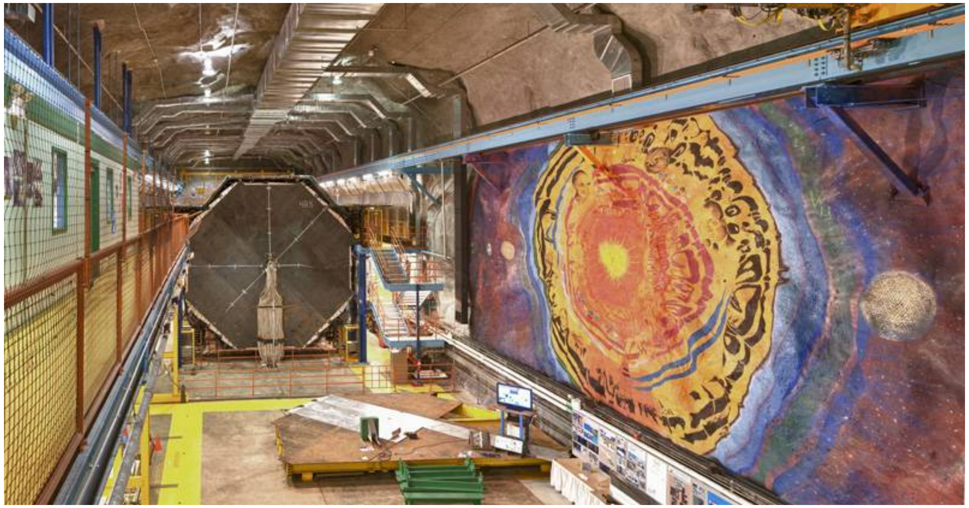
Status of the MINOS+ Experiment

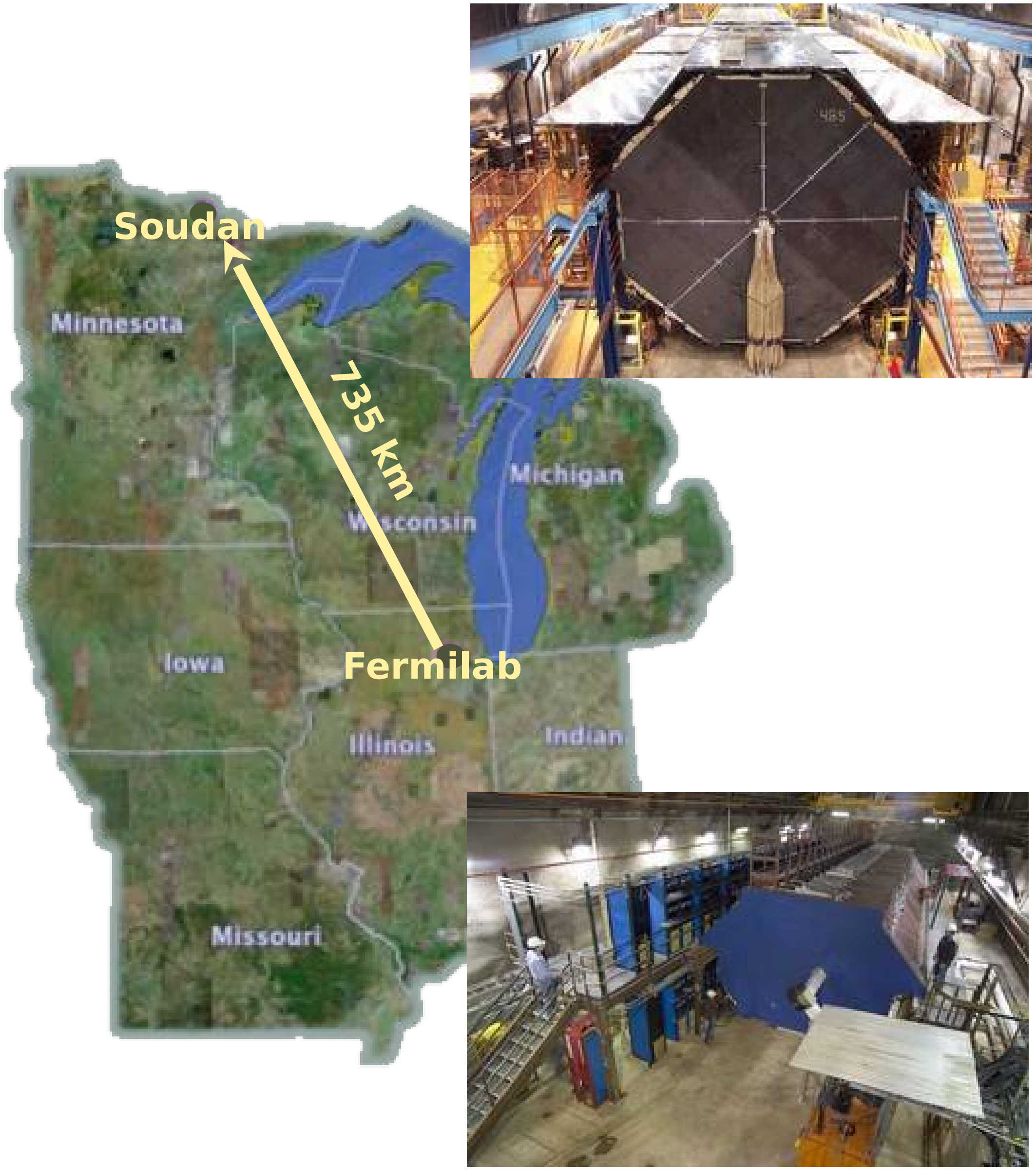


Adam Aurisano
University of Cincinnati
for the MINOS+ Collaboration

50^{th} Annual Users Meeting
8 June 2017

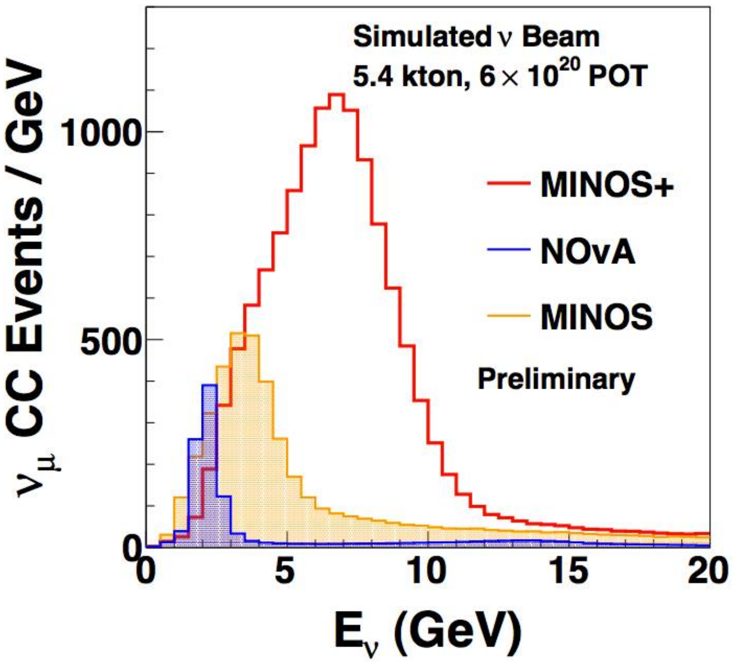
MINOS/MINOS+ Overview

- Measured energy of neutrinos from the NuMI beam with two functionally identical, magnetized, iron-scintillator tracking calorimeters
  - Near Detector at Fermilab
    - 1 km from target
    - 1 kton mass
  - Far Detector, deep underground in the Soudan mine
    - 735 km from target
    - 5.4 kton mass
- Compare Far Detector observations with extrapolation of Near Detector measurement to study neutrino oscillations.

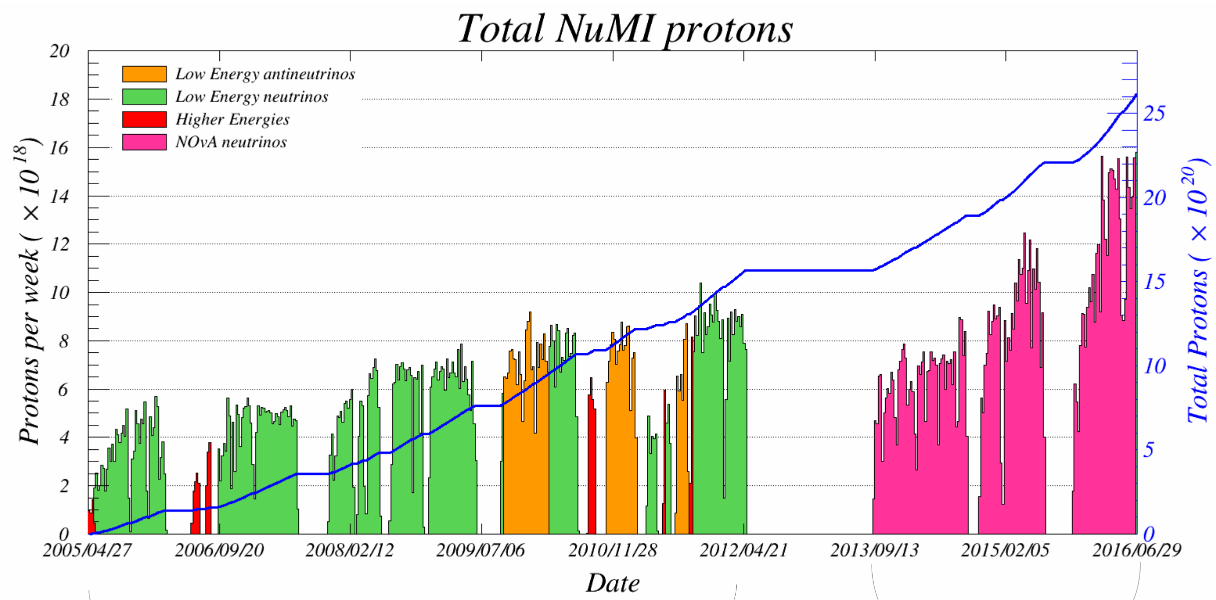


MINOS/MINOS+ Beam

- MINOS
  - 2005-2012: NuMI beam operated in low energy mode
    - Peak energy of ~3 GeV
  - Precision measurements of three-flavor oscillations
- MINOS+
  - 2013-2016: the NuMI beam operated in the medium energy mode
    - Peak energy of ~7 GeV
  - Designed to look for exotic phenomena



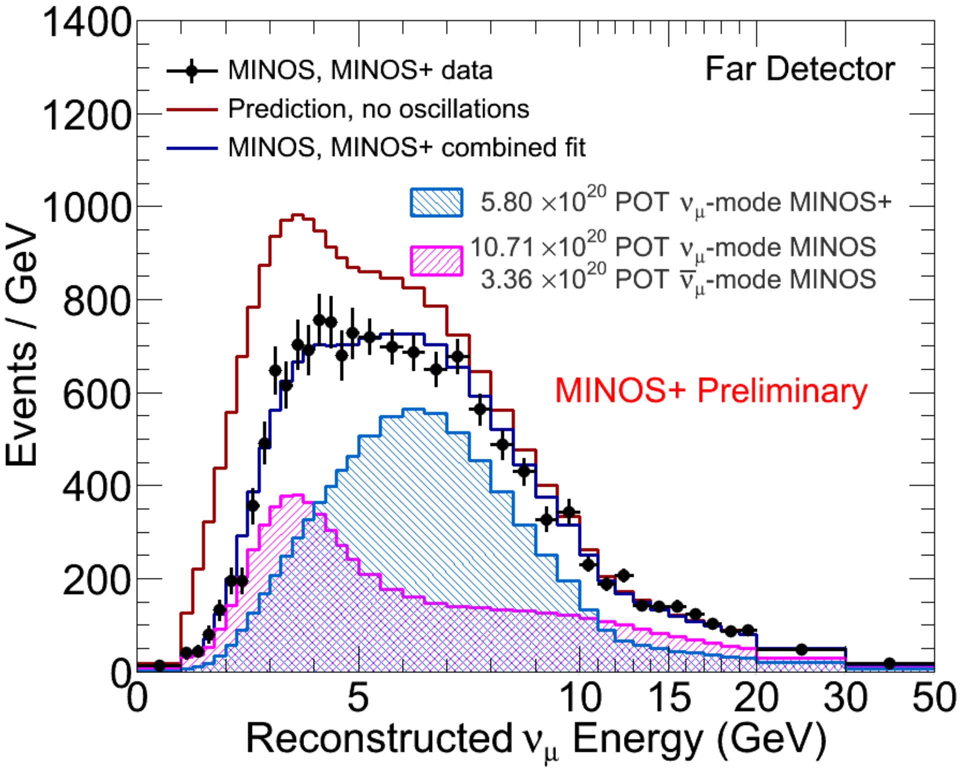
MINOS/MINOS+ collected ~25x10^{20} POT in 11 years of running
→ Largest sample of neutrinos from an accelerator ever collected!

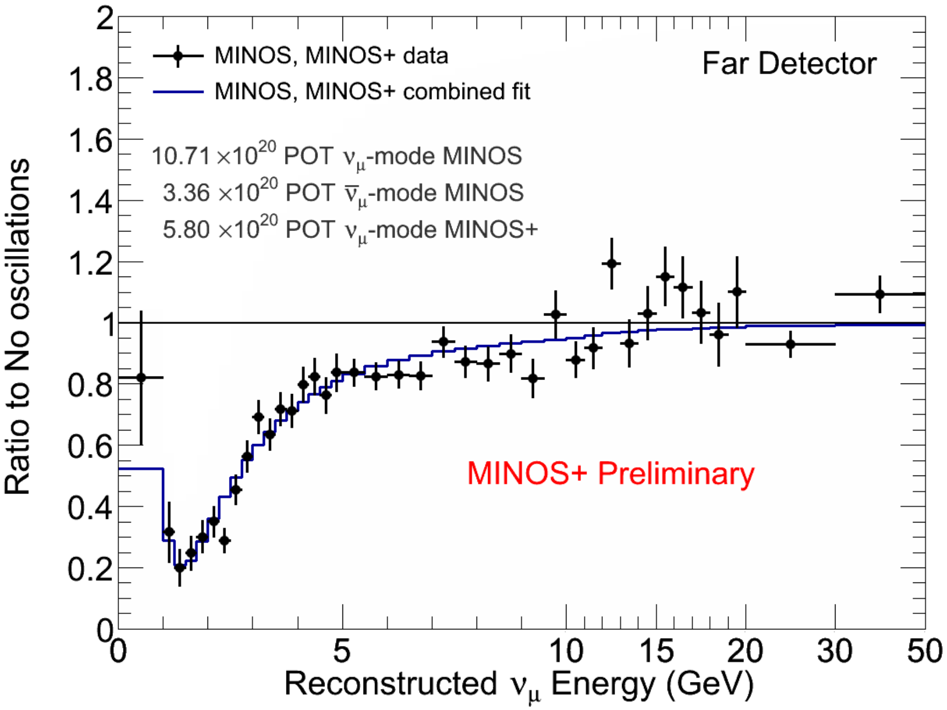


MINOS era:
10.56x10^{20} POT (neutrino-mode)
3.36x10^{20} POT (antineutrino-mode)

MINOS+ era:
9.7x10^{20} POT
~half analyzed so far

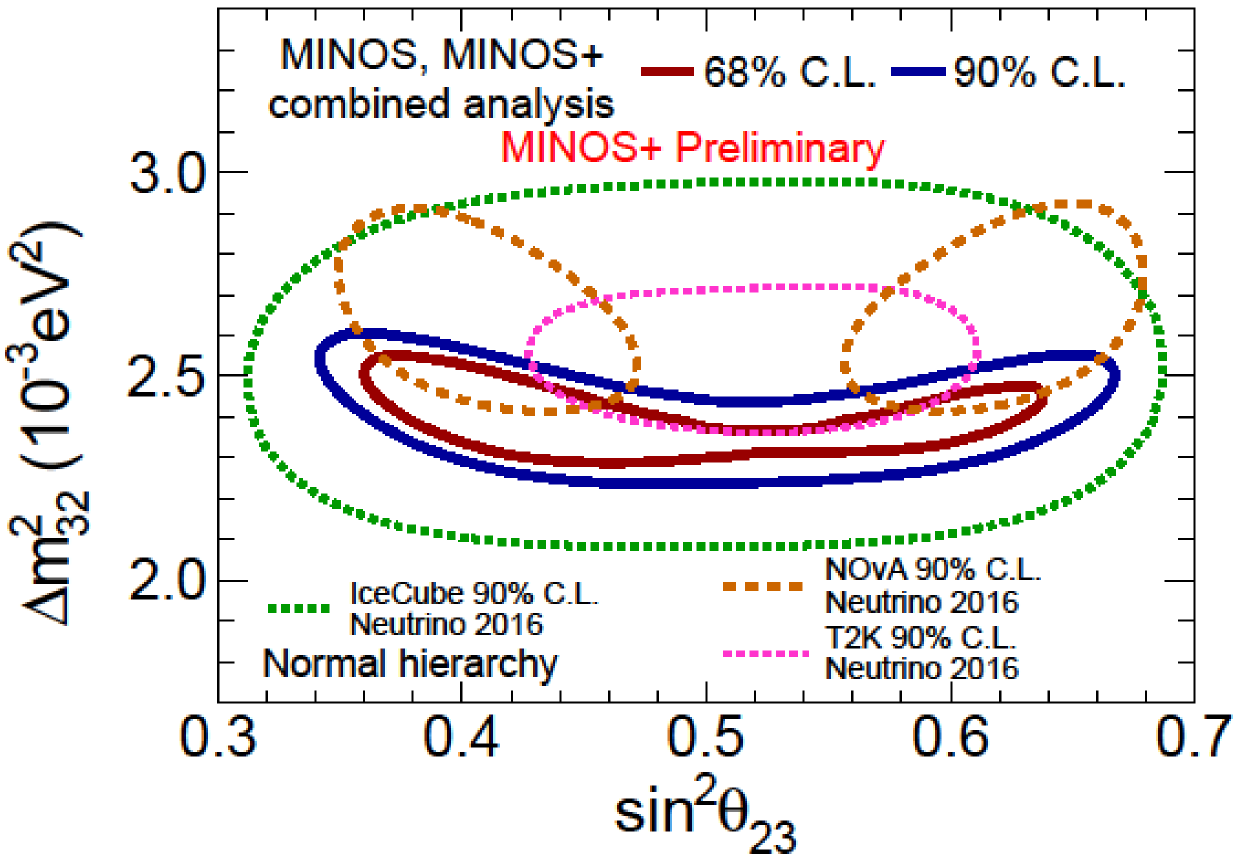
Standard Oscillations





- MINOS and MINOS+ probe muon-neutrino disappearance over a broad range of energies
  - MINOS+ energies let us explore the high energy region away from the oscillation maximum
  - The data are consistent with three-flavor oscillations at the atmospheric mass-splitting scale

Standard Oscillations



Normal hierarchy

$$\Delta m^2_{32} = 2.42 \pm 0.09 \times 10^{-3}\ \mathrm{eV}^2\ (68\%\ \mathrm{C.L.})$$

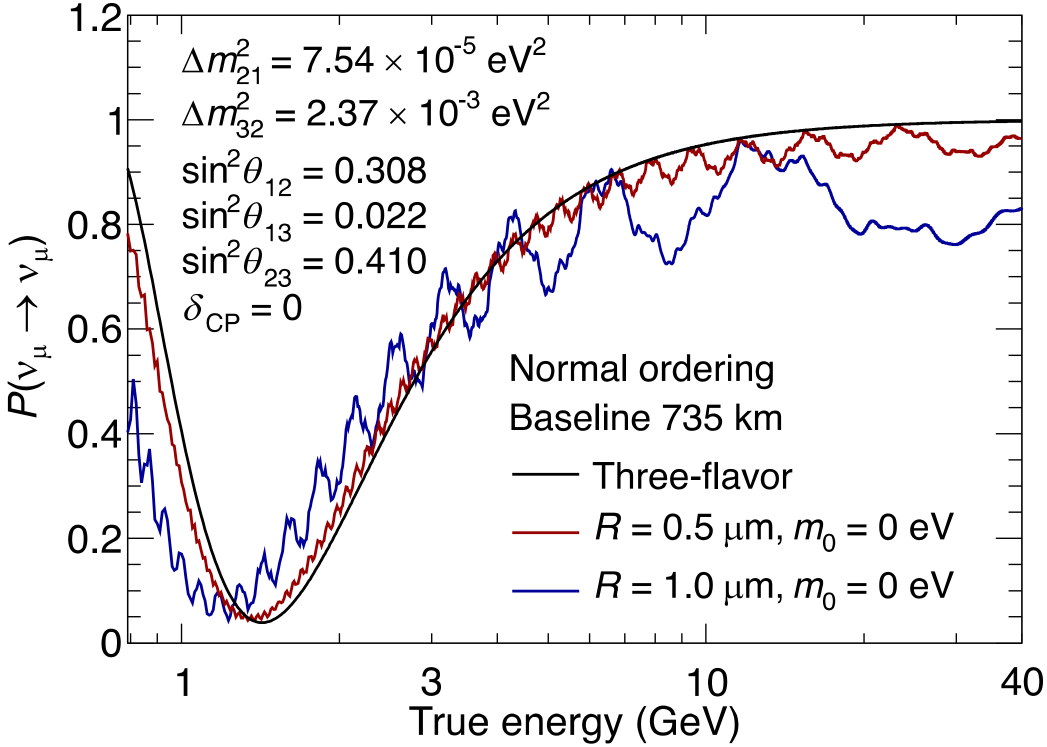
$$\sin^2\theta_{23} = 0.35 - 0.65\ (90\%\ \mathrm{C.L.})$$

Inverted hierarchy

$$\Delta m^2_{32} = -2.48^{+0.09}_{-0.11} \times 10^{-3}\ \mathrm{eV}^2\ (68\%\ \mathrm{C.L.})$$

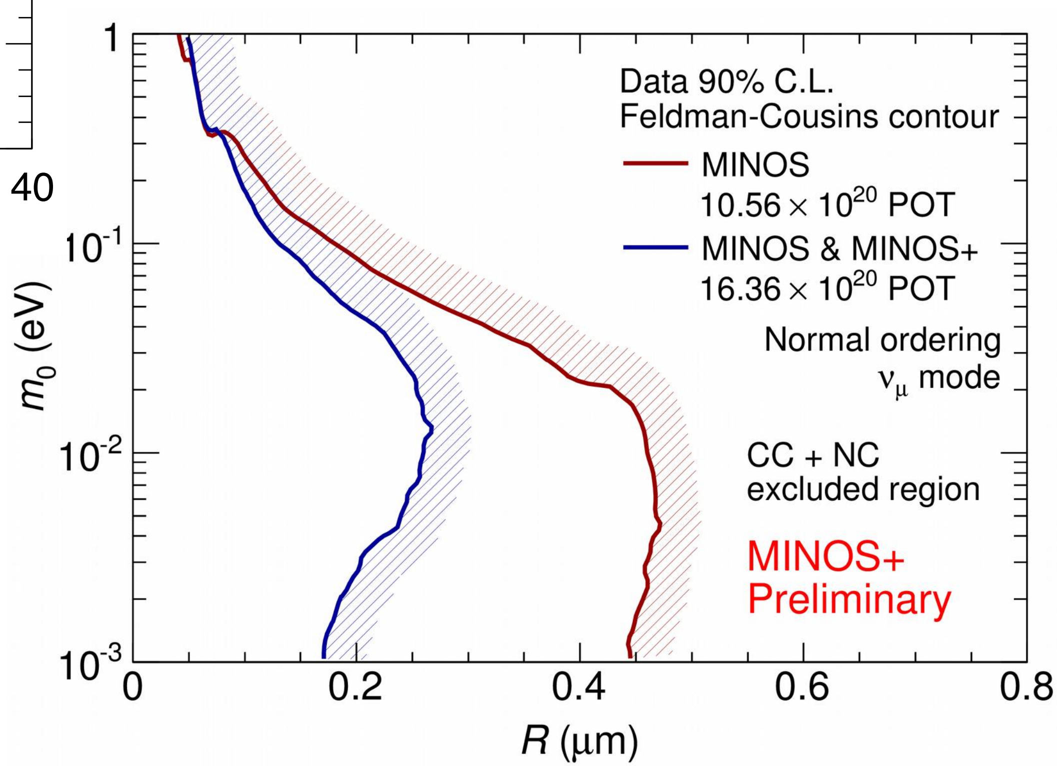
$$\sin^2\theta_{23} = 0.35 - 0.66\ (90\%\ \mathrm{C.L.})$$

Large Extra Dimensions



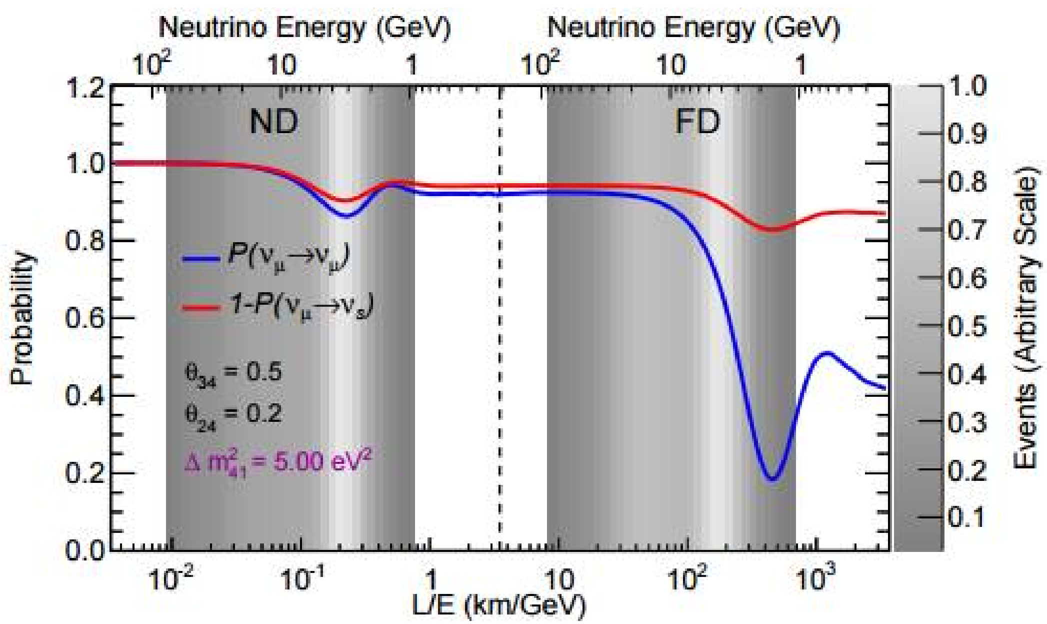
- Standard oscillation probabilities modified by mixing of active neutrinos in 3+1 space-time with three KK towers of neutrinos in an extra dimension with radius *R*

K. R. Dienes, E. Dudas, and T. Gherghetta, NPB 557 (1999) 25
N. Arkani-Hamed, S. Dimopoulos, G. R. Dvali, and J. March-Russell, PRD 65 (2001) 024032
H. Davoudiasl, P. Langacker, and M. Perelstein, PRD 65 105015 (2002)
P. A. N. Machado, H. Nunokawa, and R. Zukanovich Funchal, PRD 84 (2011) 013003



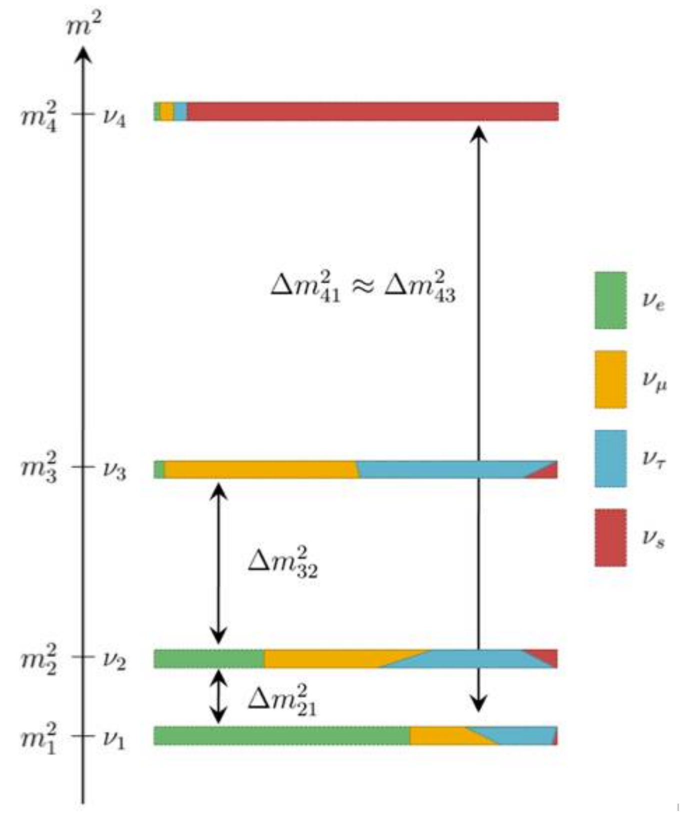
- Strongest constraint on *R* from a neutrino oscillation experiment
  - P. Adamson et al., PRD 94 (2016) 111101(R)
- Update with additional MINOS+ data and fit improvements will further improve constraints

Sterile Neutrinos Through Disappearance



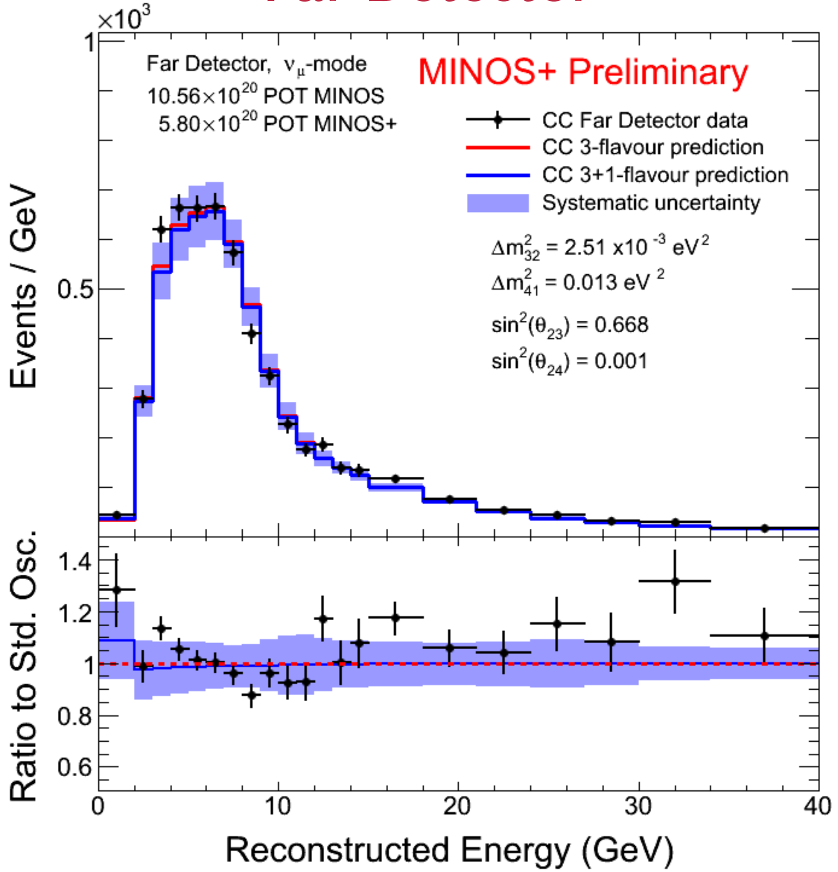
- Look for sterile neutrinos in two ways:
  - Deficit in neutral current (NC) events relative to expectation
  - Modulations on the atmospheric oscillations in the ν_μ charged current (CC) sample

- Consider the 3+1 model
  - 6 new parameters
  - ν_μ disappearance (MINOS) is sensitive to Δm^2_{41} and θ_{24}
  - ν_e disappearance (reactor experiments) is sensitive to Δm^2_{41} and θ_{14}
  - Can induce distortions in both the ND and FD

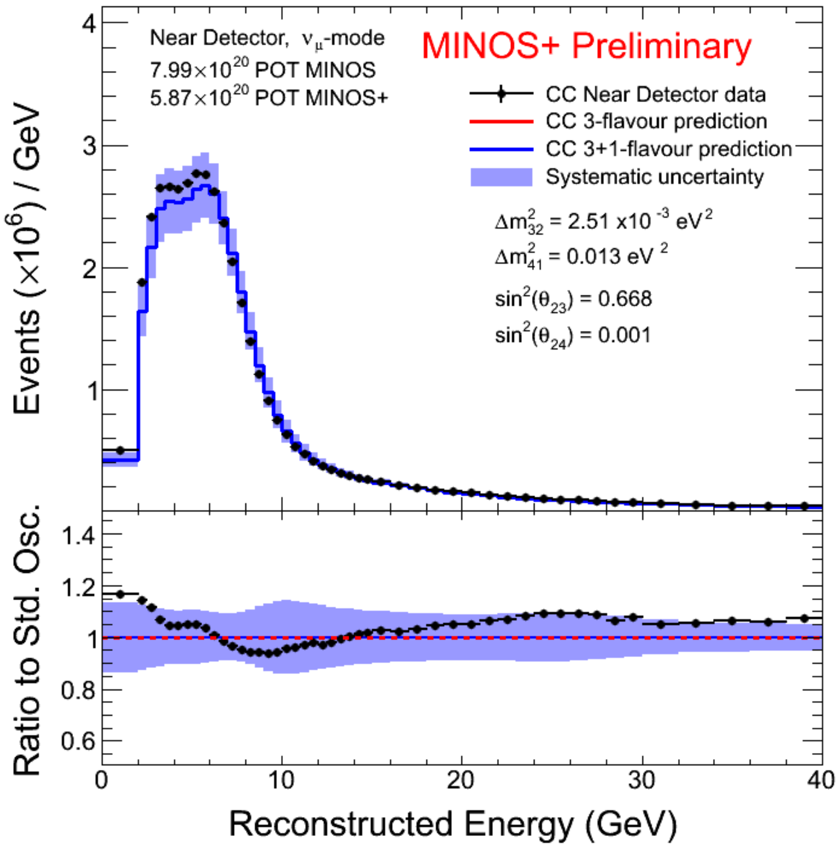


ν_μ Charged Current Sample

Far Detector



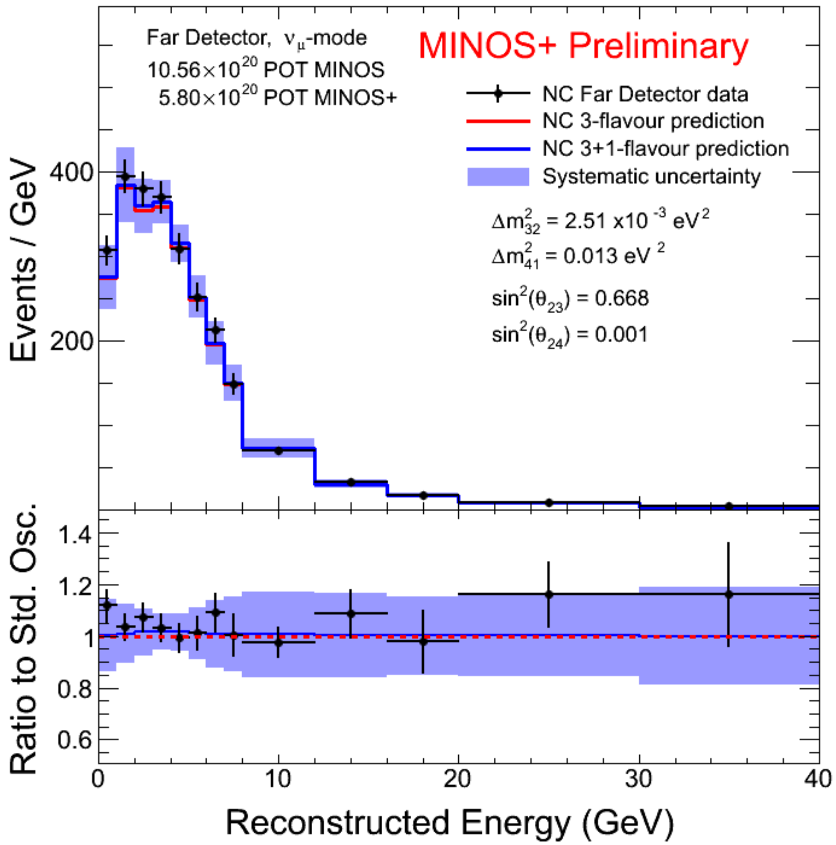
Near Detector



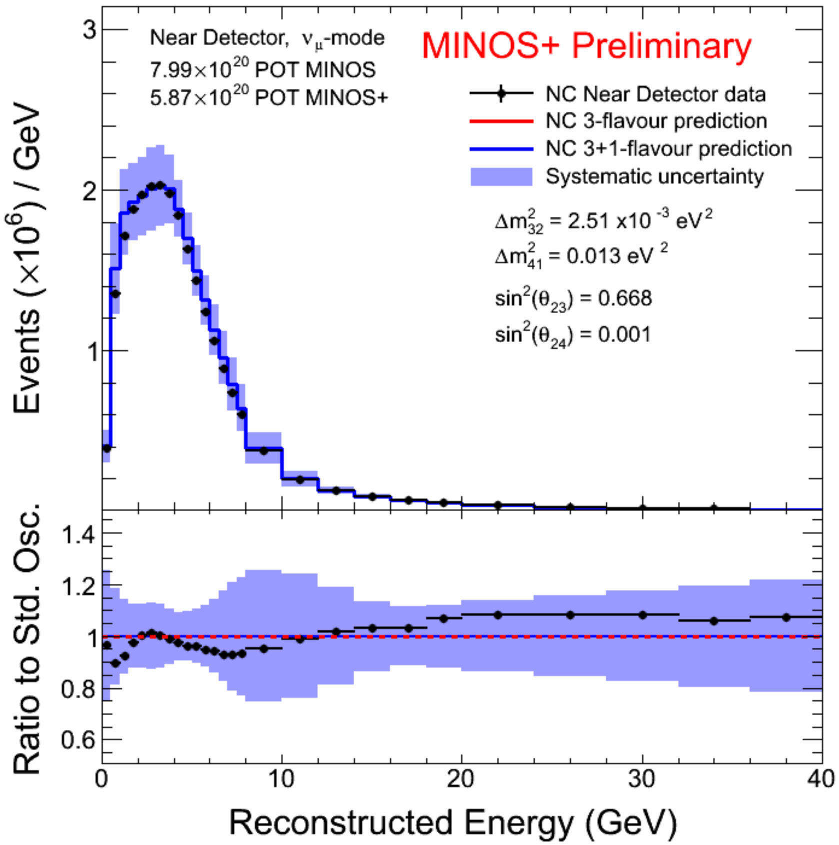
- Use a two-detector fit to both CC and NC samples to maximize sensitivity over a broad Δm^2_{41} range
- Systematics correlated between detectors are encoded in covariance matrices

Neutral Current Sample

Far Detector



Near Detector



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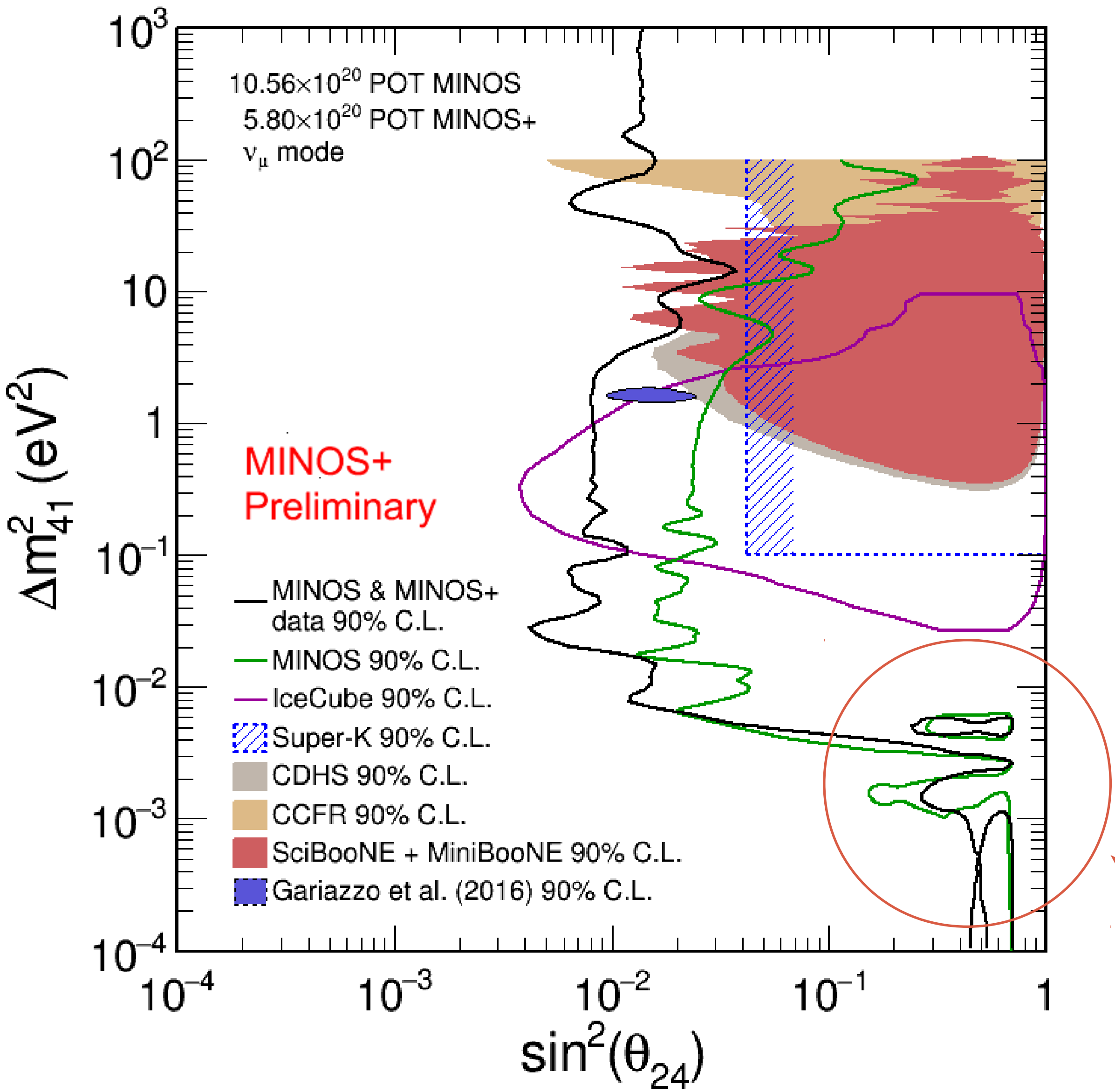
Sterile Disappearance Limit



MINOS/MINOS+ 90% C.L. exclusion limit ranges over 7 orders of magnitude in Δm^2_{41}

Improvement at large Δm^2_{41} due to ND contribution

Increased tension with global best fit
→ Displayed here with $|U_{e4}|^2 = 0.023$

Internal allowed region due to degenerate solutions.

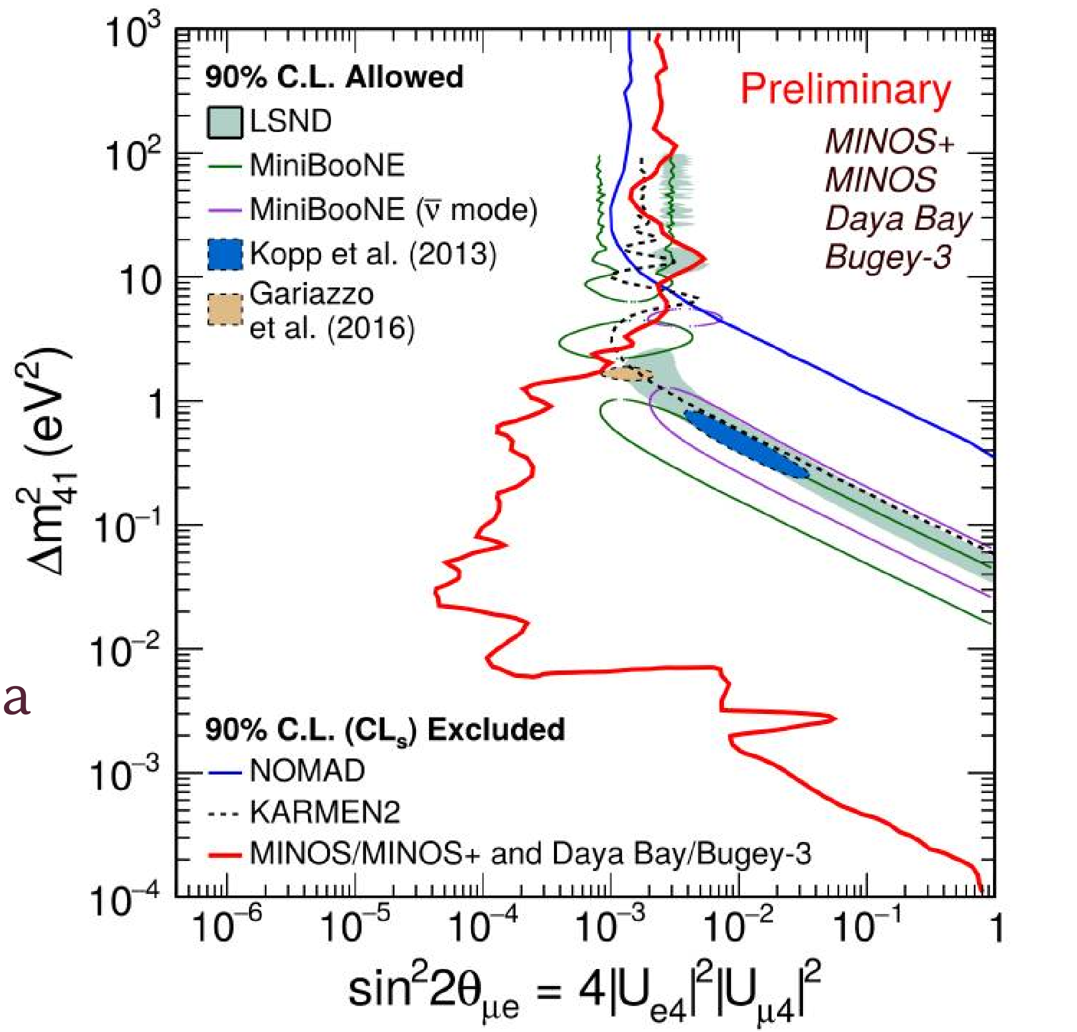
*S. Gariazzo, C. Giunti, M. Laveder, Y.F. Li, E.M. Zavanin, J.Phys.G**43**, 033001 (2016)

MINOS/Daya Bay/Bugey-3

Combine MINOS (θ_{24}) with the reactor experiments Daya Bay and Bugey-3 (θ_{14}) using the CL_s formalism to set limits on $\sin^2 2\theta_{\mu e} = \sin^2 2\theta_{14} \sin^2\theta_{24}$.

Preliminary result:
$\longrightarrow$ Ongoing collaborative effort between MINOS/MINOS+ and Daya Bay. A combination with a larger Daya Bay dataset is planned.

The combined 90% C.L. limit excludes appearance allowed regions for $\Delta m^2_{41} < \sim 1$ eV^2.



^J. Kopp, P. Machado, M. Maltoni, T. Schwetz, JHEP 1305:050 (2013)

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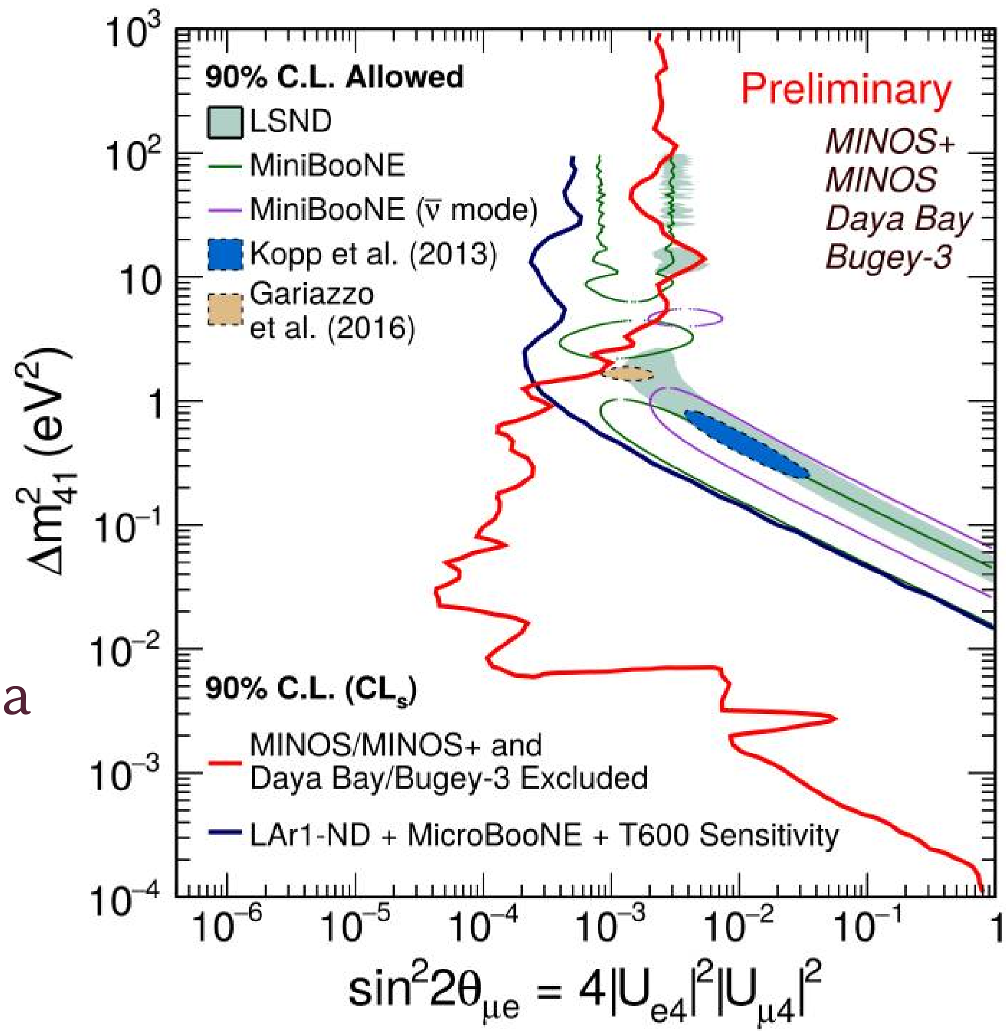

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*S. Gariazzo, C. Giunti, M. Laveder, Y.F. Li, E.M. Zavanin, J.Phys. G43 033001 (2016)

Summary

- MINOS/MINOS+ continues to set stringent limits on neutrino oscillations
  - Many results could not be included in this talk
    - NSI
    - Sterile ν_e appearance
    - Sterile antineutrino disappearance
- The higher energy of MINOS+ constrains oscillation behavior away from the atmospheric maximum
  - Strong support for the three-flavor paradigm
- Using a two-detector fit technique, MINOS+ improved its constraints on sterile neutrino mixing

Publications

- MINOS/MINOS+ had a productive history
  - Published 43 papers over the last 11 years
  - 16 PRLs!
- 2016 was one of the most productive years yet:
  - The NuMI Neutrino Beam, NIM A806 (2016) 279-306
  - Measurement of the Multiple-muon Charge Ratio in the MINOS Far Detector, PRD 93 (2016) 052017
  - Search for Sterile Neutrinos Mixing with Muon Neutrinos in MINOS, PRL 117 (2016) 151803
  - Limits on Active to Sterile Neutrino Oscillations from Disappearance Searches in the MINOS, Daya Bay, and Bugey-3 Experiments, PRL 117 (2016) 151801
  - Measurement of single π^0 production by coherent neutral-current ν FE interactions in the MINOS Near Detector, PRD 94 (2016) 072006
  - Constraints on large extra dimensions from the MINOS experiment, PRD 94 (2016) 111101(R)
  - Search for flavor-changing nonstandard neutrino interactions using ν_e appearance in MINOS, PRD 95 (2017) 012005
- We're not done yet!
  - Half of MINOS+ data is still being analyzed – stay tuned!

Thank You!

Long-Baseline Sterile Searches

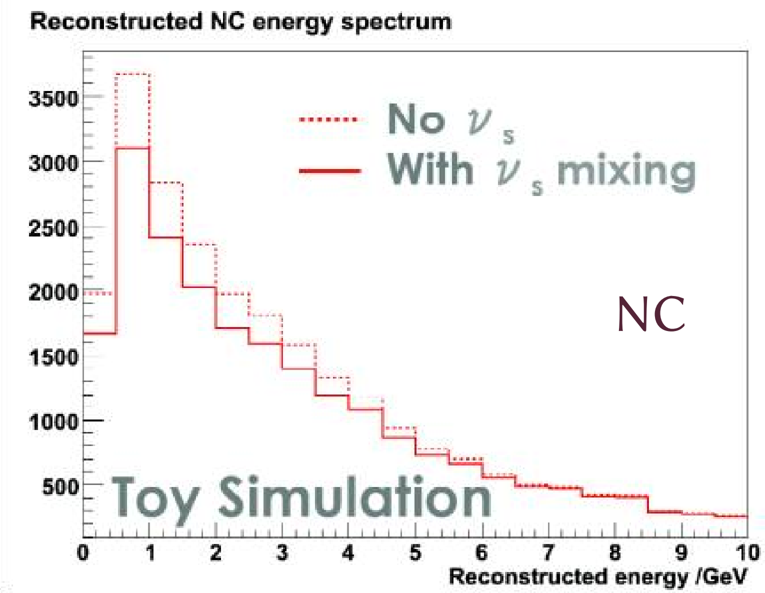
Neutral Current

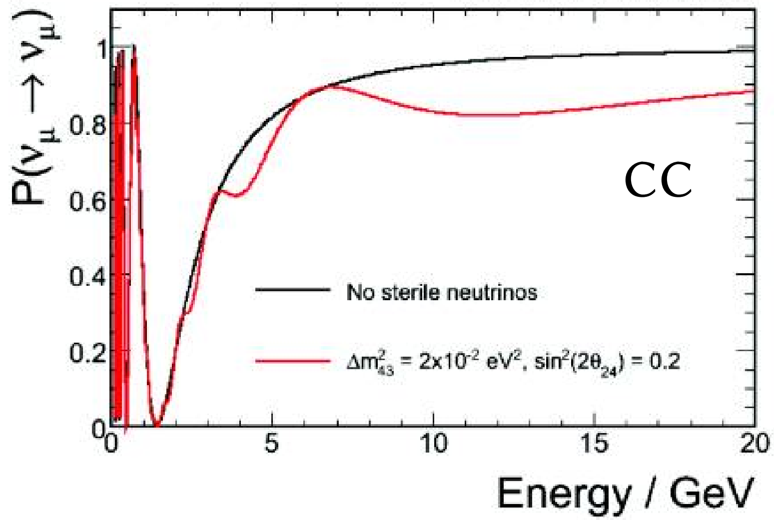
- NC interaction rate is independent of oscillations of the three active flavors.
- $\nu_\mu \longrightarrow \nu_s$ oscillations reduce the NC rate as ν_s do not interact in the detector.
- Previously investigated at MINOS
  - Phys.Rev.D81 (2010) 052004
  - Phys.Rev.Lett 107 (2011) 011802

ν_μ Charged Current

- Sterile oscillations add modulations to standard 3-flavor picture.

Fit both NC and CC spectra to the 4-flavor model to constrain sterile mixing parameters.

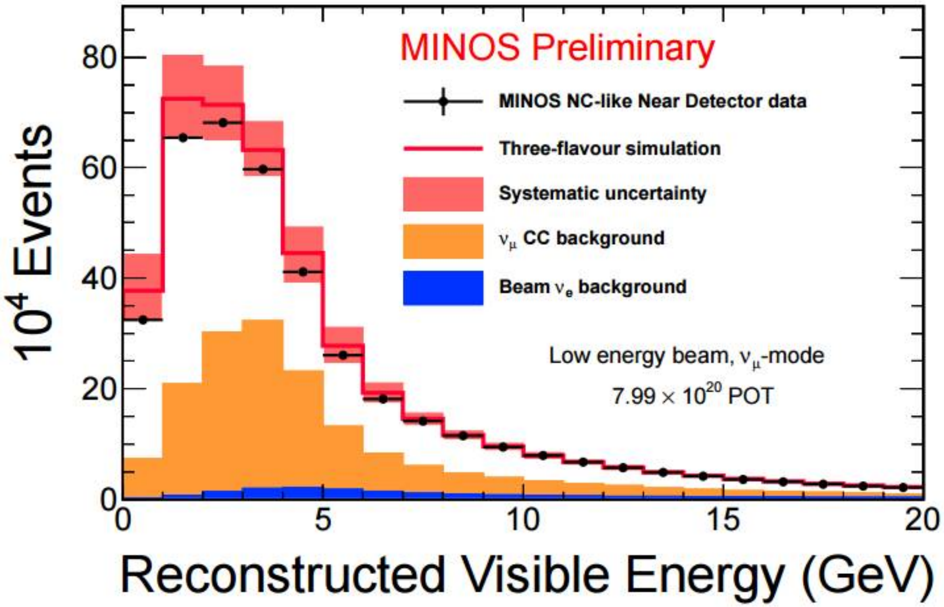




Selecting NC and ν_μ CC Samples

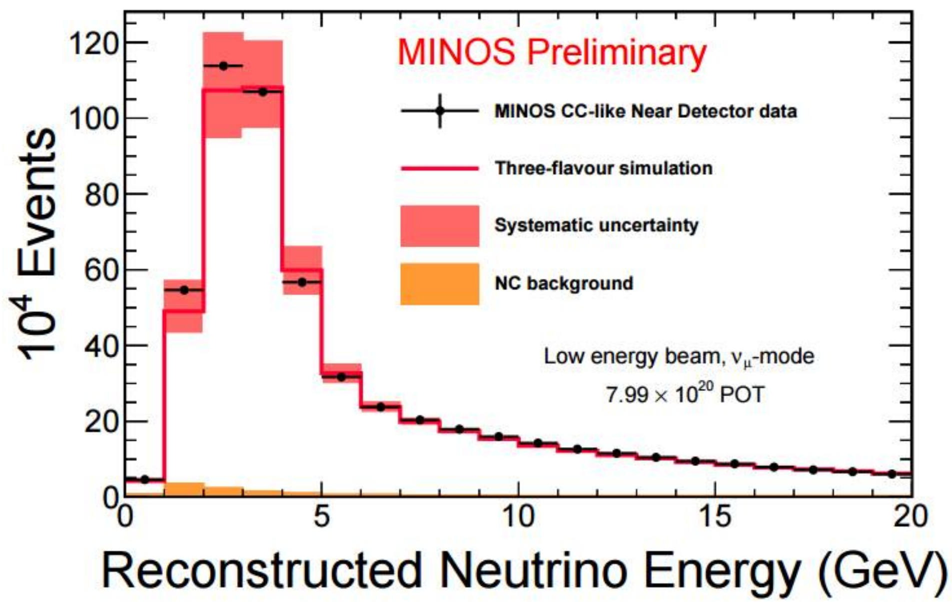
Neutral current selection

- 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



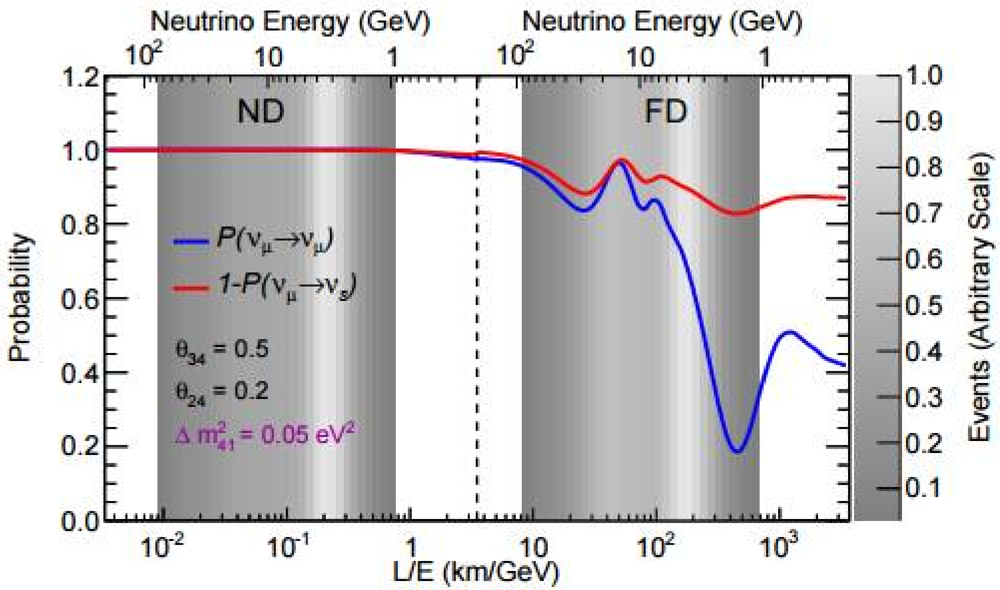
ν_μ charged current selection

- Use 4 variable kNN designed to distinguish muon from pion tracks
- Applied to events failing NC selection
- 86% efficiency, 99% purity at the FD



4-Flavor Oscillations

For sterile neutrinos, oscillations can occur in the ND!

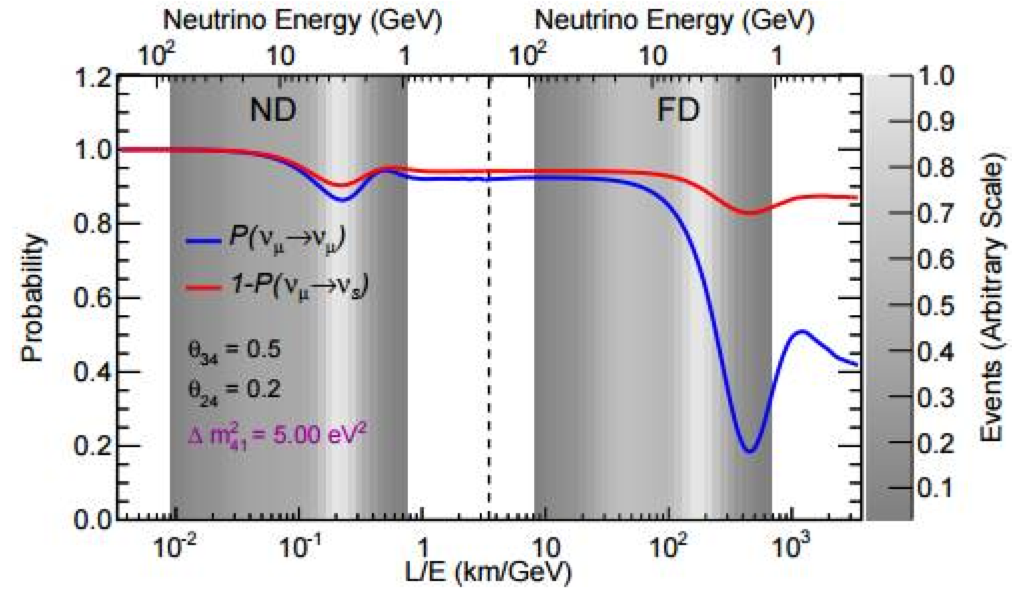


Small Δm^2_{41}:

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

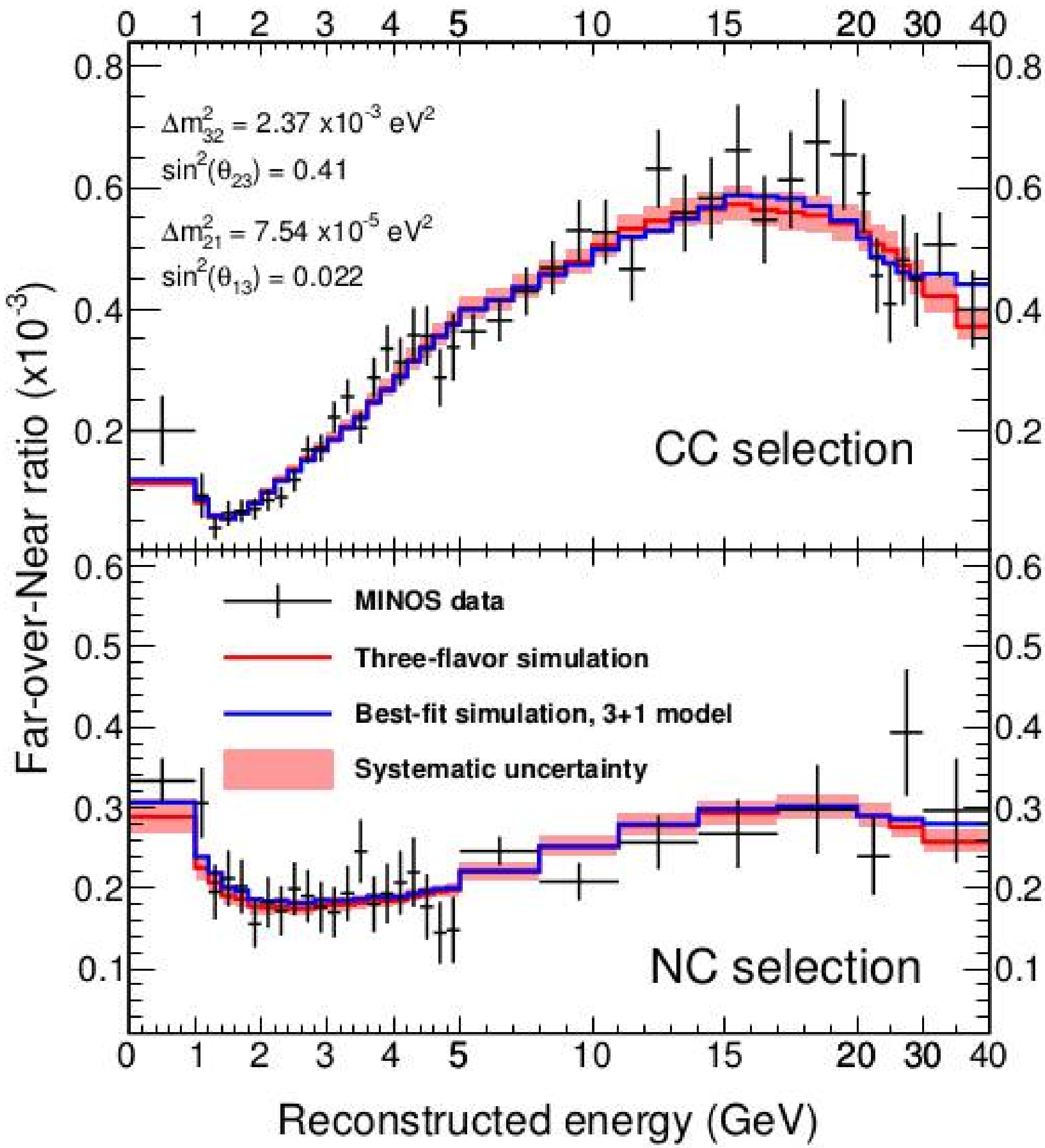
Large Δm^2_{41}:

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

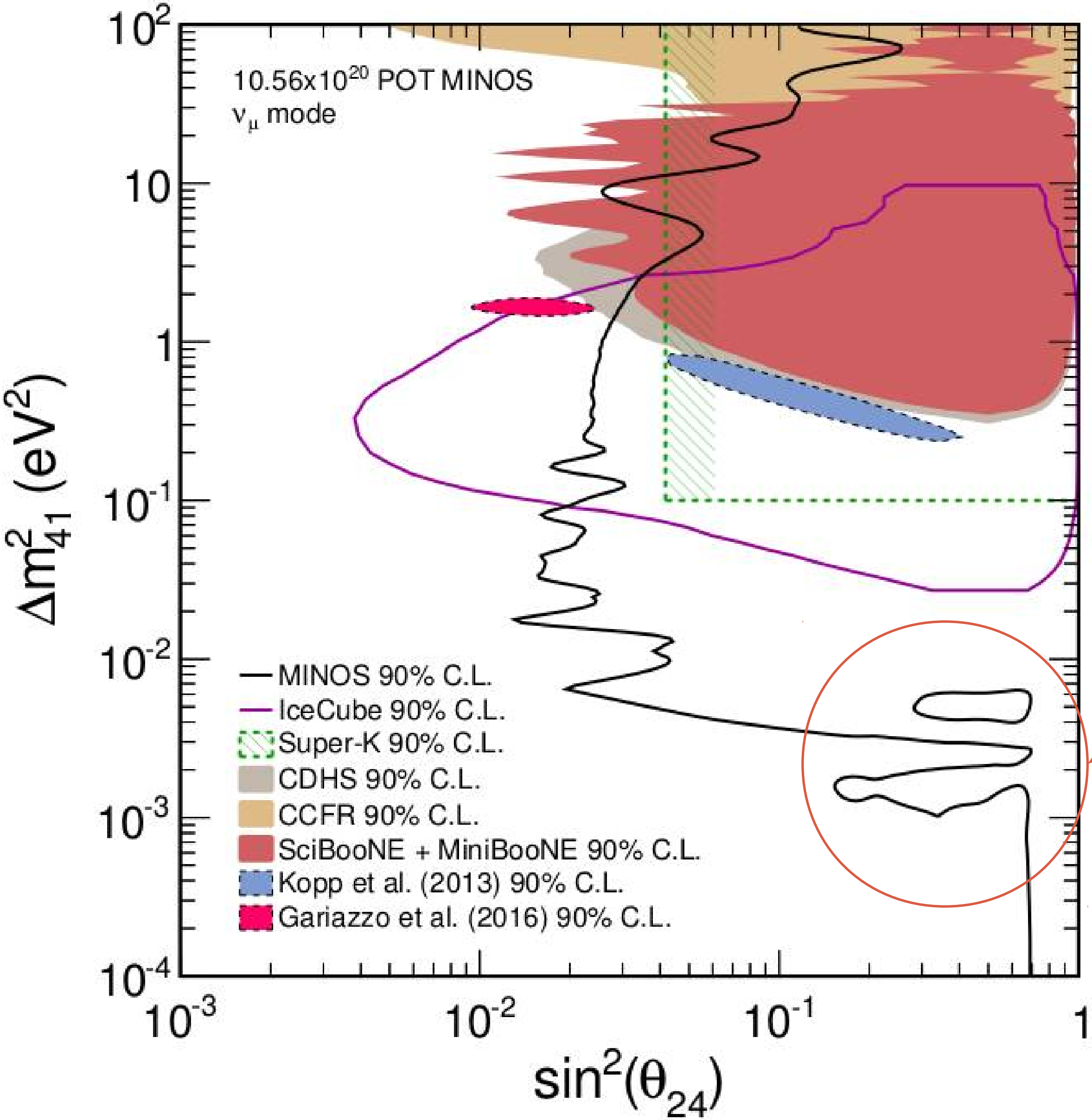


MINOS 4-Flavor Analysis Strategy

- Fit oscillated F/N MC ratio directly to F/N data ratio.
- Fix parameters this analysis is not sensitive to (δ_{13}, δ_{14}, δ_{24}, and θ_{14}) to zero.
- Fit the NC and CC spectra simultaneously to determine θ_{23}, θ_{24}, θ_{34}, Δm^2_{32}, and Δm^2_{41}.



Disappearance Limit



MINOS 90% C.L. exclusion limit ranges over 6 orders of magnitude and is the strongest constraint on ν_μ disappearance into ν_s for low Δm^2_{41}.

Internal allowed region due to degenerate solutions.

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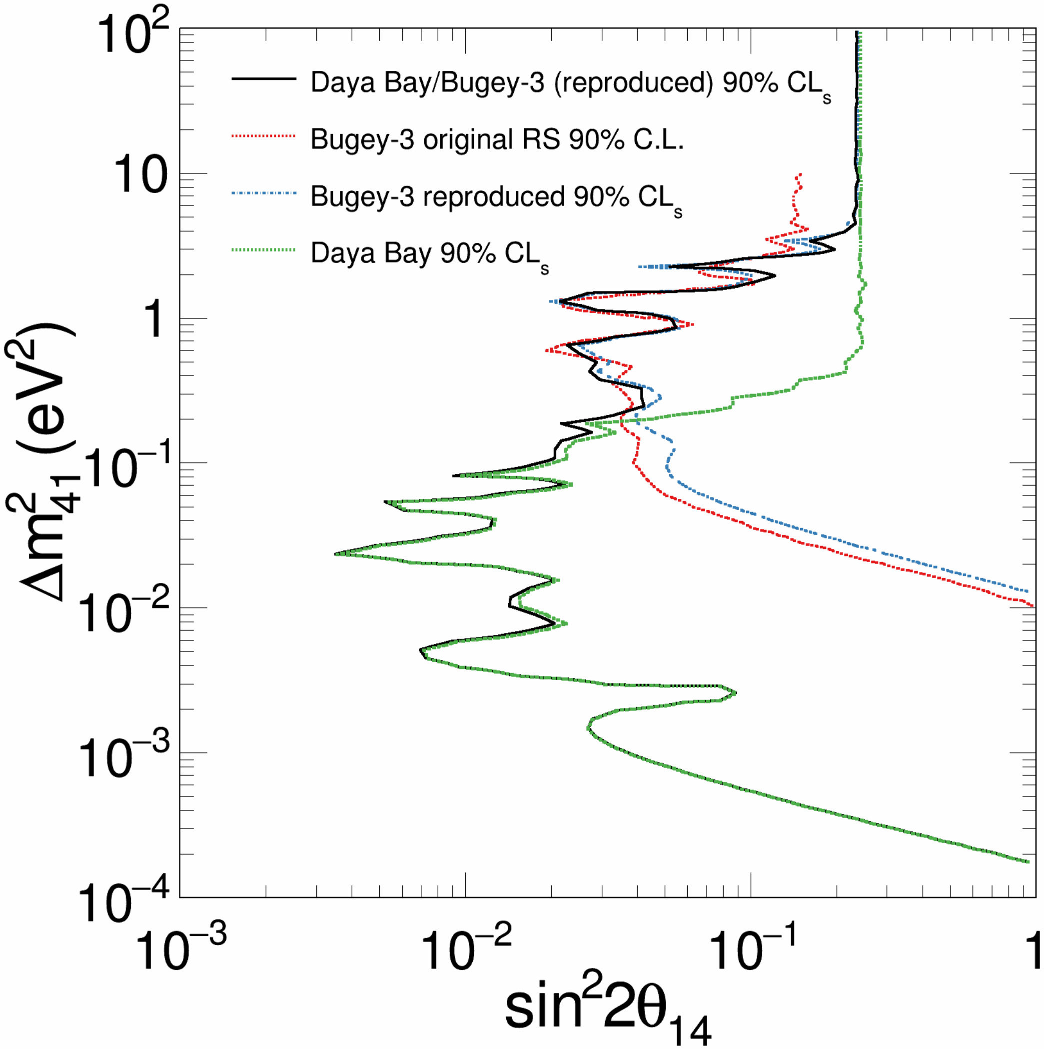
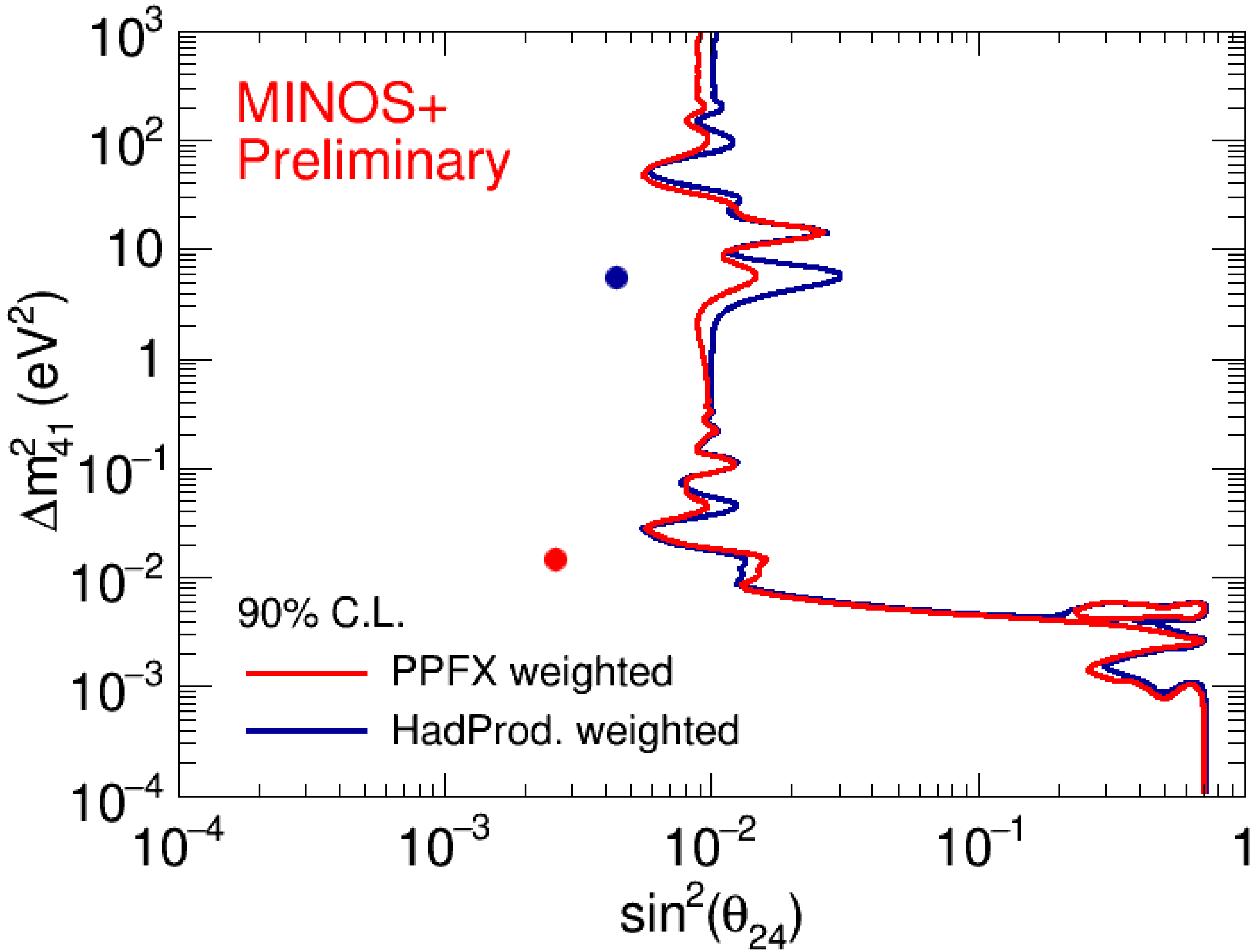
Daya Bay Results

- Generate predictions using Huber-Mueller reactor flux model
- Oscillate predictions from each detector and find best fit to data
- Jointly fit Bugey-3 reactor data to extend to higher Δm_{41}^2 values.
  - Correct Bugey-3 predictions using modern fluxes and neutron lifetime measurement



Phys. Rev. Lett. 117, 151801 (2016)

Comparison of PPFX and SKZP in Sterile Fit



Sterile Systematics

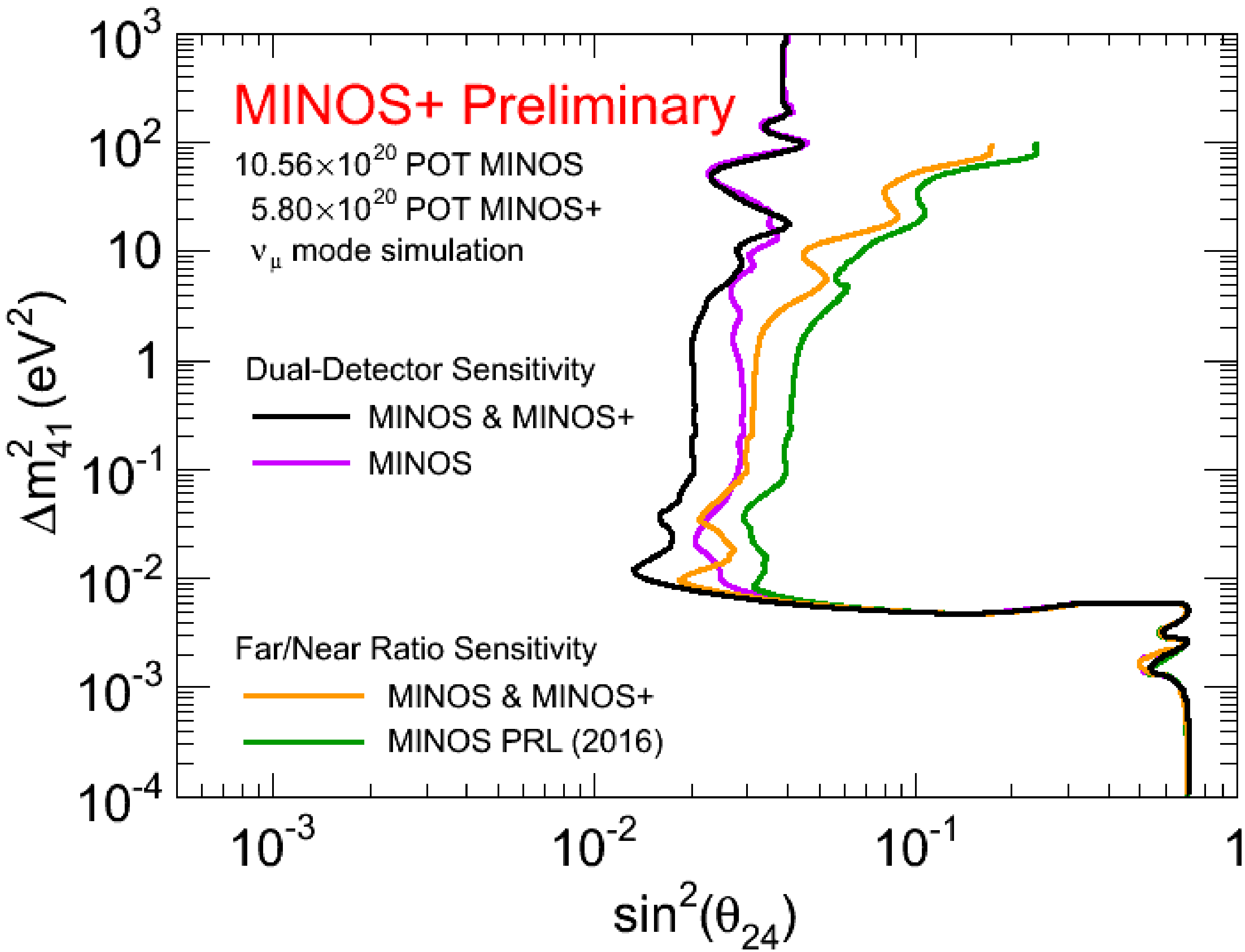
- We consider 44 total sources of systematic uncertainty in five categories
- Largest contributions arise from energy calibration uncertainty for NC events and cross-section uncertainties for CC events
- Statistical and systematic uncertainties are incorporated via covariance matrix
- Covariance matrix cross-terms allow for cancellation of uncertainties

Sources of Systematic Uncertainty

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%

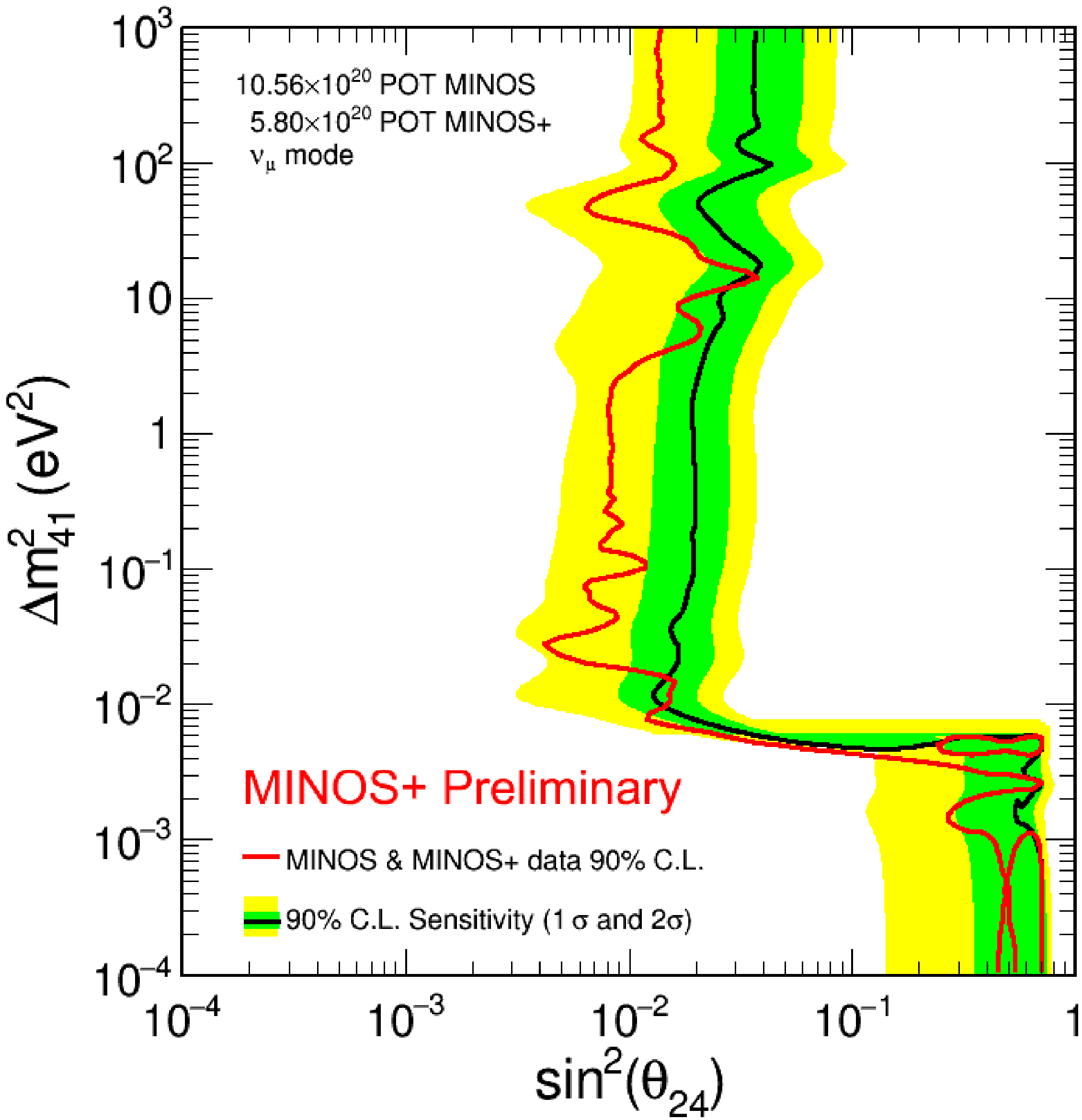
$$\chi^2 = \sum_{i=1}^{N}\sum_{j=1}^{N}(o_i - e_i)^T [V^{-1}]_{ij}(o_j - e_j)$$

Comparison of F/N and Two-Detector Fit



- Sensitivities are calculated using the two fit methods indicated
- Far/Near ratio methods lose coverage in Near Detector dominated region

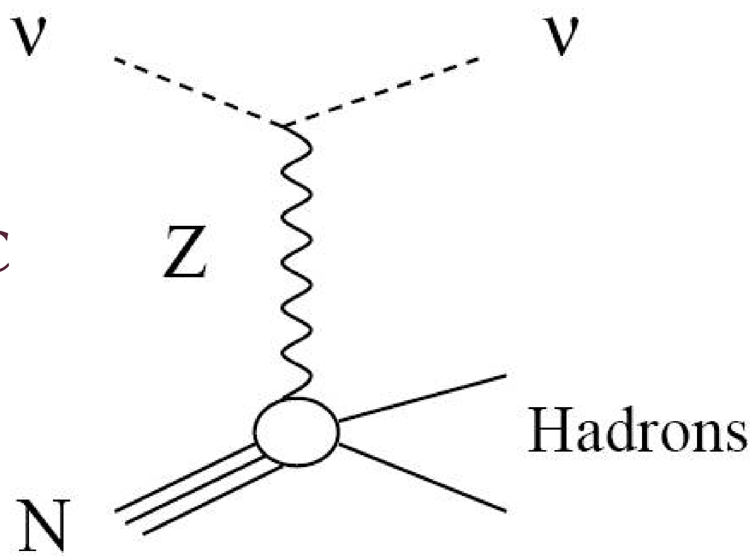
Sensitivity Band

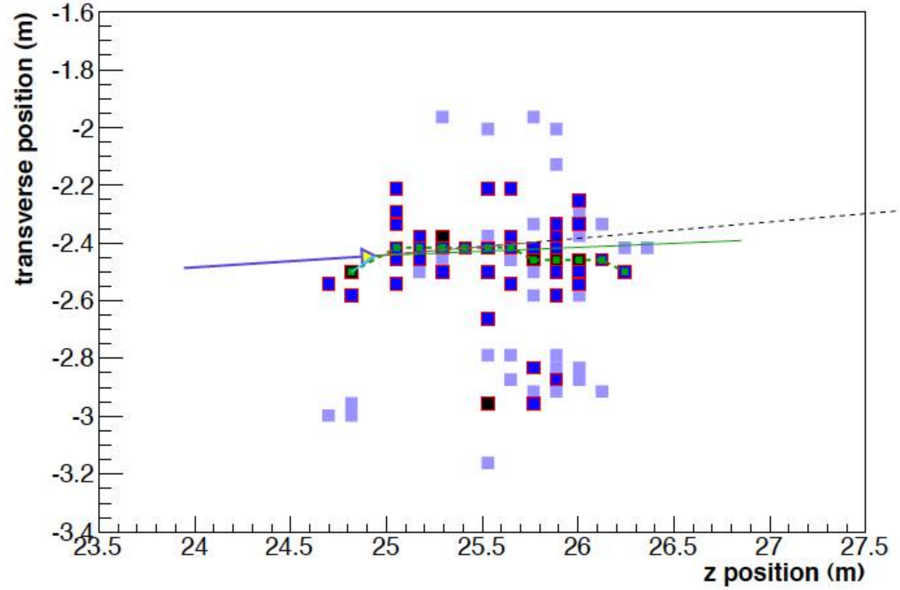


- Limit is constructed using Unified Approach of Feldman and Cousins
- MINOS & MINOS+ data excludes parameter space over seven orders of magnitude in Δm^2_{41}
- The exclusion limit falls within the 2σ expected sensitivity band which accounts for the effects of systematic fluctuations

Event Topologies

NC





ν_μ CC