Recent Results from MINOS and MINOS+

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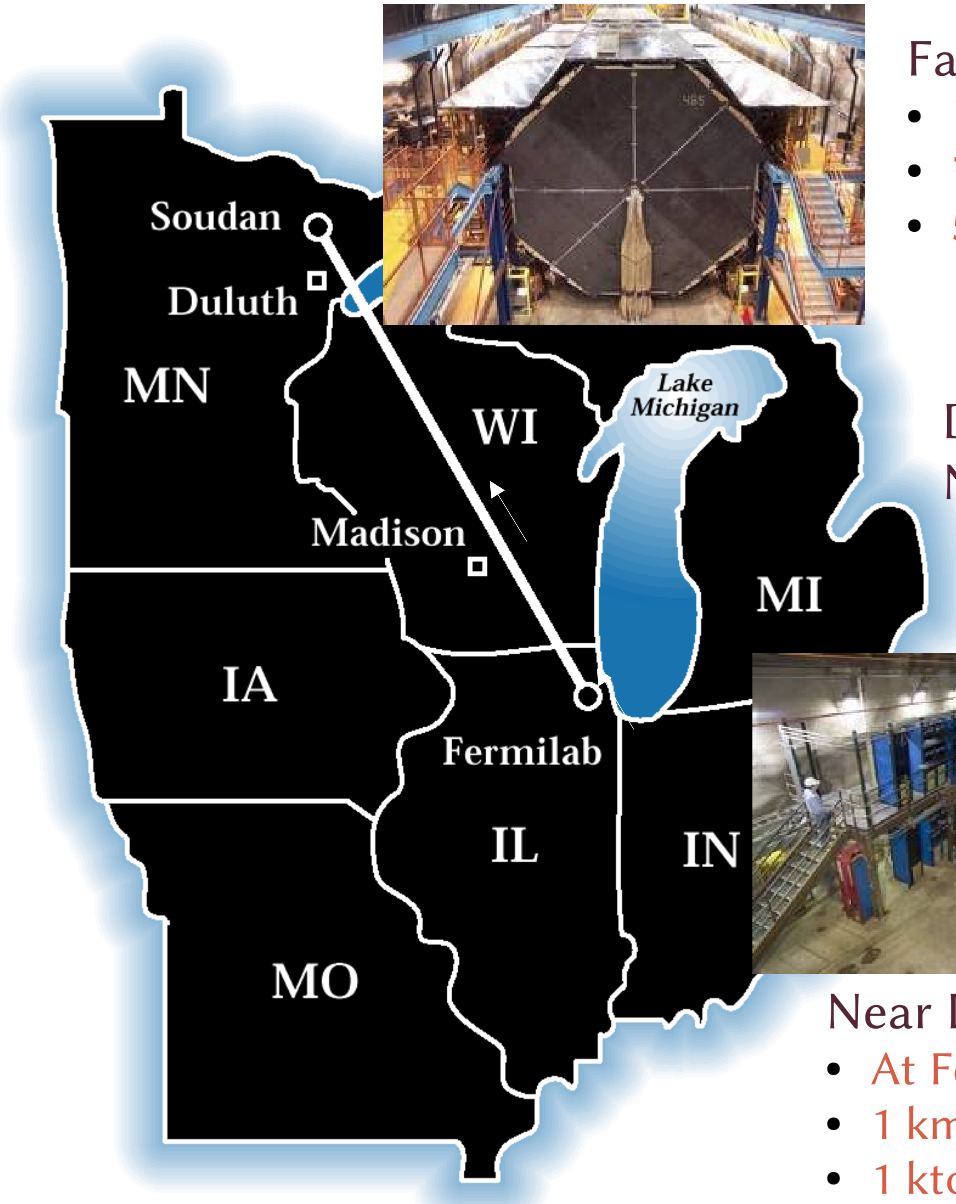
Outline

- MINOS and MINOS+ overview
- **New:** Final Three-flavor oscillation results
  - Full MINOS and MINOS+ ν_μ and $\bar{\nu}_\mu$ beam samples
    - Updated with final year of beam data
  - Full MINOS and MINOS+ atmospheric samples
    - Updated with final three years of atmospheric data
  - MINOS ν_e appearance sample
- **New:** Search for sterile neutrinos
  - ν_μ-CC and NC disappearance
    - Full MINOS beam sample
    - First two years of MINOS+
  - New two-detector joint fit
- Additional Beyond the Standard Model searches
- Conclusions

MINOS and MINOS+ Overview

- MINOS and MINOS+ were designed to study neutrino oscillations over long baselines using two detectors that are:
  - Iron-scintillator tracking calorimeters to contain muons
  - Functionally identical for systematic uncertainty reduction
  - Magnetized for sign selection and energy estimation



Far Detector
- Underground in Soudan mine
- 735 km from target
- 5.4 kton mass

Detectors are on-axis for NuMI neutrino beam

Near Detector
- At Fermilab
- 1 km from target
- 1 kton mass

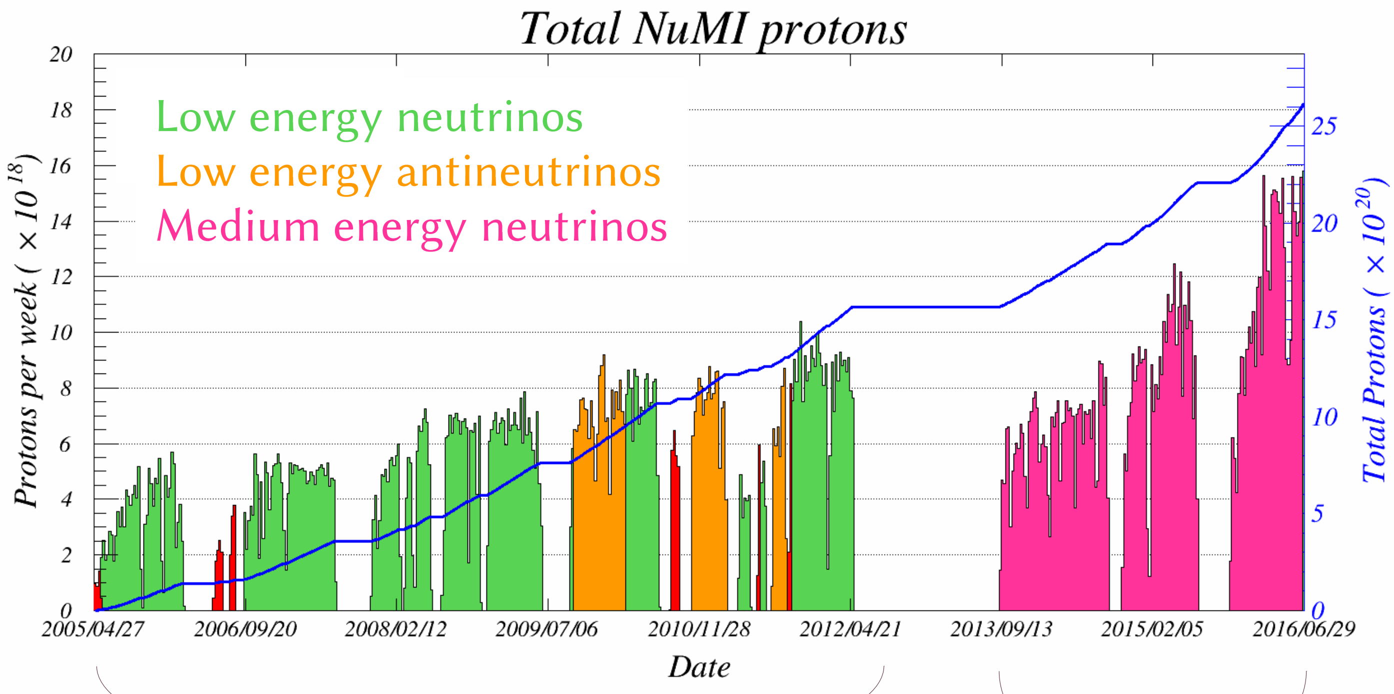
MINOS and MINOS+ Beam

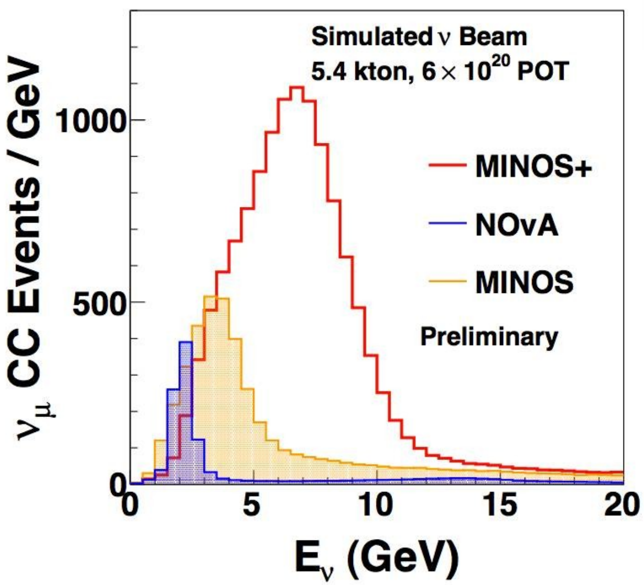
MINOS:

- ~3 GeV peak energy
- Study oscillations at atmospheric frequency

MINOS+:

- ~7 GeV peak energy
- Constrain deviations from 3 flavor paradigm





MINOS era:

- 10.56×10^{20} POT (neutrino-mode)
- 3.36×10^{20} POT (antineutrino-mode)

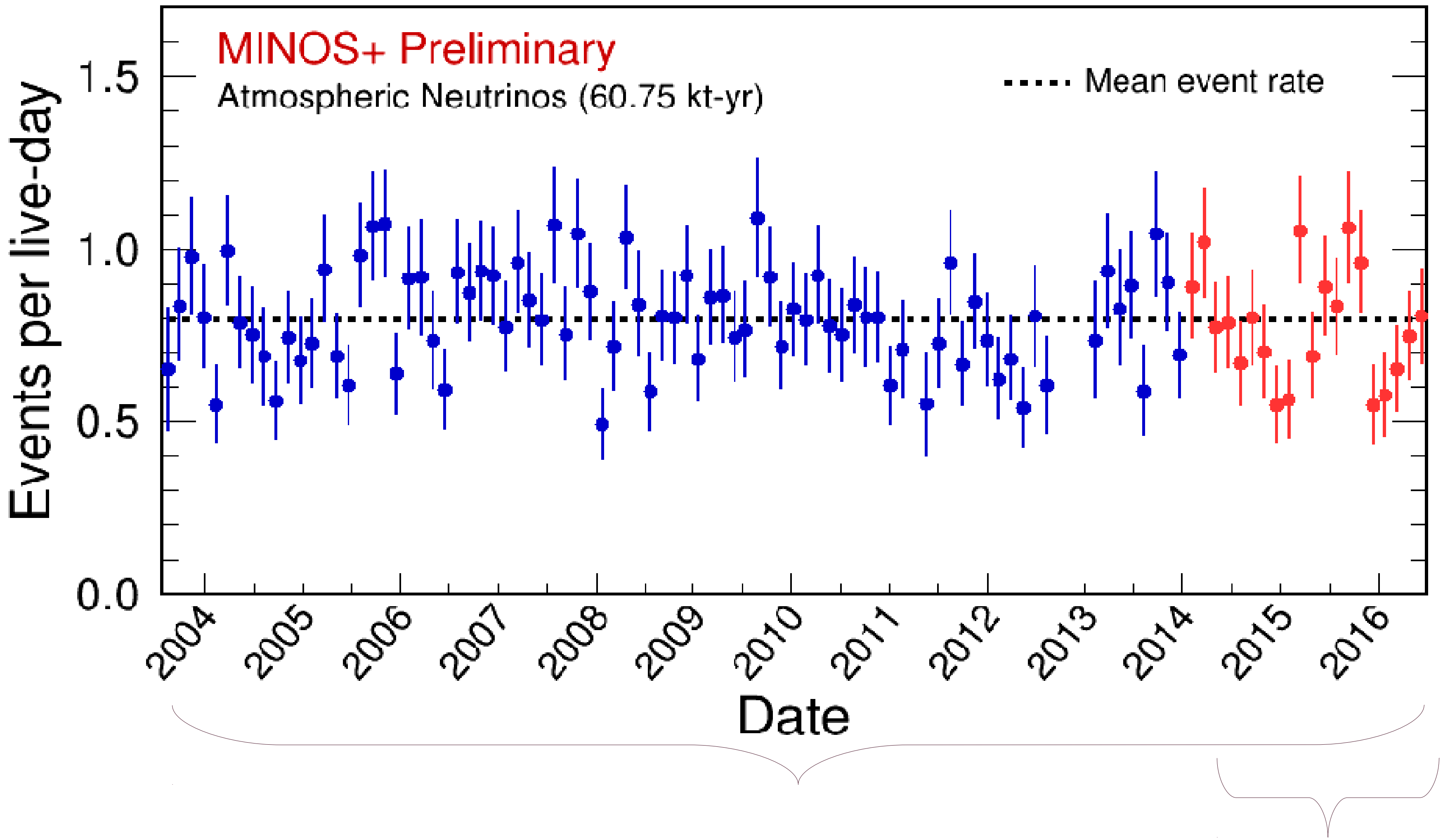
MINOS+ era:

- 9.69×10^{20} POT

Total:

- $\sim 25 \times 10^{20}$ POT in 11 years of running

MINOS and MINOS+ Atmospheric Neutrinos



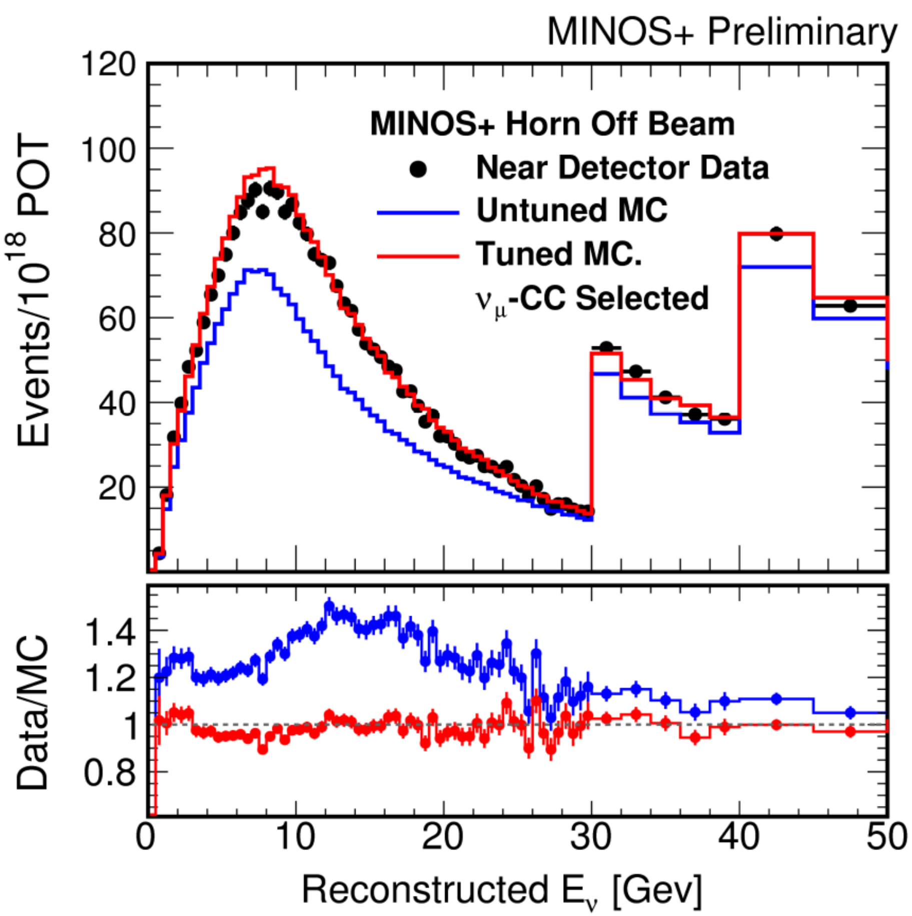
Full dataset (2003 – 2016): 60.8 kt-yr

New:
12.1 kt-yr (~20% of total sample)

Three-Flavor Oscillation Analysis

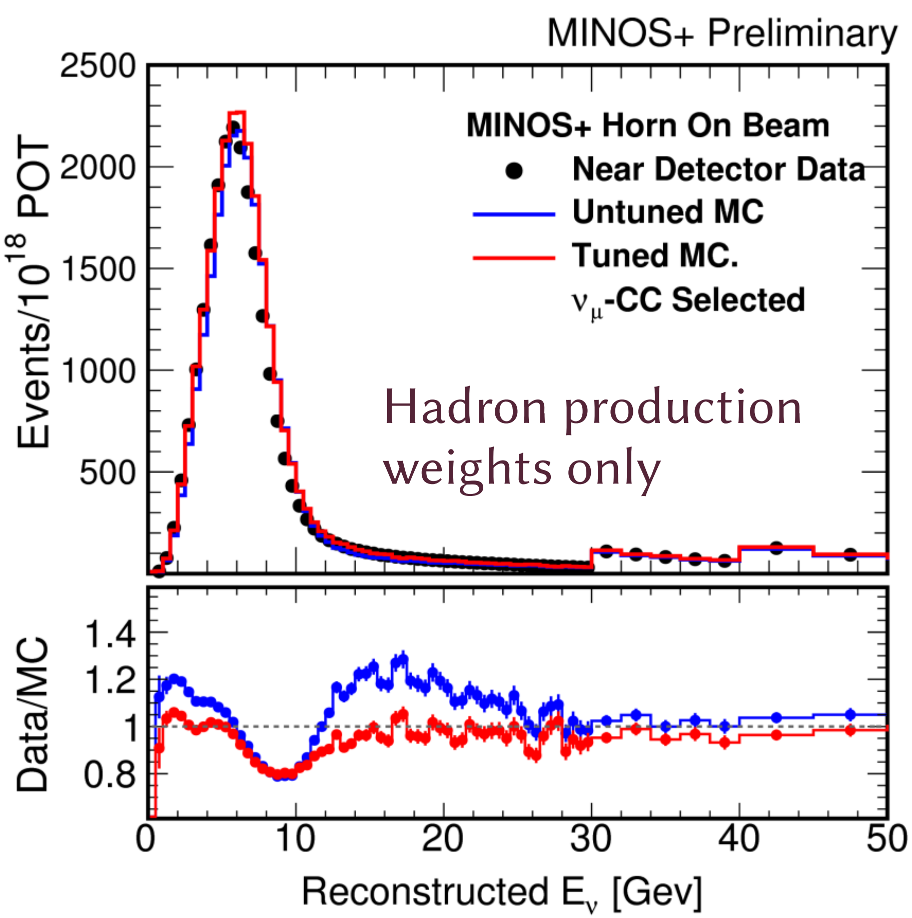
Beam Flux Estimation: Hadron Production

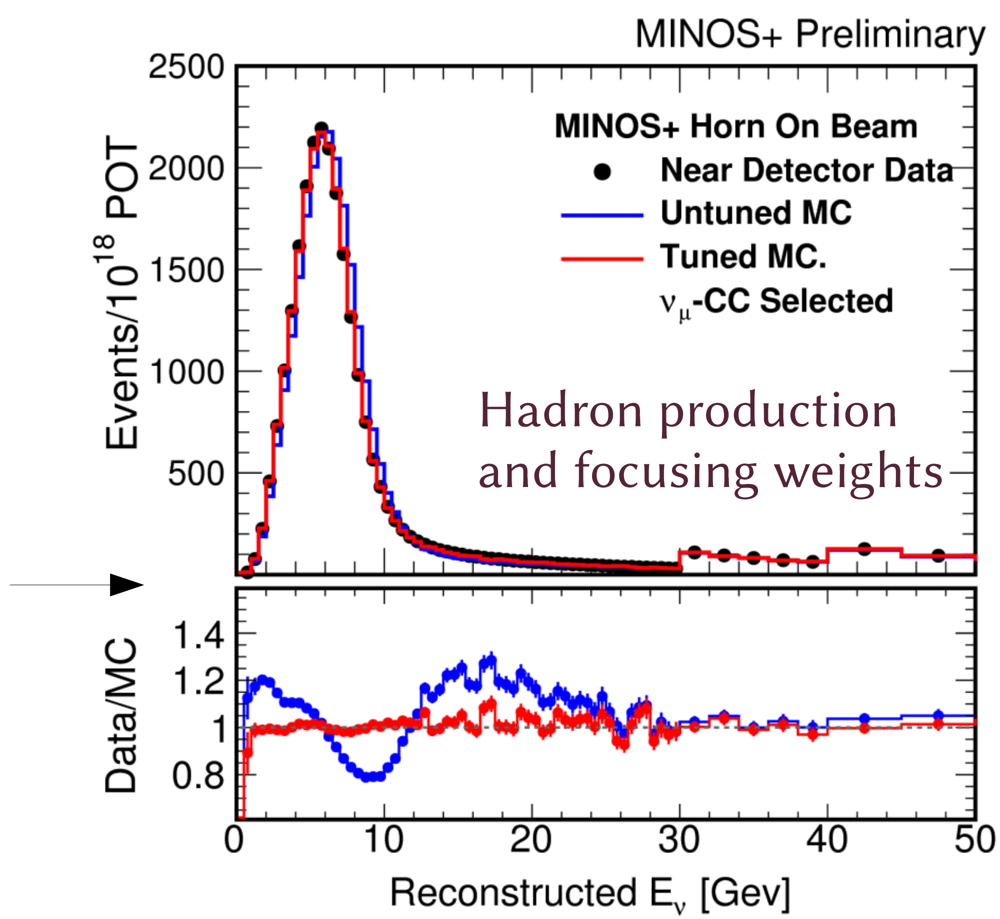
- Standard analysis uses ND data to produce extrapolated FD predictions
- Improving the beam flux estimate makes this technique more powerful
- Parameterize hadron production for pions and translate to kaons using measured pion/kaon ratios
- Warp parameterization to fit ND data with no focusing to isolate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



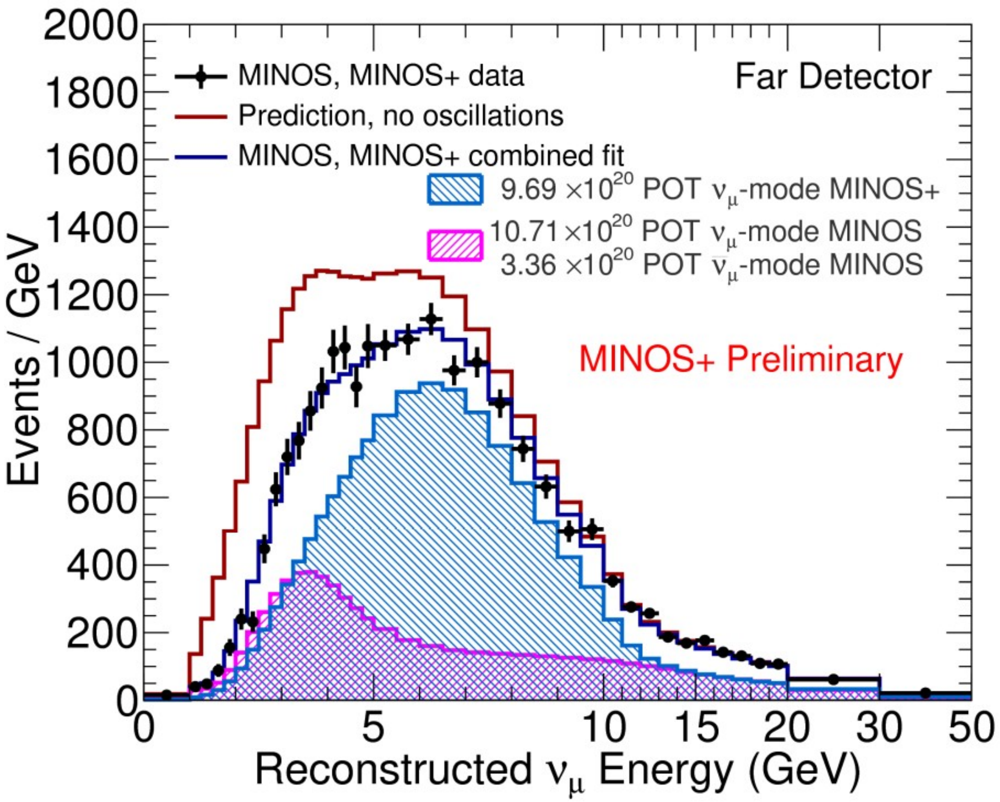
Beam Flux Estimation: Focusing

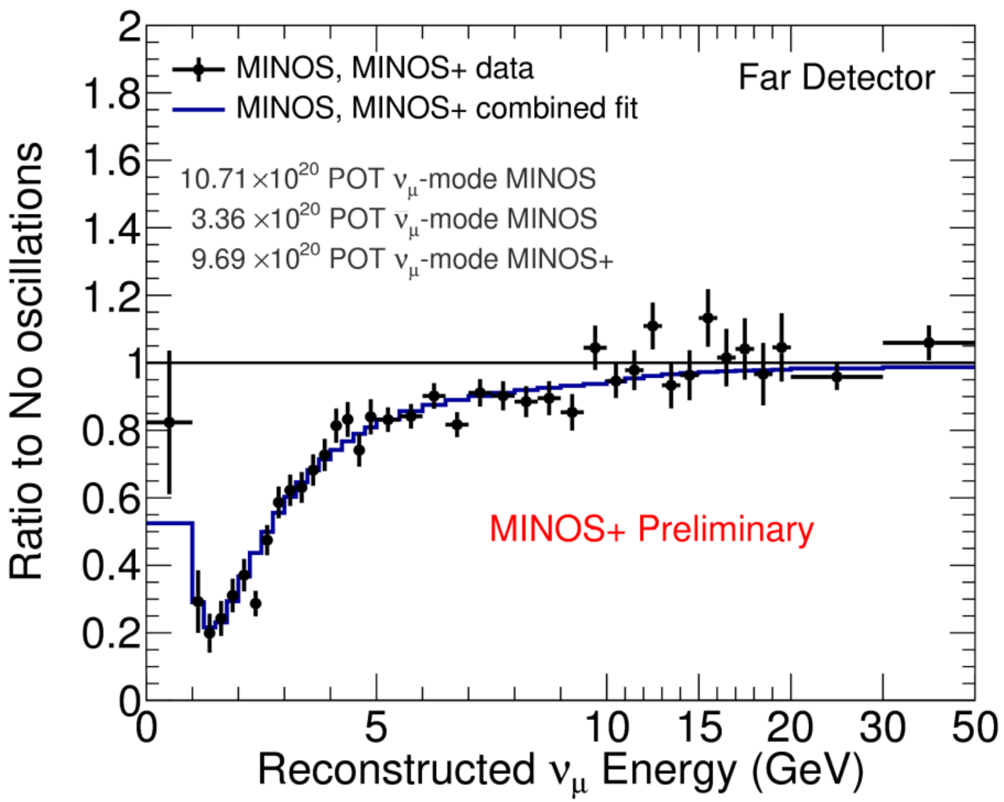
- Hadron production and focusing effects are separable
  - Apply hadron production weights from focusing off sample to sample with focusing on
  - Fit for focusing effects
- Poster: Wednesday #89, A. Holin





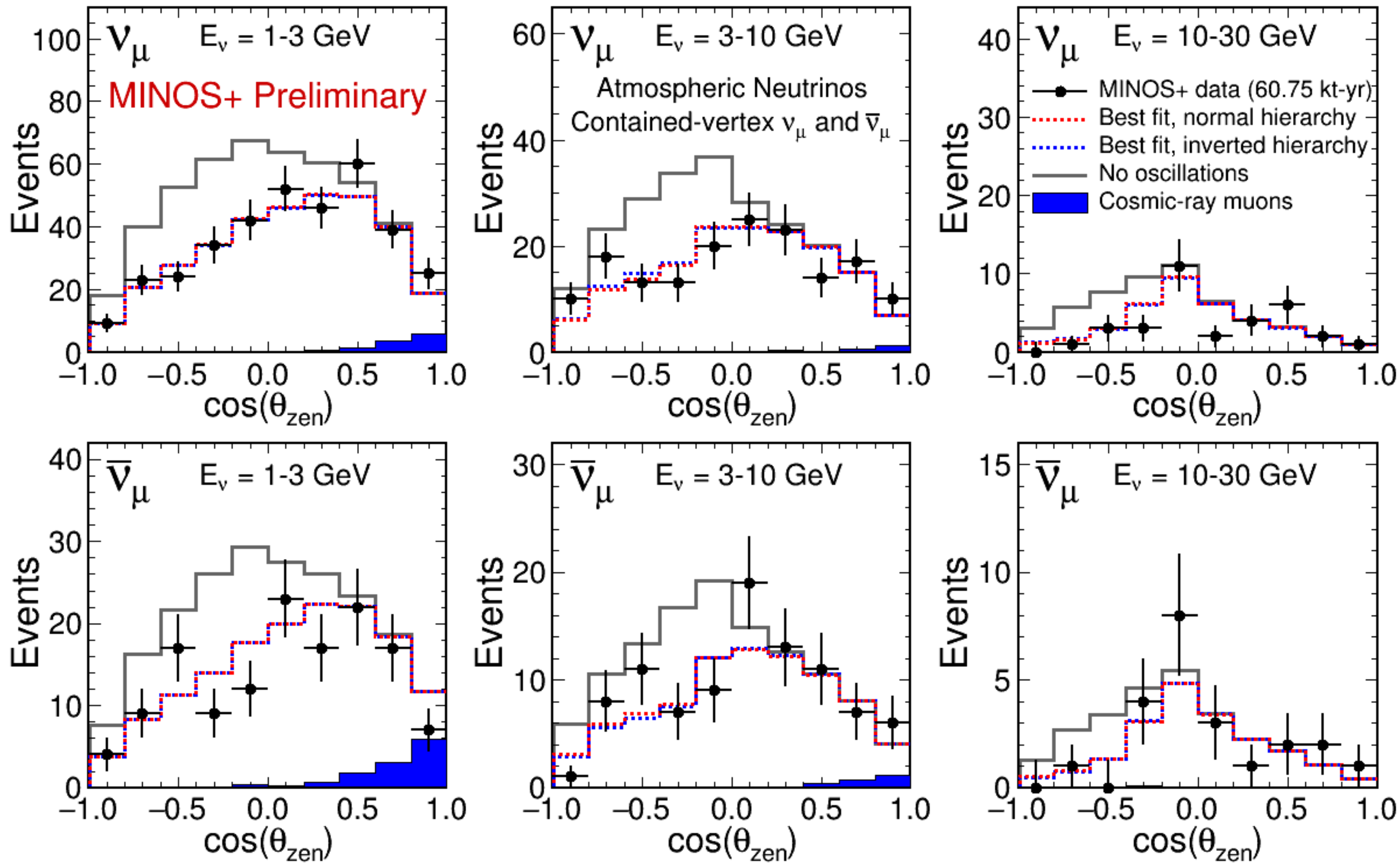
Far Detector Beam Data





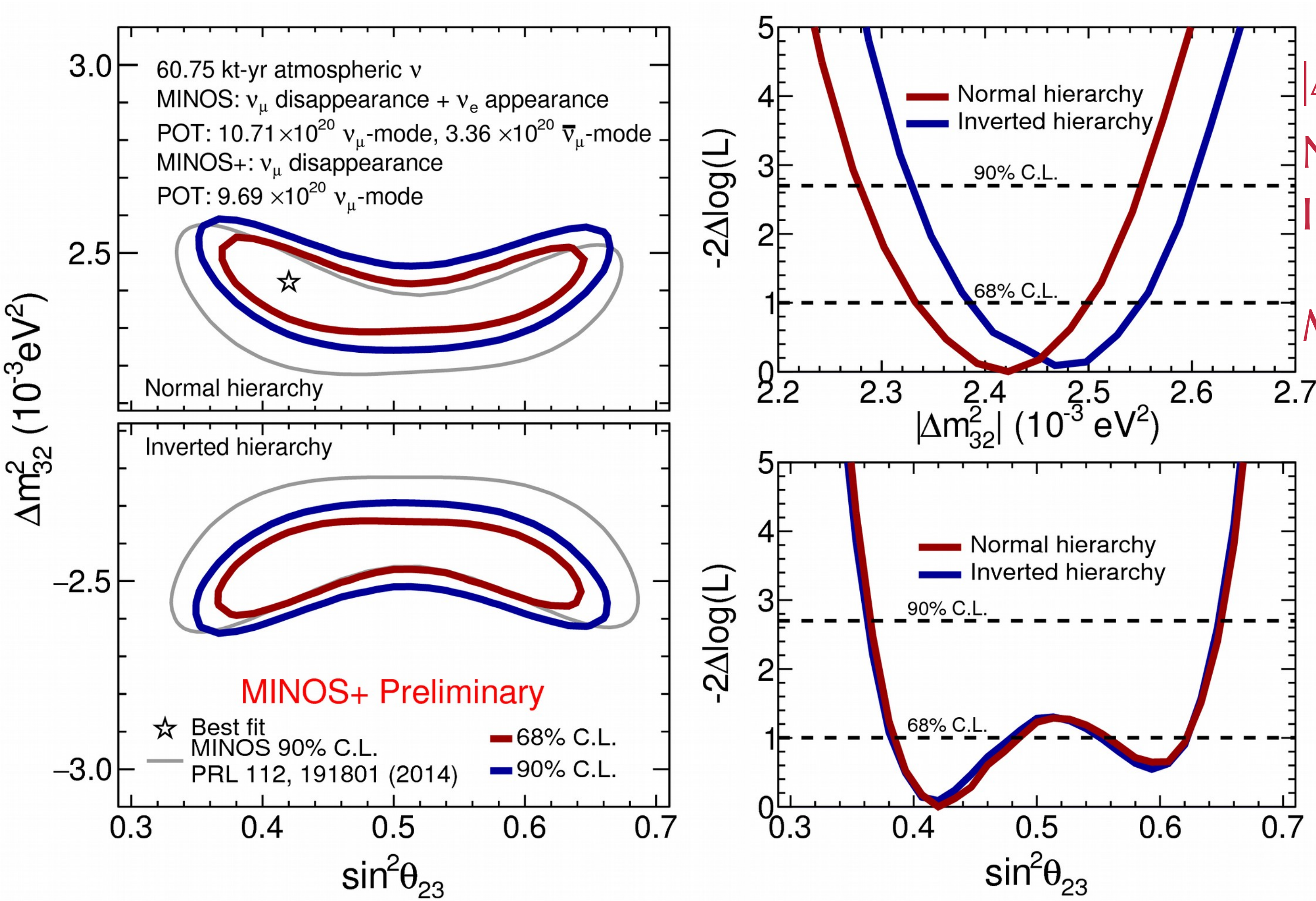
- MINOS and MINOS+ probe muon-neutrino disappearance over a broad range of energies
- Consistency with three flavor prediction tightly constrains alternate oscillations hypotheses

Far Detector Atmospheric Data



- Fit in bins of $\cos(\theta_{zen})$ and energy
- Magnetic field helps separate atmospheric neutrino and antineutrino samples for extra mass hierarchy discrimination
- Complements beam neutrino samples

Combined Fit Results



$|\Delta m^2_{32}|$ 90% C.L. intervals

NH: $(2.28 - 2.55) \times 10^{-3}$ eV^2

IH: $(2.33 - 2.60) \times 10^{-3}$ eV^2

Measured to ~3.5% at 68% C.L.

$\sin^2\theta_{23}$ 90% C.L. interval

0.36 – 0.65

Best fit

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

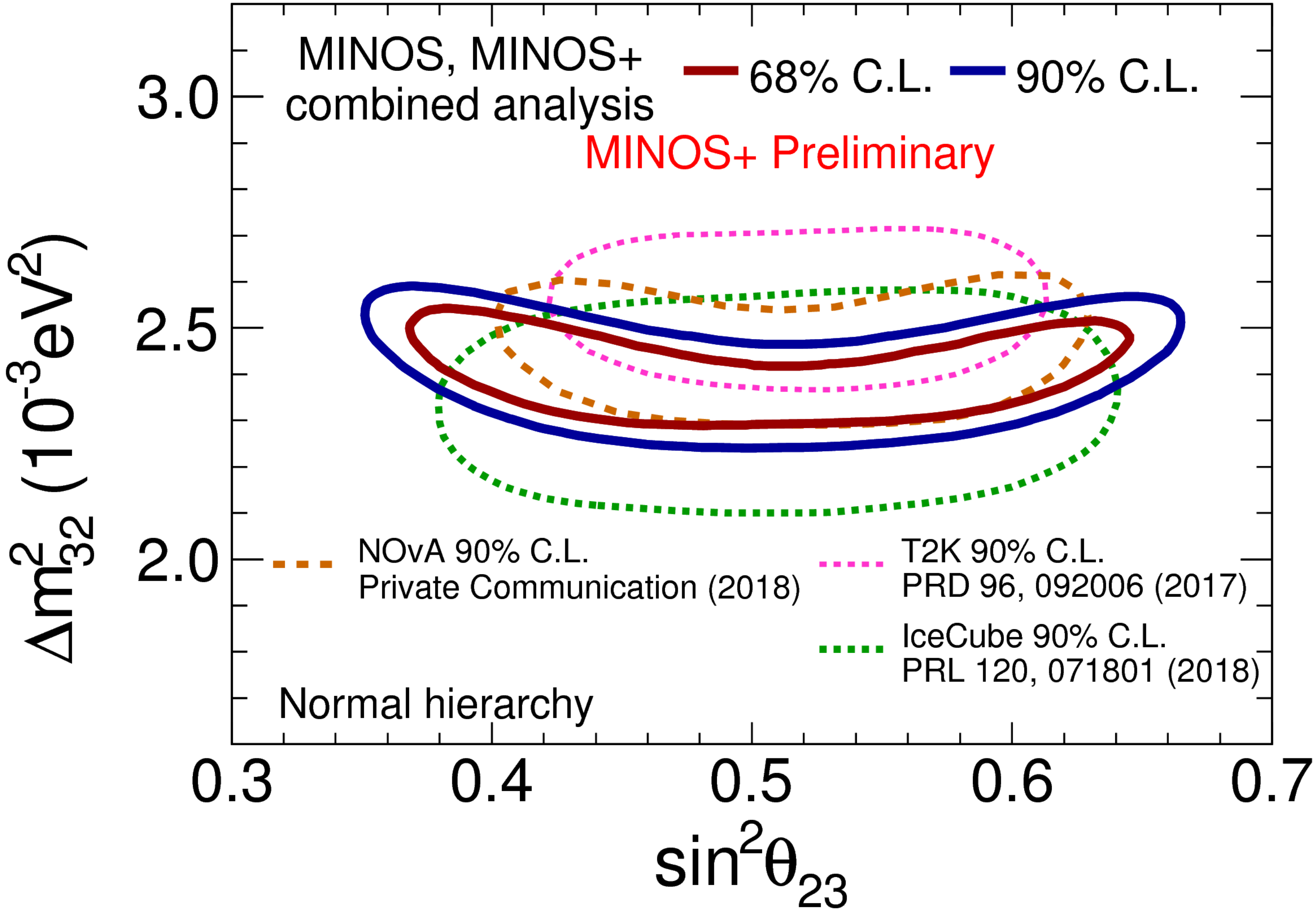
$\sin^2\theta_{23} = 0.42$

Exclusion of maximal mixing: 1.1σ

Preference for lower octant: 0.8σ

Preference for normal hierarchy: 0.2σ

Comparison with Other Experiments



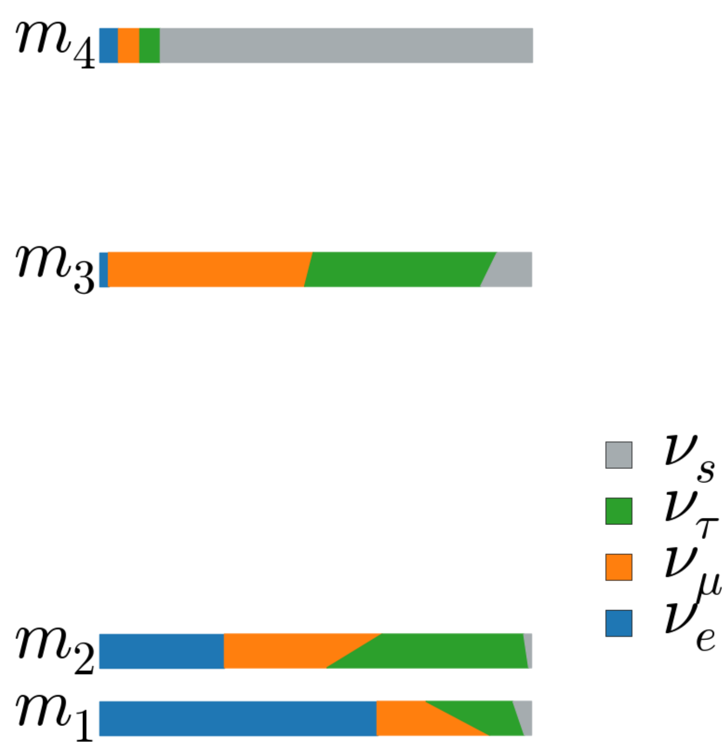
Poster: Wednesday #53, T. Carroll

Sterile Neutrino Search

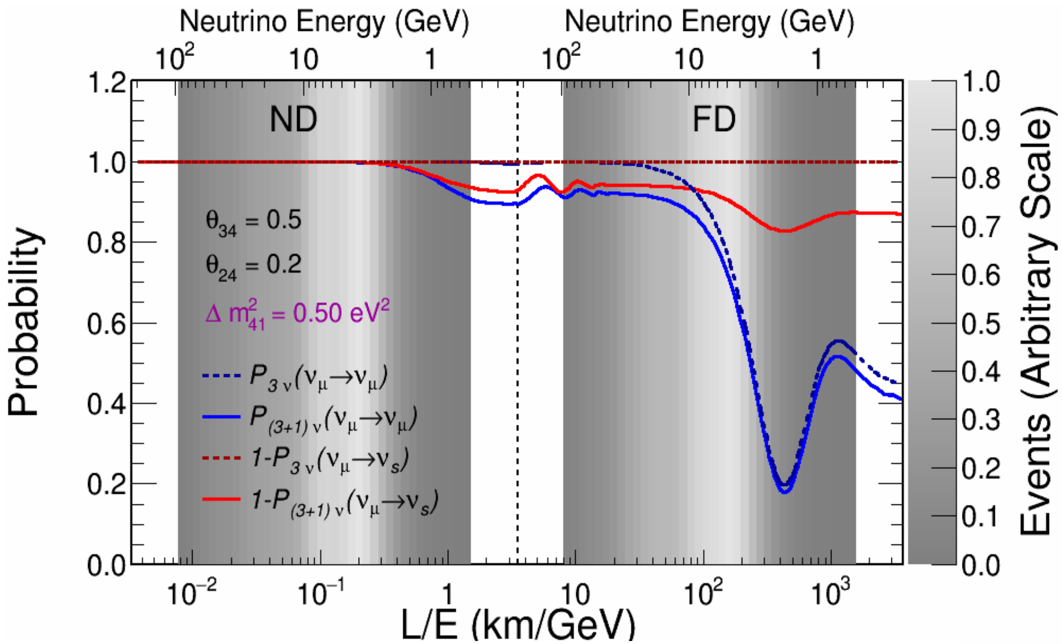
3+1 Model

- Anomalous short-baseline results consistent with new mass state and new sterile flavor
- Expand PMNS matrix from 3x3 ⟶ 4x4
- 6 new parameters
  - One mass scale (Δm^2_{41})
  - Three mixing angles (θ_{14}, θ_{24}, θ_{34})
  - Two CP-violating phases (δ_{14}, δ_{24})
- Search in two modes
  - Neutral current disappearance
    - NC rate is insensitive to 3 flavor mixing
    - Sterile neutrinos do not couple to the Z boson
    - Sensitive to Δm^2_{41}, θ_{24}, θ_{34}
  - ν_μ charged current disappearance
    - Three flavor oscillations are modulated by the higher frequency sterile oscillations
    - Sensitive to Δm^2_{41} and θ_{24}

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



4-Flavor Oscillations

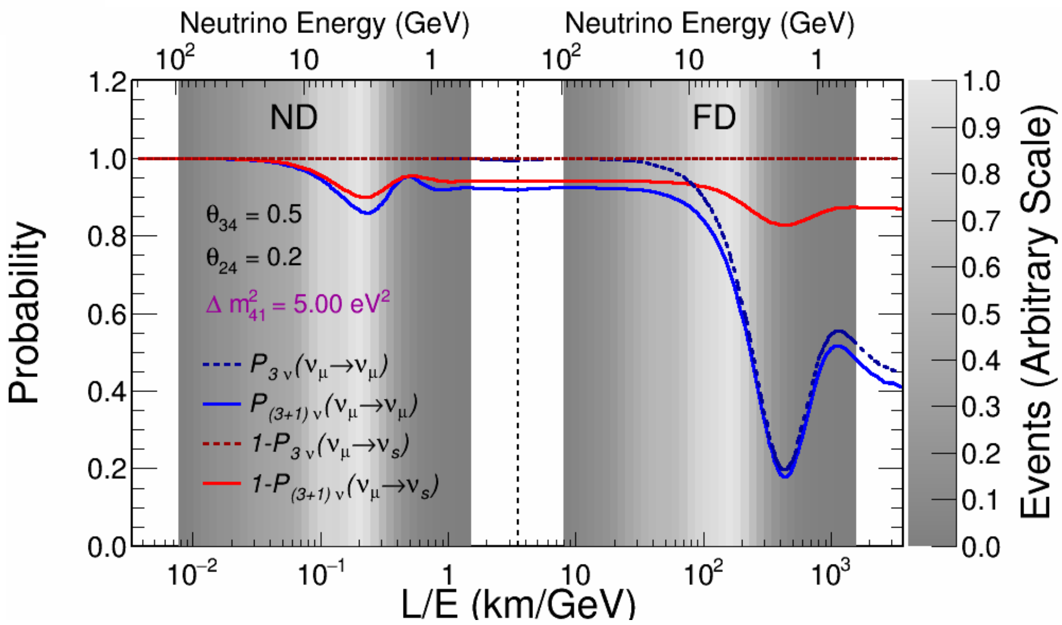


Small Δm^2_{41}:

- Oscillations at high energies in the FD
- No oscillation at the ND

Large Δm^2_{41}:

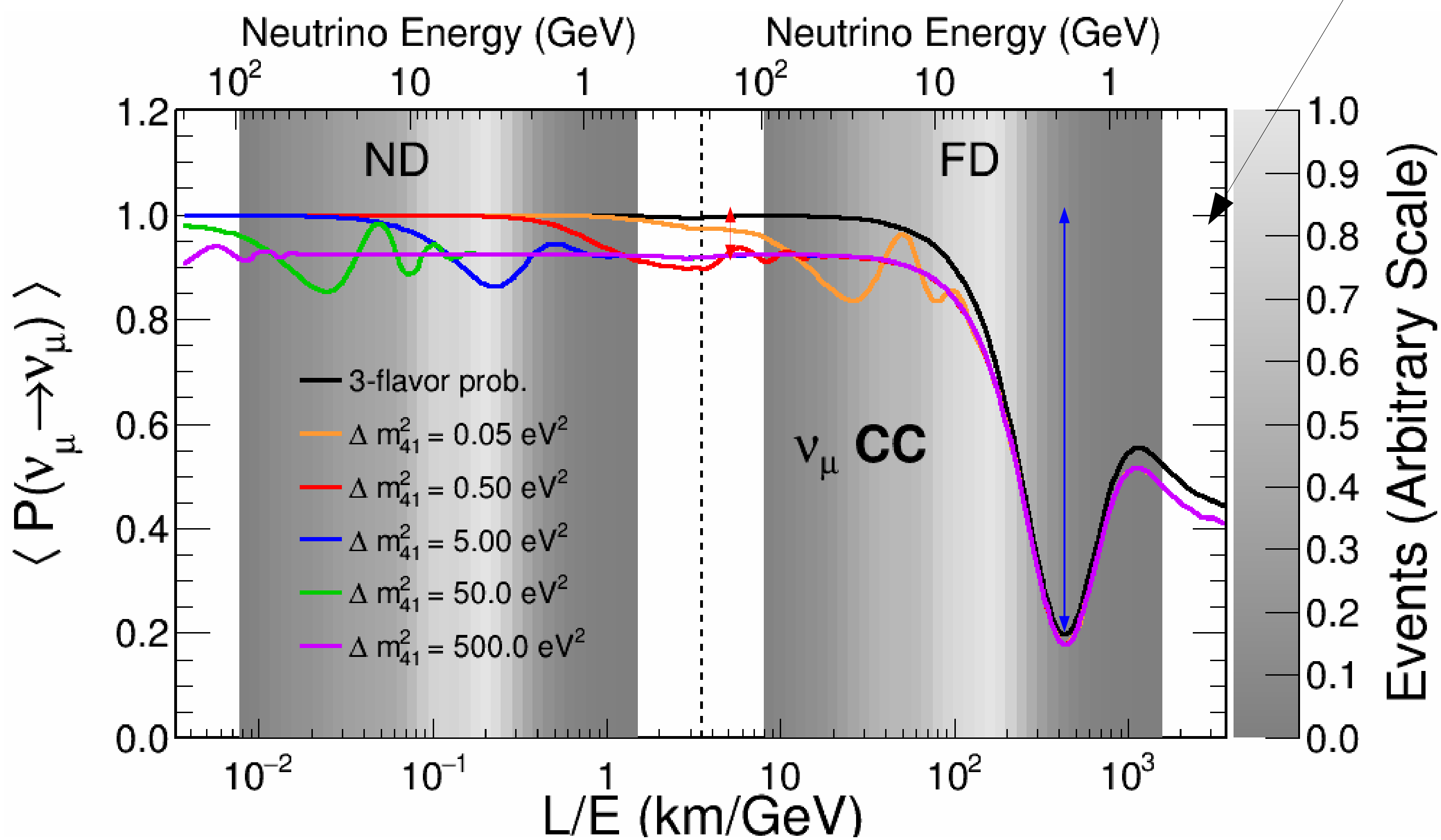
- Due to finite energy resolution, rapid oscillations at the FD average out
- Large oscillations at the ND



Oscillations at Very Large Δm^2_{41}

Interplay between shape and normalization gives strong constraints even at very large Δm^2_{41}

Independent of Δm^2_{41}



Rapid oscillation regime causes normalization shifts

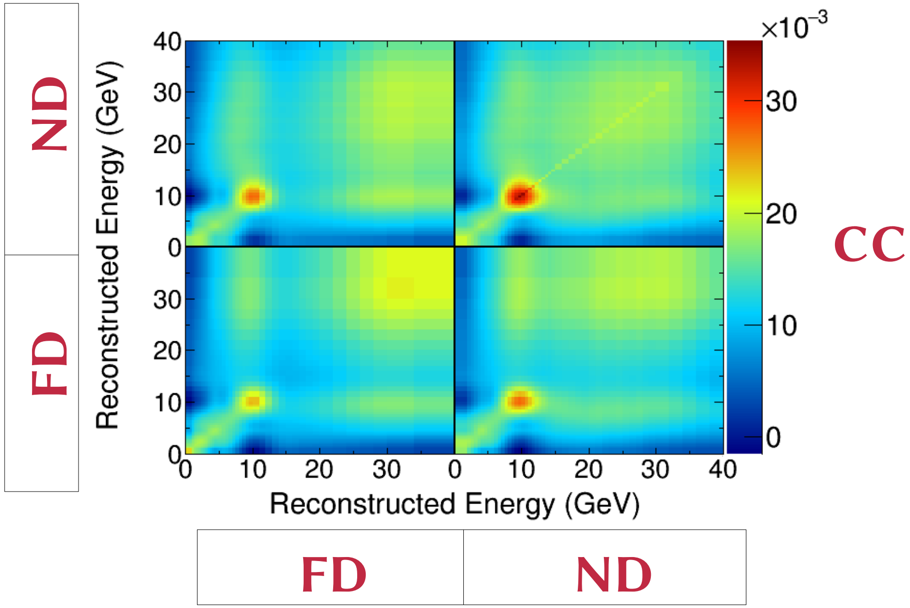
$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \cos 2\theta_{24} \sin^2 \Delta_{31} - \sin^2 2\theta_{24} \sin^2 \Delta_{41}$$

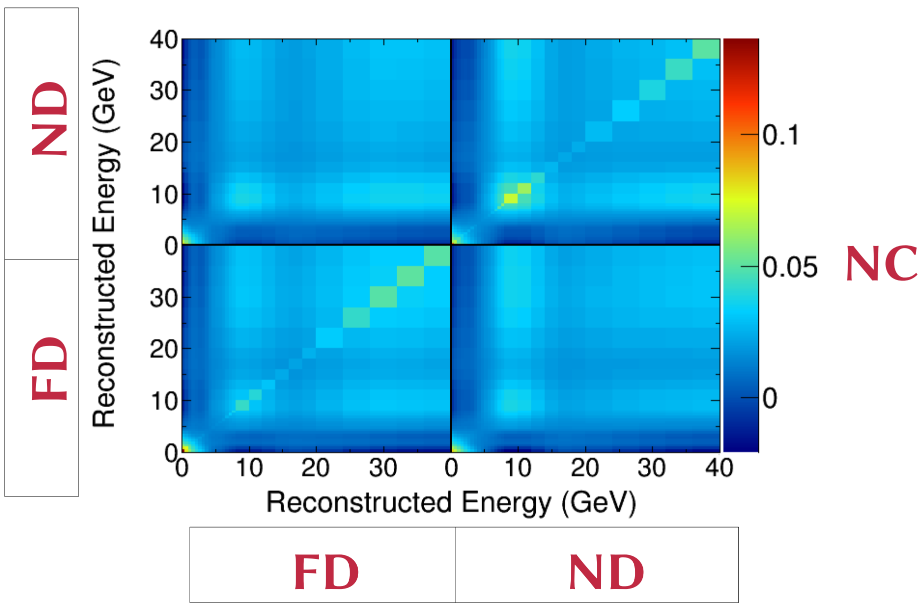
Already constrained by near-maximal mixing

Analysis Strategy

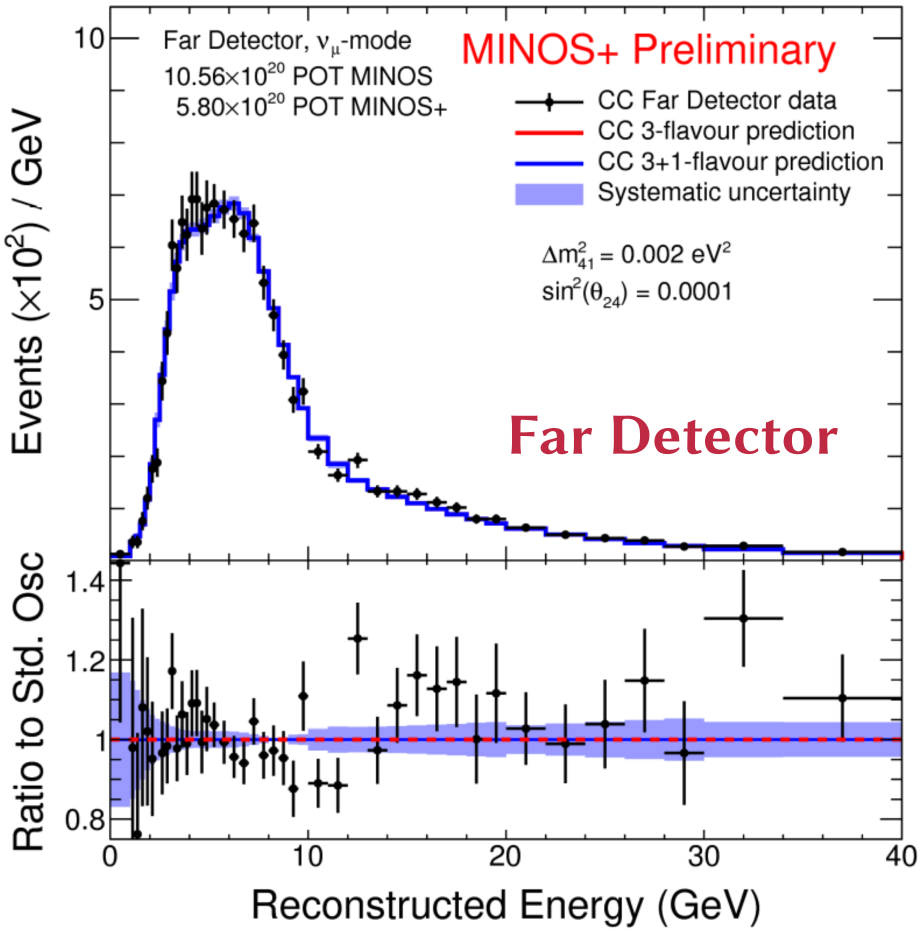
- To handle oscillations at many scales, analysis treats Near and Far Detectors on equal footing
  - Replace ND beam constraint from three-flavor analysis with flux estimate derived from a method using only hadron production experiment data developed by MINERvA
- Joint fit for ν_μ charged current and neutral current disappearance in Near and Far Detectors
  - Uses full statistical power of Near Detector, unlike the Far-to-Near ratio dominated by FD statistics
- Encode correlations due to systematic uncertainties between energy bins and detectors with a covariance matrix
  - 26 systematic uncertainties considered
- Minimize covariance-matrix-based χ^2 function to allow for a high degree of cancellation of correlated shape uncertainties:

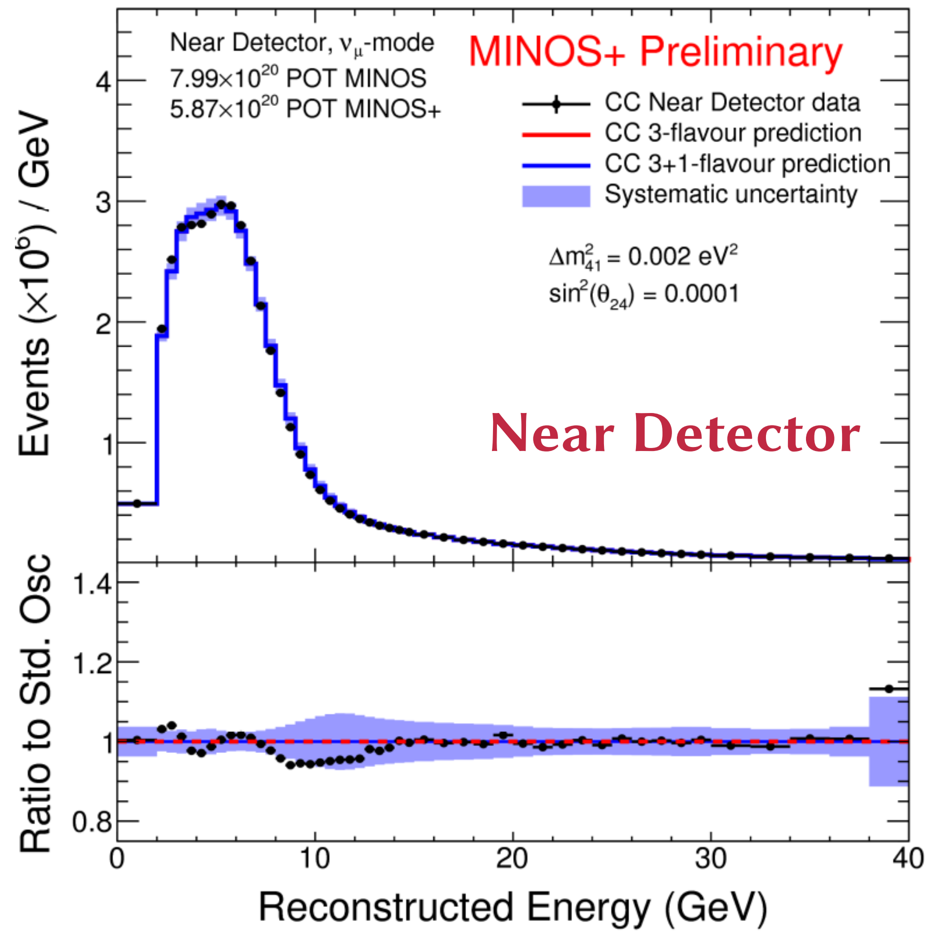
$$\chi^2_{CC,NC} = \sum_{i=1}^{N}\sum_{j=1}^{N}(x_i - \mu_i)[\mathbf{V}^{-1}]_{ij}(x_j - \mu_j)$$





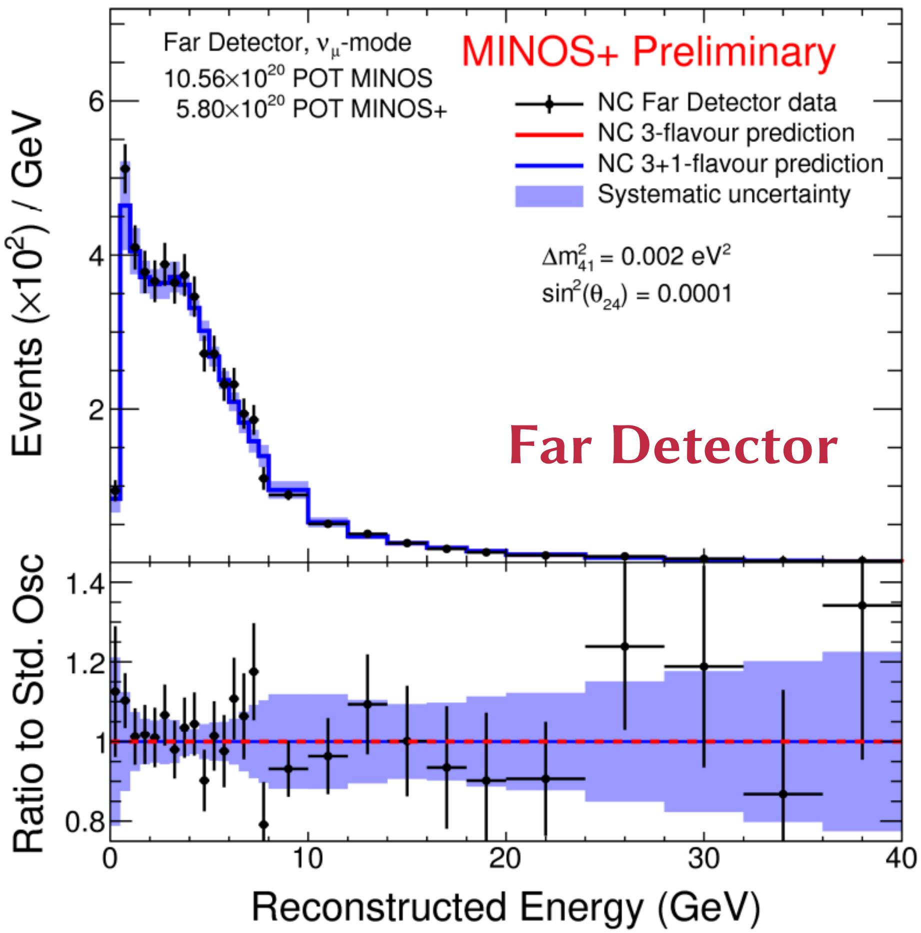
ν_μ CC Sample

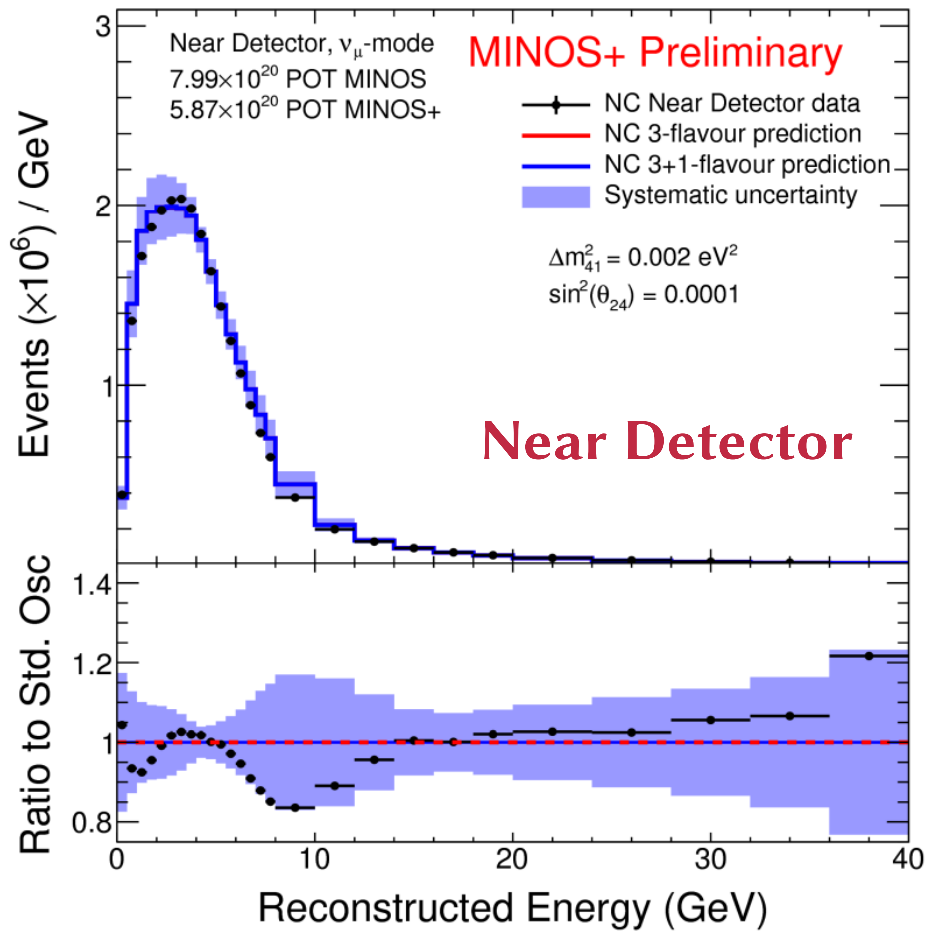




- Covariance matrix fits do not include systematics as nuisance parameters
- The error bands and prediction account for off-diagonal elements to indicate the equivalent of post-fit agreement

NC Sample

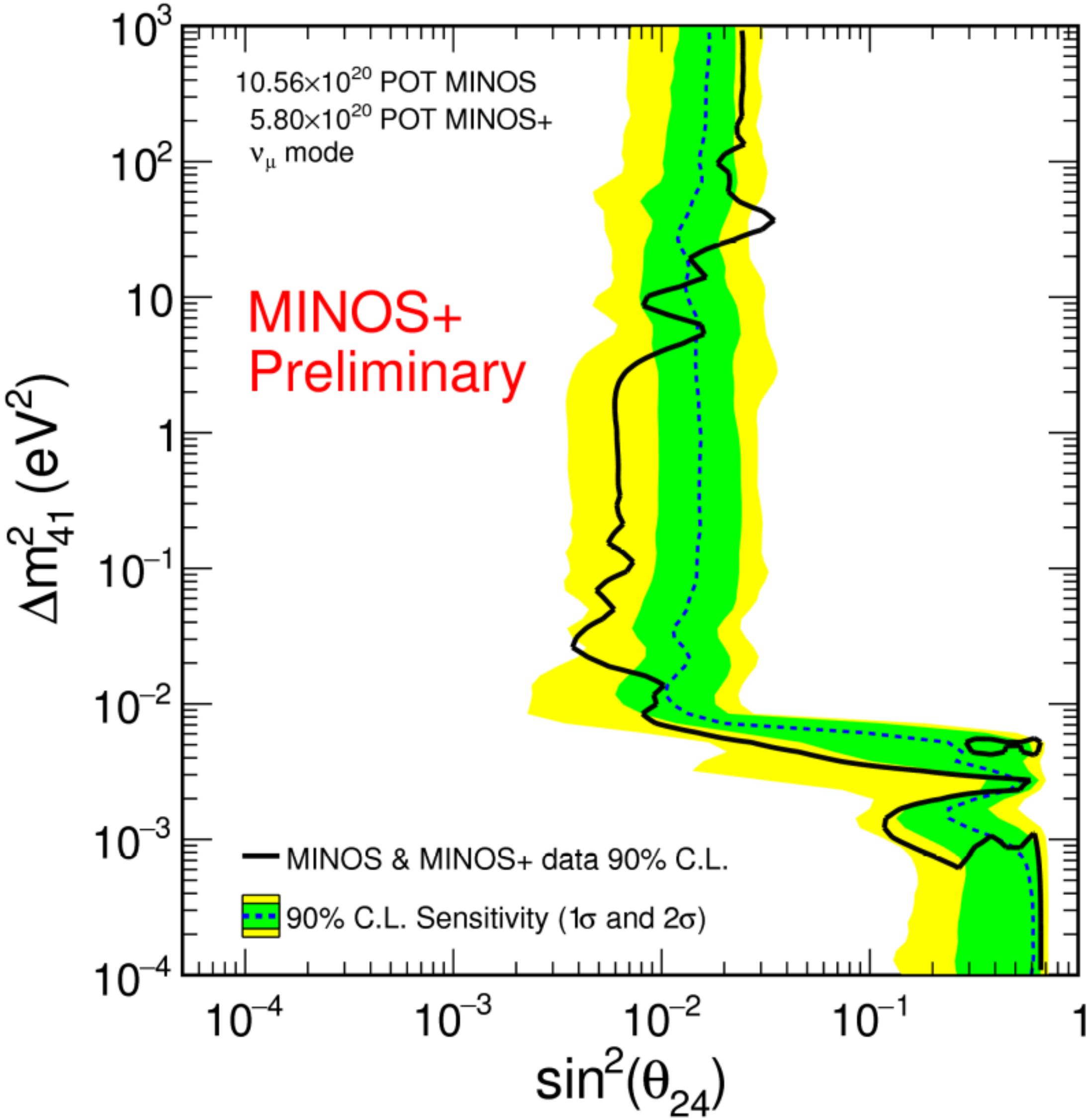




- Covariance matrix fits do not include systematics as nuisance parameters
- The error bands and prediction account for off-diagonal elements to indicate the equivalent of post-fit agreement

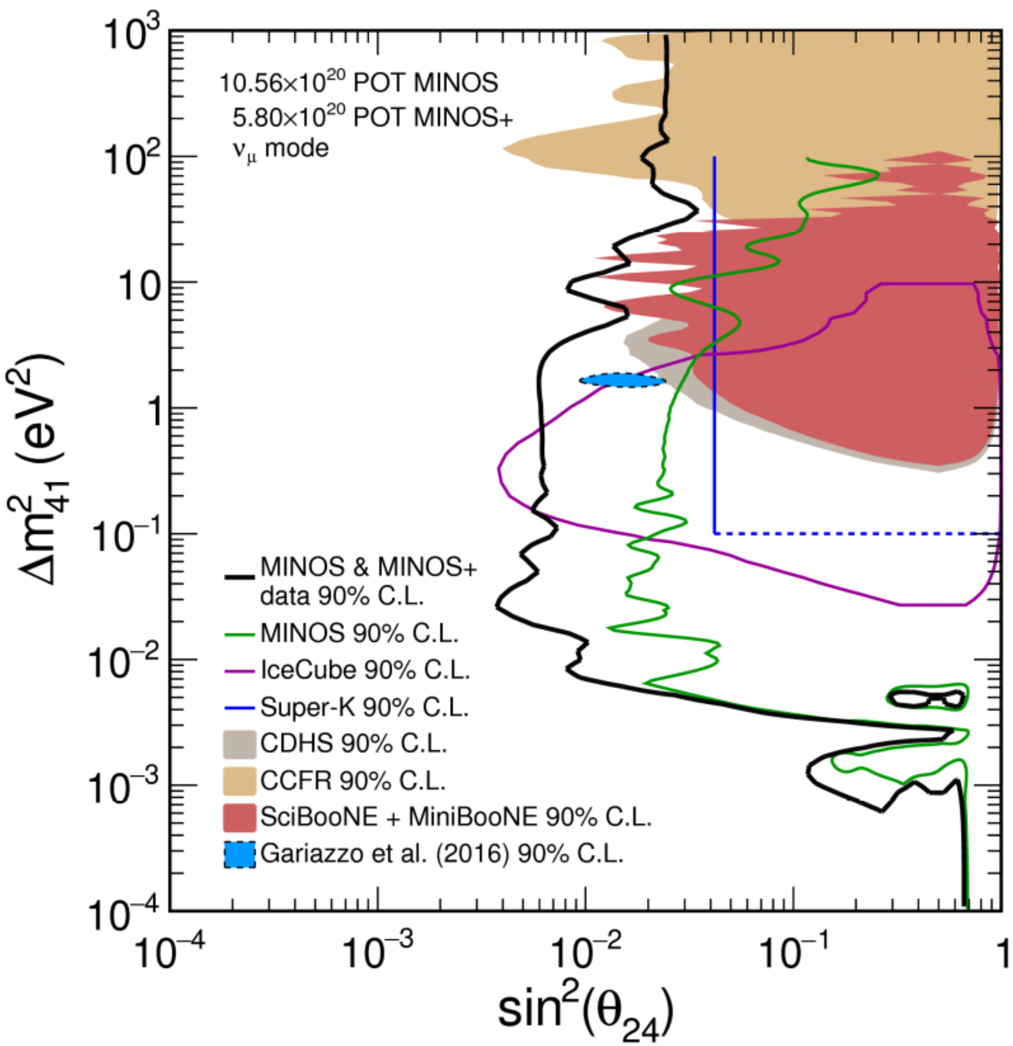
Sterile Disappearance Limit

- Use full NC and CC samples in both detectors
- Fit for θ_{23}, θ_{24}, θ_{34}, Δm^2_{32}, and Δm^2_{41}
- Fix δ_{13}, δ_{14}, δ_{24}, and θ_{14} to zero
- Median sensitivity from Feldman-Cousins corrected 90% CL contours from pseudo-experiments
- Best fit:
  - $\Delta m^2_{41} = 2.33 \times 10^{-3}$ eV^2
  - $\sin^2\theta_{24} = 1.1 \times 10^{-4}$
  - $\theta_{34} < 8.4 \times 10^{-3}$
  - $\sin^2 2\theta_{23} = 0.92$
  - $\chi^2_{min}/\text{dof} = 99.3/140$
  - $\chi^2(4\nu) - \chi^2(3\nu) = 0.01$



Sterile Disappearance Limit

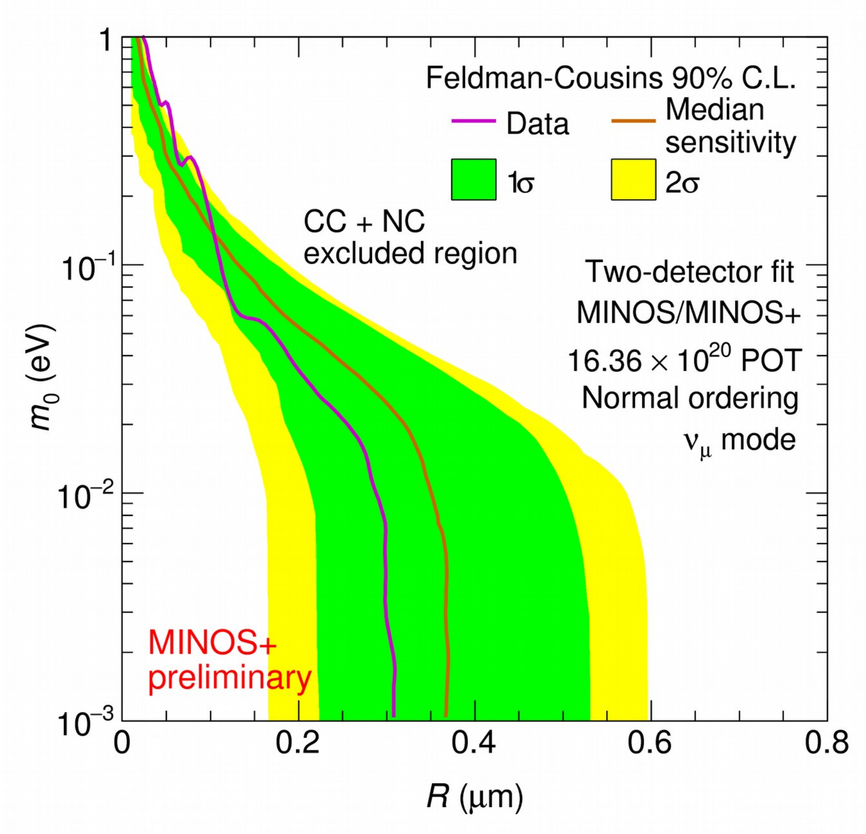
- MINOS and MINOS+ 90% C.L. exclusion limit over 7 orders of magnitude in Δm^2_{41}
- Improvement at large Δm^2_{41} over previous MINOS result due to:
  - Near Detector statistical power
  - Sensitivity to normalization shifts
  - Improved binning around atmospheric dip in Far Detector
- Increased tension with global best fit
  - Displayed here with $|U_{e4}|^2 = 0.023$
- Final year of data is still to be analyzed
- Poster: Monday #140, A. Aurisano
- Posted to arXiv:1710.06488 and submitted to PRL
  - See arXiv paper and ancillary materials for more details



^S. Gariazzo, C. Giunti, M. Laveder, Y.F. Li, E.M. Zavanin, J.Phys.G43, 033001 (2016)

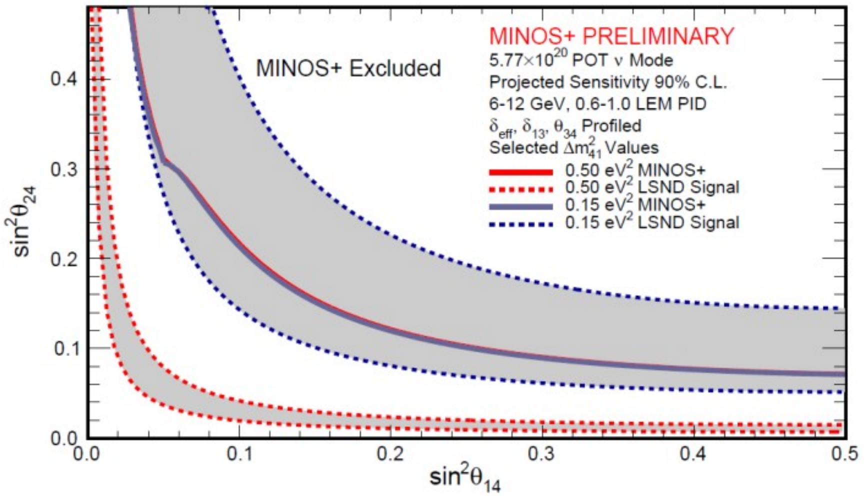
Additional Beyond the Standard Model Searches

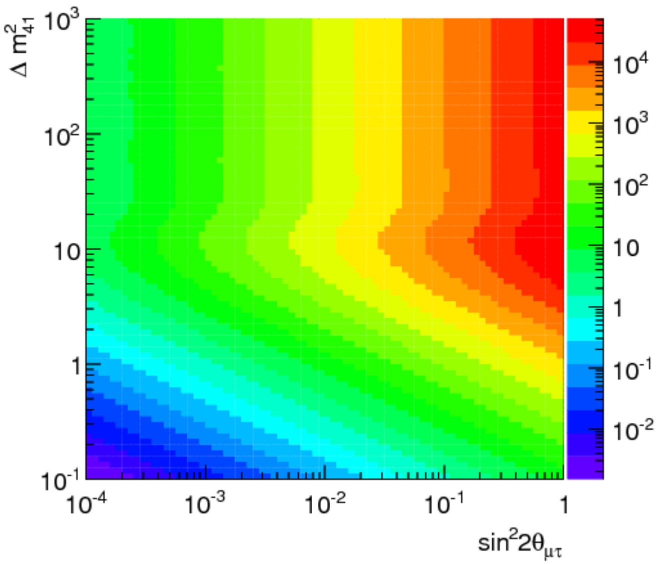
New: Large Extra Dimensions
Poster: Wednesday #52, S. De Rijck



In progress: Sterile-driven ν_τ appearance at the MINOS Near Detector
Poster: Monday #143, K. Grzelak

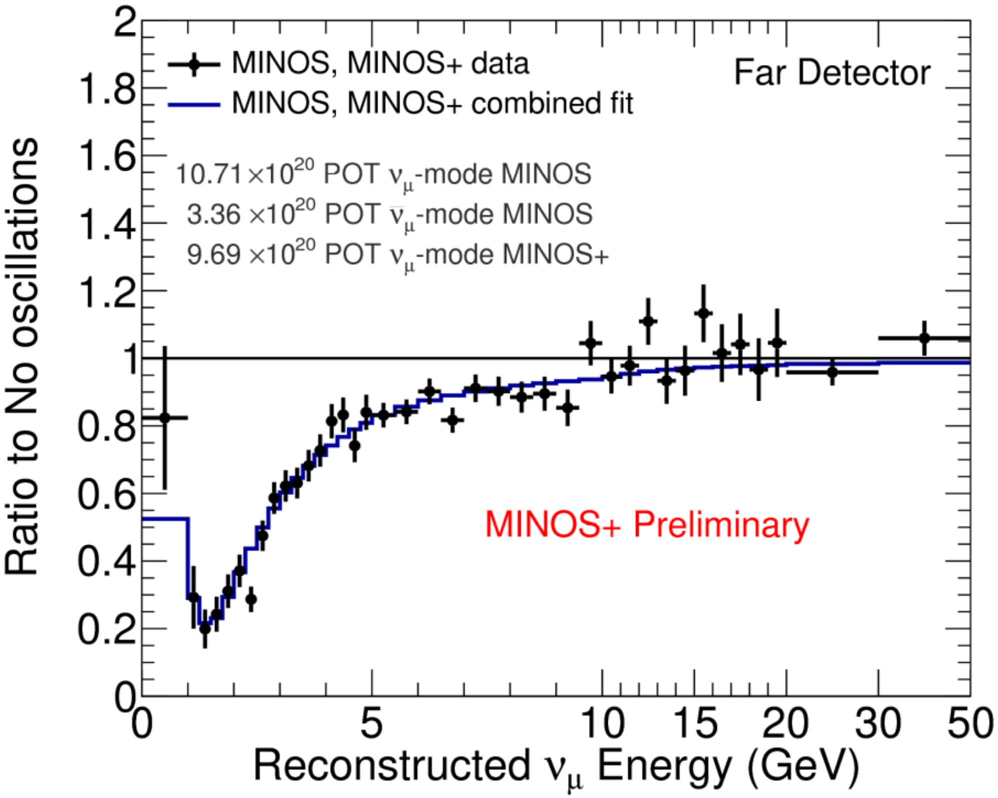
In progress: Sterile-driven ν_e appearance
Poster: Wednesday #62, G. Pawolski





Conclusions

- MINOS/MINOS+ has improved its standard oscillation measurement using the full sample of beam and atmospheric neutrinos
  - Results are competitive with running experiments
  - Measured Δm^2_{32} to 3.5%
- Using a new two-detector fit technique, MINOS+ sets leading limits on sterile neutrino mixing, especially in the critical 1 – 10 eV² region

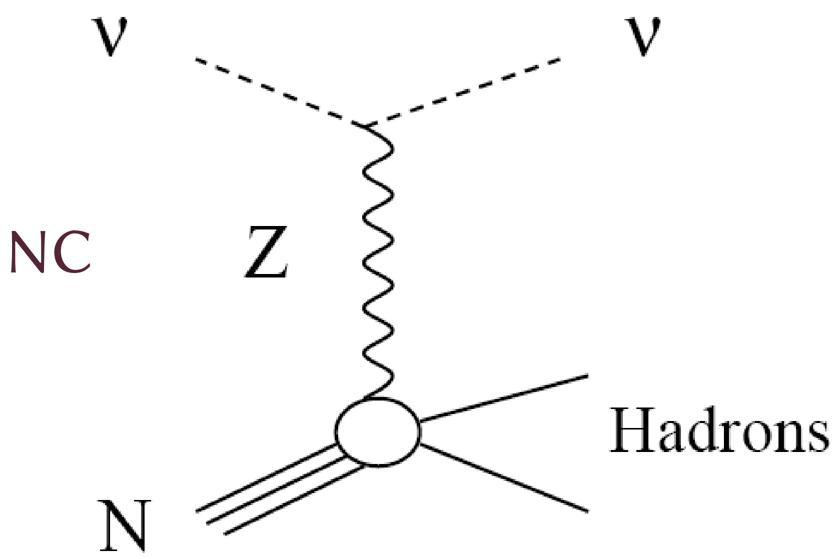


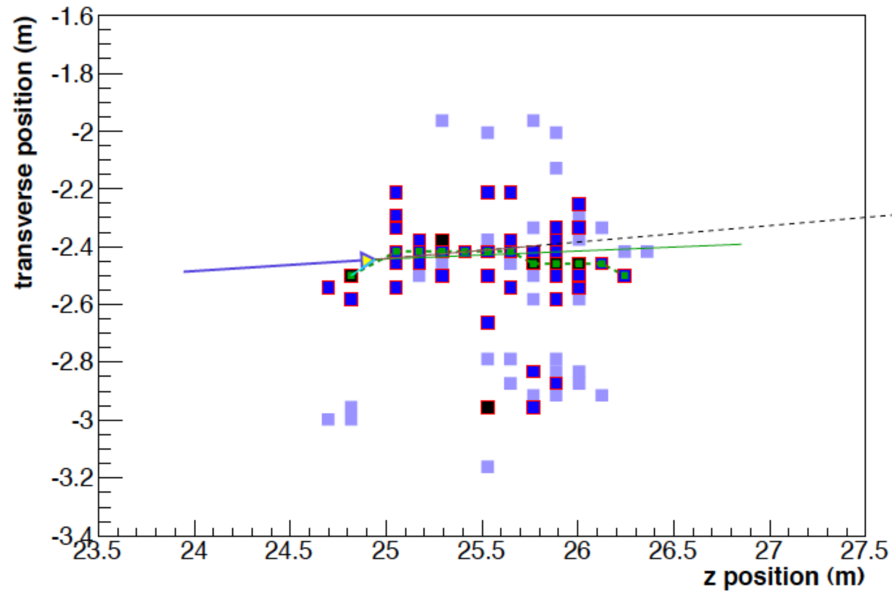
- Over 11 years of running, MINOS/MINOS+ has collected a large dataset over a broad energy range
- The high resolution mapping of the first atmospheric maximum provides strong support for the three-flavor paradigm

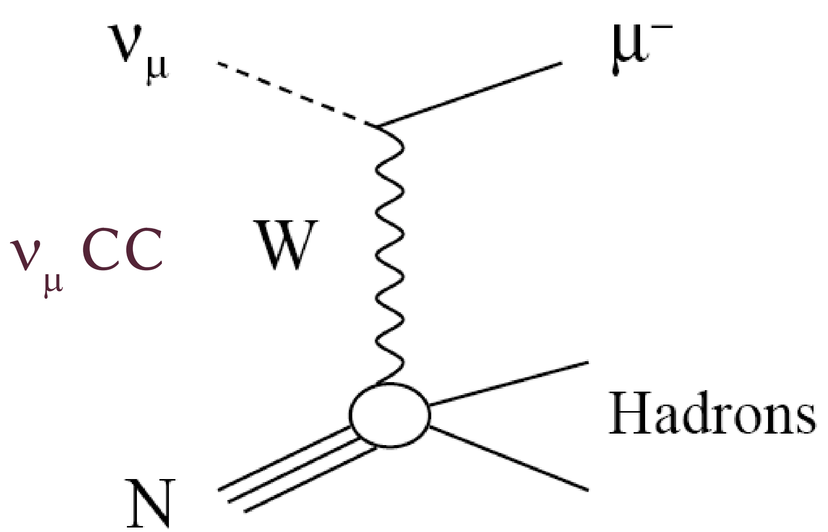
Thank you!

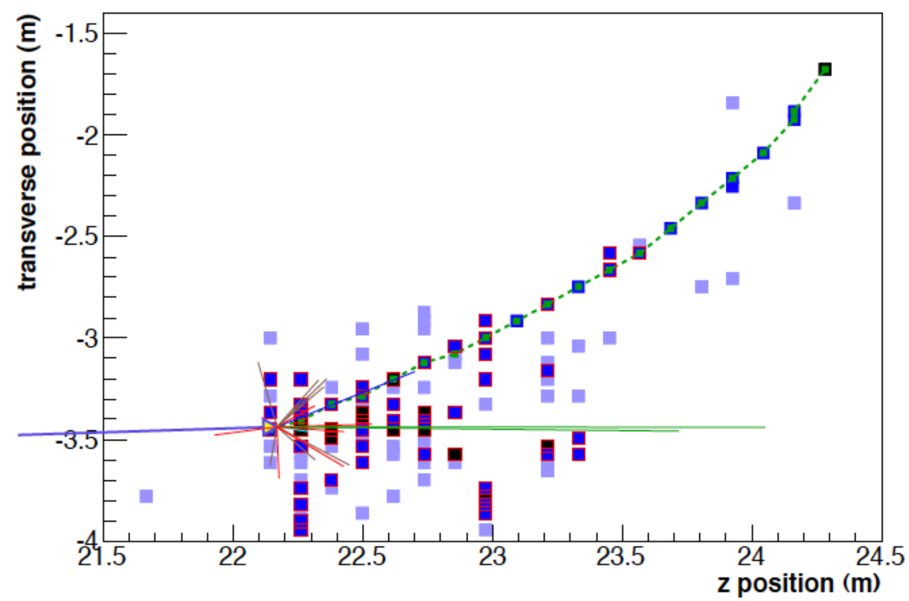
Backup Slides

Event Topologies





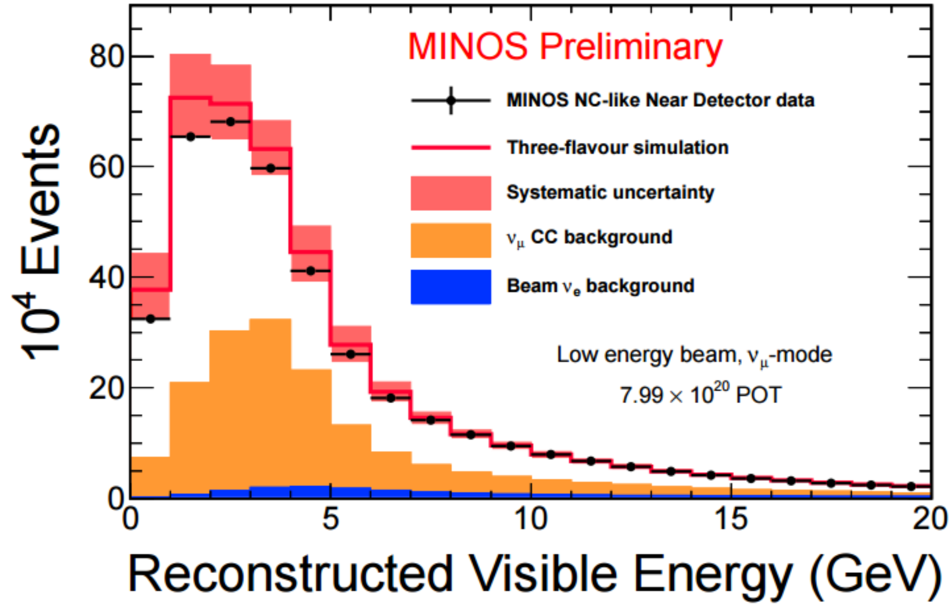




Selecting NC and ν_μ CC Samples

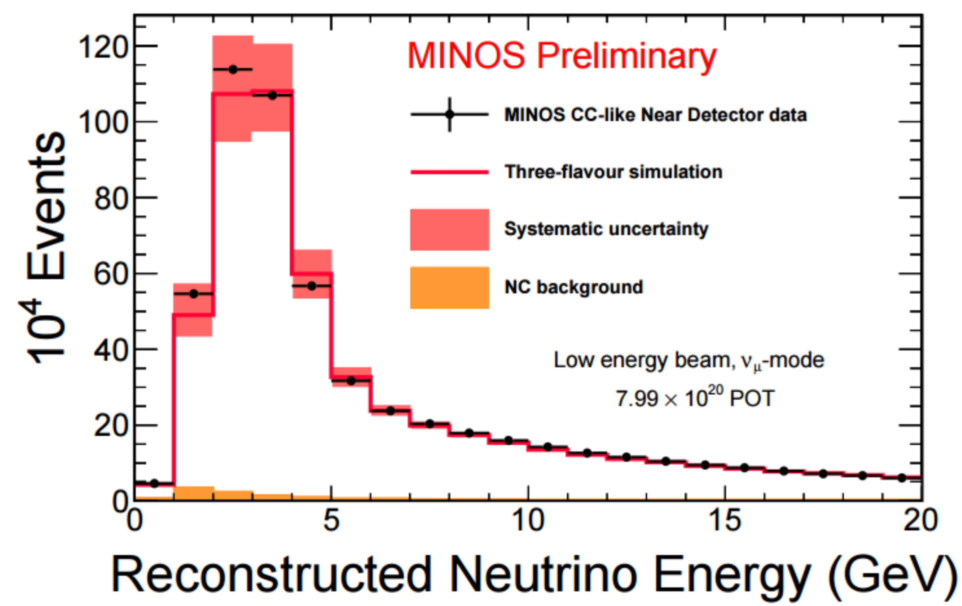
Neutral current selection

- Selection based on topological quantities
  - Require compact events
  - No long tracks extending out of the hadronic shower
- 89% efficiency and 61% purity at FD
- Primary background is inelastic ν_μ CC
- 97% of ν_e CC pass 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

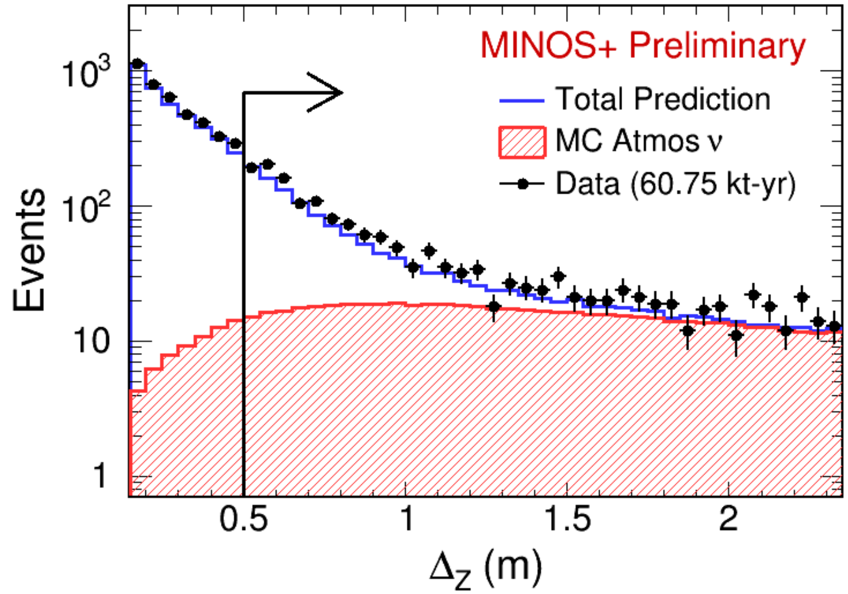


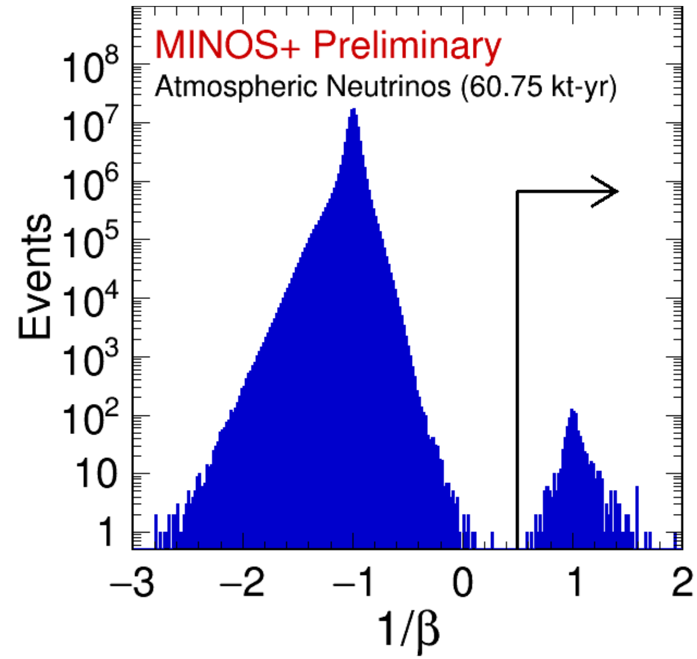
Atmospheric data and fit

- 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).

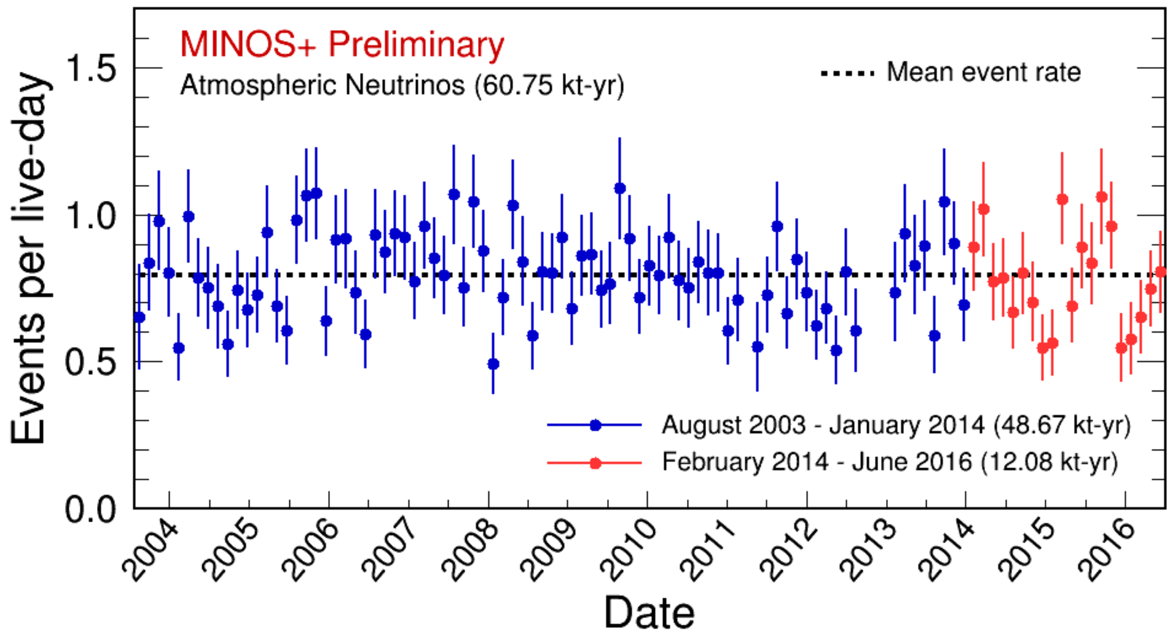


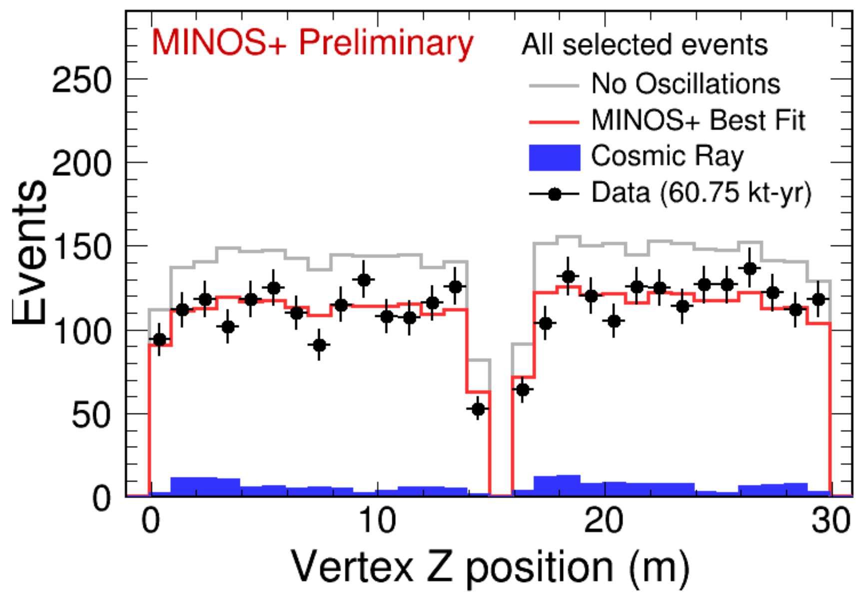


Atmospheric data and fit

◆ Selected atmospheric neutrinos are categorised based on event topology:

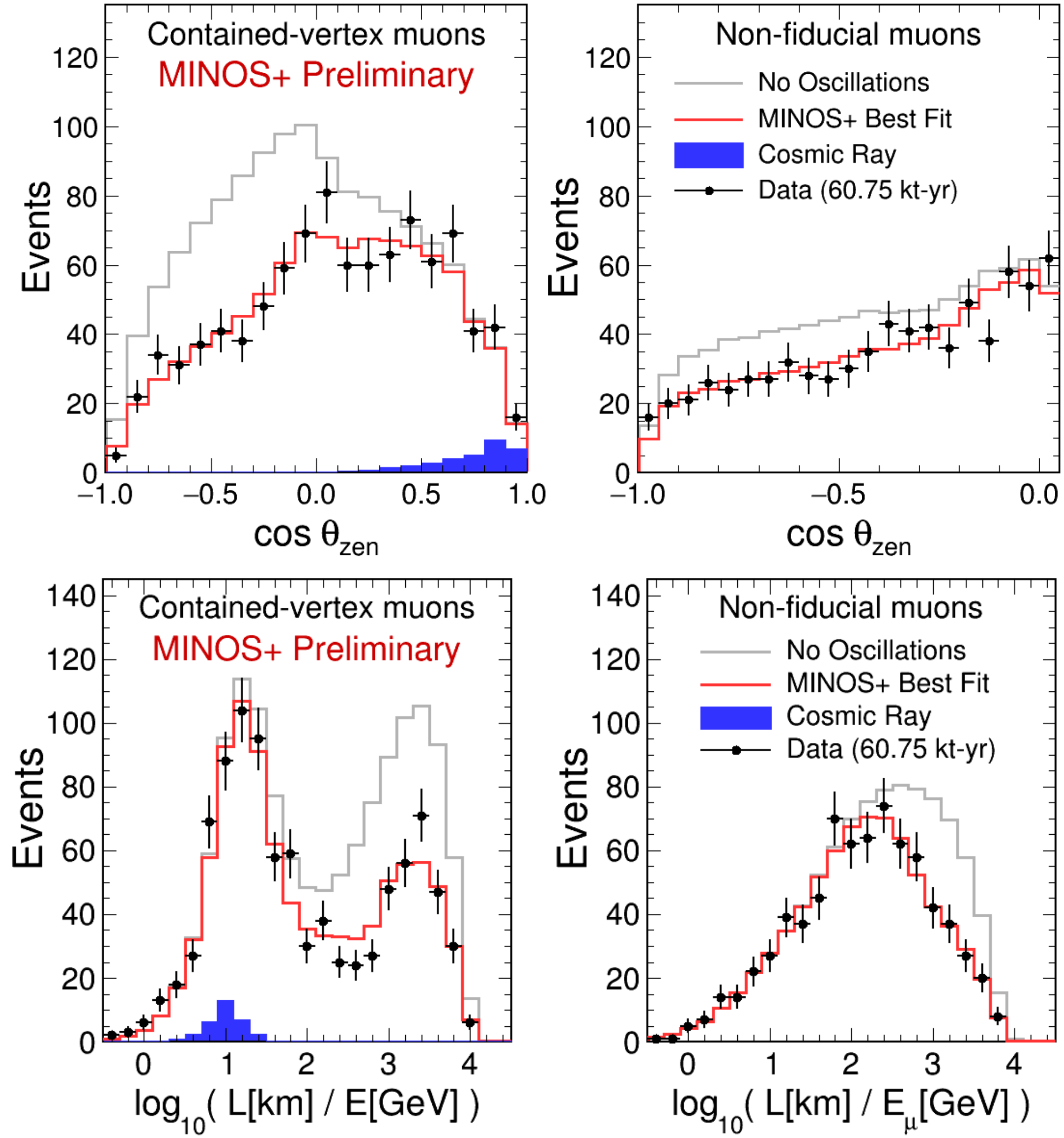
Event Classification	Data	No oscillations	Best fit
Contained-vertex showers	1123	1248	1134
Contained-vertex muons	1399	1923	1379
Non-fiducial muons	736	924	737
Total events	**3258**	**4095**	**3250**





Atmospheric data and fit

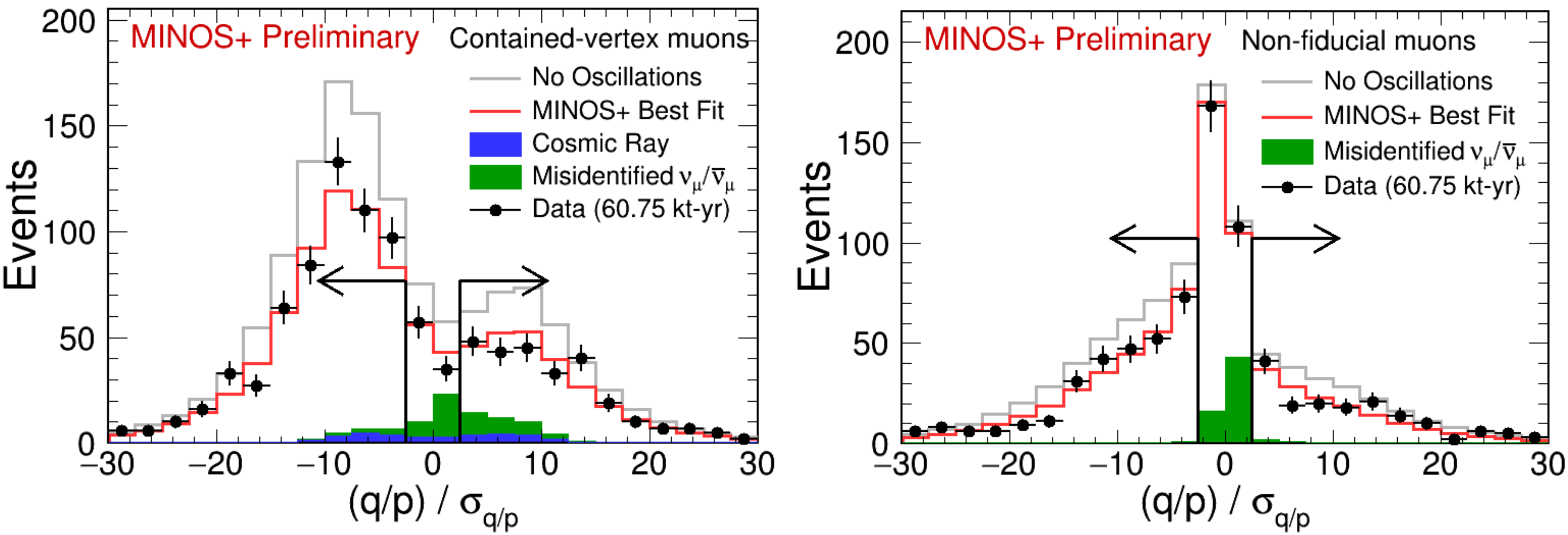
- Timing information is used to select "high resolution" sample of events with well-measured muon propagation direction.
  - 950 contained-vertex muons and all 736 non-fiducial muons pass this selection.
  - Can reconstruct zenith angle and L/E for these events.
- Plots on right show zenith angle and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

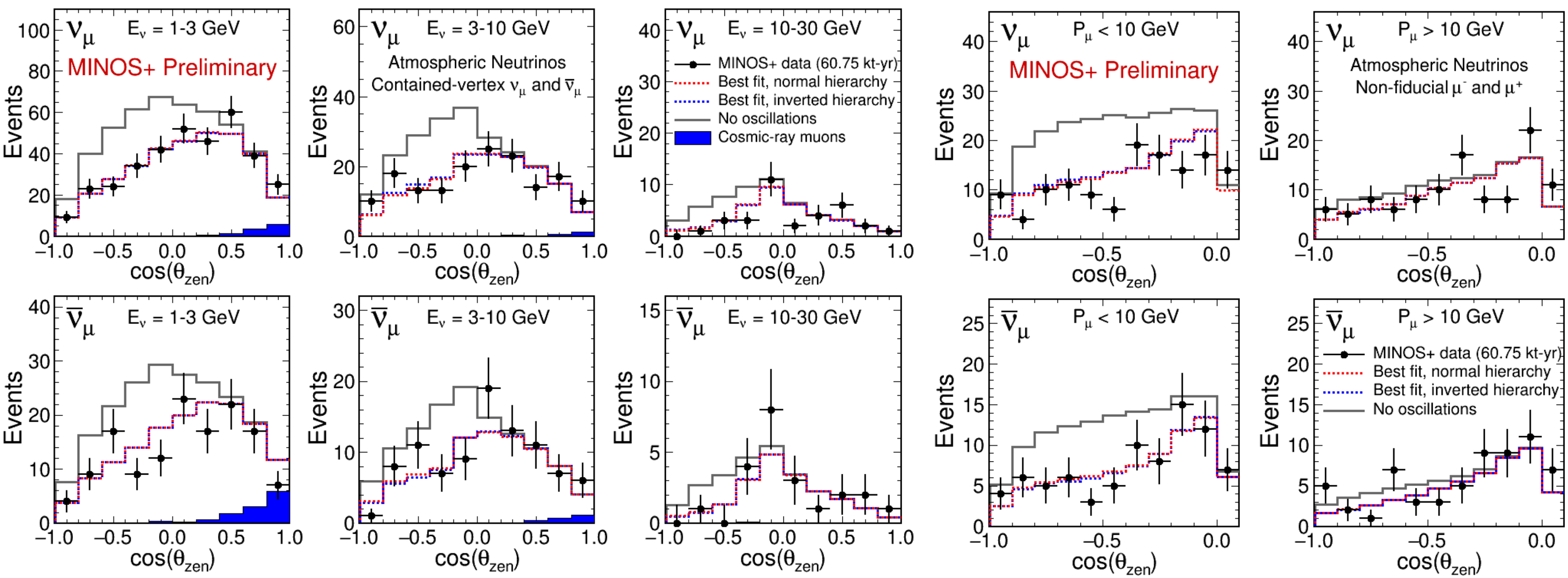
	Selected ν_μ	Selected anti-ν_μ	Total
Contained-vertex muons	574	255	829
Non-fiducial muons	239	143	382
Total	813	398	1211



◆ In the MINOS+ oscillation analysis, atmospheric neutrino data are binned as a function of reconstructed energy and zenith angle.

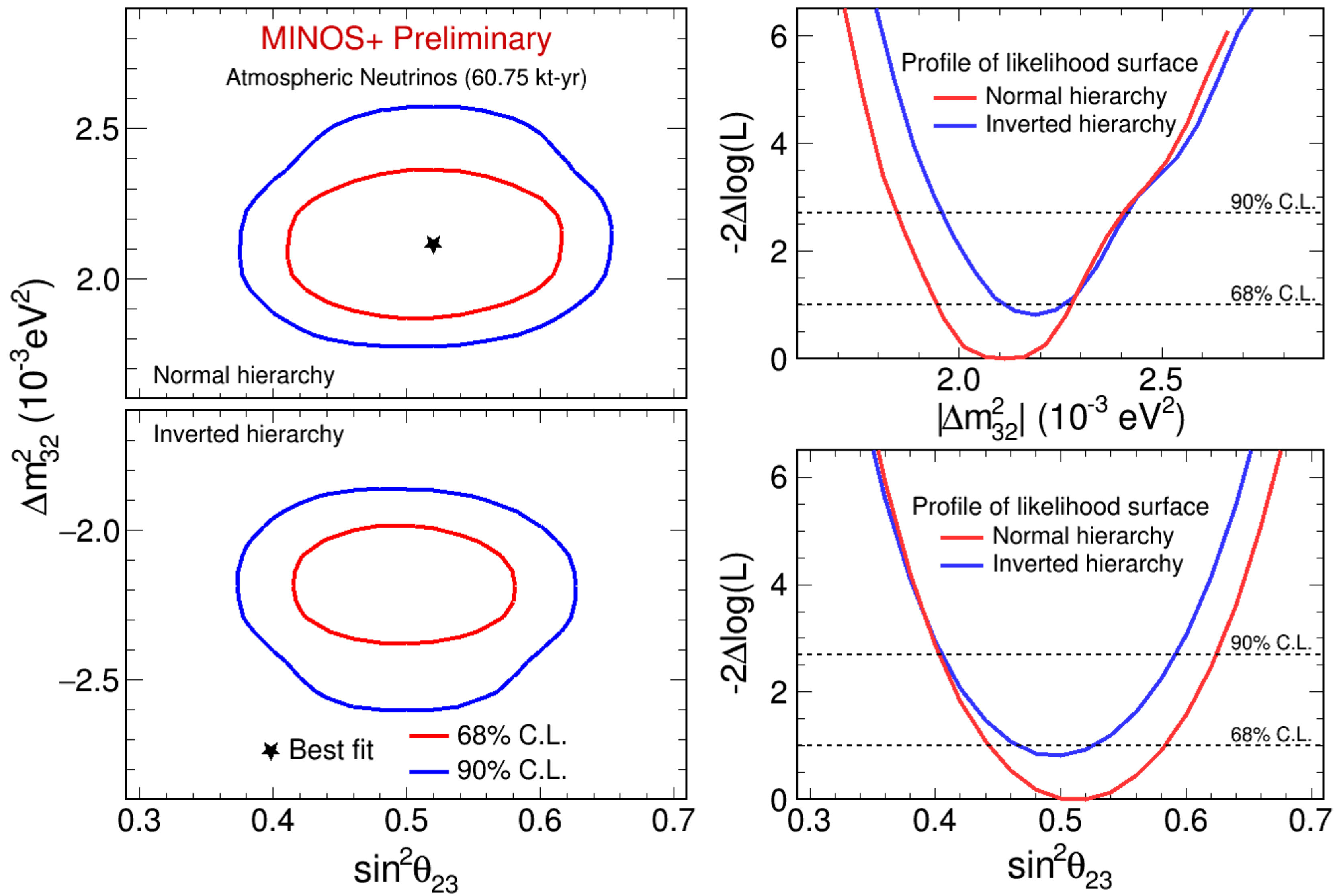
– Sensitivity to Δm^2_{32} and $\sin^2\theta_{23}$ is complementary with accelerator data.

– Additional limited sensitivity to mass hierarchy in MSW resonance region.

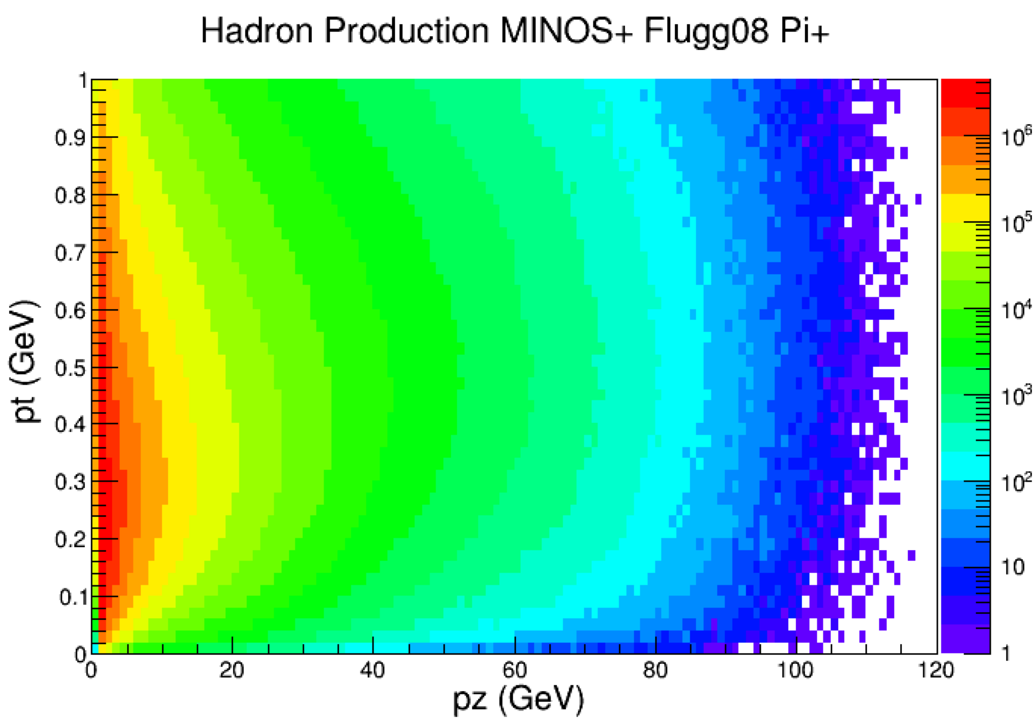


Atmospheric data and fit

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

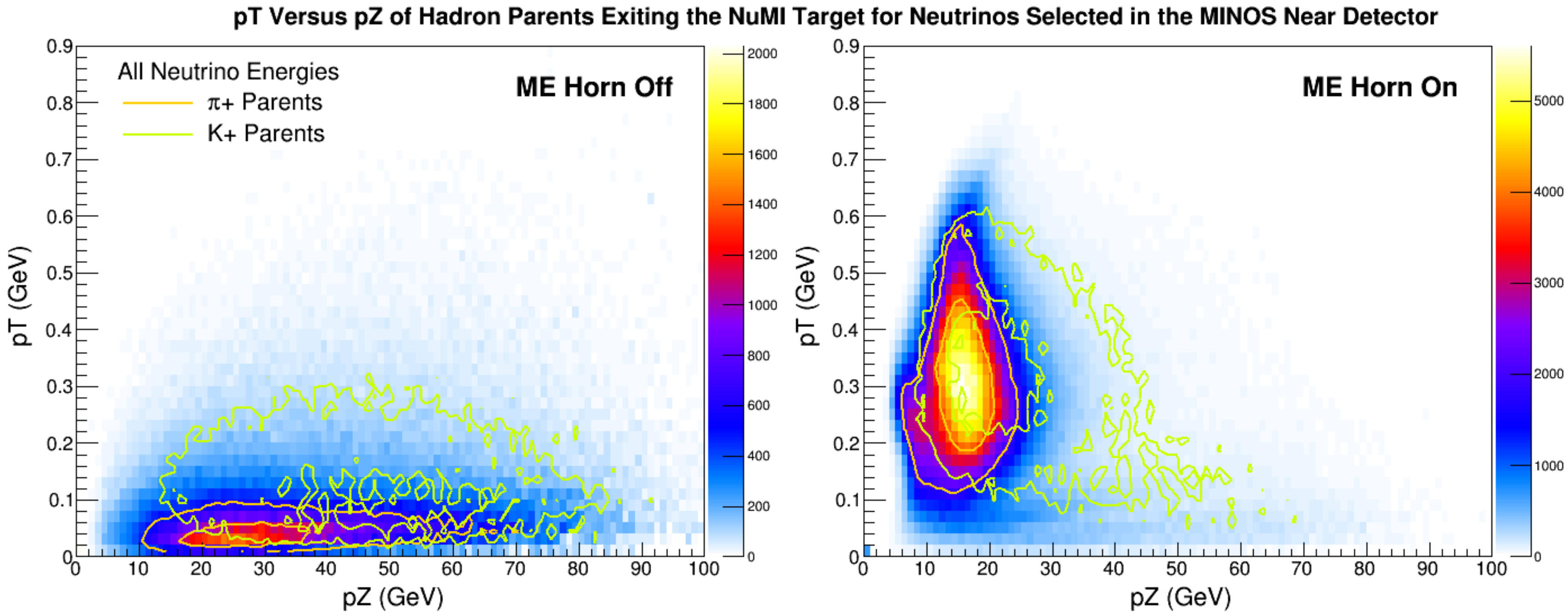


Flux Estimation: Hadron Production



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

Flux Estimation: Hadron Production



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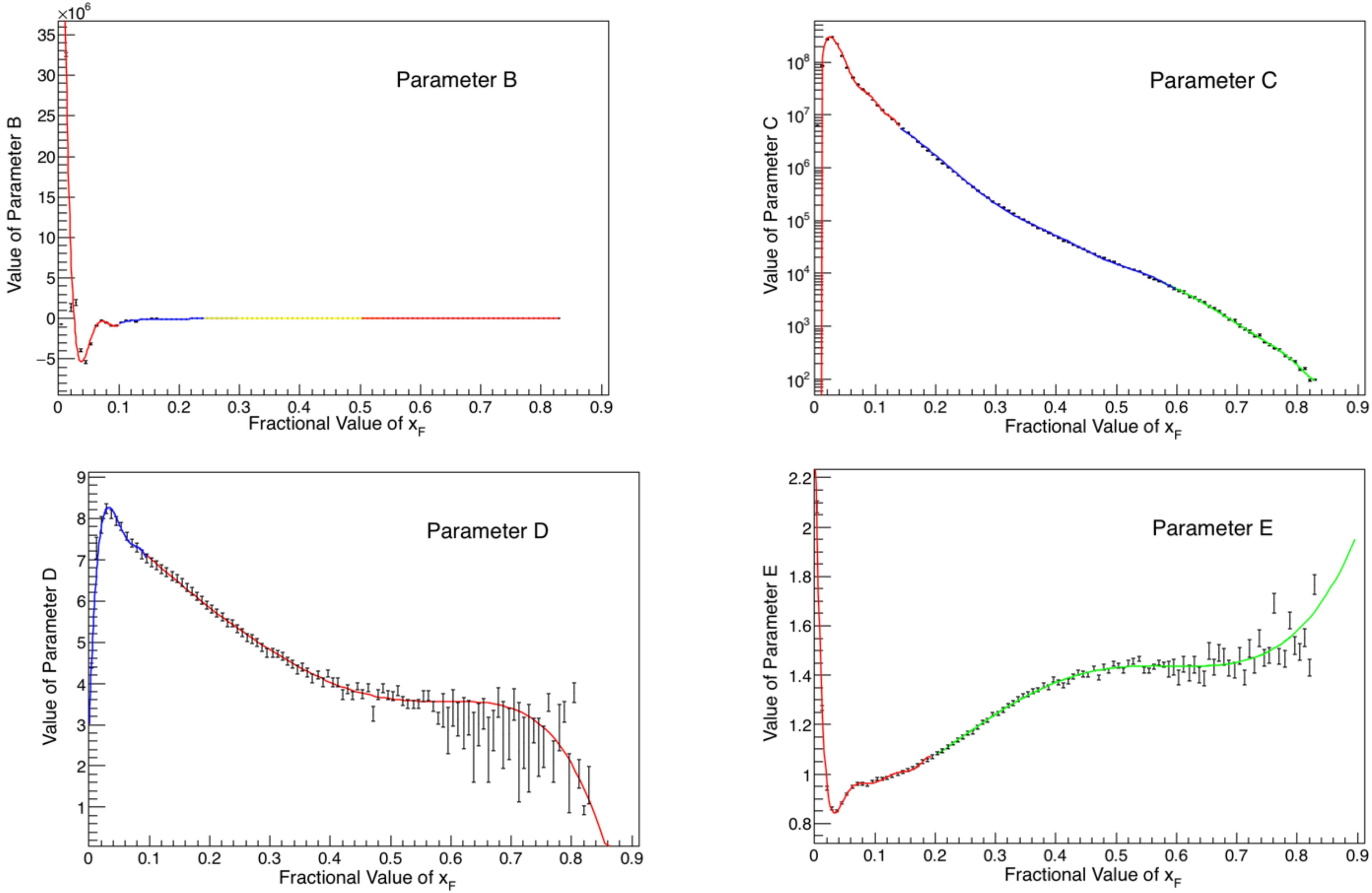
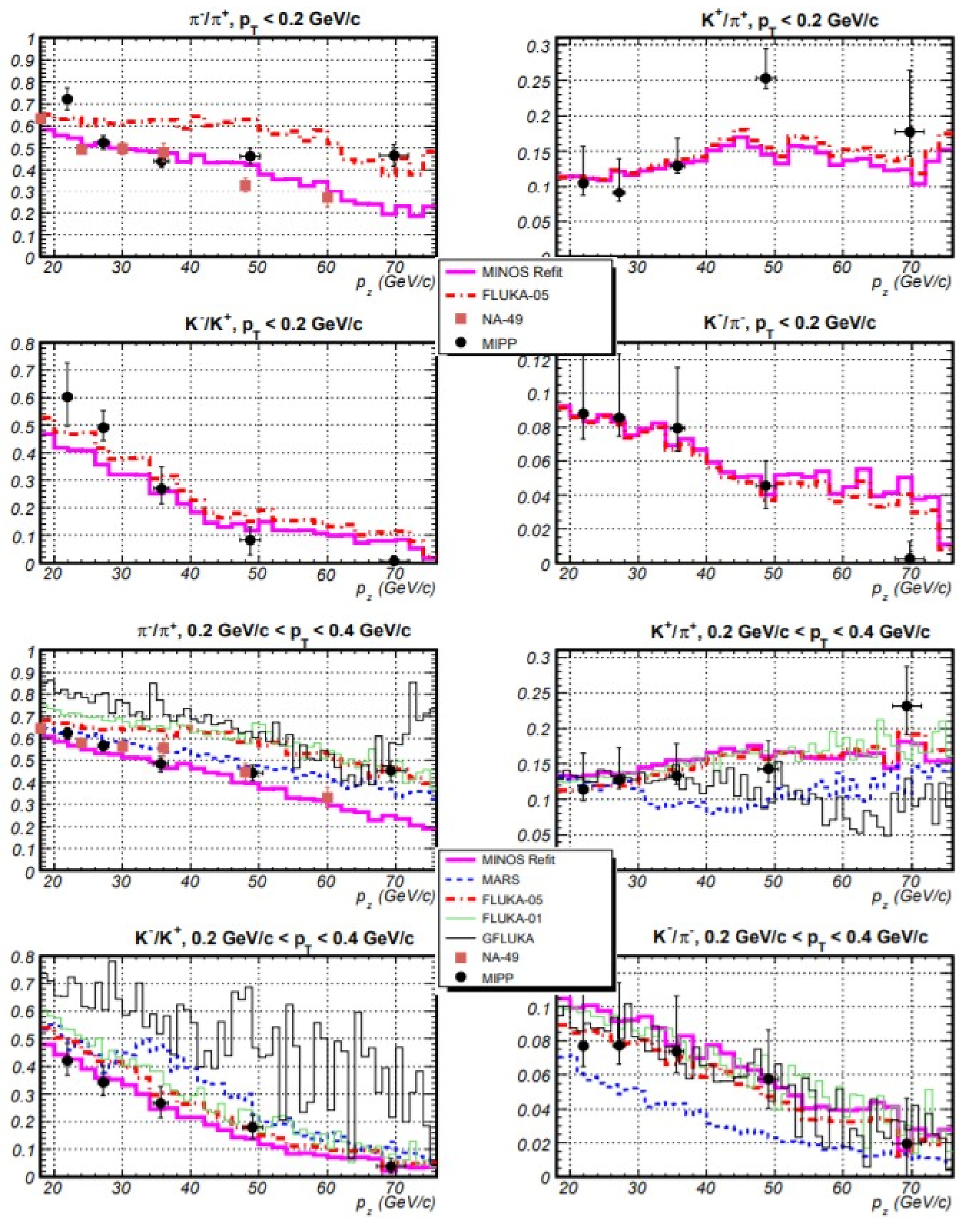


Flux Estimation: Hadron Production

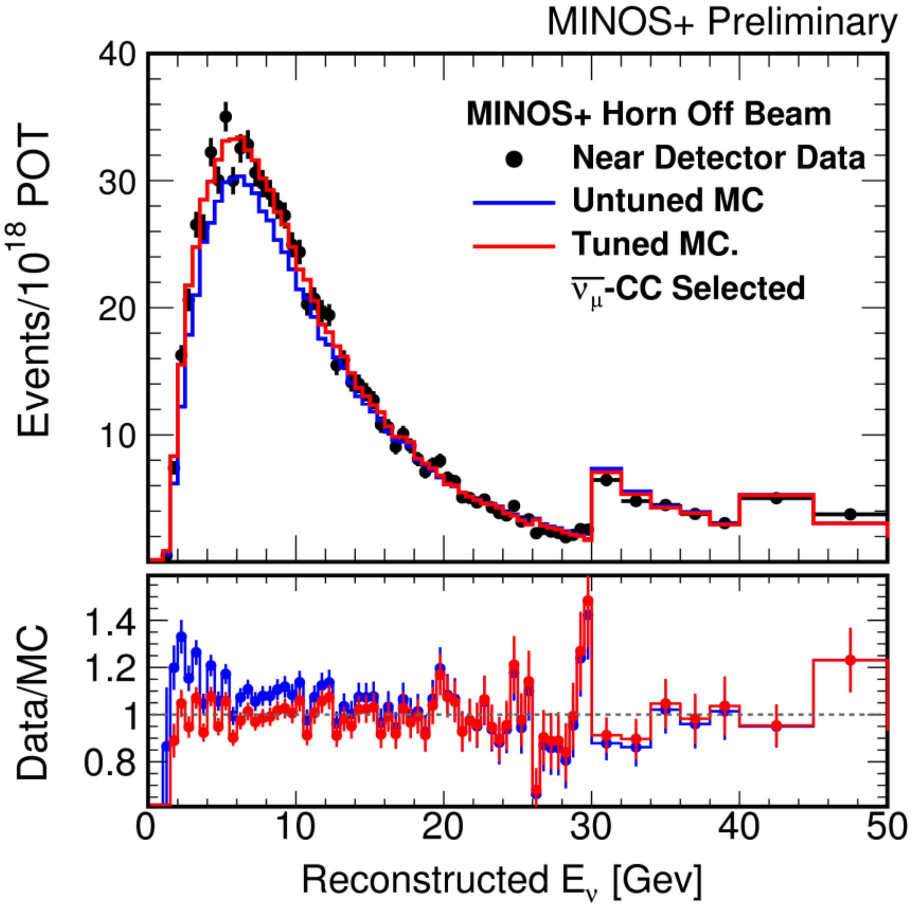


A. Lebedev, Ph.D. thesis, Harvard University (2007)

Beam Flux Estimation: Hadron Production

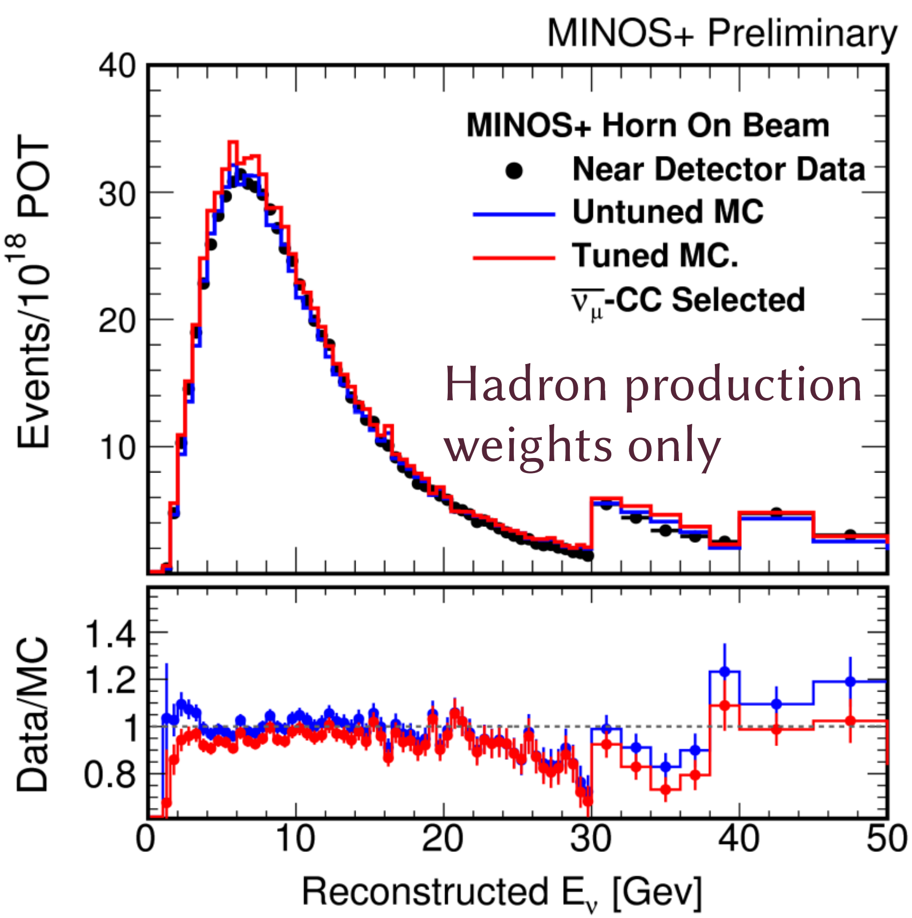
- ND data provides a powerful constraint on beam flux
- Use samples with focusing horns off to isolate hadron production
- Fit empirical pion hadron production parameters for neutrinos and antineutrinos
- Transfer weights to kaons using measured pion/kaon ratios

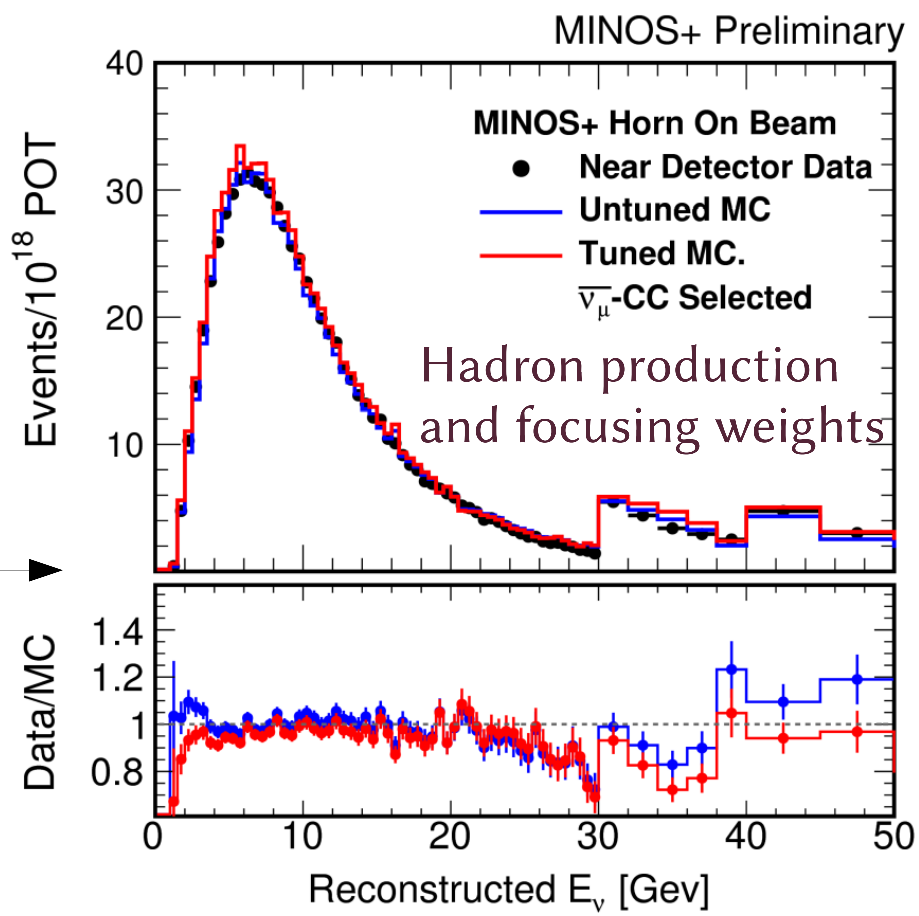
Antineutrinos – Horn-off



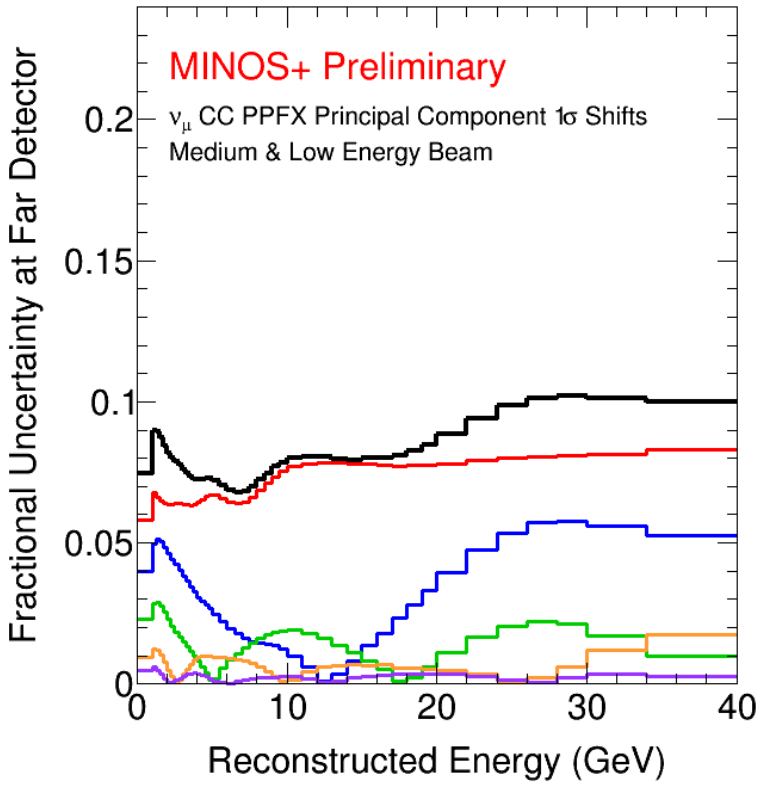
Beam Flux Estimation: Focusing

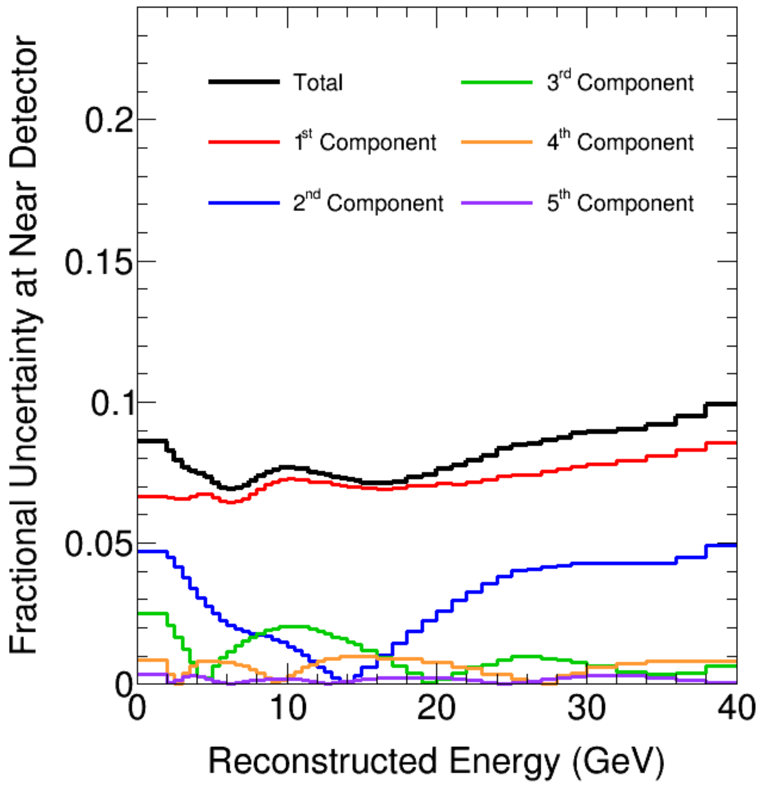
- Apply hadron production weights to sample with focusing on
- Fit for focusing effects
- Poster: Wed. # 89, A. Holin



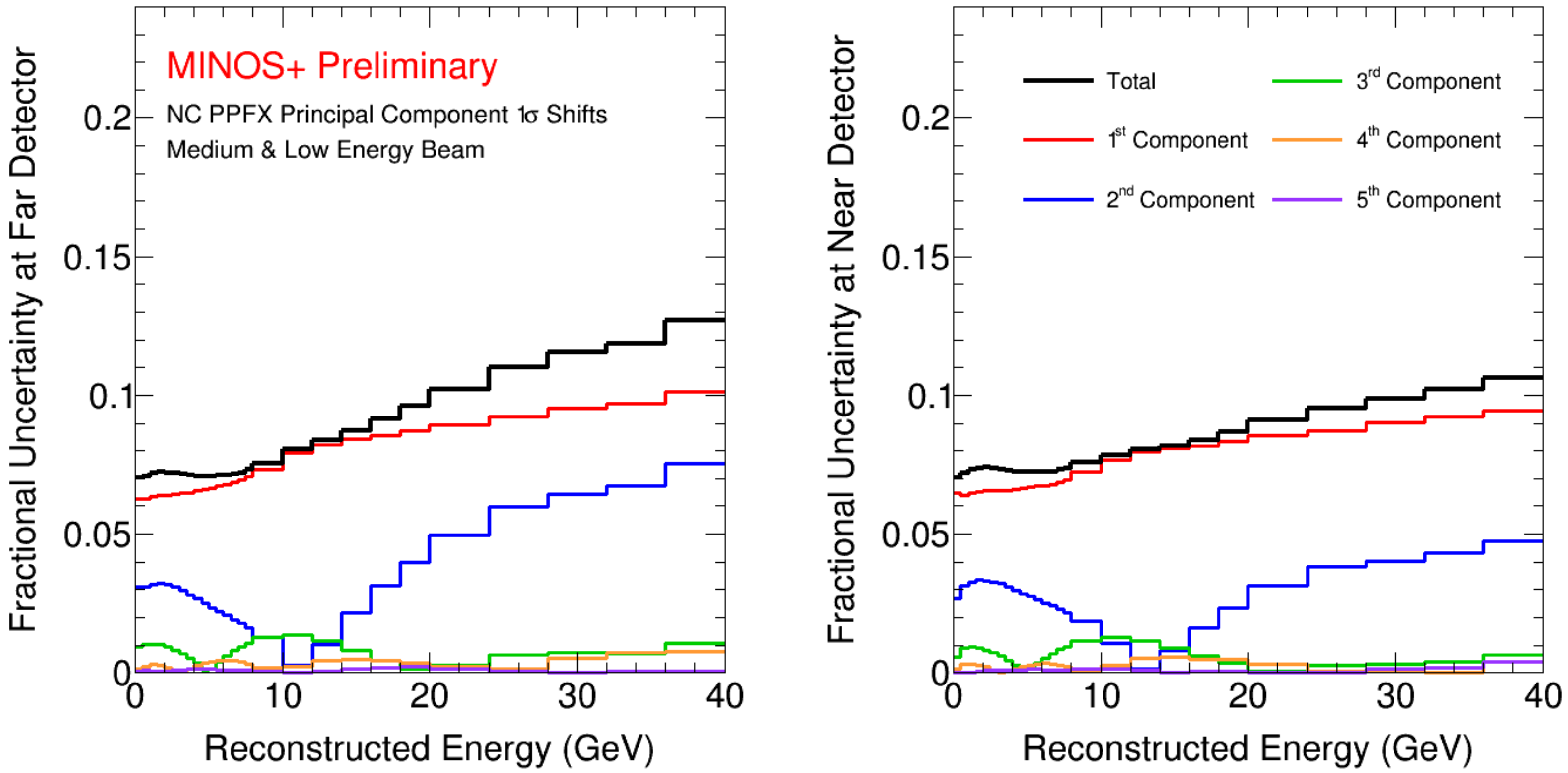


Systematics: Hadron Production - CC

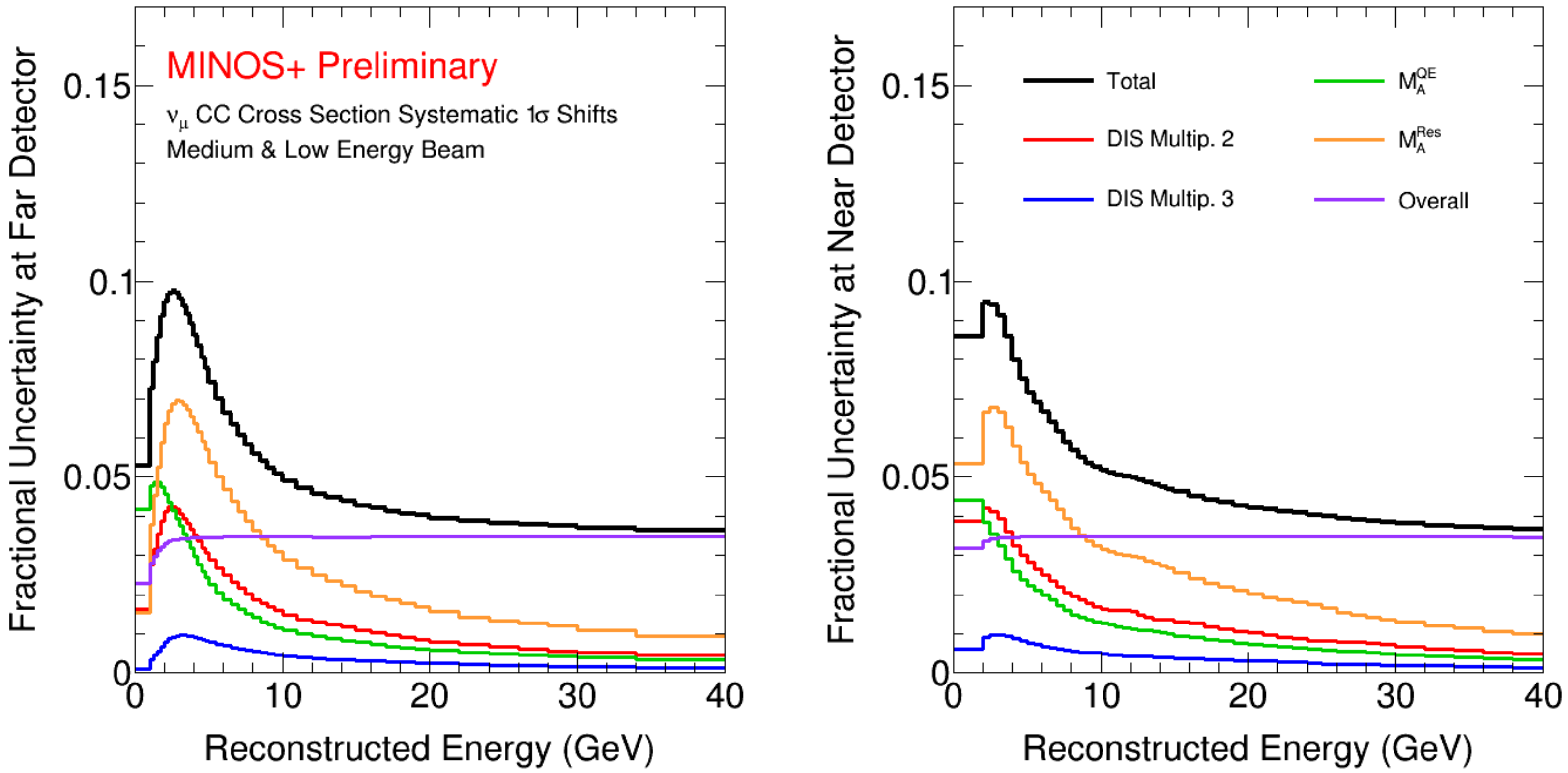




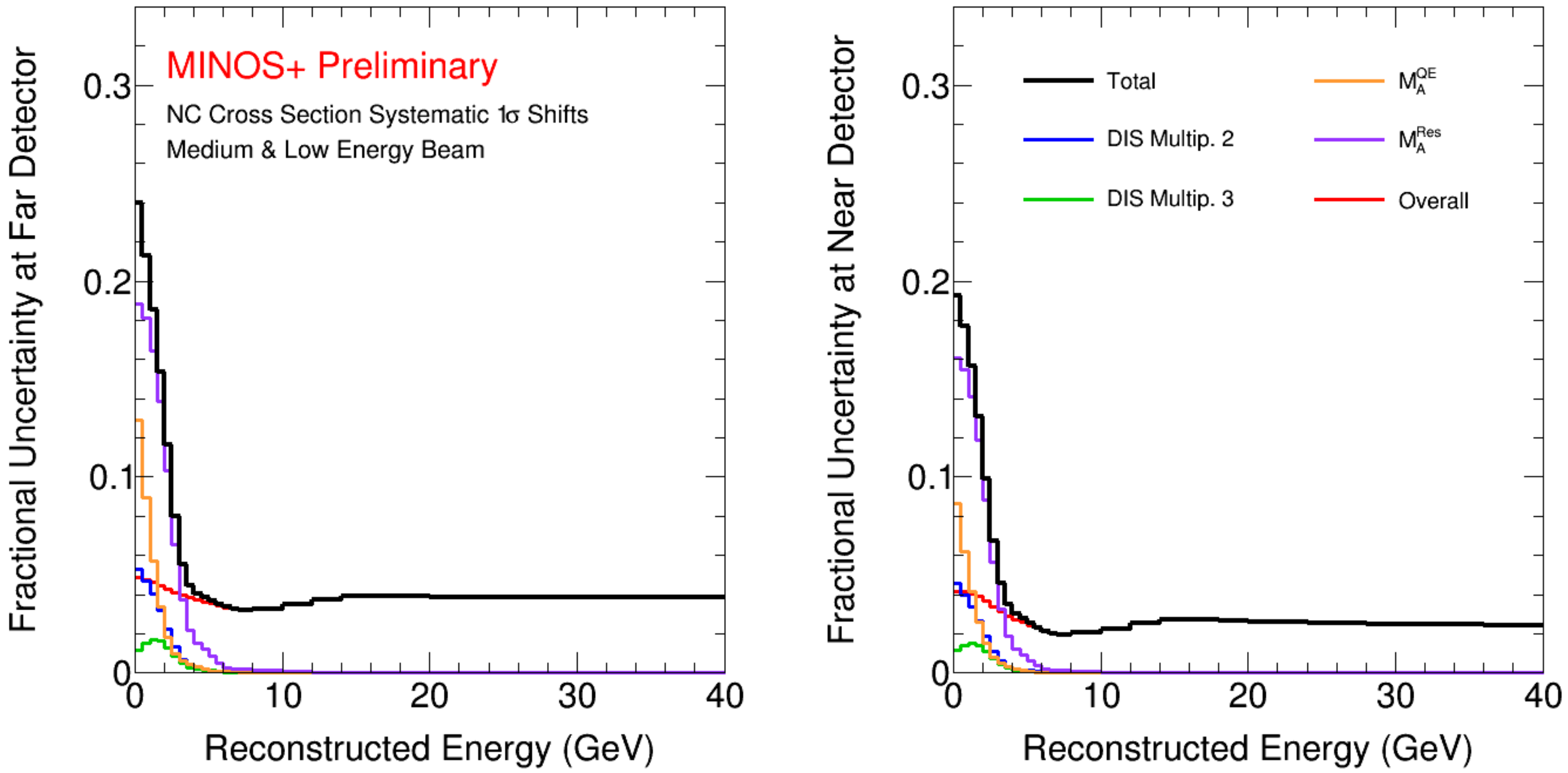
Systematics: Hadron Production - NC



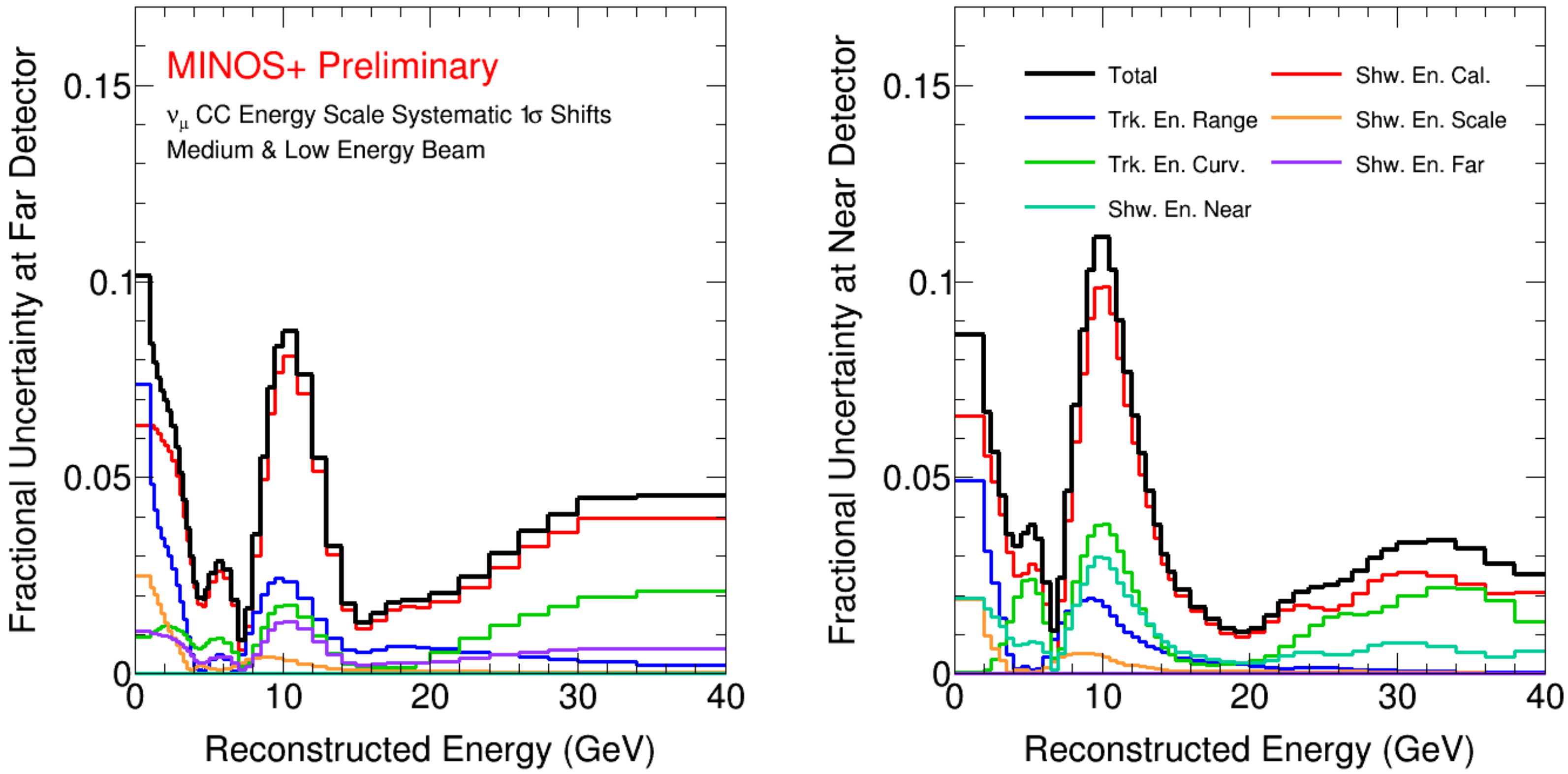
Systematics: Cross Sections - CC



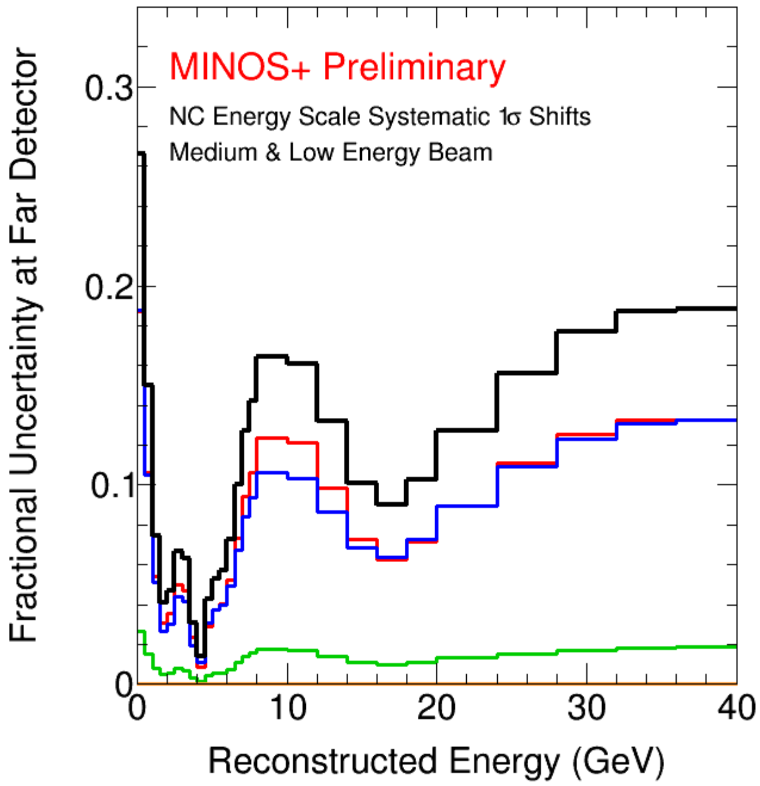
Systematics: Cross Sections - NC

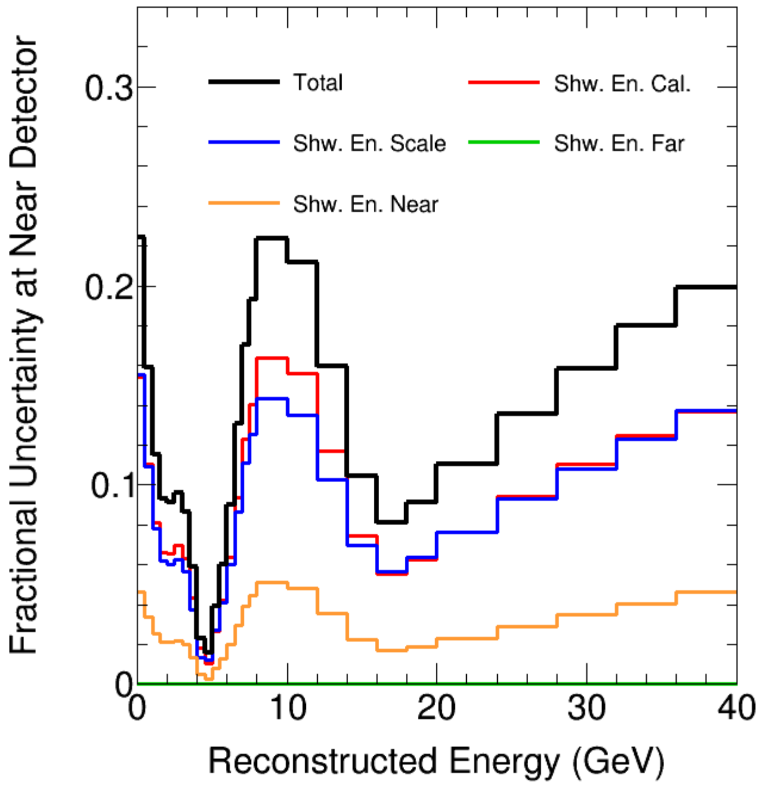


Systematics: Energy Scale - CC

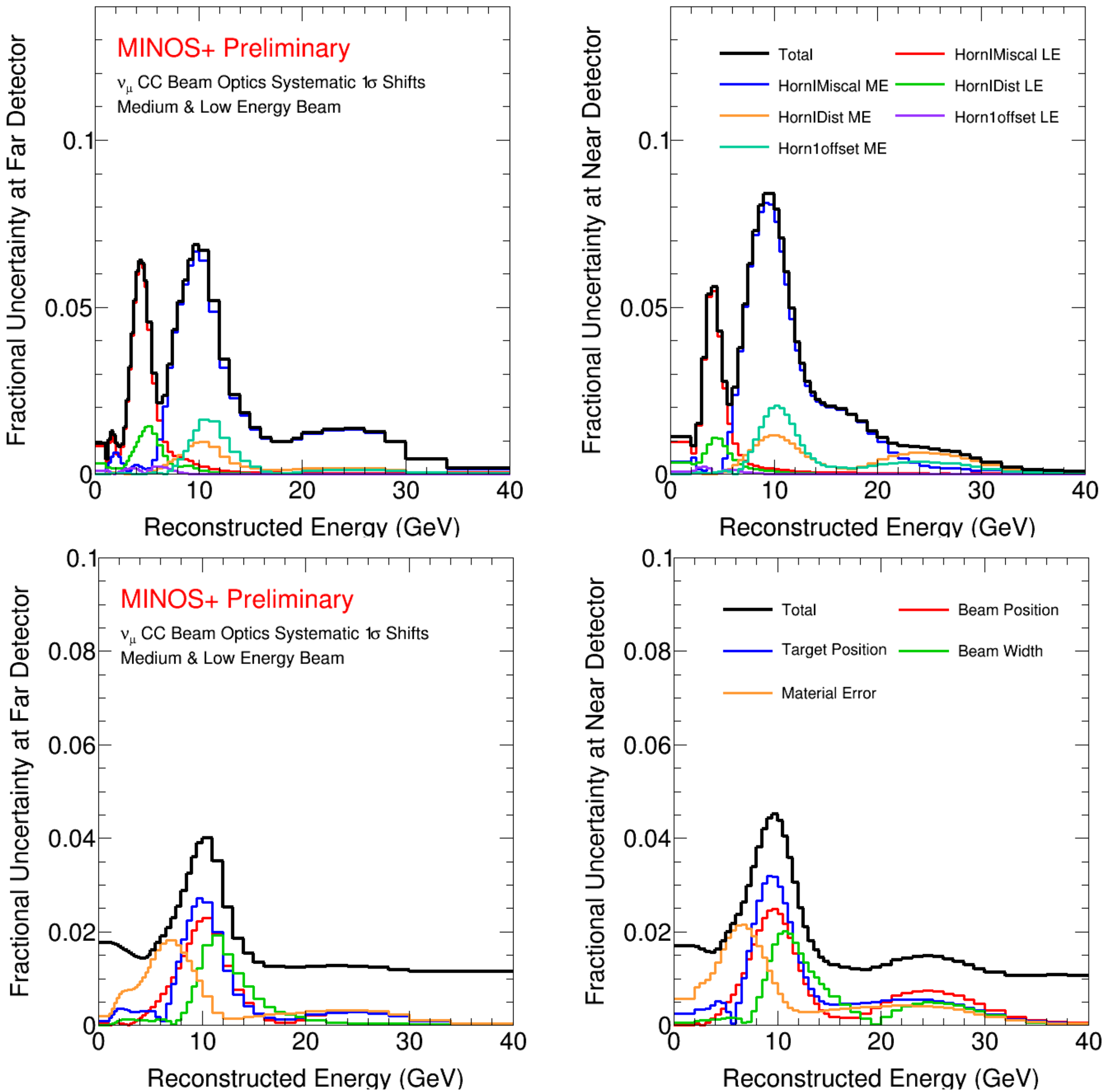


Systematics: Energy Scale - NC

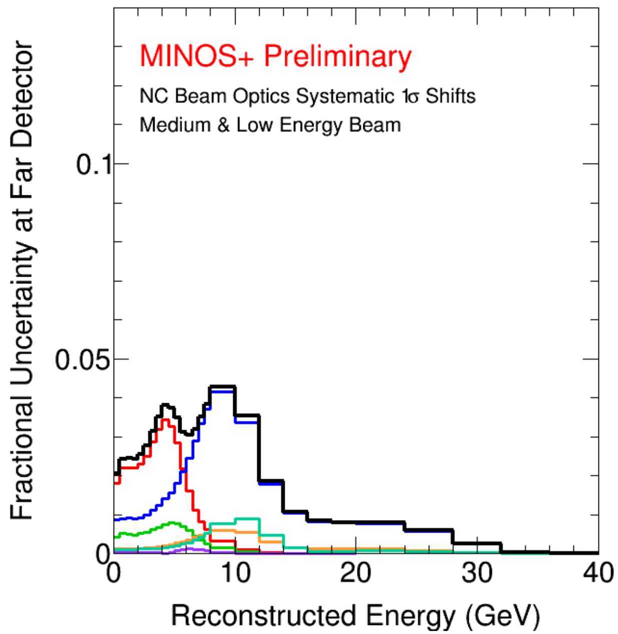


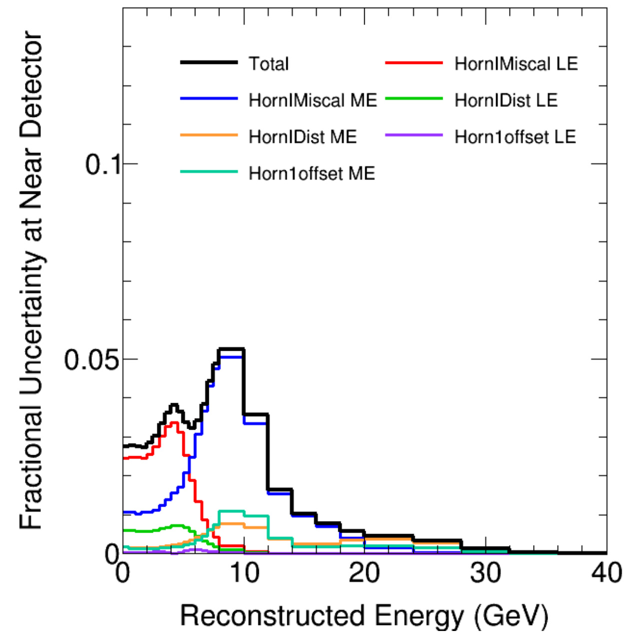


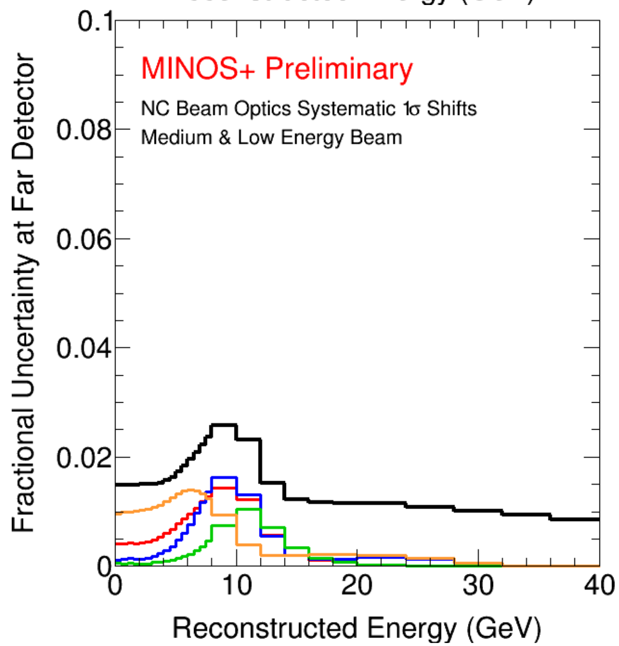
Systematics: Beam Optics - CC

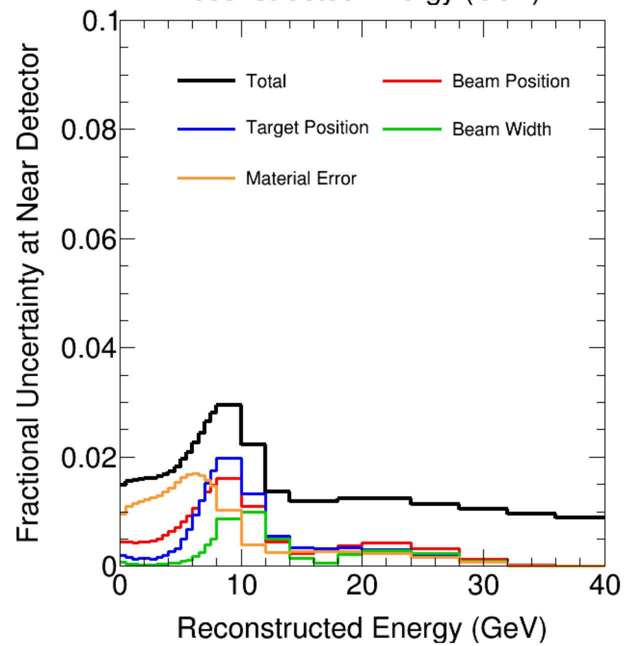


Systematics: Beam Optics - NC

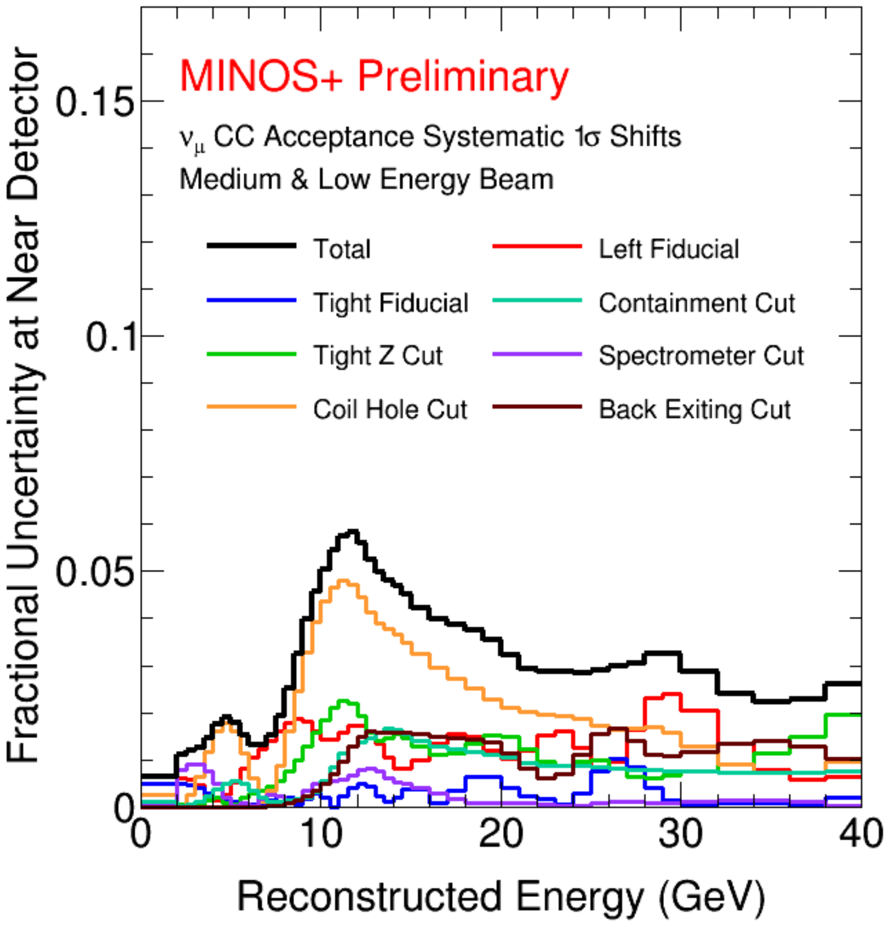


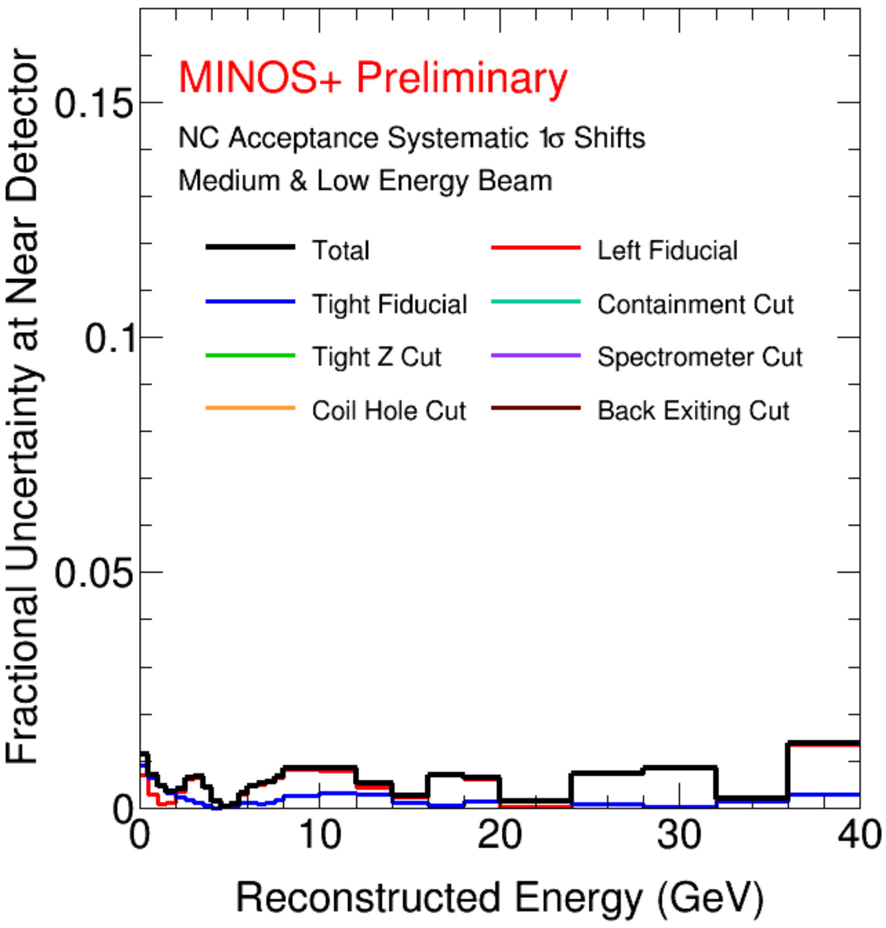




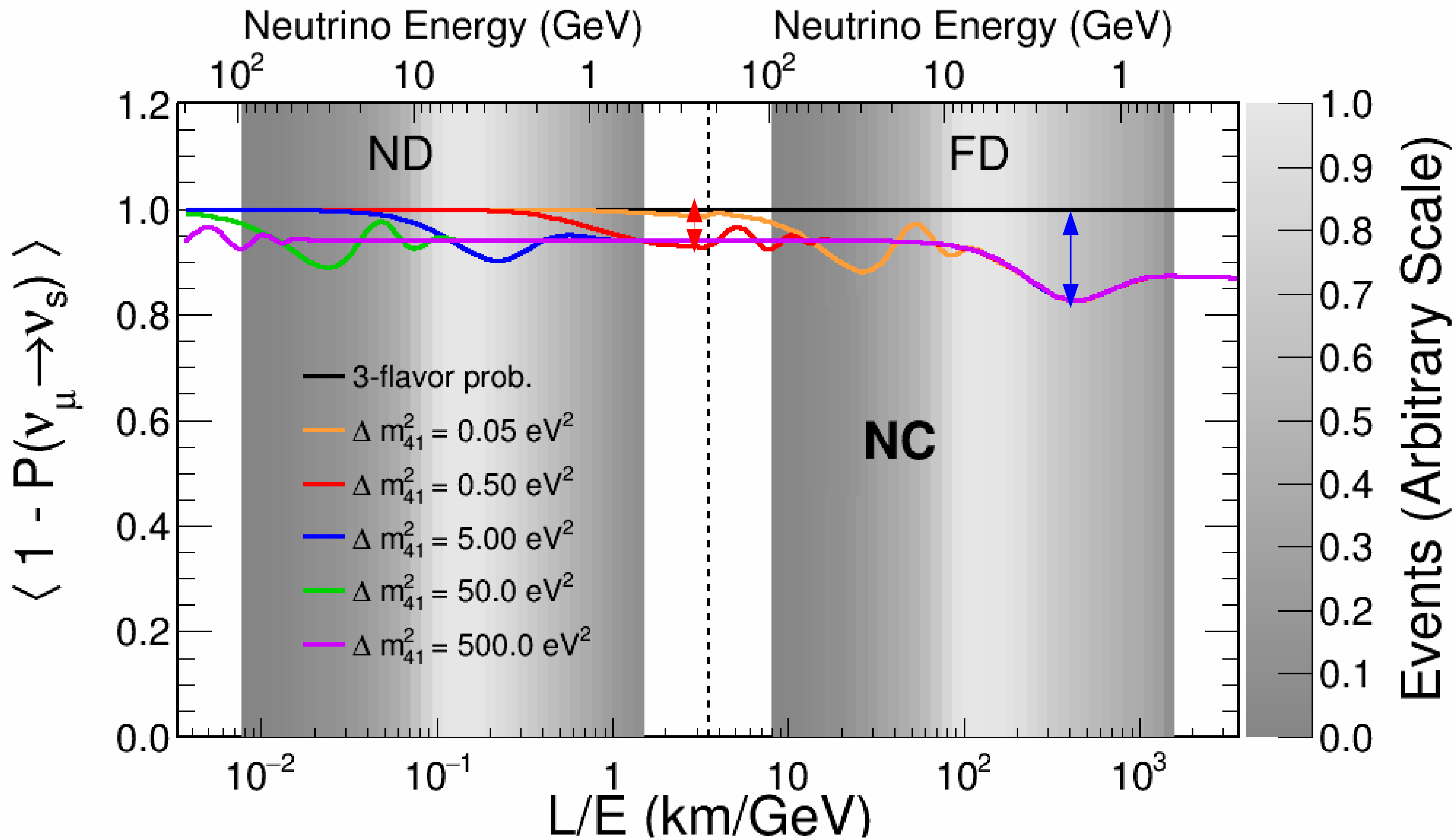


Systematics: Acceptance





Oscillations at Very Large Δm^2_{41}



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

Degeneracies

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

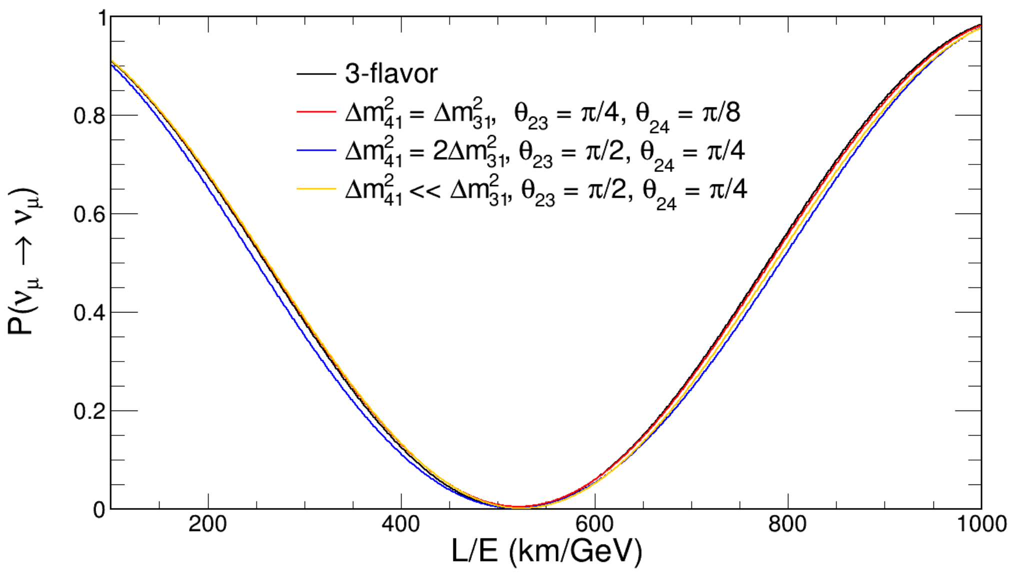
where $\Delta_{ij} = \frac{\Delta m^2_{ij} L}{4E}$

If:

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

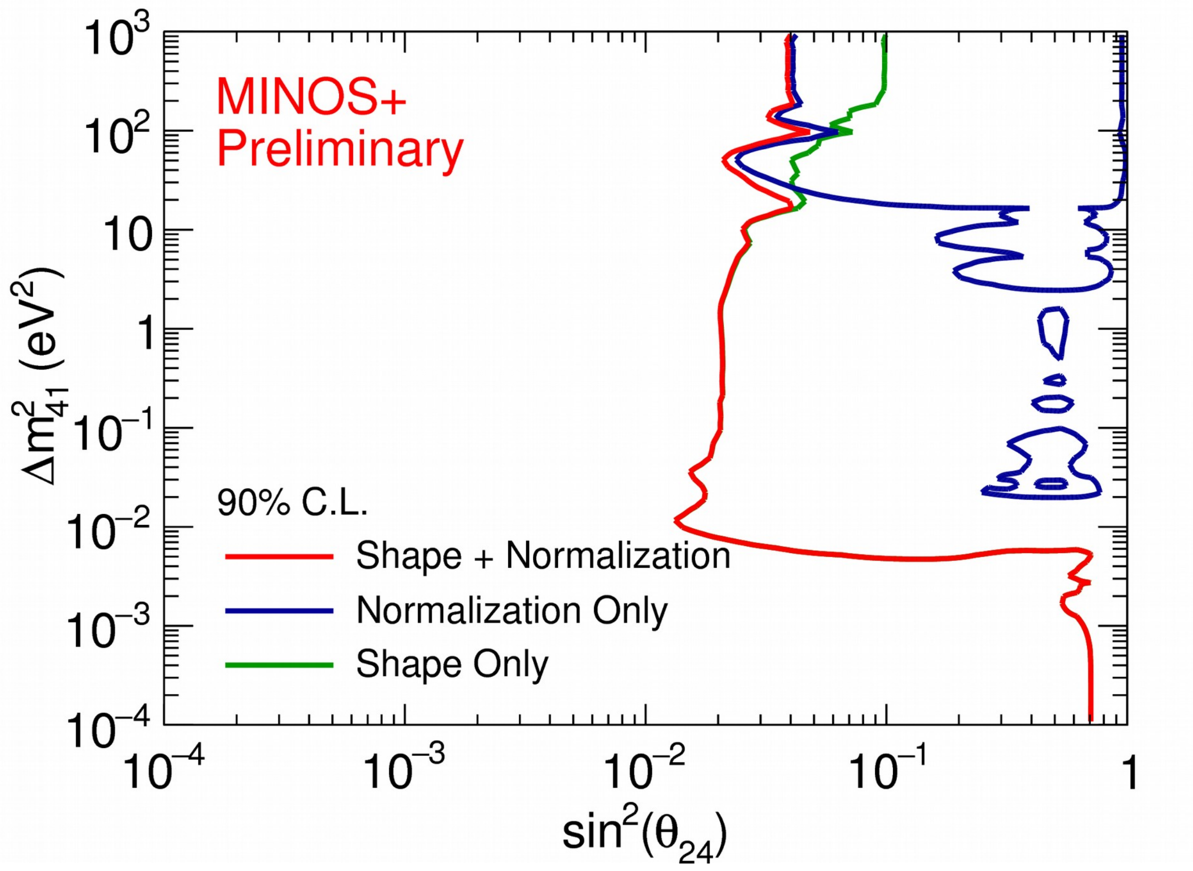
Certain combinations of θ_{23}, θ_{24}, and θ_{34} can produce 4-flavor solutions nearly indistinguishable from 3-flavor.

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

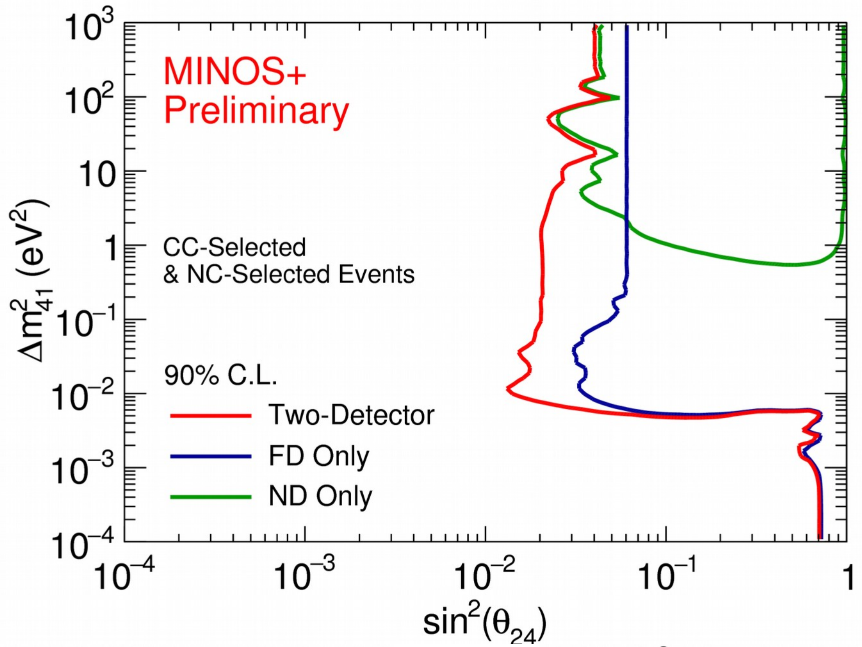


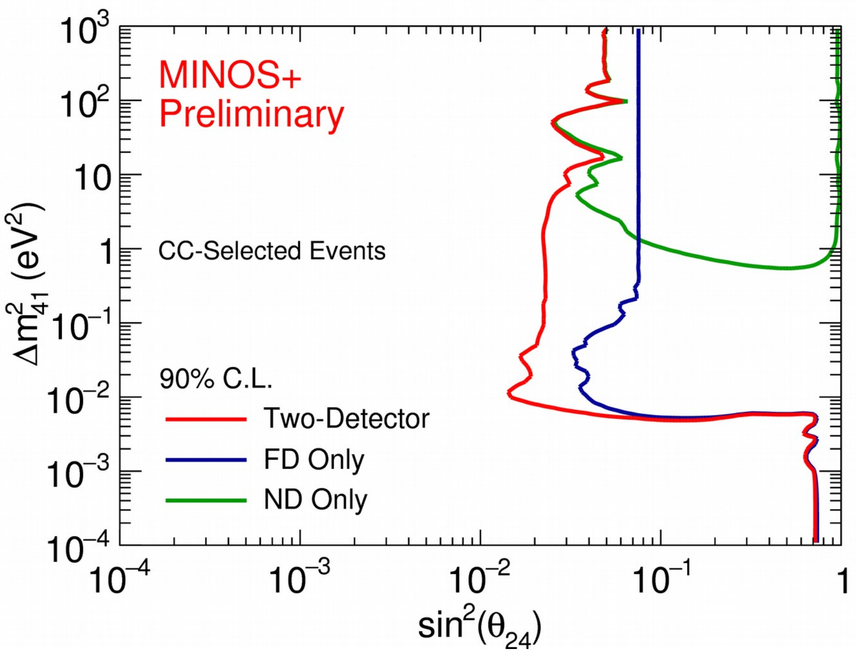
Example degenerate scenarios

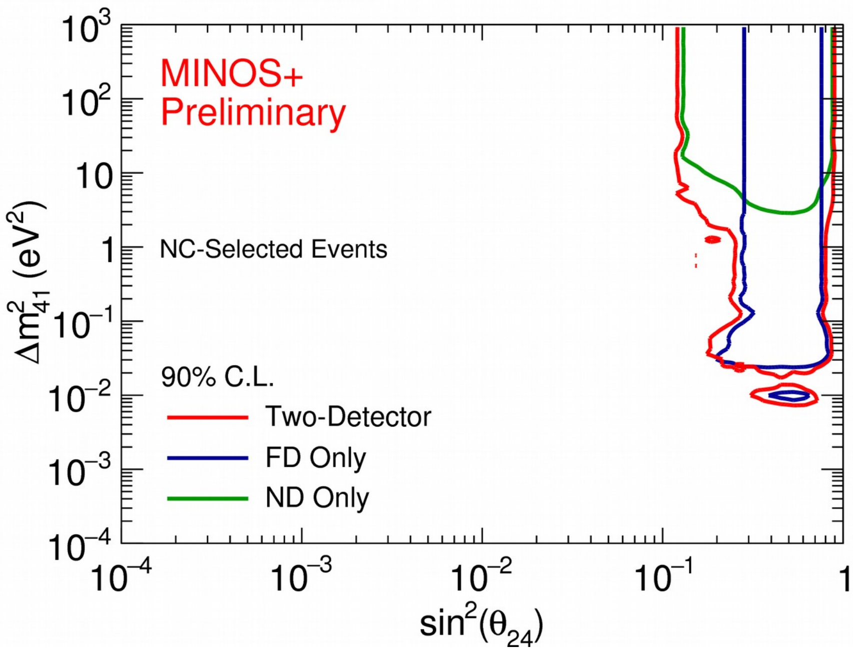
Sensitivity: Shape vs. Normalization



Sensitivity: CC vs. NC







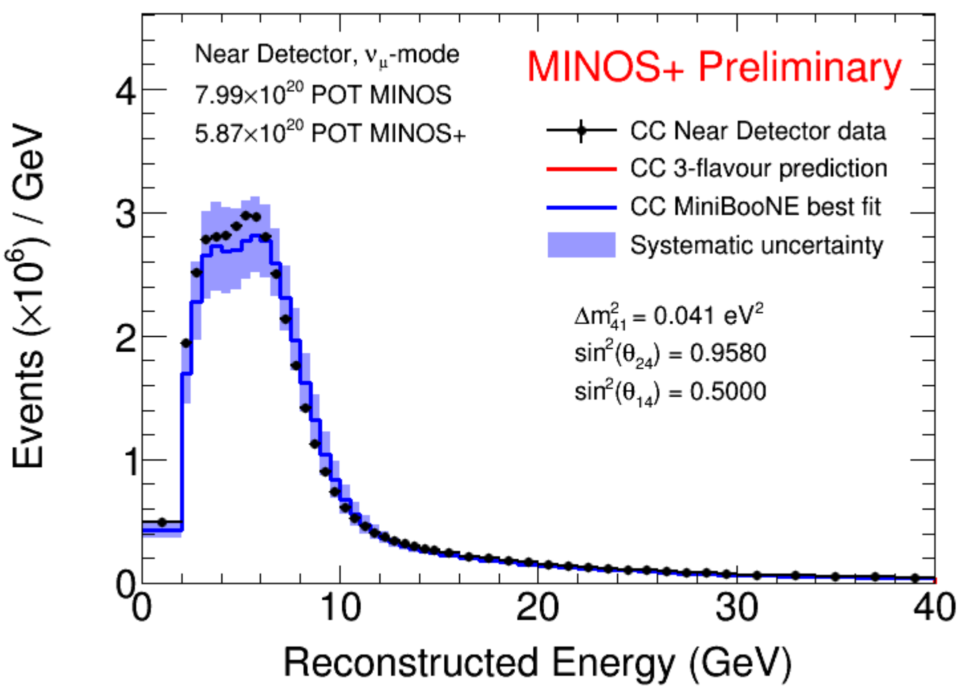
Comparison to MiniBooNE's Best Fit: CC Sample

New MiniBooNE paper – arXiv:1805.12028

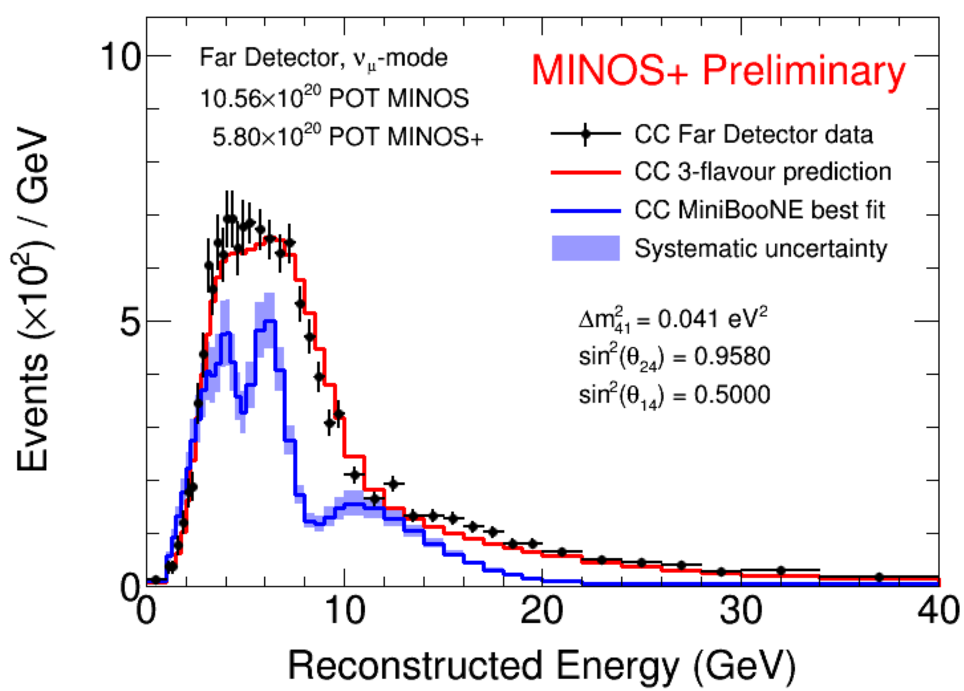
Best fit: $\Delta m^2 = 0.041\ eV^2$ and $\sin^2 2\theta_{\mu e} = 0.958$

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

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



Near Detector

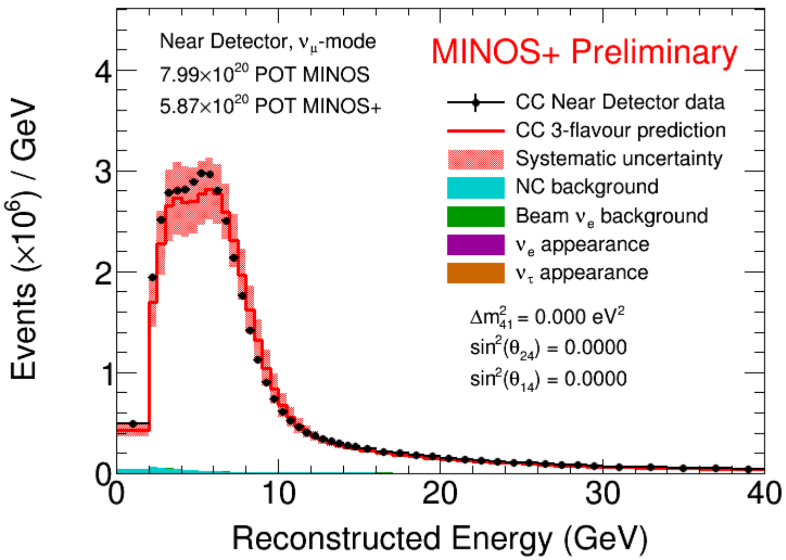


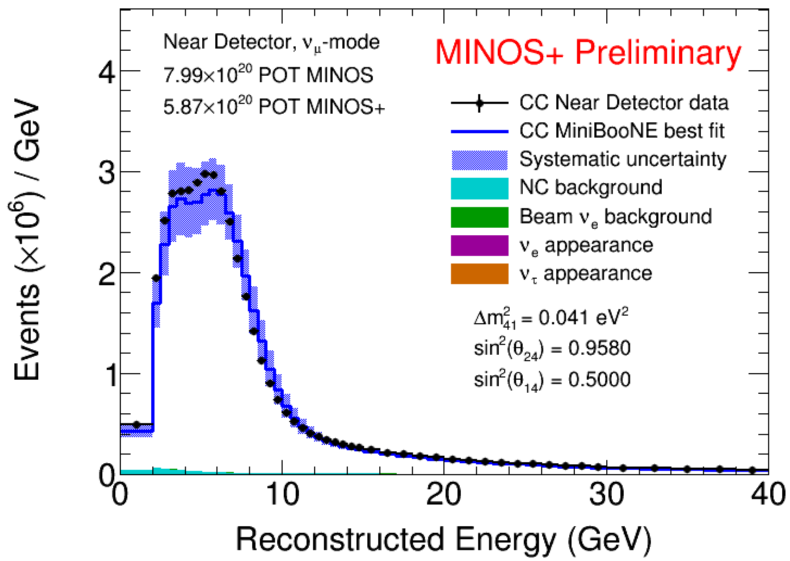
Far Detector

Comparison to MiniBooNE's Best Fit: CC Sample

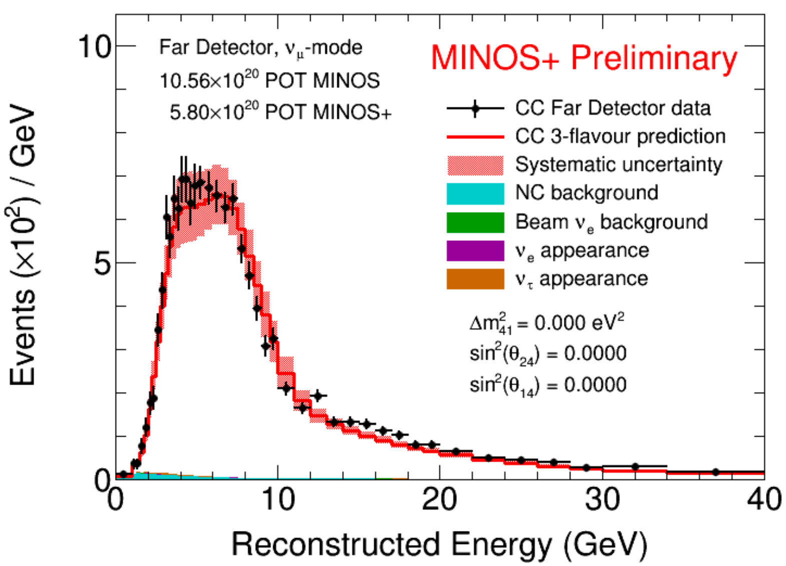
Three-flavor Oscillations | MiniBooNE's Best Fit

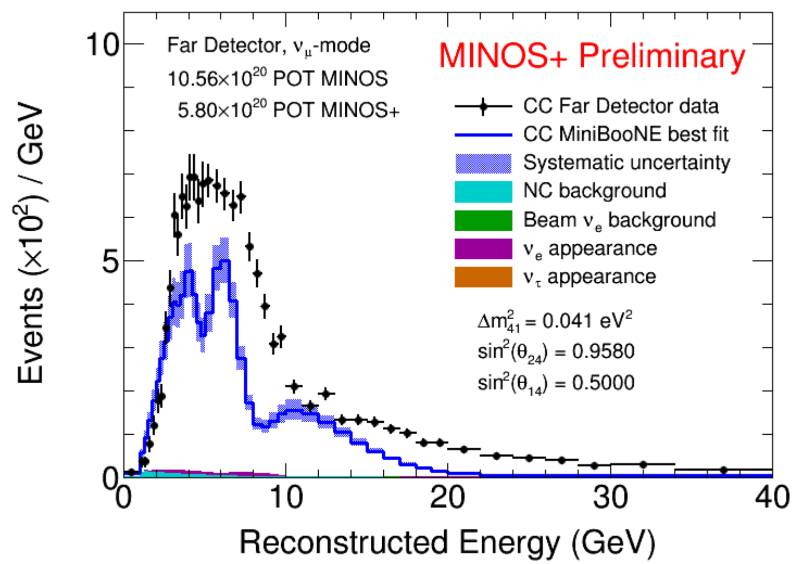
Near Detector





Far Detector





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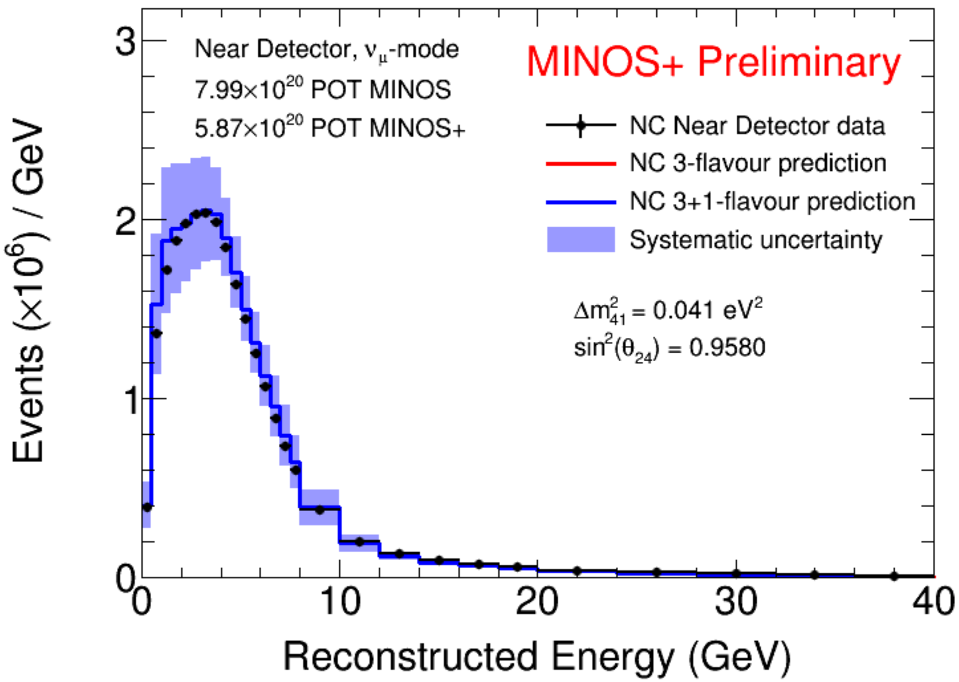
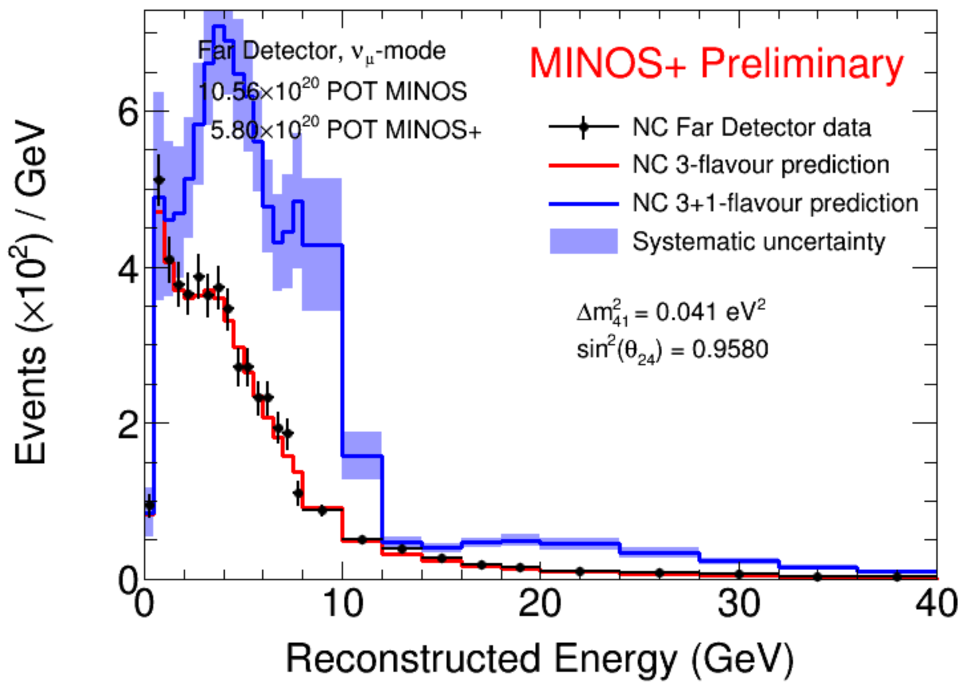


Near Detector



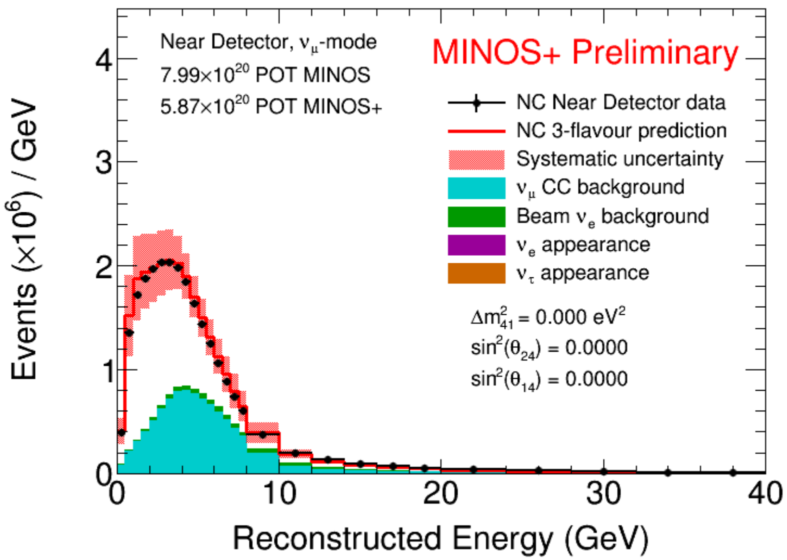
Far Detector

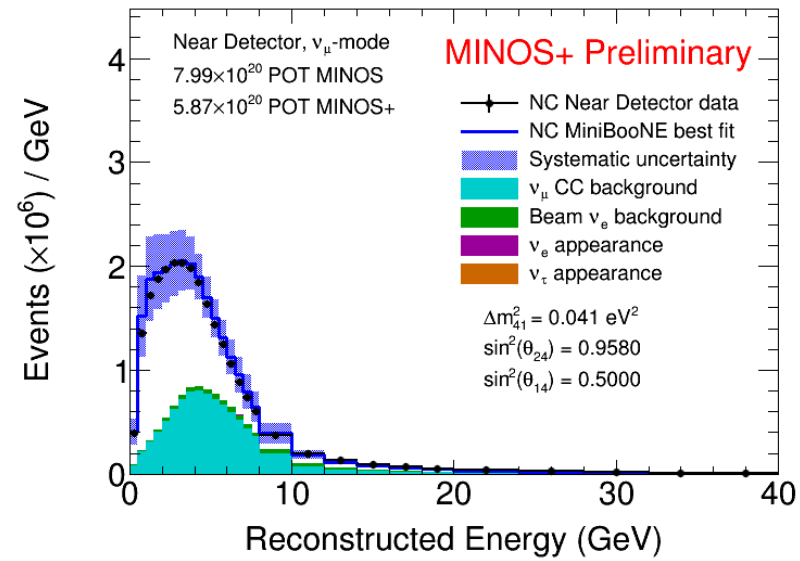
Comparison to MiniBooNE's Best Fit: NC Sample

Three-flavor Oscillations

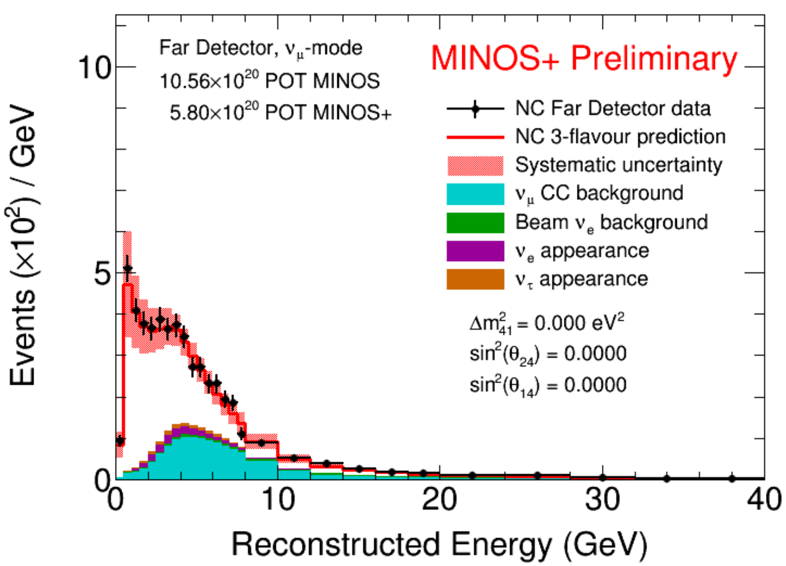
MiniBooNE's Best Fit

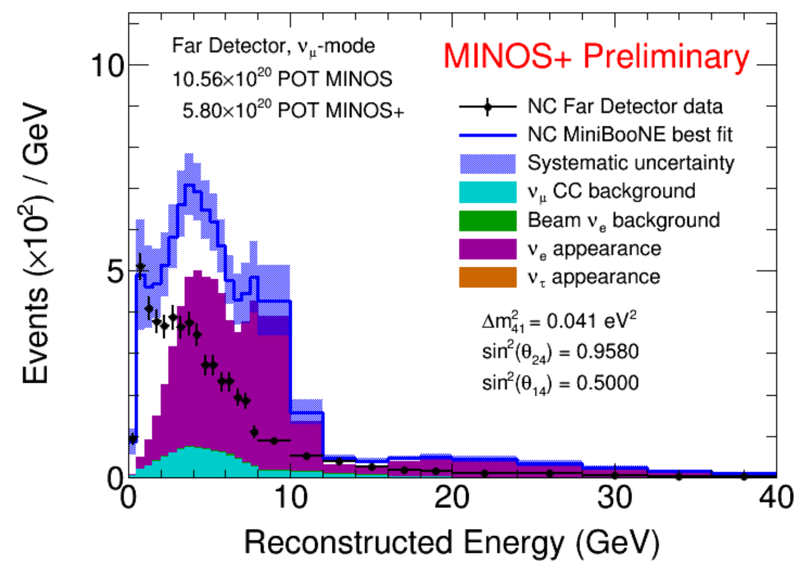
Near Detector



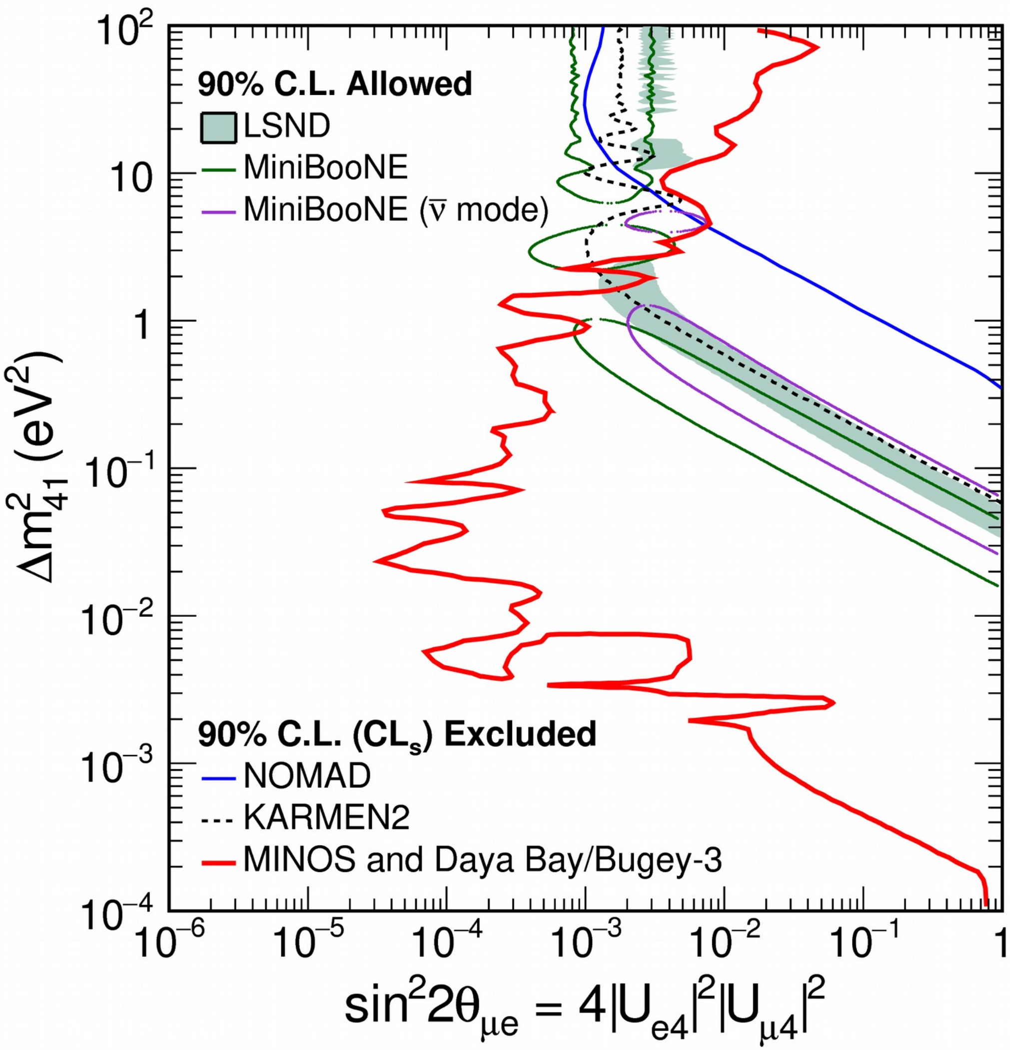


Far Detector



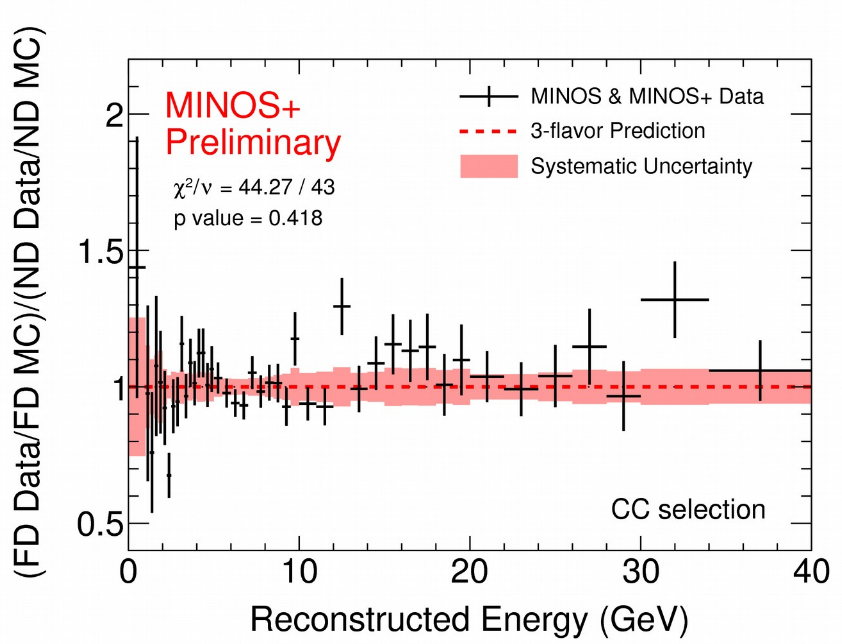


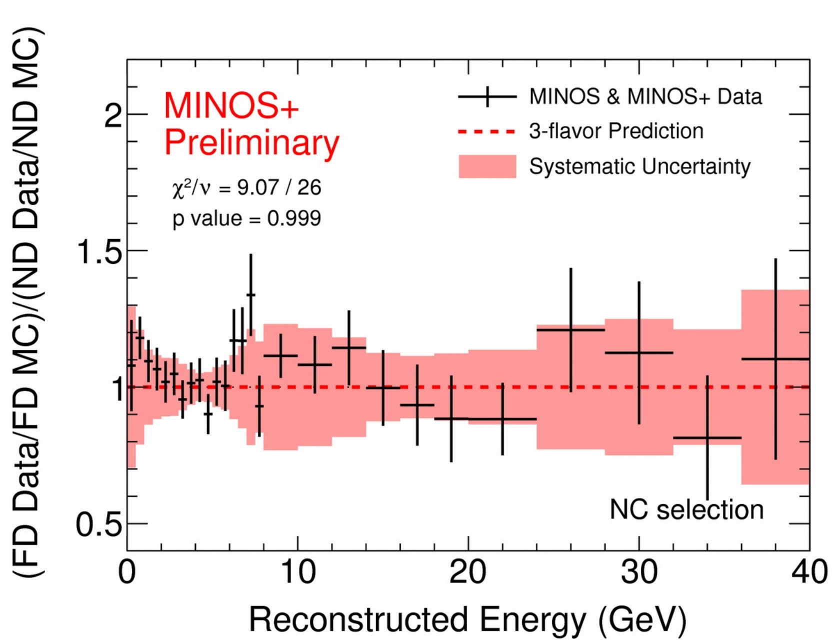
Comparison to MiniBooNE: MINOS/Daya Bay/Bugey Combination



- 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

Consistency with Three Flavor Oscillations





Inadequacy of the Asimov Sensitivity