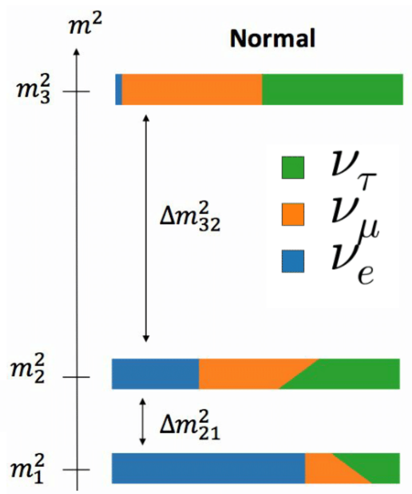
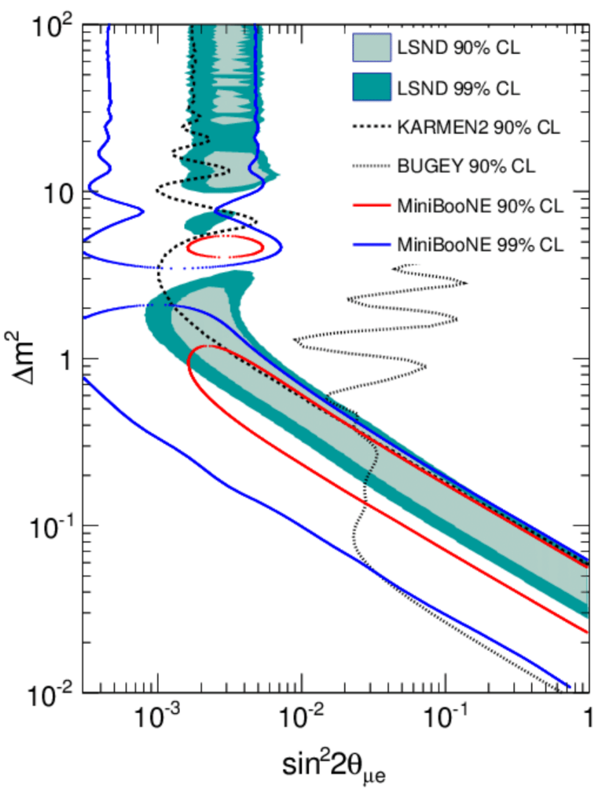
Latest News from MINOS+

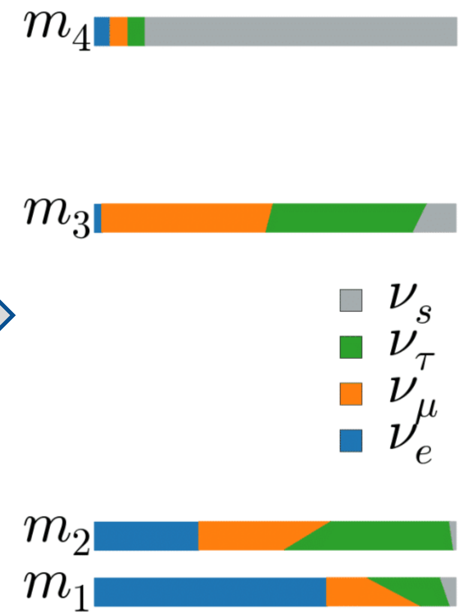
A.P. Schreckenberger - UT Austin – on behalf of MINOS/MINOS+
2017-05-09

Beyond Three-Flavor Oscillation

- Some experimental results suggest neutrino oscillations inconsistent with three-flavor oscillation paradigm
  - MINOS/MINOS+ sensitive to exotic neutrino oscillations
    - Including NSI, large extra dimensions, and sterile neutrinos

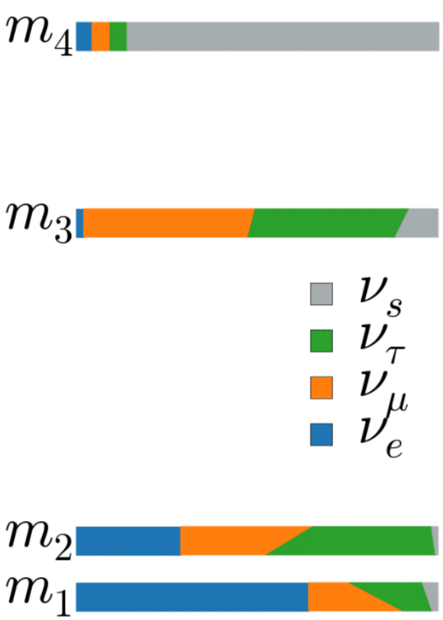


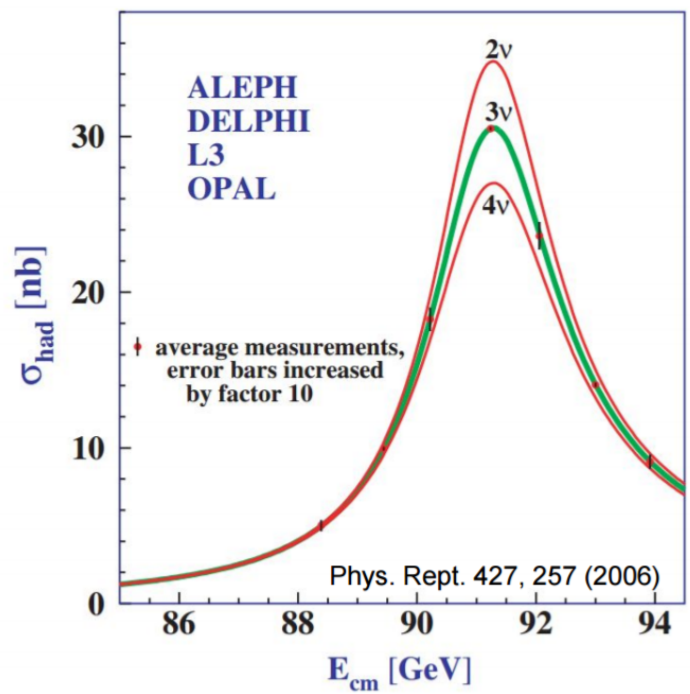




Beyond Three-Flavor Oscillation

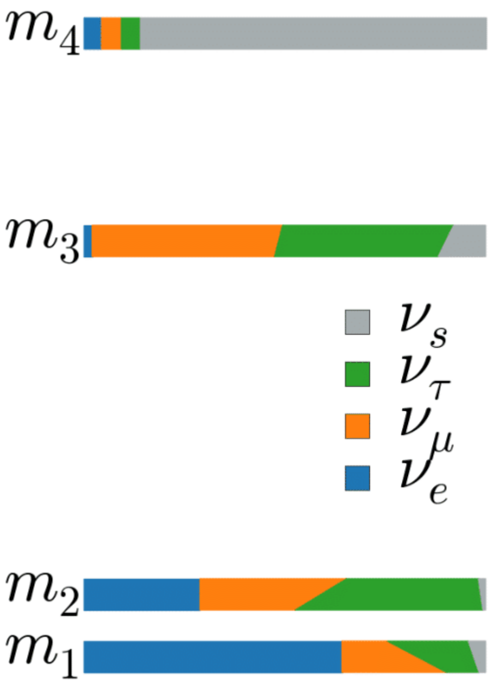
- Z line width measurements set strong limit of three active neutrino flavors
  - Any additional flavor states from exotic models cannot interact via weak nuclear force
    - Detection with traditional methods is not possible





The 3+1 Oscillation Paradigm

- Exotic models probed through neutrino oscillation mechanism
  - Consider simplest sterile neutrino model (3+1)



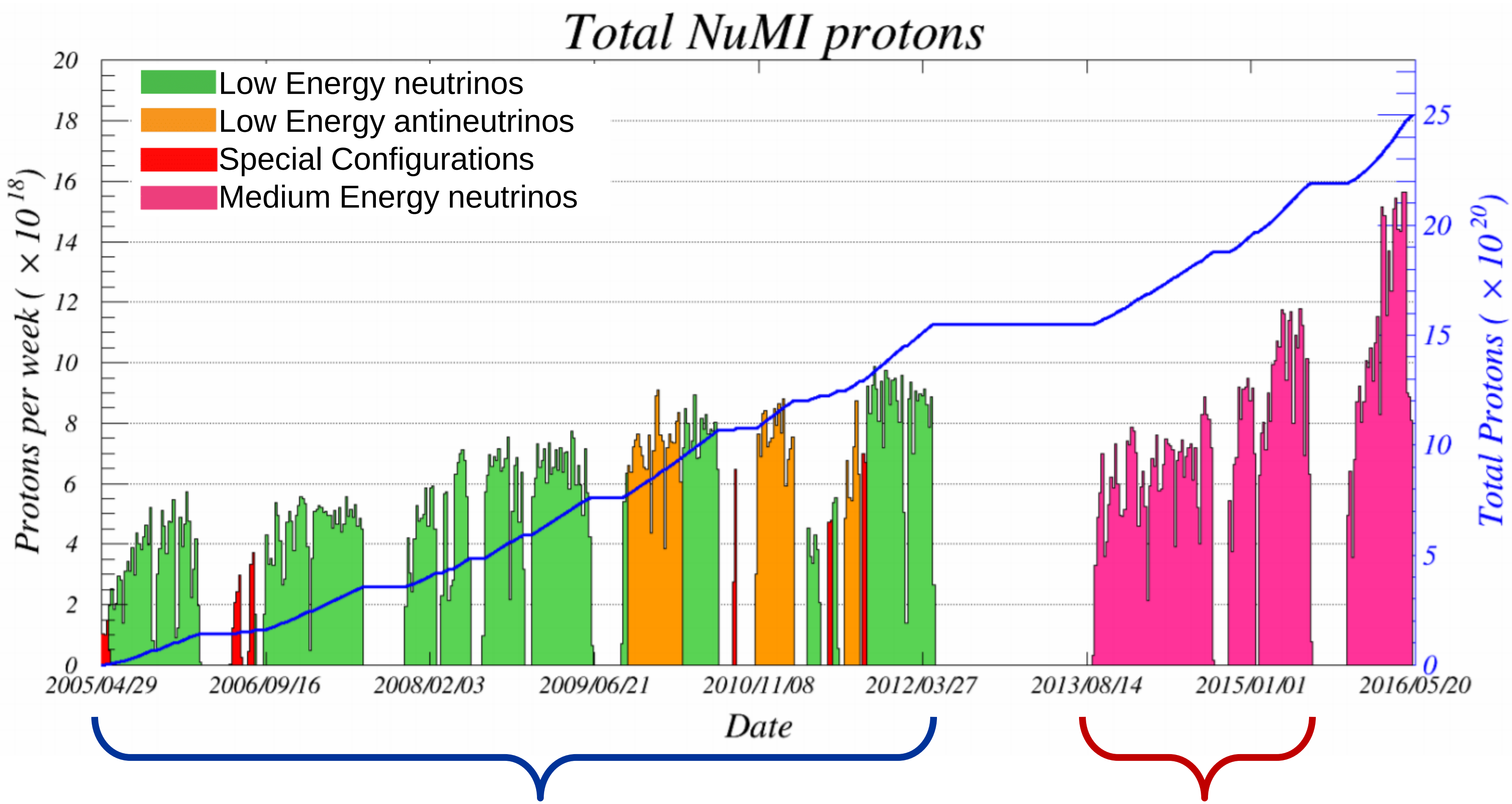
- $$U_{PMNS}^{3+1} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

- Mixing angles: $\theta_{12}, \theta_{13}, \theta_{23}, \theta_{14}, \theta_{24}, \theta_{34}$
- CP-violating phases: $\delta_{13}, \delta_{14}, \delta_{24}$
- Mass scales: $\Delta m^2_{21}, \Delta m^2_{32}, \Delta m^2_{41}$

The MINOS & MINOS+ Experiments

- Two *functionally identical* magnetized steel-scintillator tracking sampling calorimeters (ND and FD)
- Positioned on-axis in the Fermilab NuMI beam
  - Reconstructed neutrino energy spectrum peaked at around 3 GeV in MINOS and 6 GeV in MINOS+

A Robust Data Set

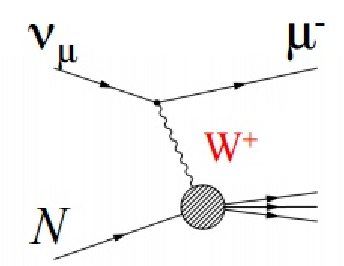


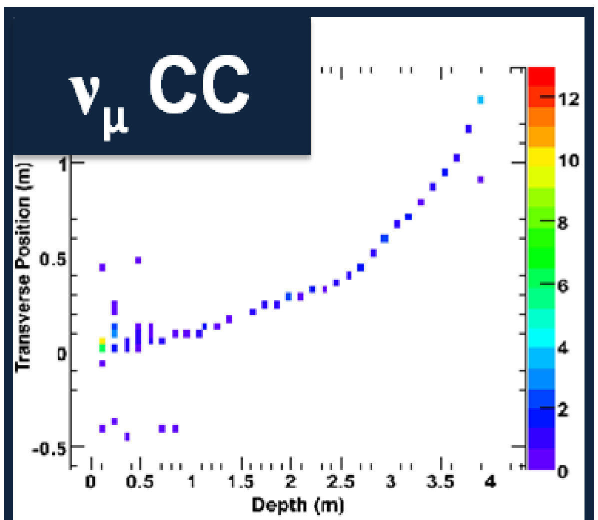
10.56 x 10^{20} POT **MINOS**

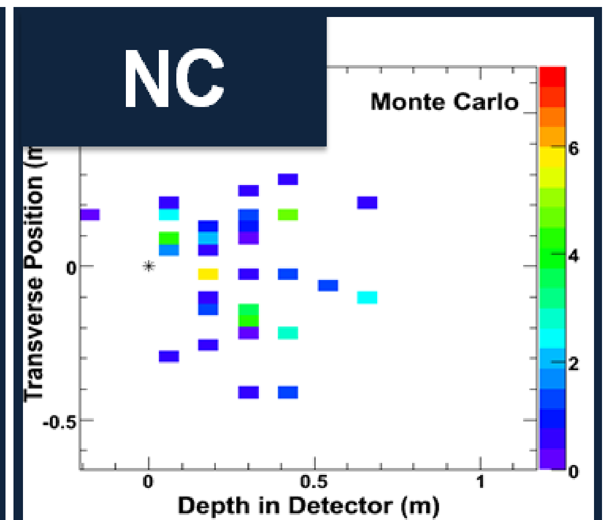
5.80 x 10^{20} POT **MINOS+**

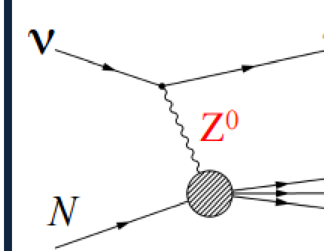
Events

- This sterile neutrino analysis selects two event topologies
  - Muon neutrino charge current (CC)
    - Distinguished in reconstruction by long muon track
  - Neutral current (NC)
    - Hadronic shower
  - Other CC events observed in the detector
    - Enter primarily as small backgrounds in the NC sample

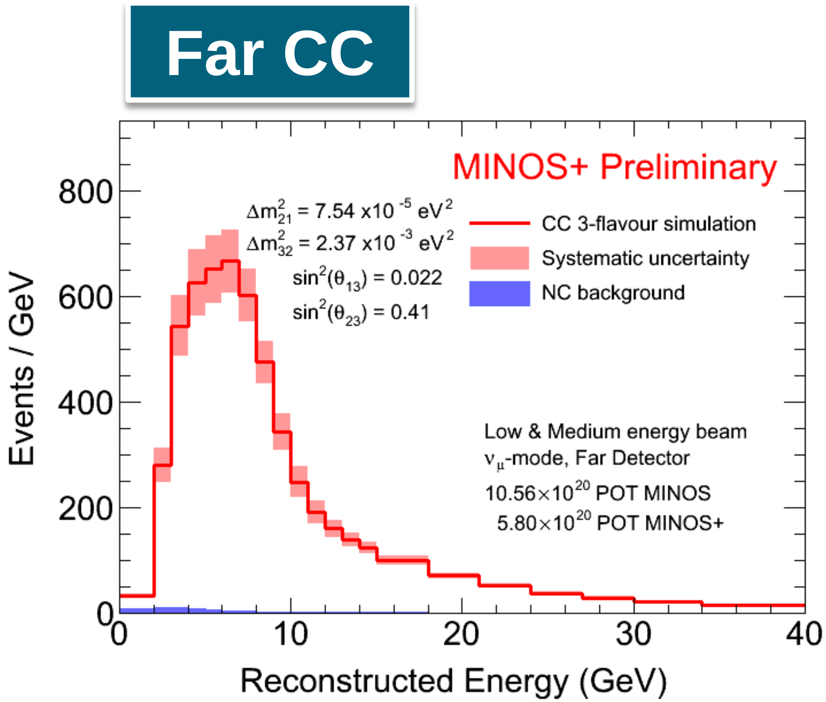


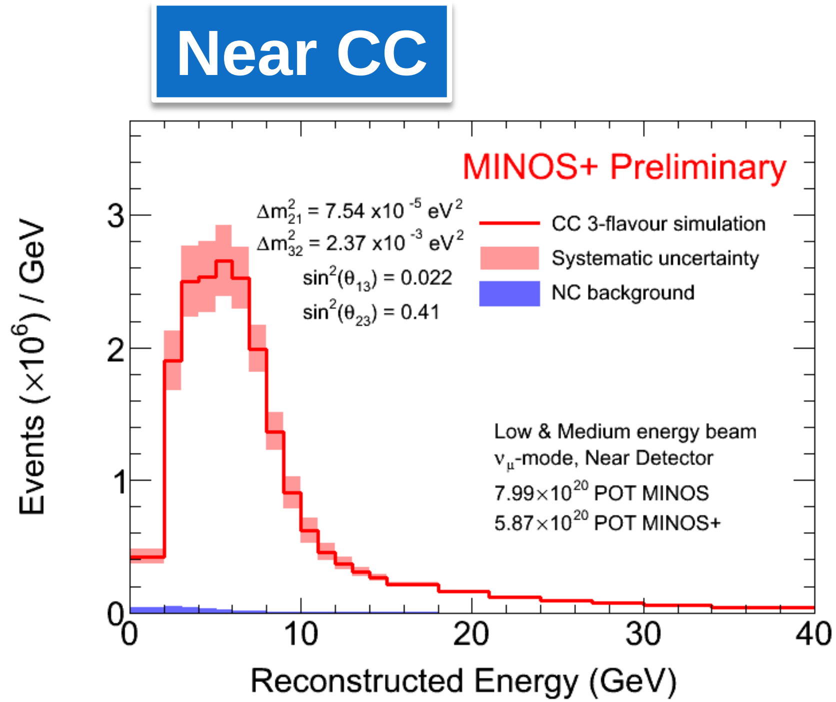






Event Predictions – CC (Three-Flavor)

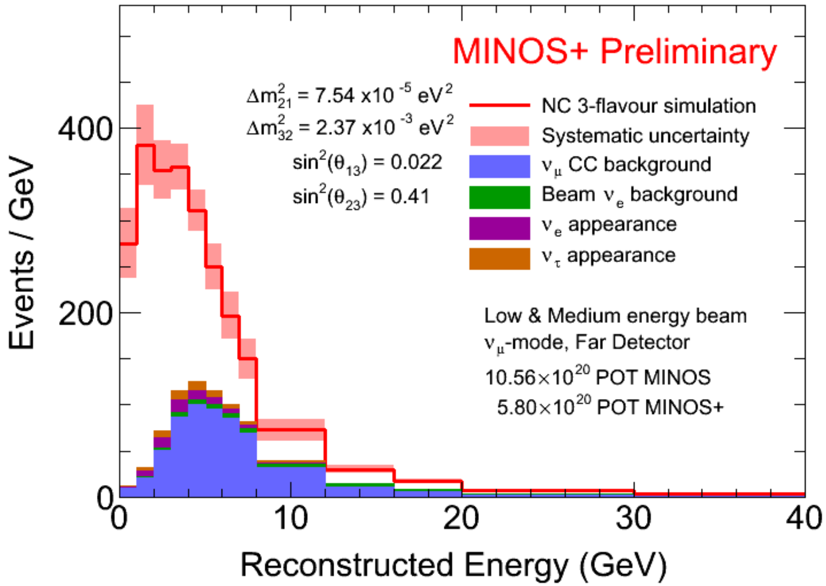




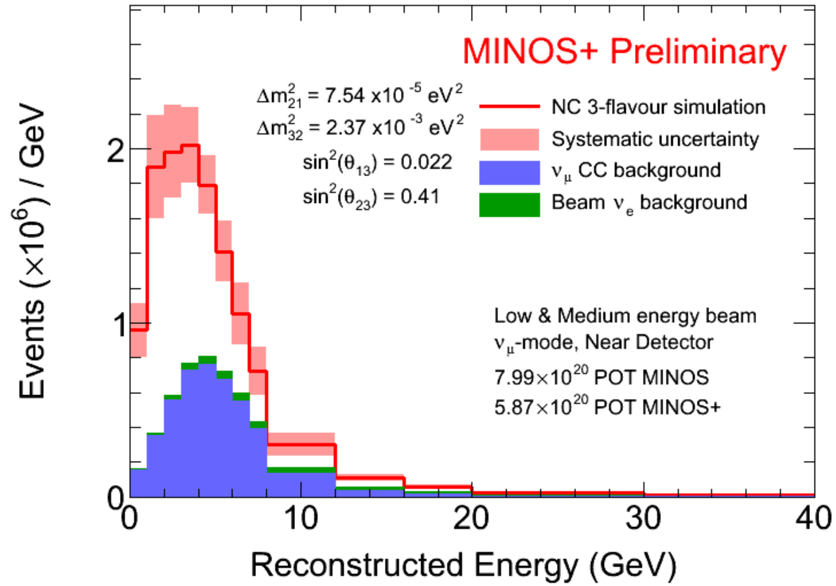
- CC selection predictions for MINOS & MINOS+
  - Neutral current events enter as small background

Event Predictions – NC (Three-Flavor)

Far NC



Near NC

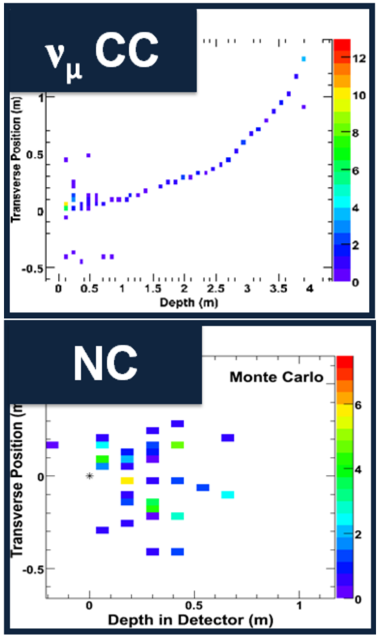


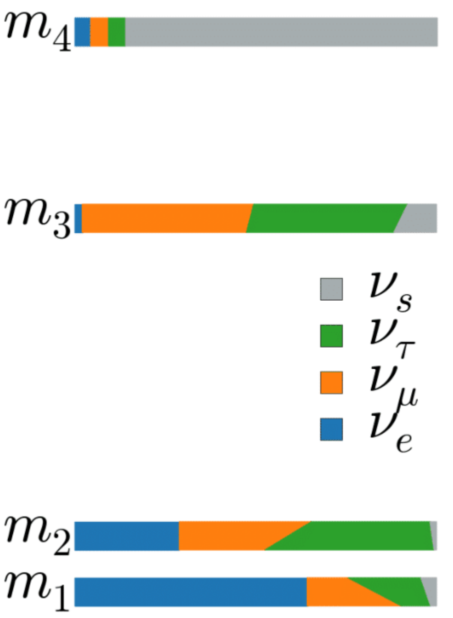
- NC selection predictions for MINOS & MINOS+
  - CC events enter as more substantial background
  - Appearance events expected in FD

Developing the Analysis Framework

- Characteristic event topologies identified
- 3+1 oscillations introduce new considerations that necessitate:
  - Determining the impact of the oscillation parameters on event rates
  - Assessing the state of the fit method

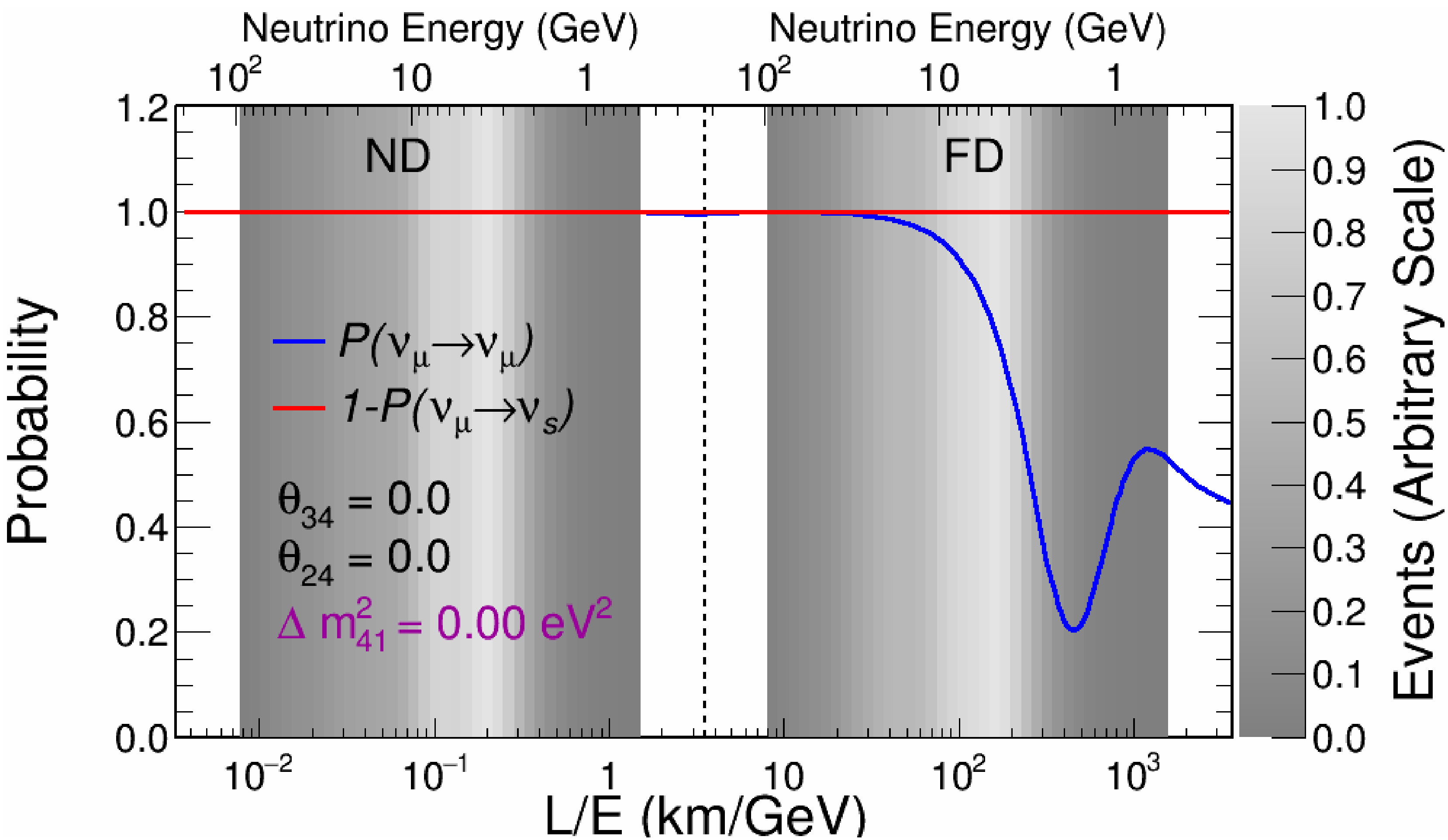
$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$





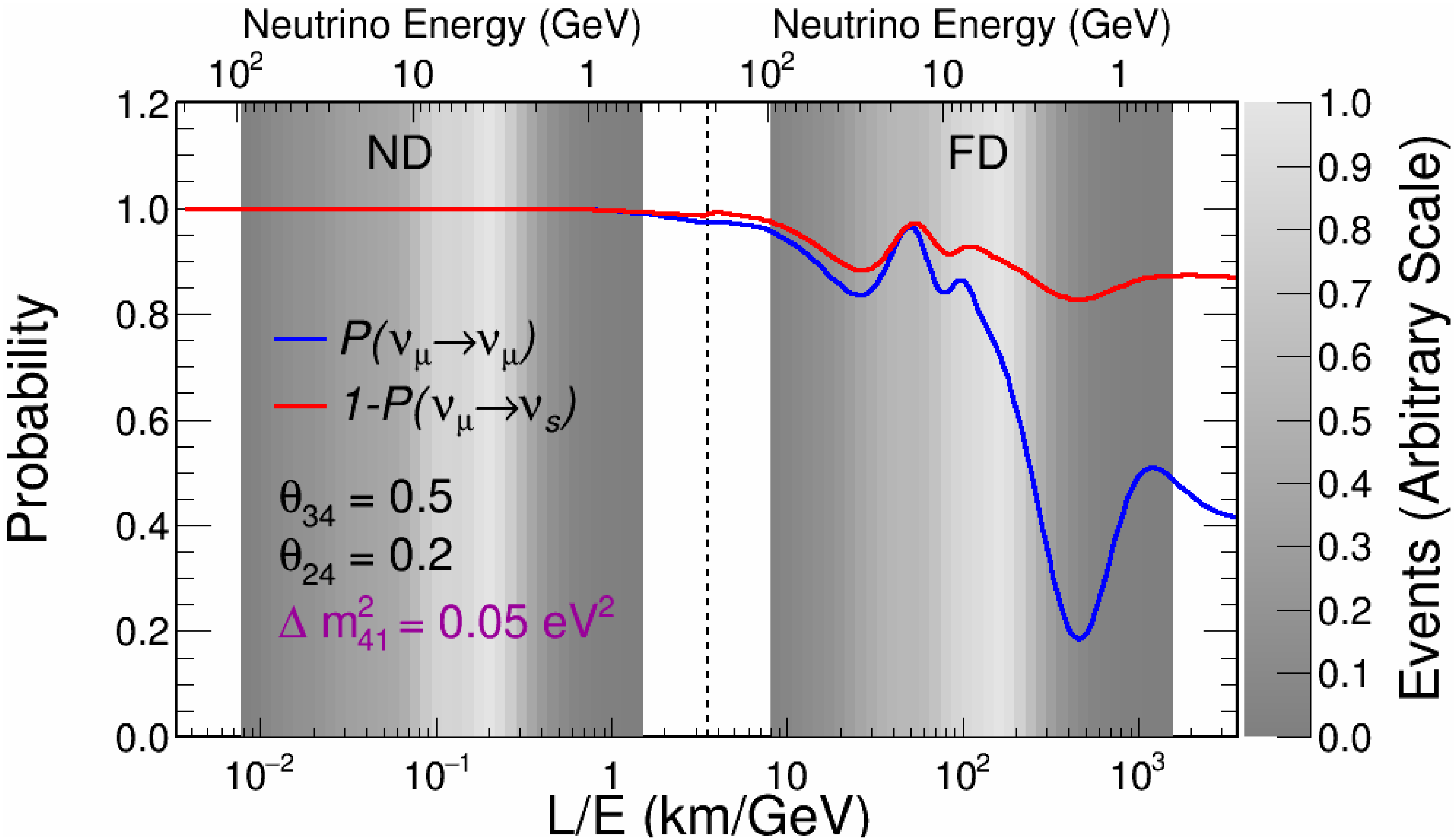
The Impact of 3+1 Oscillations

- Three-flavor oscillation picture:



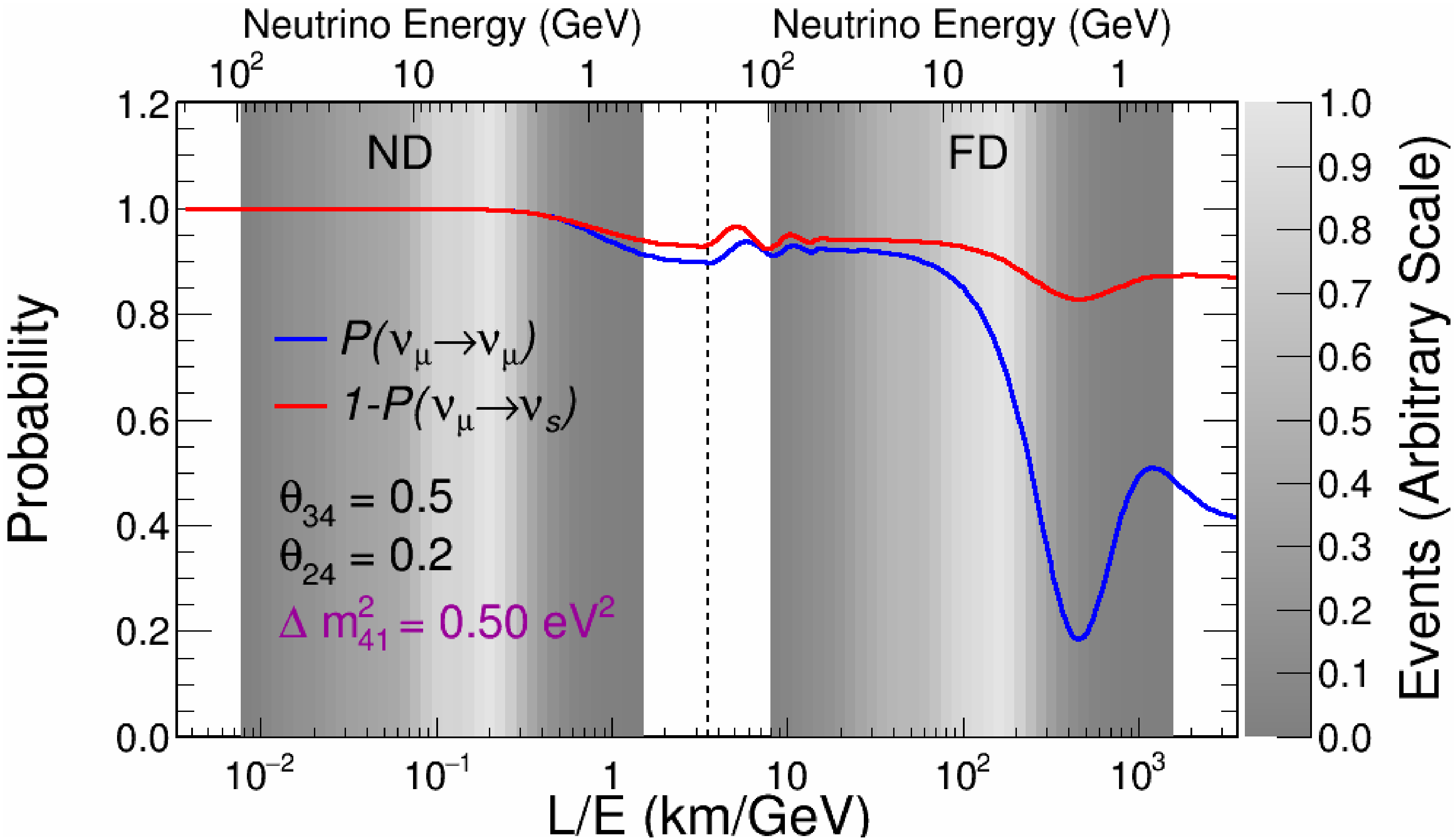
The Impact of 3+1 Oscillations

- Small Δm^2_{41}: Distortions in FD above oscillation maximum



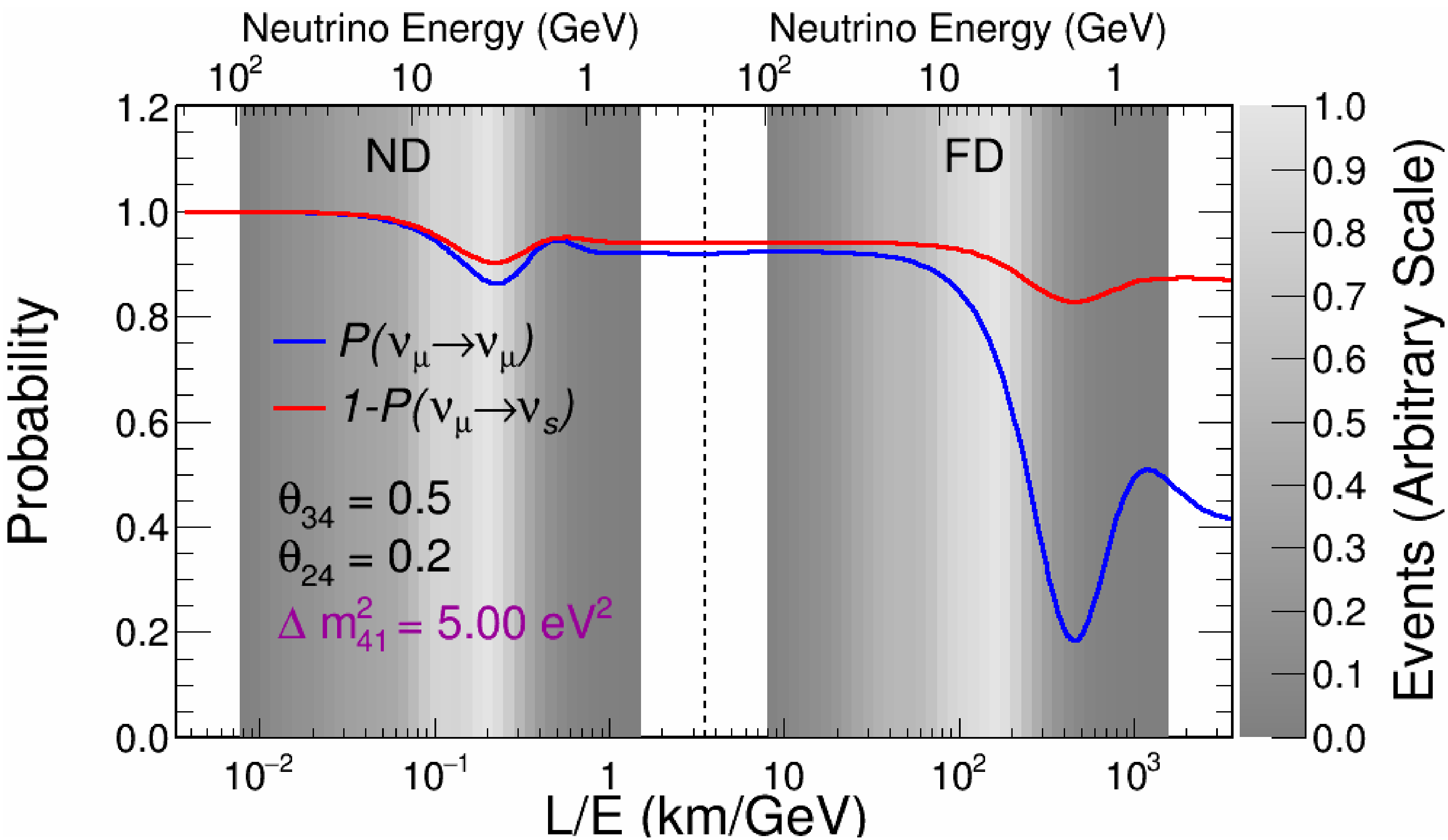
The Impact of 3+1 Oscillations

- Increasing Δm^2_{41}: Deficit driven by rapid FD oscillations



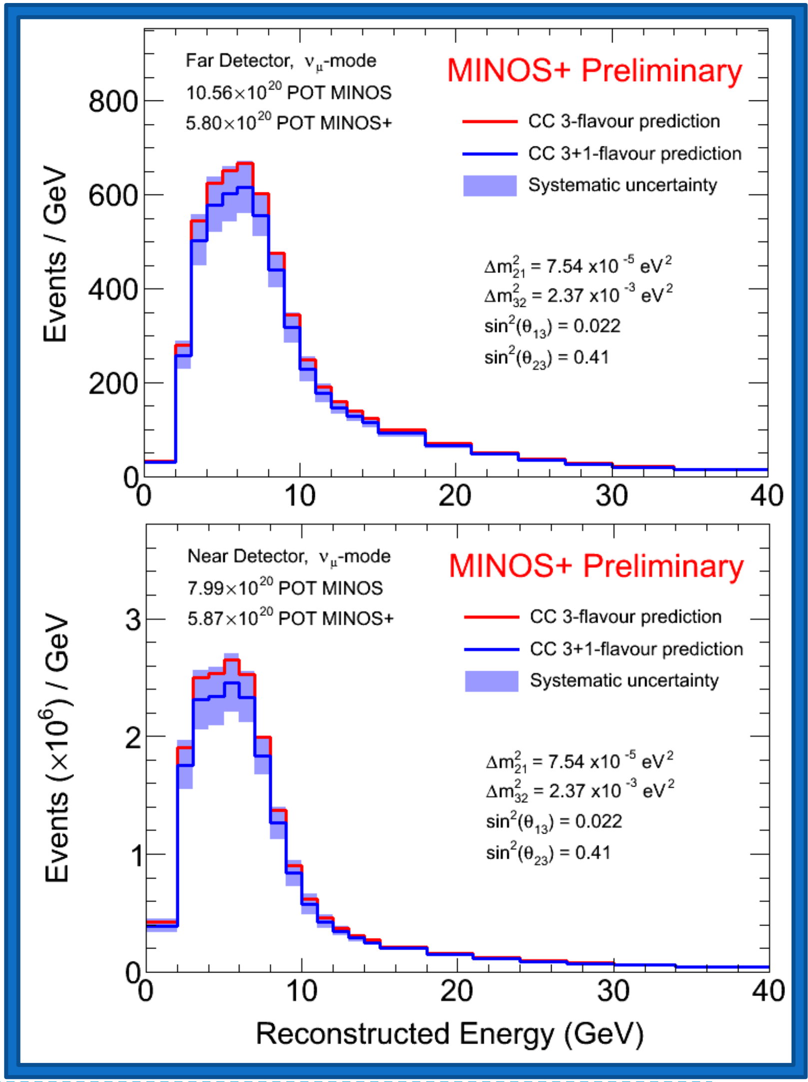
The Impact of 3+1 Oscillations

- Larger Δm^2_{41}: Rapid oscillations in FD + *Distortions in ND*



Building the Fit Method

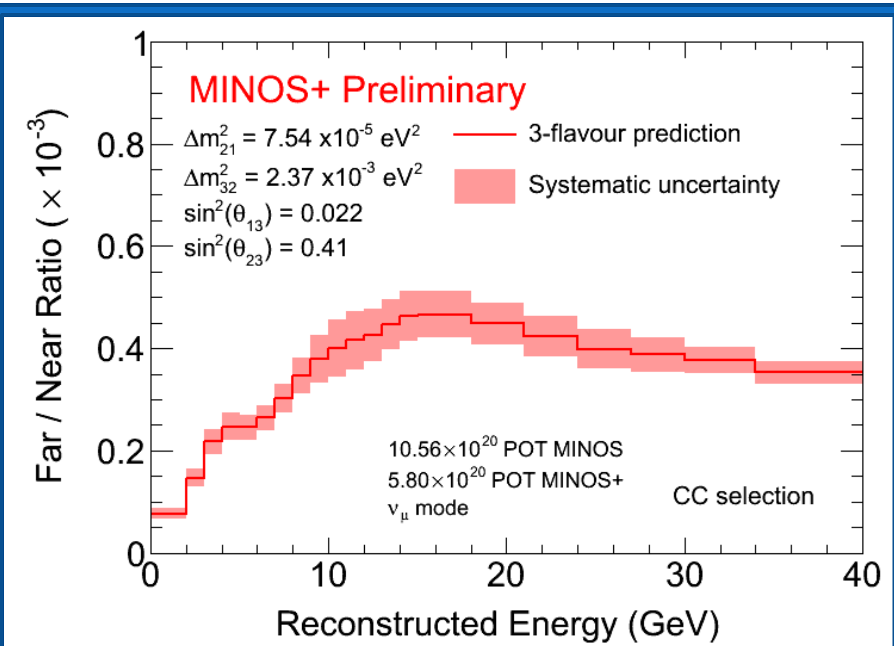
- Analysis is sensitive to θ_{24} over many orders of magnitude of Δm^2_{41}
  - $\theta_{23}, \theta_{34}, \Delta m^2_{32}$ also fit simultaneously as they impact the sensitivity
    - Direct impact on event rates of muon neutrino channels
  - $\theta_{14}, \delta_{13}, \delta_{14}, \delta_{24}$ set to zero as this analysis is not sensitive to those parameters

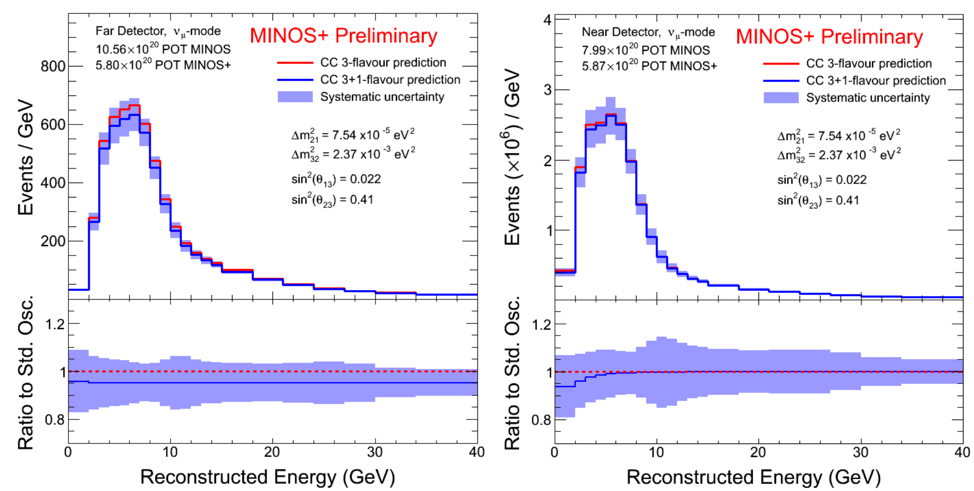


Sample: $\Delta m^2_{41} = 80\ \mathrm{eV}^2, \theta_{24} = 0.2$

Building the Fit Method

- Distortions in ND spectrum at larger values of Δm^2_{41} necessitate a different procedure
  - Three-flavor MINOS analyses compared FD data to unoscillated prediction based upon ND data
- Previously shown MINOS sterile results utilized a Far/Near fitting method
  - Now using a simultaneous two-detector fit to maximize information

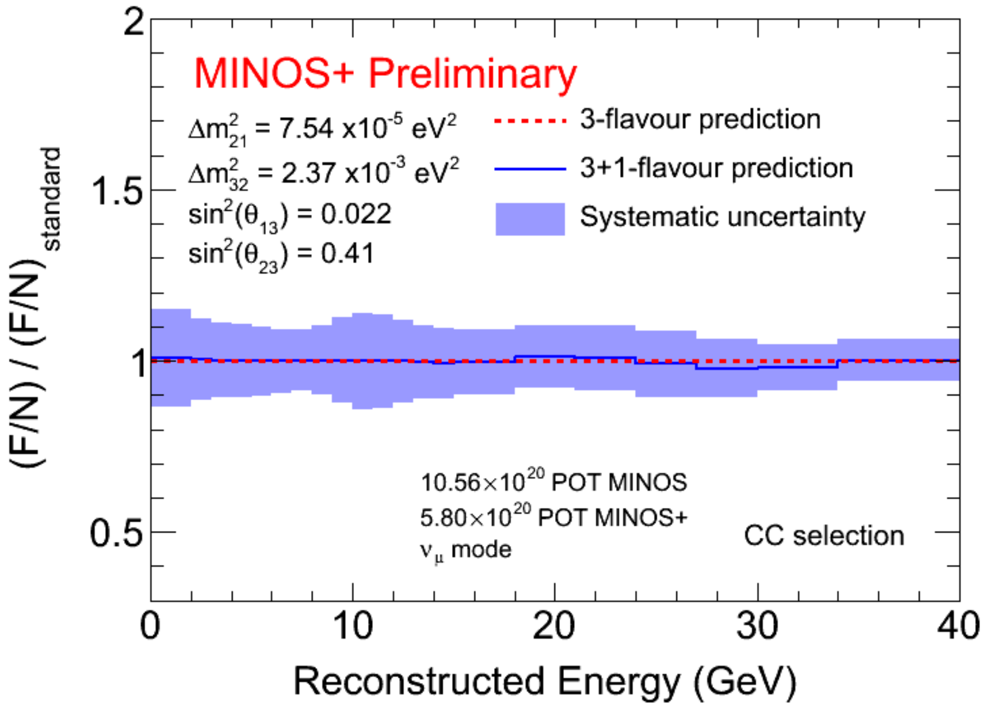




$$\Delta m^2_{41} = 80\ \text{eV}^2, \theta_{24} = 0.2$$

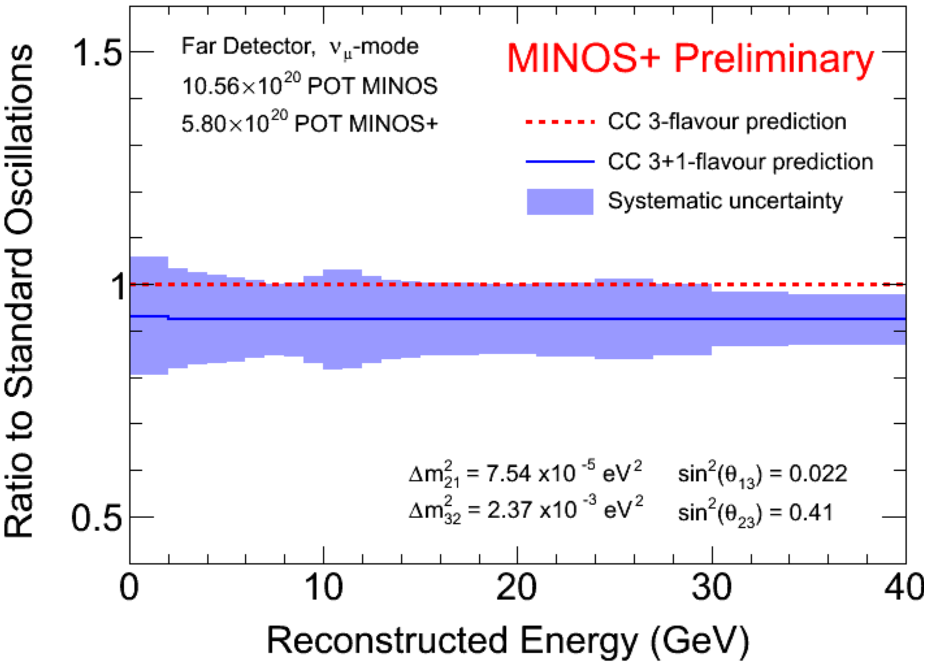
The Case for the Two-Detector Fit

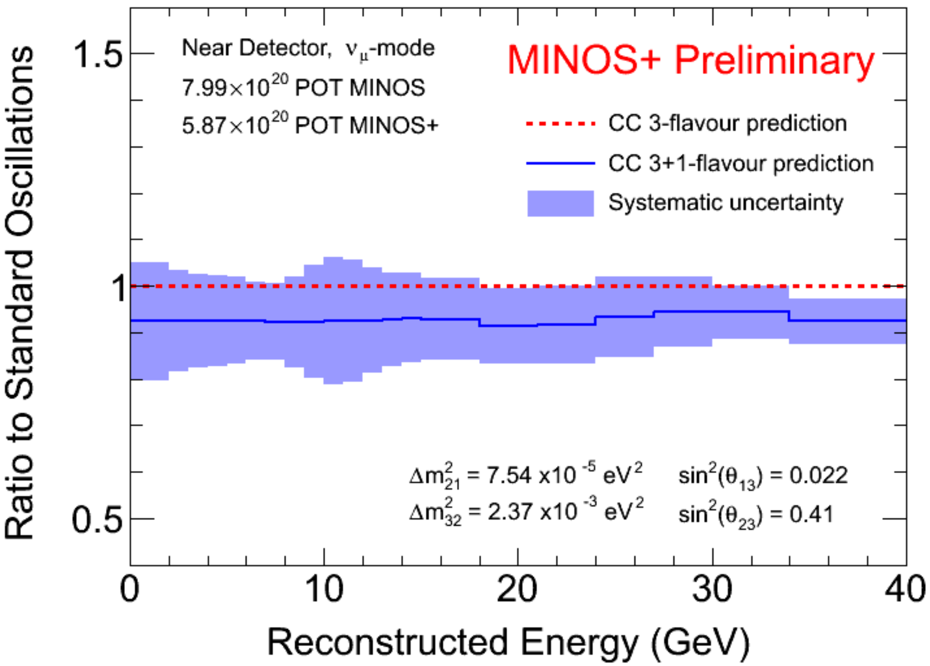
- Comparison of the 3+1 and three-flavor models with the Far/Near method in ND oscillation region
  - $\Delta m^2_{41} = 80 \text{ eV}^2, \theta_{24} = 0.2$
  - Indistinguishable from three-flavor oscillation



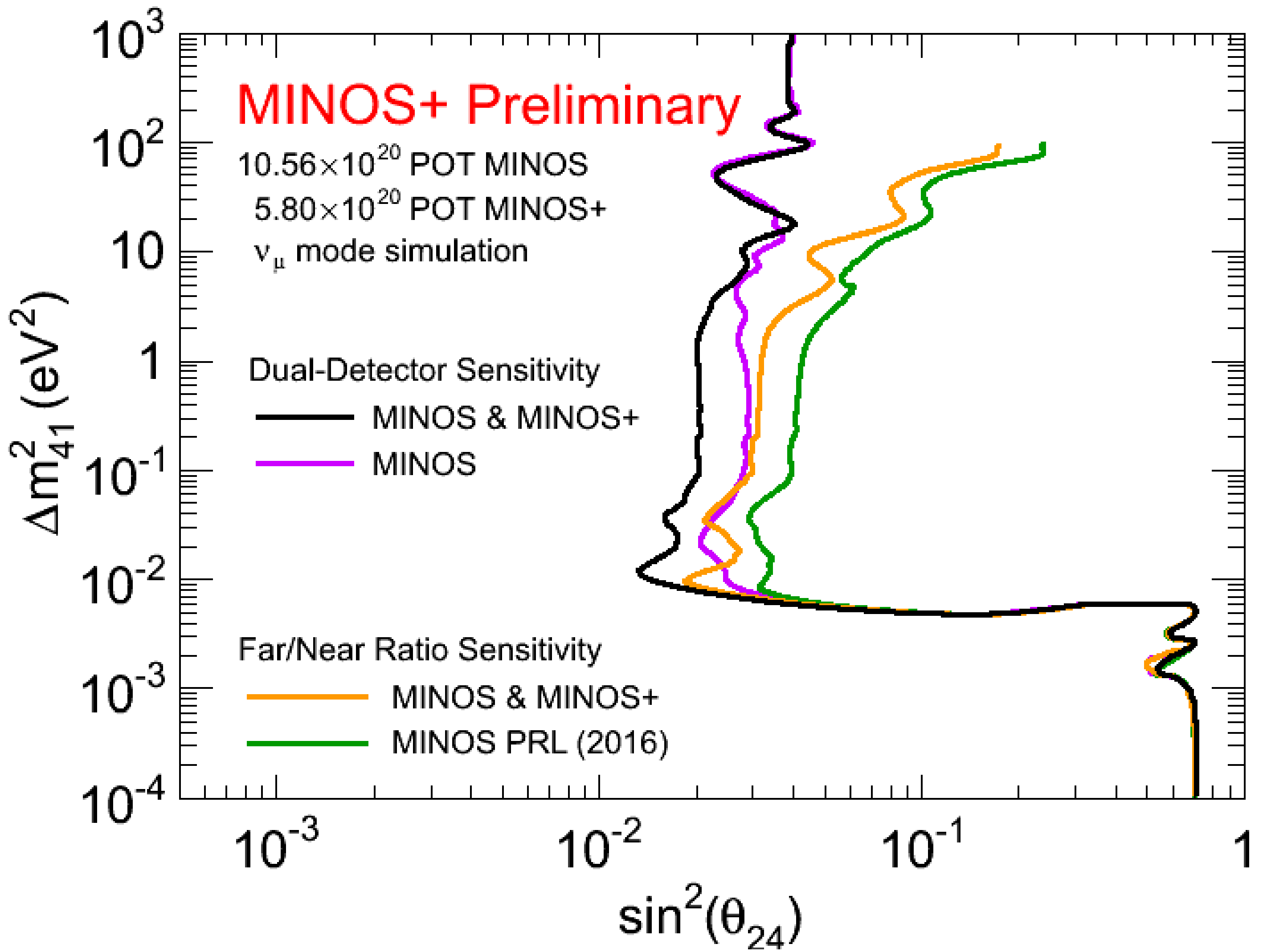
The Case for the Two-Detector Fit

- Comparison of the 3+1 and three-flavor models in each detector
  - $\Delta m^2_{41} = 80\ \text{eV}^2, \theta_{24} = 0.2$
  - Greater distinction from three-flavor expectation





Sensitivity – Benefit of the Two-Detector Fit



Systematics

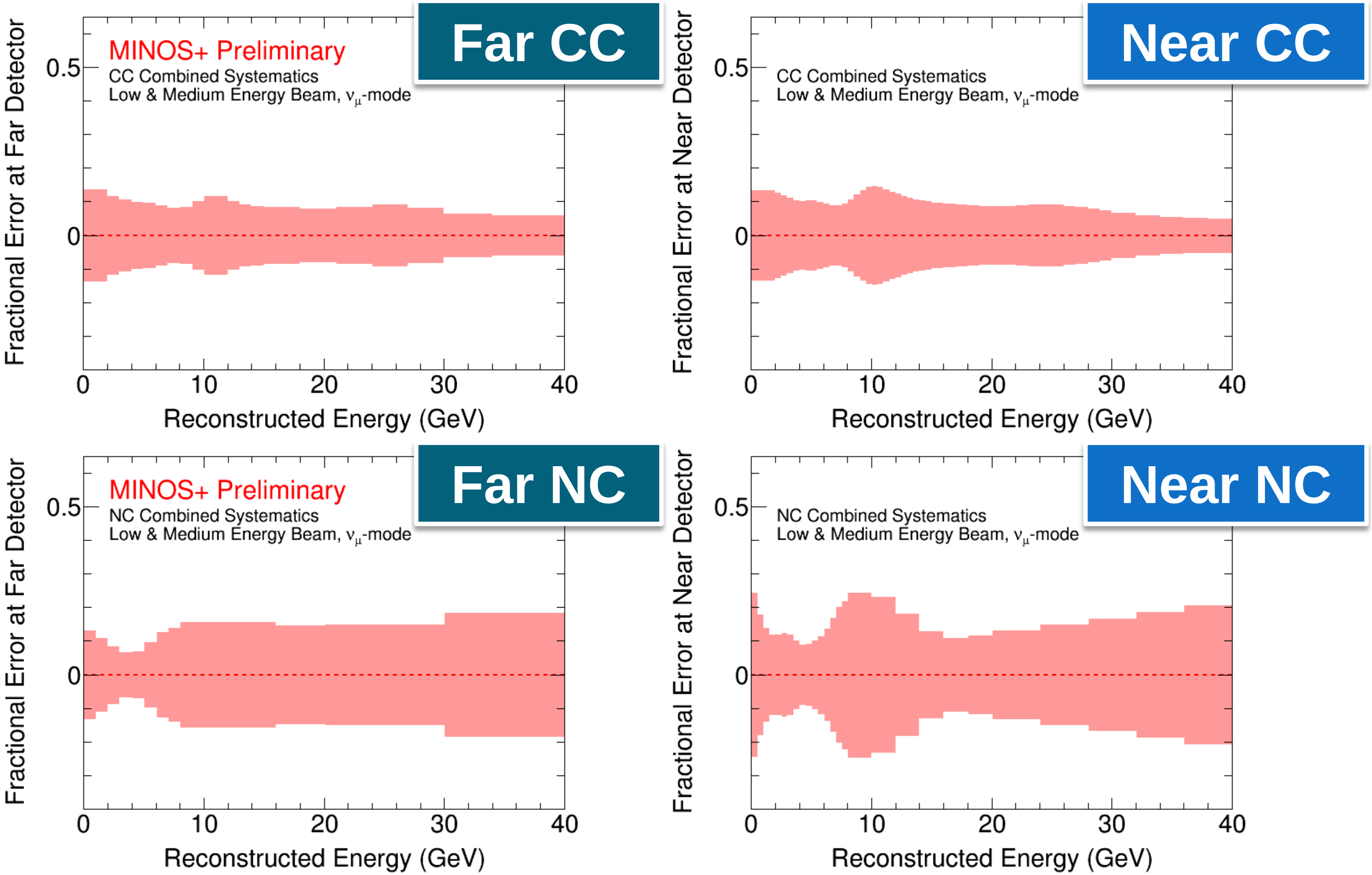
- Statistical and systematic uncertainties enter fit through a covariance matrix
  - Cross-terms in matrix facilitate cancellation of some uncertainties

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

- 44 systematics are considered in the analysis, shown in the table in terms of 5 categories

Uncertainty source	Maximum uncertainty (%) ND CC	FD CC	ND NC	FD NC
Hadron production	7%	7%	7%	7%
Cross-sections	10%	10%	11%	13%
Backgrounds	1%	1%	10%	5%
Energy scale	10%	8%	20%	18%
Other	6%	3%	6%	3%
Total	15%	12%	25%	20%

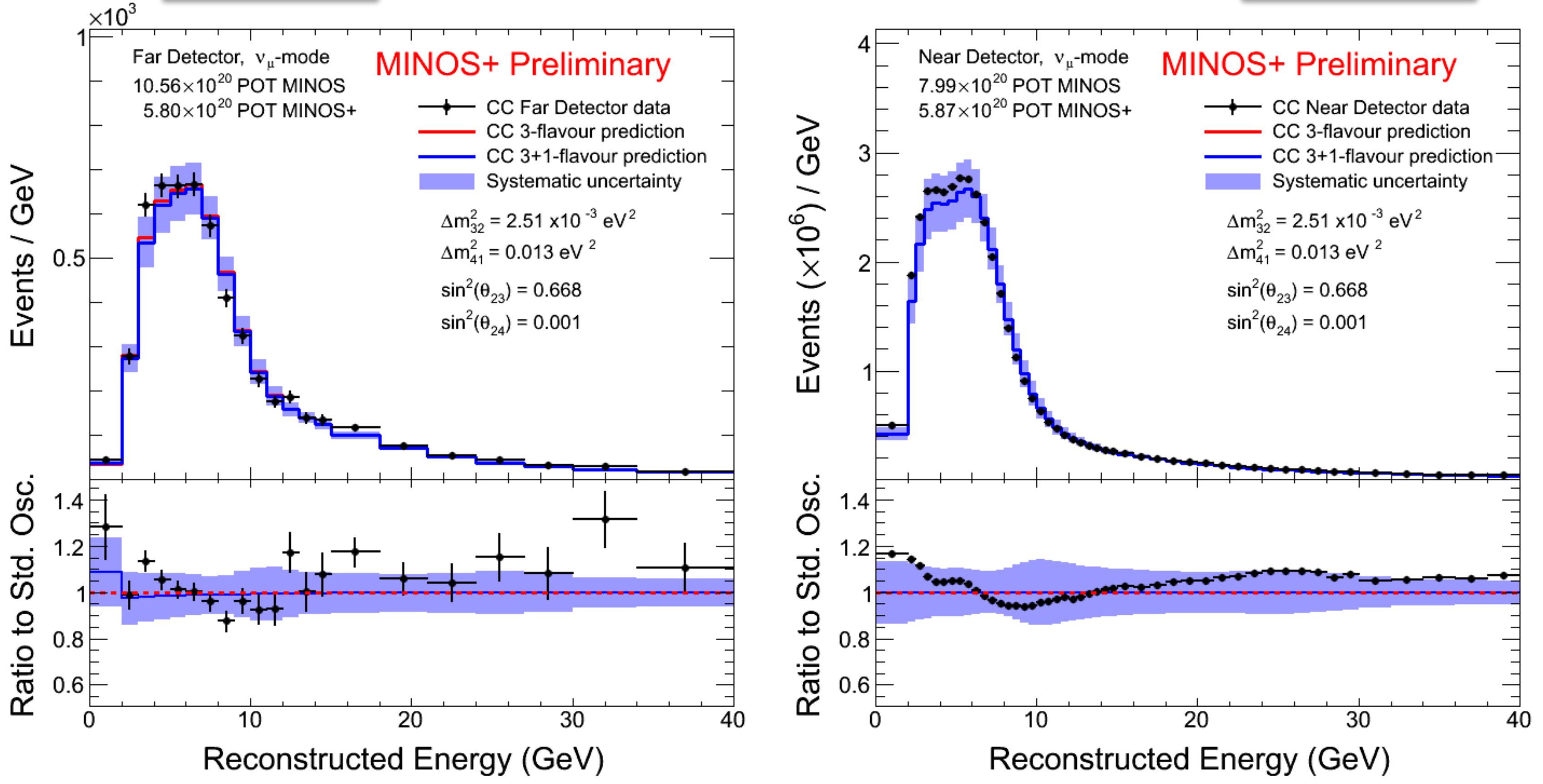
Systematics



Looking at the Data

CC Events

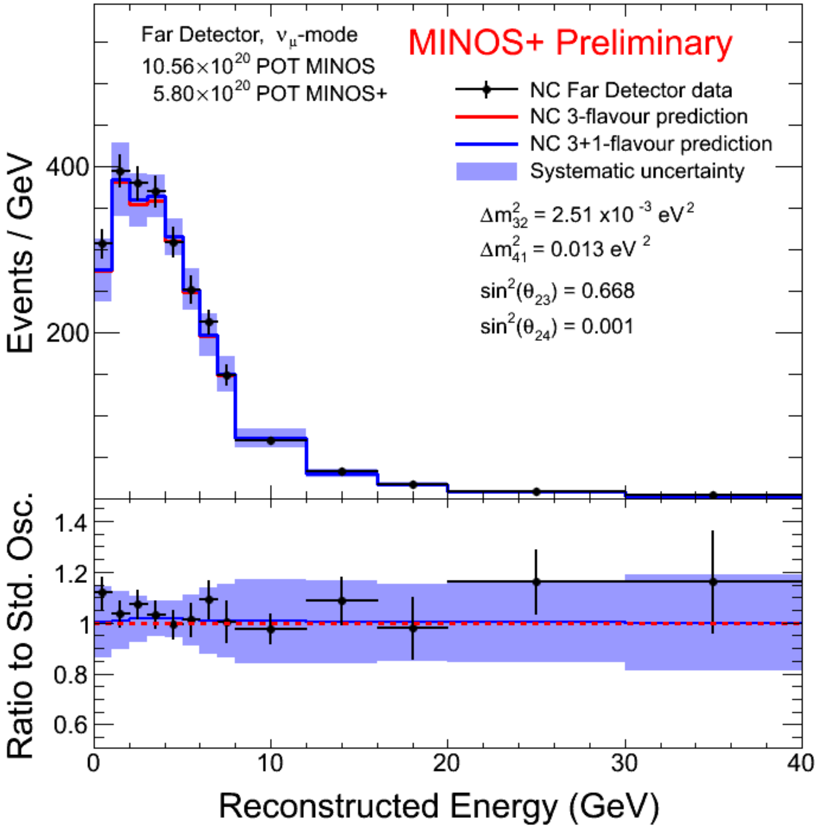
Far **Near**



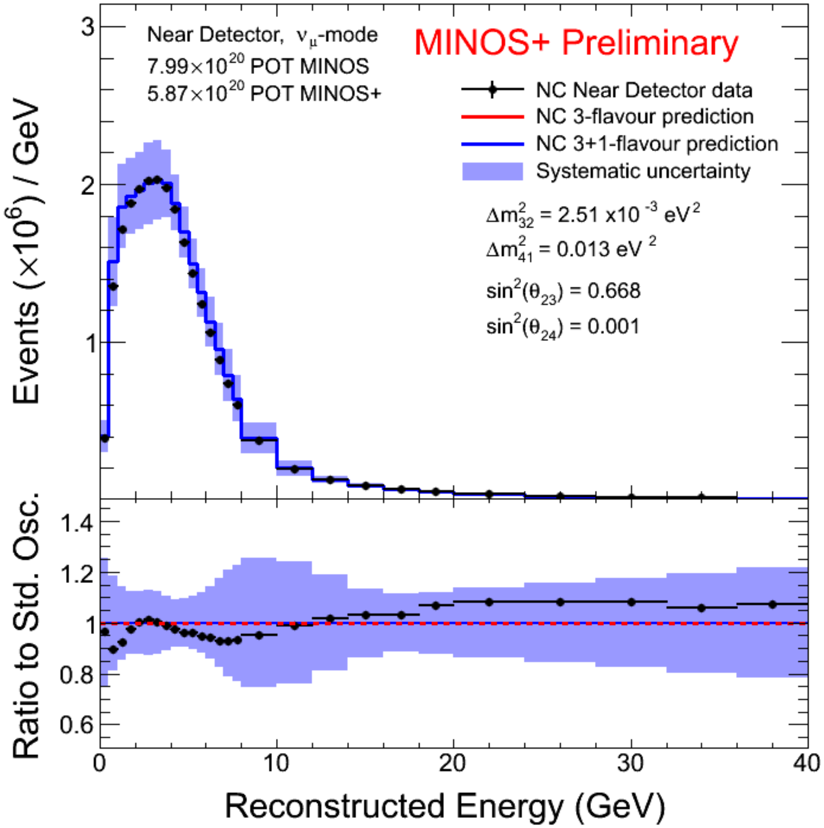
Looking at the Data

NC Events

Far

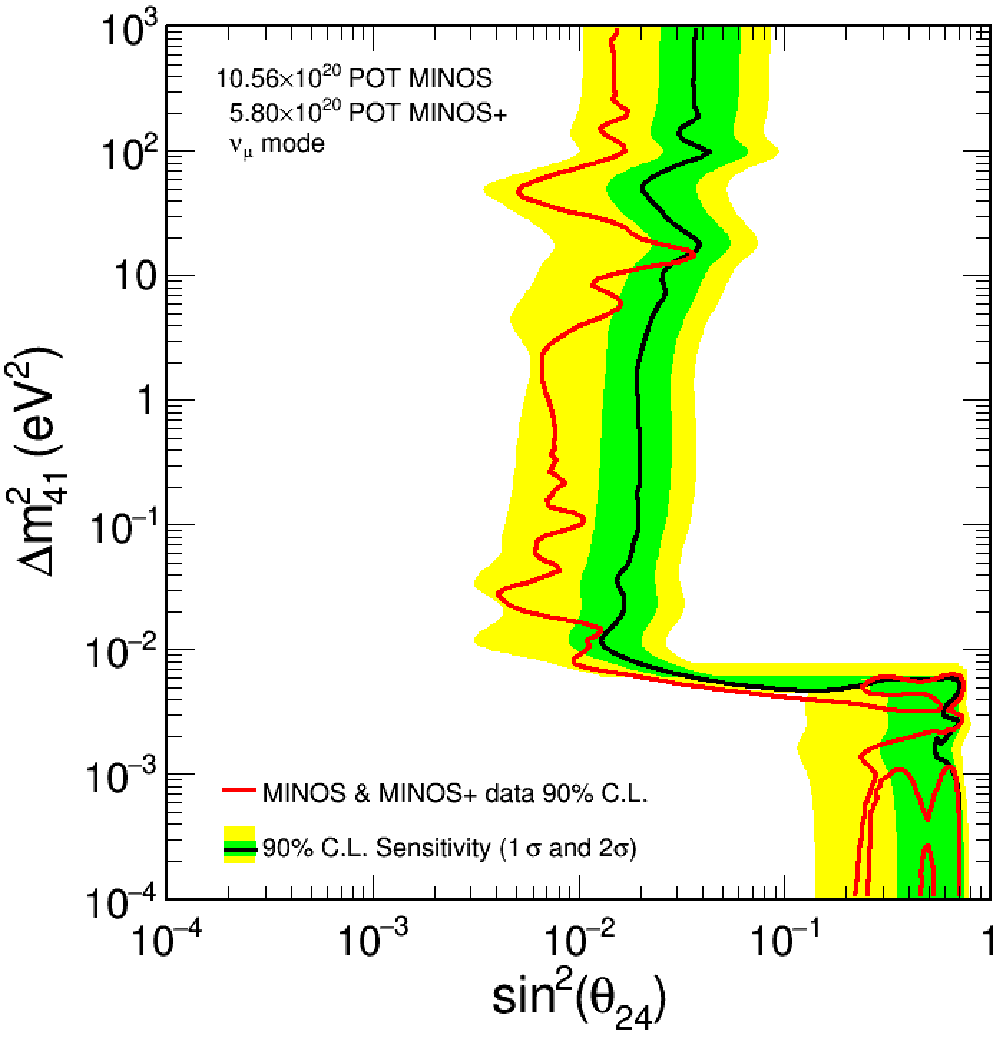


Near



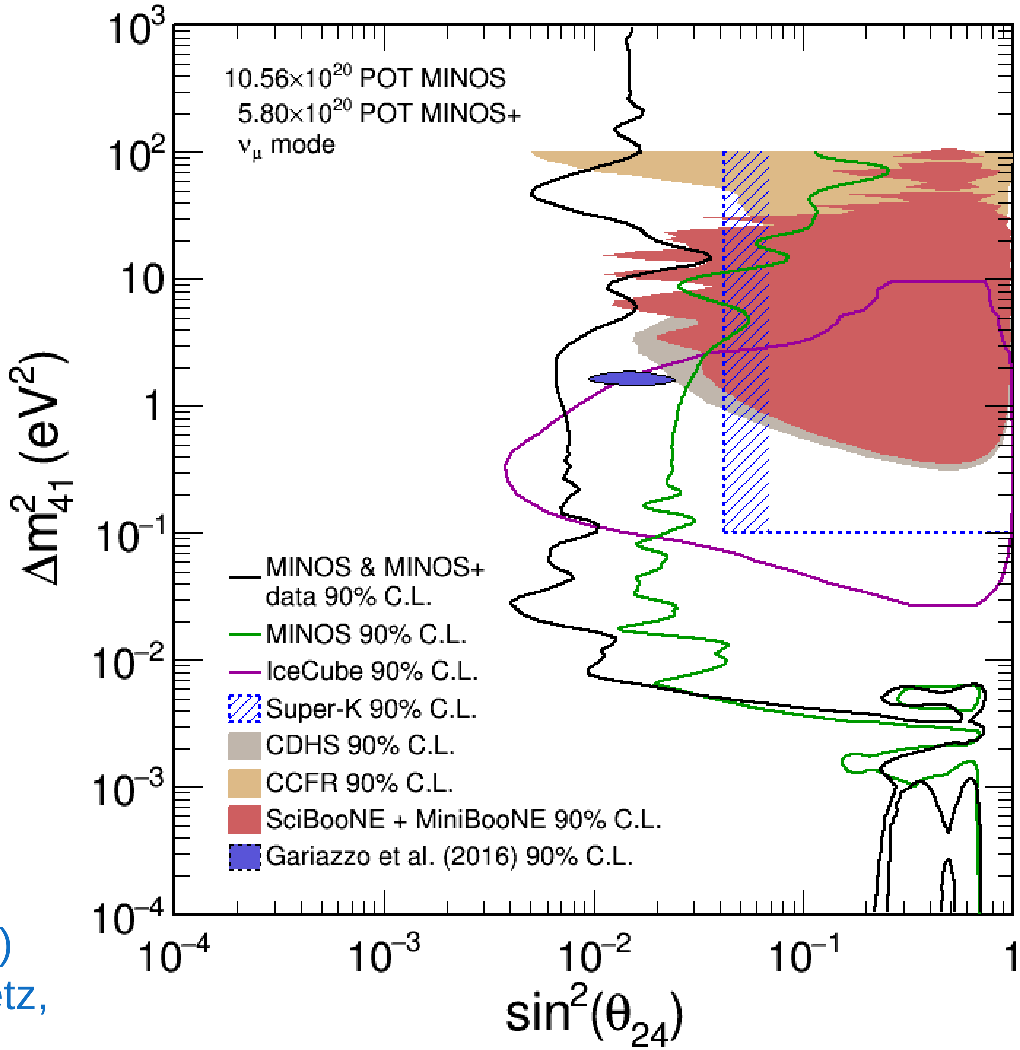
Exclusion Contour

- 90% C.L. constructed with Feldman-Cousins
- Spans seven orders of magnitude in Δm^2_{41}
- Exclusion from data contained within the 2σ expected sensitivity region



Exclusion Contour

- Result improves upon MINOS constraint
  - At larger values of Δm^2_{41}, two-detector fit yielded stronger limits
- Increased the tension with the global best fit
  - Gariazzo et al. region[†] drawn with $\theta_{14} = 0.15$[‡]



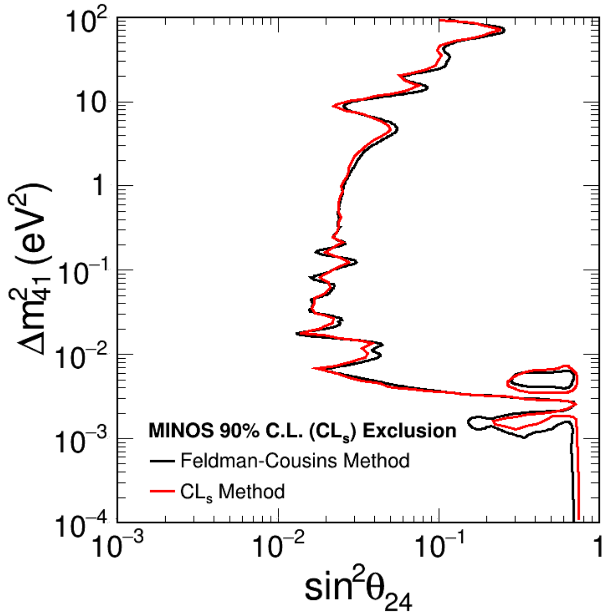
MINOS: Phys. Rev. Lett. **117**, 151803
[†]S. Gariazzo, C. Giunti, M. Laveder, Y.F. Li, E.M. Zavanin, J. Phys. G **43**, 033001 (2016)
[‡]J. Kopp, P. Machado, M. Maltoni, T. Schwetz, JHEP 1305:050 (2013)

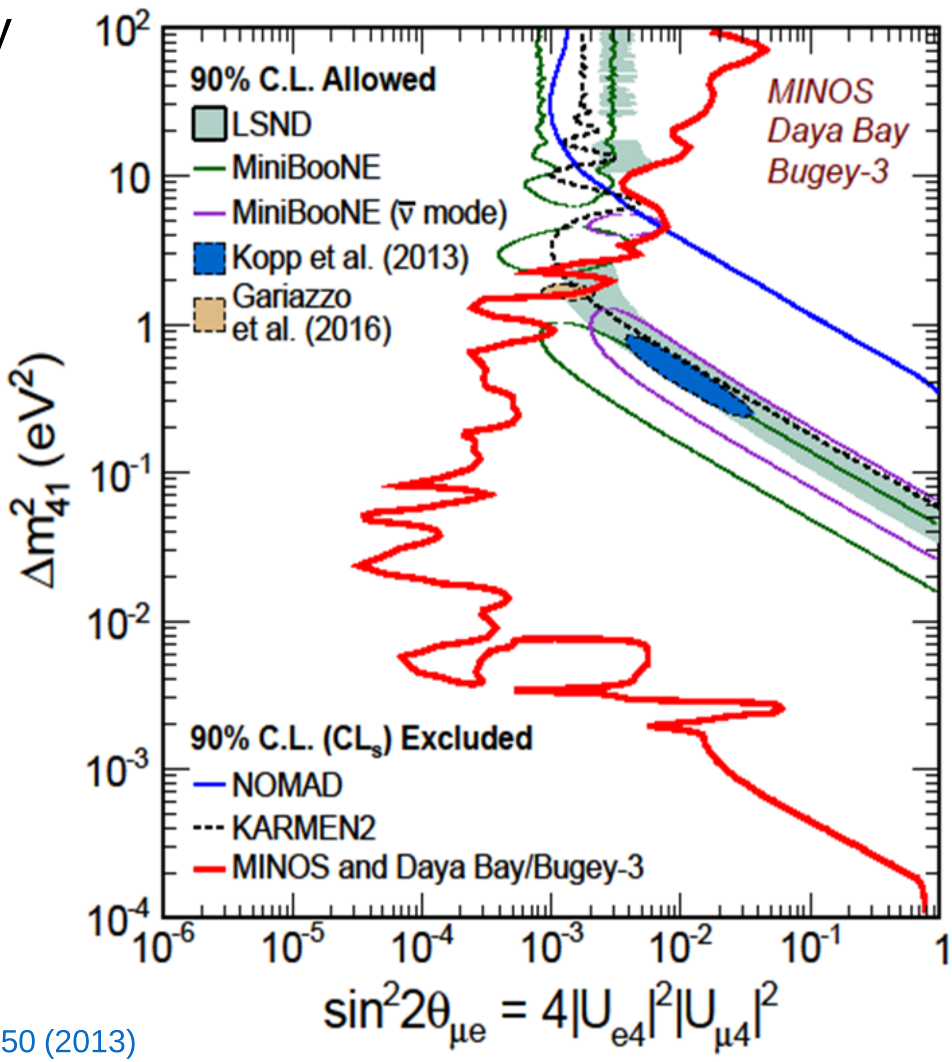
MINOS+/MINOS/Daya Bay/Bugey-3 Combination

1) MINOS: Phys. Rev. Lett. **117**, 151803
2) Daya Bay: Phys. Rev. Lett. **117**, 151802
3) Combined: Phys. Rev Lett. **117**, 151801

Combined Result

- MINOS and Daya Bay previously published combined analysis
  - Motivated by the comparison to LSND and MiniBooNE
  - In MINOS, this necessitated introduction of CL_s method

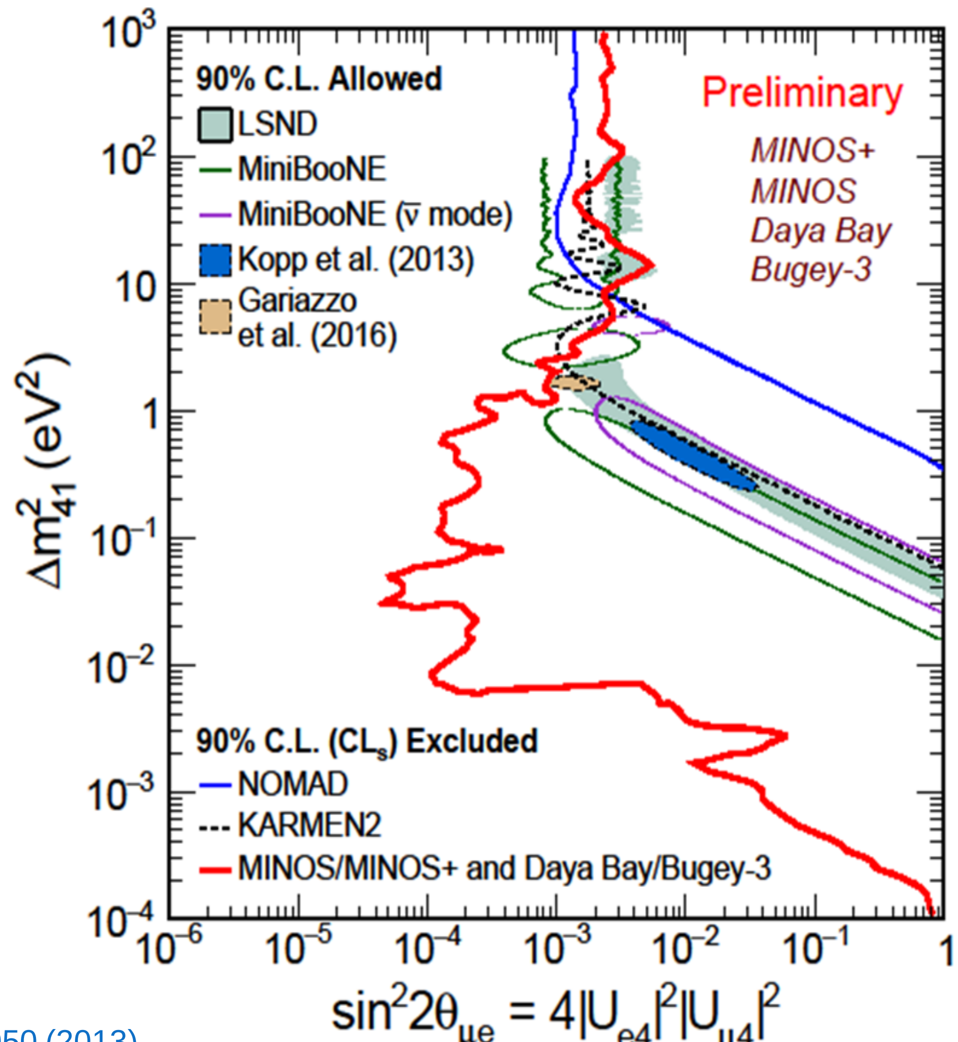




4) S. Gariazzo, C. Giunti, M. Laveder, Y.F. Li, E.M. Zavanin, J. Phys. G **43**, 033001 (2016)
5) J. Kopp, P. Machado, M. Maltoni, T. Schwetz, JHEP 1305:050 (2013)

Combined Result

- New 90% C.L. using the CL_s method
  - Includes MINOS+ data in a new combination with MINOS, Daya Bay, and Bugey-3
  - Preliminary result part of an ongoing joint effort between MINOS+ and Daya Bay
    - Combination with larger Daya Bay data set planned
- Increases tension with allowed regions



1) S. Gariazzo, C. Giunti, M. Laveder, Y.F. Li, E.M. Zavanin, J. Phys. G **43**, 033001 (2016)
2) J. Kopp, P. Machado, M. Maltoni, T. Schwetz, JHEP 1305:050 (2013)

Summary and Outlook

- MINOS and MINOS+ are continuing to lead the way in accelerator, long-baseline sterile neutrino searches
- A new two-detector fit method was introduced, significantly improving the exclusion placed upon the parameter space
  - No evidence of sterile neutrino mediated oscillations found
  - New preliminary combined fit with Daya Bay/Bugey-3 presented
  - Increased the tension with the global allowed region
- Additional 50% statistics from MINOS+ left to analyze, a new combination with more data from Daya Bay, an antineutrino analysis, and a new search using electron neutrino appearance also on the way!

Thank you!

The MINOS+ Collaboration thanks 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.

We also thank Daya Bay for its cooperative efforts to jointly search for new neutrino oscillation phenomena

Fermilab

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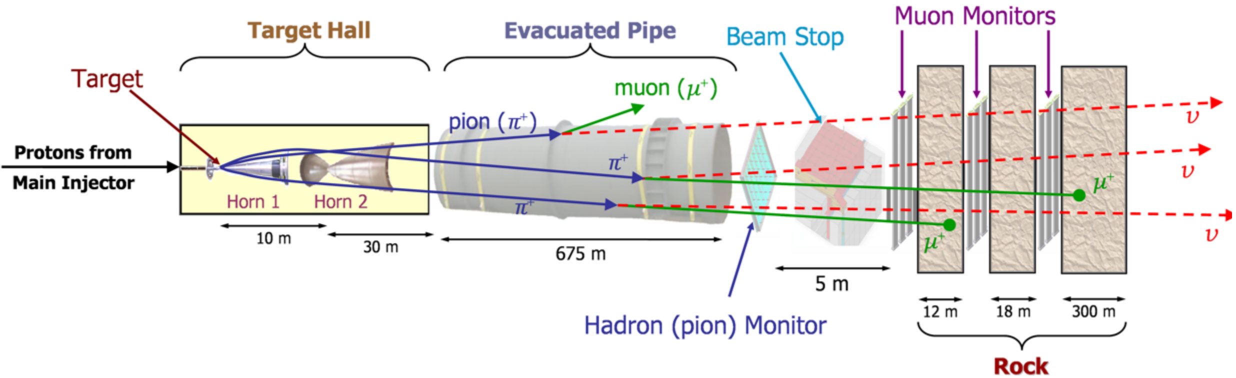
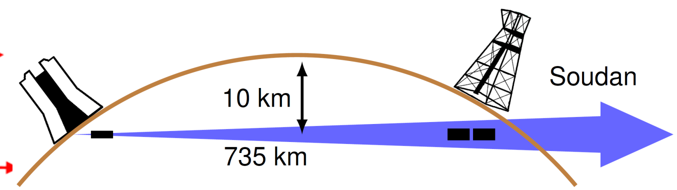
Science & Technology Facilities Council

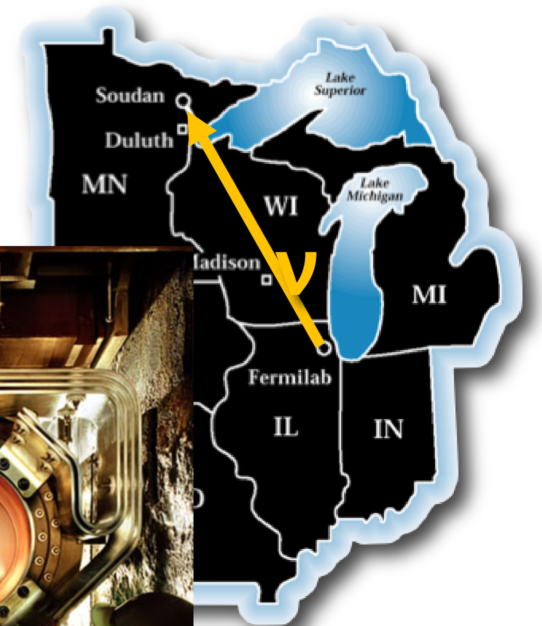
Backup

The MINOS Experiment – NuMI Beam

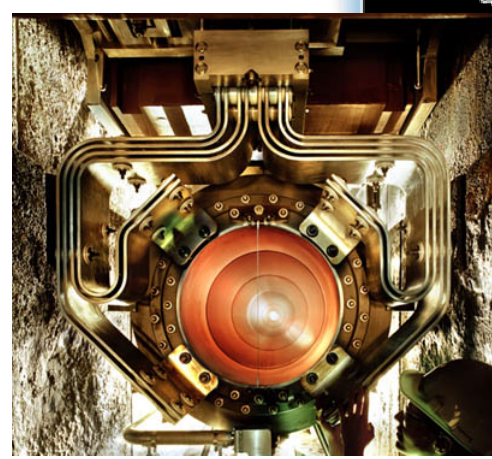
- Long-baseline, accelerator-based neutrino oscillation experiment







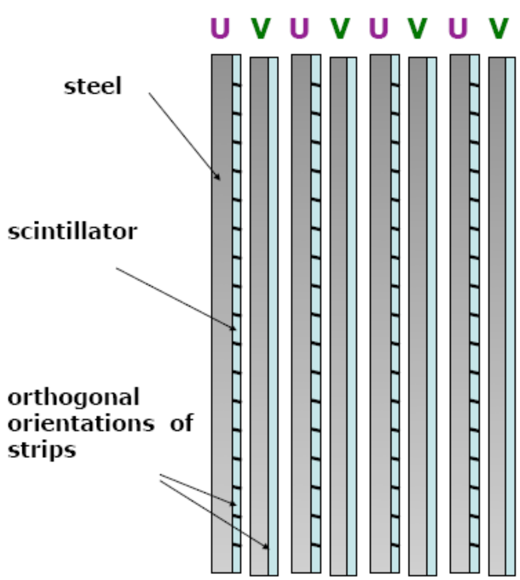
- 120 GeV protons from Fermilab Main Injector
- Graphite fin target
- Two-horn focusing system
- Configurable beam optics; tunable spectra
  - Exploited in analysis

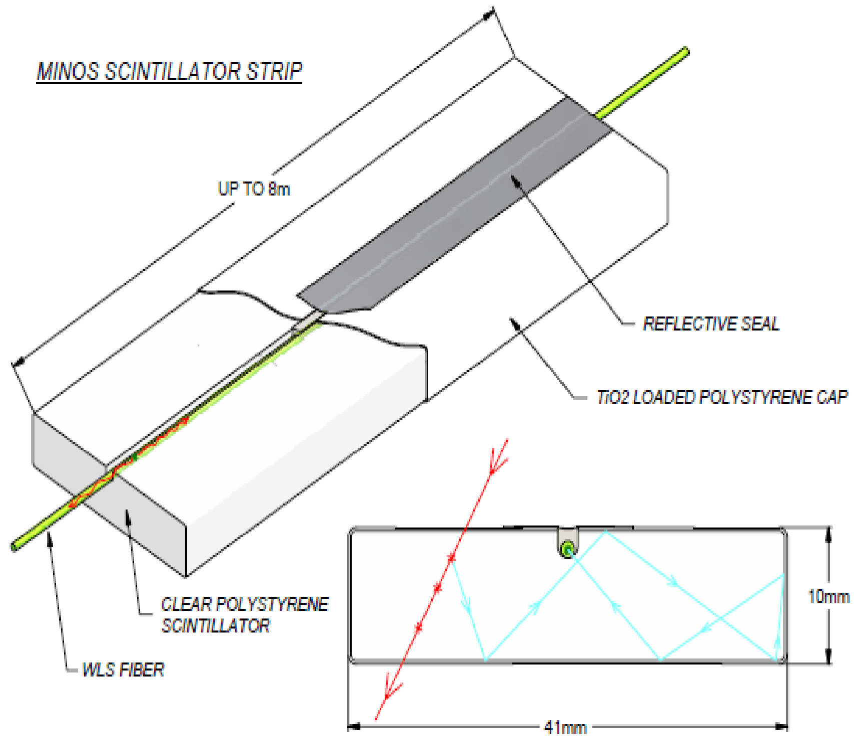


FNAL

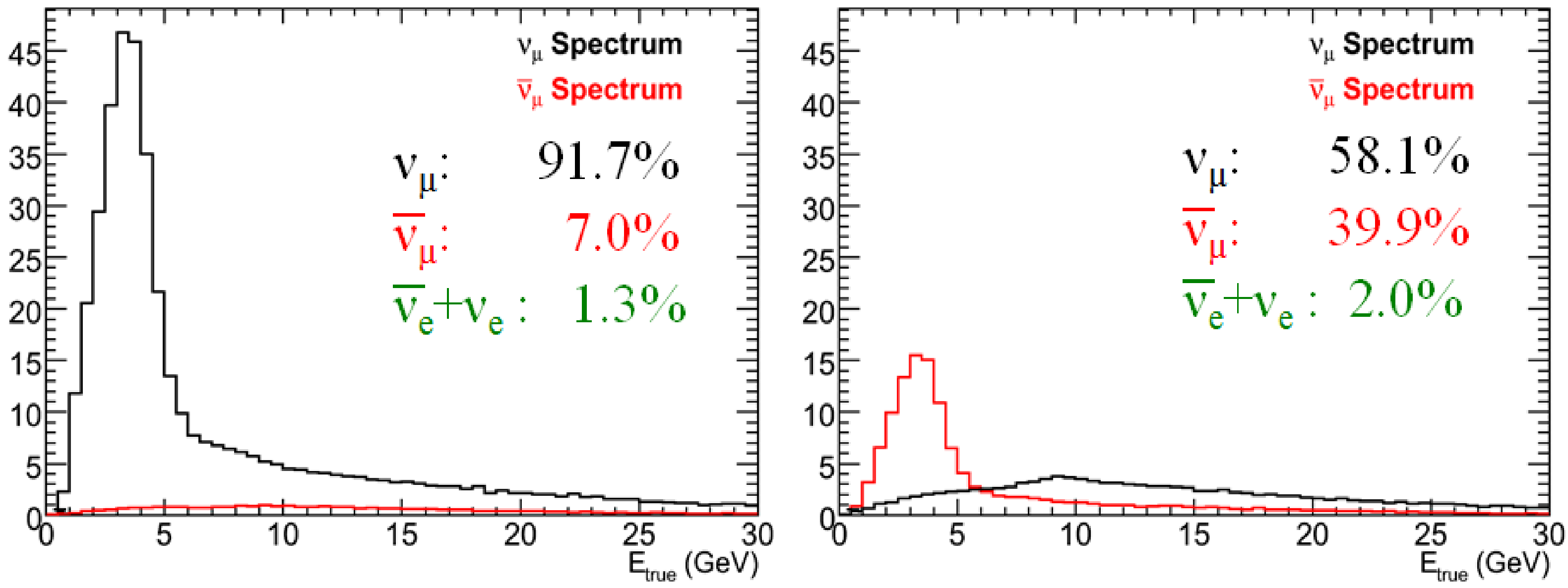
The MINOS Experiment – Detector Tech

- Each steel plane is paired with a layer of polystyrene plastic scintillator
- Adjacent scintillator planes have orthogonal orientations for track reconstruction
- Wavelength shifting fibers collect light and carry signal to Hamamatsu multi-anode photomultipliers





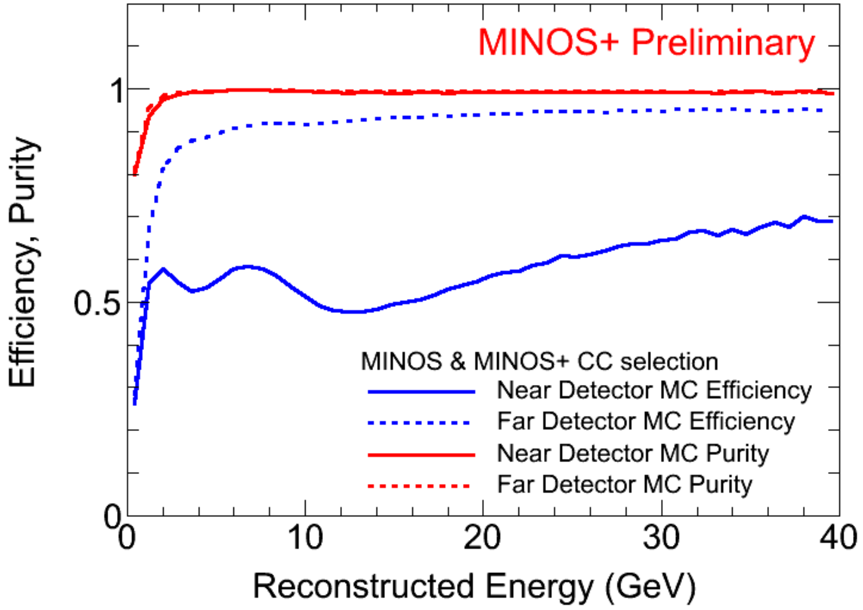
Near Detector

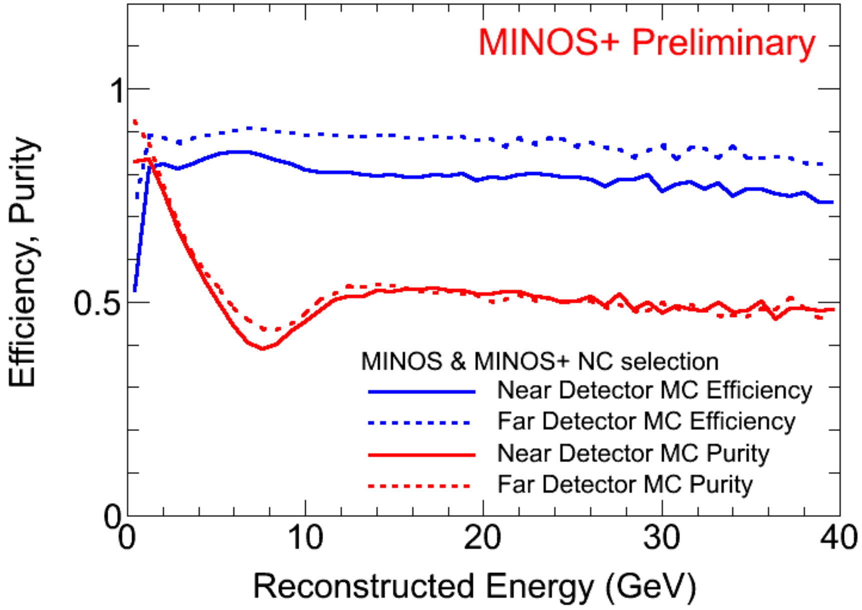


- Simulated Near Detector energy distributions for MINOS LE neutrino (left) and antineutrino (right) modes

Events – Selection and Purity

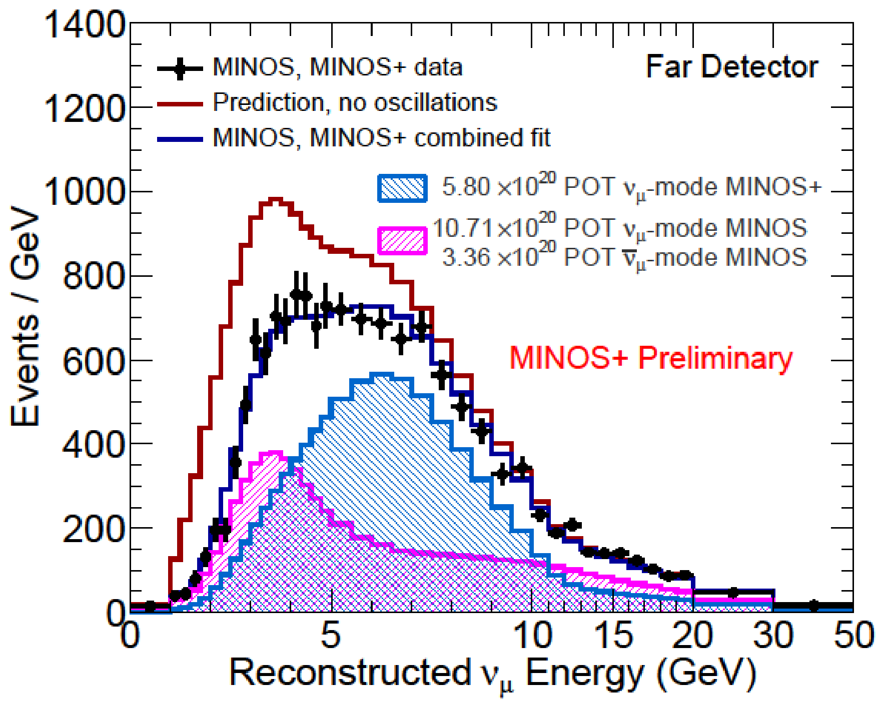
- ND efficiency reduction in CC selection due to tracks entering coil region
- Purity reduction in NC selection due to CC backgrounds

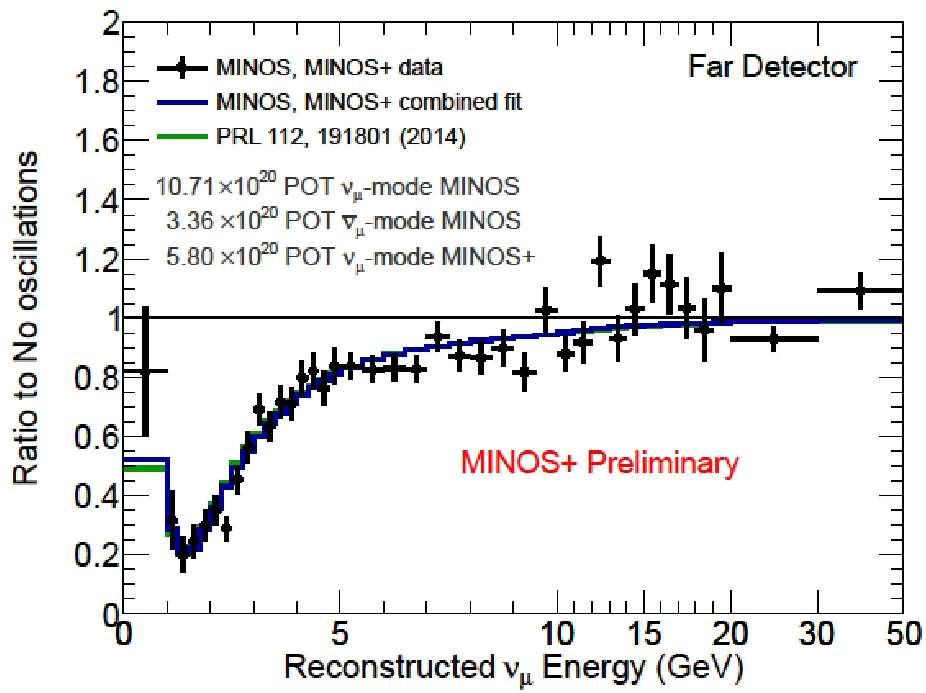




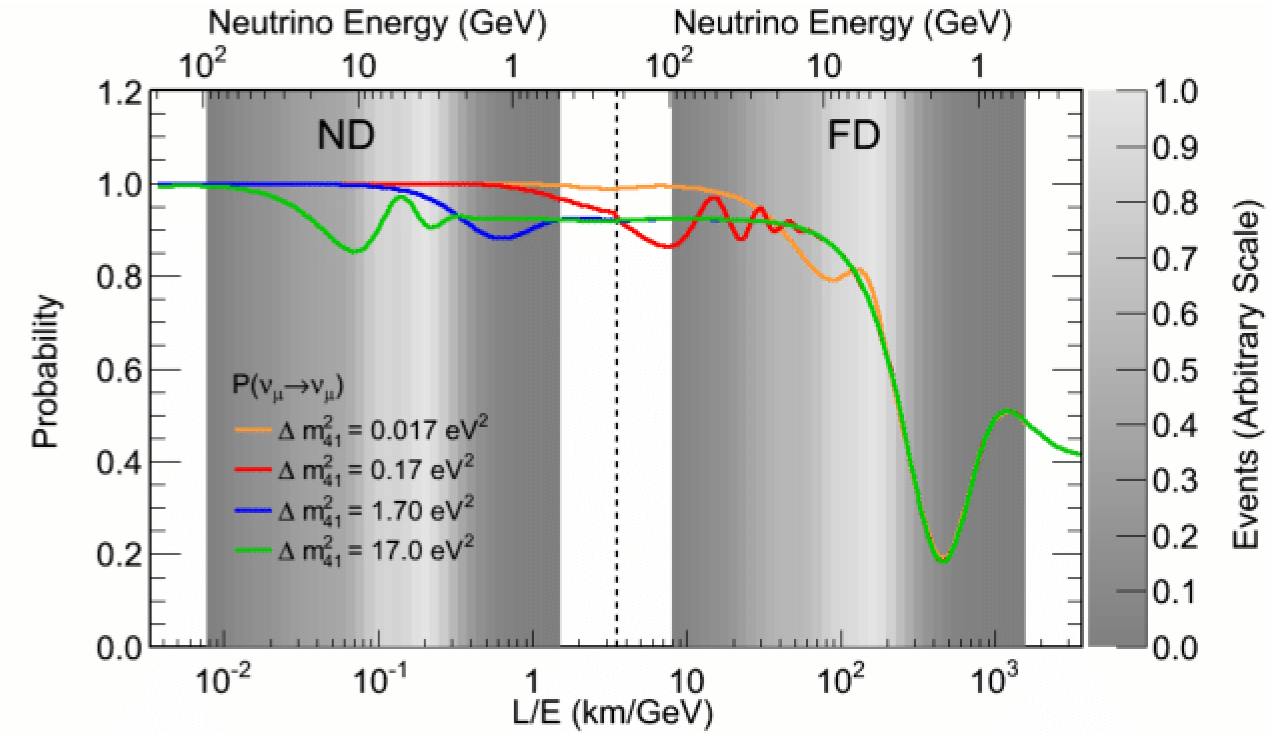
Events and Spectra

Event Type	MINOS Obs. (Exp.)	MINOS+ Obs. (Exp.)
ν_μ	2579 (3201)	3692 (4312)
$\bar{\nu}_\mu$	312 (363)	179 (183)



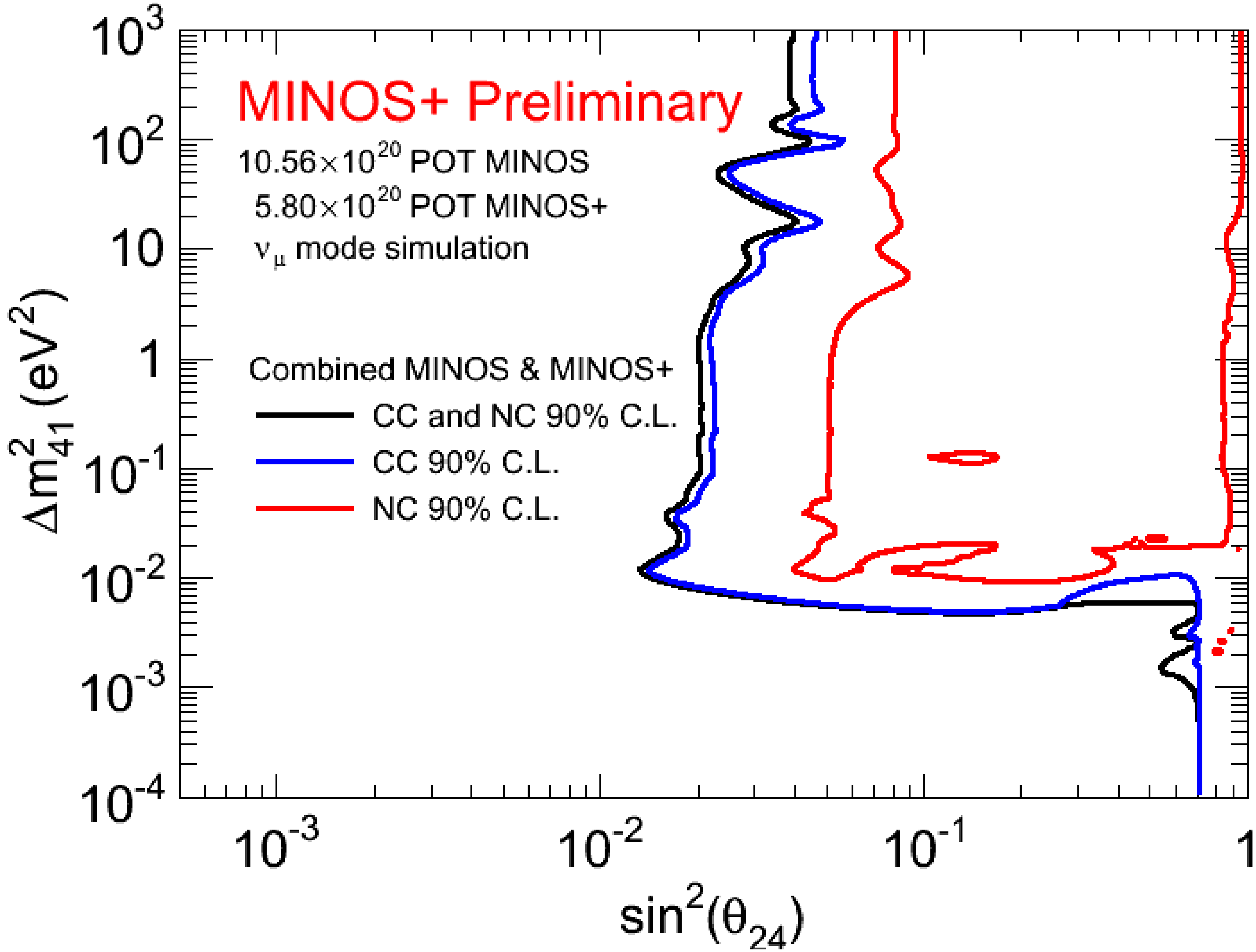


3+1 Oscillations – A Test Case



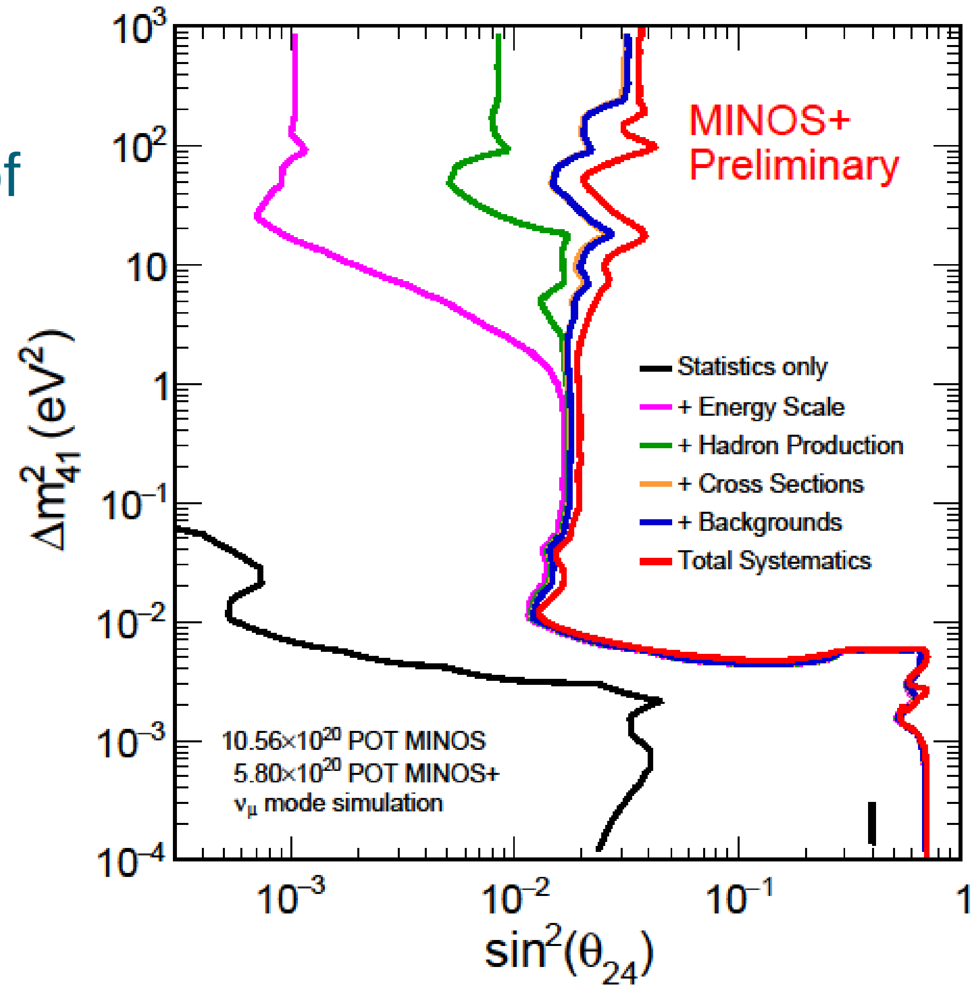
- Smaller Δm^2_{41}: Distortions in FD above oscillation maximum
- Larger Δm^2_{41}: Rapid oscillations in FD + *Distortions in ND*

Sensitivity



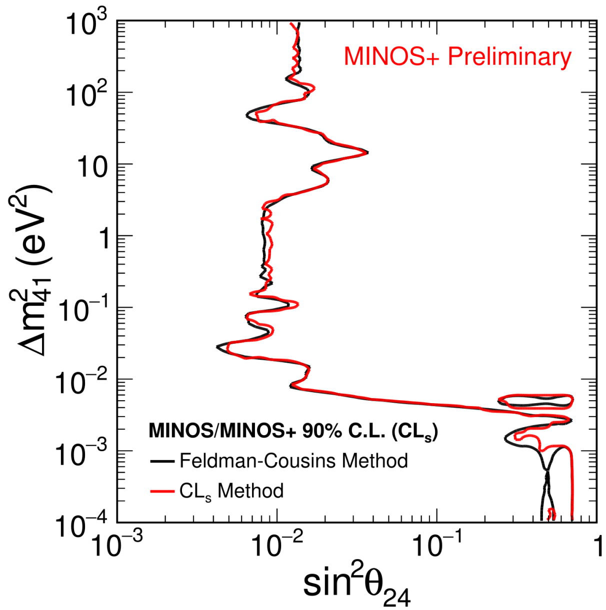
Systematics

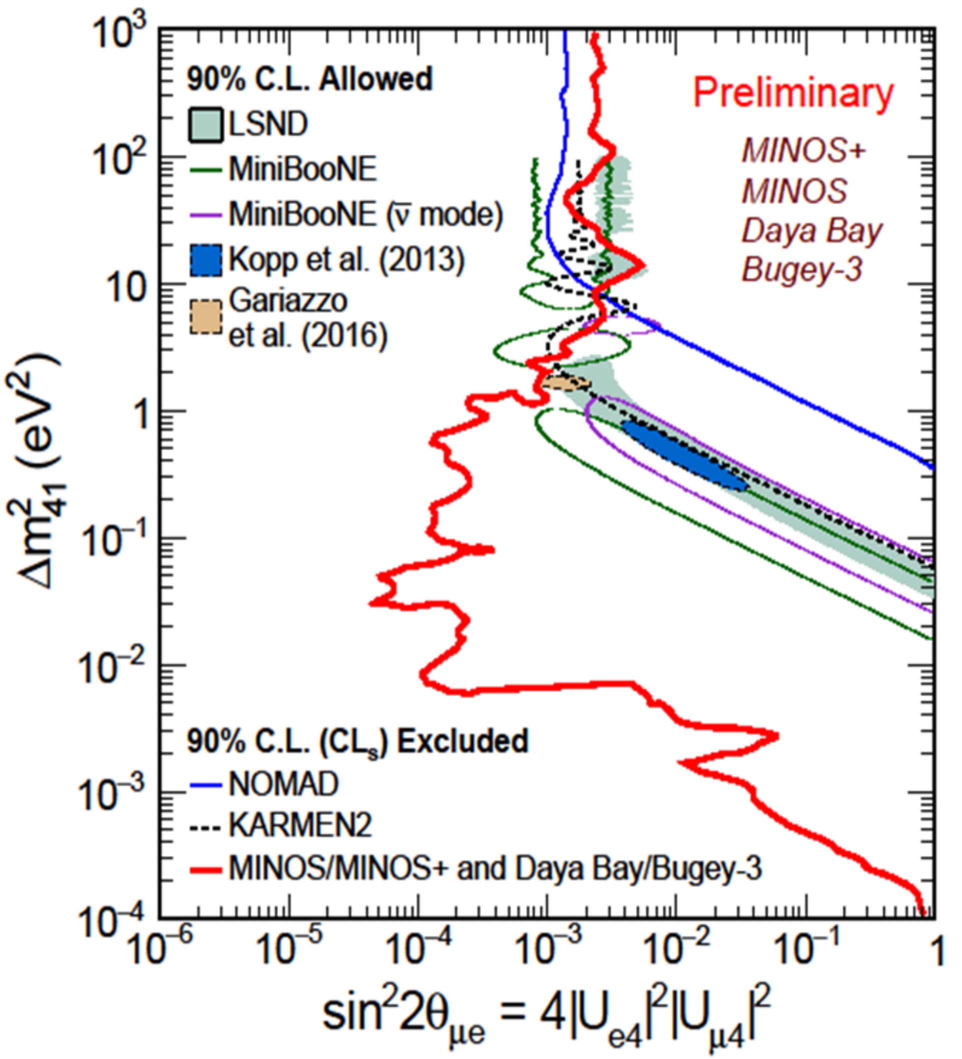
- Impact of individual systematic categories
  - Excluding to the right of the shown contours (90% C.L.)
  - Statistics only case is dominated by ND
  - Energy scale dominates in the FD oscillation region



Combined Result

- New result increases tension with allowed regions
  - Improved limit at high Δm^2_{41} due to the use of two-detector fit method





Summary and Outlook

- MINOS and MINOS+ are continuing to lead the way in accelerator, long-baseline sterile neutrino searches
- A new two-detector fit method was introduced, significantly improving the exclusion placed upon the parameter space
  - No evidence of sterile neutrino mediated oscillations found
  - Increased the tension with the global allowed region
- Additional 50% statistics from MINOS+ left to analyze, an antineutrino analysis, and a new search using electron neutrino appearance also on the way!

Thank you!

The MINOS+ Collaboration thanks 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!

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