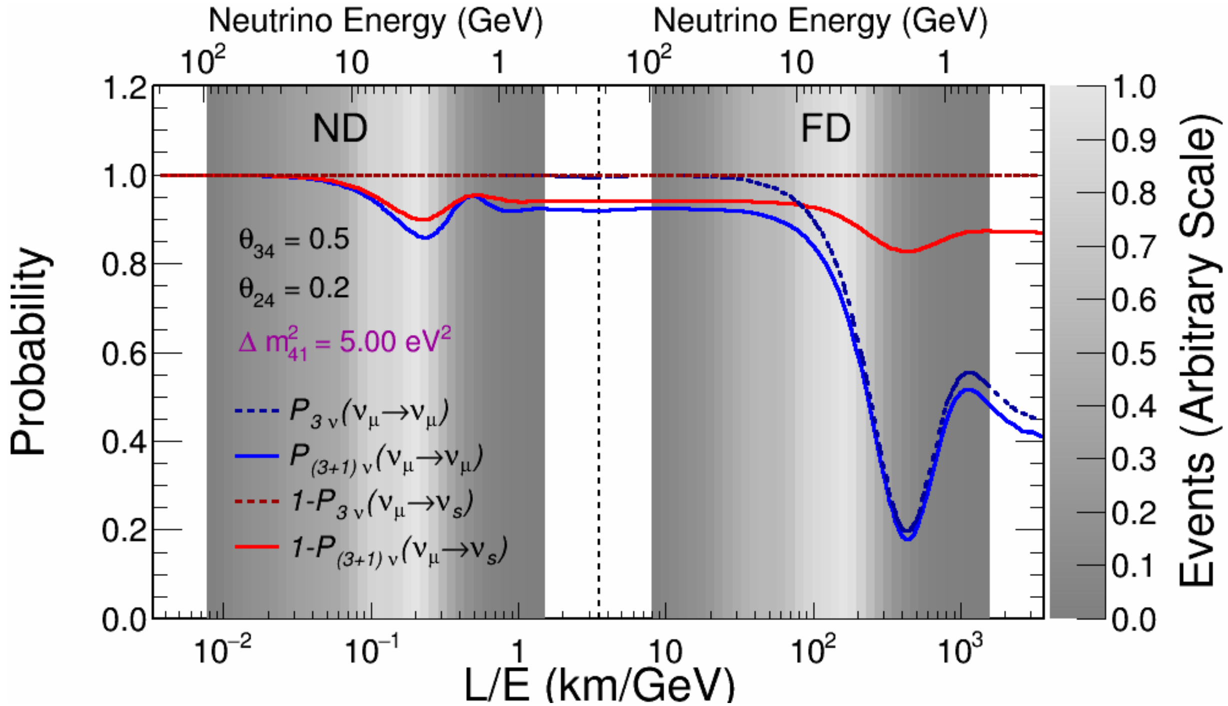
- ◆ Far Detector oscillations at two frequencies
  - CC signal – modulation on 3-flavor at high energy, net deficit
  - NC signal – deficit inconsistent with 3-flavor
- ◆ Near Detector observes low energy deficit



(3+1)-flavor Oscillations

$\Delta m^2_{41} = 5.0\ eV^2$

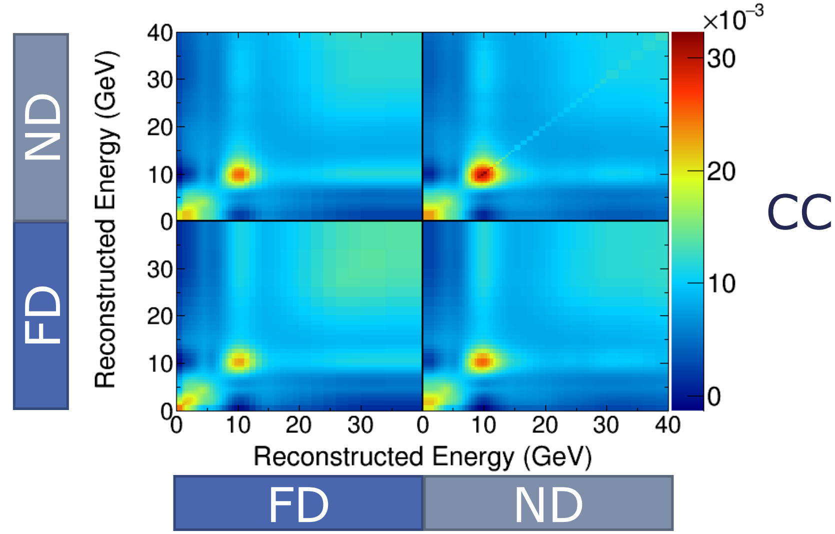
- Far Detector oscillations at two frequencies
  - CC signal – modulation on 3-flavor at high energy, net deficit
  - NC signal – deficit inconsistent with 3-flavor
- Near Detector observes oscillations inconsistent with 3-flavor in both samples

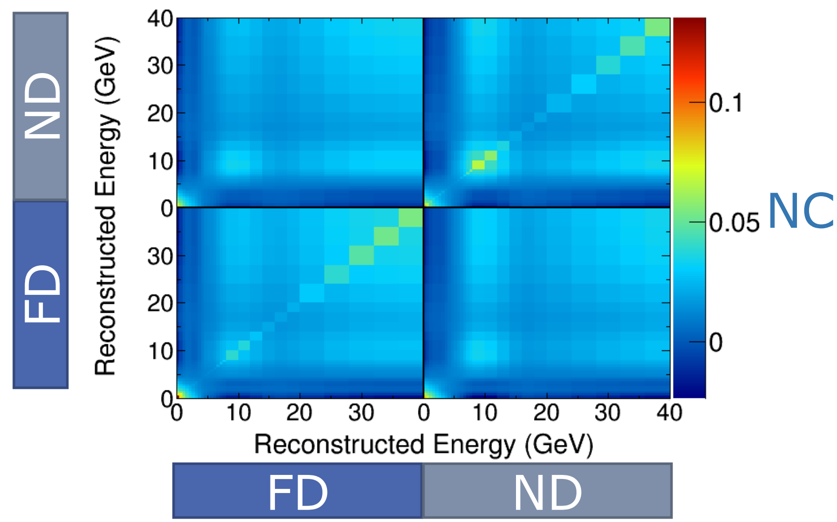


Simultaneous Two-Detector Fit

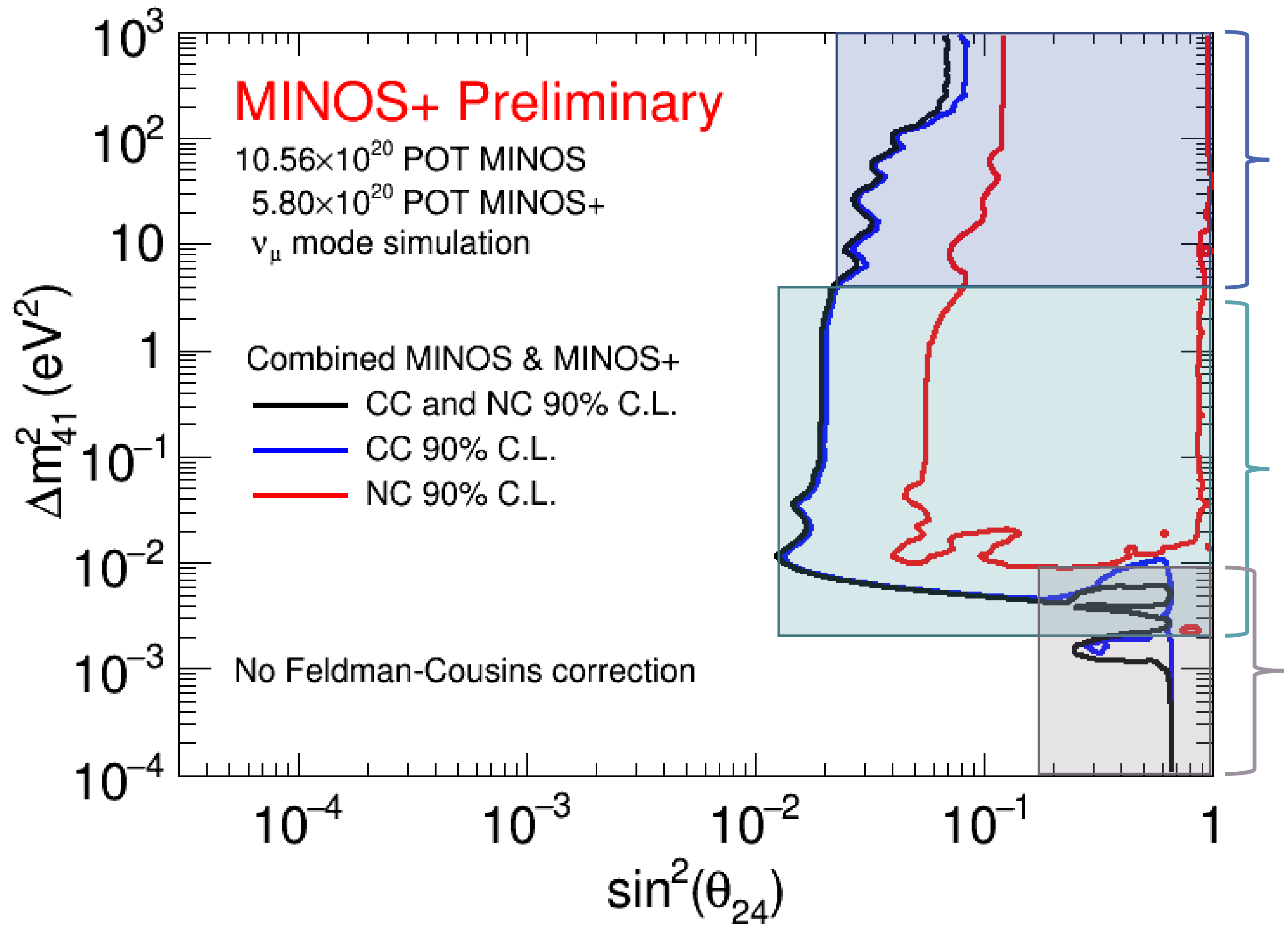
- Near and Far Detectors are fit simultaneously with coequal treatment
  - Maximal utilization of extremely high Near Detector event rate – low statistical error
  - Flux estimate derived from PPFX method which uses only hadron production experimental data
- Systematic uncertainties are encoded in covariance matrices
  - 26 sources of systematic uncertainty
  - Effects of correlated systematics are mitigated by off-diagonal cancellations
- Best fit determined by minimization of χ^2 function computed from covariance matrices
- ν_μ-CC and NC samples fit jointly by summing the χ^2 contributions

$$\chi^2 = \sum_{i=1}^{N}\sum_{j=1}^{N}(o_i - e_i)[V^{-1}]_{ij}(o_j - e_j)$$





Asimov Sensitivity

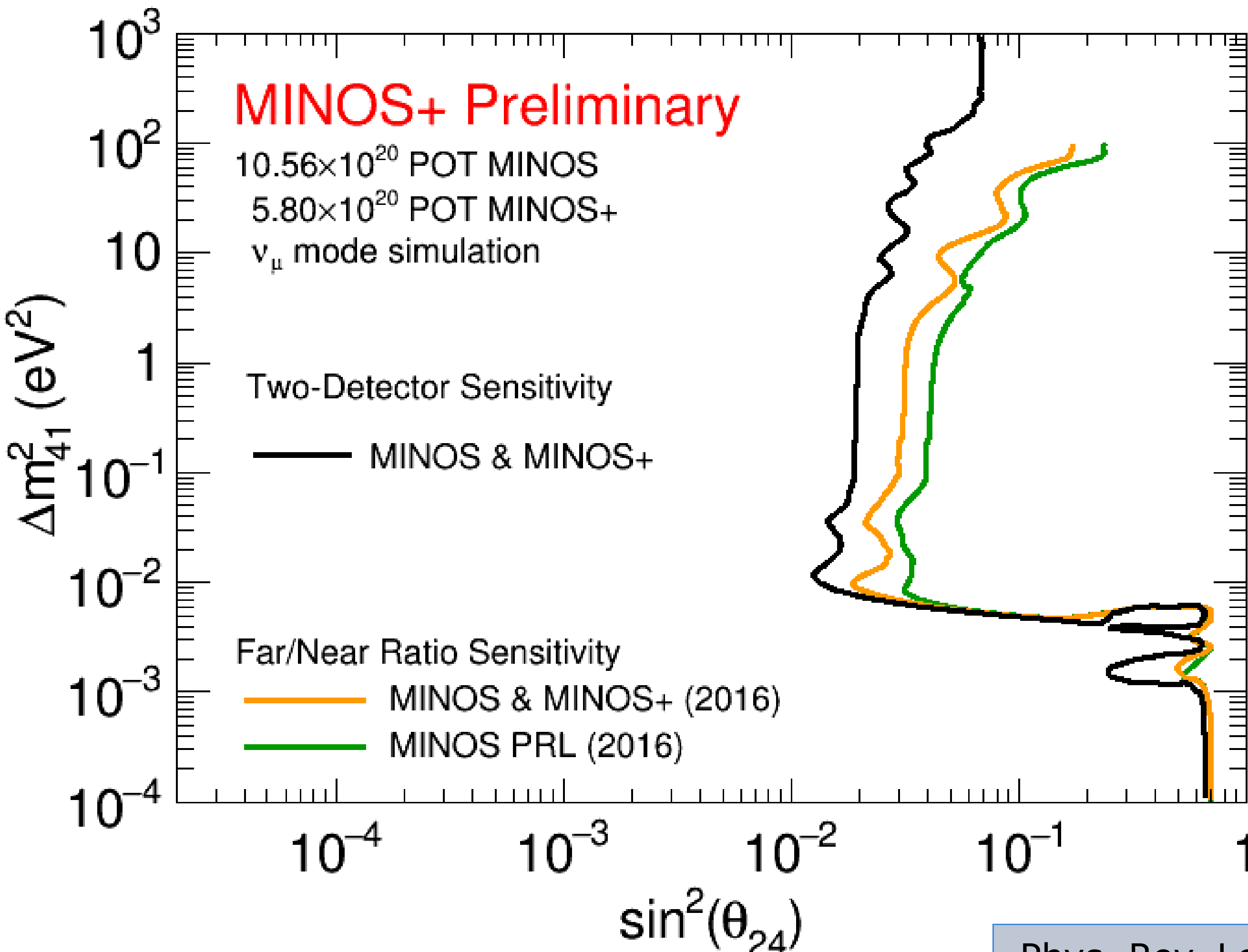


$\Delta m^2_{41} \geq 4$ eV^2; *Near Detector dominates*

$\Delta m^2_{41} \geq 10^{-3}$ eV^2; *Far Detector dominates*

NC oscillations with $\Delta m^2_{41} \sim \Delta m^2_{32}$ or $\Delta m^2_{41} < \Delta m^2_{32}$

An Improved Search Paradigm



- Asimov sensitivity calculated using the Two-Detector and Far/Near Methods as indicated
- Far/Near ratio method loses sensitivity due to limited Near Detector constraint

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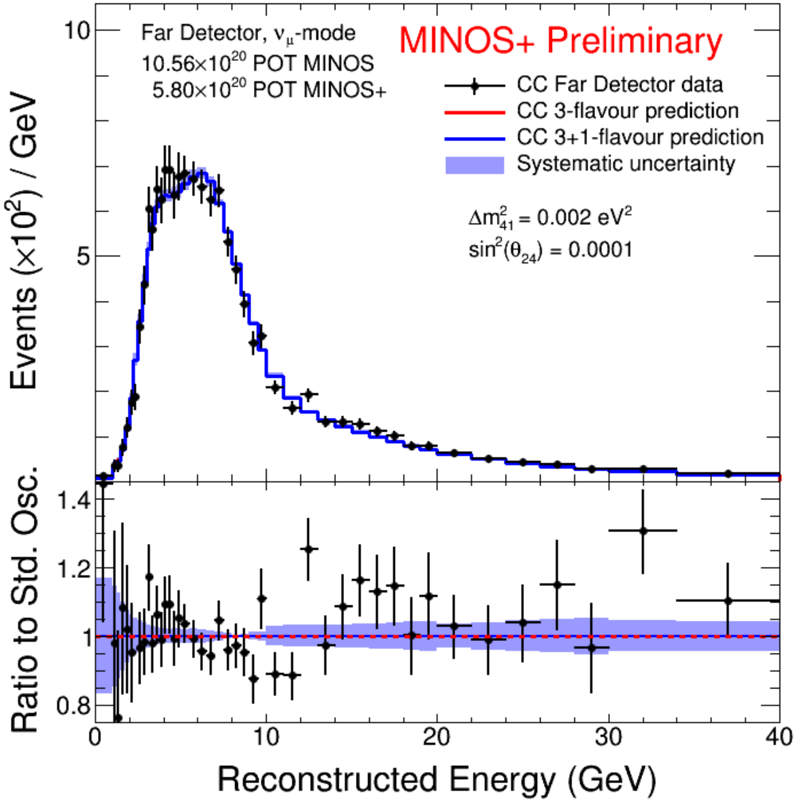
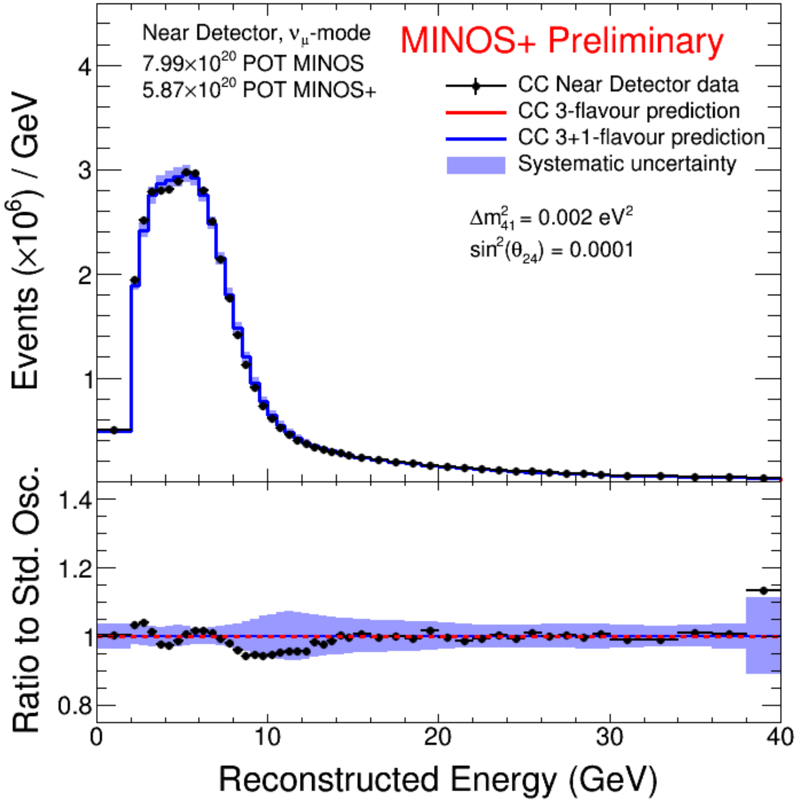
ν_μ CC Sample

- Data consistent with 3-flavor oscillations paradigm
- Evidence indicates that variations from 3-flavor prediction are attributable to statistical and systematic uncertainty

Far Detector



Near Detector



NC Sample

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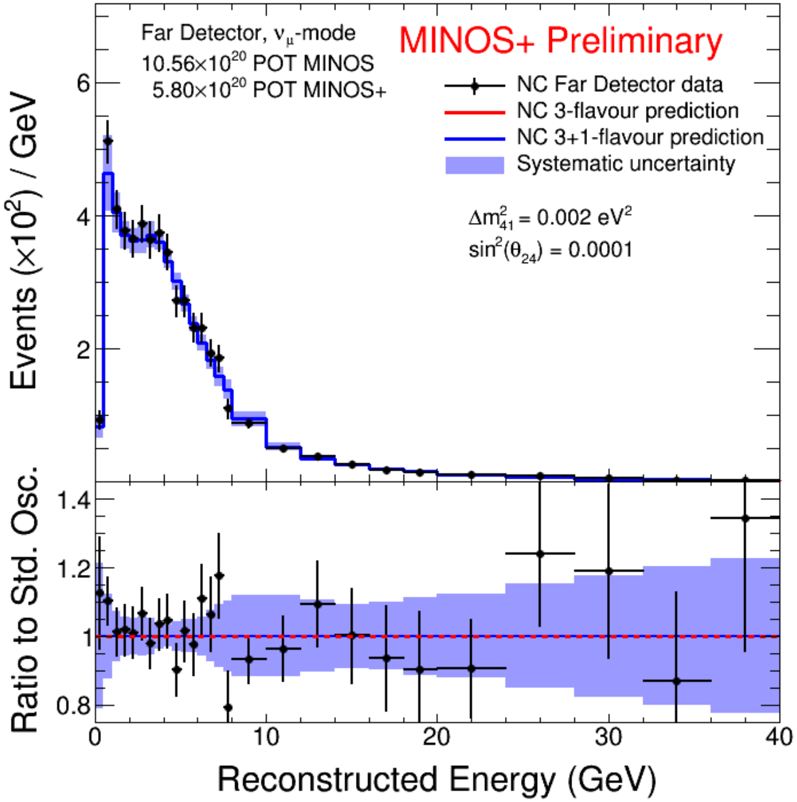
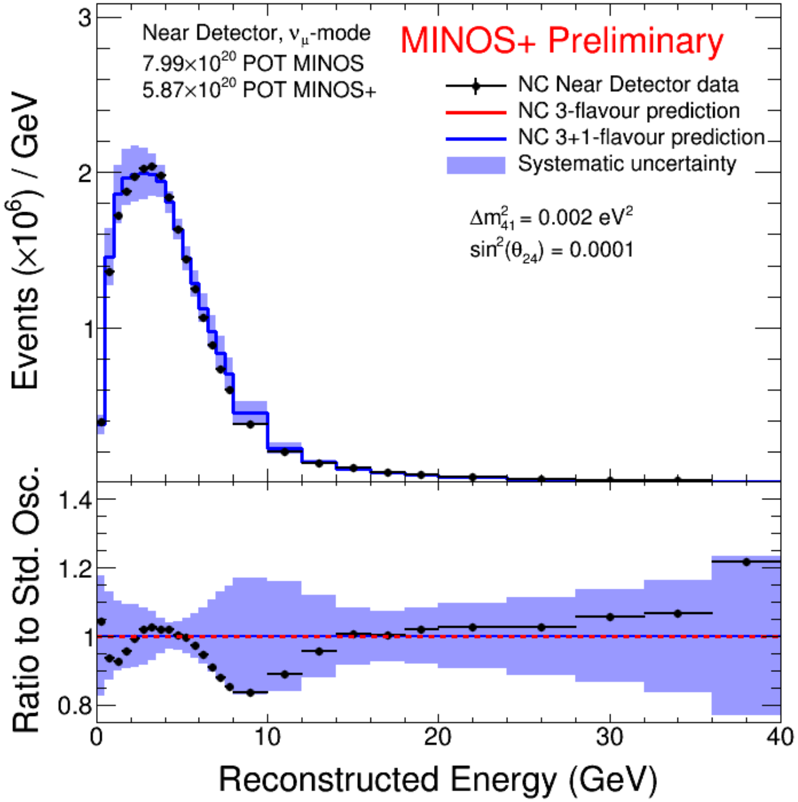
Far Detector



Near Detector



(3+1)-flavor Disappearance Limit

- Upper limit from joint CC and NC sample fit using the simultaneous two-detector method
- Free Parameters: Δm^2_{41}, Δm^2_{32}, θ_{24}, θ_{34}, θ_{23}
- Null Parameters: δ_{14}, δ_{24}, δ_{13}, θ_{14}
- Fixed (3-flavor) Parameters: Δm^2_{21}, θ_{12}, θ_{13}
- Feldman-Cousins method used to form proper 90% C.L. frequentist intervals

Best Fit

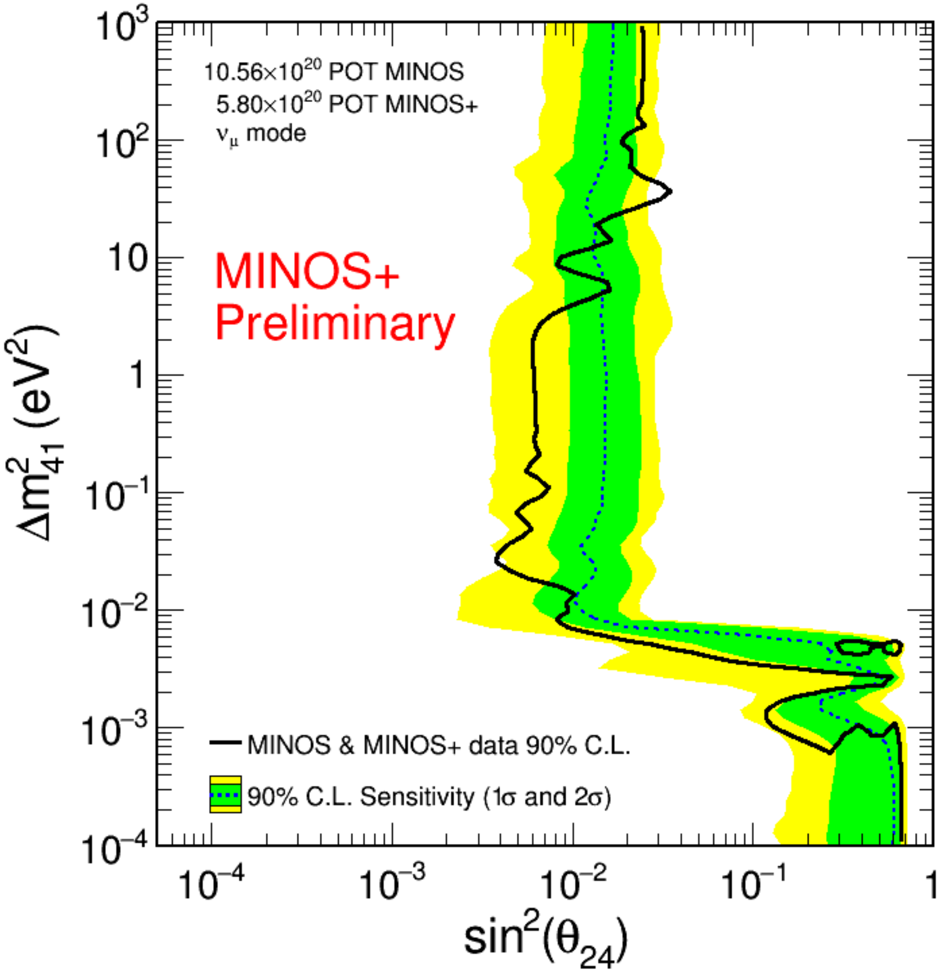
$\Delta m^2_{41} = 2.33 \times 10^{-3}\ eV^2$

$\sin^2\theta_{24} = 1.1 \times 10^{-4}$

$\theta_{34} = 7.0 \times 10^{-5}$

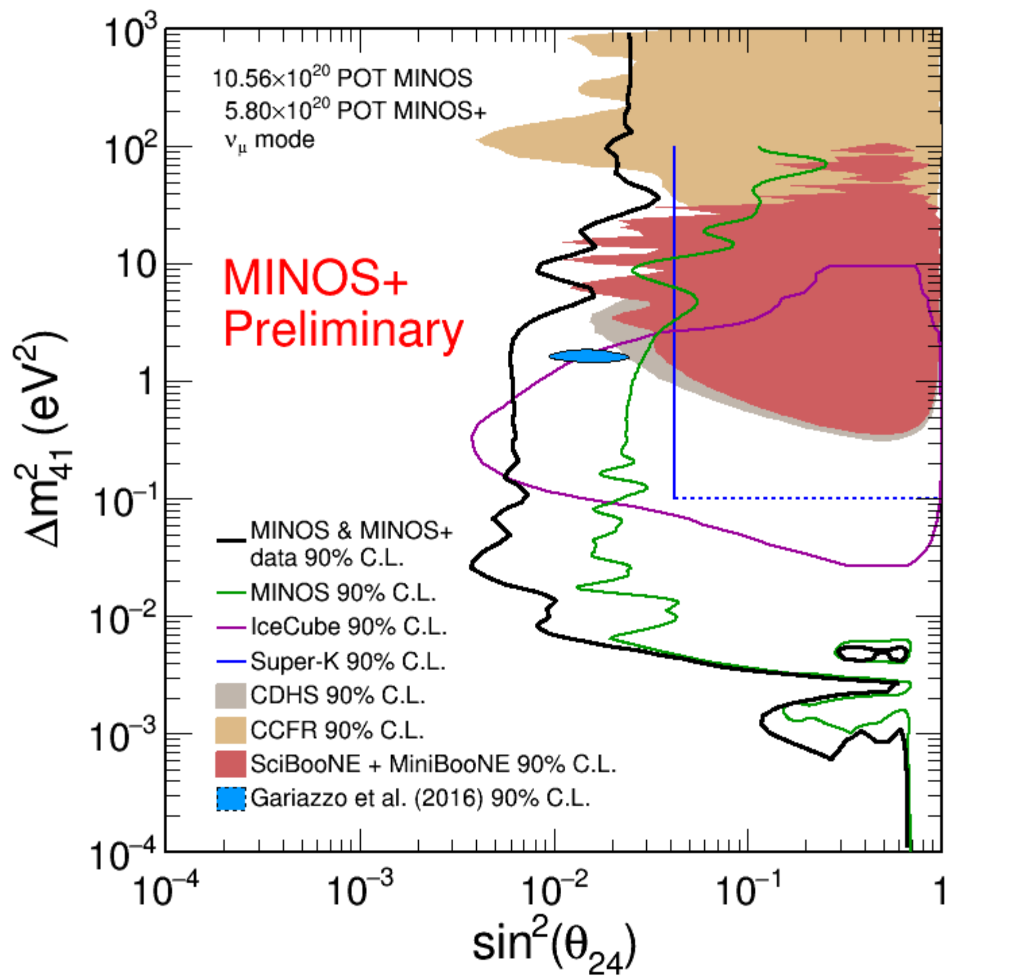
$\chi^2_{min}/dof = 99.3/140$

$\chi^2_{3\nu} - \chi^2_{4\nu} < 0.01$



(3+1)-flavor Limit Comparison

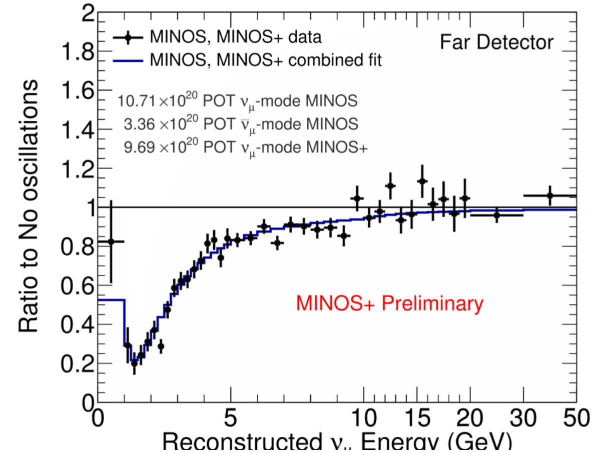
- MINOS & MINOS+ sets 90% C.L. limit over 7 orders of magnitude in Δm^2_{41}
- Improvement over previous MINOS fit due to:
  - Utilizing Near Detector statistical power
  - Covariance matrix systematic uncertainty cancellations
  - Improved binning for atmospheric oscillations in Far Detector
- Increased tension with global best fit
- Final year of MINOS+ data yet to be analyzed
  - Represents 50% more data in MINOS+ spectrum
- View the manuscript and data release:
  - arXiv:1710.06488
  - Ancillary materials included for more detail



^S. Gariazzo, C. Giunti, M. Laveder, Y.F. Li, E.M. Zavanin, J.Phys. G**43** 033001 (2016)

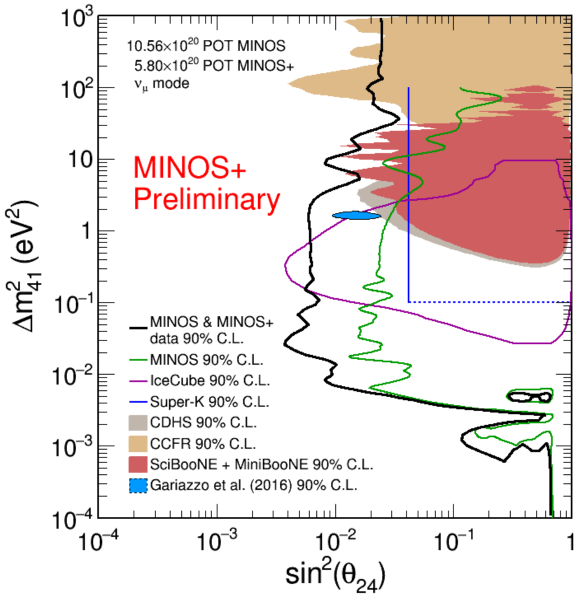
Summary

- Standard Oscillations: Improved measurement of atmospheric oscillation parameters using the full sample of beam and atmospheric neutrino data
  - Results competitive with running experiments
  - Measured Δm^2_{32} to 3.5% precision



- Using simultaneous two-detector fit, MINOS+ places strong constraints on (3+1)-flavor sterile neutrino mixing
  - Tension with the critical global best fit region

- Over 11 years of running MINOS & MINOS+ have mapped neutrino oscillations across a broad energy spectrum
  - Strong evidence for 3-flavor oscillations paradigm
  - Sharpening constraints to guide future sterile neutrino searches



Thank You!

The MINOS+ Collaboration would like to express our sincere thanks to the many Fermilab groups who provided technical expertise and support in the design, construction, installation and operation of the experiment.

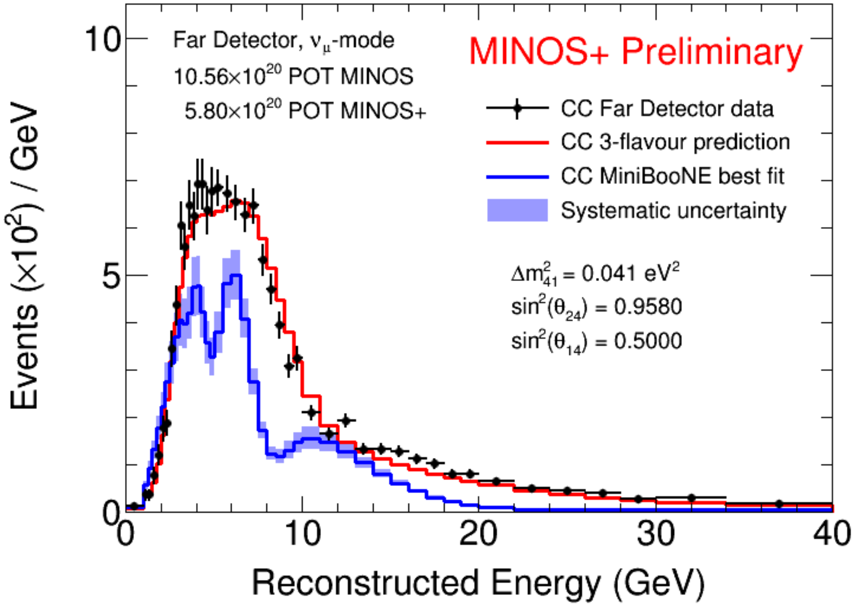
We wish to thank the crew at the Soudan Underground Laboratory for their efforts in maintaining and running the Far Detector.

We also gratefully acknowledge financial support from DOE, STFC(UK), NSF and thank the University of Minnesota and Minnesota DNR for hosting us.

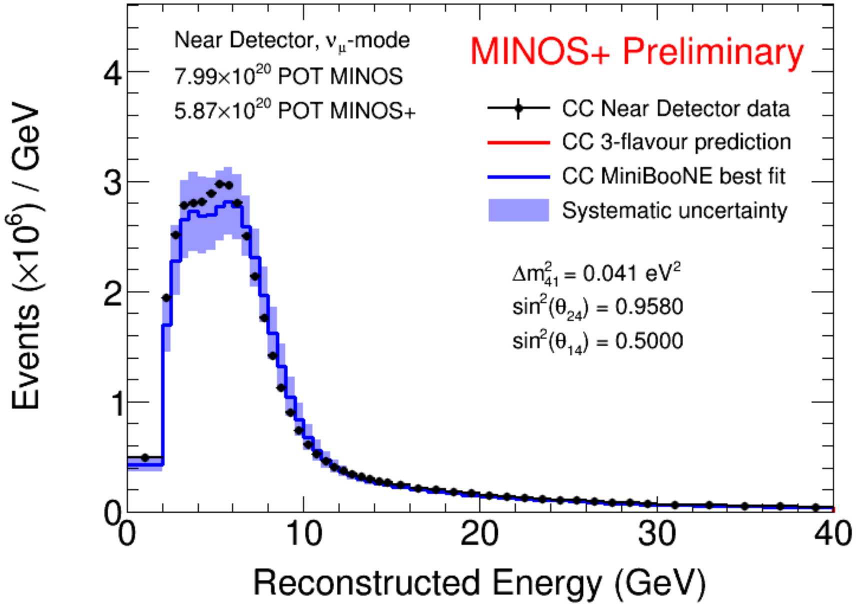
Backup

Comparison to MiniBooNE + LSND Best Fit: CC Selected Events

Far Detector



Near Detector



New MiniBooNE paper – arXiv:1805.12028

Best fit: $\Delta m^2 = 0.041$ eV^2 and $\sin^2 2\theta_{\mu e} = 0.958$

$$\sin^2_{\mu e} = 4|U_{e4}|^2|U_{\mu4}|^2 = \sin^2 2\theta_{14}\sin^2\theta_{24}$$

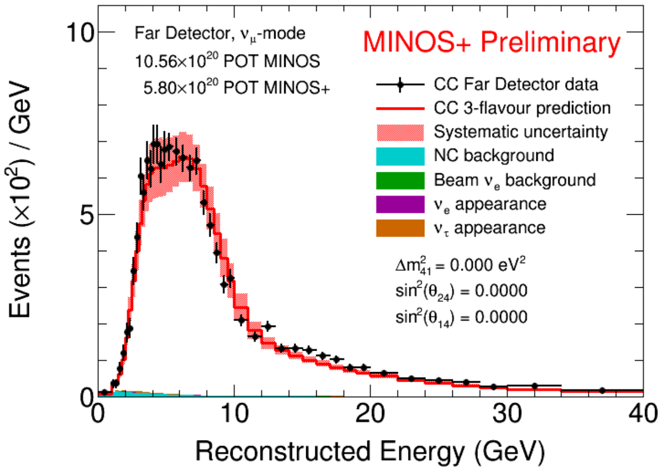
Take $\sin^2 2\theta_{14} = 1$ to minimize ν_μ disappearance

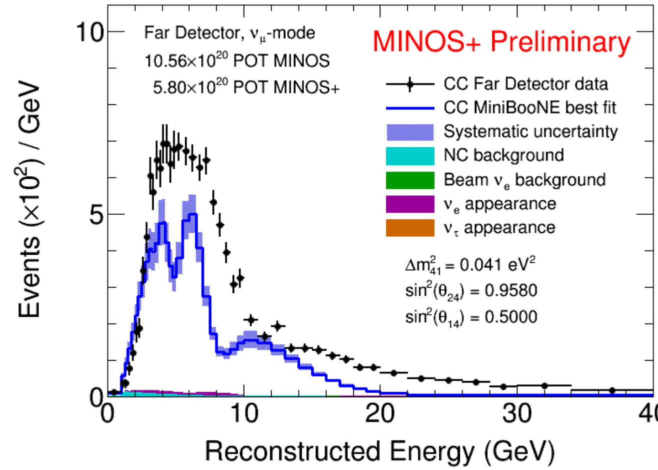
Comparison to MiniBooNE + LSND Best Fit: CC Selected Events

Three-flavor Oscillations

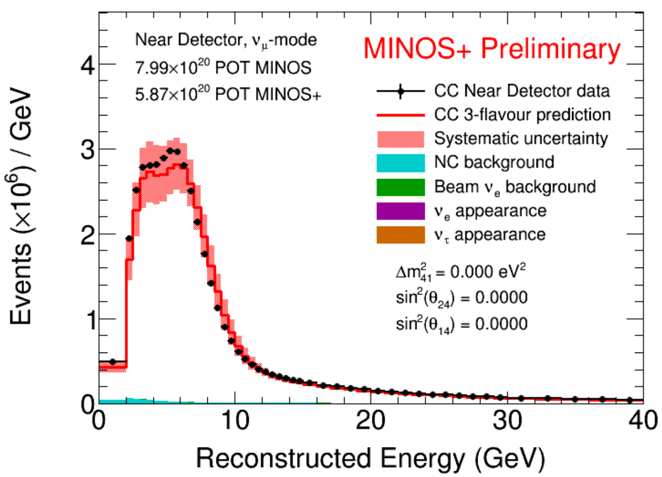
MiniBooNE + LSND Best Fit

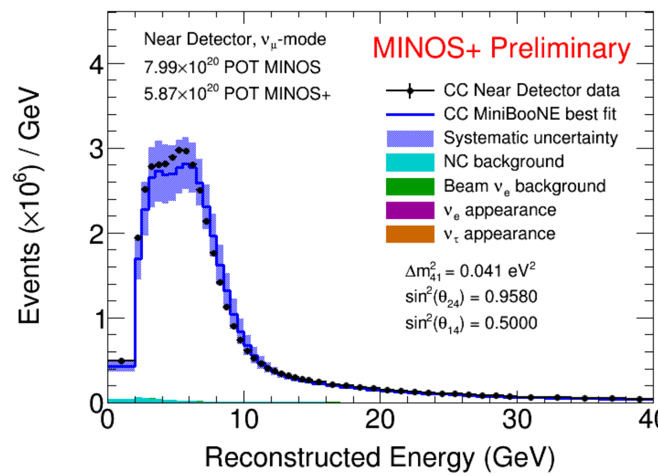
FD





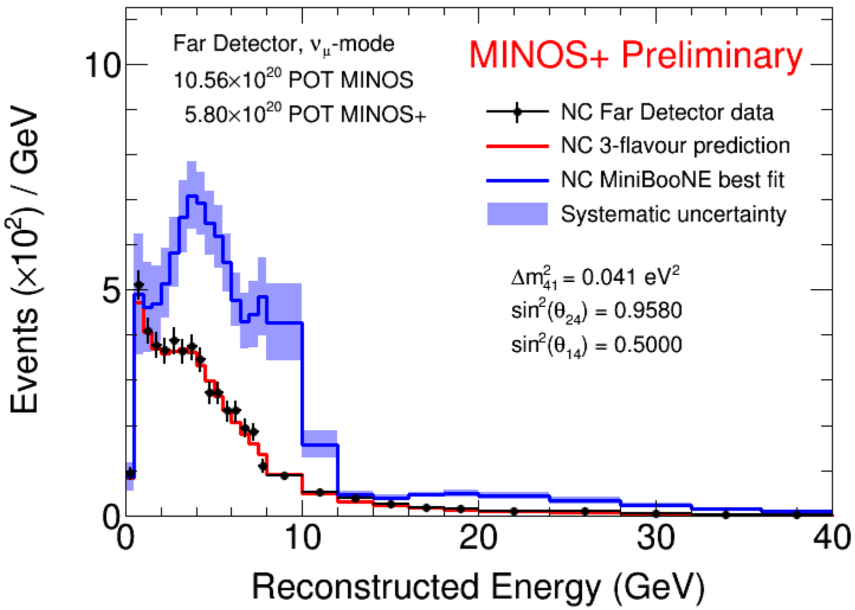
ND



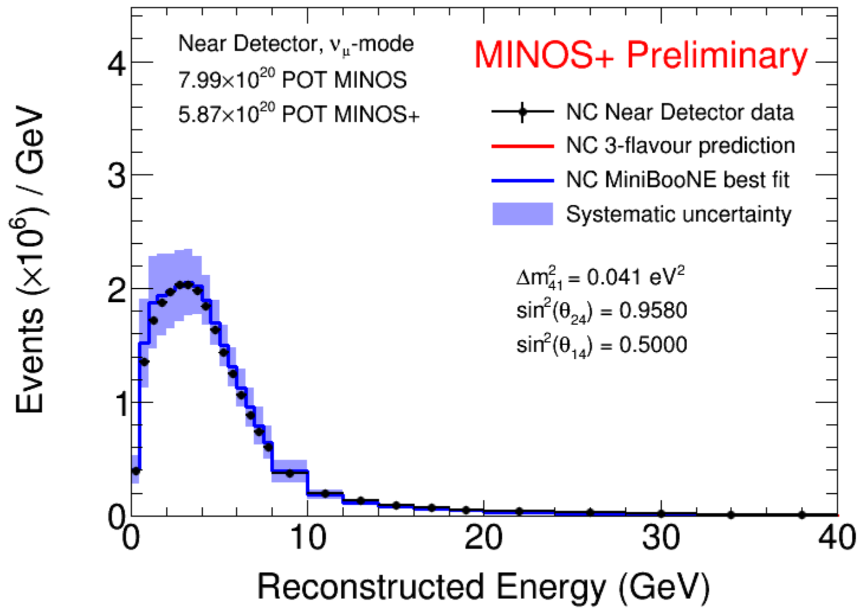


Comparison to MiniBooNE + LSND Best Fit: NC Selected Events

Far Detector



Near Detector



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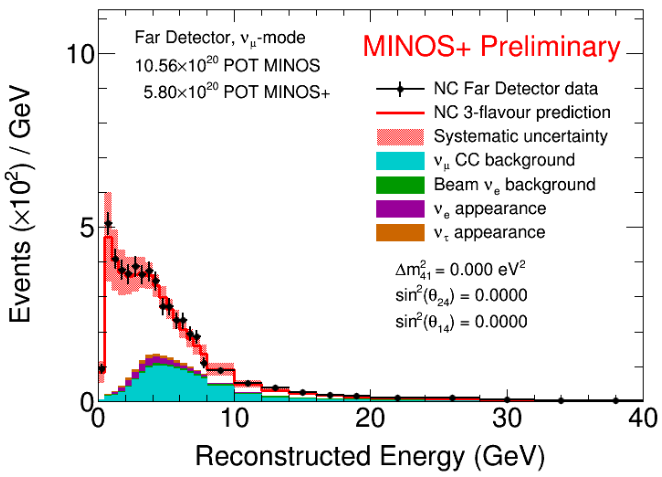
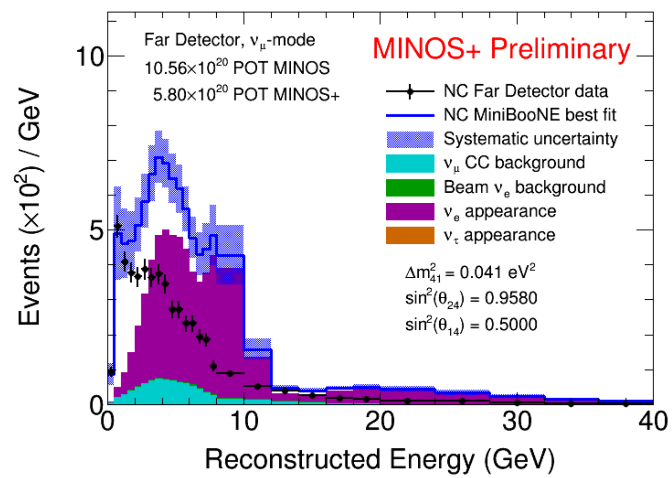
Comparison to MiniBooNE + LSND Best Fit: NC Selected Events

	Three-flavor Oscillations	MiniBooNE + LSND Best Fit

FD





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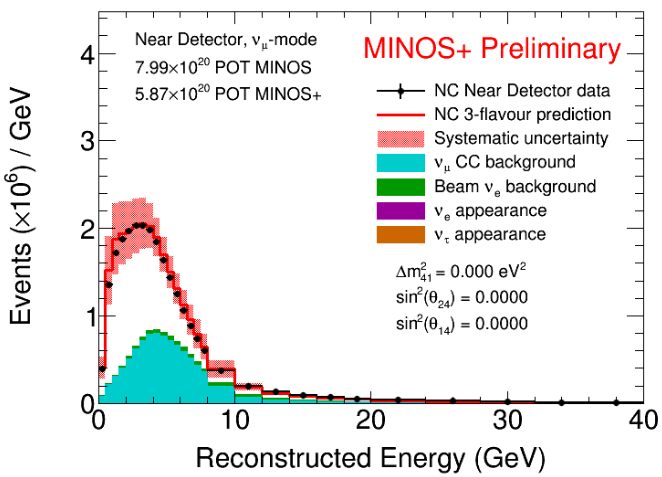
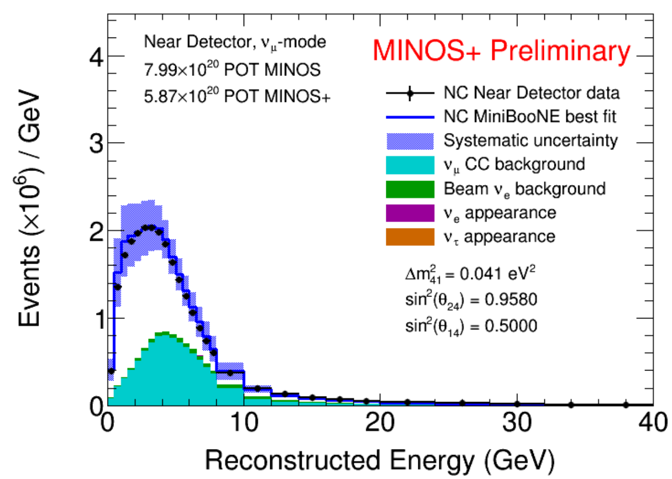
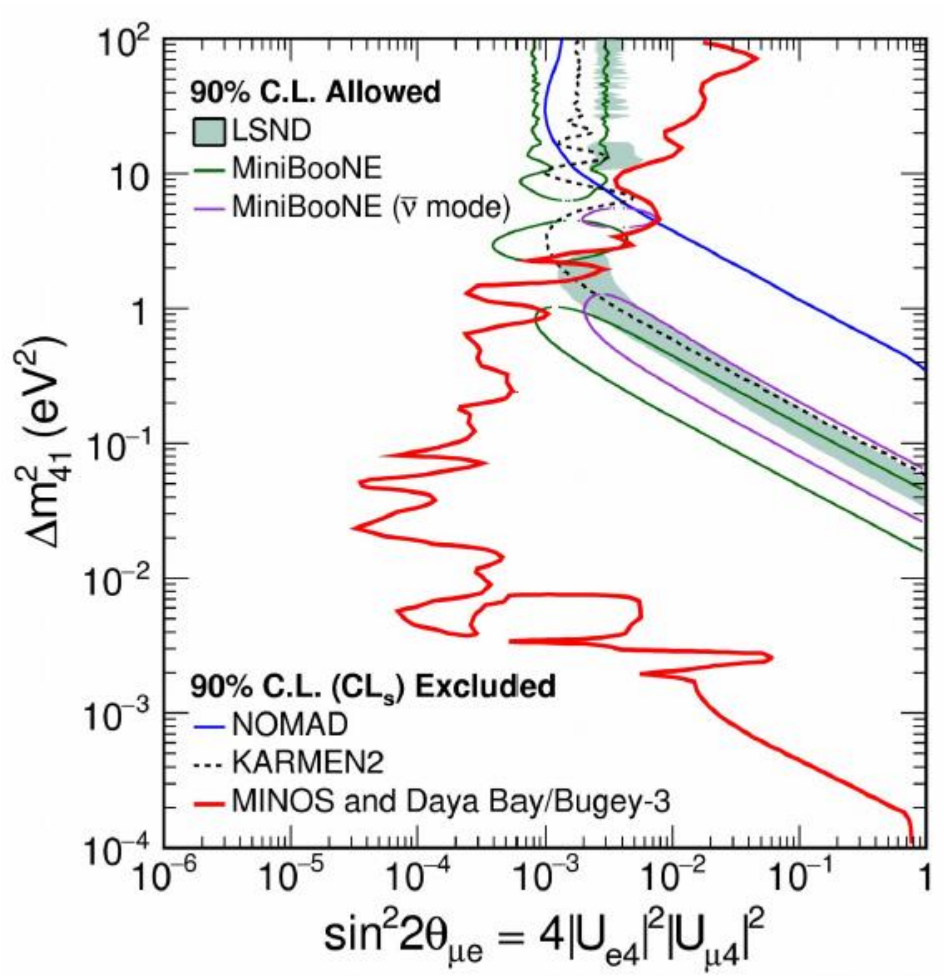




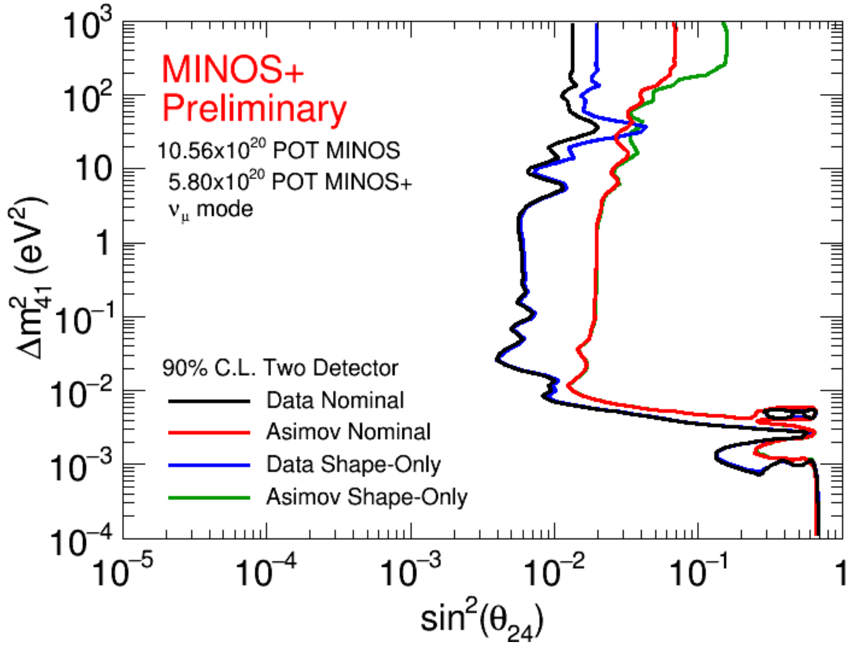
Comparison to MiniBooNE: MINOS/Daya Bay/Bugey Combination



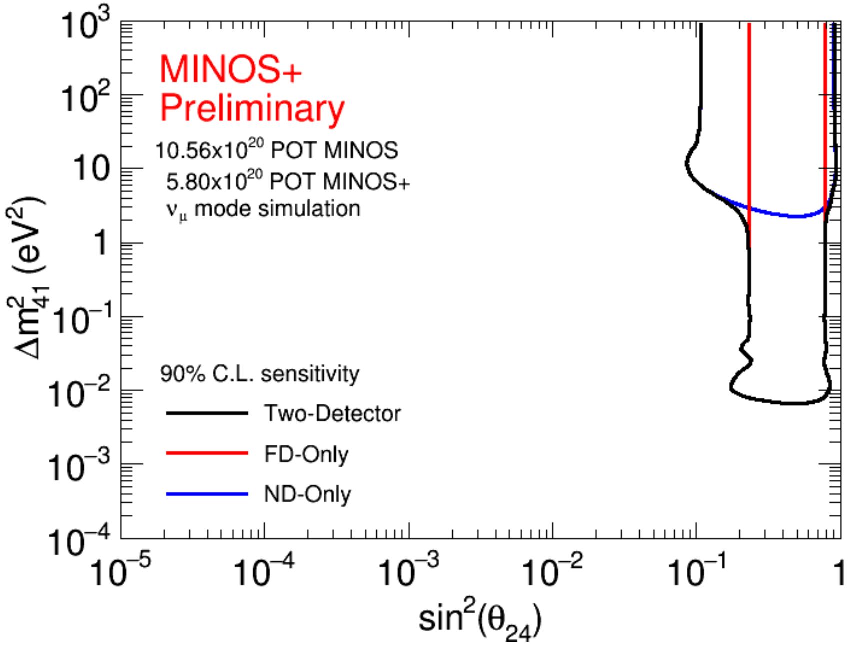
- MINOS and MINOS+ are in significant tension with the new MiniBooNE result, even assuming a conservative $\sin^2 2\theta_{14} = 1$
- Using θ_{14} from Daya Bay and Bugey combined with the previous MINOS result leads to an even larger tension, which will only increase if a future combination with Daya Bay is performed

Shape/Normalization Factorization

Nominal vs. Shape

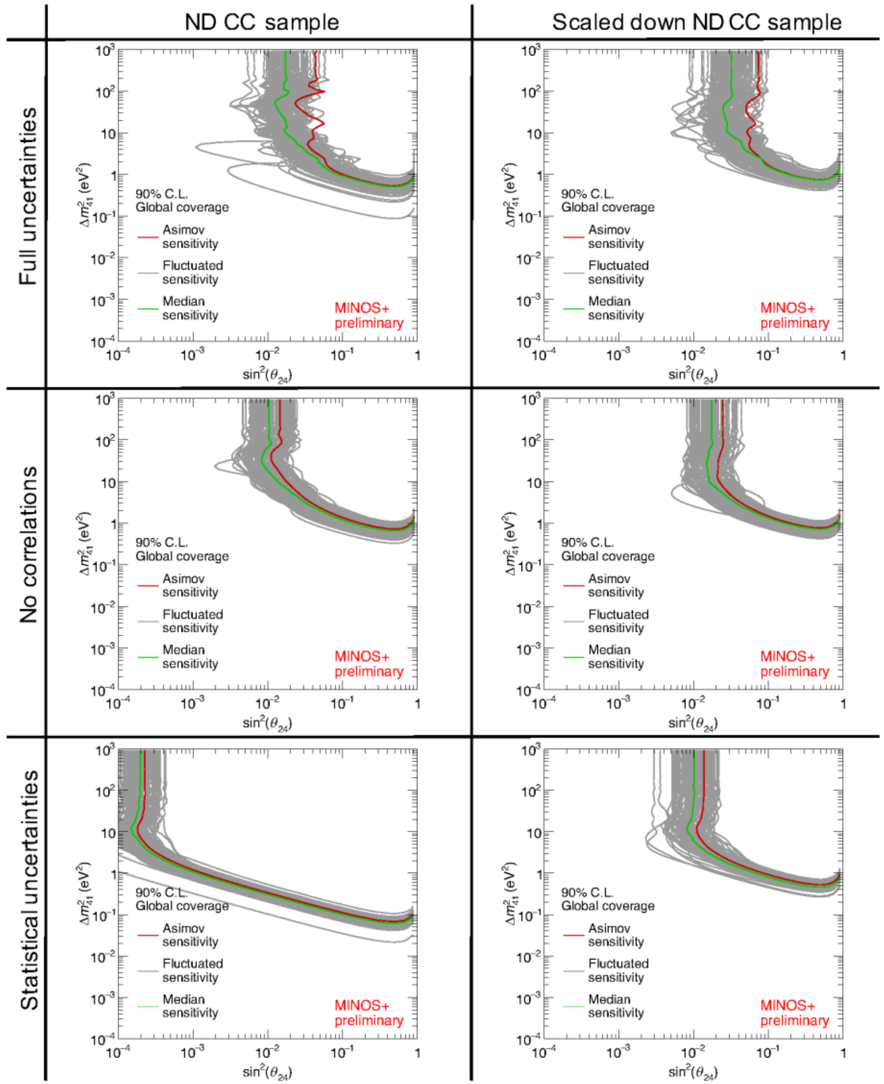


Normalization

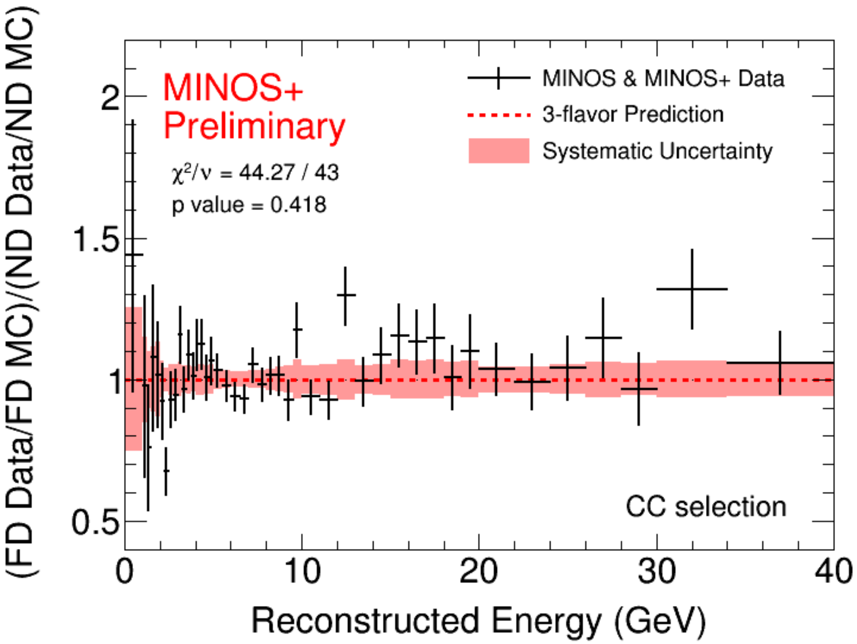


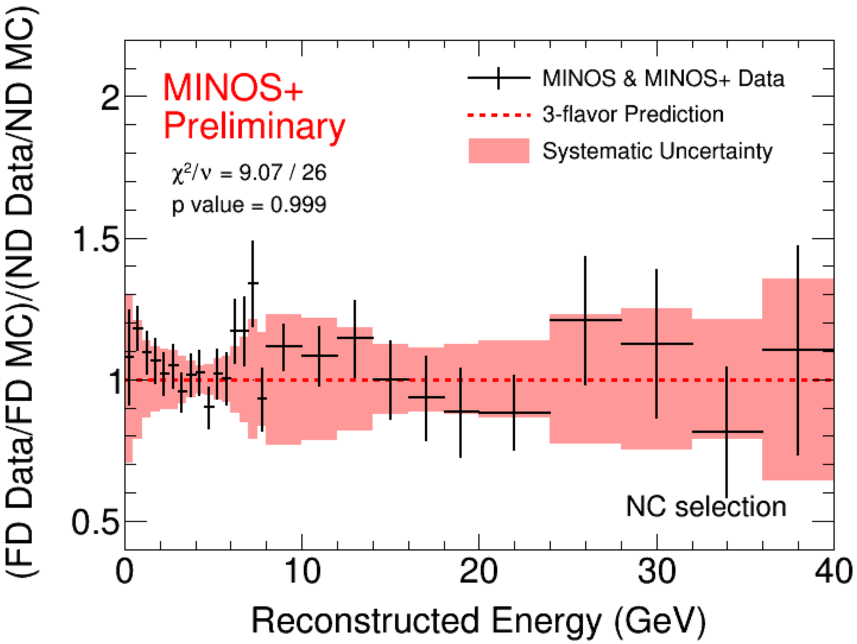
"Counting Experiment"

Median vs. Asimov Sensitivity



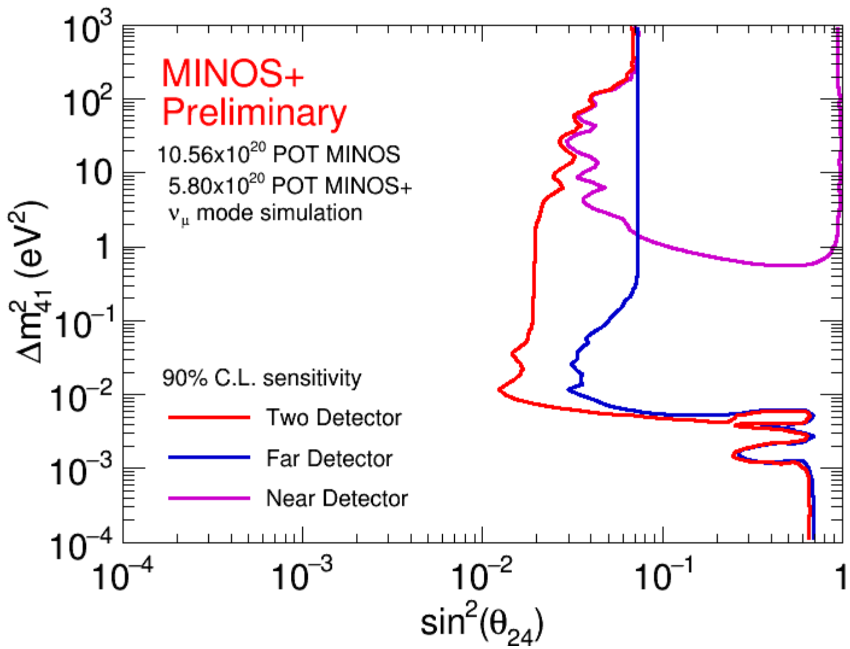
Consistency with Three Flavor Oscillations

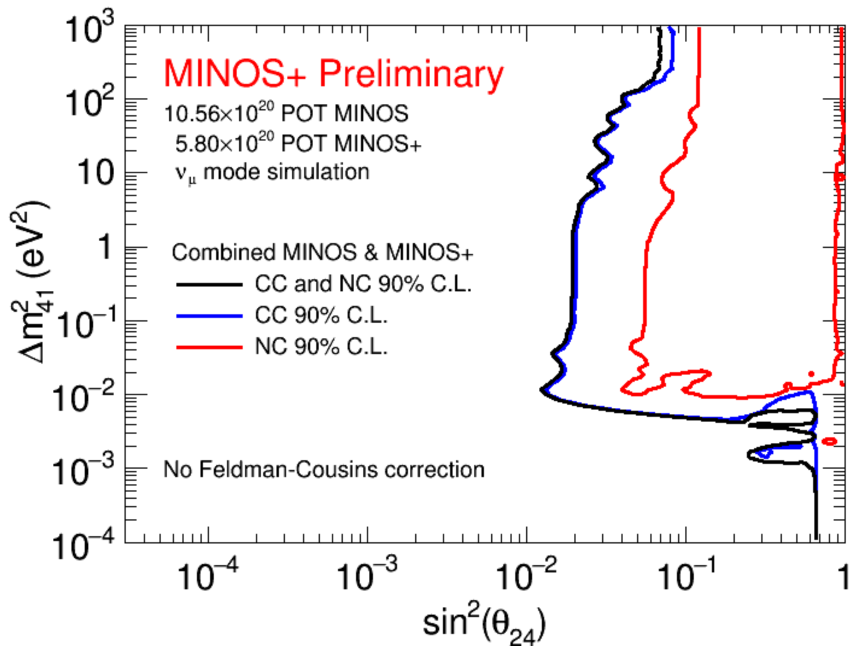




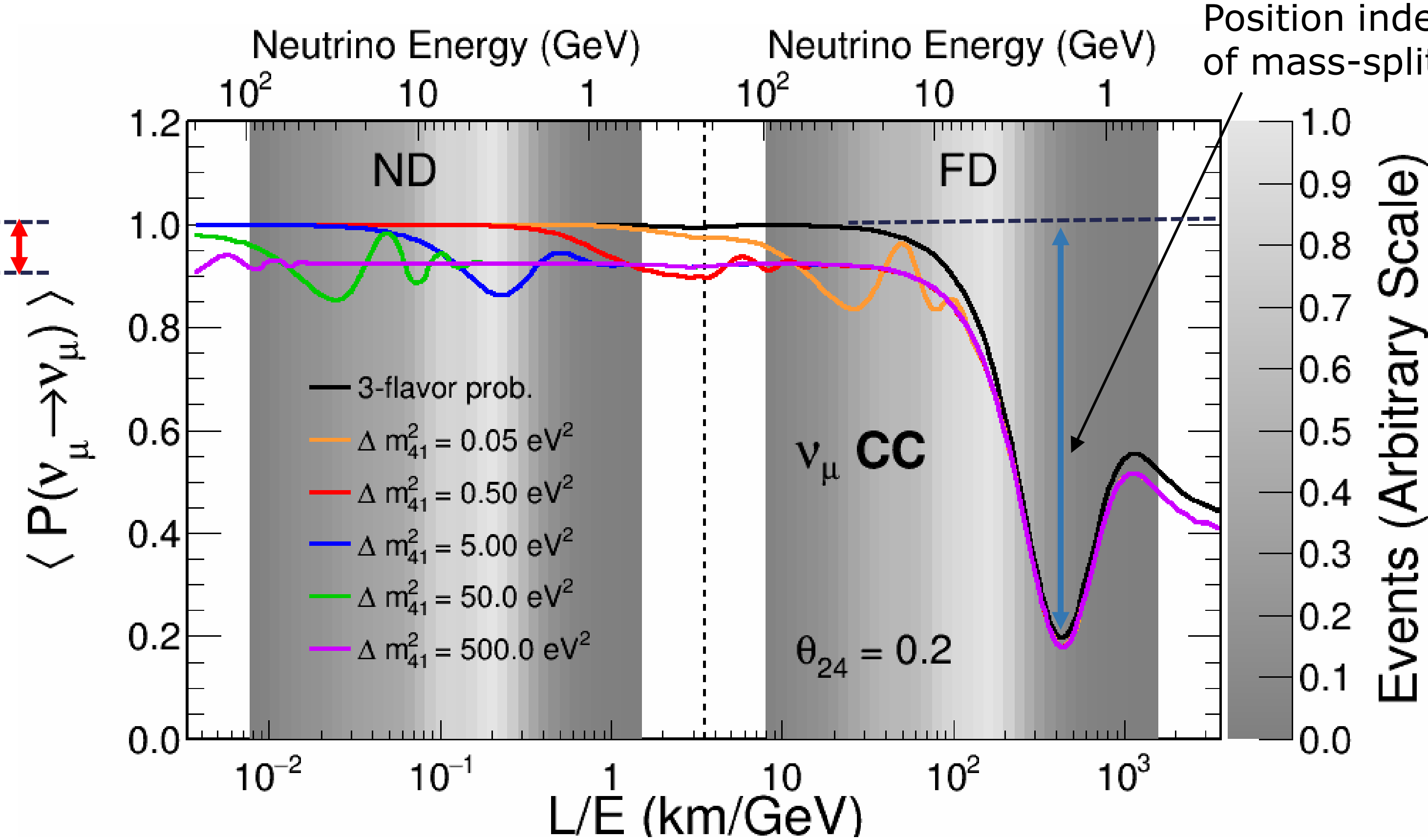
Detector and Sample Contributions

Asimov Sensitivities





(3+1)-Flavor Oscillations



Position independent of mass-splitting

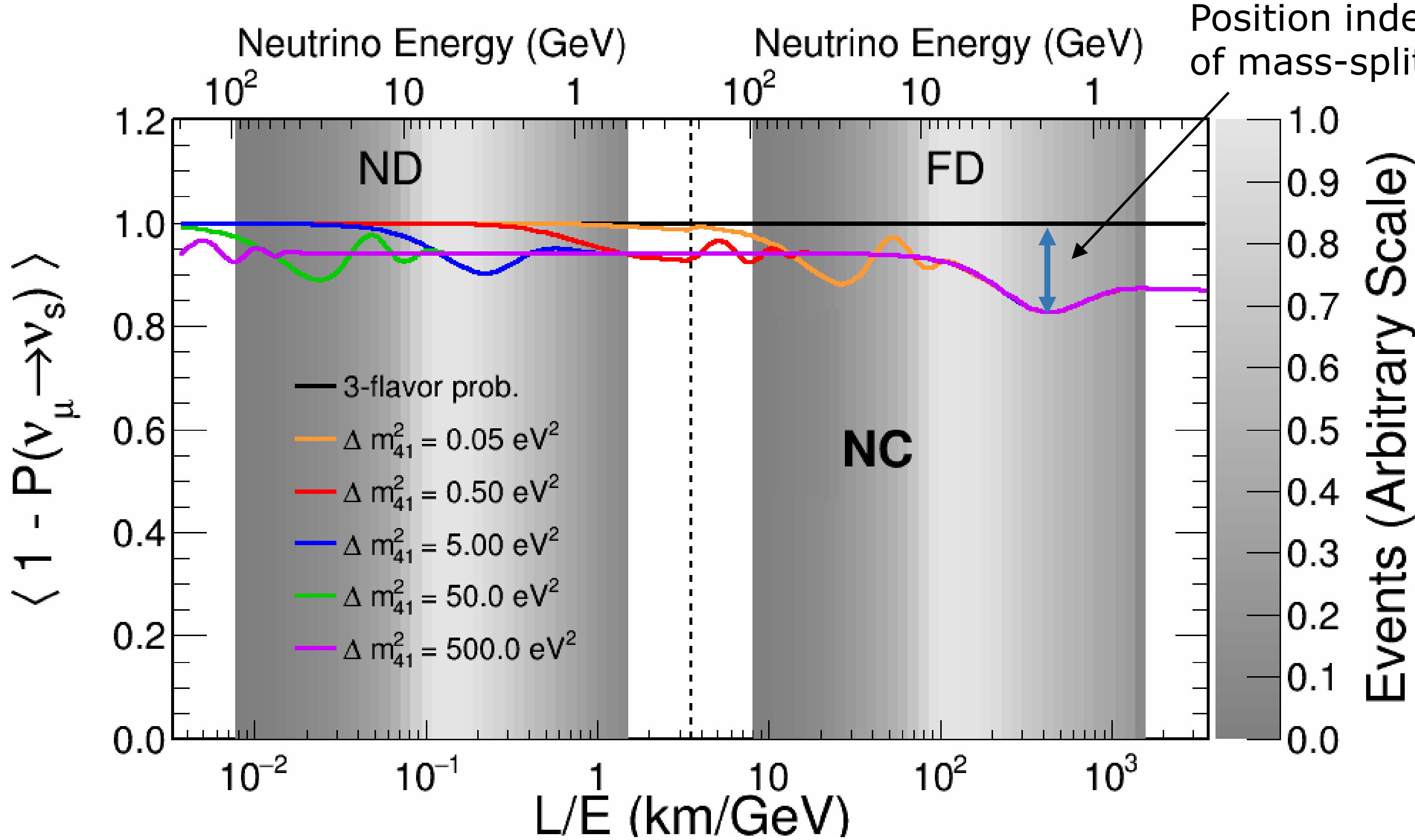
Rapid oscillations regime causes normalization shifts

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \cos 2\theta_{24} \sin^2 \Delta_{31} - \sin^2 2\theta_{24} \sin^2 \Delta_{41}$$

Constrained by observation of near-maximal mixing

(3+1)-Flavor Oscillations

Position independent of mass-splitting

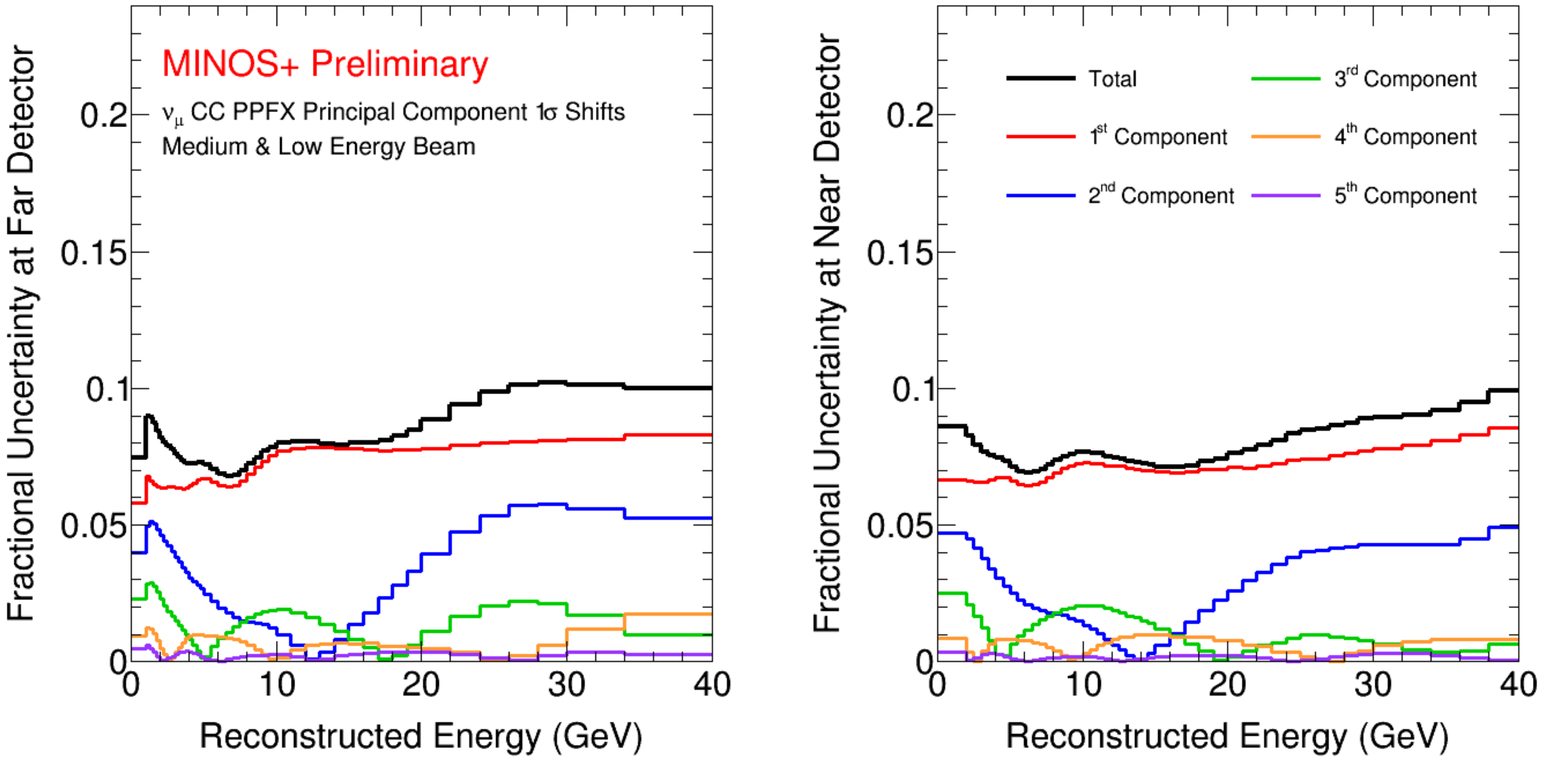


$$1 - P(\nu_\mu \to \nu_s) \approx 1 - \cos^4\theta_{14}\cos^2\theta_{34}\sin^2 2\theta_{24}\sin^2\Delta_{41}$$
$$- \sin^2\theta_{34}\sin^2 2\theta_{23}\sin^2\Delta_{31}$$
$$\cancel{+\frac{1}{2}\sin\delta_{24}\sin\theta_{24}\sin 2\theta_{23}\sin\Delta_{31}} \rightarrow 0$$

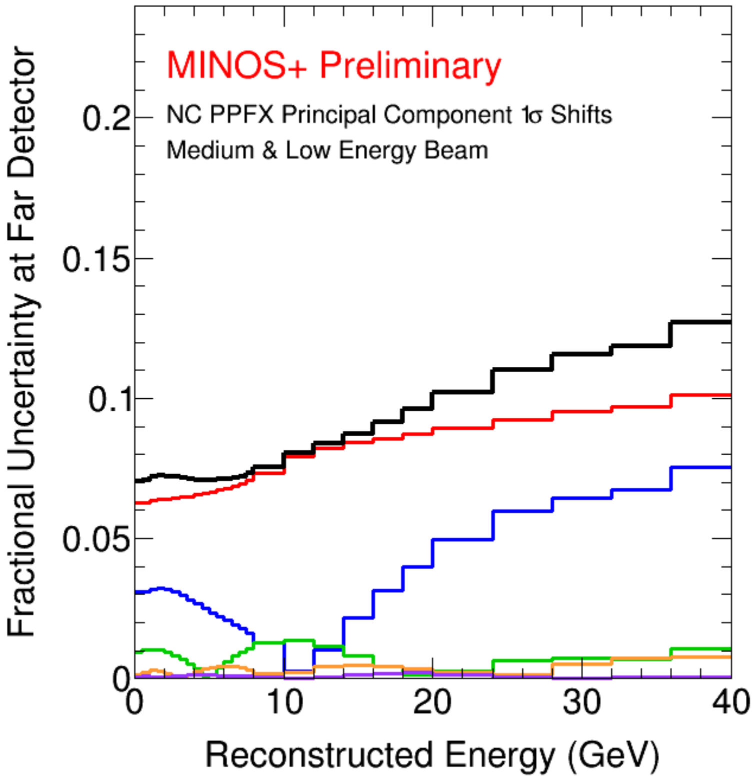
Rapid oscillations regime causes normalization shifts

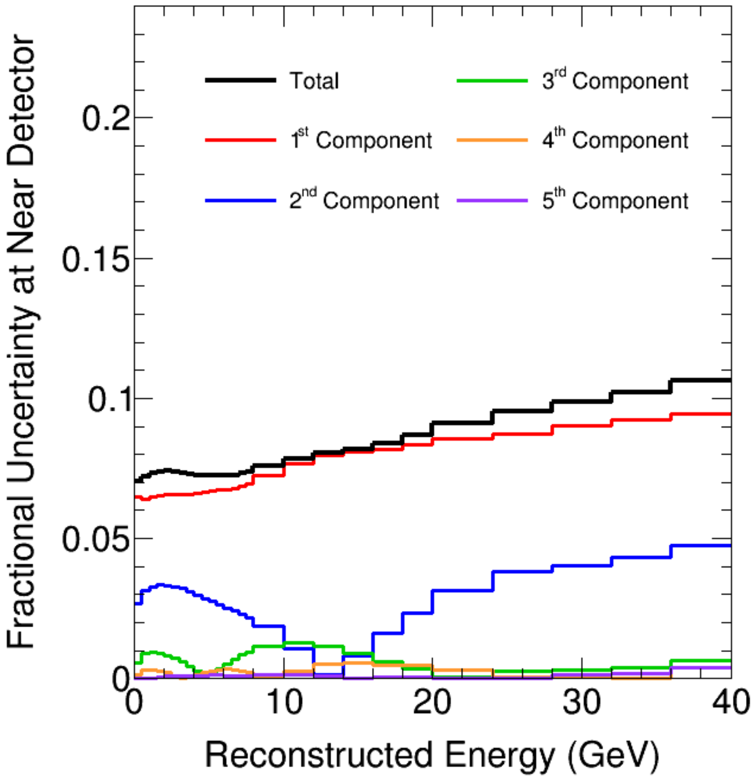
Constrained by observation of near-maximal mixing

Sterile Systematics: CC Hadron Production

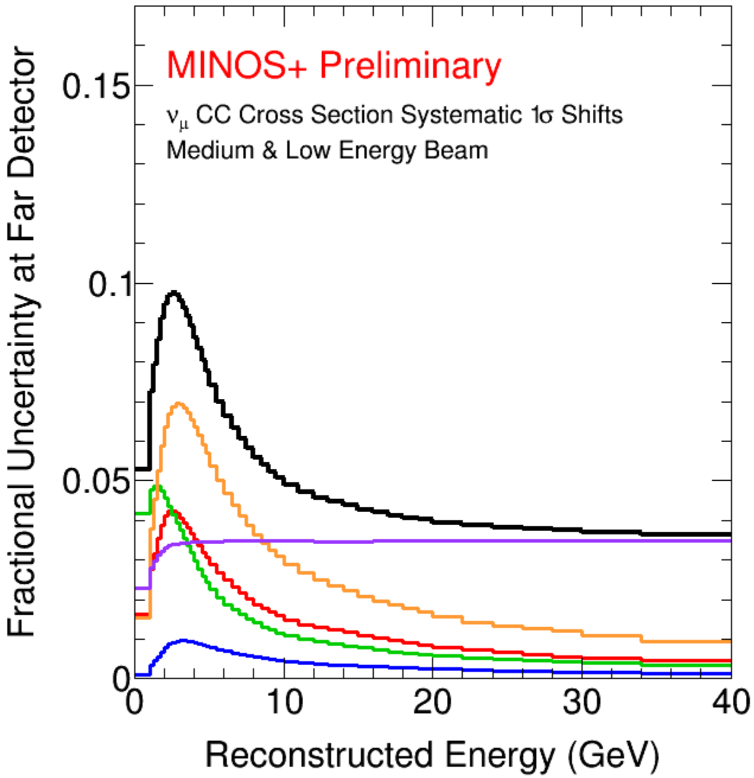


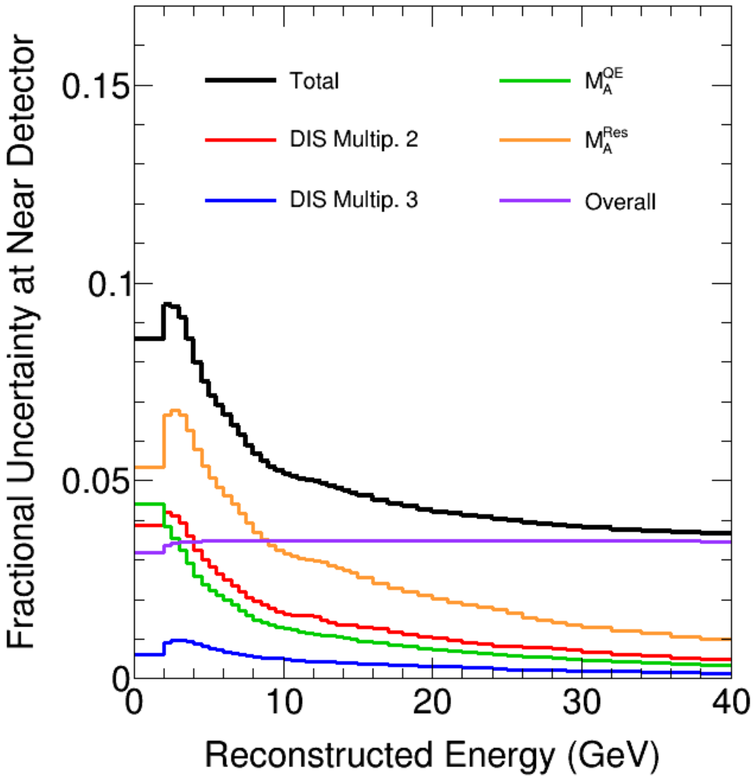
Sterile Systematics: NC Hadron Production



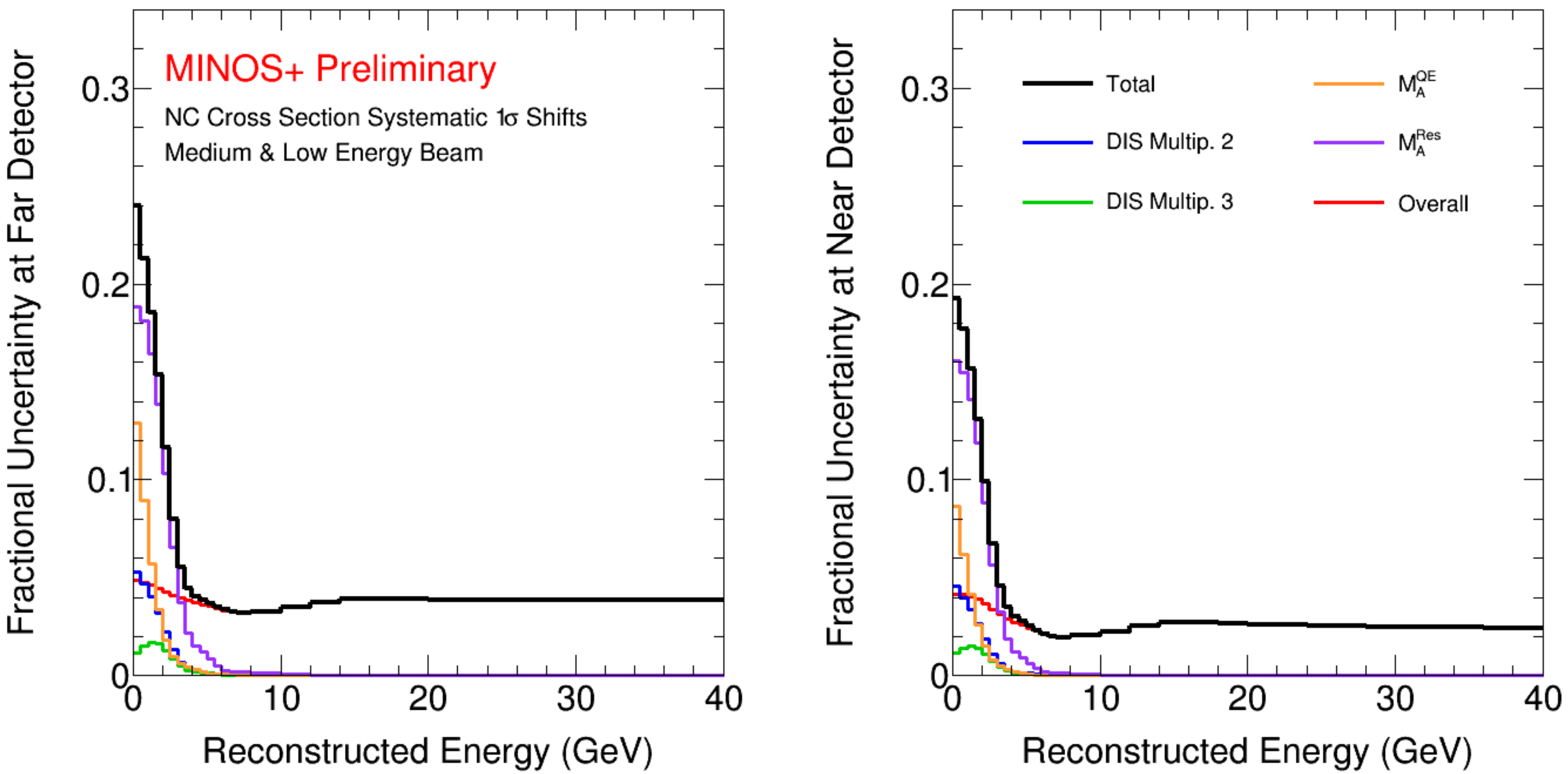


Sterile Systematics: CC Cross Sections

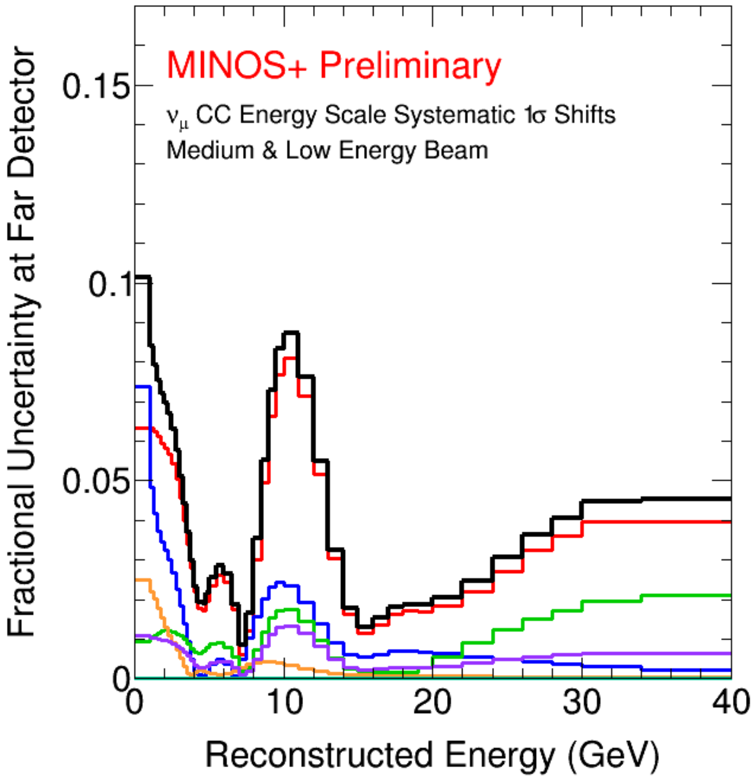


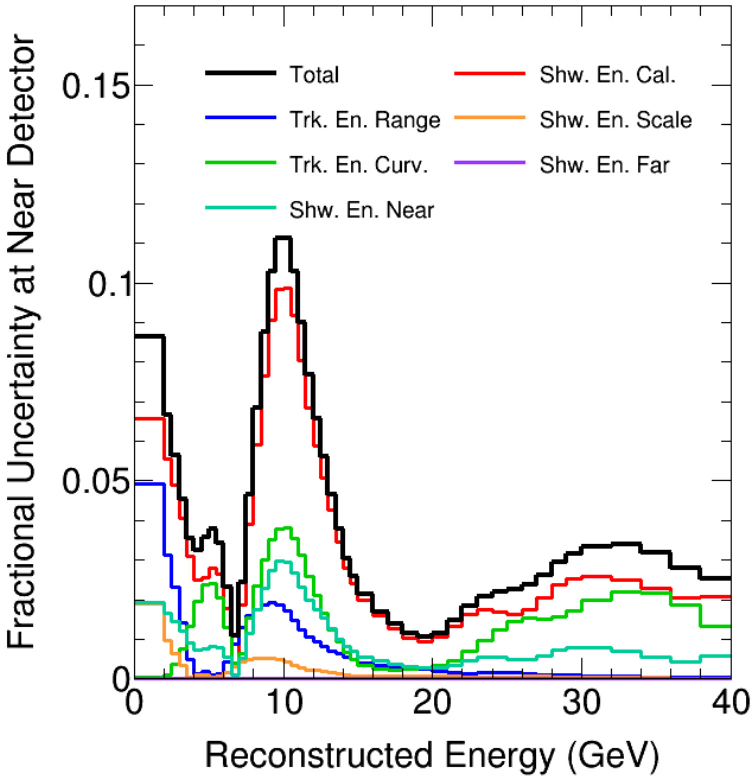


Sterile Systematics: NC Cross Sections

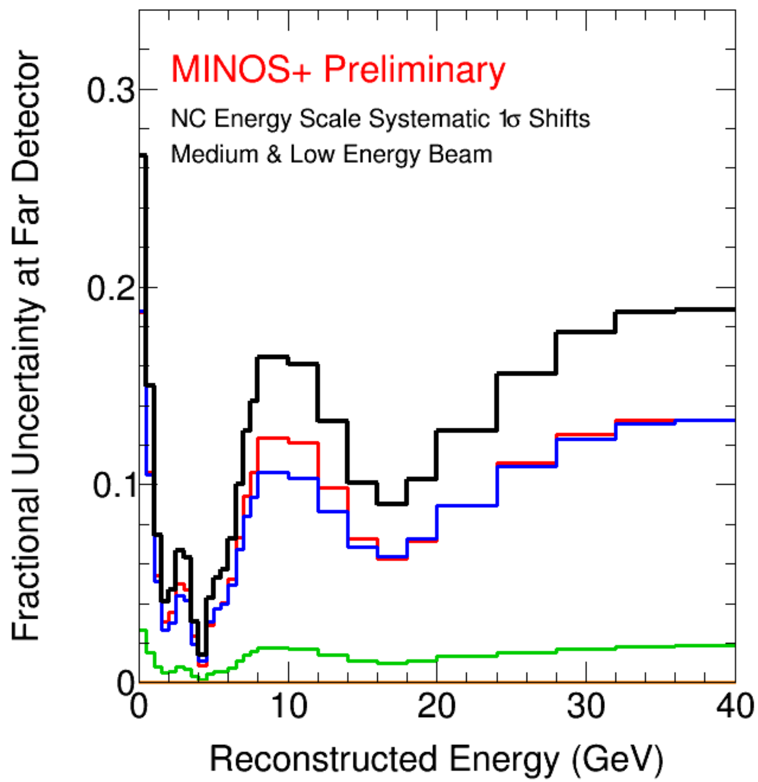


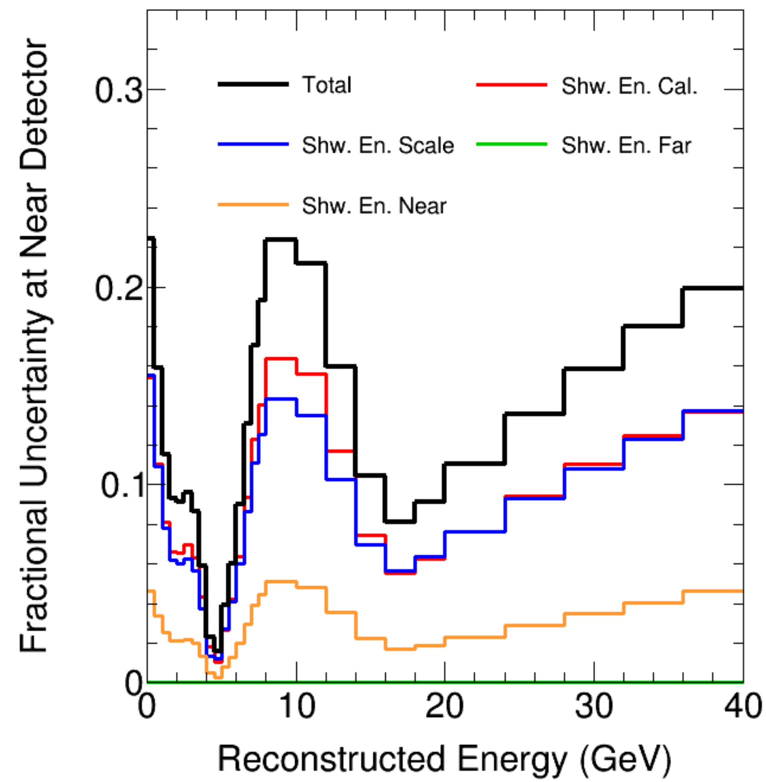
Sterile Systematics: CC Energy Scale



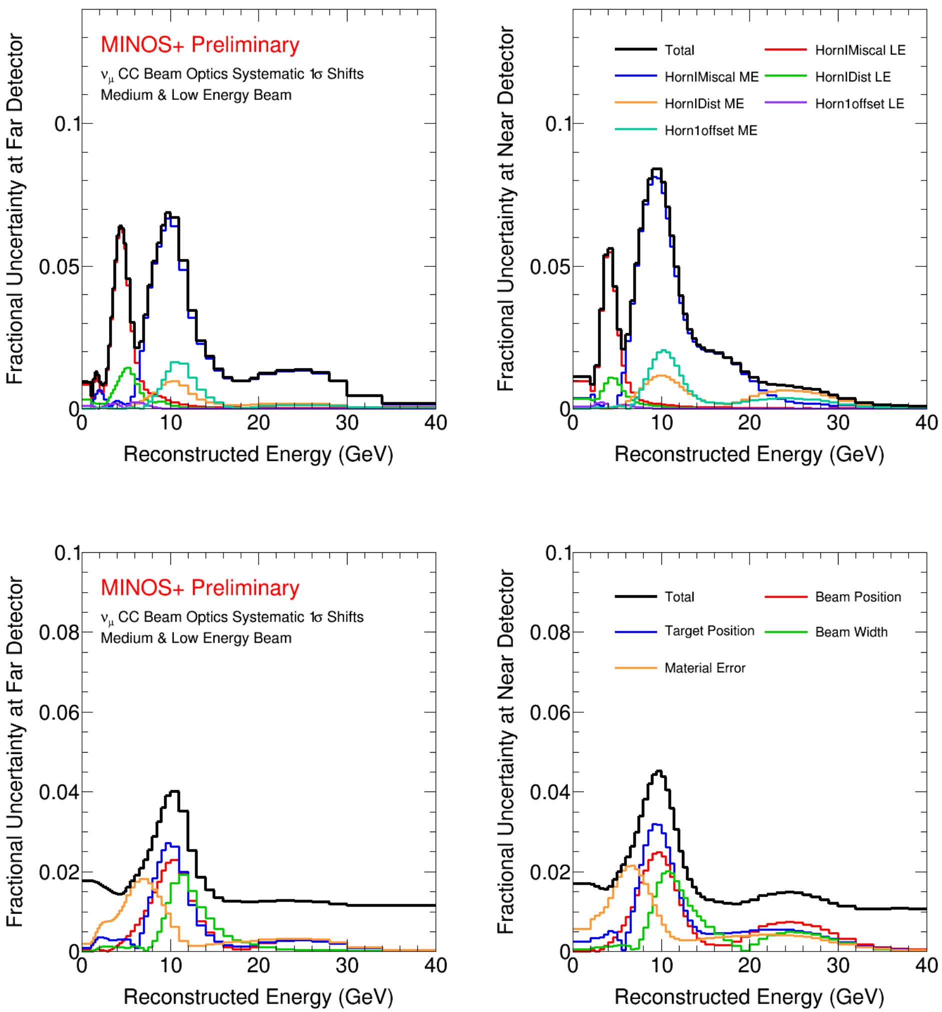


Sterile Systematics: NC Energy Scale

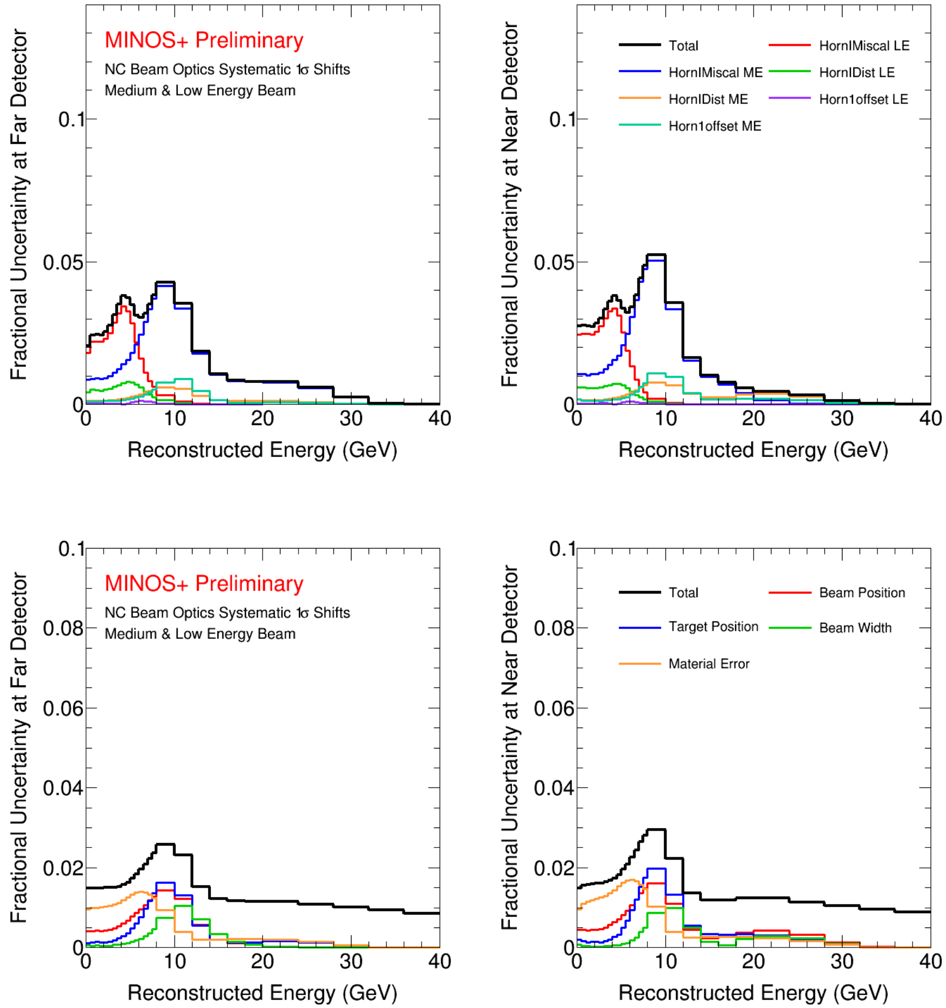




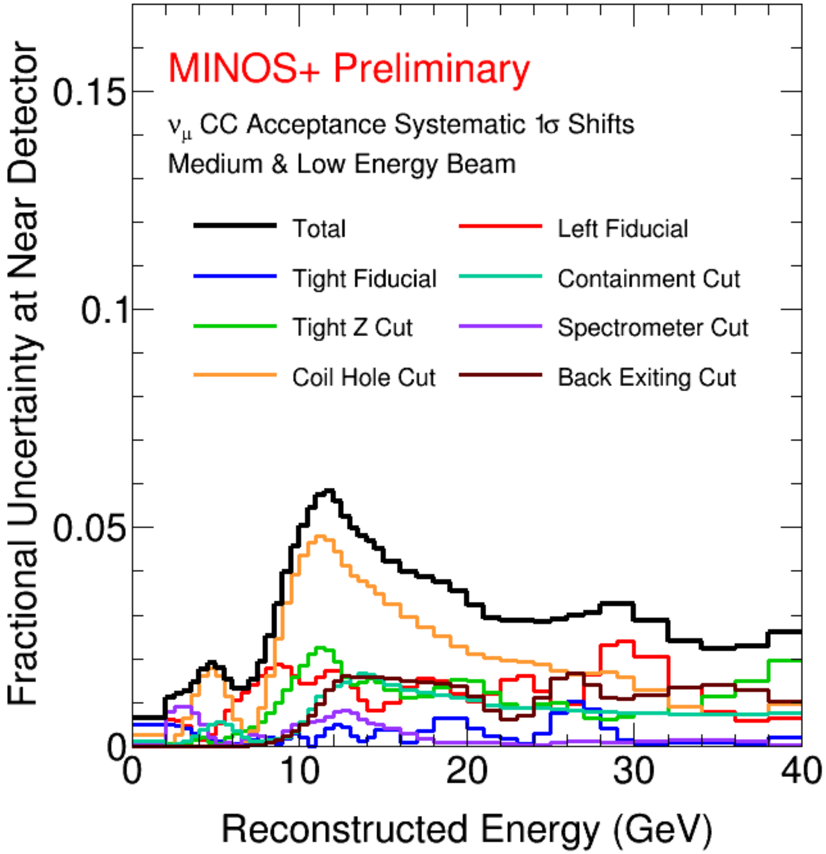
Sterile Systematics: CC Beam Optics

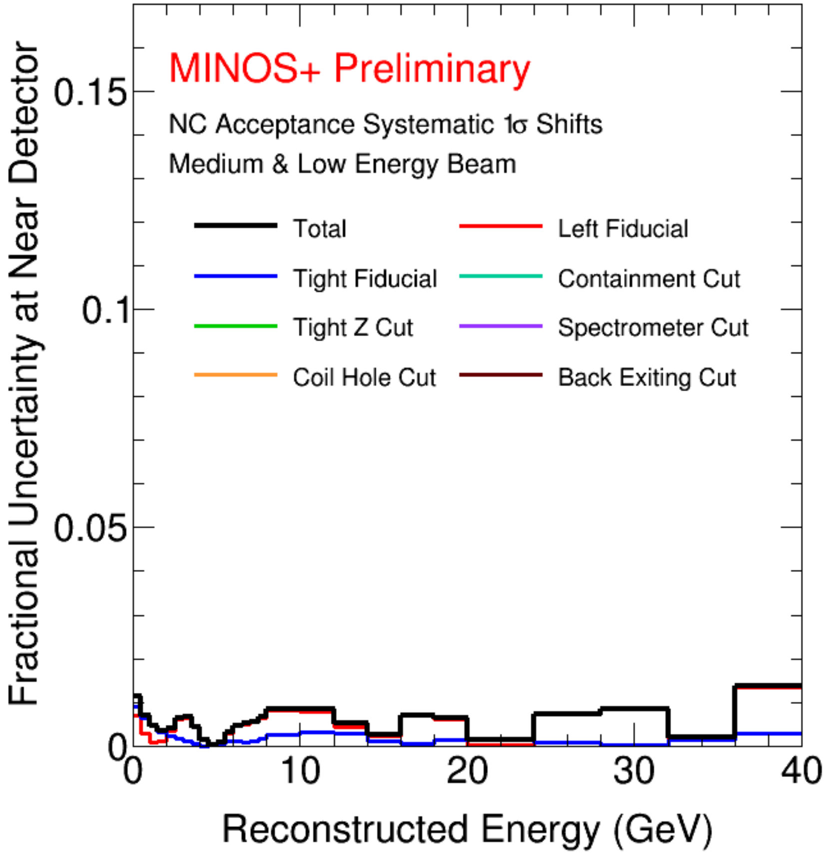


Sterile Systematics: NC Beam Optics



Sterile Systematics: Acceptance





(3+1)-Flavor Degeneracies

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - 4\,|U_{\mu 3}|^2 \left(1 - |U_{\mu 3}|^2 - |U_{\mu 4}|^2\right) \sin^2 \Delta_{31}$$
$$- 4\,|U_{\mu 4}|^2\,|U_{\mu 3}|^2 \sin^2 \Delta_{43} - 4\,|U_{\mu 4}|^2 \left(1 - |U_{\mu 3}|^2 - |U_{\mu 4}|^2\right) \sin^2 \Delta_{41}$$

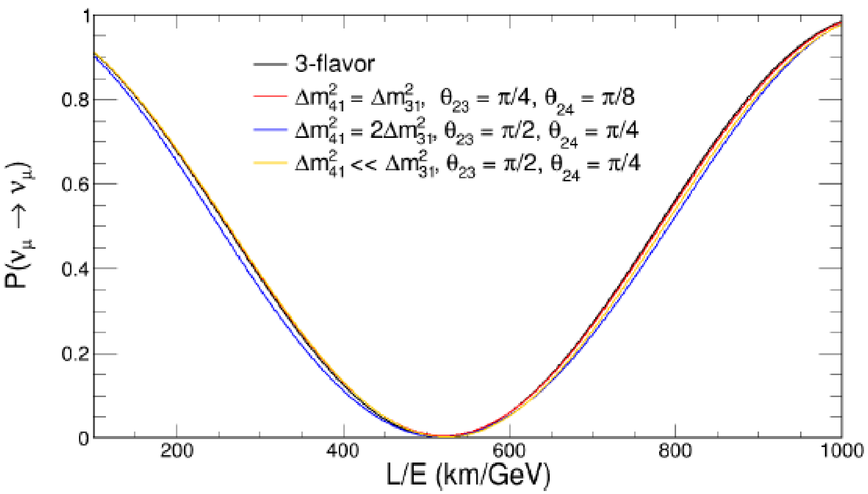
where $\Delta_{ij} = \dfrac{\Delta m^2_{ij} L}{4E}$

If:

- $\Delta m^2_{41} \approx \Delta m^2_{31}$
- $\Delta m^2_{41} \approx 2\Delta m^2_{31}$
- $\Delta m^2_{41} \ll \Delta m^2_{31}$

Certain combinations of θ_{23}, θ_{24}, and θ_{34} can produce 4-flavor solutions nearly indistinguishable from 3-flavor.

Run each fit five times → each θ_{23} octant and mass hierarchy choice and the degenerate region.



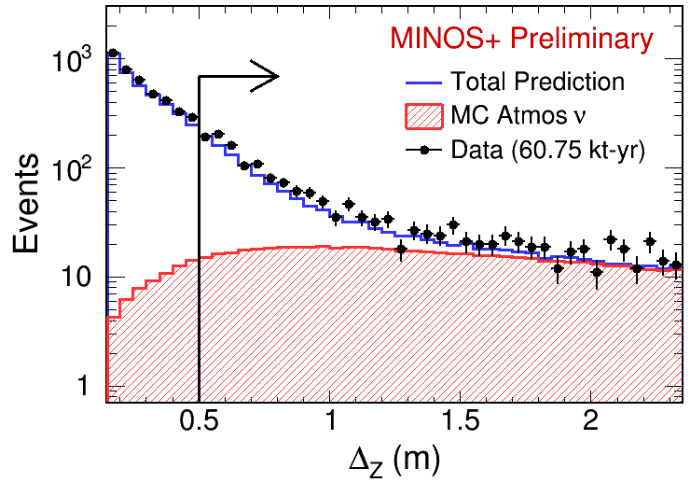
Example degenerate scenarios

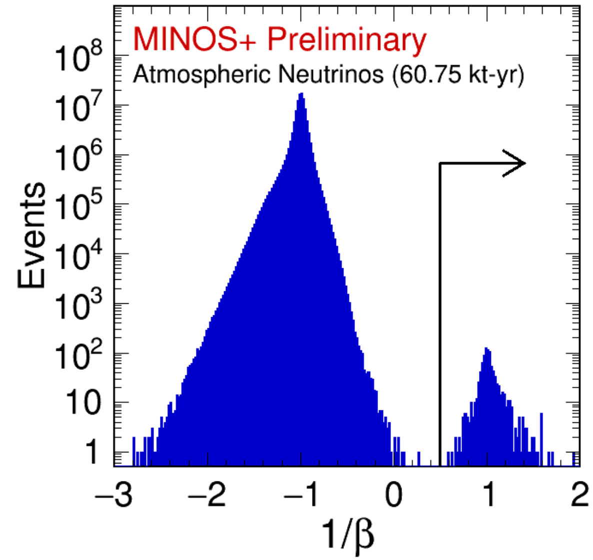
Atmospheric Data and Fit

- Two techniques used to identify atmospheric neutrinos in the Far Detector.

1) Contained-vertex events:
   - Apply series of containment requirements on reconstructed tracks and showers to reduce cosmic-ray backgrounds.
   - Far Detector is equipped with a scintillator veto shield, which tags cosmic-ray muons with 96% efficiency.

2) Upward and horizontal muons:
   - Far Detector has a timing resolution of 2.5ns.
   - Can identify neutrino-induced upward and horizontal muons using timing information.
   - Soudan mine has a uniform rock overburden, enabling events to be identified above the horizon ($\cos\theta_{zen}$<0.05).

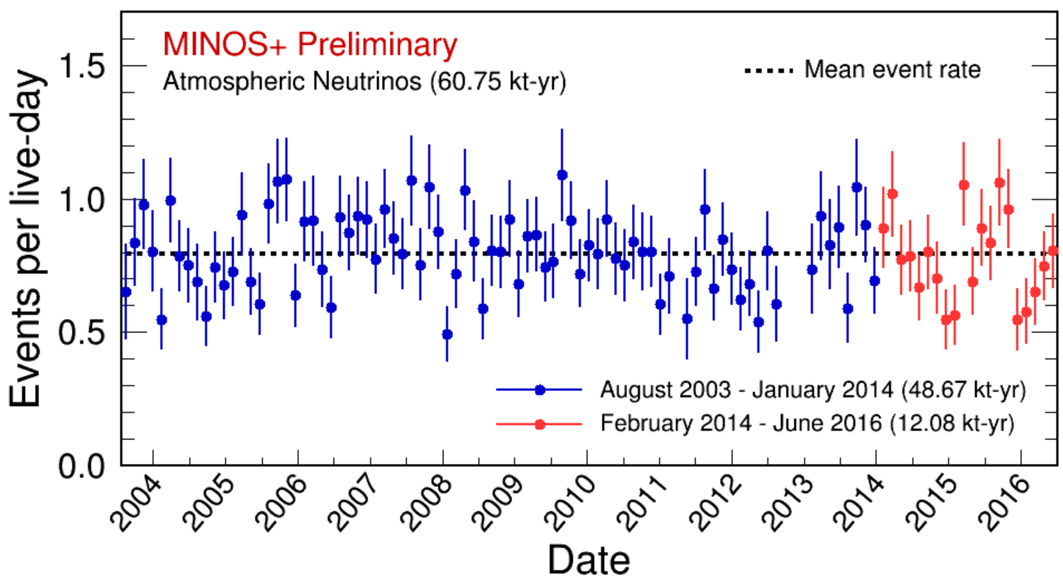


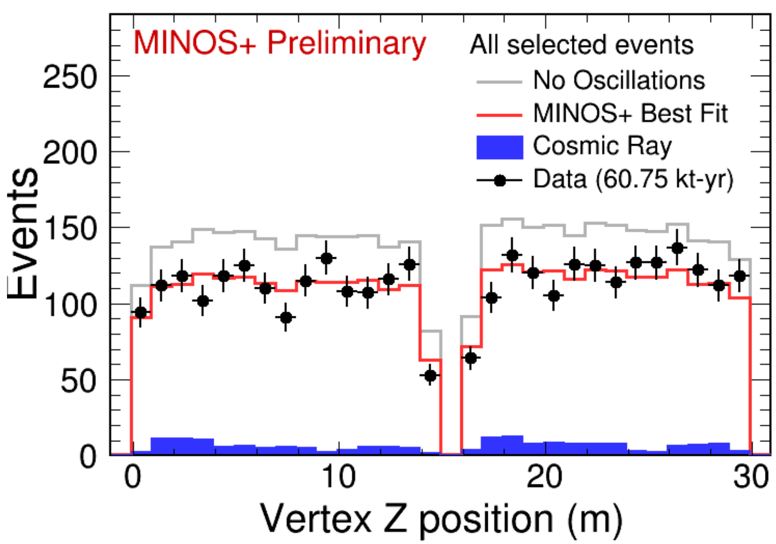


Atmospheric Data and Fit

◆ Selected atmospheric neutrinos are categorised based on event topology:

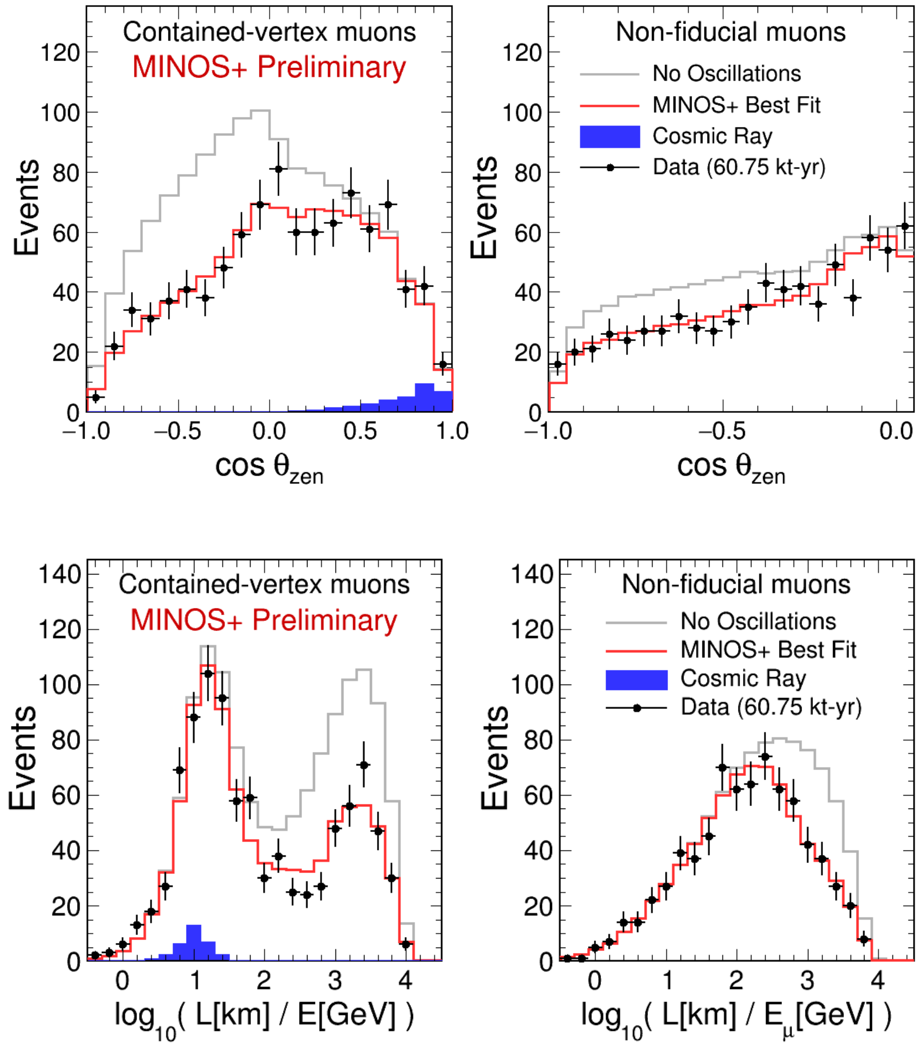
Event Classification	Data	No oscillations	Best fit
Contained-vertex showers	1123	1248	1134
Contained-vertex muons	1399	1923	1379
Non-fiducial muons	736	924	737
Total events	**3258**	**4095**	**3250**





Atmospheric Data and Fit

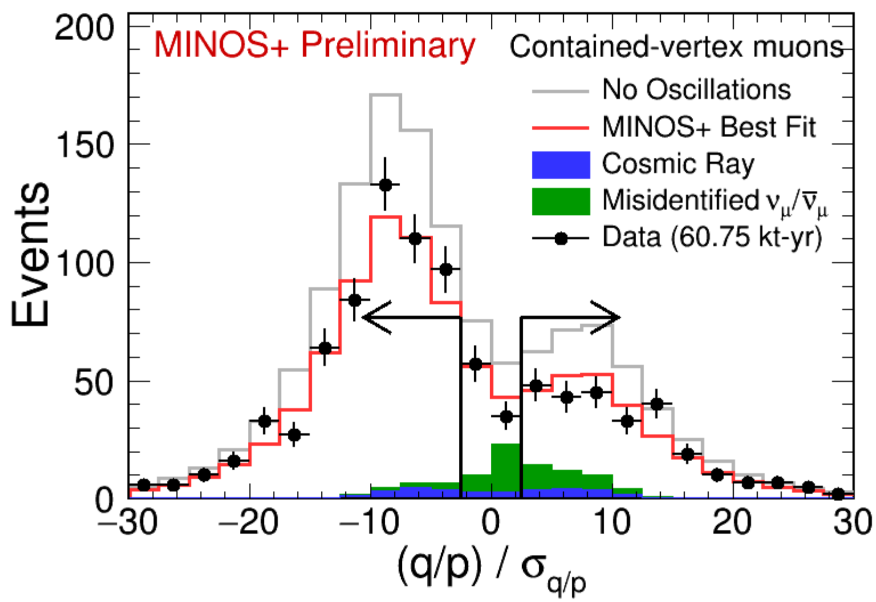
- Timing information is used to select "high resolution" sample of events with well-measured muon propagation direction.
  - 950 contained-vertex muons and all 736 non-fiducial muons pass this selection.
  - Can reconstruct zenith angle and L/E for these events.
- Plots on right show zenith angle and L/E distributions of selected high-resolution events.
  - Clear oscillation signature!

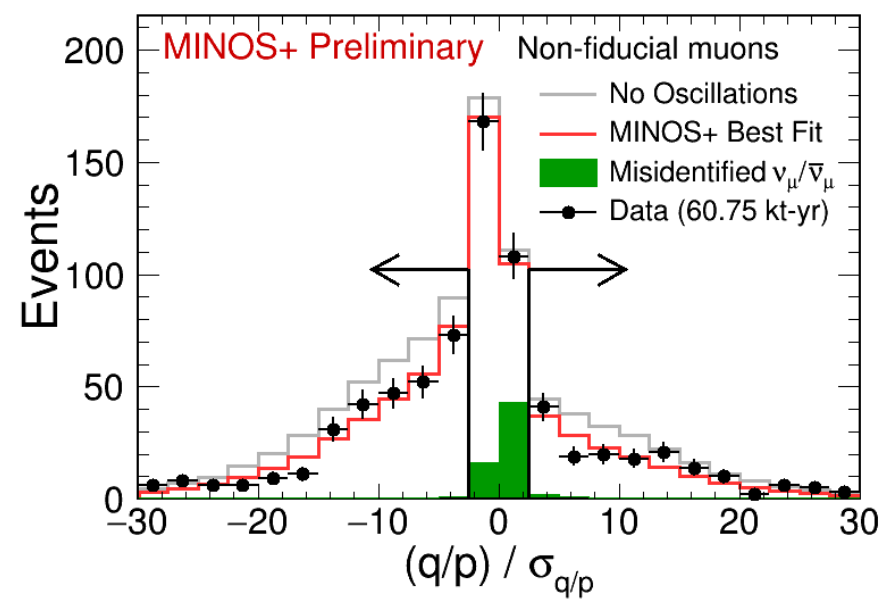


Atmospheric Data and Fit

◆ Neutrinos and antineutrinos are separated based on muon charge sign, which is reconstructed using curvature of final-state muon tracks.

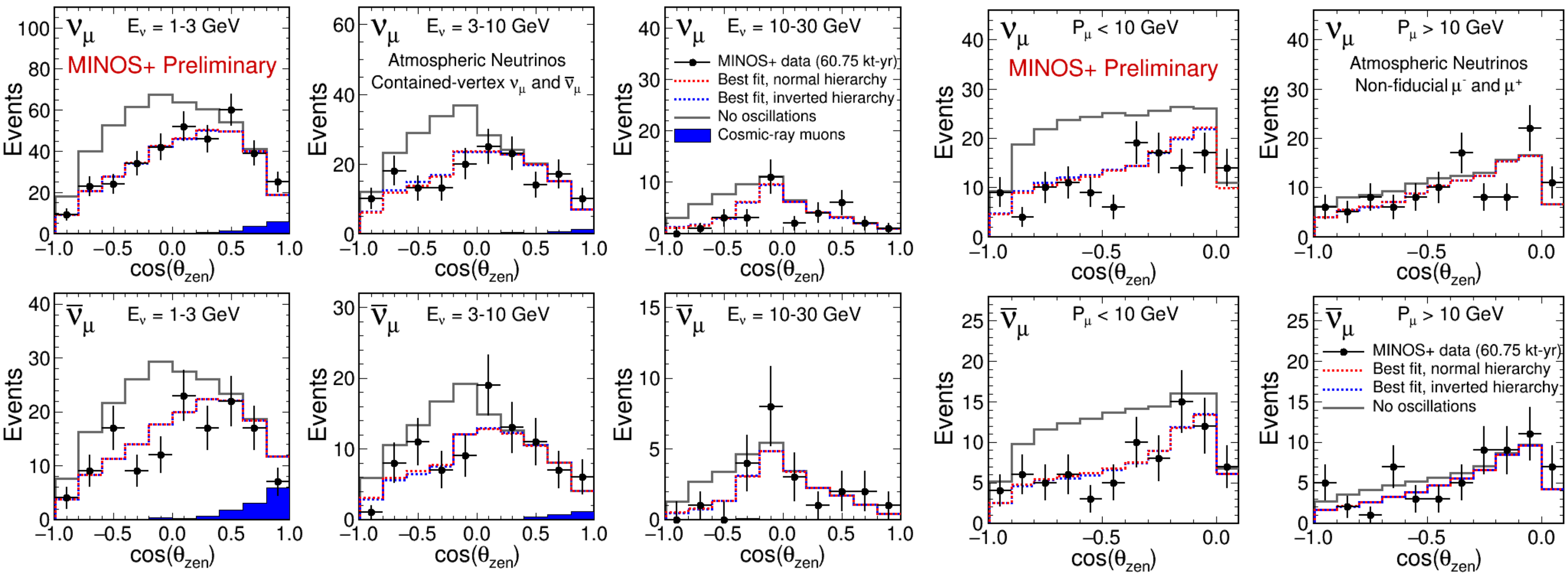
	Selected ν_μ	Selected anti-ν_μ	Total
Contained-vertex muons	574	255	829
Non-fiducial muons	239	143	382
Total	813	398	1211





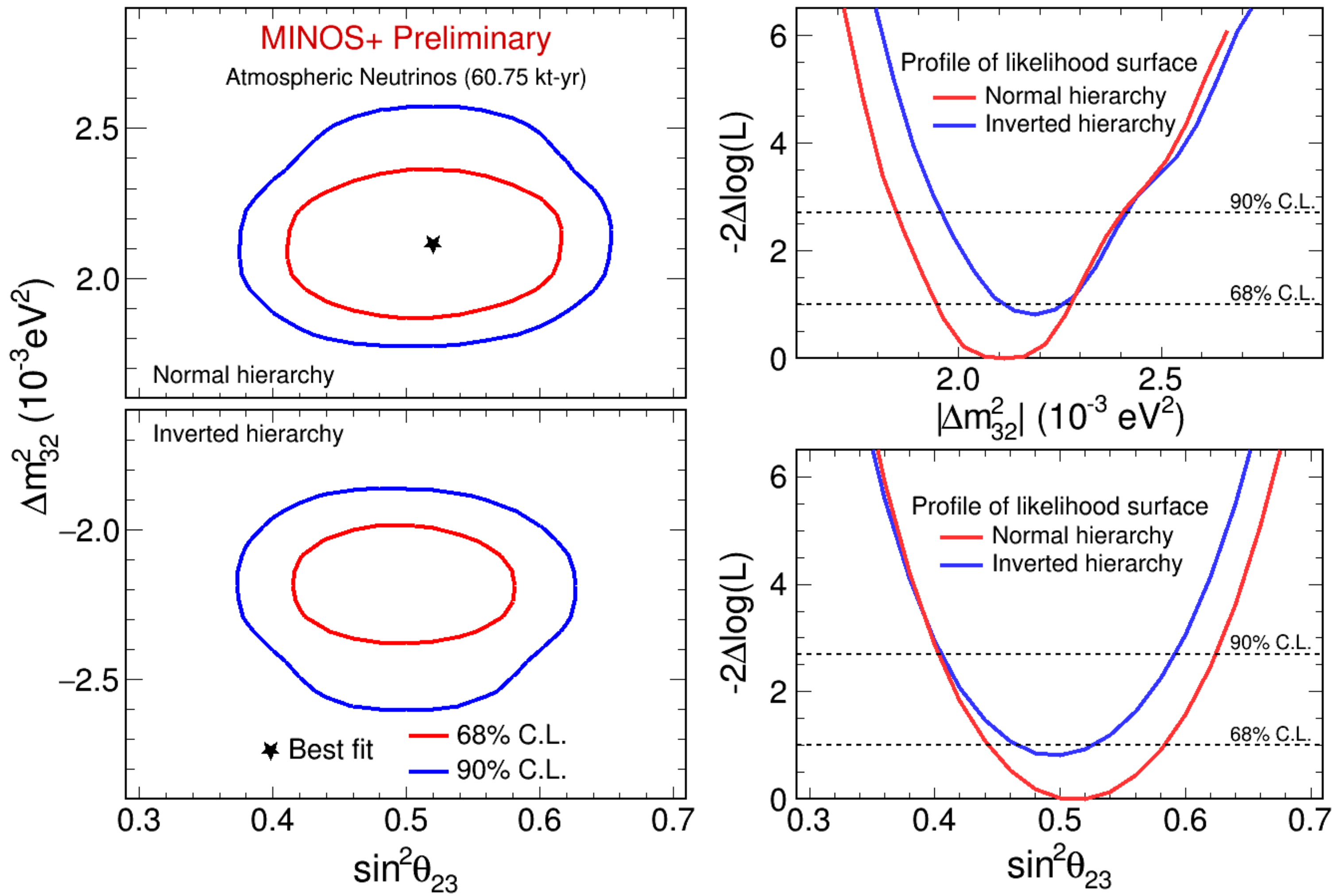
Atmospheric Data and Fit

- In the MINOS+ oscillation analysis, atmospheric neutrino data are binned as a function of reconstructed energy and zenith angle.
  - Sensitivity to Δm^2_{32} and $\sin^2\theta_{23}$ is complementary with accelerator data.
  - Additional limited sensitivity to mass hierarchy in MSW resonance region.

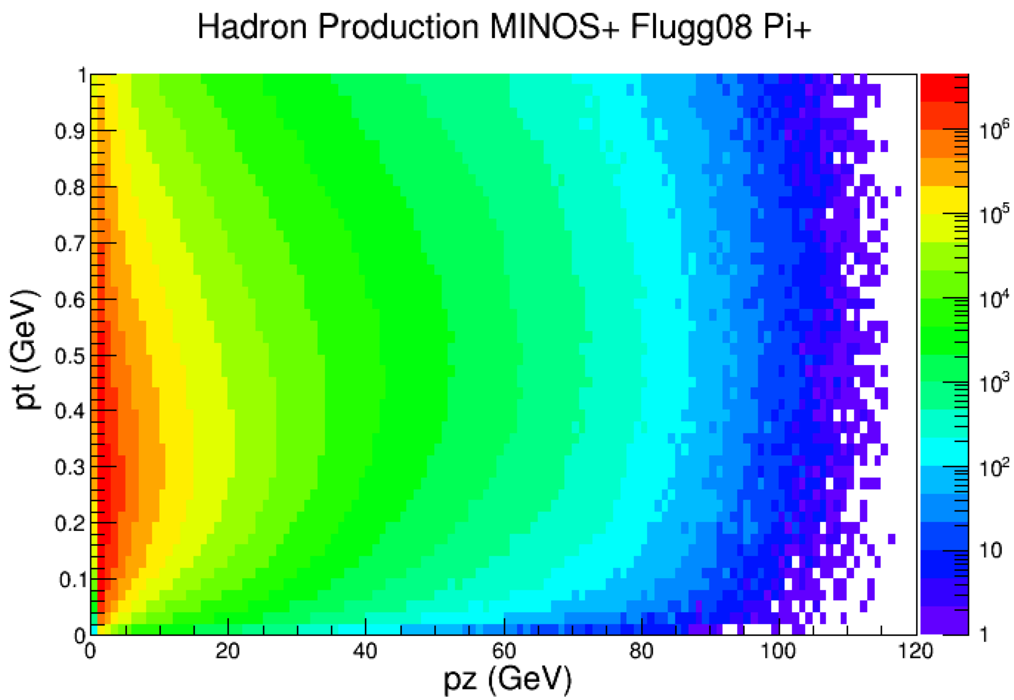


Atmospheric Data and Fit

- ◆ Results of oscillation fit to MINOS/MINOS+ atmospheric neutrino data:

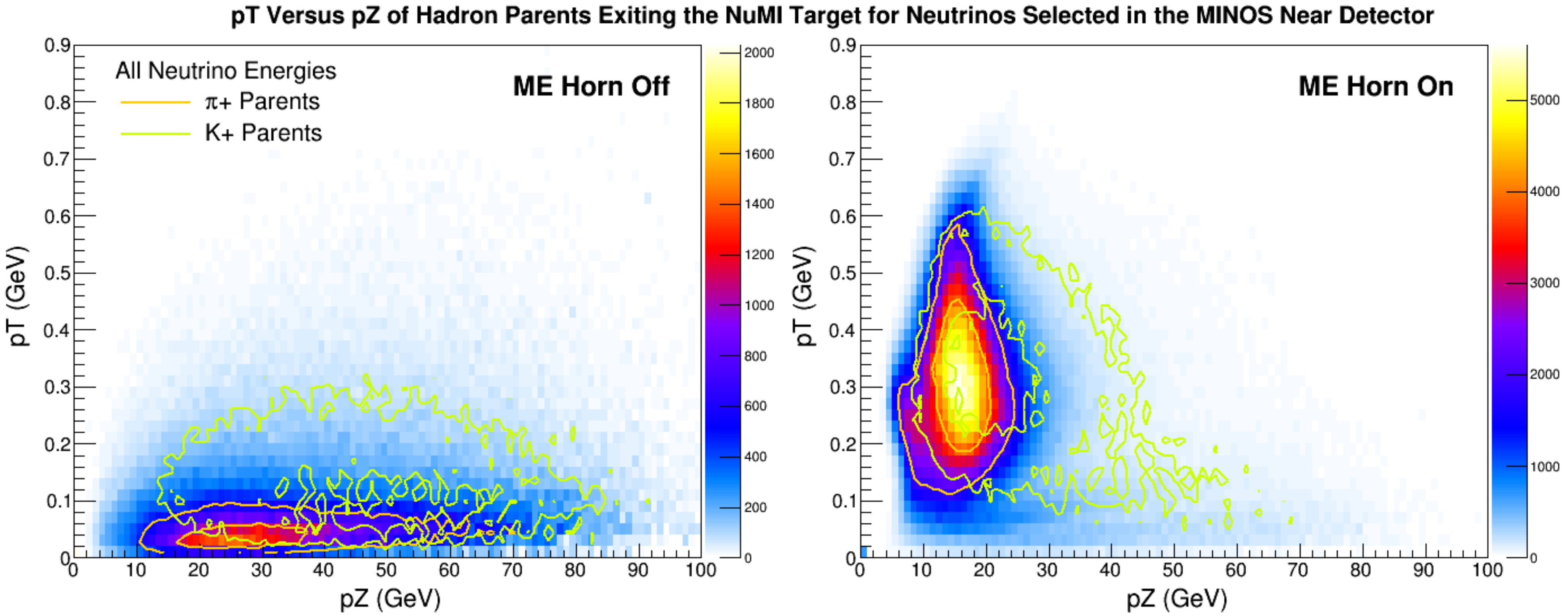


Beam Flux Estimation: Hadron Production

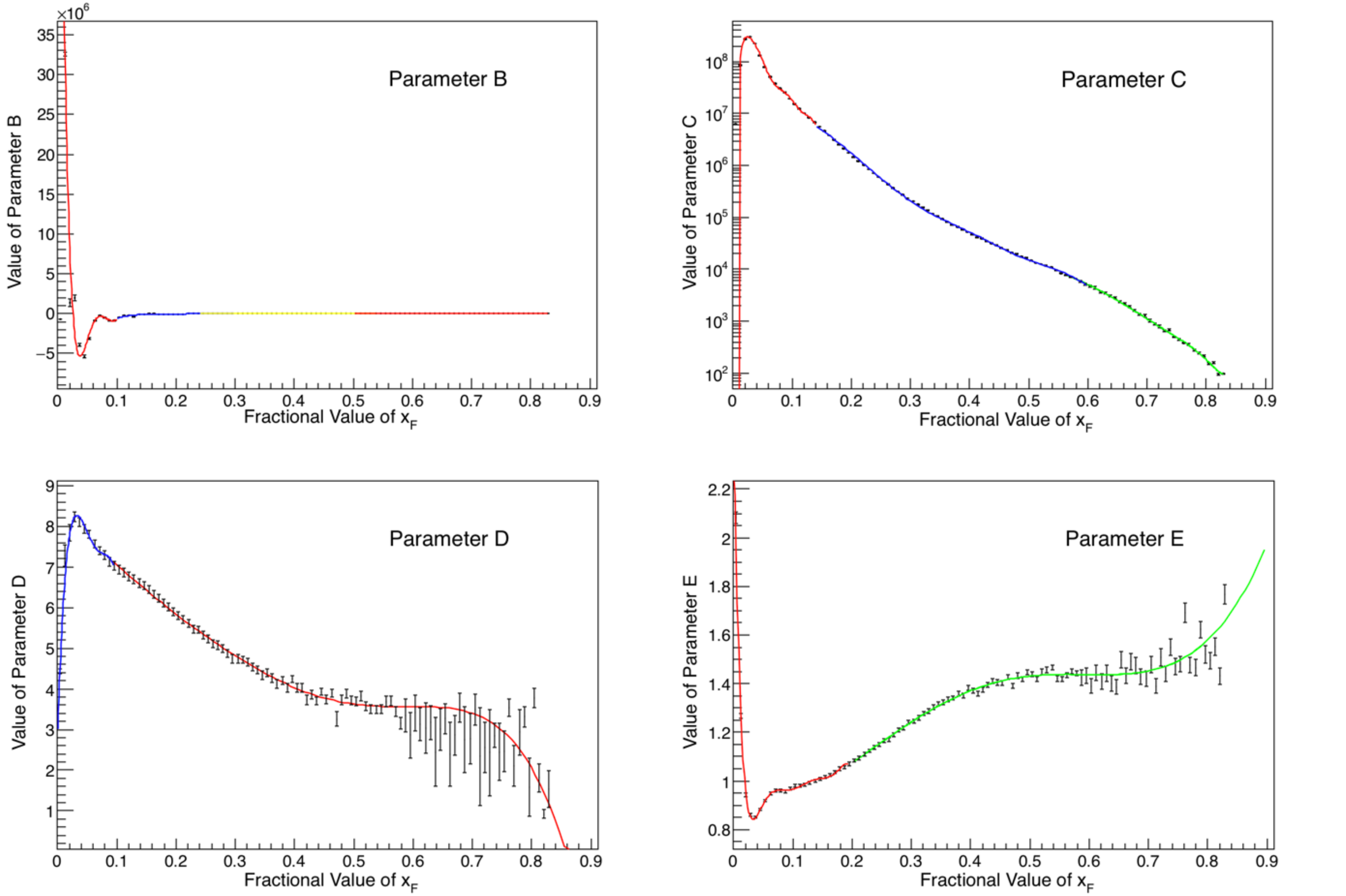


$$\frac{d^2N}{dx_F dp_T} = [B(x_F)p_T + C(x_F)p_T^2]e^{-D(x_F)p_T^{E(x_F)}}$$

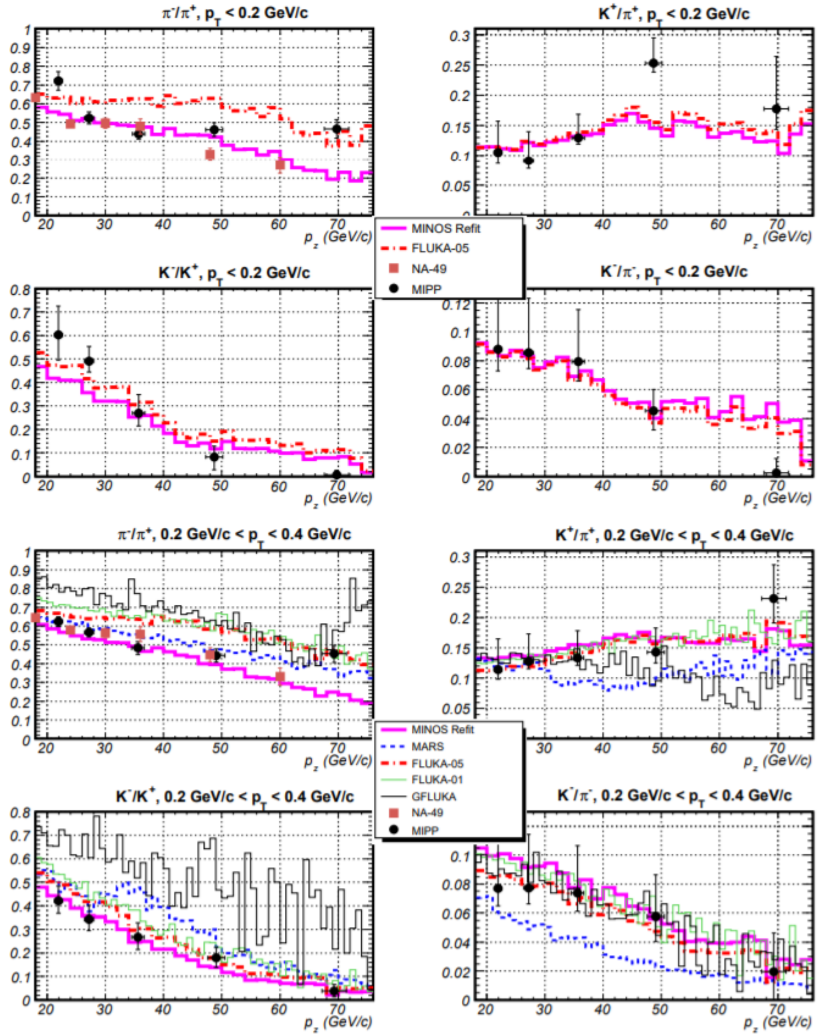
Beam Flux Estimation: Hadron Production



Beam Flux Estimation: Hadron Production



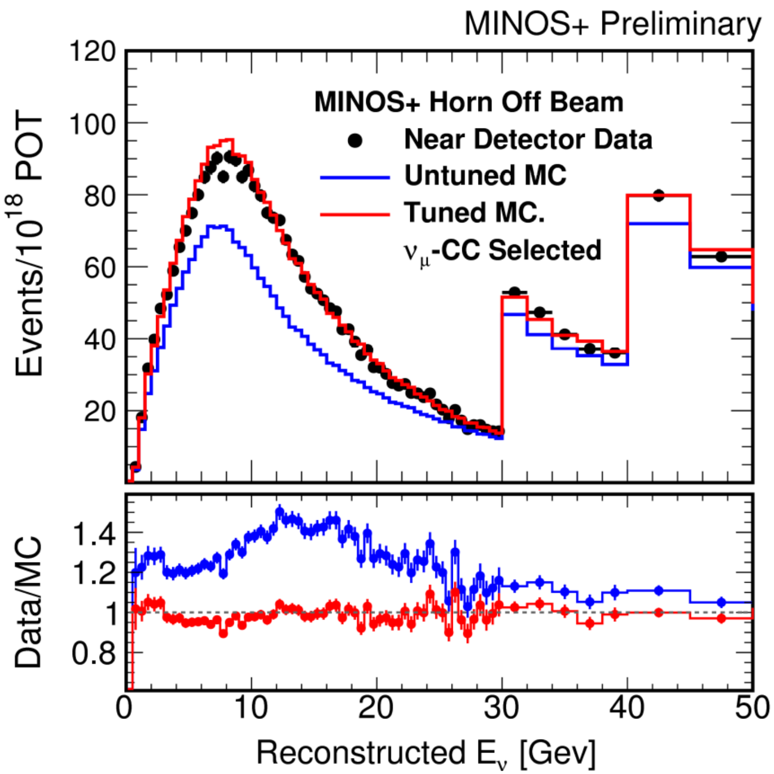
Beam Flux Estimation: Hadron Production



Beam Flux Estimation: Hadron Production

- ◆Standard analysis uses ND data to produce extrapolated FD predictions
- ◆Improving the beam flux estimate makes this technique more powerful
- ◆Parameterize hadron production for pions and translate to kaons using measured pion/kaon ratios
- ◆Warp parameterization to fit ND data with no focusing to isolate hadron production only

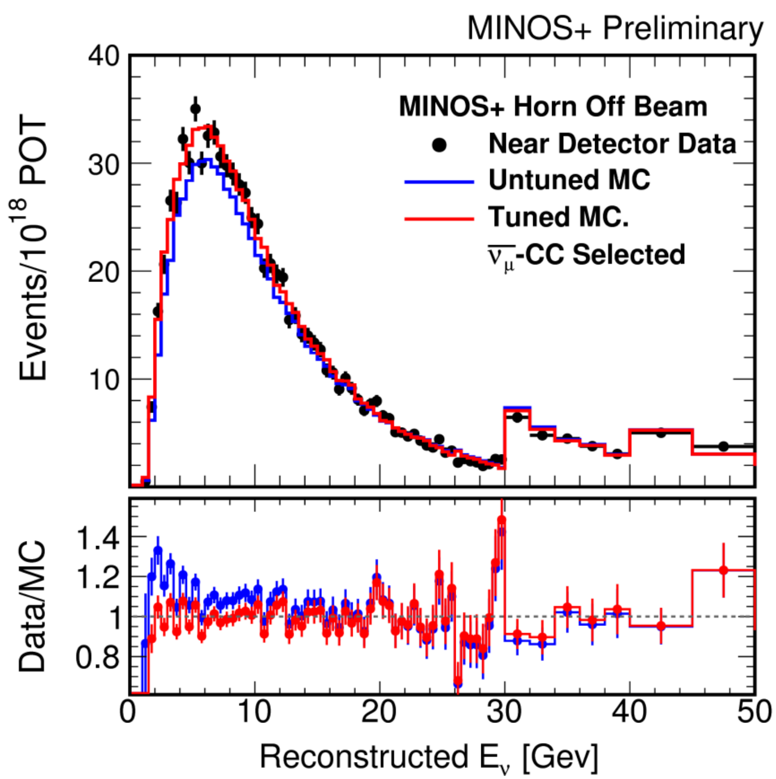
Neutrinos – Horn-off



Beam Flux Estimation: Hadron Production

- ND data provides a powerful constraint on beam flux
- Use samples with focusing horns off to isolate hadron production
- Fit empirical pion hadron production parameters for neutrinos and antineutrinos
- Transfer weights to kaons using measured pion/kaon ratios

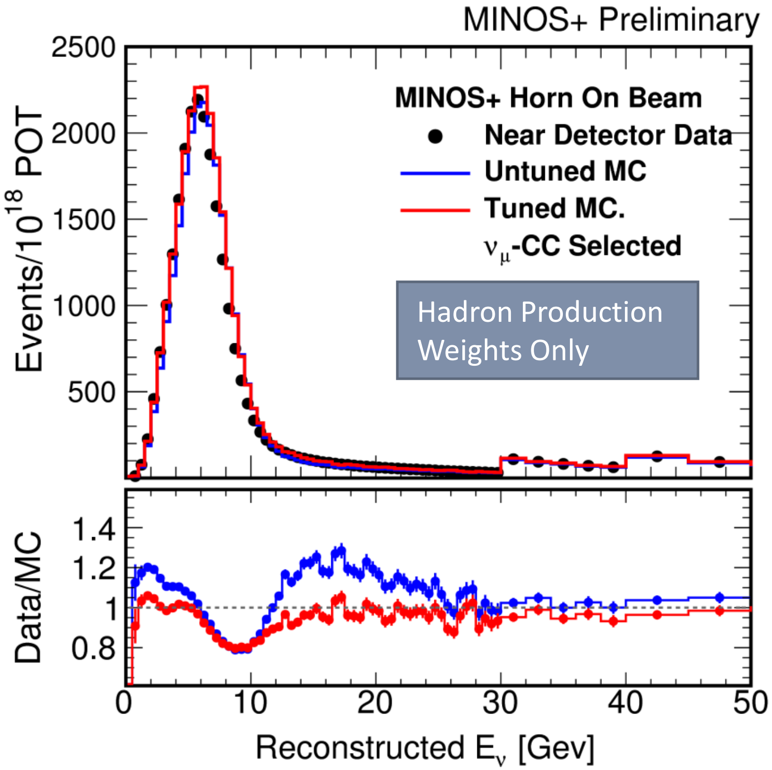
Antineutrinos – Horn-off

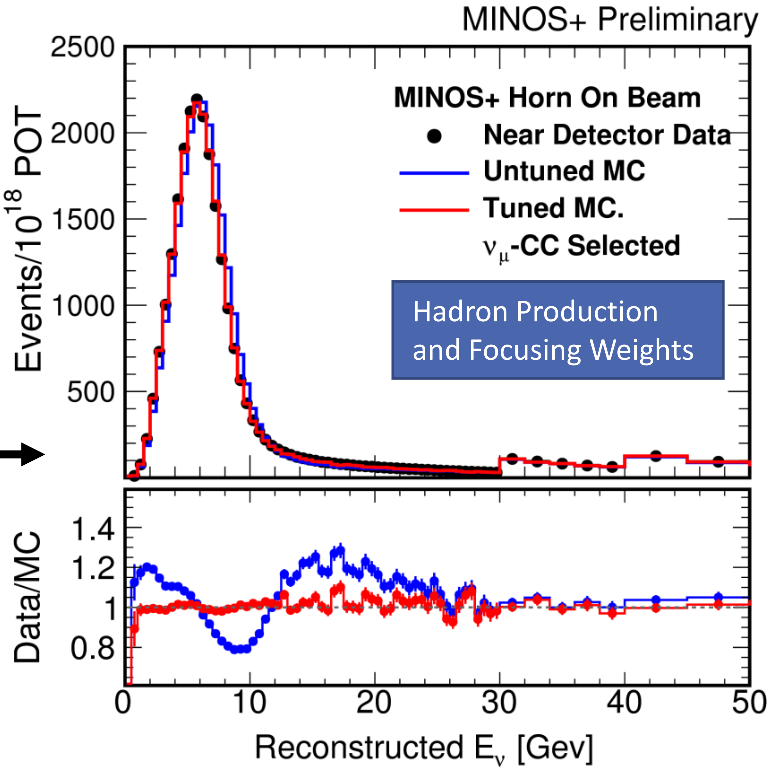


Beam Flux Estimation: Focusing

- ◆Apply hadron production weights to sample with focusing on
- ◆Fit for focusing effects

Neutrinos





Beam Flux Estimation: Focusing

- ◆Apply hadron production weights to sample with focusing on
- ◆Fit for focusing effects

Antineutrinos