

Searching for Sterile Neutrinos with MINOS & MINOS+

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URA Thesis Award

52nd Annual Fermilab Users Meeting

12 June 2019



Outline

- ◆ MINOS and MINOS+
- ◆ Final Three-flavor oscillations results
- ◆ Sterile Neutrino Search
 - *Recently published*
 - Two-detector simultaneous fit
 - ν_μ -CC and NC disappearance
 - Full MINOS ν_μ beam sample
 - First two years of MINOS+
- ◆ Summary



The MINOS+ Collaboration



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+

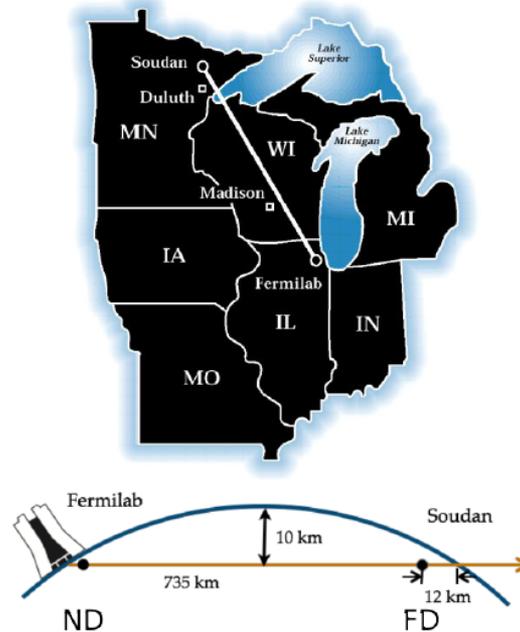
◆ Designed to study neutrino oscillations over a long-baseline using two functionally identical detectors

- Iron-scintillator tracking calorimeters – good muon containment
- Magnetized for sign selection and energy estimation
- Numerous systematics cancel to first order

◆ Detectors are on the NuMI beam axis

◆ Near Detector

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



◆ Far Detector

- Location: Soudan Underground Laboratory
- 5.4 kton mass
- 735 km baseline



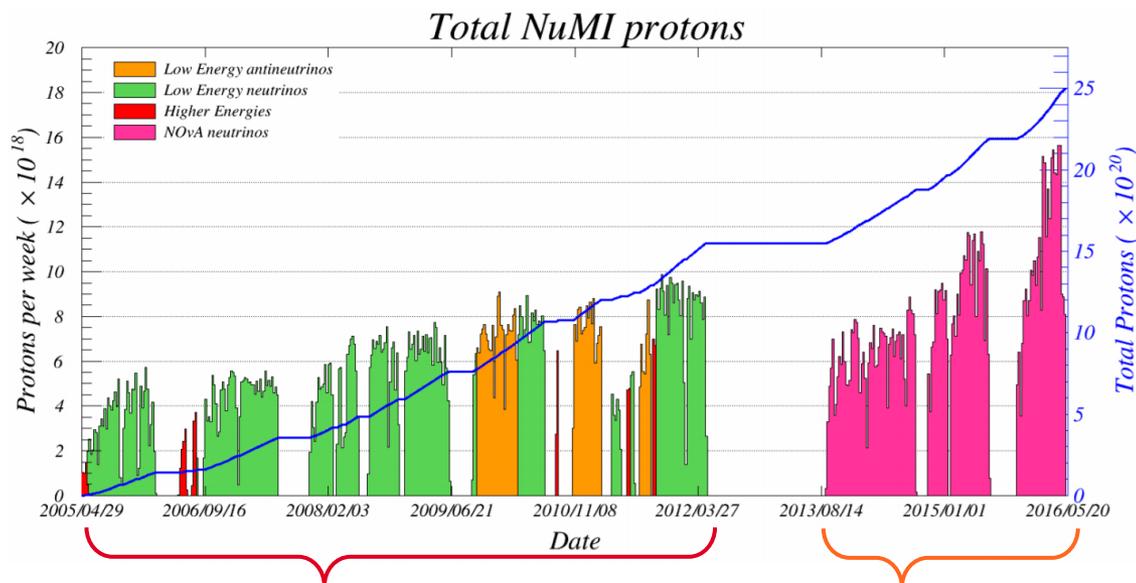
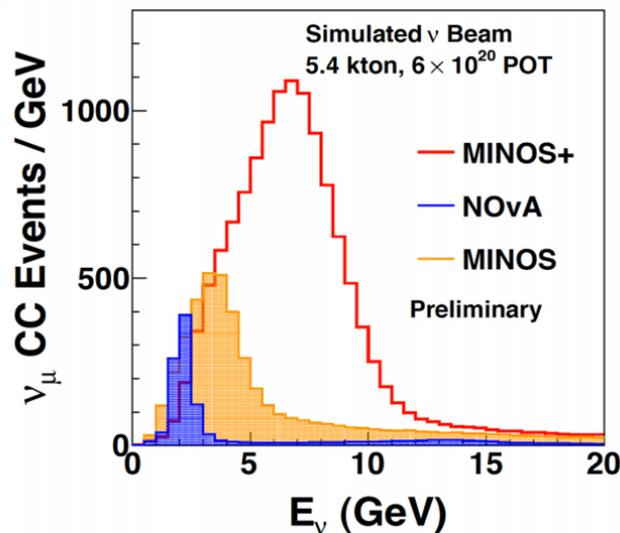
The NuMI Beam

◆ 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+:

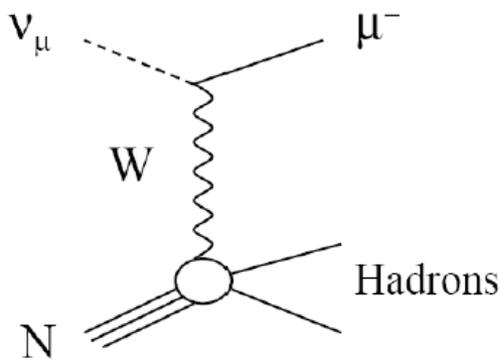
- 9.69×10^{20} POT (ν_{μ} -mode)

MINOS & MINOS+

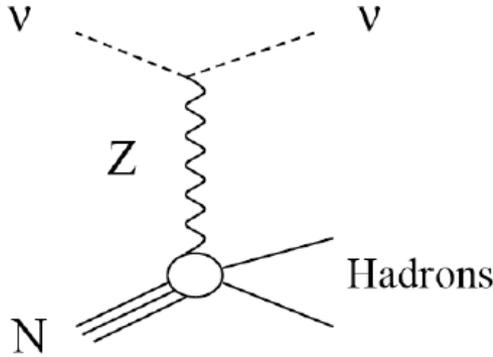
- $\sim 25 \times 10^{20}$ POT in 11 years of running

Event Topologies

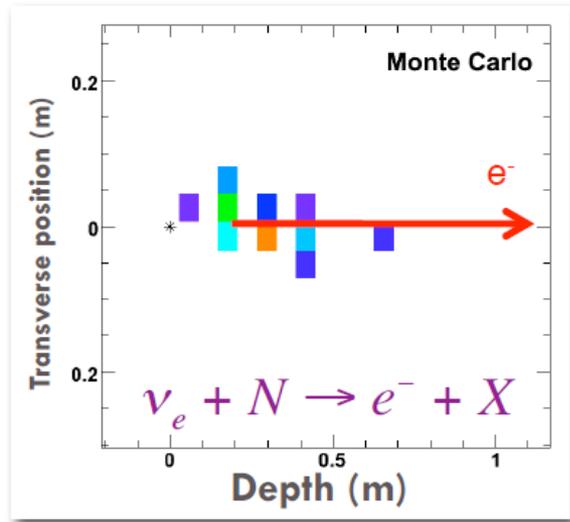
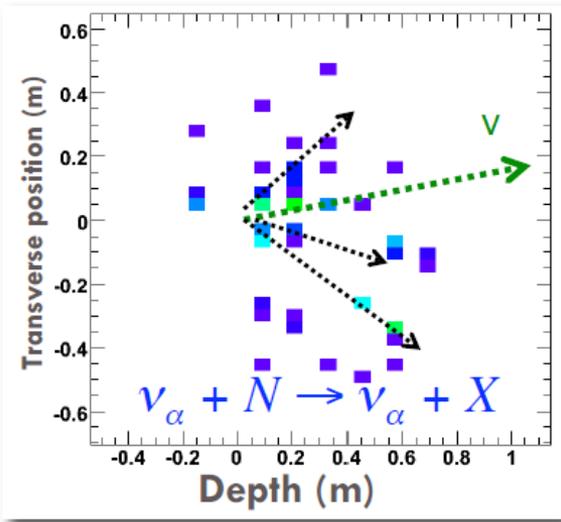
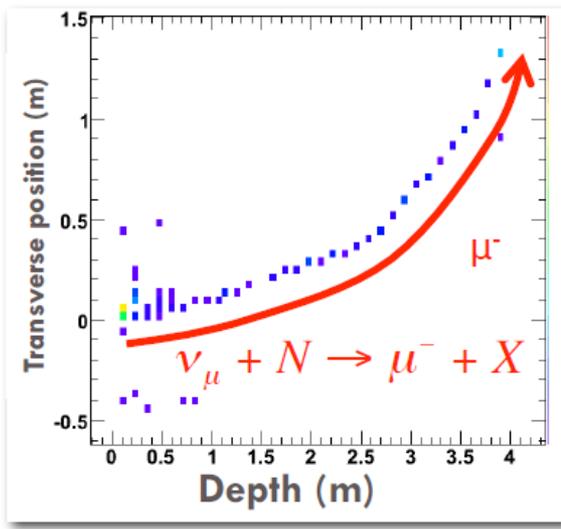
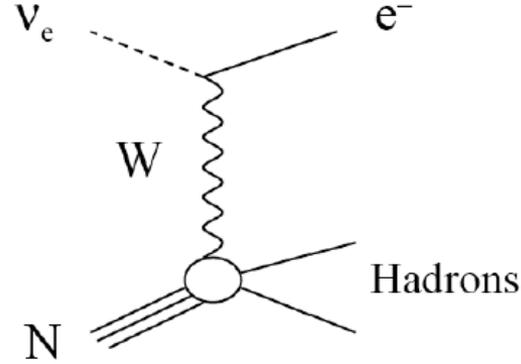
ν_μ CC Event



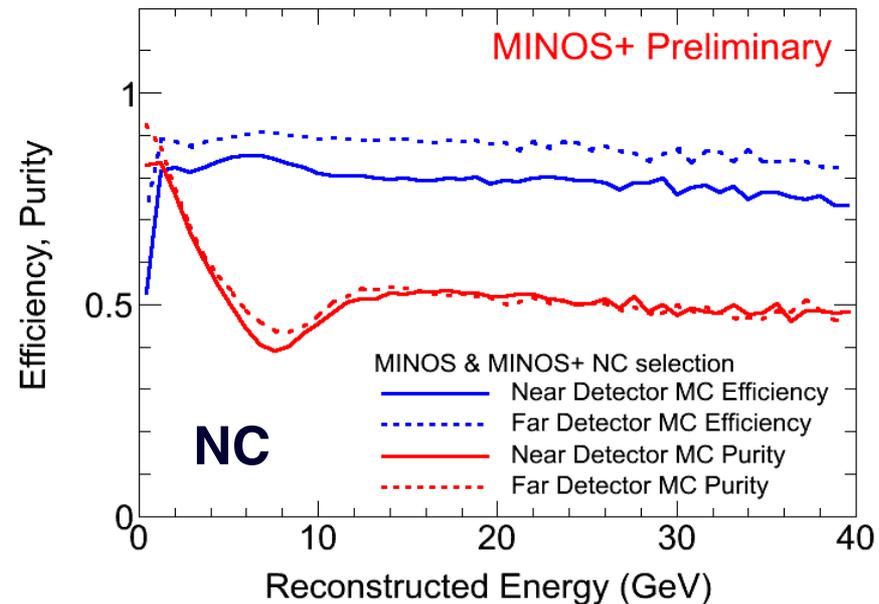
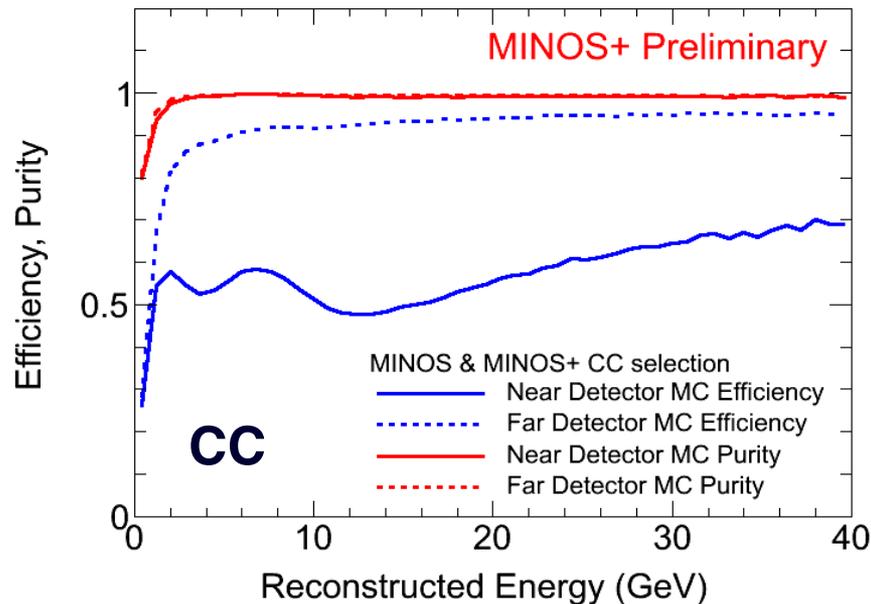
NC Event



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

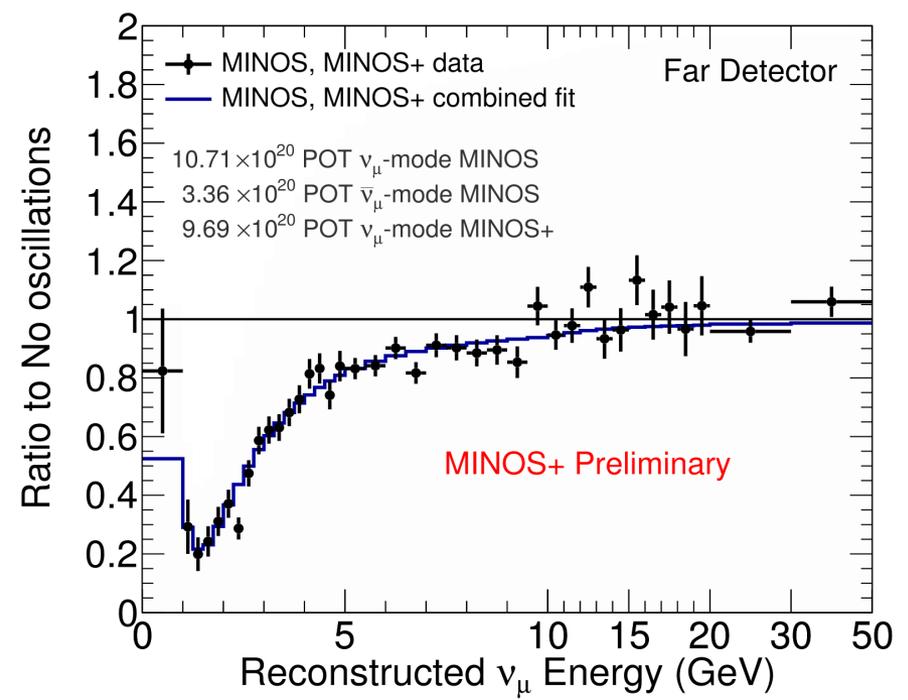
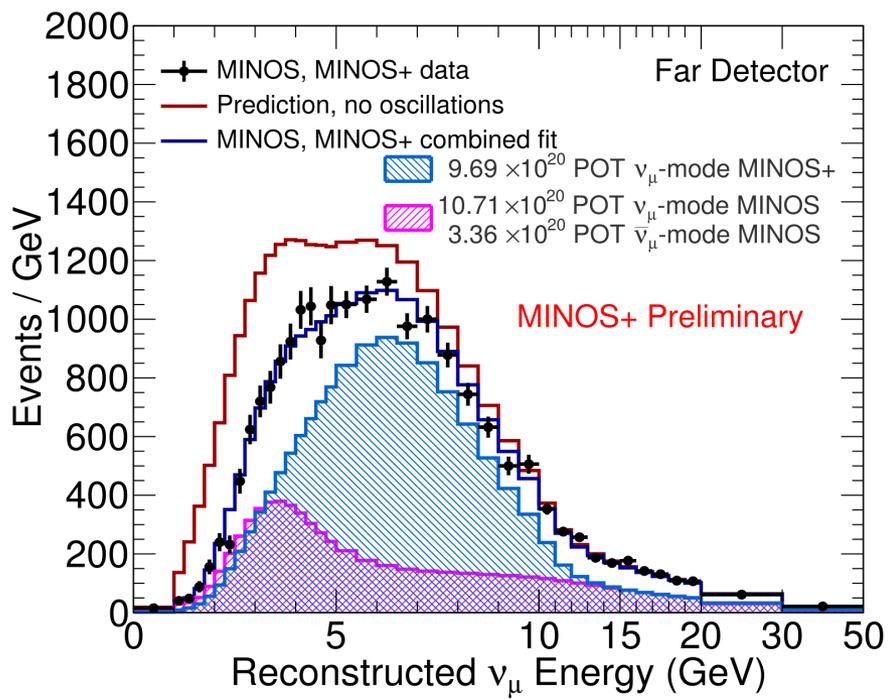


485

V_μ

Three-Flavor Oscillations Analysis

Far Detector Beam Data



- ◆ MINOS and MINOS+ probe muon-neutrino disappearance over a broad range of energies
- ◆ Strong agreement with three flavor prediction
 - Constrains potential for alternate oscillation hypotheses

Combined Fit Results

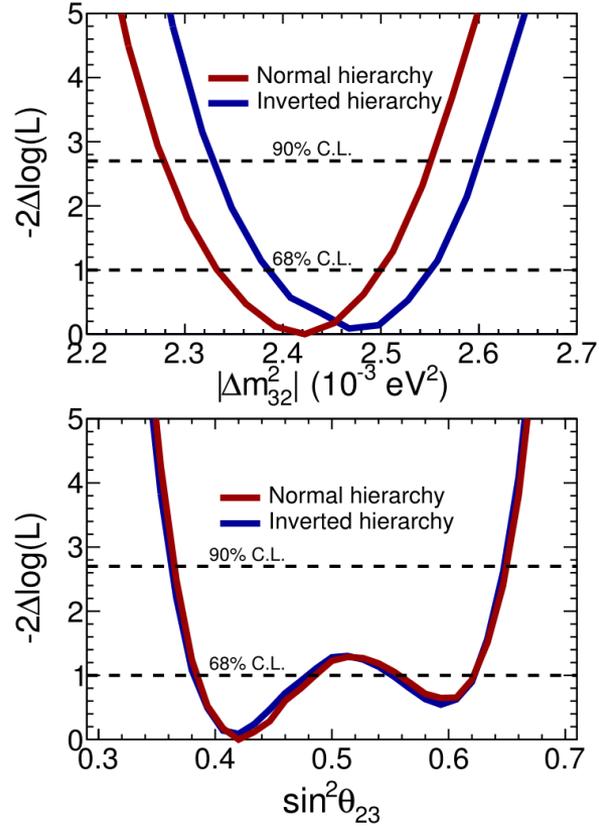
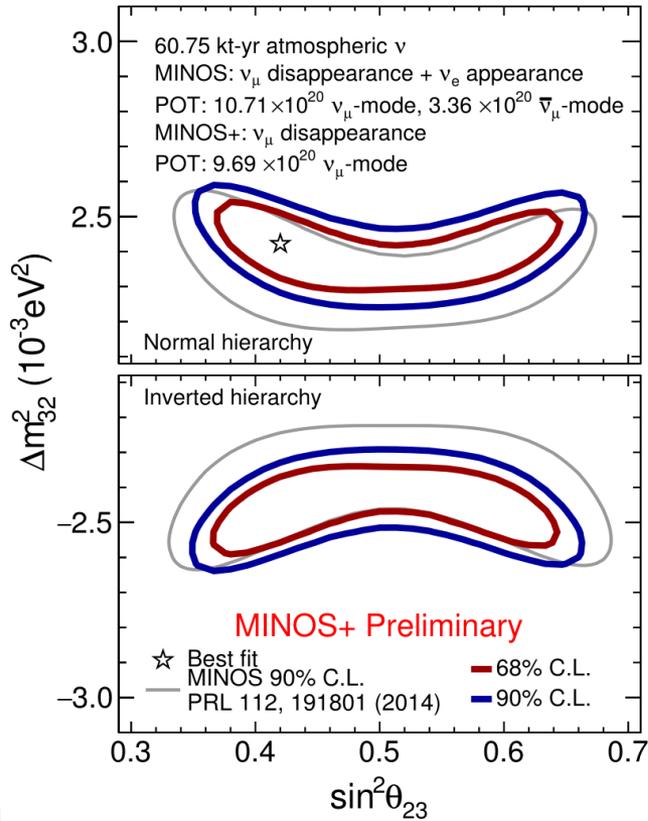
Best Fit

$\Delta m^2_{32} = 2.42 \times 10^{-3} \text{ eV}^2$
 $\sin^2 \theta_{23} = 0.42$

Confidence Intervals

Mass Splitting ($\times 10^{-3} \text{ eV}^2$)
 NH: $2.33 < \Delta m^2_{32} < 2.50$
 IH: $-2.38 > \Delta m^2_{32} > -2.55$

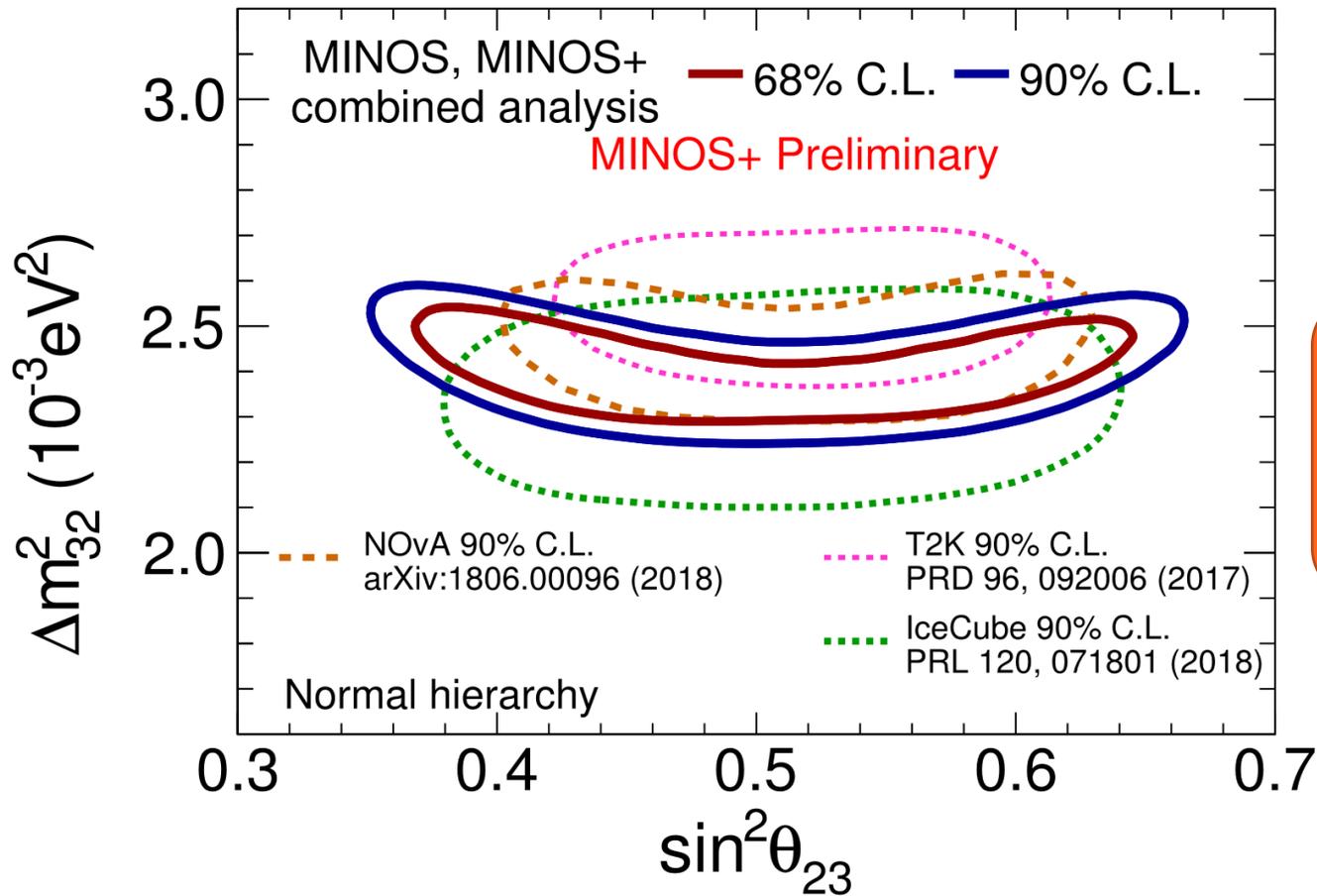
Mixing Angle
 NH: $0.37 < \sin^2 \theta_{23} < 0.65$
 IH: $0.36 < \sin^2 \theta_{23} < 0.65$



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.

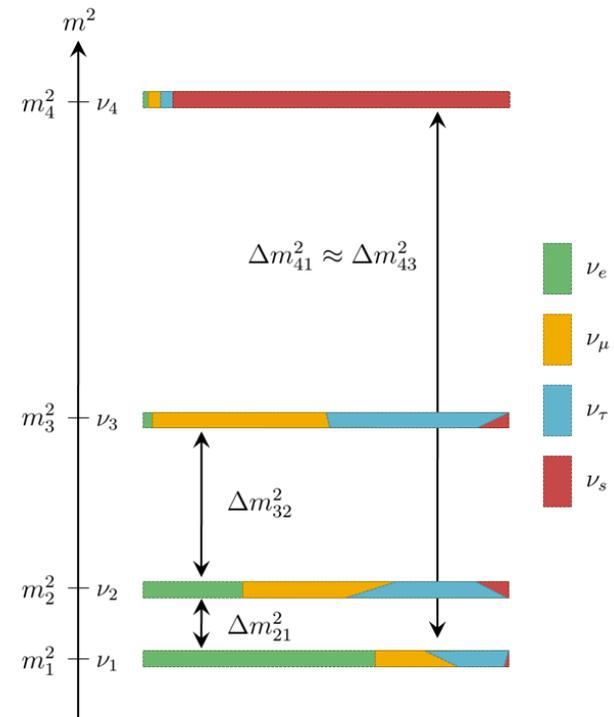
Sterile Neutrino Search



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 ($\theta_{14}, \theta_{24}, \theta_{34}$)
 - Two CP-violating phases (δ_{14}, δ_{24})
- ◆ Search for two signals
 - Neutral current disappearance
 - NC events unaffected by 3-flavor oscillations
 - Sterile neutrinos cause apparent depletion
 - Sensitive to $\Delta m^2_{41}, \theta_{24}, \theta_{34}$
 - ν_μ -charged current disappearance
 - Sterile neutrinos cause modulations with differing frequency to 3-flavor oscillations
 - Sensitive to Δm^2_{41} and θ_{24}

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$



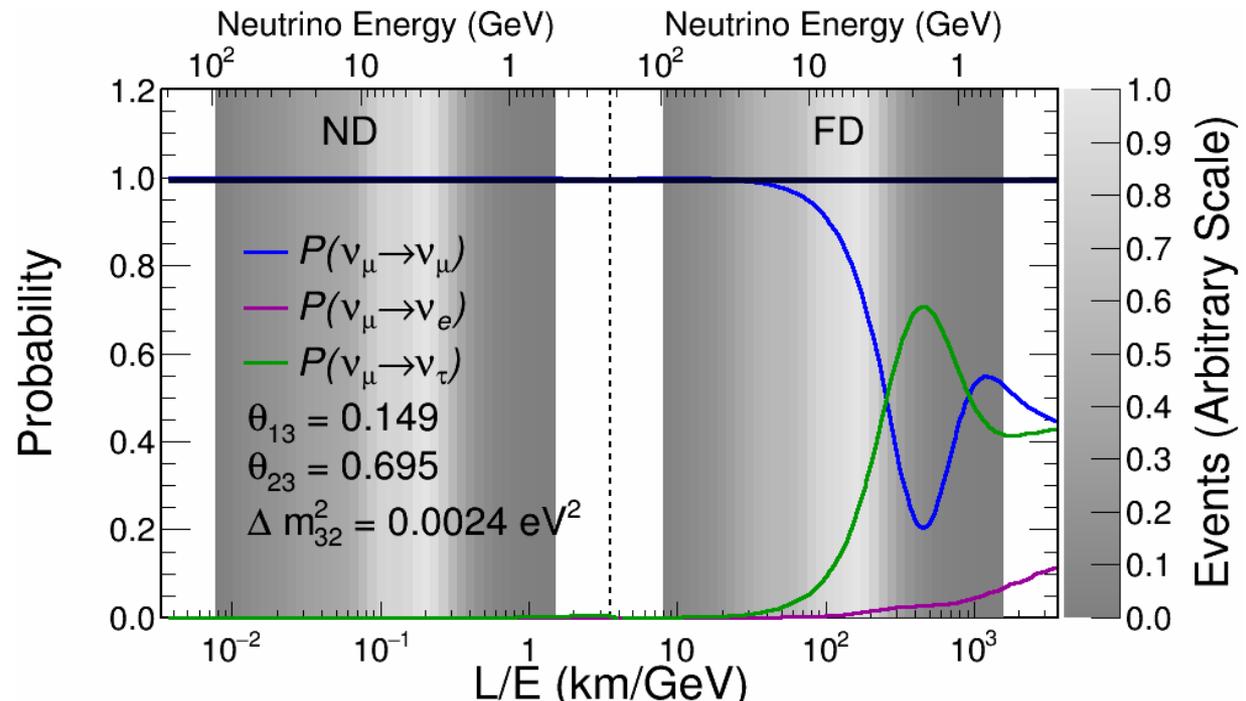
Standard (3-flavor) Oscillations

$$\Delta m_{41}^2 = 0 \text{ eV}^2$$

◆ Far Detector oscillations *only*

- CC signal – single pronounced oscillation maximum
- NC signal – no oscillations observed

◆ Near Detector observes no oscillations, constrains beam and cancels systematics

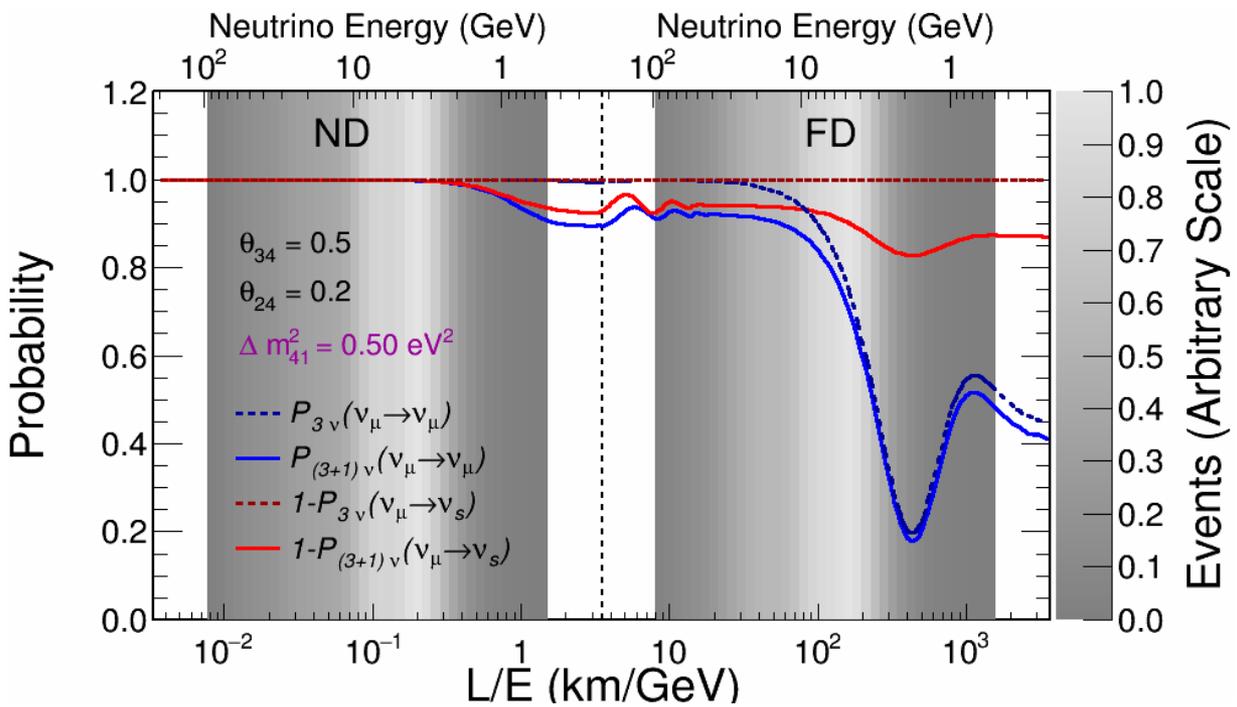


(3+1)-flavor Oscillations

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

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

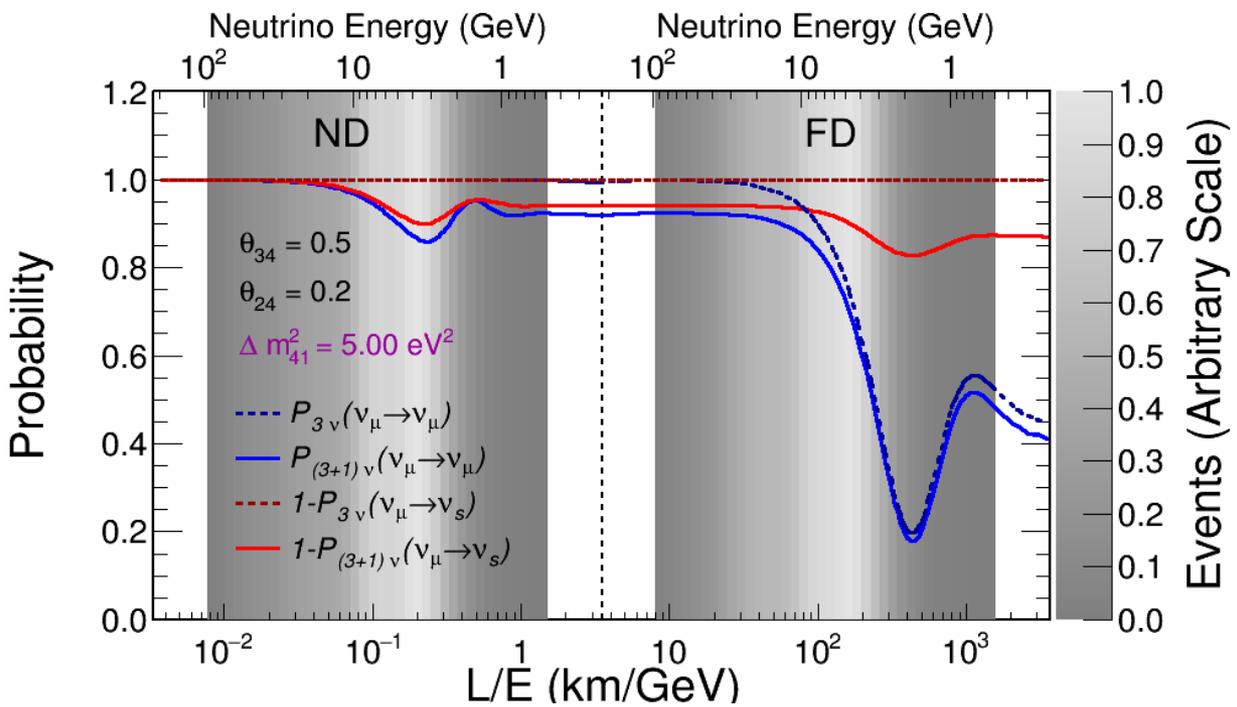
- ◆ Near Detector observes low energy deficit



(3+1)-flavor Oscillations

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

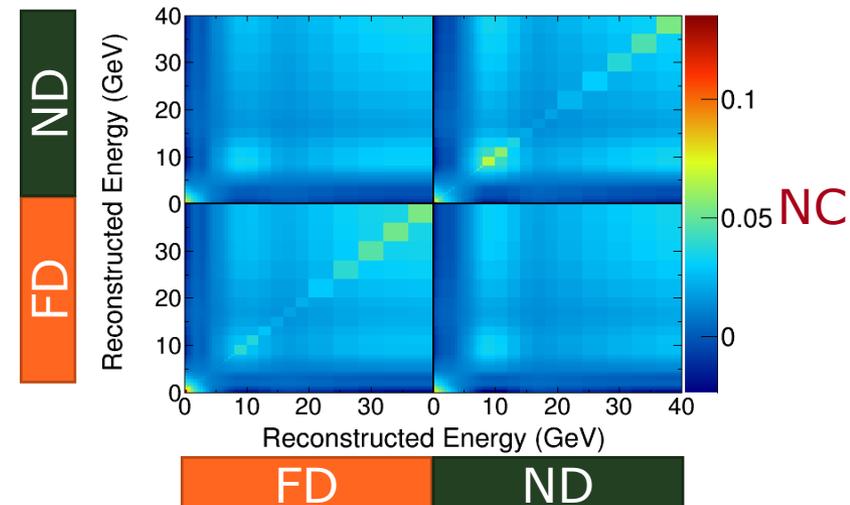
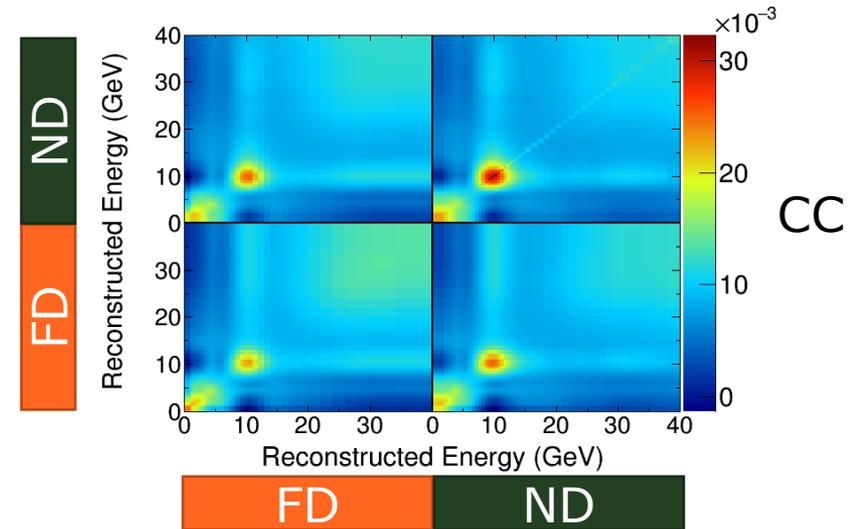
- ◆ Far Detector oscillations at two frequencies
 - CC signal – modulation on 3-flavor at high energy, net deficit
 - NC signal – deficit inconsistent with 3-flavor
- ◆ Near Detector observes oscillations inconsistent with 3-flavor in both samples



Simultaneous Two-Detector Fit

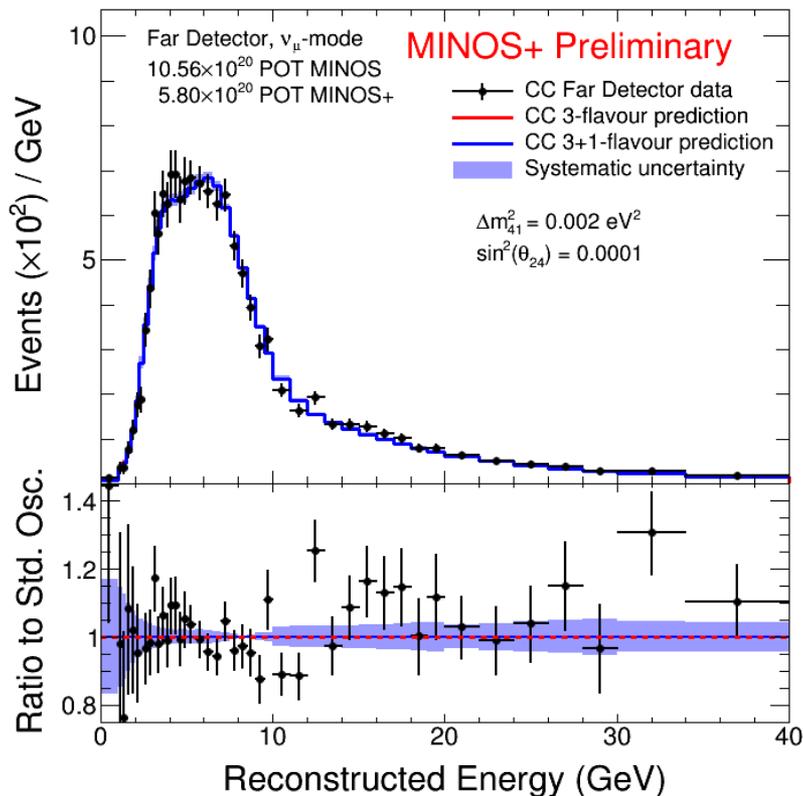
- ◆ Near and Far Detectors are fit simultaneously with coequal treatment
 - Maximal utilization of extremely high Near Detector event rate
 - Flux estimate derived from MINERvA PPFX method which uses only hadron production experiment data
- ◆ Systematic uncertainties are encoded in covariance matrices
 - 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

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

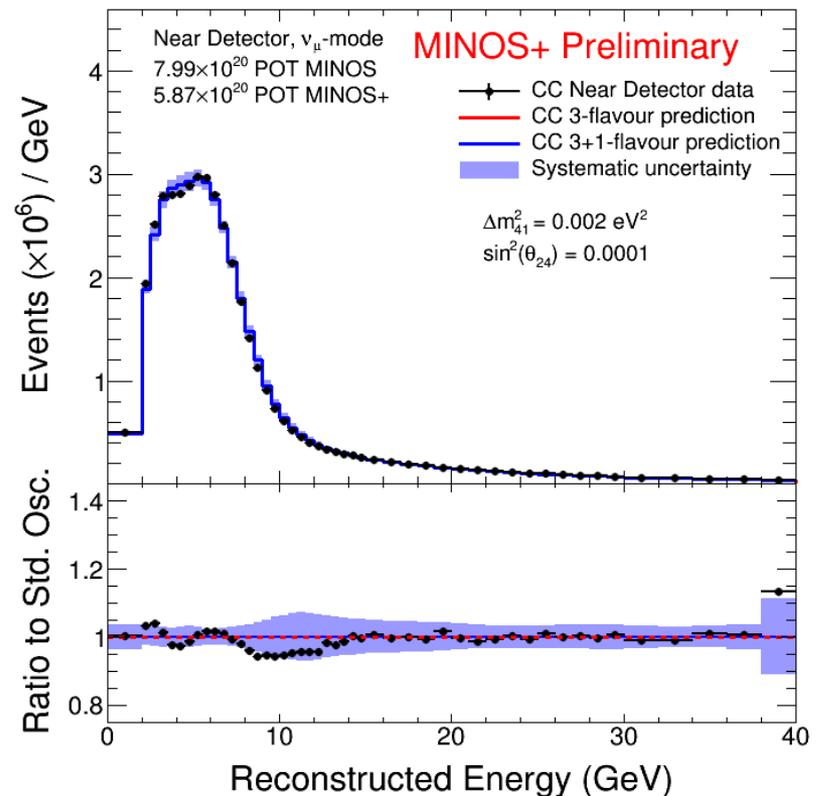


ν_μ CC Sample

Far Detector



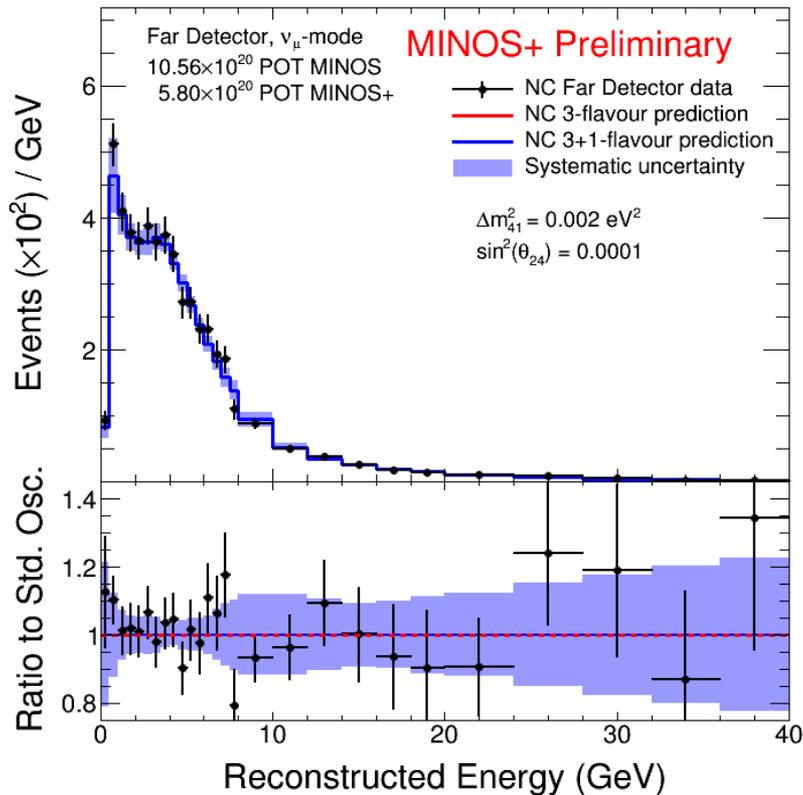
Near Detector



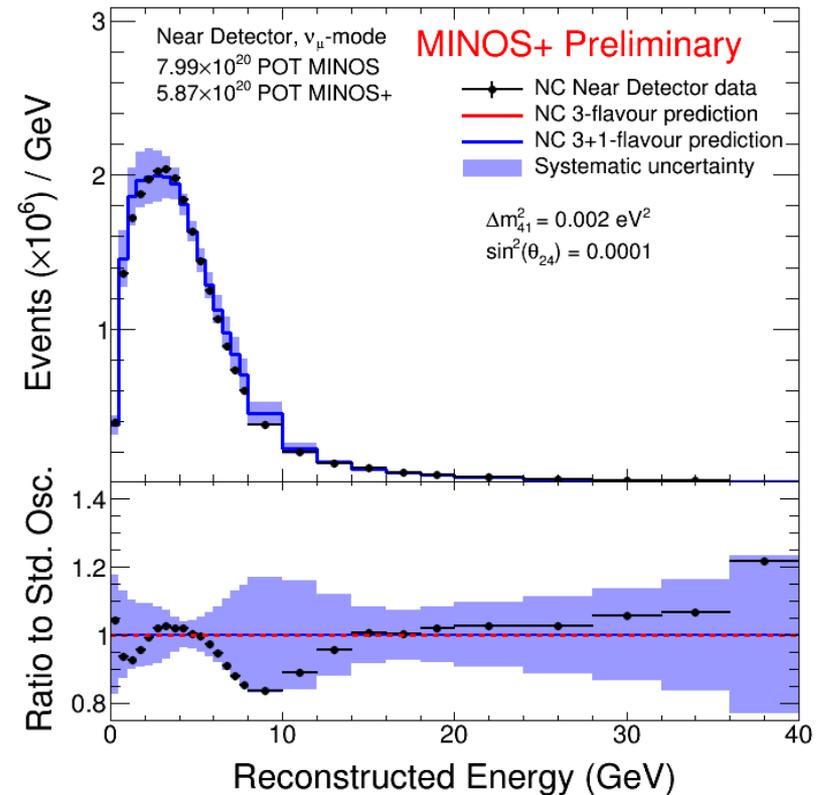
- ◆ Data consistent with 3-flavor oscillations paradigm
- ◆ No evidence for significant spectral modulations outside of systematic or statistical sources

NC Sample

Far Detector



Near Detector



- ◆ Data consistent with 3-flavor oscillations paradigm
- ◆ Greater systematic uncertainties correspond with the larger observed fluctuations

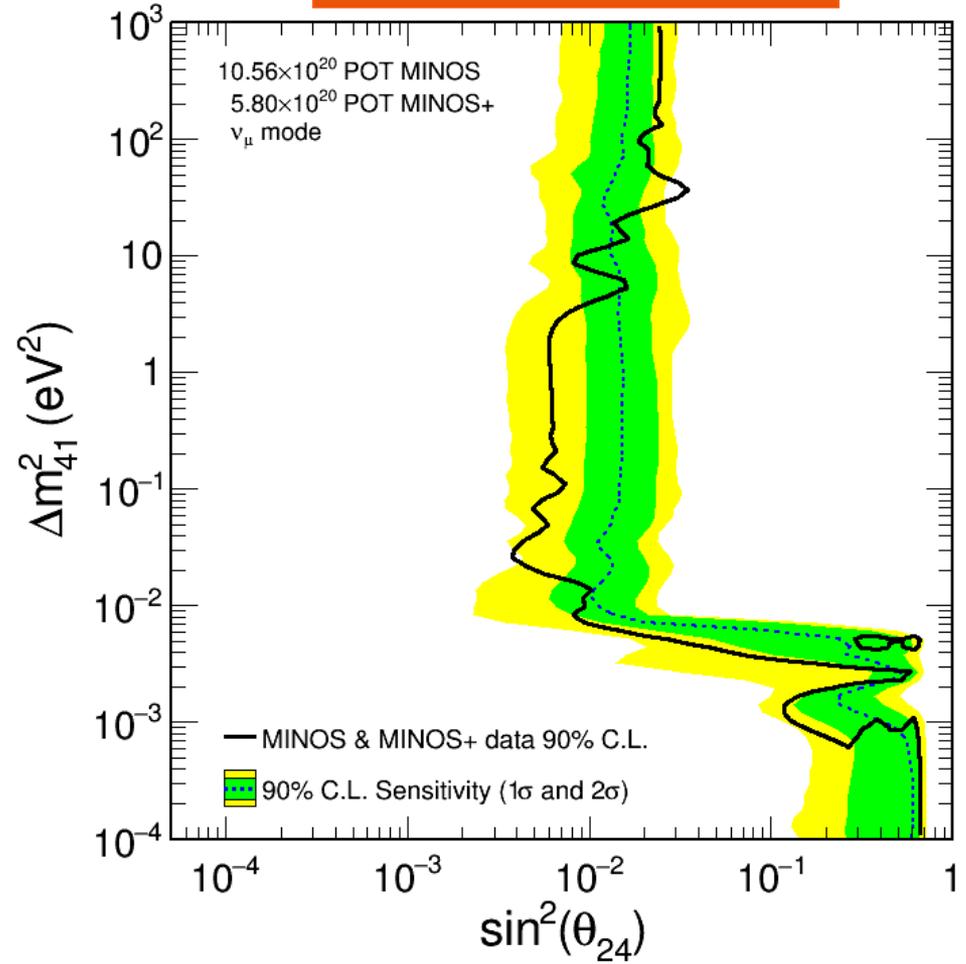
(3+1)-flavor Disappearance Limit

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

Best Fit

$\Delta m^2_{41} = 2.33 \times 10^{-3} \text{ eV}^2$
 $\sin^2 \theta_{24} = 1.1 \times 10^{-4}$
 $\theta_{34} = 7.0 \times 10^{-5}$
 $\chi^2_{\text{min}}/\text{dof} = 99.3/140$
 $\chi^2_{3\nu} - \chi^2_{4\nu} < 0.01$

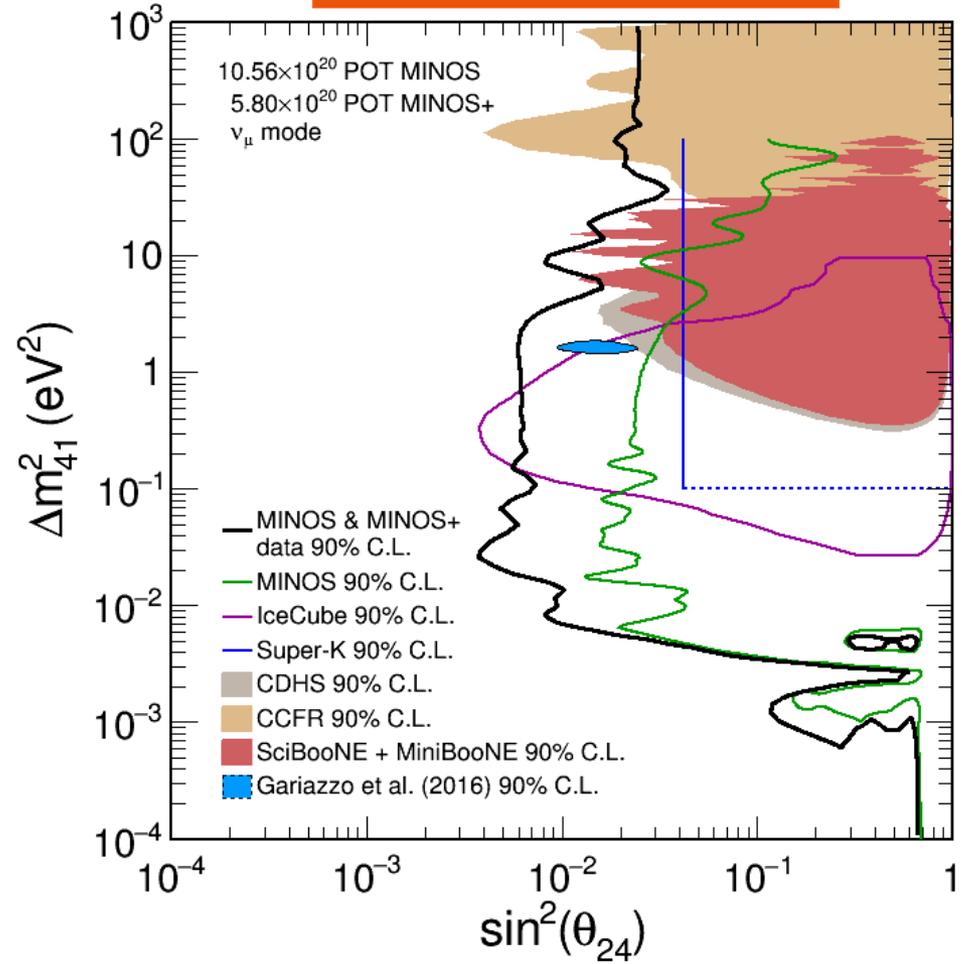
Phys. Rev. Lett. **122**, 091803



(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](https://arxiv.org/abs/1710.06488)
 - Ancillary materials included for more detail

Phys. Rev. Lett. **122**, 091803



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

Constraining (3+1)-flavor Appearance

◆ LSND and MiniBooNE observe excess electron neutrino appearance

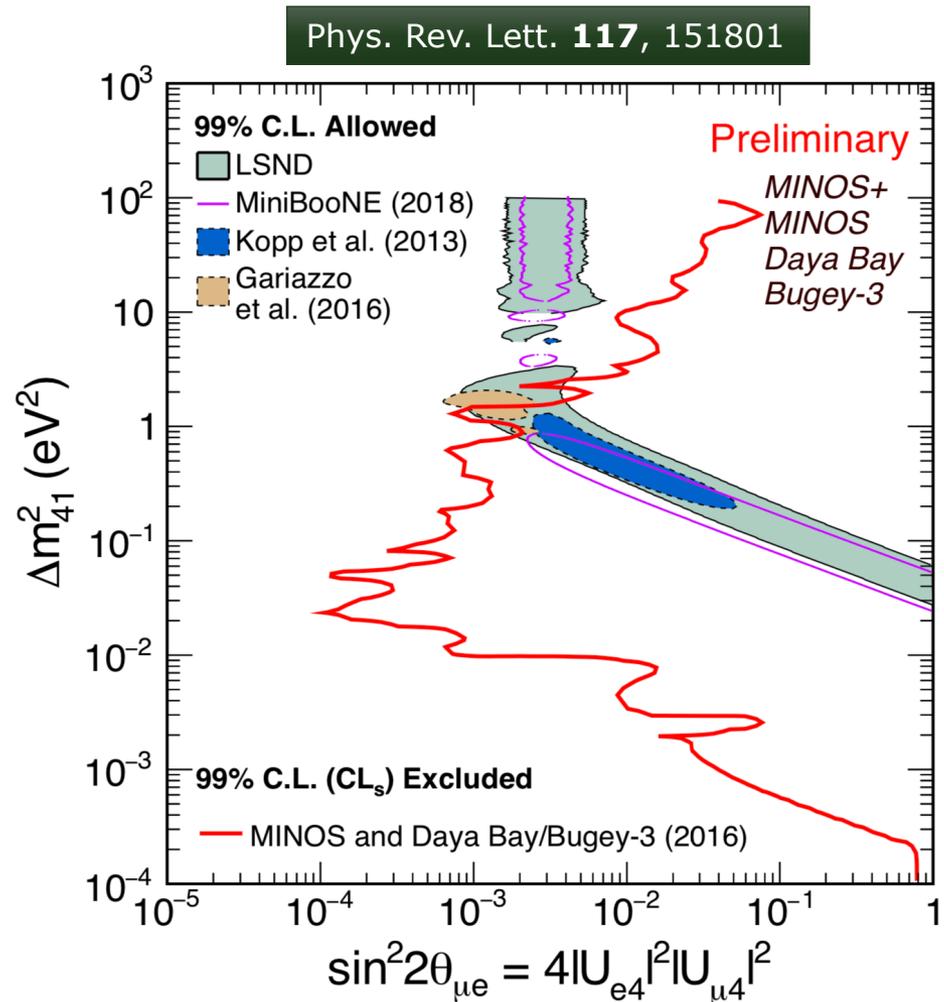
◆ Effective mixing angle observed in these short-baseline experiments given by:

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

◆ Daya Bay nuclear reactor experiment constrains $\sin^2(2\theta_{14})$

◆ Combination of results yields limit in the appearance space

- Previous combination published for MINOS-only analysis
- Combination in progress for new two-detector result



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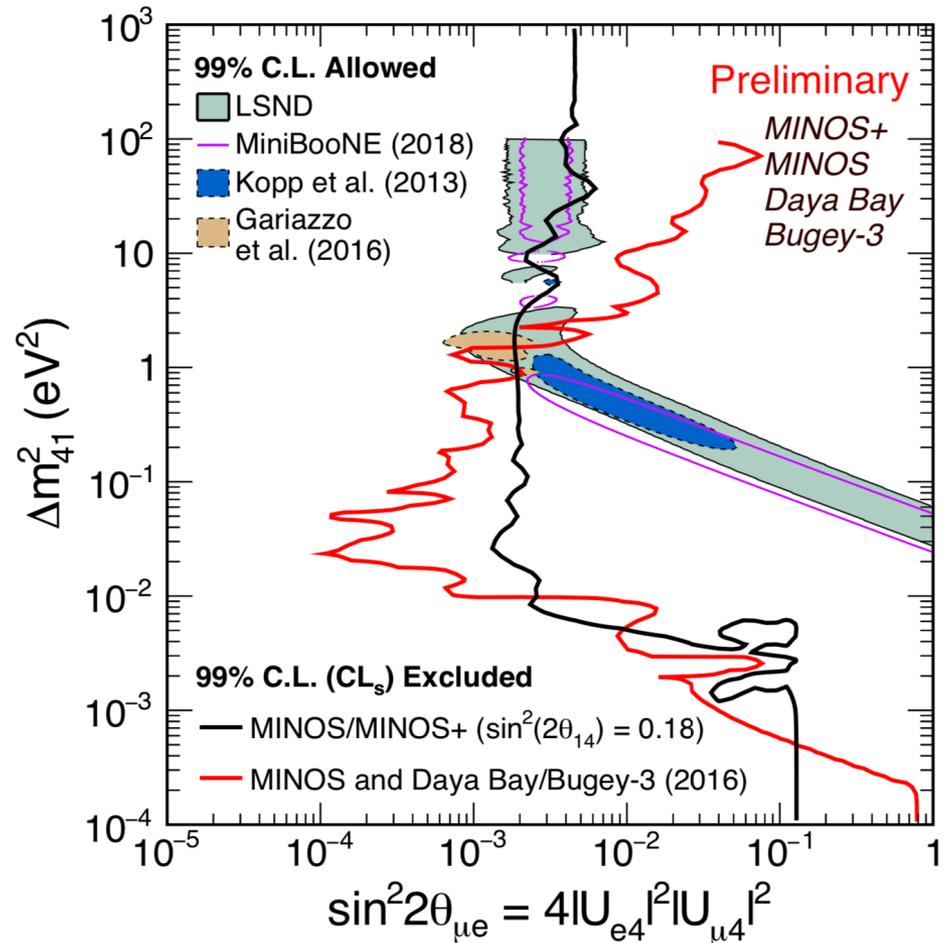
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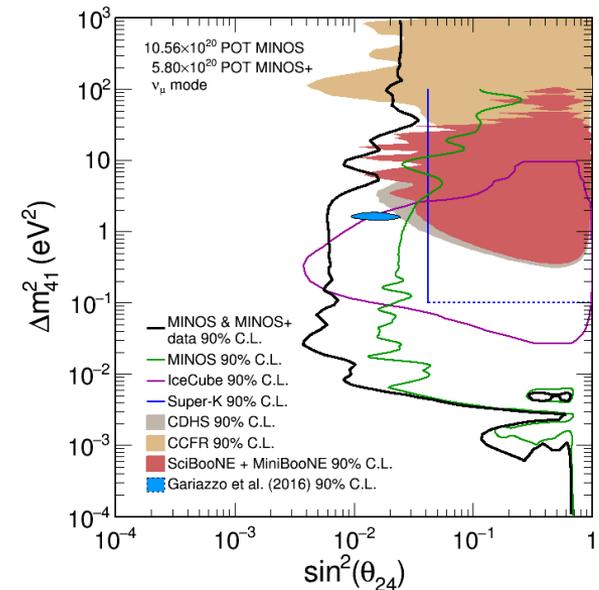
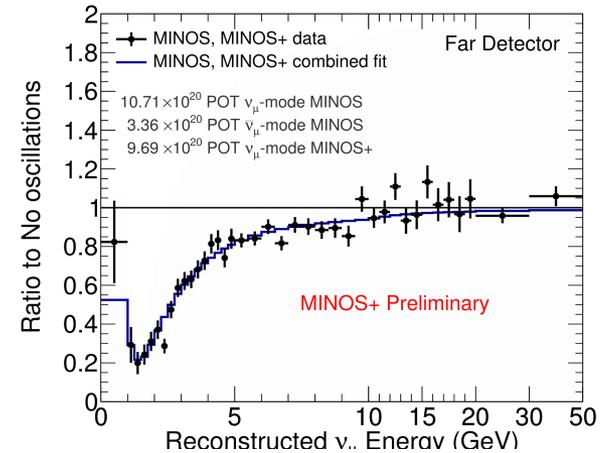
◆ Estimated constraint of two-detector analysis in the effective appearance space enforcing unitarity constraint*



*S. Parke and M. Ross-Lonergan, Phys. Rev. D 93, 113009 (2016)

Summary

- ◆ Standard Oscillations: Highly precise measurement of atmospheric oscillation parameters using the full sample of beam and atmospheric neutrino data
 - Results competitive with ongoing 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
 - Of particular interest in 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



Backup

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



U.S. DEPARTMENT OF
ENERGY



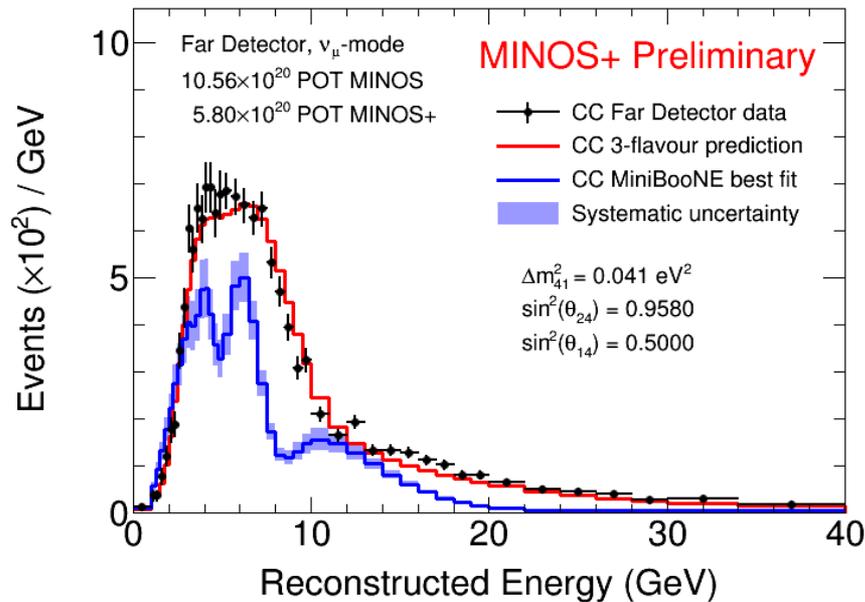
mi DEPARTMENT OF
NATURAL RESOURCES



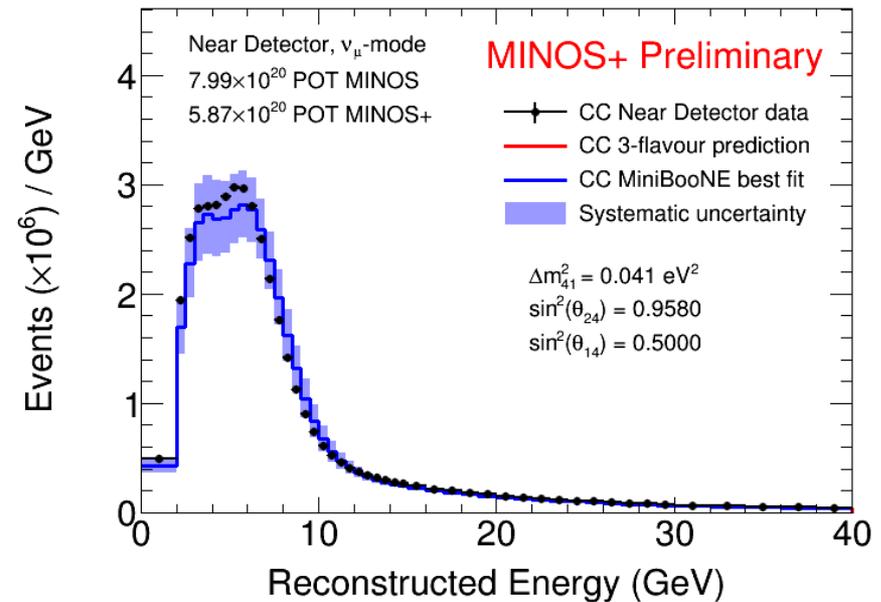
Science & Technology
Facilities Council

Comparison to MiniBooNE + LSND Best Fit: CC Selected Events

Far Detector



Near Detector



New MiniBooNE paper – arXiv:1805.12028

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

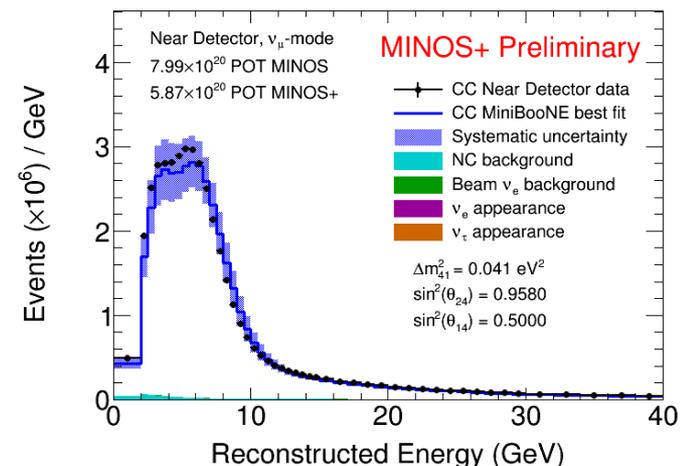
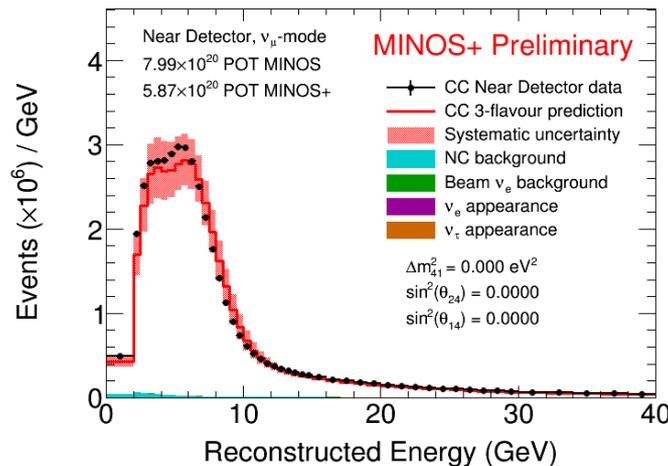
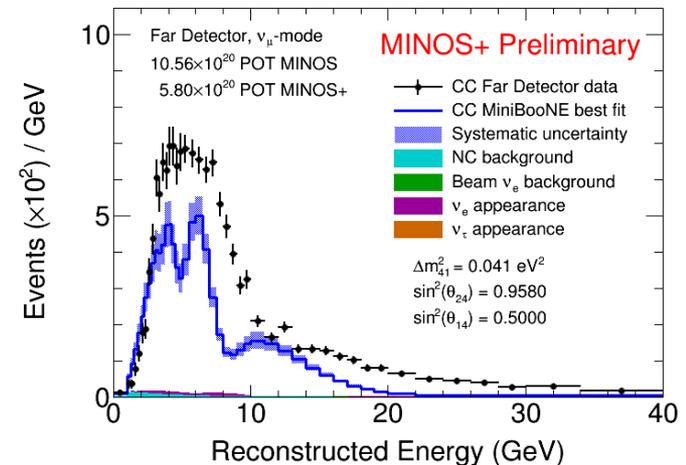
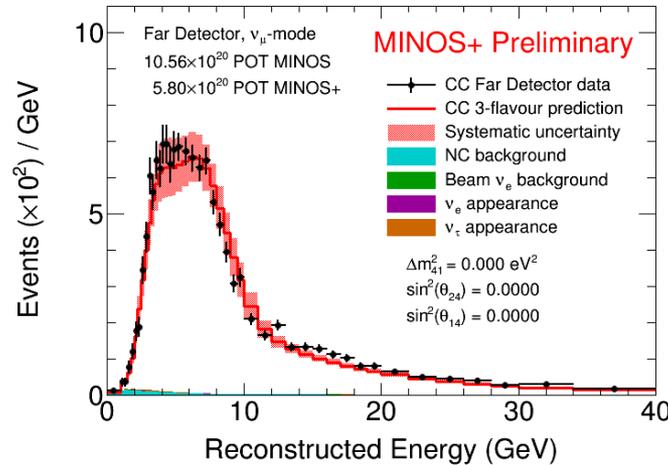
$$\sin^2_{\mu e} = 4|U_{e4}|^2|U_{\mu 4}|^2 = \sin^2 2\theta_{14} \sin^2 \theta_{24}$$

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

Comparison to MiniBooNE + LSND Best Fit: CC Selected Events

Three-flavor Oscillations

MiniBooNE + LSND Best Fit

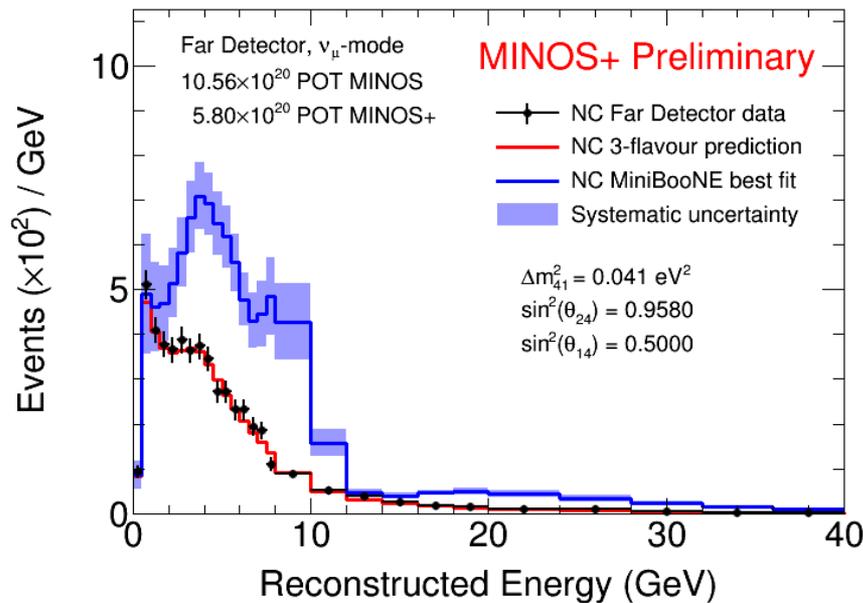


FD

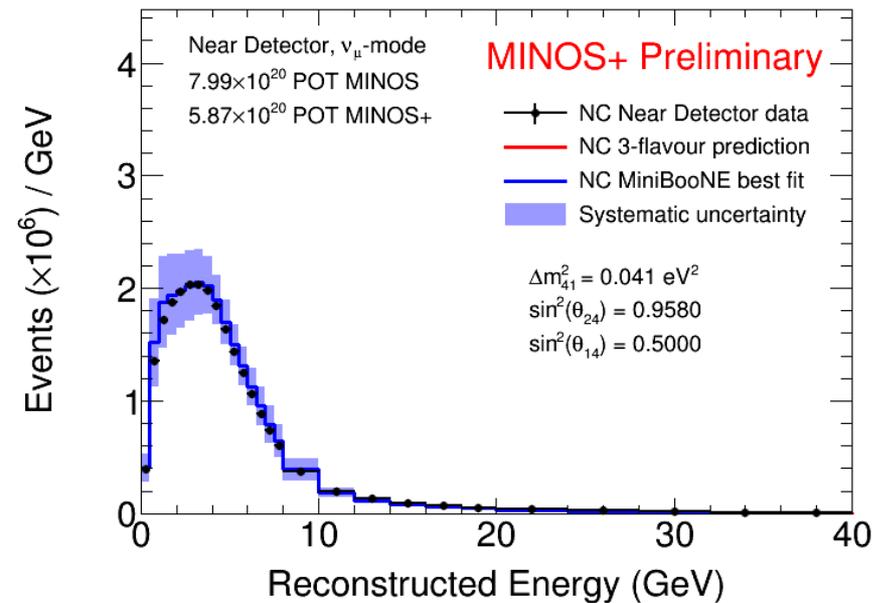
ND

Comparison to MiniBooNE + LSND Best Fit: NC Selected Events

Far Detector



Near Detector



New MiniBooNE paper – arXiv:1805.12028

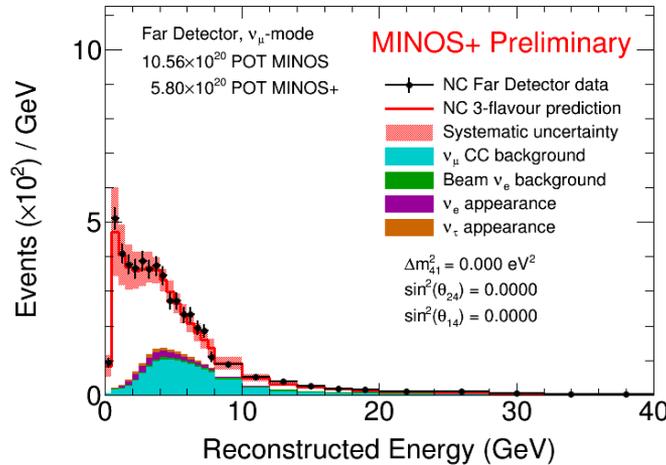
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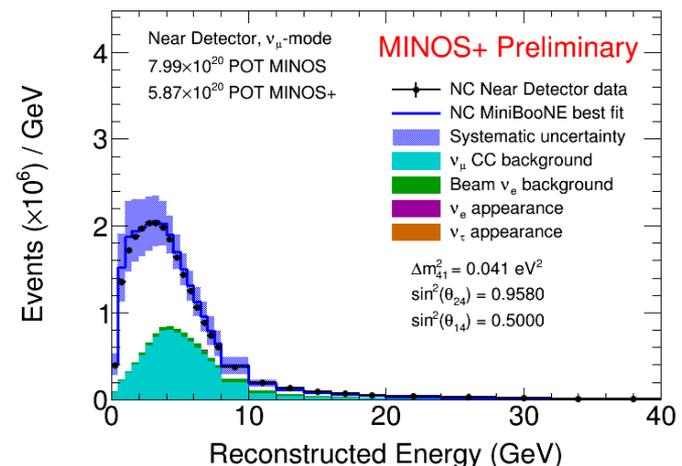
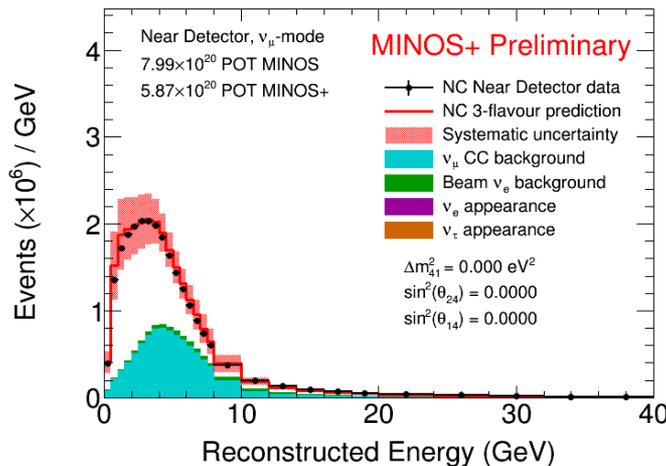
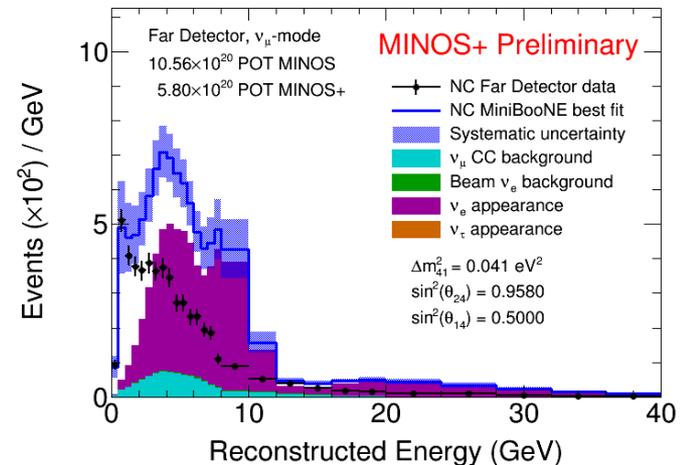
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Comparison to MiniBooNE + LSND Best Fit: NC Selected Events

Three-flavor Oscillations



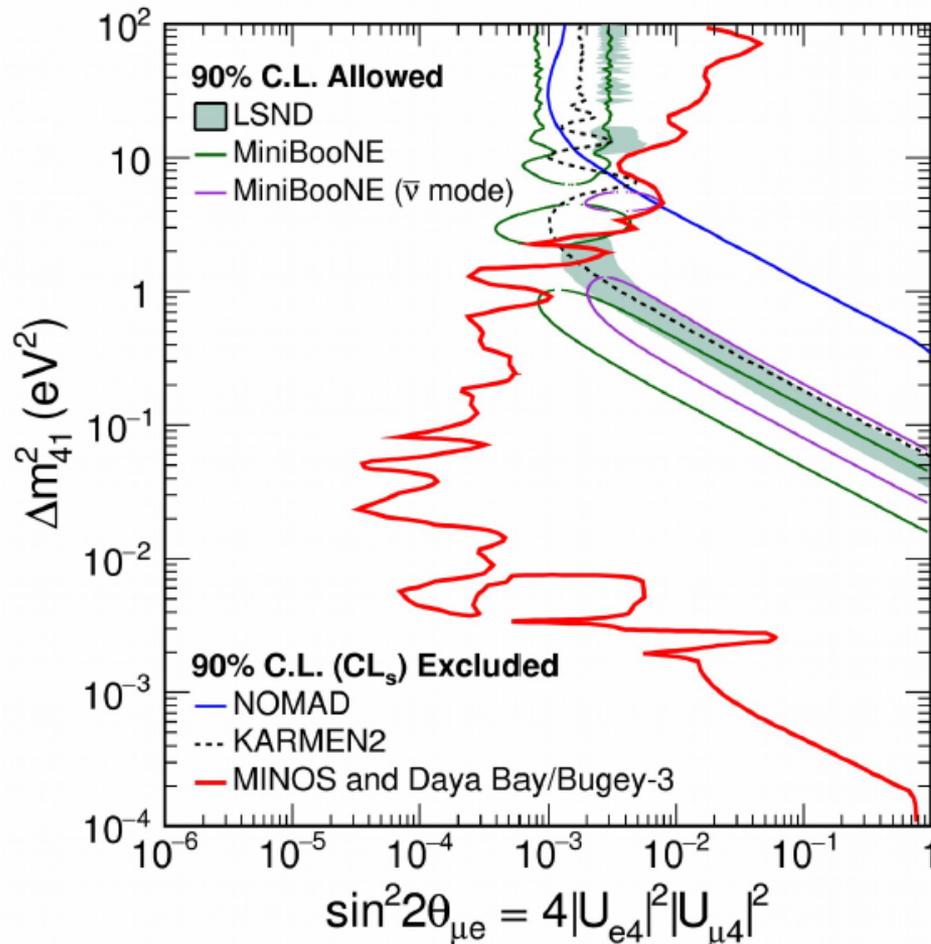
MiniBooNE + LSND Best Fit



FD

ND

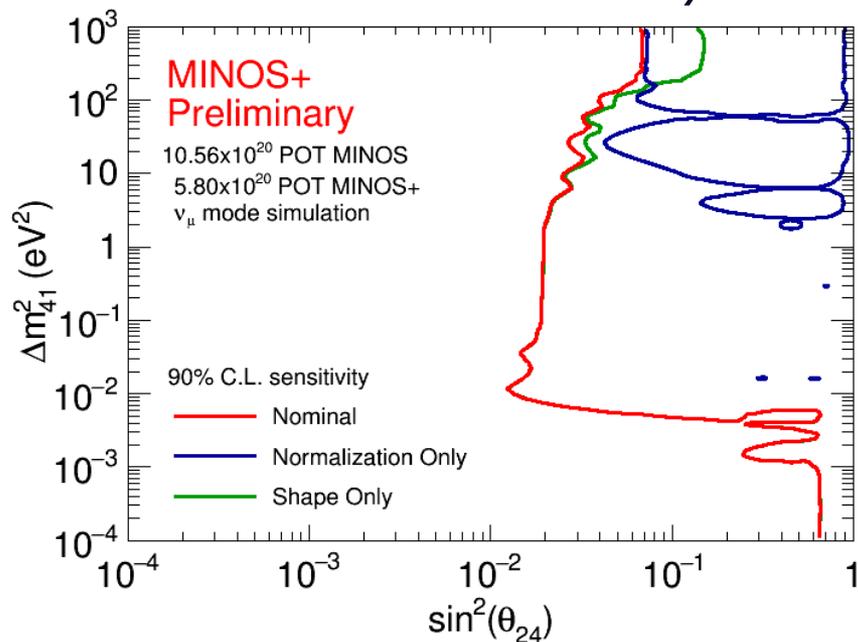
Comparison to MiniBooNE: MINOS/Daya Bay/Bugey Combination



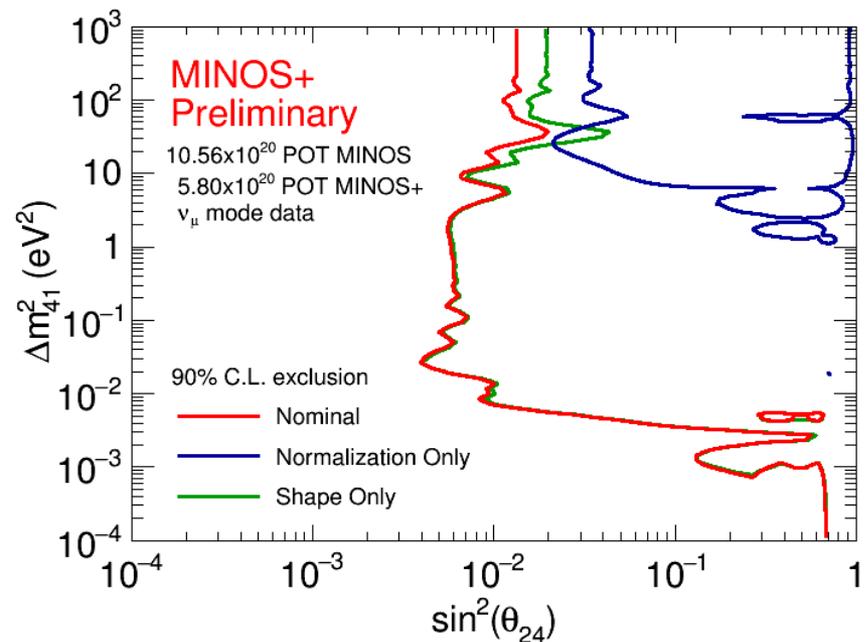
- ◆ MINOS and MINOS+ are in significant tension with the new MiniBooNE result, even assuming a conservative $\sin^2 2\theta_{14} = 1$
- ◆ Using θ_{14} from Daya Bay and Bugey combined with the previous MINOS result leads to an even larger tension, which will only increase if a future combination with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

Shape/Normalization Factorization

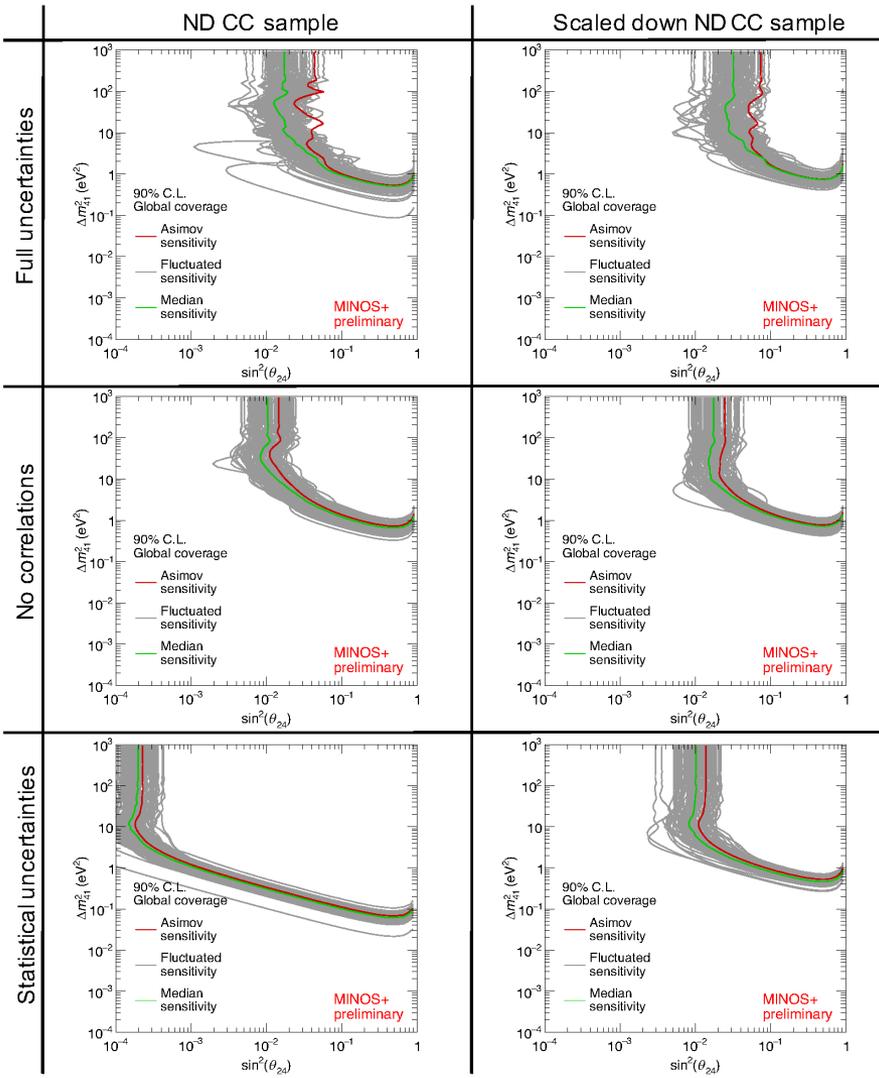
Asimov Sensitivity



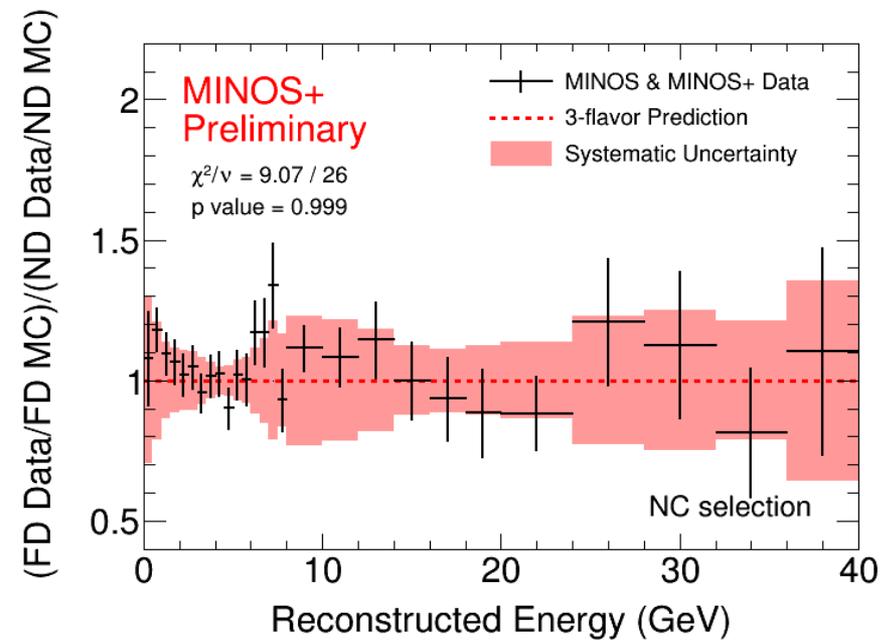
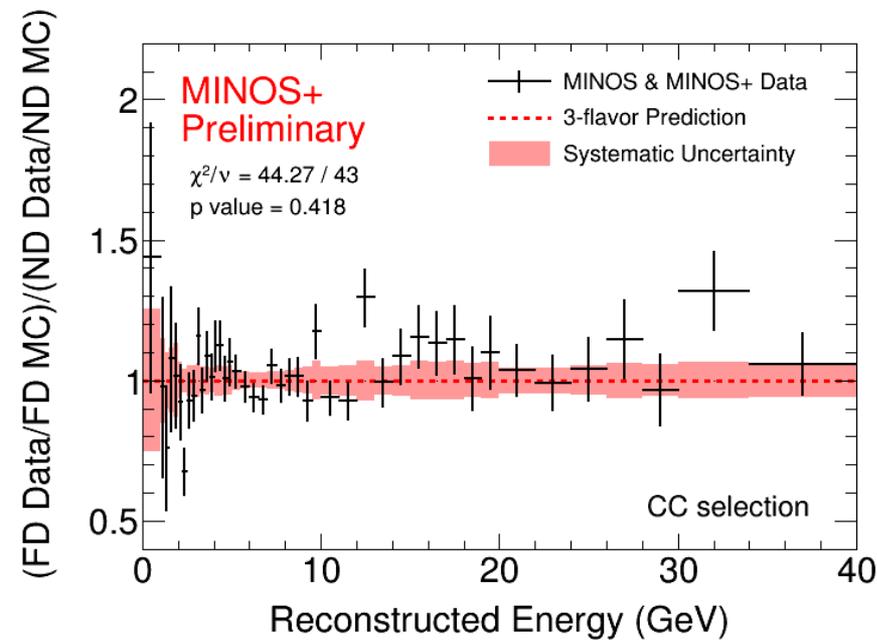
Data Limit



Median vs. Asimov Sensitivity

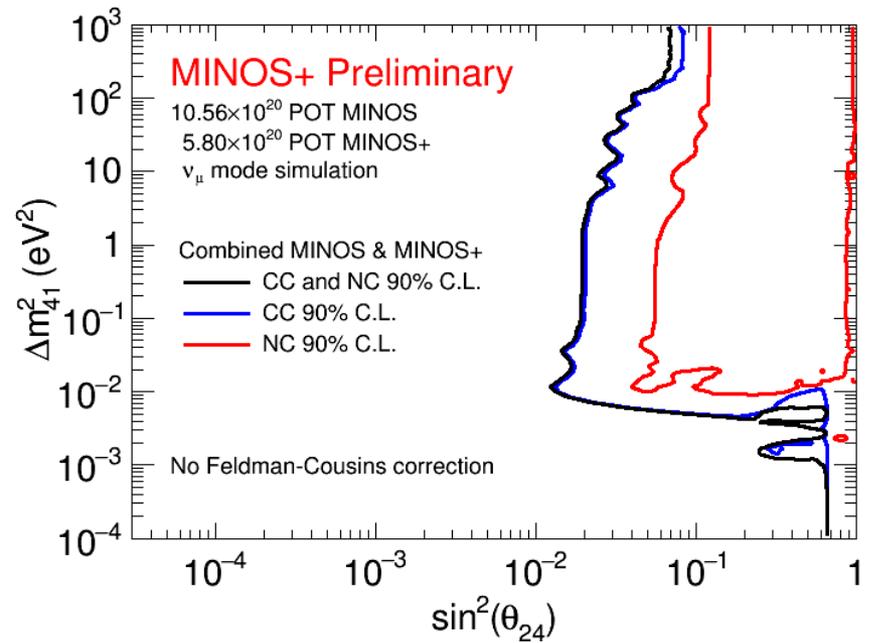
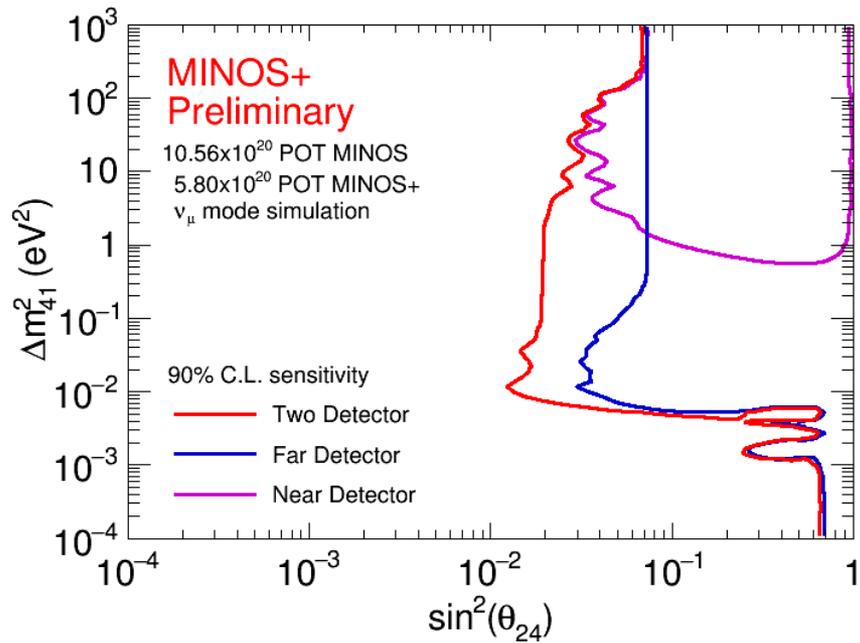


Consistency with Three Flavor Oscillations

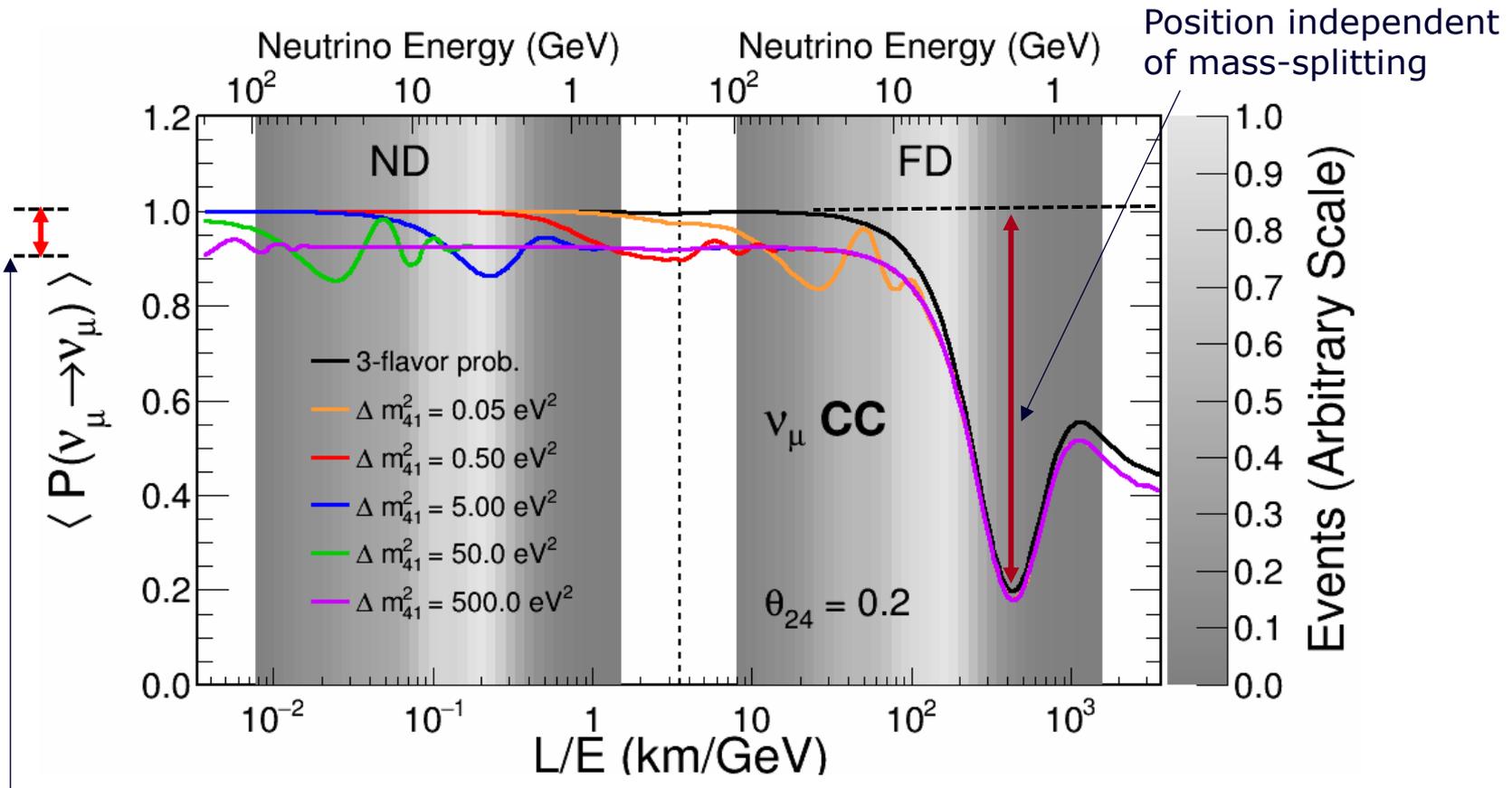


Detector and Sample Contributions

Asimov Sensitivities



(3+1)-Flavor Oscillations

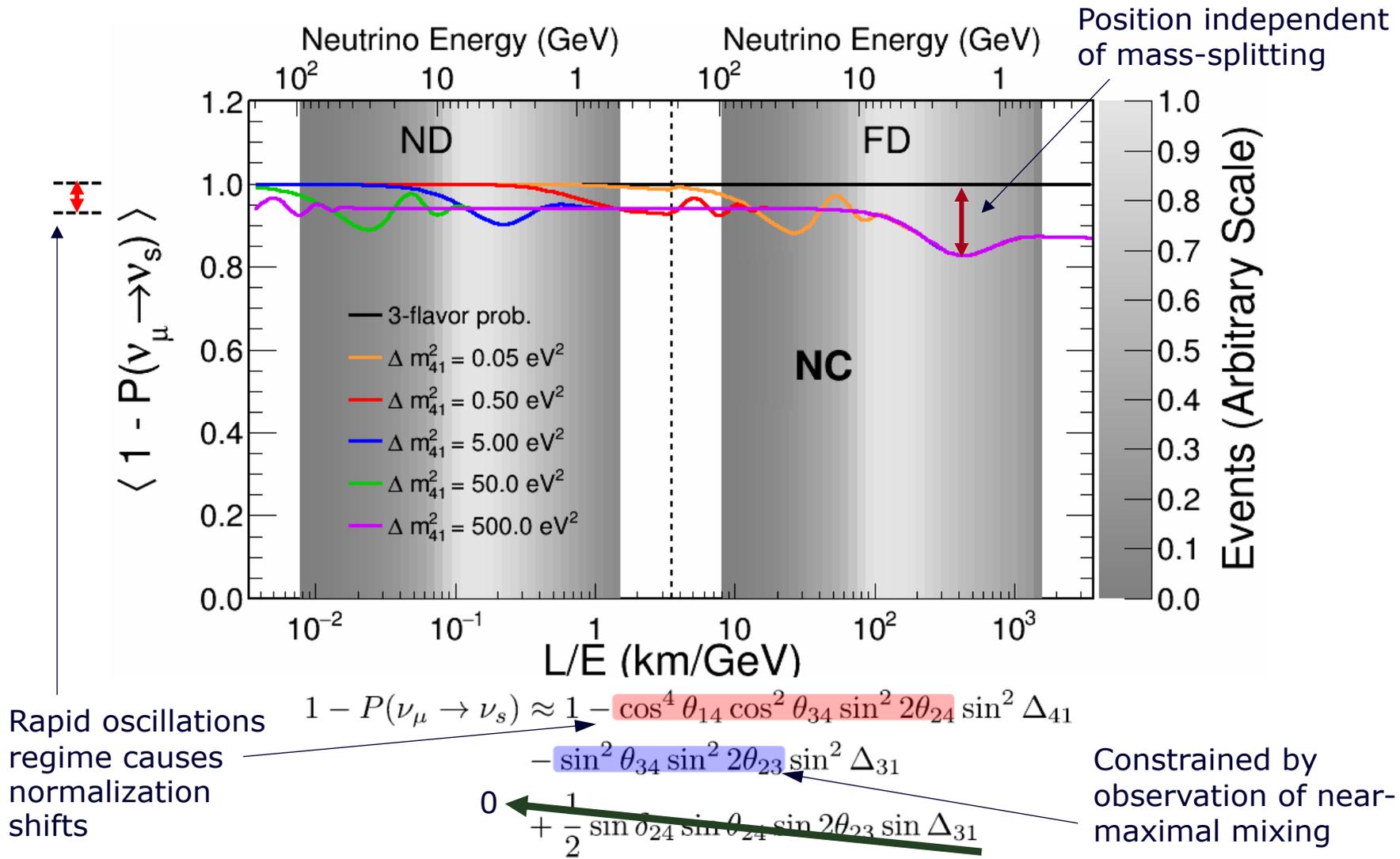


Rapid oscillations regime causes normalization shifts

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

Constrained by observation of near-maximal mixing

(3+1)-Flavor Oscillations



(3+1)-Flavor Degeneracies

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

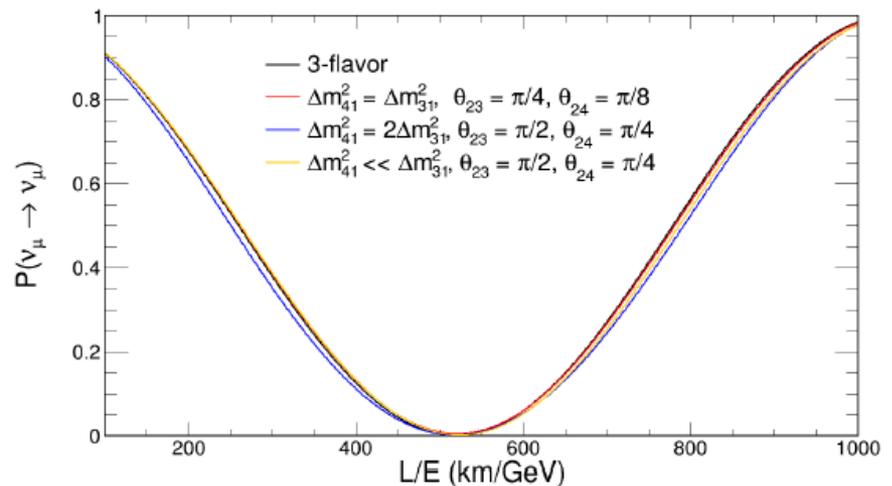
where $\Delta_{ij} = \frac{\Delta m_{ij}^2 L}{4E}$

If:

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

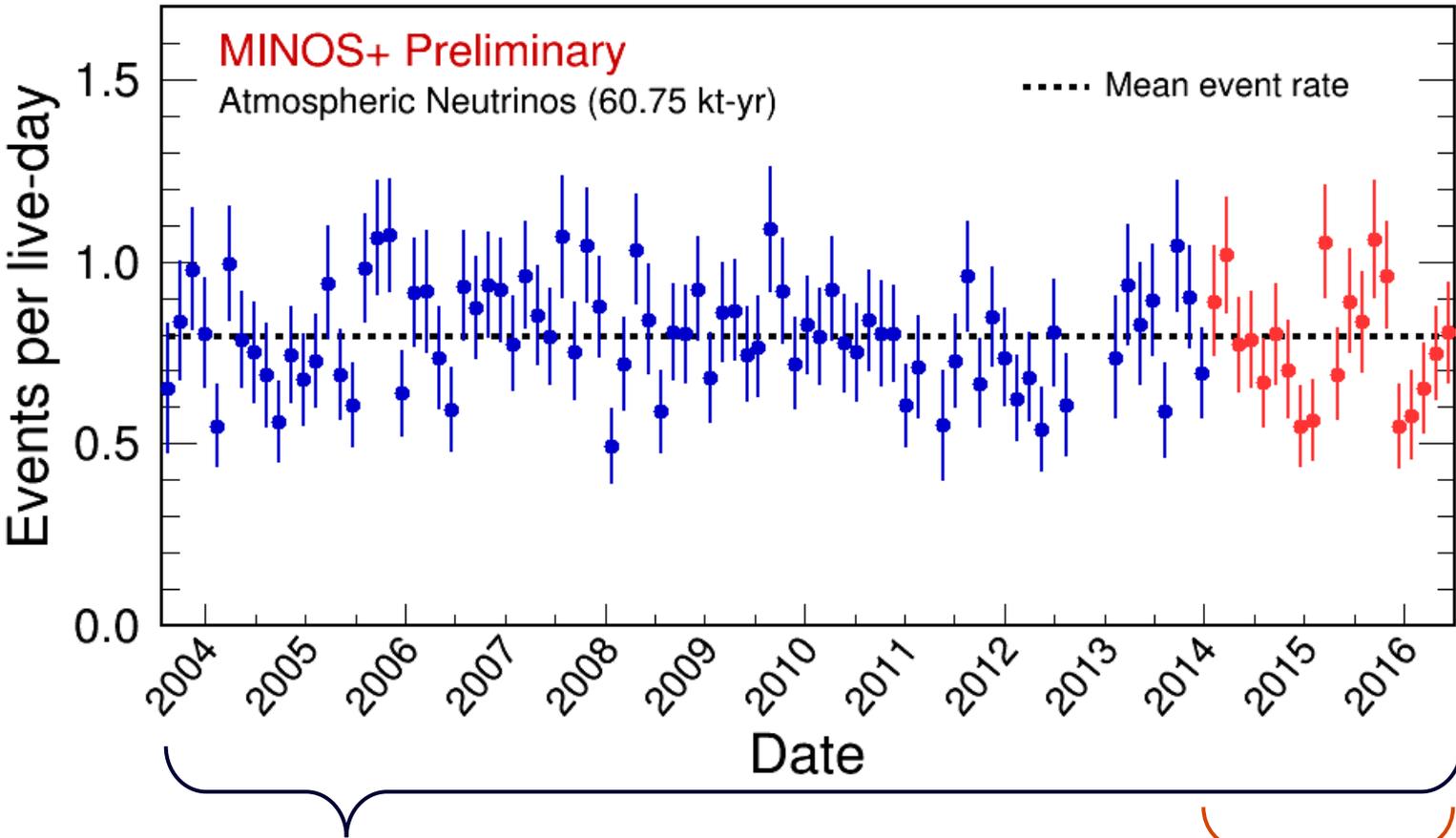
Certain combinations of θ_{23} , θ_{24} , and θ_{34} can produce 4-flavor solutions nearly indistinguishable from 3-flavor.

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



Example degenerate scenarios

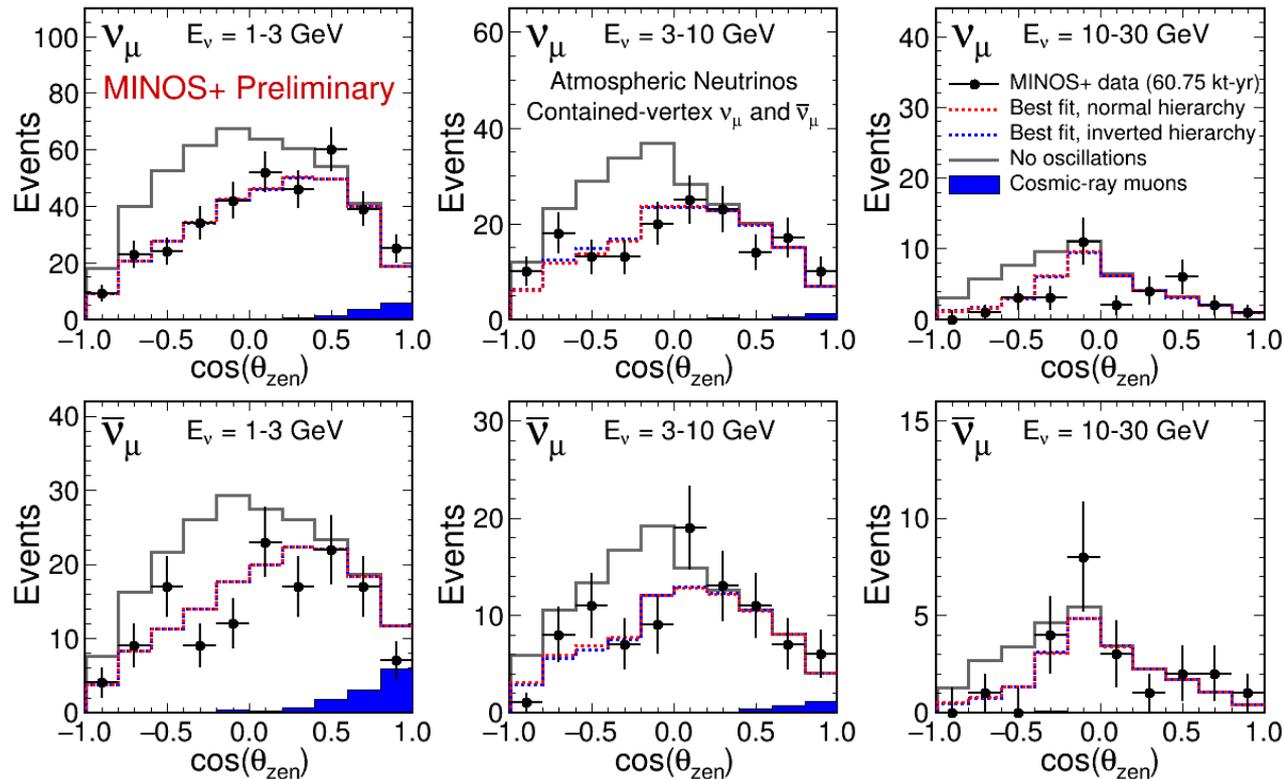
MINOS & MINOS+ Atmospheric Neutrinos



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

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

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

Atmospheric Data and Fit

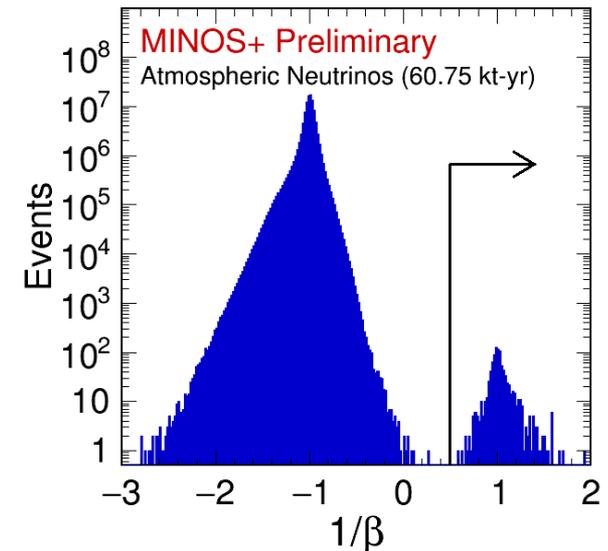
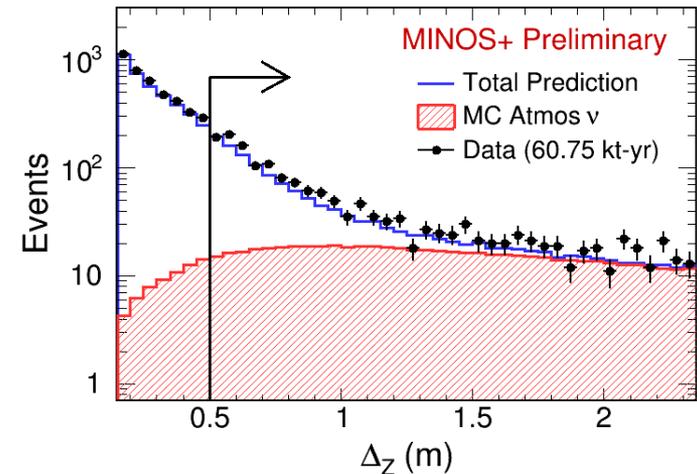
- ◆ Two techniques used to identify atmospheric neutrinos in the Far Detector.

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:

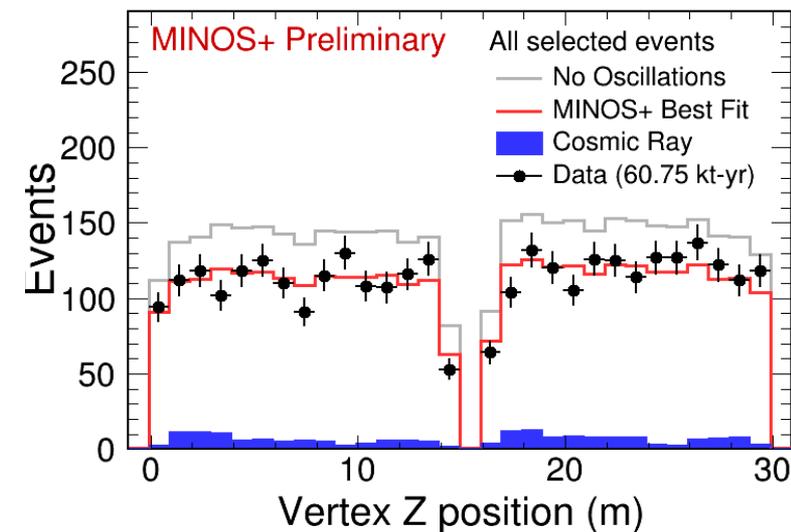
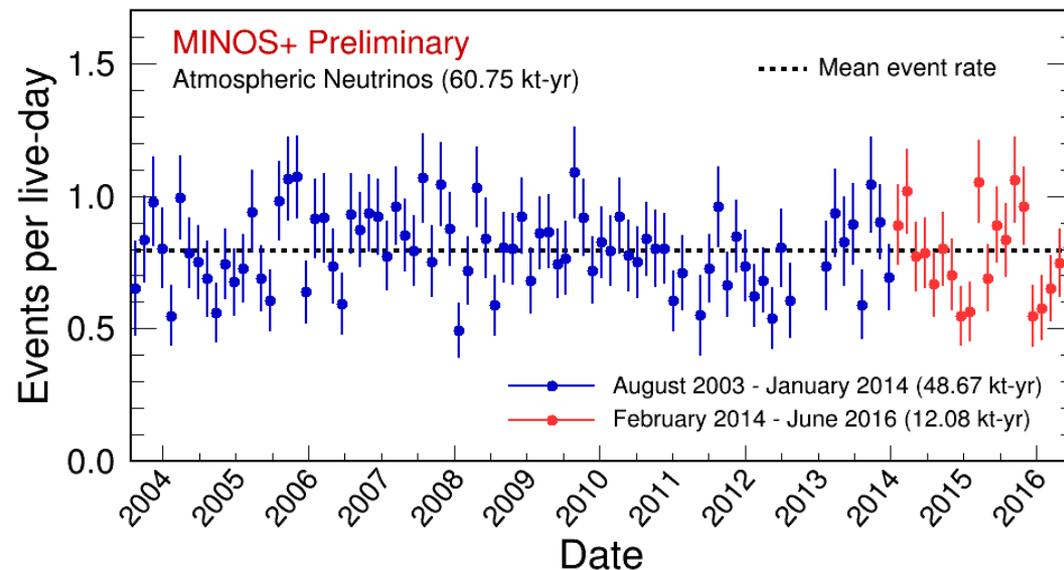
- Far Detector has a timing resolution of 2.5ns.
- Can identify neutrino-induced upward and horizontal muons using timing information.
- Soudan mine has a uniform rock overburden, enabling events to be identified above the horizon ($\cos\theta_{zen} < 0.05$).



Atmospheric Data and Fit

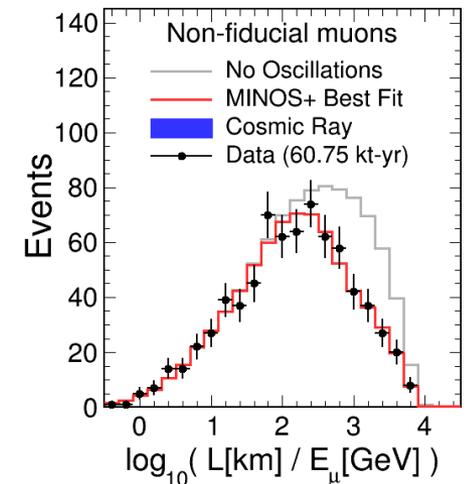
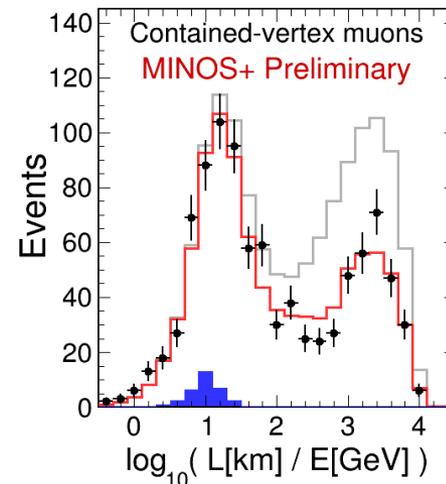
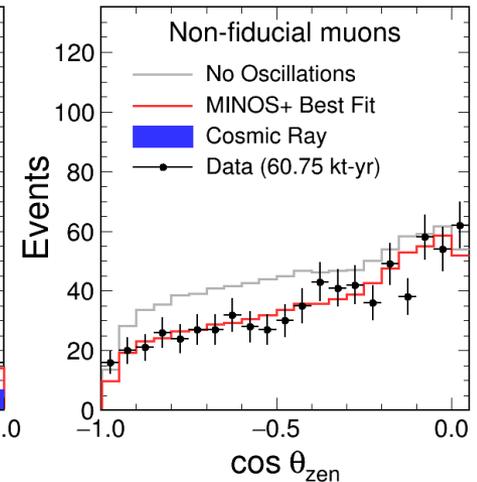
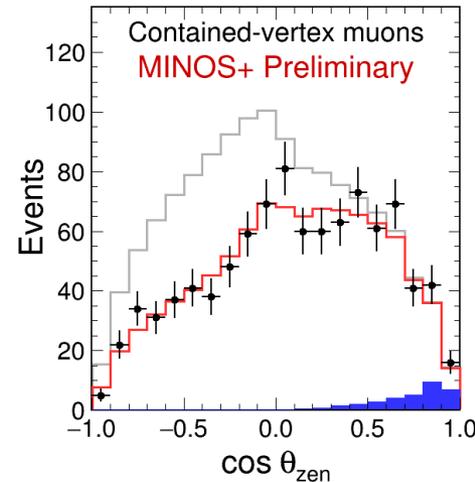
◆ Selected atmospheric neutrinos are categorised based on event topology:

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

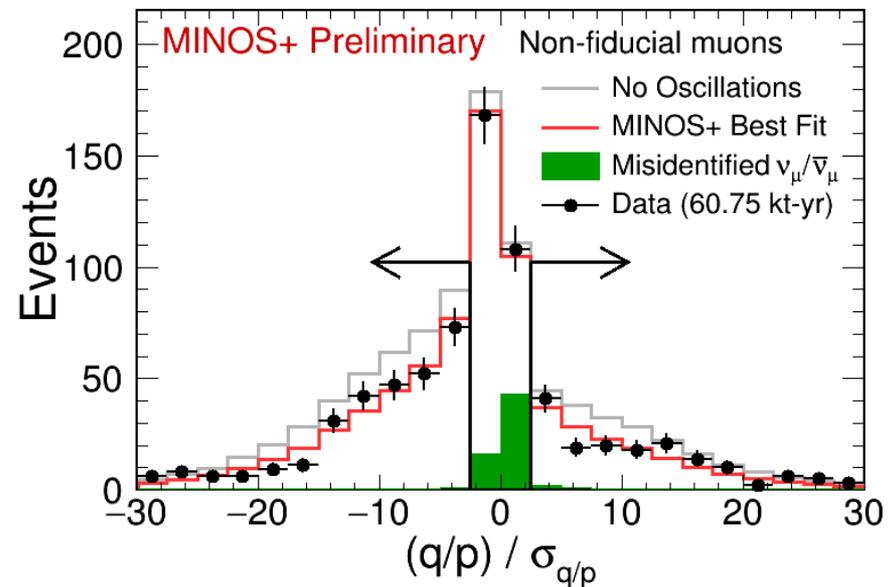
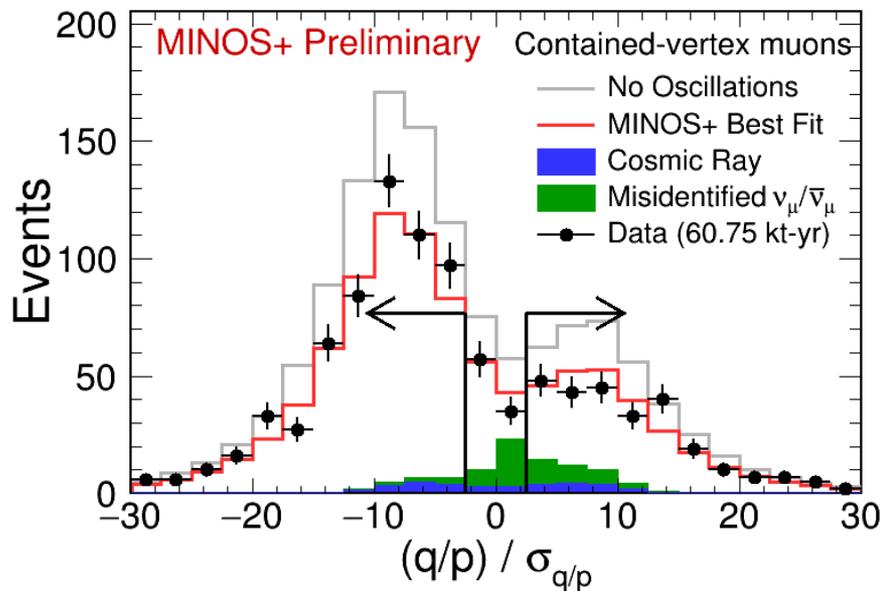
- ◆ Timing information is used to select “high resolution” sample of events with well-measured muon propagation direction.
 - 950 contained-vertex muons and all 736 non-fiducial muons pass this selection.
 - Can reconstruct zenith angle and L/E for these events.
- ◆ Plots on right show zenith angle and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



Atmospheric Data and Fit

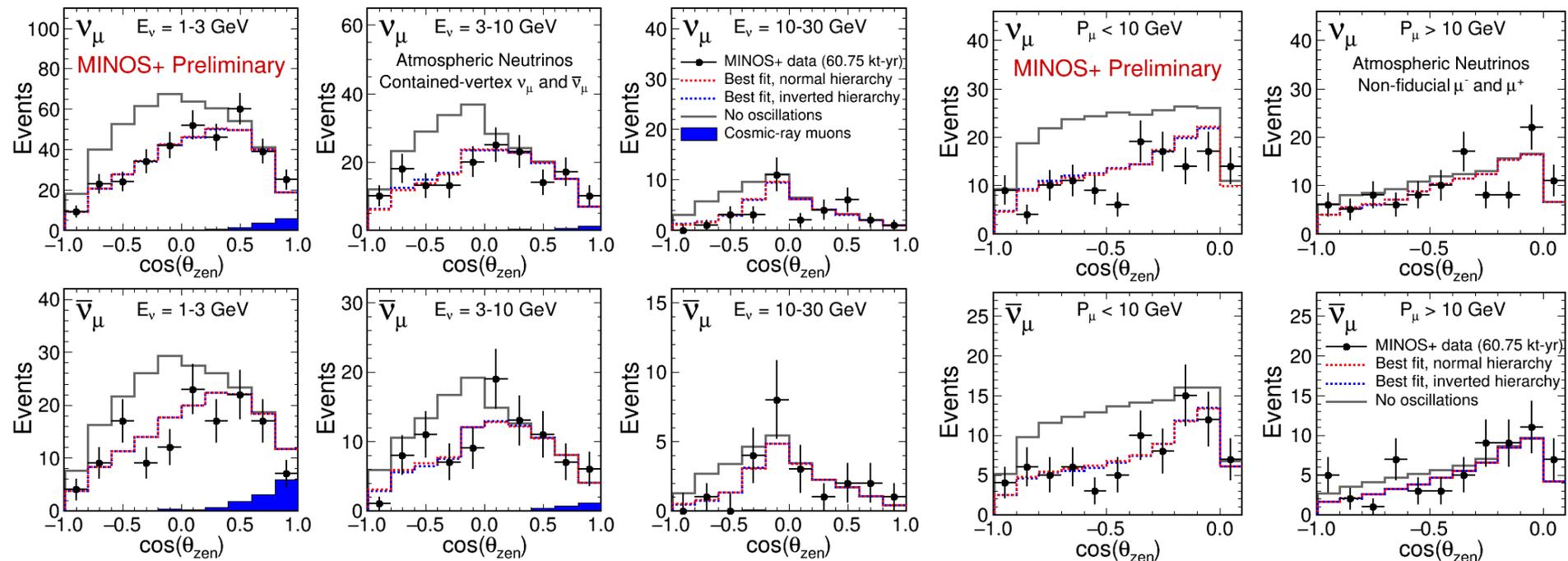
- ◆ Neutrinos and antineutrinos are separated based on muon charge sign, which is reconstructed using curvature of final-state muon tracks.

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



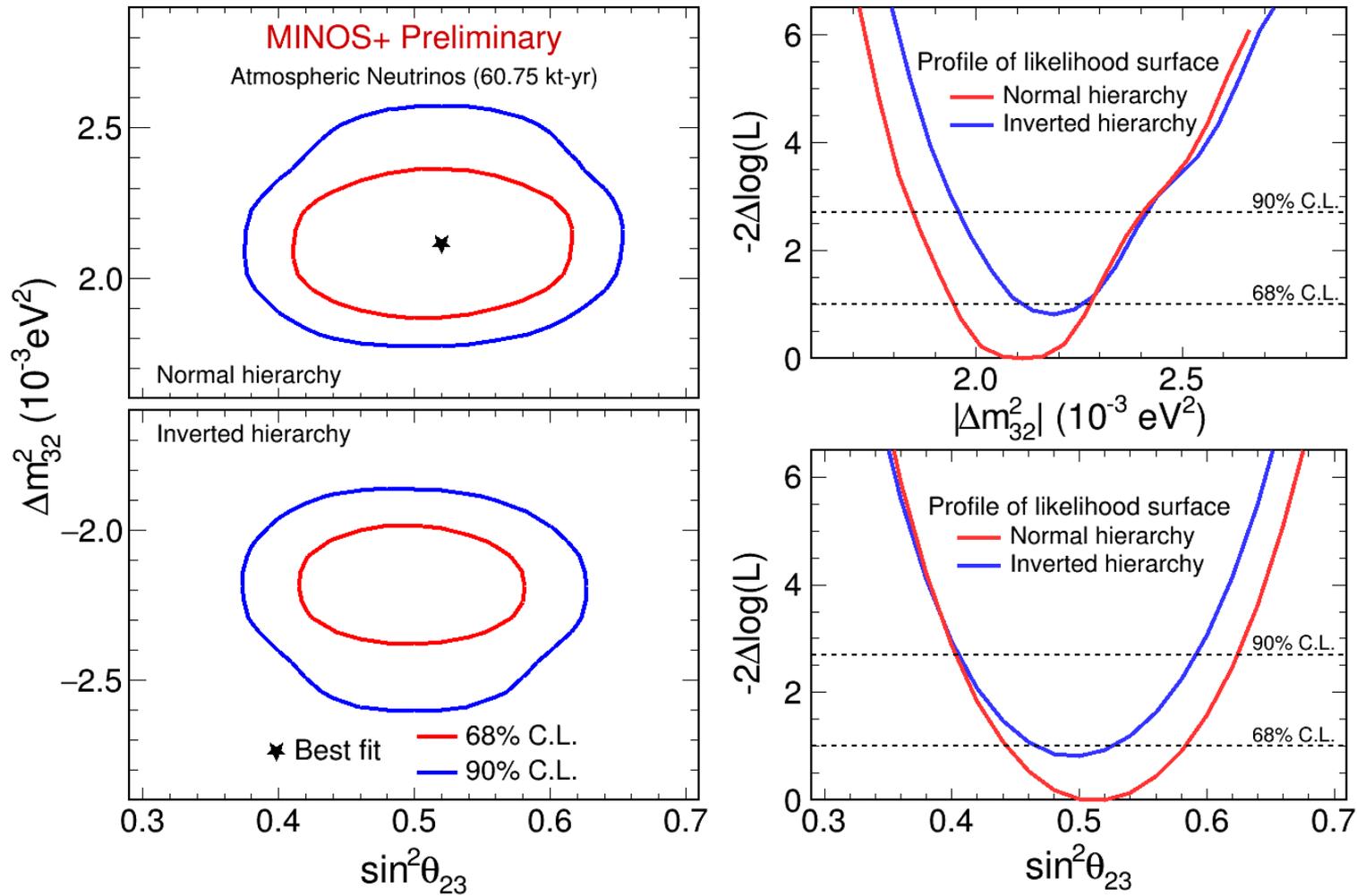
Atmospheric Data and Fit

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



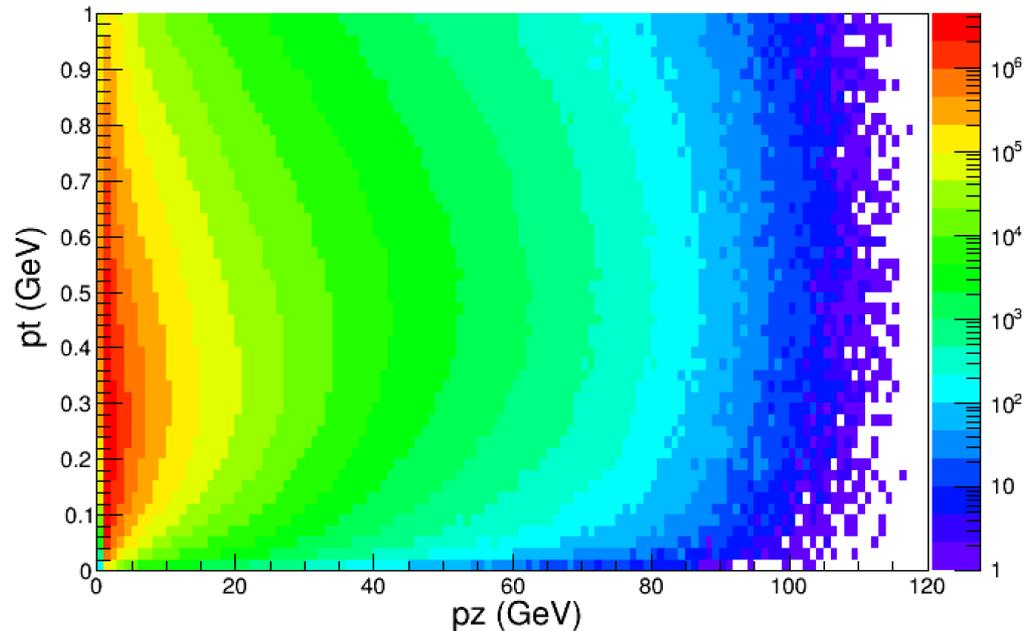
Atmospheric Data and Fit

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



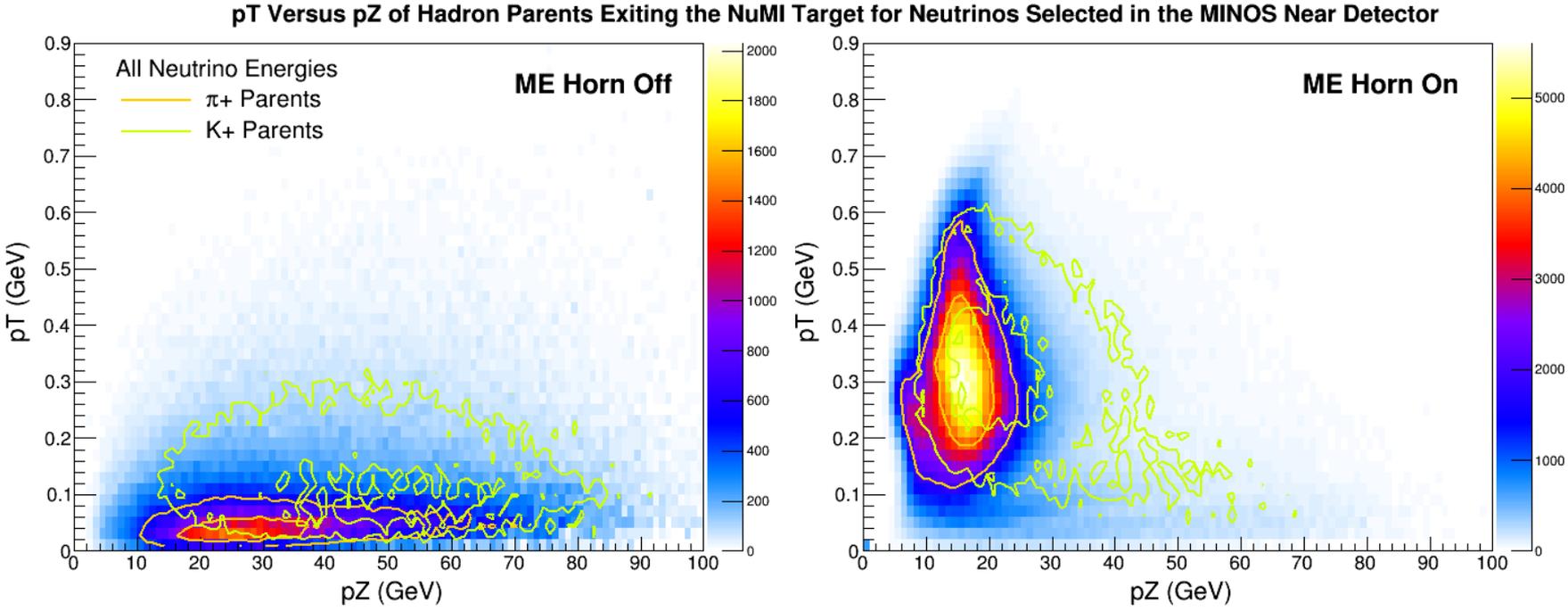
Beam Flux Estimation: Hadron Production

Hadron Production MINOS+ Flugg08 Pi+

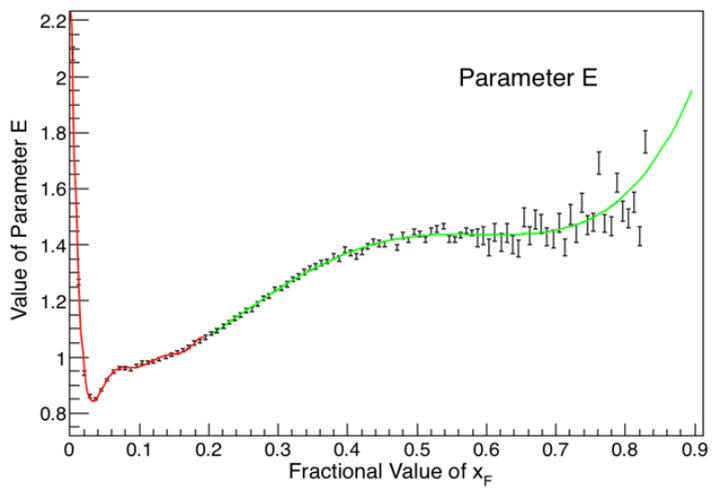
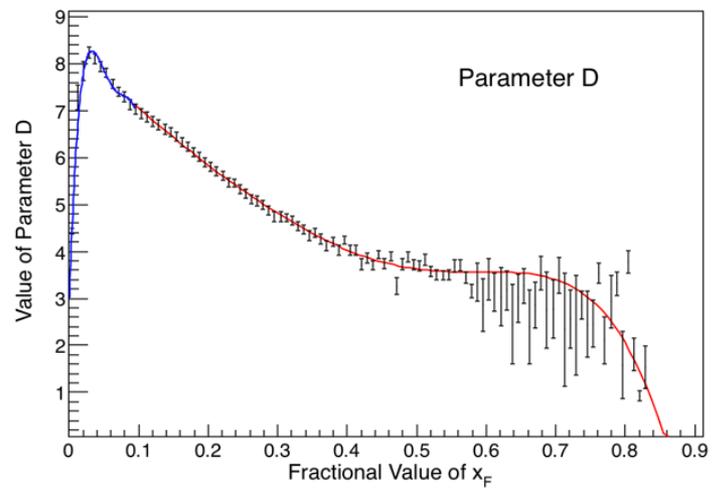
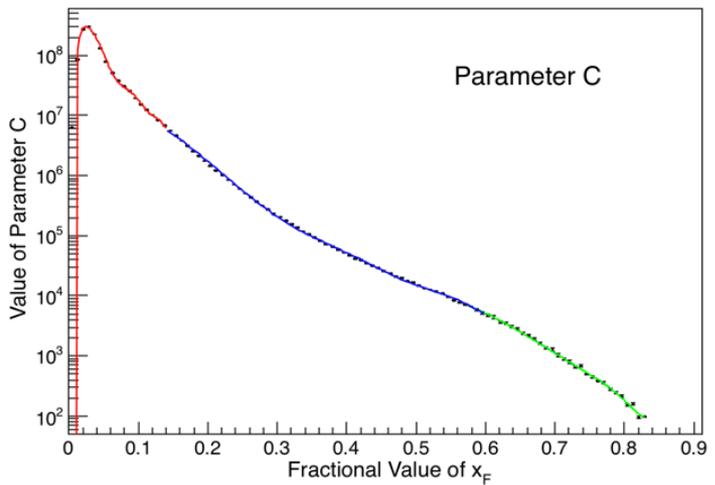
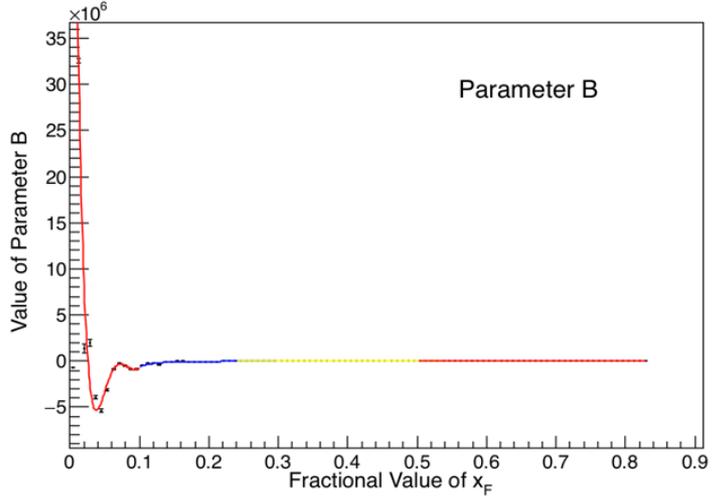


$$\frac{d^2 N}{dx_F dp_T} = [B(x_F)p_T + C(x_F)p_T^2]e^{-D(x_F)p_T^{E(x_F)}}$$

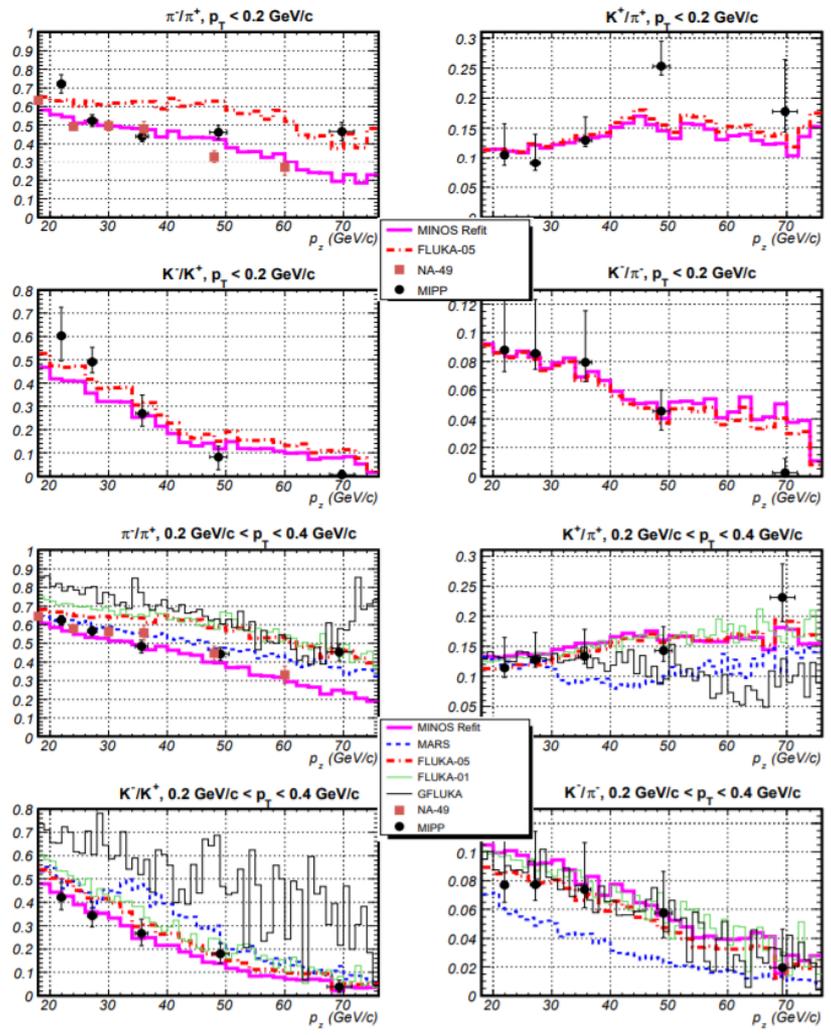
Beam Flux Estimation: Hadron Production



Beam Flux Estimation: Hadron Production

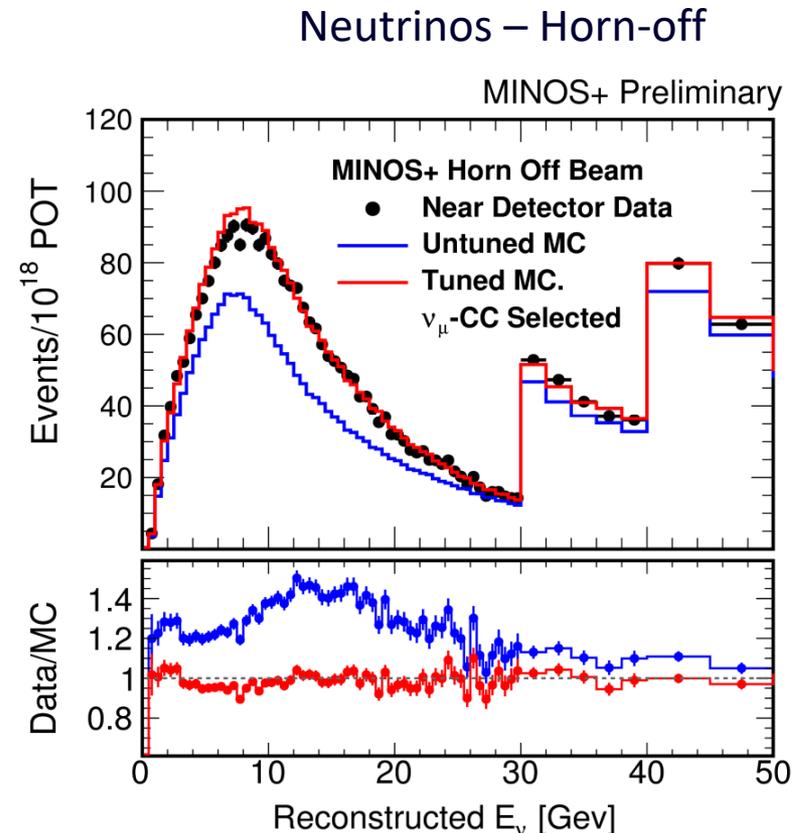


Beam Flux Estimation: Hadron Production



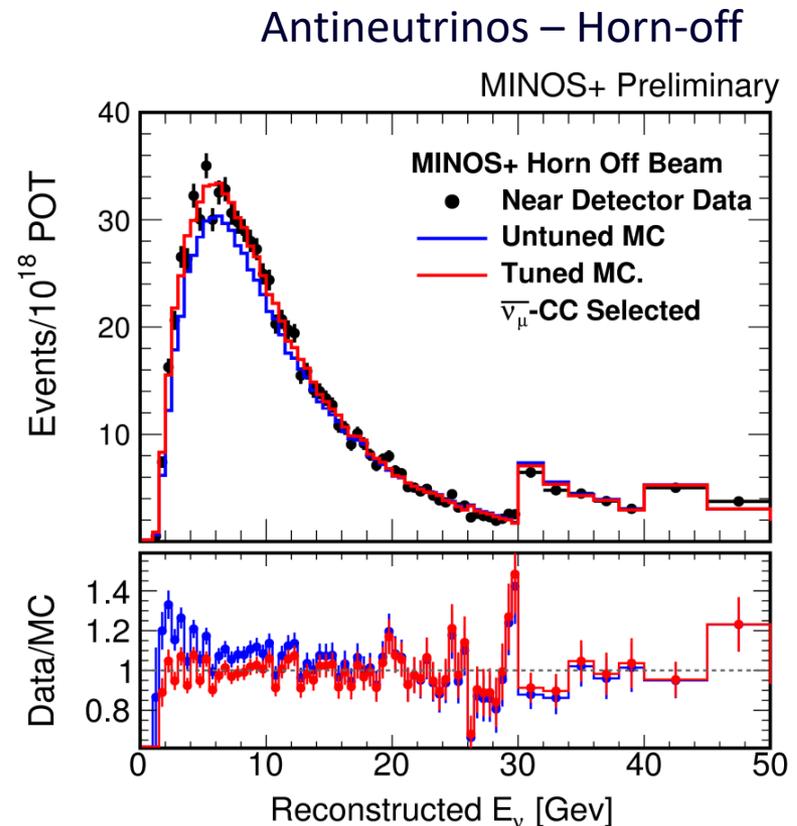
Beam Flux Estimation: Hadron Production

- ◆ 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



Beam Flux Estimation: Hadron Production

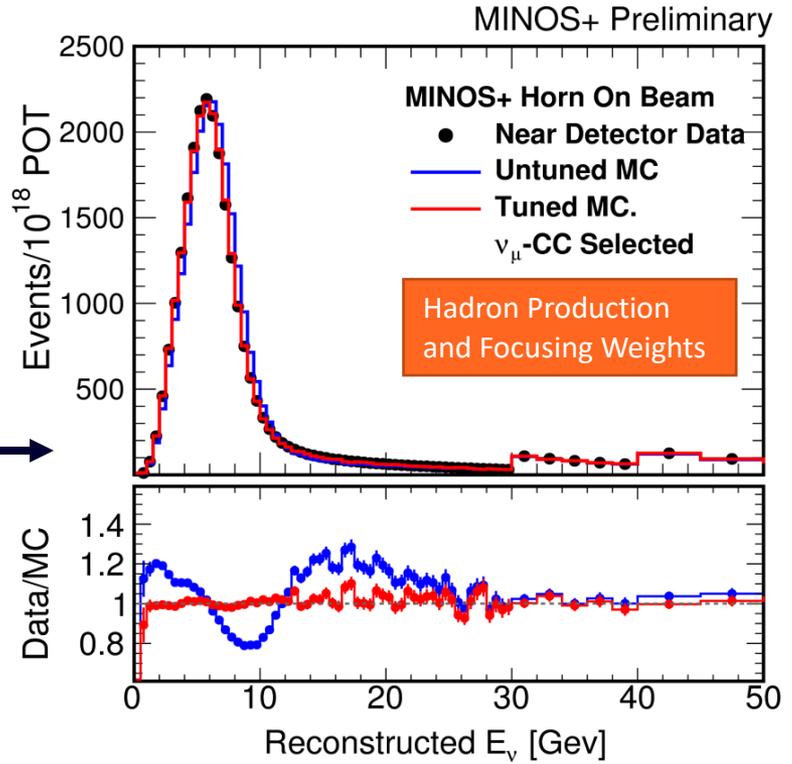
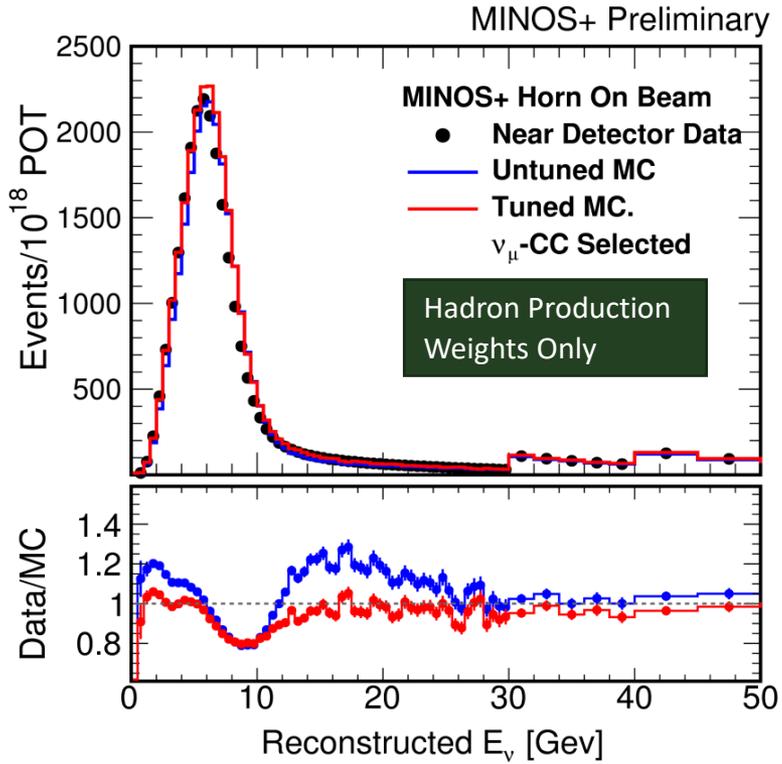
- ◆ ND data provides a powerful constraint on beam flux
- ◆ Use samples with focusing horns off to isolate hadron production
- ◆ Fit empirical pion hadron production parameters for neutrinos and antineutrinos
- ◆ Transfer weights to kaons using measured pion/kaon ratios



Beam Flux Estimation: Focusing

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

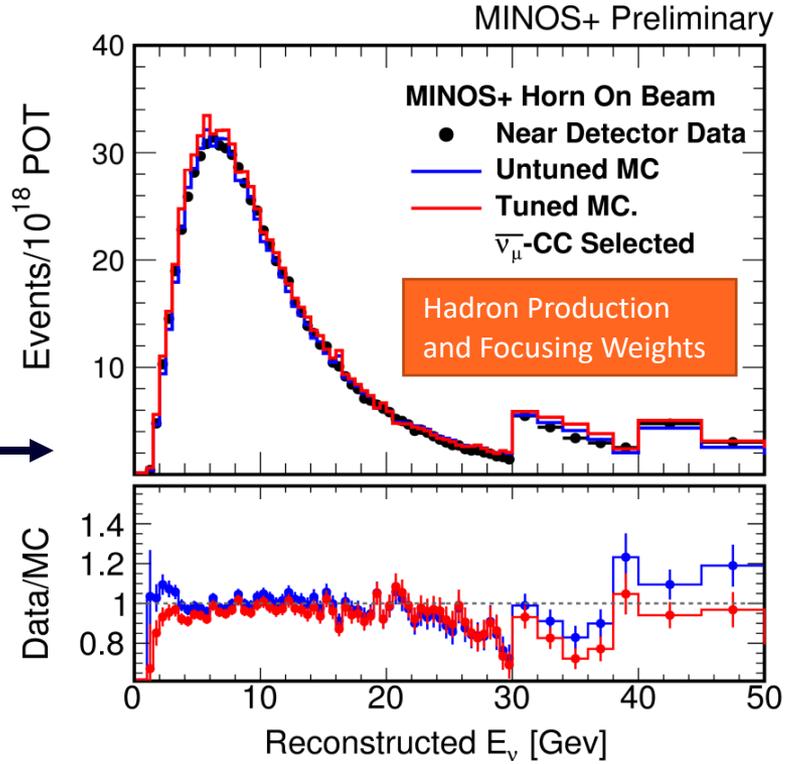
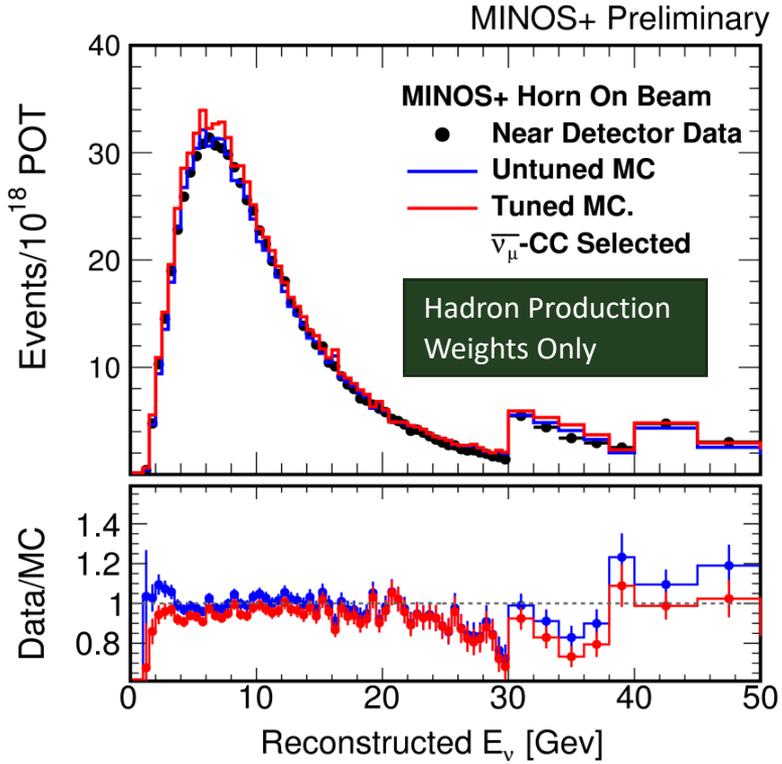
Neutrinos



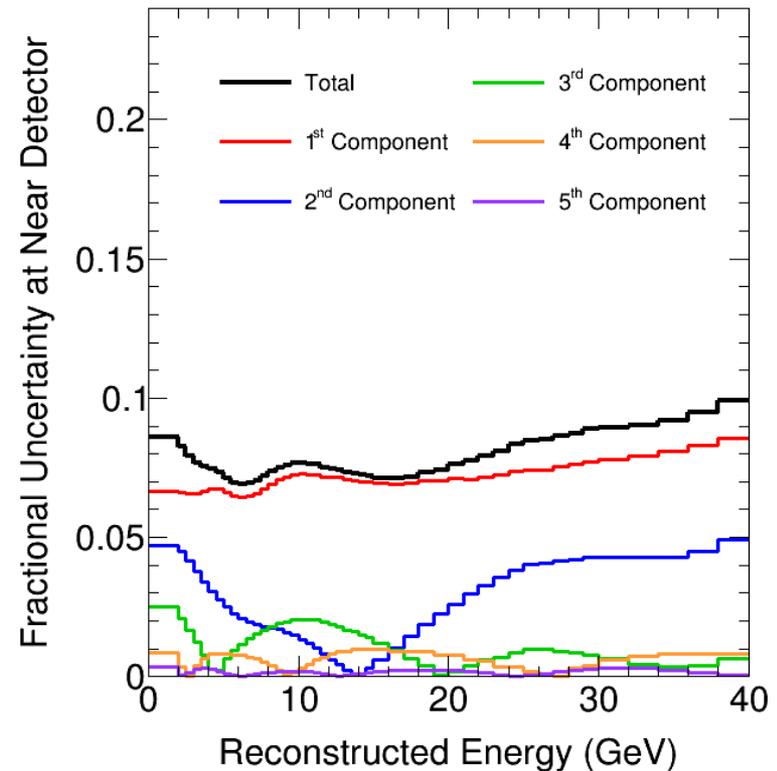
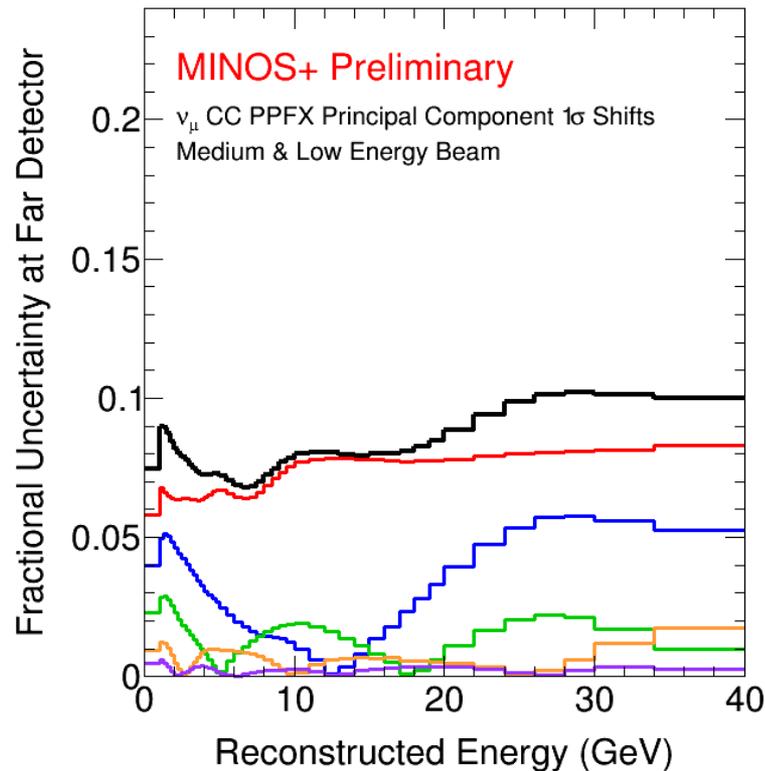
Beam Flux Estimation: Focusing

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

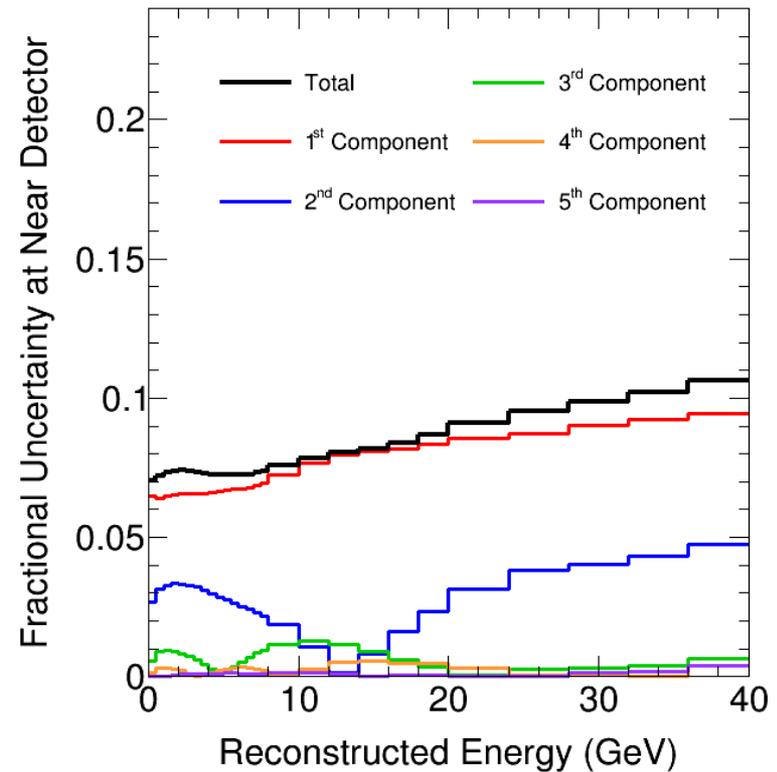
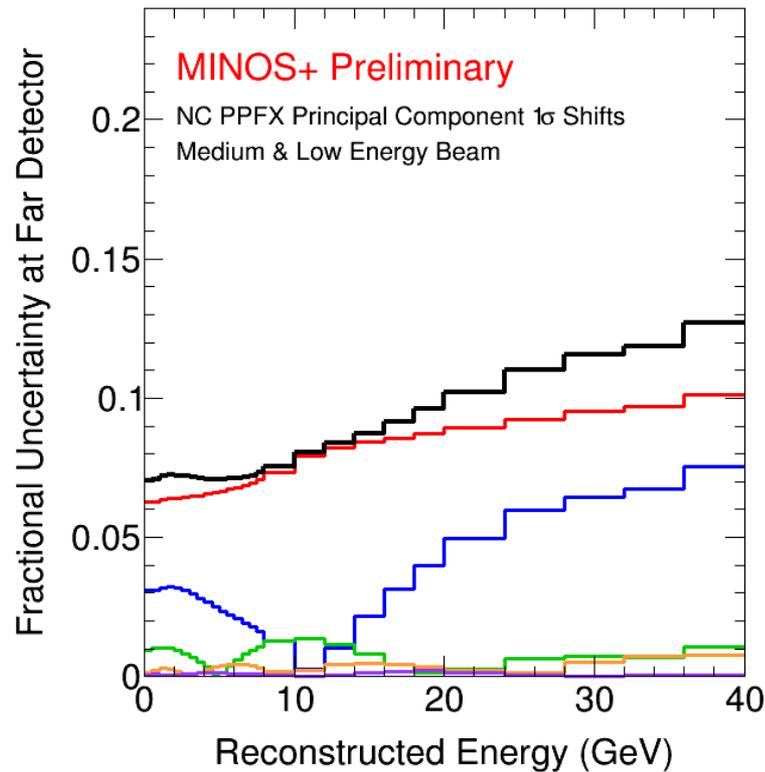
Antineutrinos



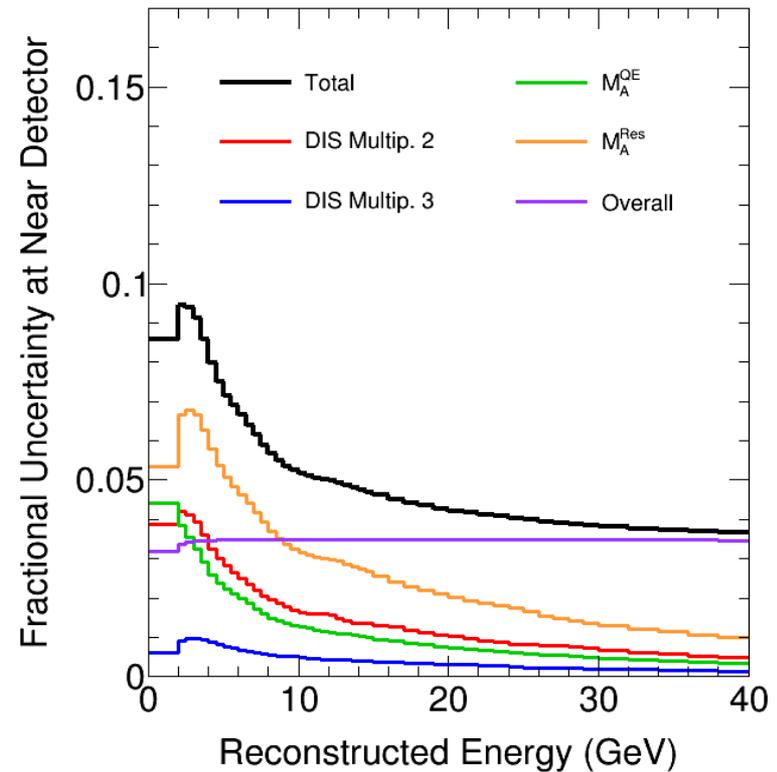
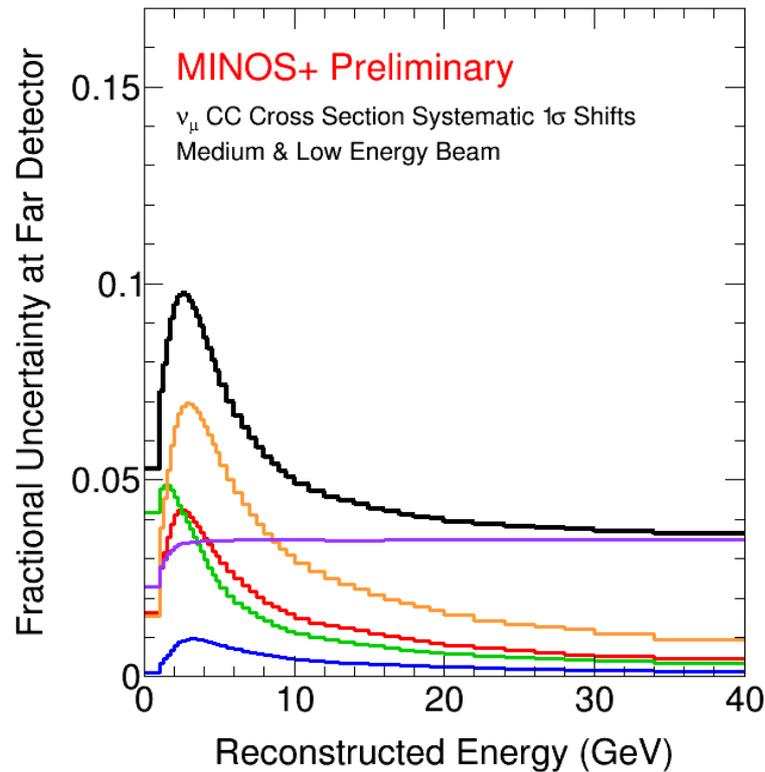
Sterile Systematics: CC Hadron Production



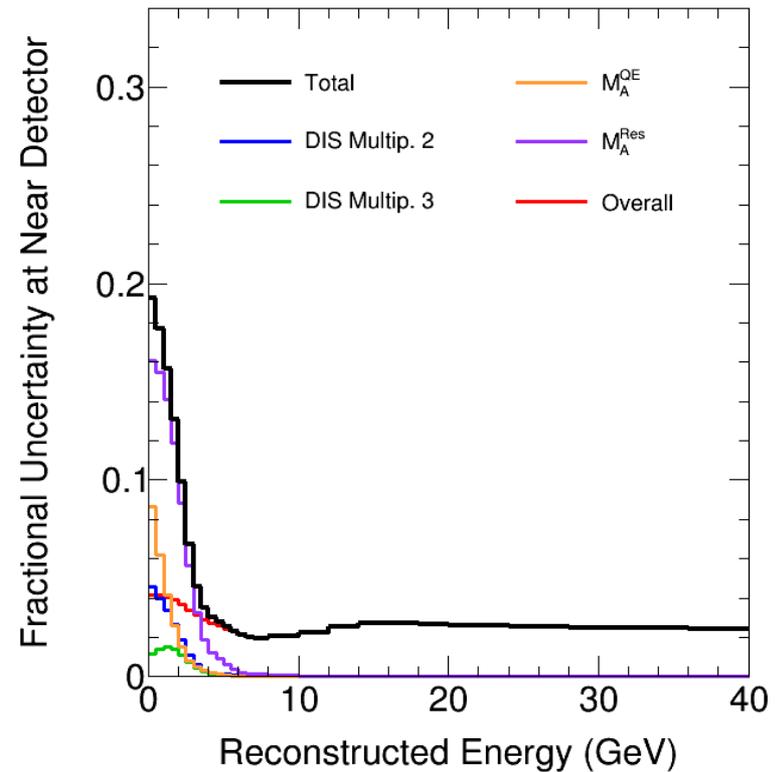
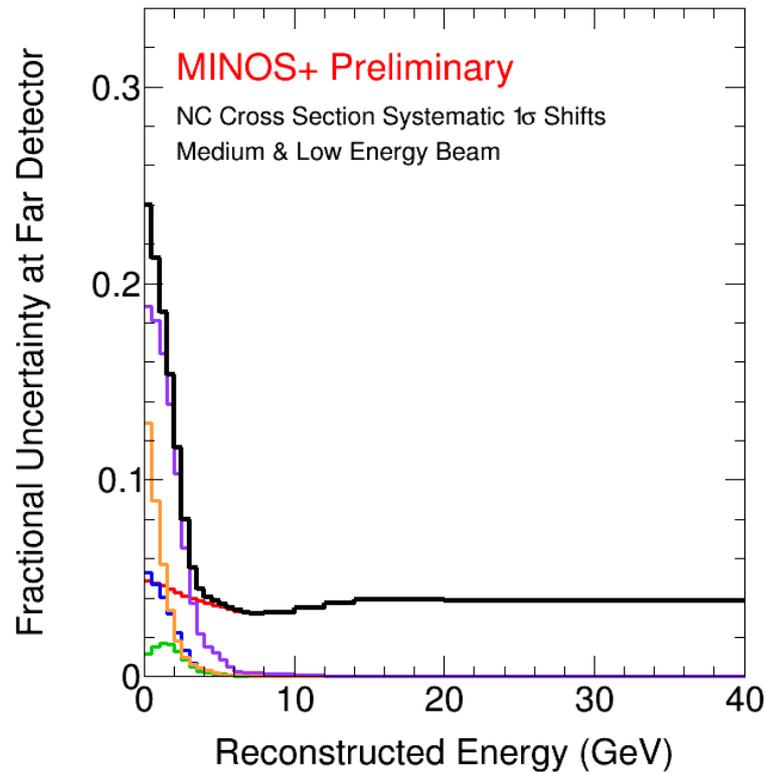
Sterile Systematics: NC Hadron Production



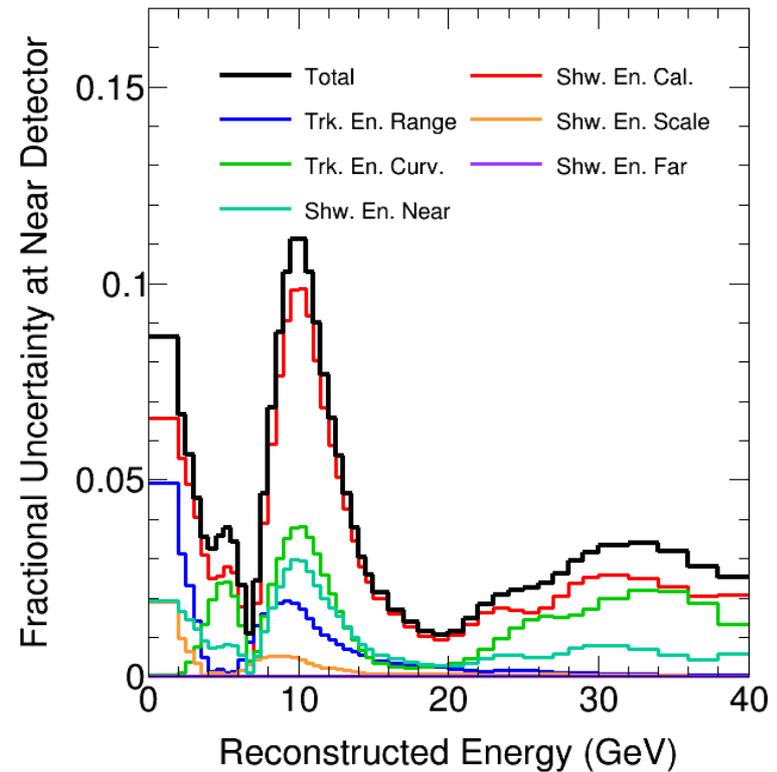
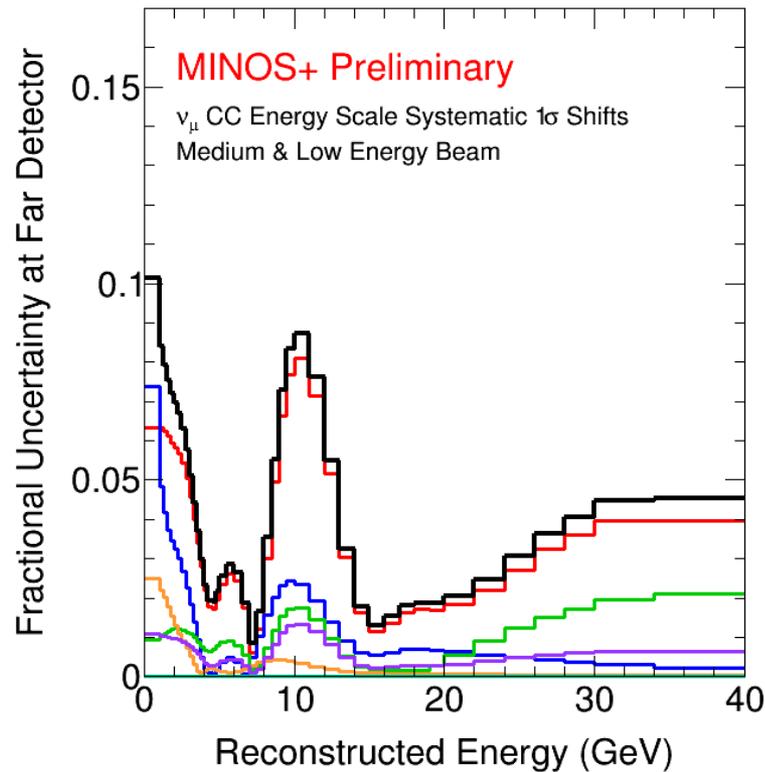
Sterile Systematics: CC Cross Sections



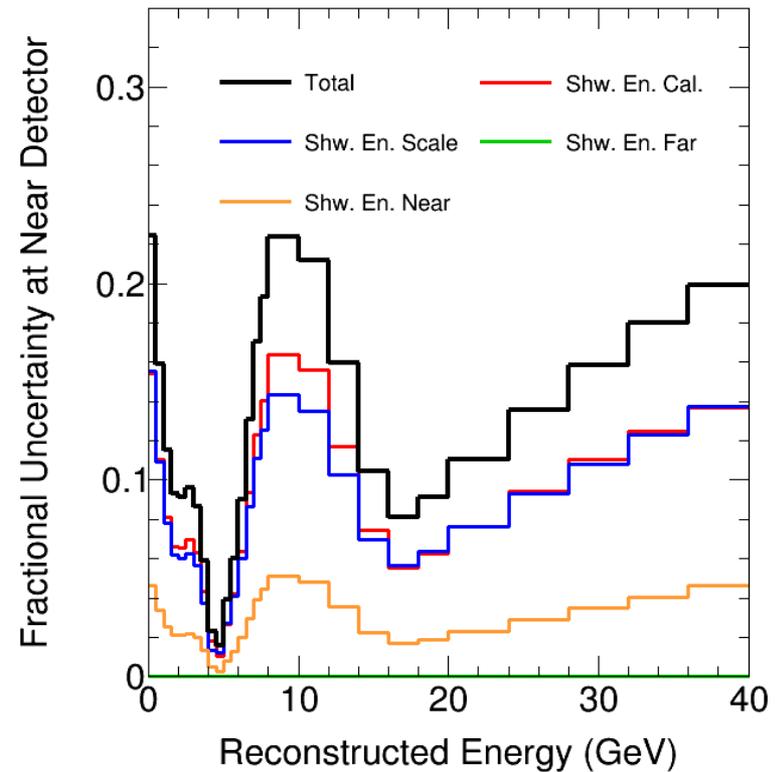
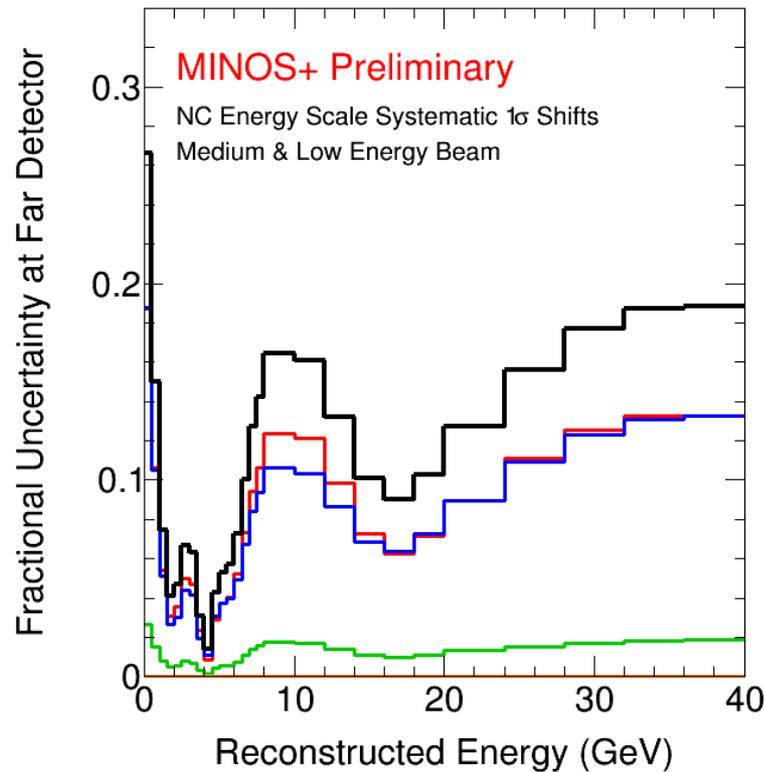
Sterile Systematics: NC Cross Sections



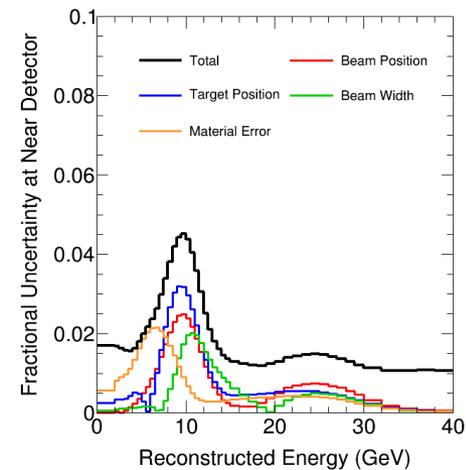
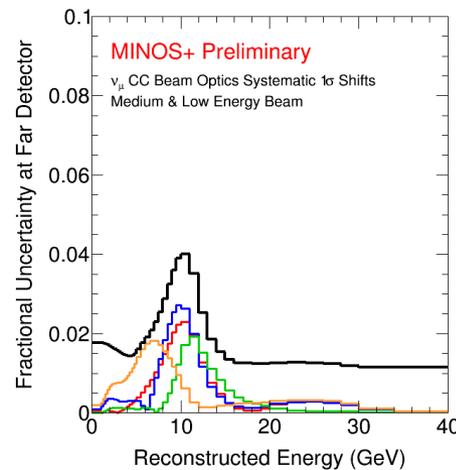
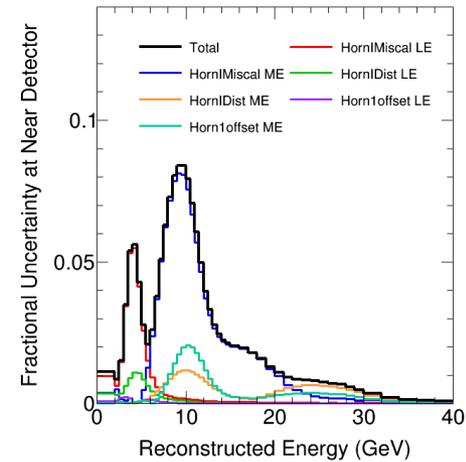
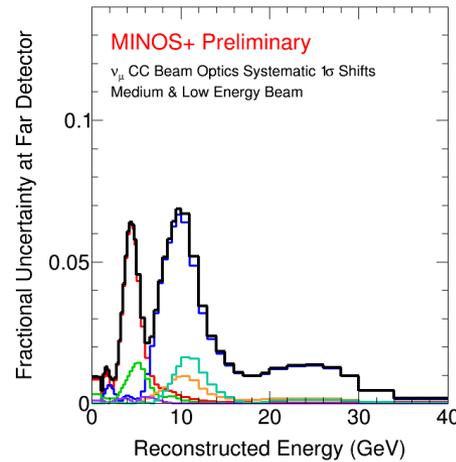
Sterile Systematics: CC Energy Scale



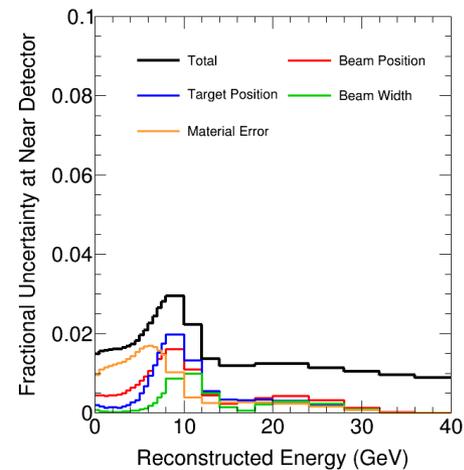
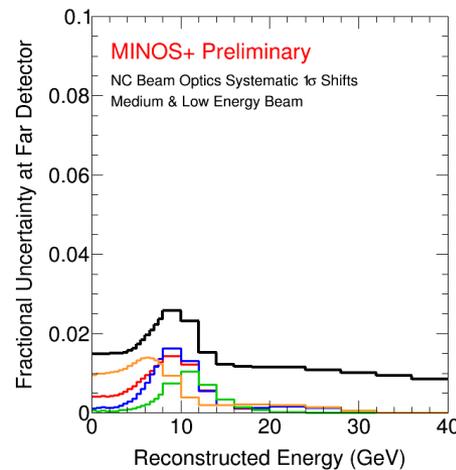
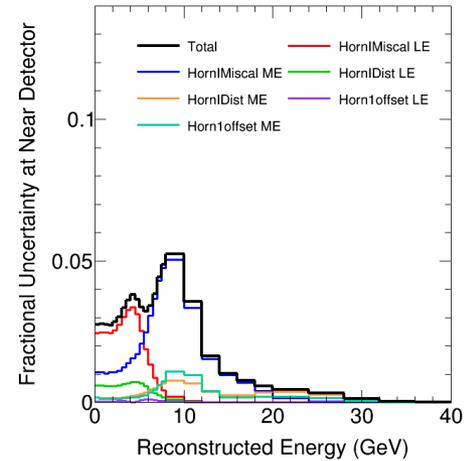
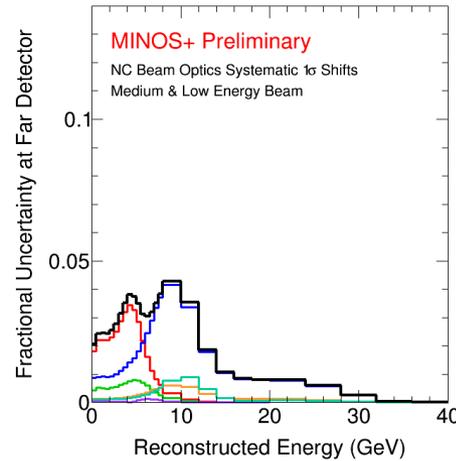
Sterile Systematics: NC Energy Scale



Sterile Systematics: CC Beam Optics



Sterile Systematics: NC Beam Optics



Sterile Systematics: Acceptance

