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On behalf of the MINOS+ Collaboration

Final Long-Baseline Results from MINOS and MINOS+

XXIX International Conference on Neutrino Physics and Astrophysics
2 July 2020



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New 3-flavor oscillation results



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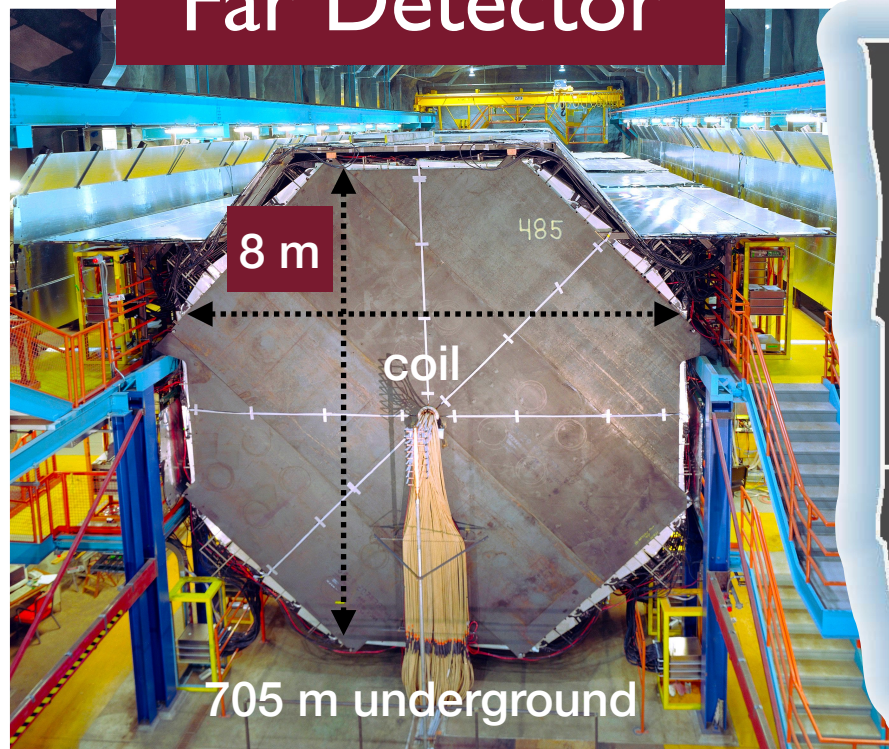
New 3-flavor oscillation results

New sterile search results
 ν_μ disappearance
 ν_e appearance



MINOS Detectors

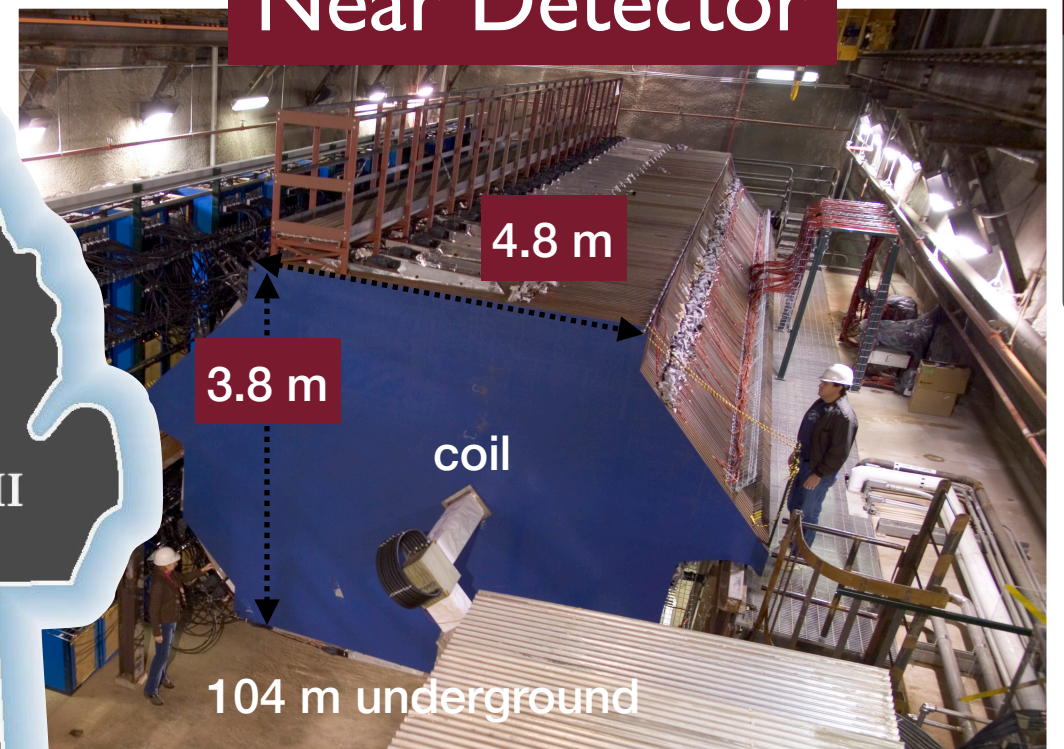
Far Detector



- 735 km from target
- 5.4 ktons



Near Detector

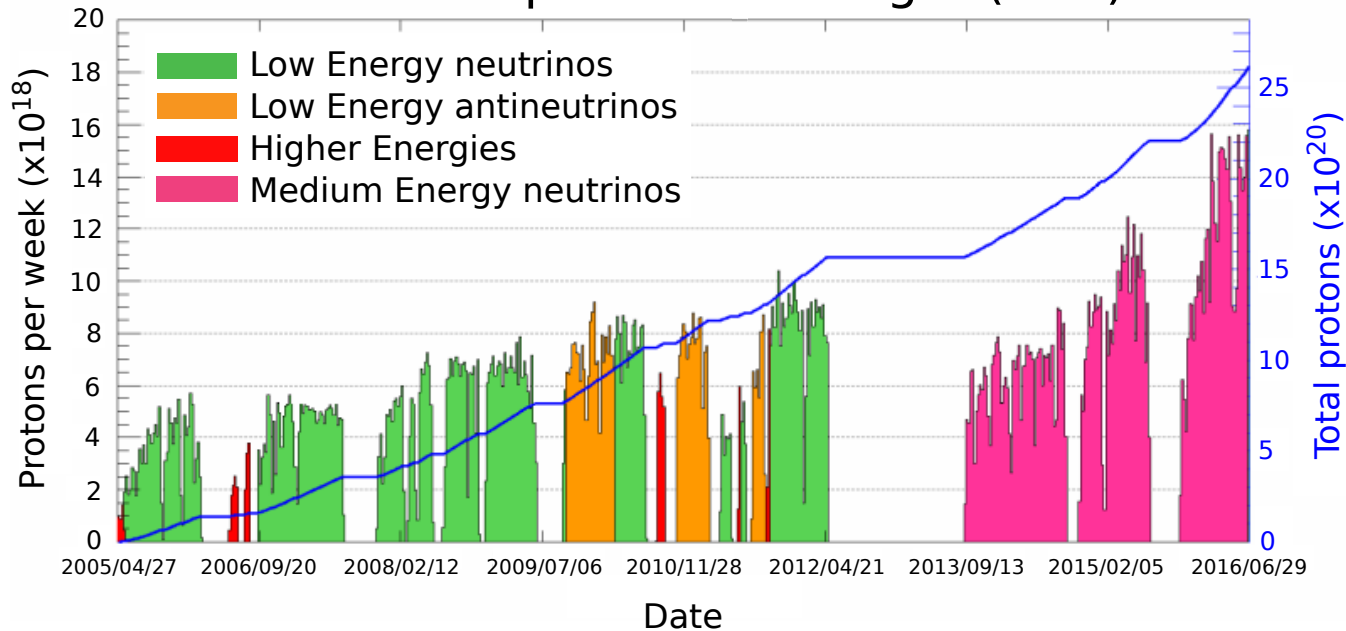


- 1 km from target
- 980 tons

- * On-axis long-baseline neutrino oscillation experiments
- * Identical detector technology
- * Magnetized steel tracking sampling calorimeters

MINOS and MINOS+ Exposures

Total NuMI protons-on-target (POT)



MINOS
(2005-2012)

MINOS+
(2013-2016)

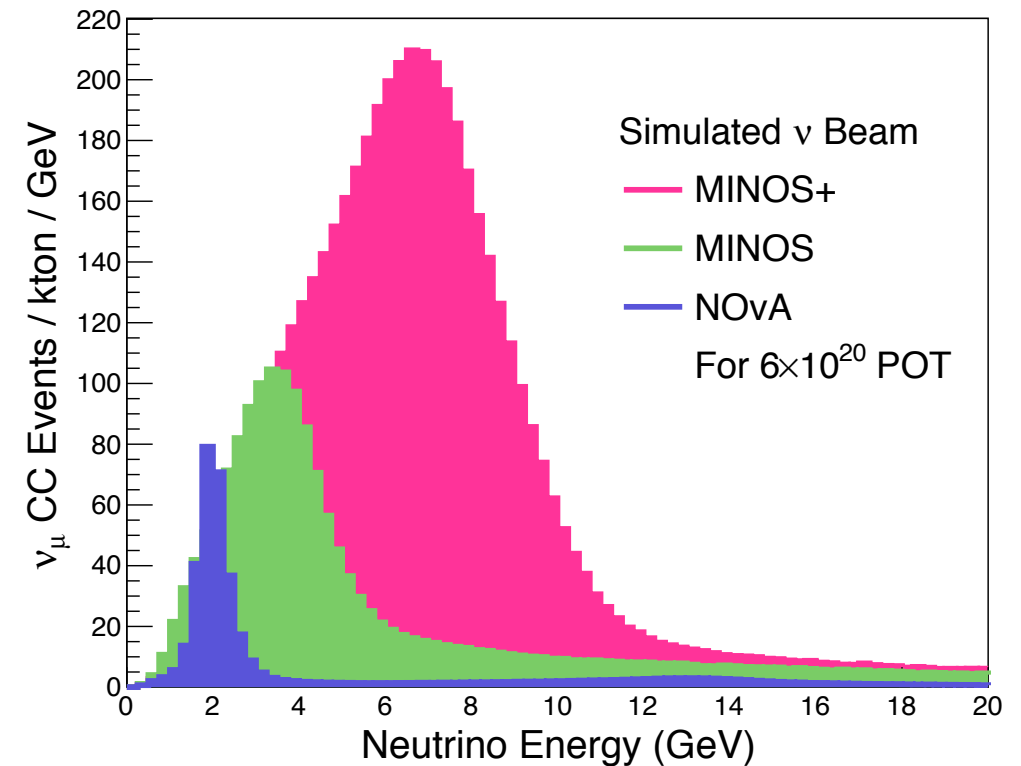
10.56×10^{20} POT 3.36×10^{20} POT 9.69×10^{20} POT

11 years of accelerator neutrino data

* 23.61×10^{20} protons on target

13 years of atmospheric neutrino data

* 60.75 kt-yr exposure

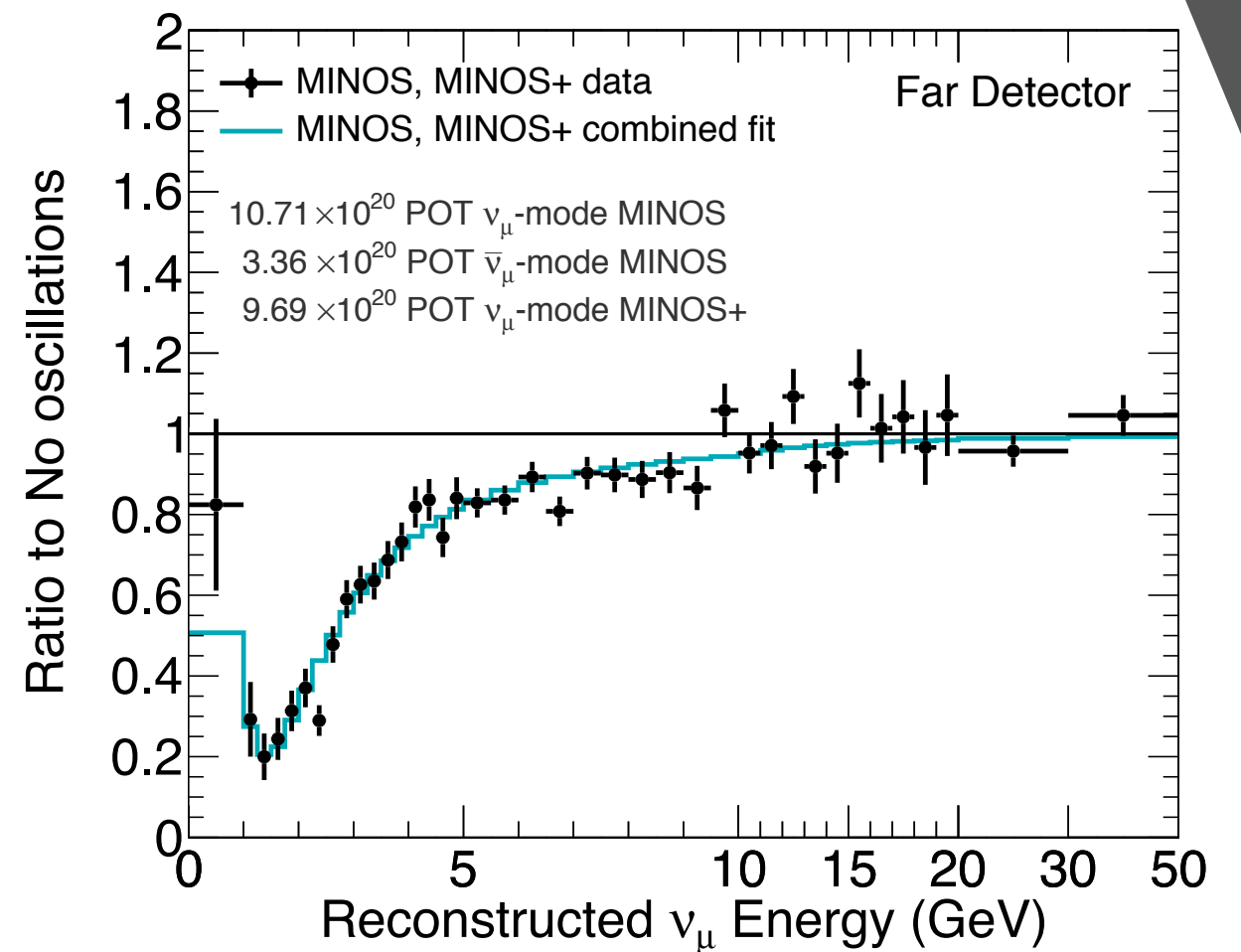
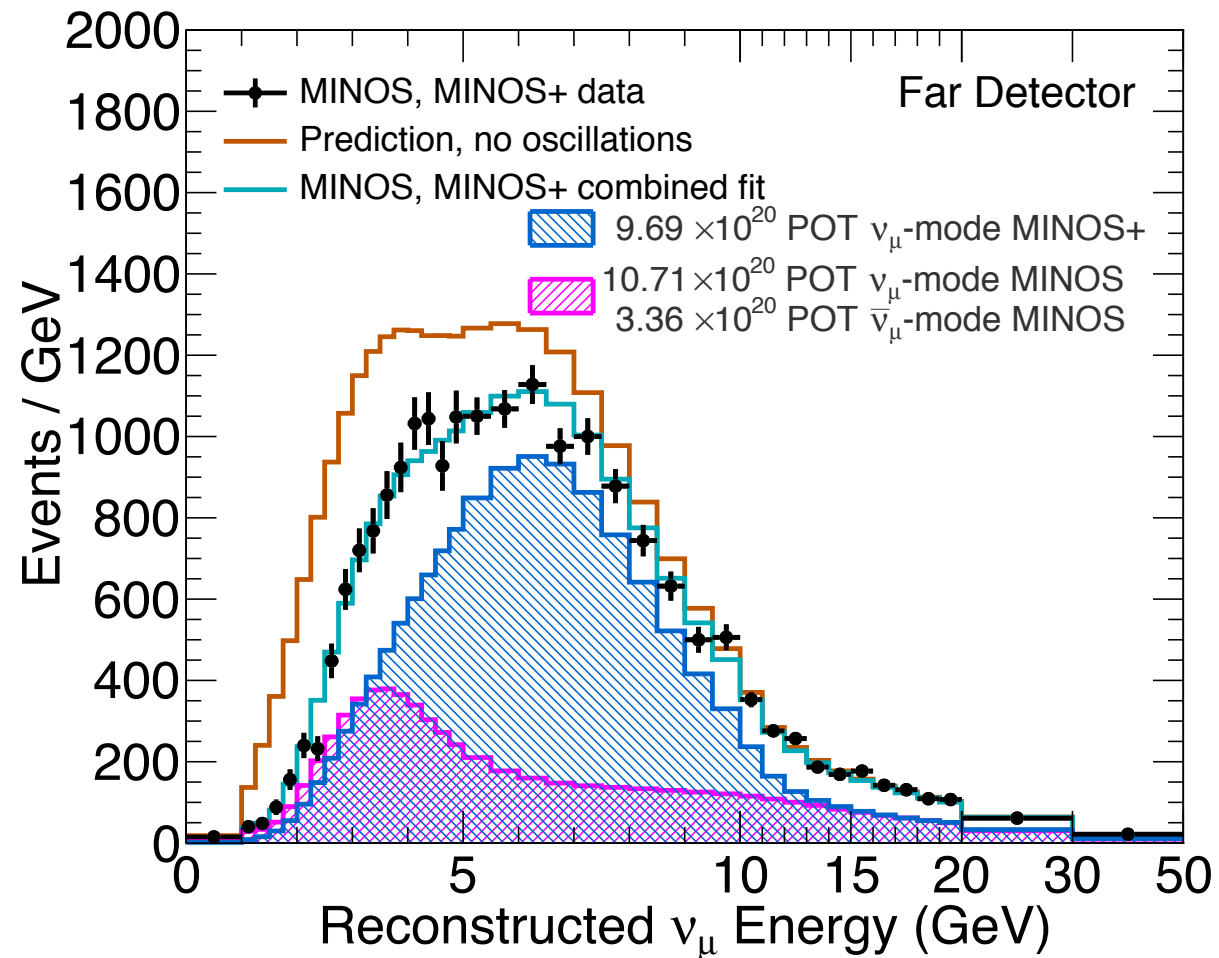


**High Statistics
Dataset**

Three-Flavor Oscillations

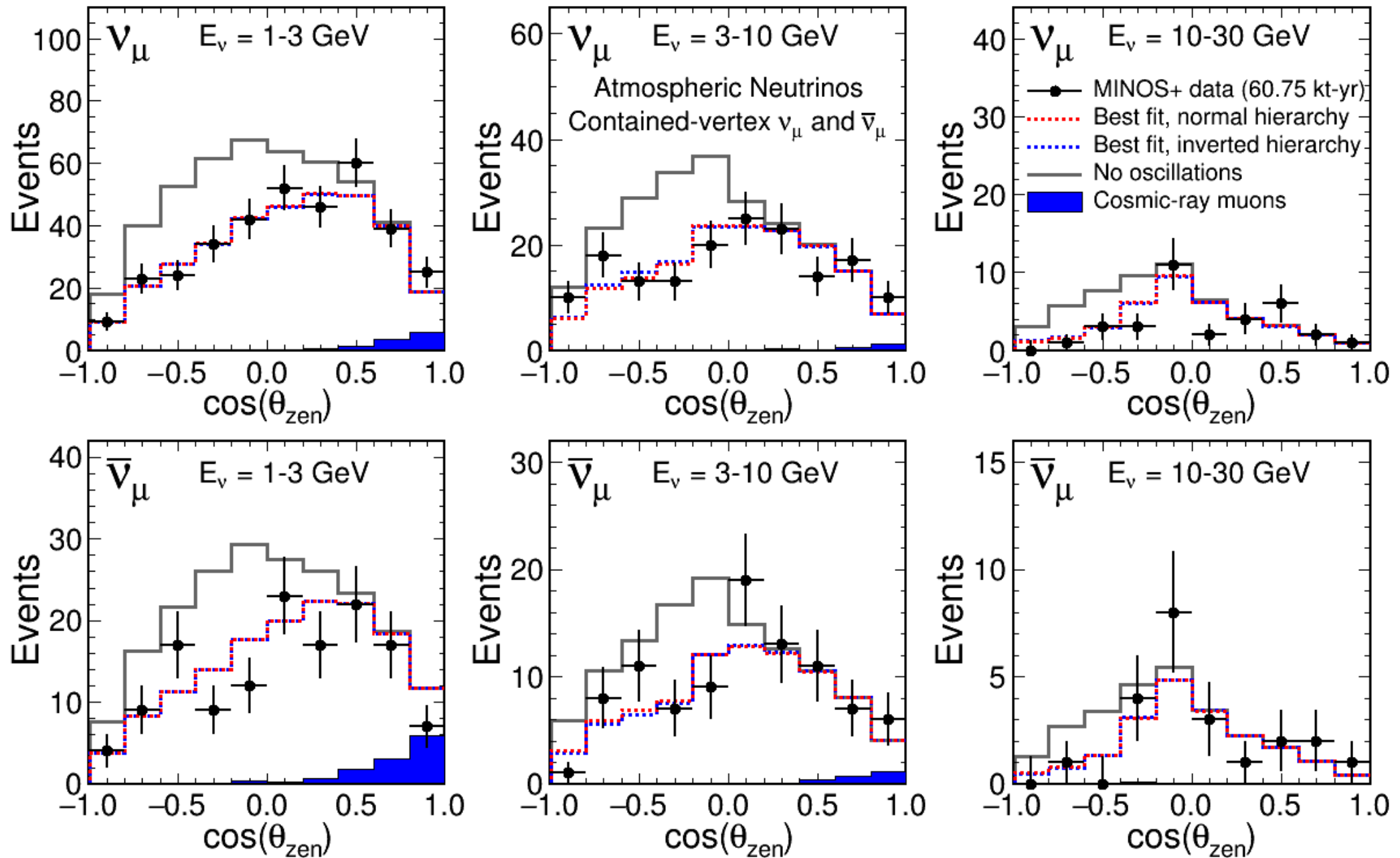


Far Detector Beam Data



$$P_{\nu_\mu \rightarrow \nu_\mu} \approx 1 - \cos^2 \theta_{13} \sin^2(2\theta_{23}) \sin^2 \frac{\Delta m_{32}^2 L}{4E_\nu}$$

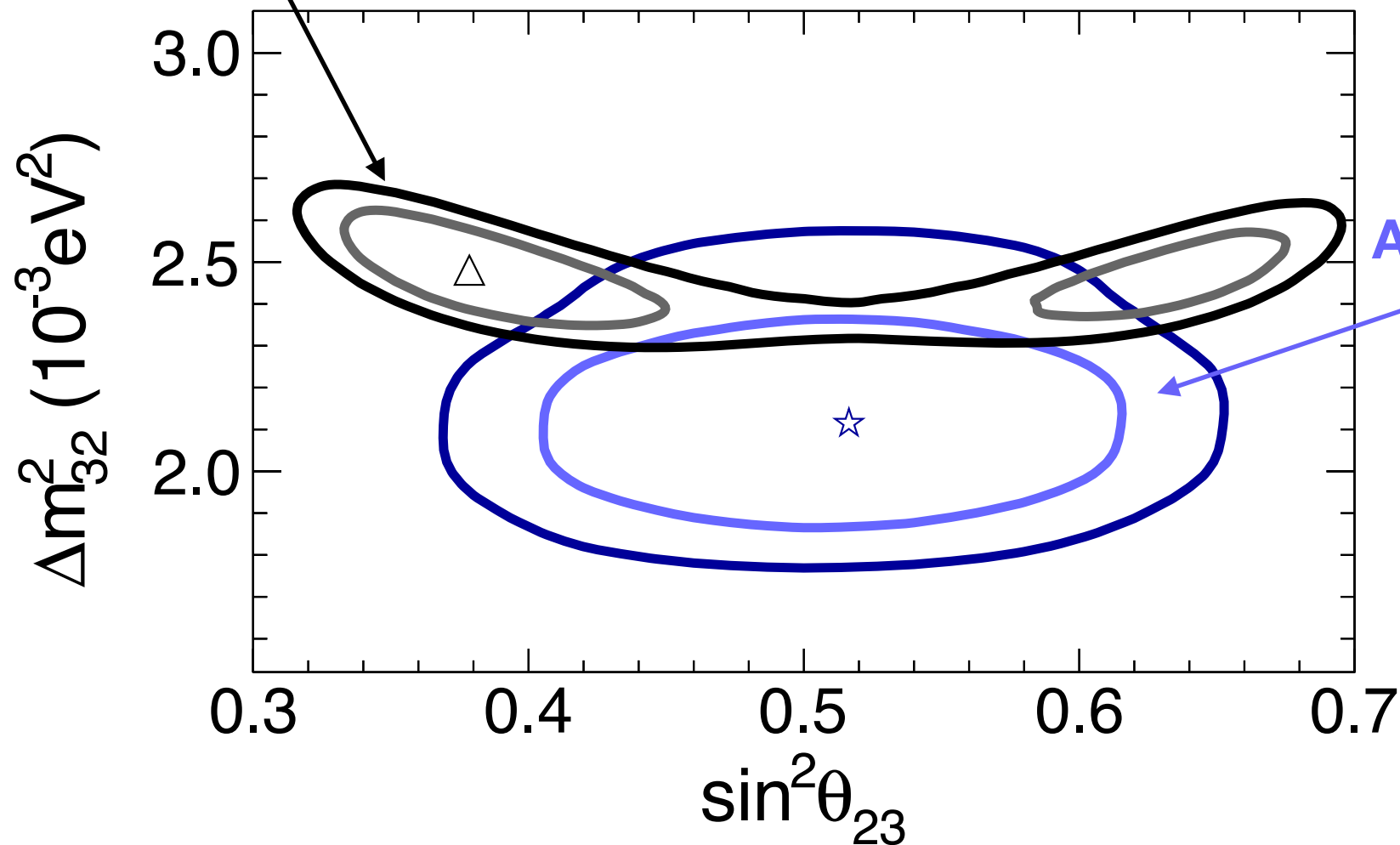
Atmospheric Data

 ν_{μ}
 $\bar{\nu}_{\mu}$


- Fit in neutrino energy and $\cos(\theta_{zen})$
- Complements beam neutrinos with different baselines

Beam and Atmospheric Constraints

Beam Neutrinos



Atmospheric Neutrinos

Results consistent with the combined fit with a p-value of 22%

Beam Best Fit

Normal Hierarchy

$$\Delta m_{32}^2 = 2.48 \times 10^{-3} \text{ eV}^2$$

$$\sin^2 \theta_{23} = 0.38$$

Atmospheric Best Fit

Normal Hierarchy

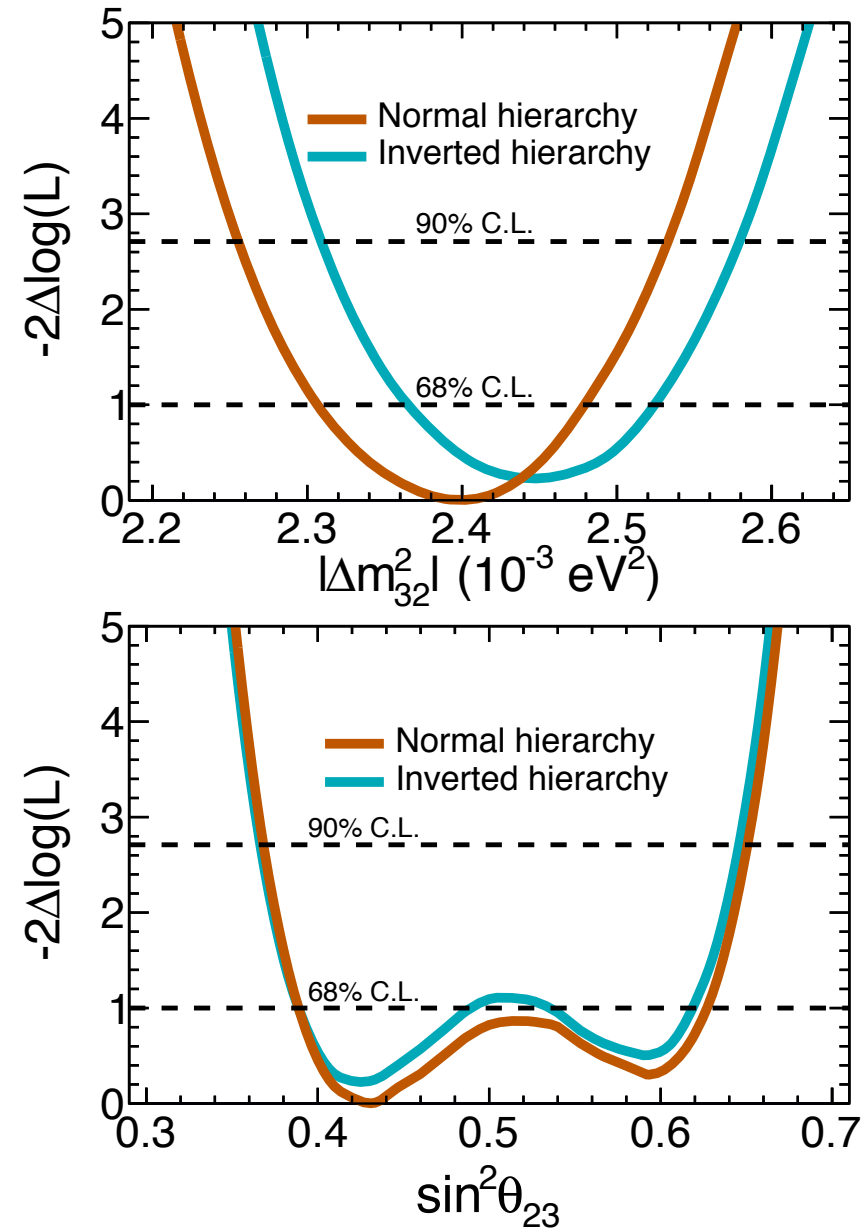
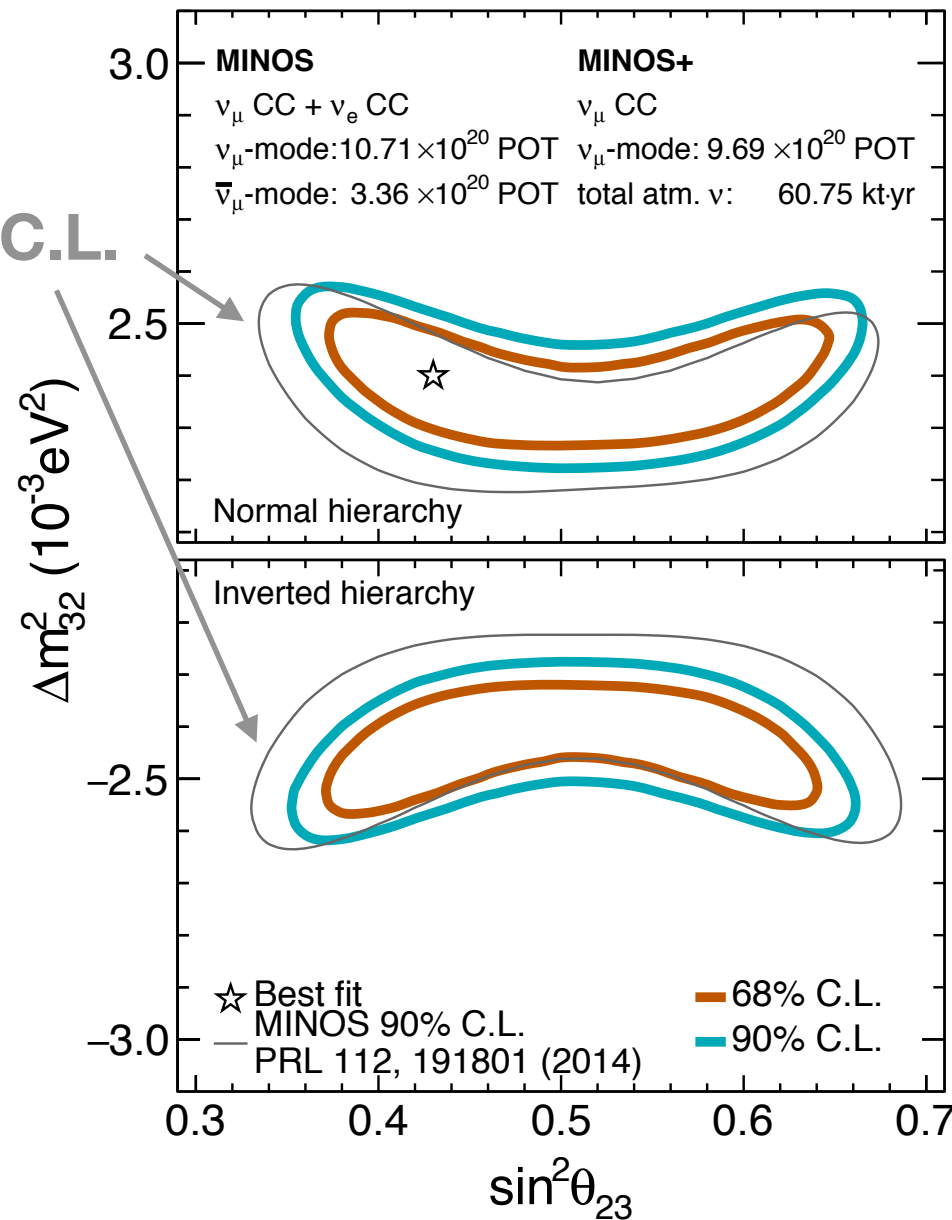
$$\Delta m_{32}^2 = 2.11 \times 10^{-3} \text{ eV}^2$$

$$\sin^2 \theta_{23} = 0.52$$

Combined Fit Results

arXiv:2006.15208 (submitted to PRL)

MINOS 90% C.L.



Best fit in Normal Hierarchy

$$\Delta m_{32}^2 = 2.40^{+0.08}_{-0.09} \times 10^{-3} \text{ eV}^2$$

$$\sin^2 \theta_{23} = 0.43 \text{ (0.39} \leftrightarrow \text{0.63)}$$

Inverted Hierarchy

$$2.45^{+0.07}_{-0.08} \times 10^{-3} \text{ eV}^2$$

$$0.42 \text{ (0.39} \leftrightarrow \text{0.49)}$$

Disfavor maximal mixing:

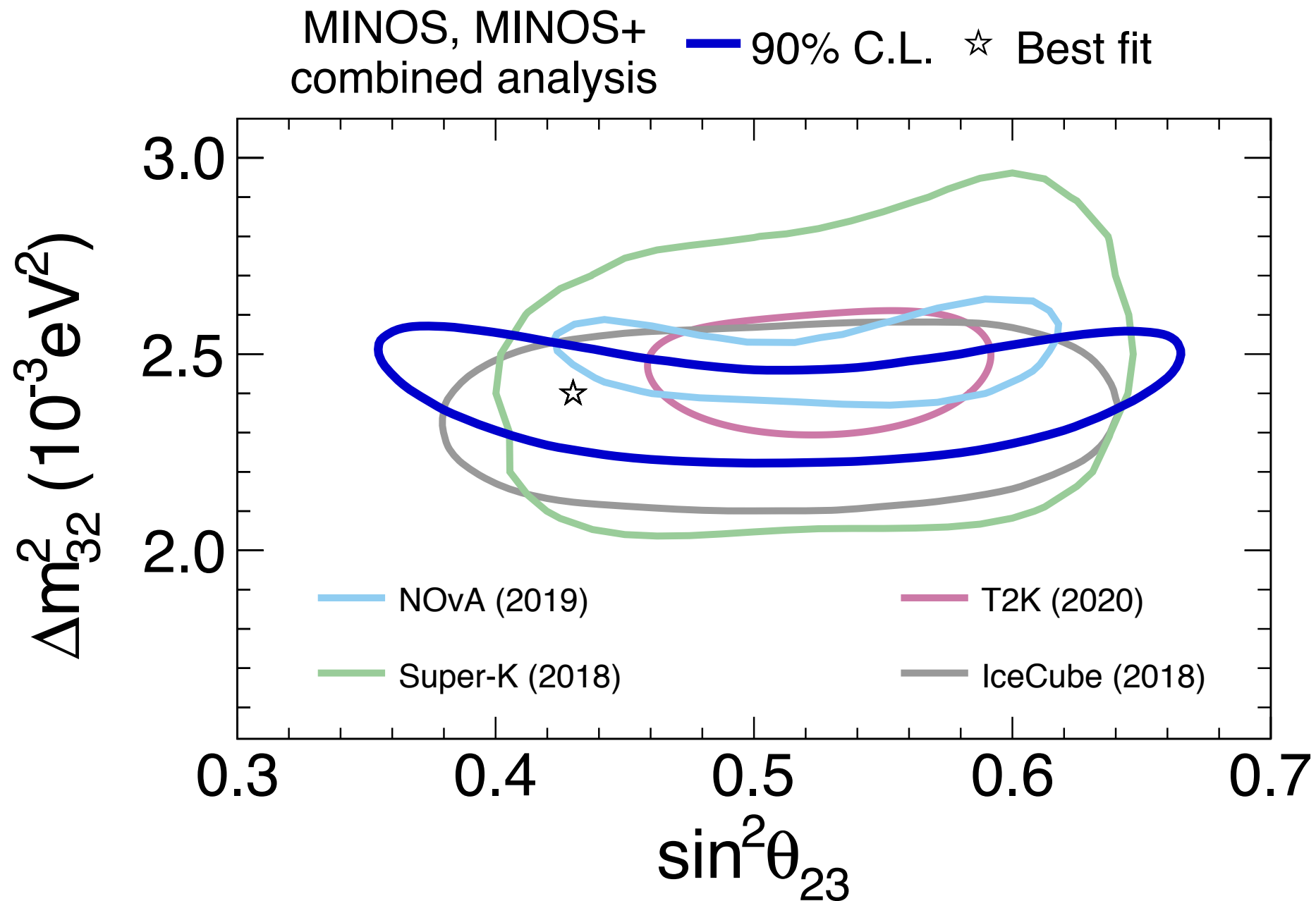
0.91σ

Preference for lower octant:

0.55σ

Preference for normal hierarchy: 0.45σ

Comparison with Other Experiments



Best fit in Normal Hierarchy

$$\Delta m_{32}^2 = 2.40^{+0.08}_{-0.09} \times 10^{-3} \text{eV}^2$$

$$\sin^2 \theta_{23} = 0.43 \text{ (0.39} \leftrightarrow \text{0.63)}$$

Inverted Hierarchy

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$$\sin^2 \theta_{23} = 0.42 \text{ (0.39} \leftrightarrow \text{0.49)}$$

Beyond 3-Flavor Oscillations

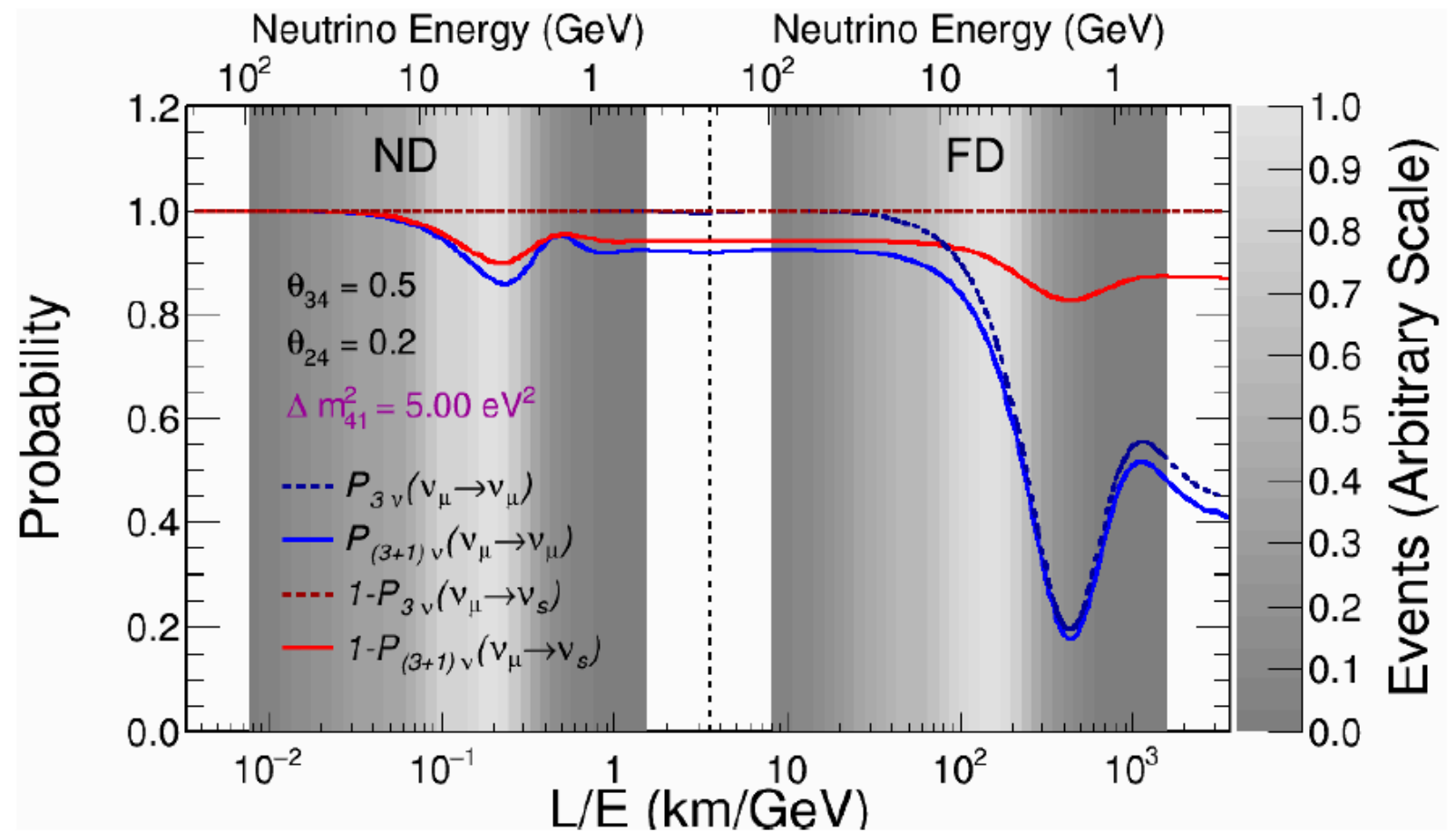
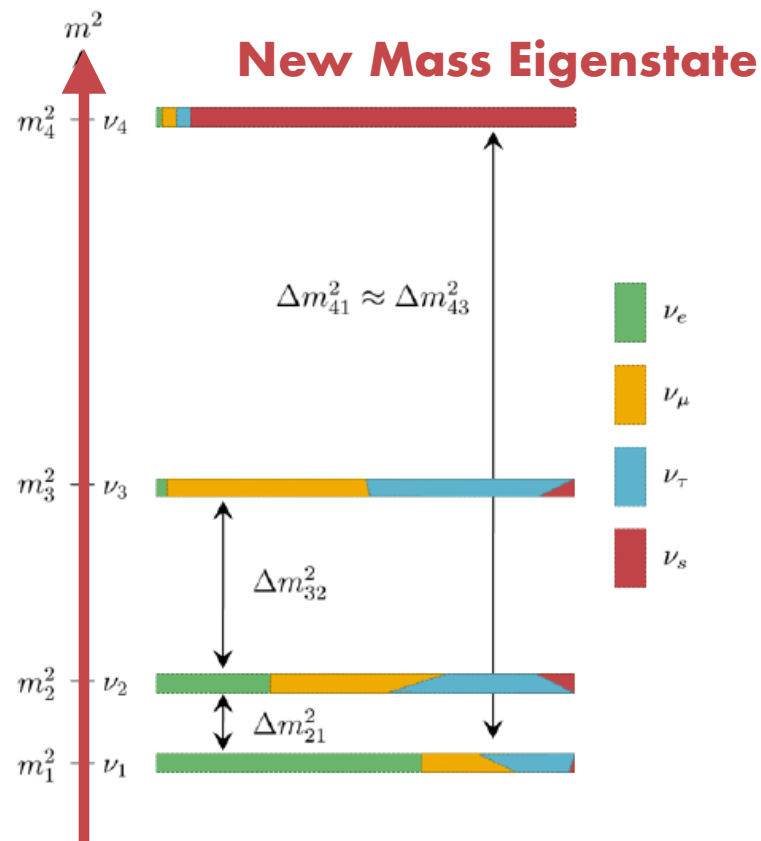


3+1 Neutrino Model

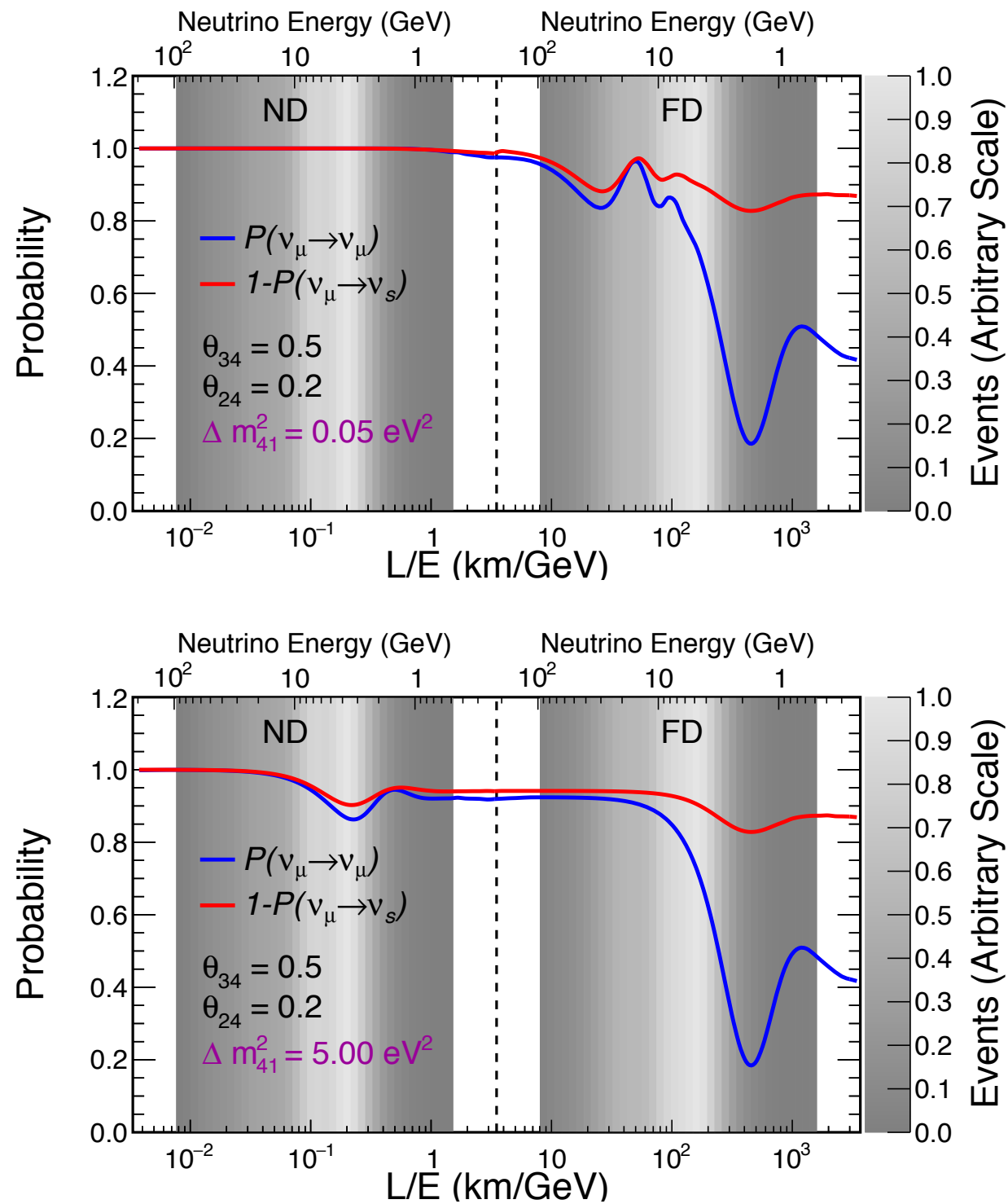
$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

- * 3 mass scales: Δm_{21}^2 , Δm_{32}^2 , Δm_{41}^2
- * 6 mixing angles: θ_{12} , θ_{23} , θ_{13} , θ_{14} , θ_{24} , θ_{34}
- * 3 CP-violating phases: δ_{13} , δ_{14} , δ_{24}

Large Δm_{41}^2 splitting



4-Flavor Oscillations at MINOS

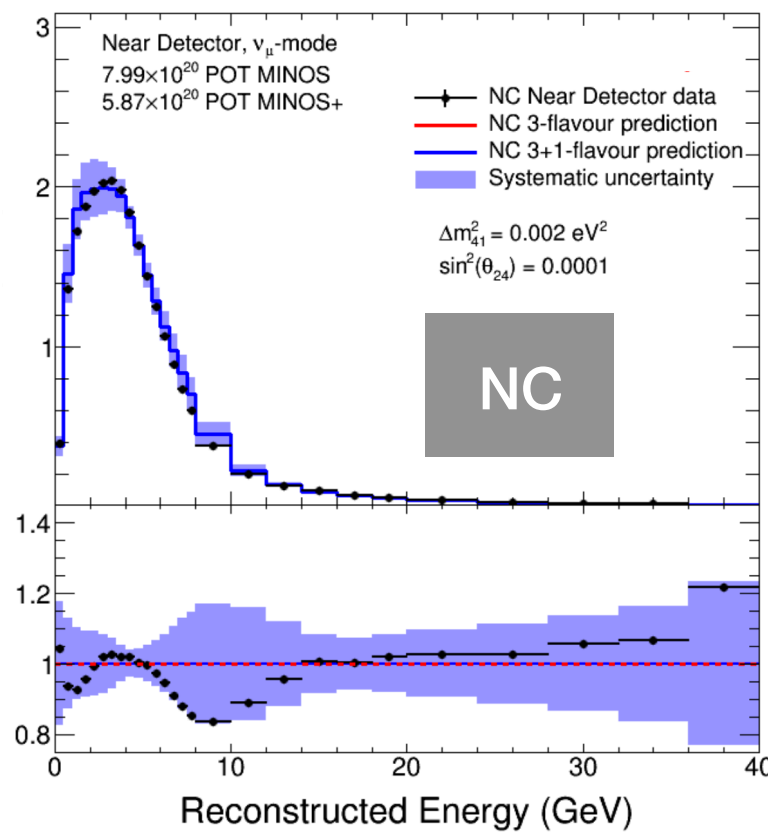
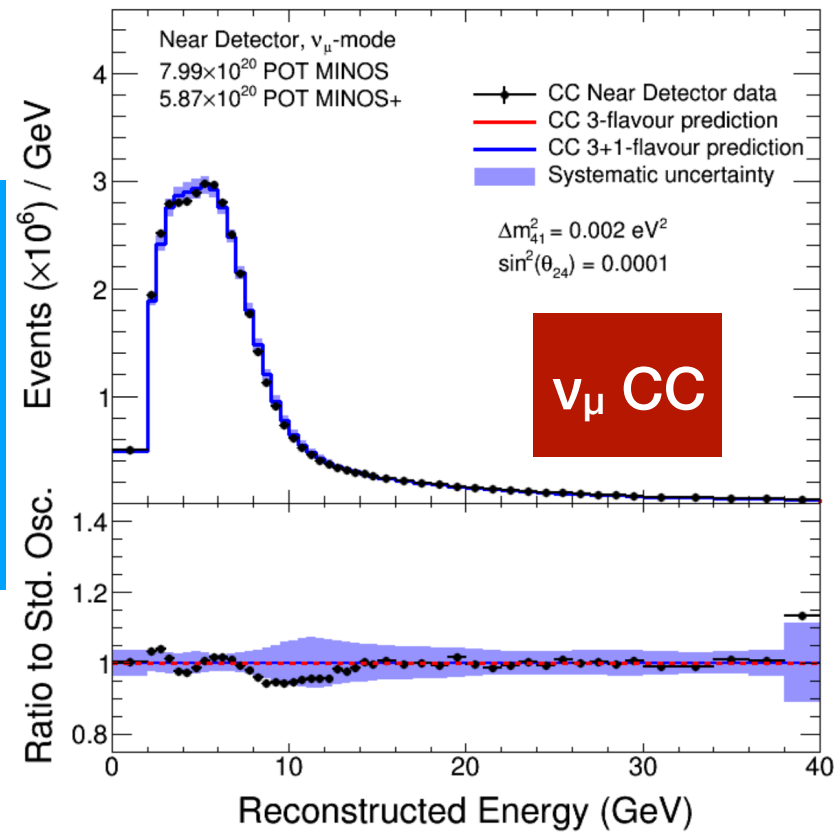


Small Δm^2_{41} :
Oscillations at the FD

Large Δm^2_{41} :
Large oscillations at the ND

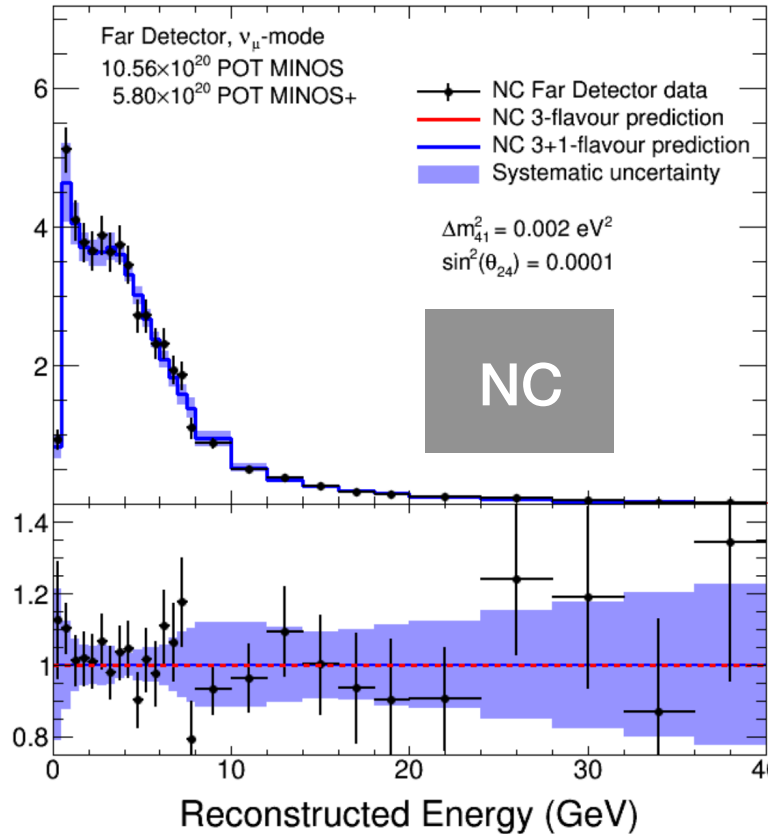
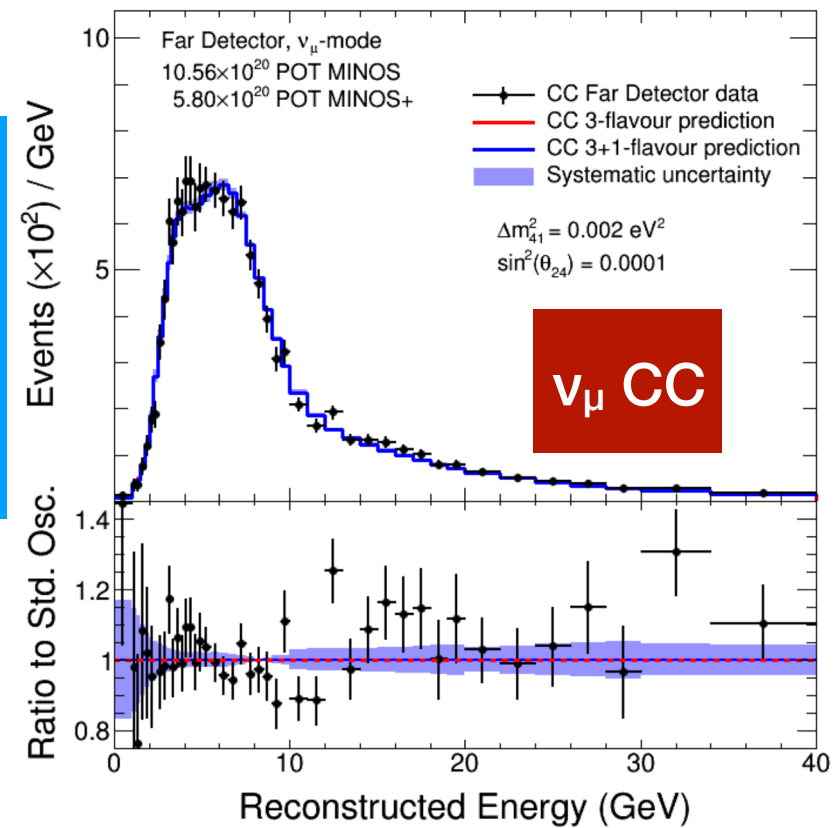
Data Samples

Near Detector



CC EVENTS
 Sensitive to Δm_{41}^2 and θ_{24}

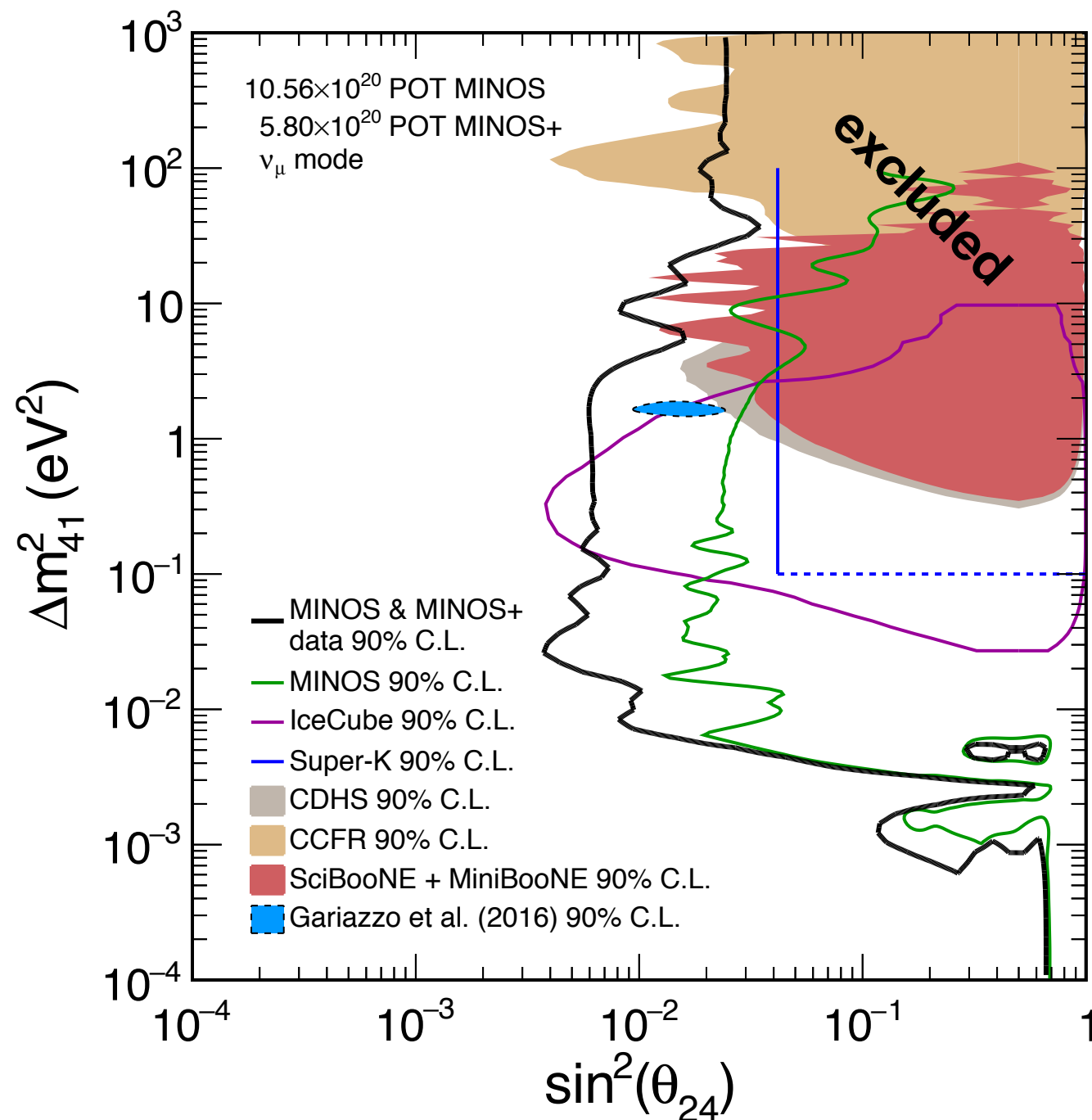
Far Detector



NC EVENTS
 Sensitive to Δm_{41}^2 and θ_{24}
 Sensitive to θ_{34}

MINOS+ Exclusion

P.Adamson et al. [MINOS Collaboration], Phys. Rev. Lett. **122**, 091803 (2019)

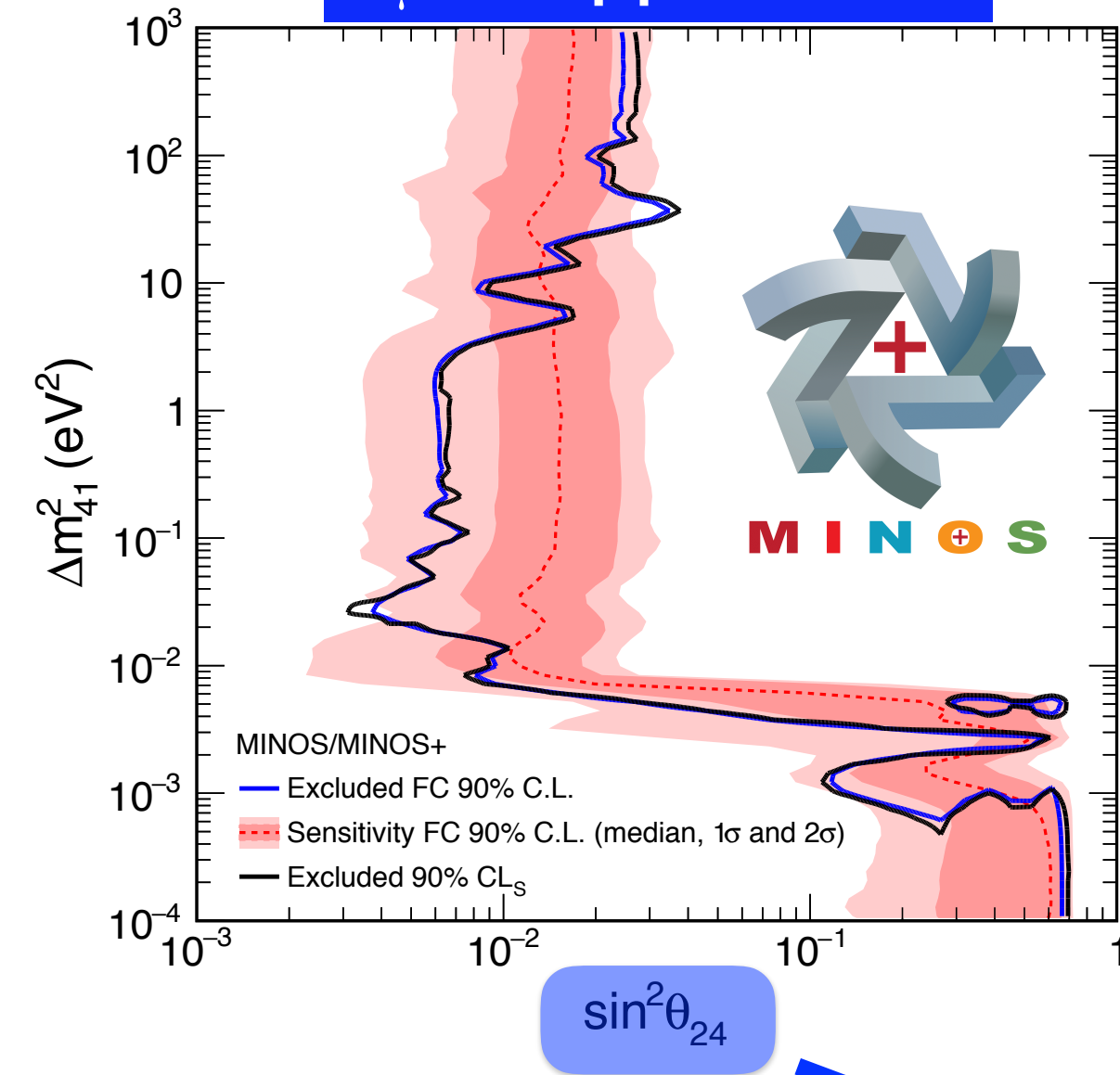


Fit θ_{23} , θ_{24} , Δm_{32}^2 , and Δm_{41}^2
Fix δ_{13} , δ_{14} , δ_{24} , and θ_{14} to zero
(no sensitivity)

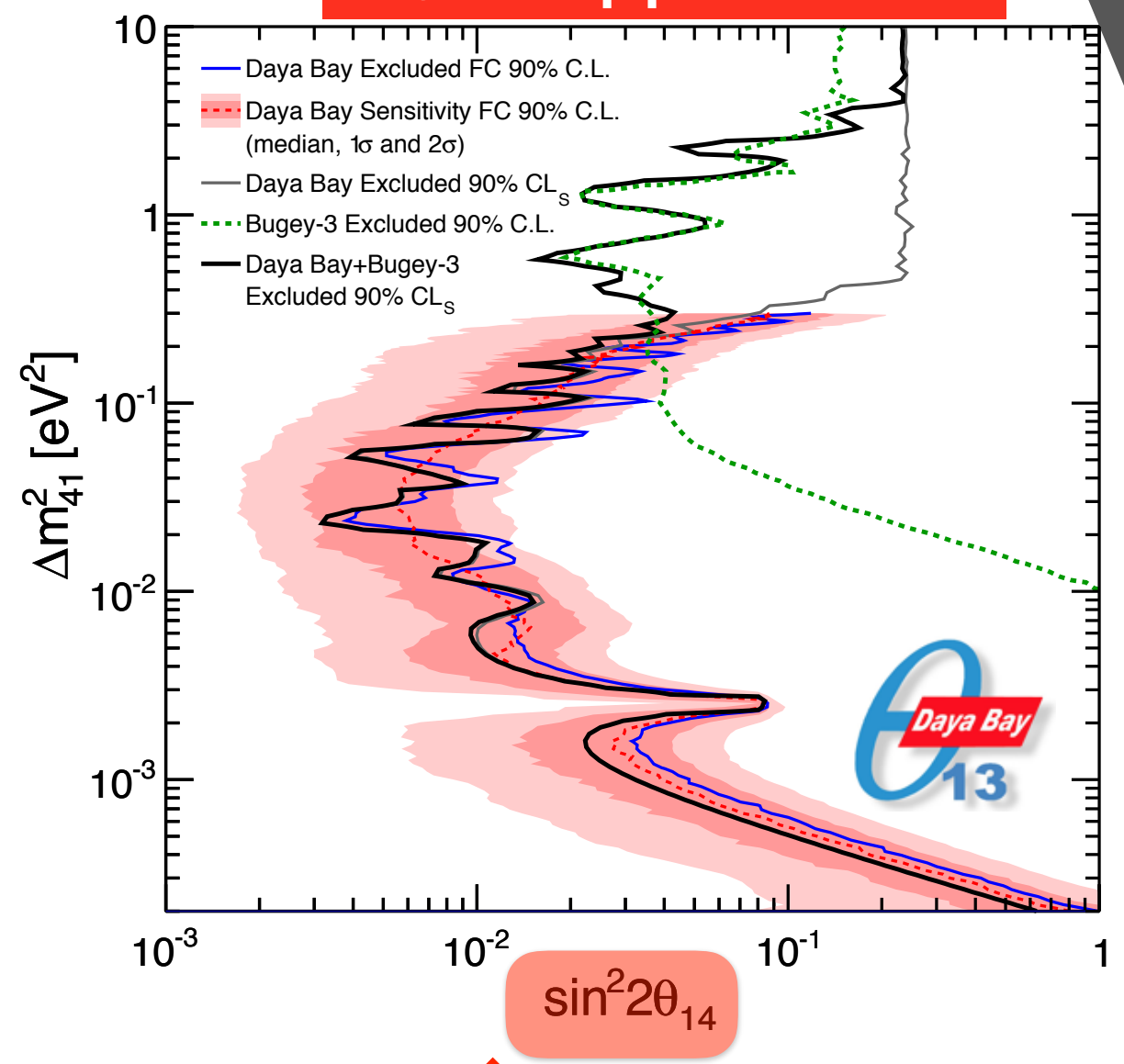
- * Simultaneous 2 detector fit over long baseline
- * Improvement over previous FD/ND ratio method
- * Improvement with MINOS+ extra statistics

MINOS+/Daya Bay/Bugey-3 Exclusion

ν_μ disappearance



$\bar{\nu}_e$ disappearance

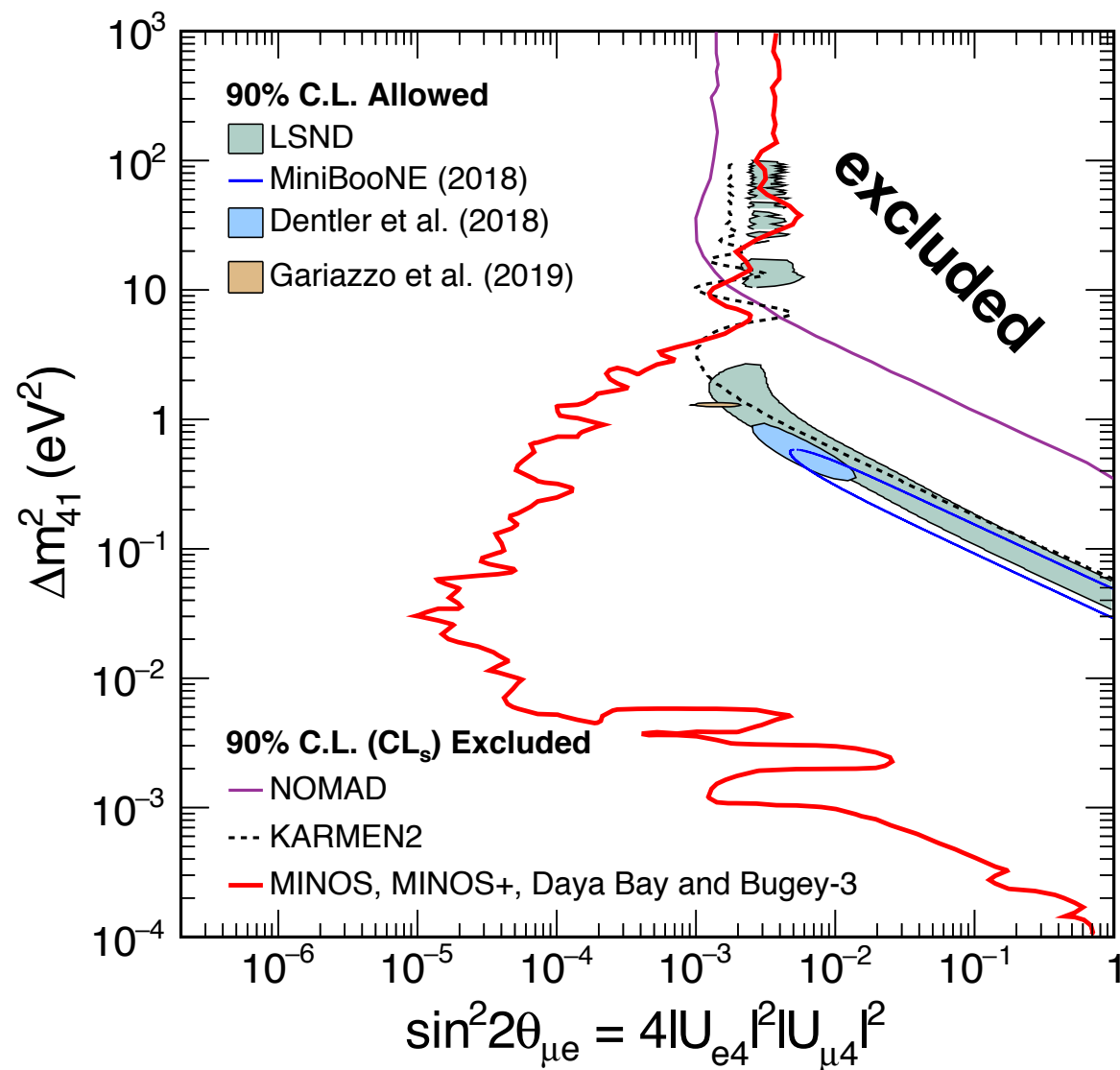


$$4|U_{e4}|^2|U_{\mu4}|^2 = \sin^2 \theta_{24} \sin^2 2\theta_{14} \equiv \sin^2 2\theta_{\mu e}$$

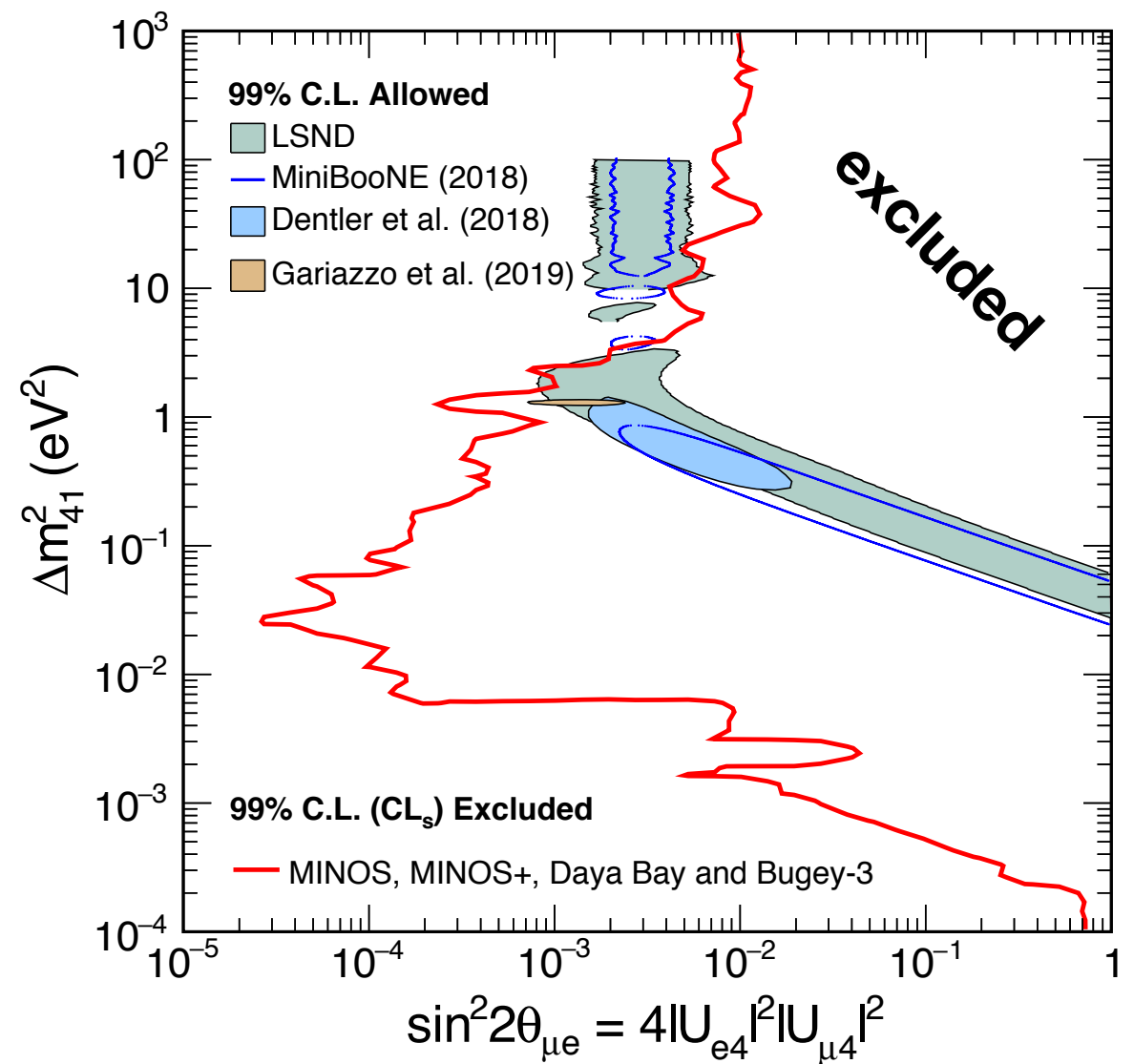
arXiv:2002.00301 (accepted by PRL)

MINOS+/Daya Bay/Bugey-3 Exclusion

90% C.L.



99% C.L.



arXiv:2002.00301 (accepted by PRL)



Sterile-driven ν_e appearance



Sterile-driven ν_e appearance

3-flavor terms

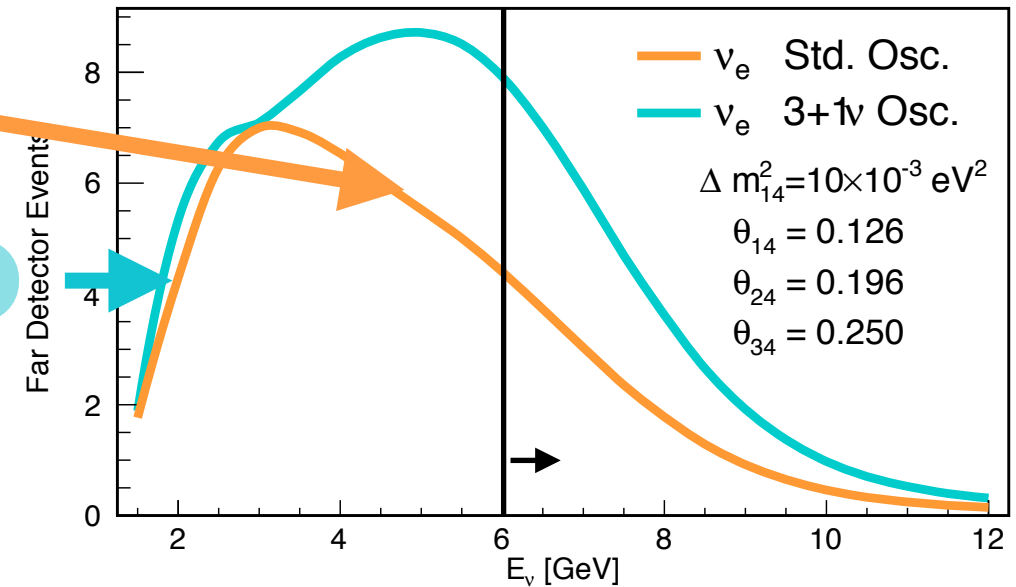
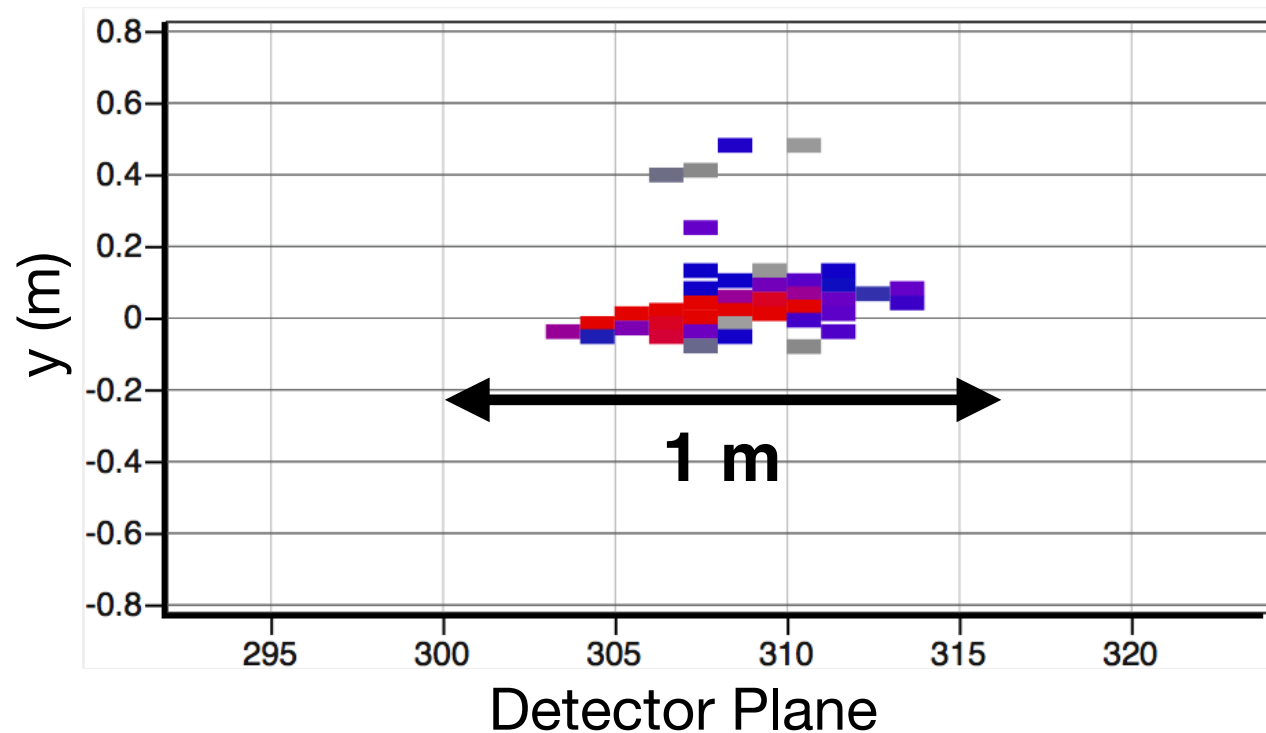
$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2(2\theta_{13}) \sin^2(\theta_{23}) \sin^2(1.27 \Delta m^2 L/E)$$



$$\sin(\theta_{23}) \sin(2\theta_{13}) \sin(2\theta_{24}) \sin(\theta_{14}) \sin^2 \Delta_{32} + \sin^2(2\theta_{14}) \sin^2(\theta_{24}) \sin^2 \Delta_{43} +$$

3+1 terms

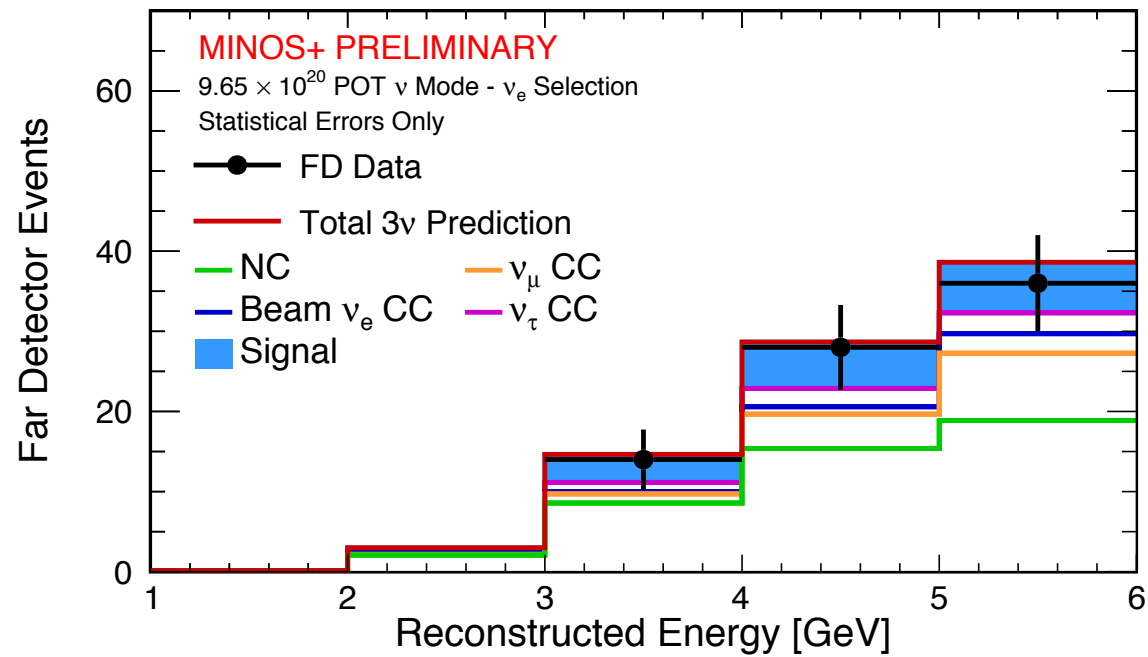
ν_e candidate



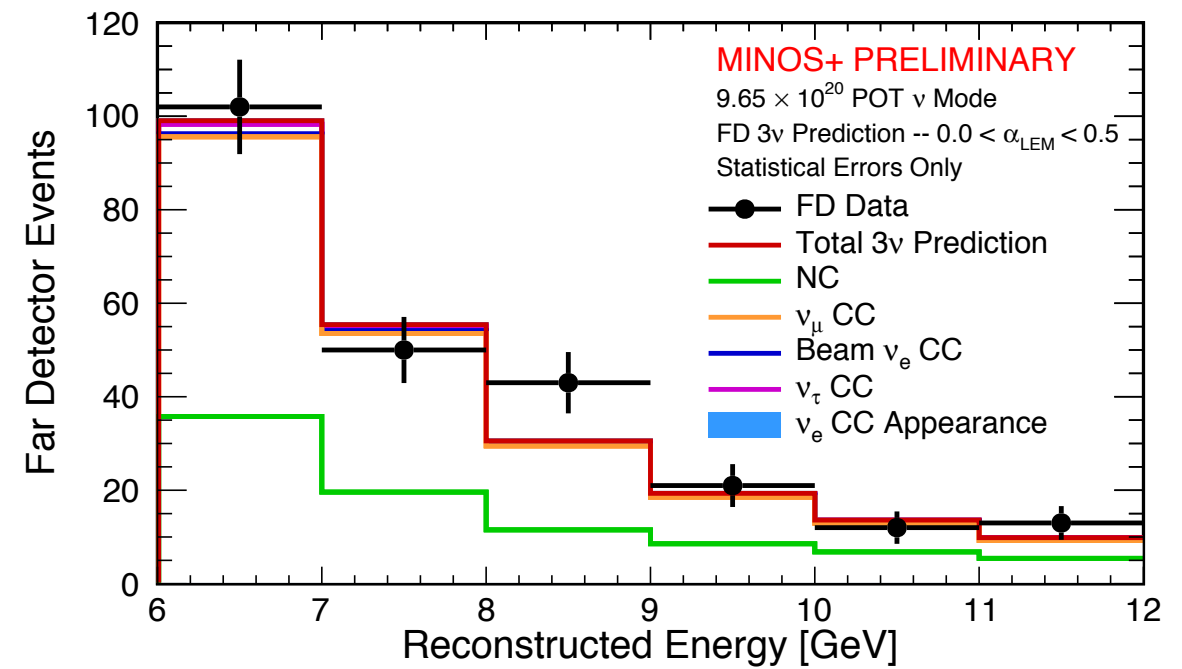
- * MINOS+ data set is at high energy
- * Standard ν_e sample drops off above 6 GeV
- * Signal events are more compact showers
- * Background to ν_e events in MINOS+ manageable at high energy

Sterile-driven ν_e Extrapolation Checks

ν_e Candidate events

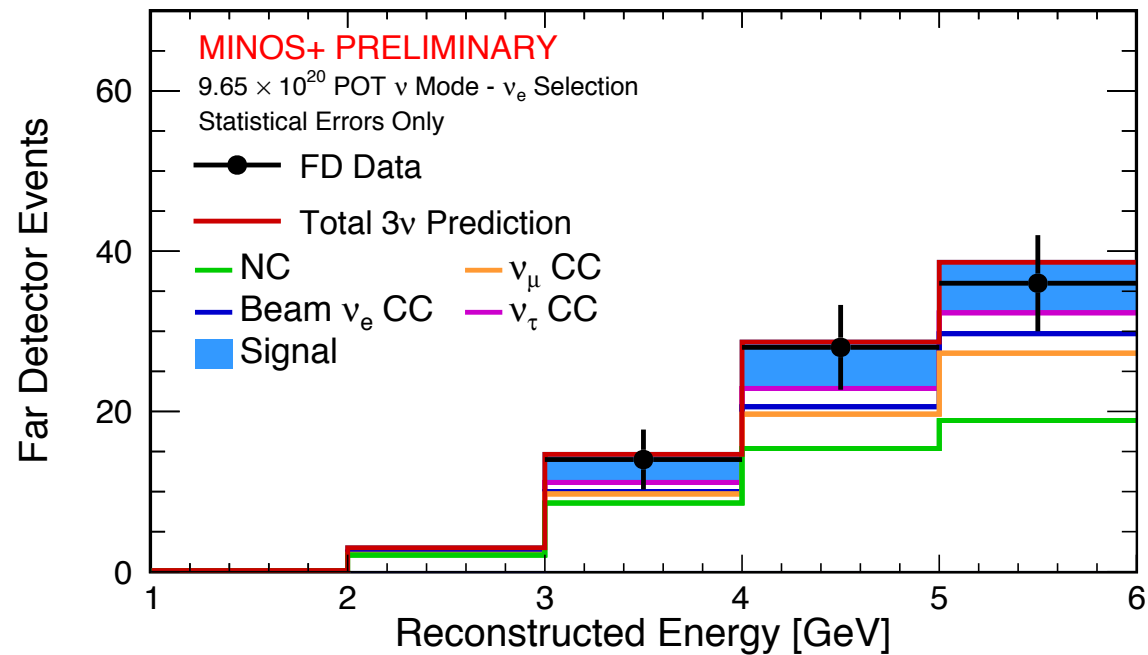


Background-like events

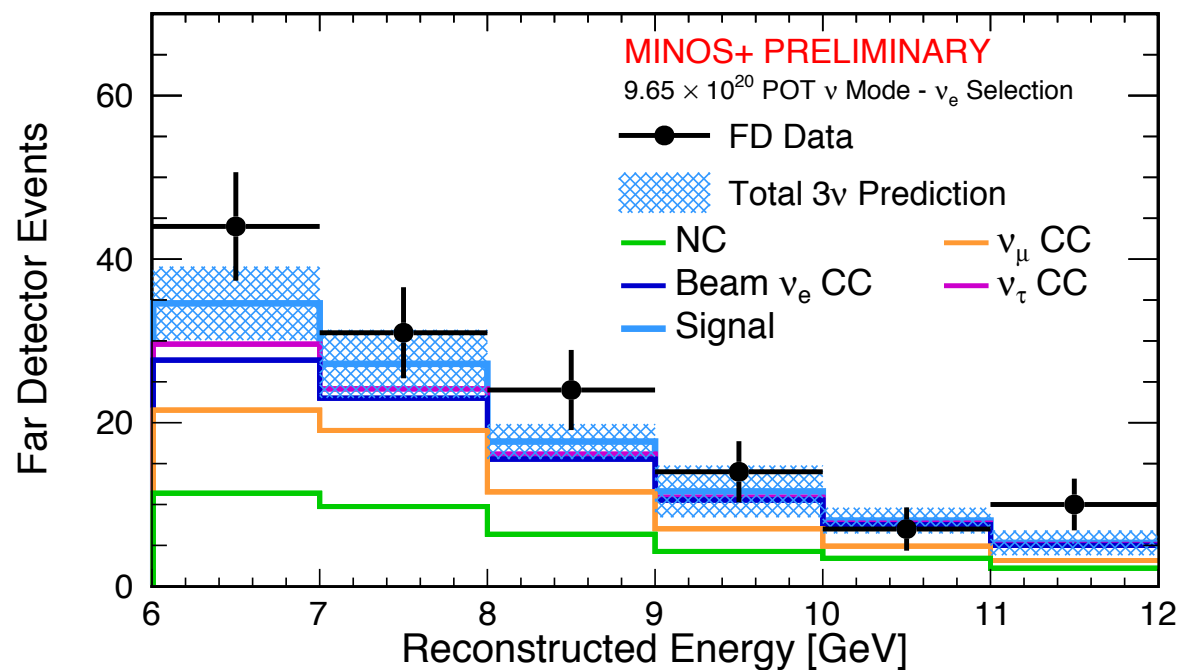
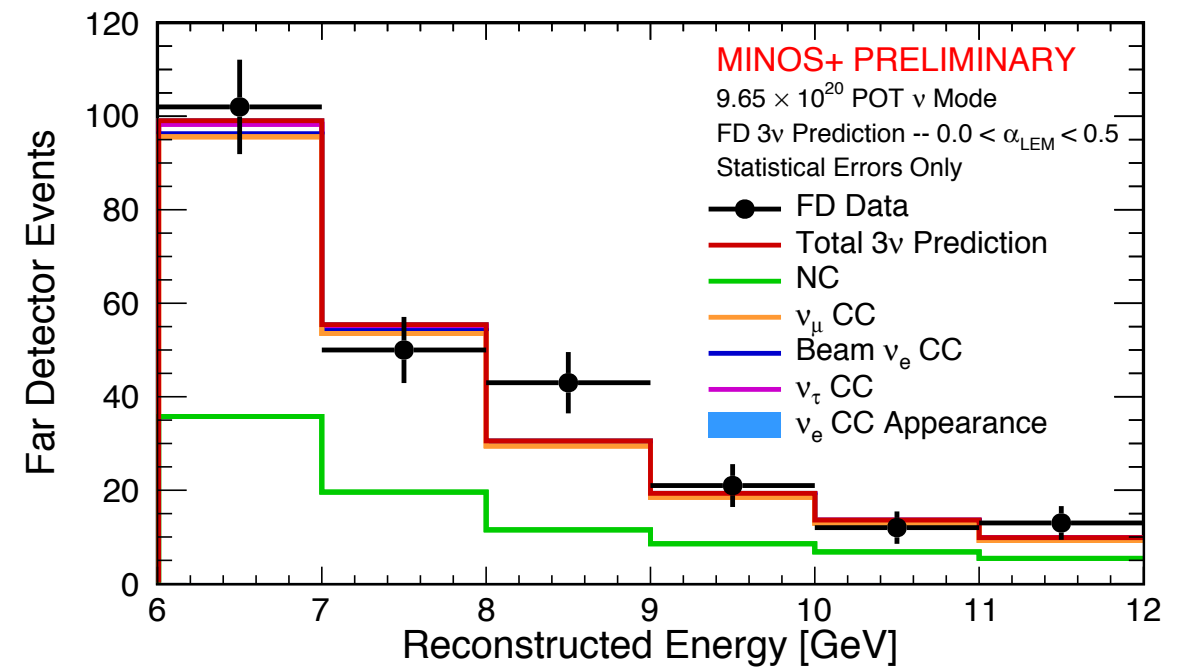


Sterile-driven ν_e and 3-flavor

ν_e Candidate events

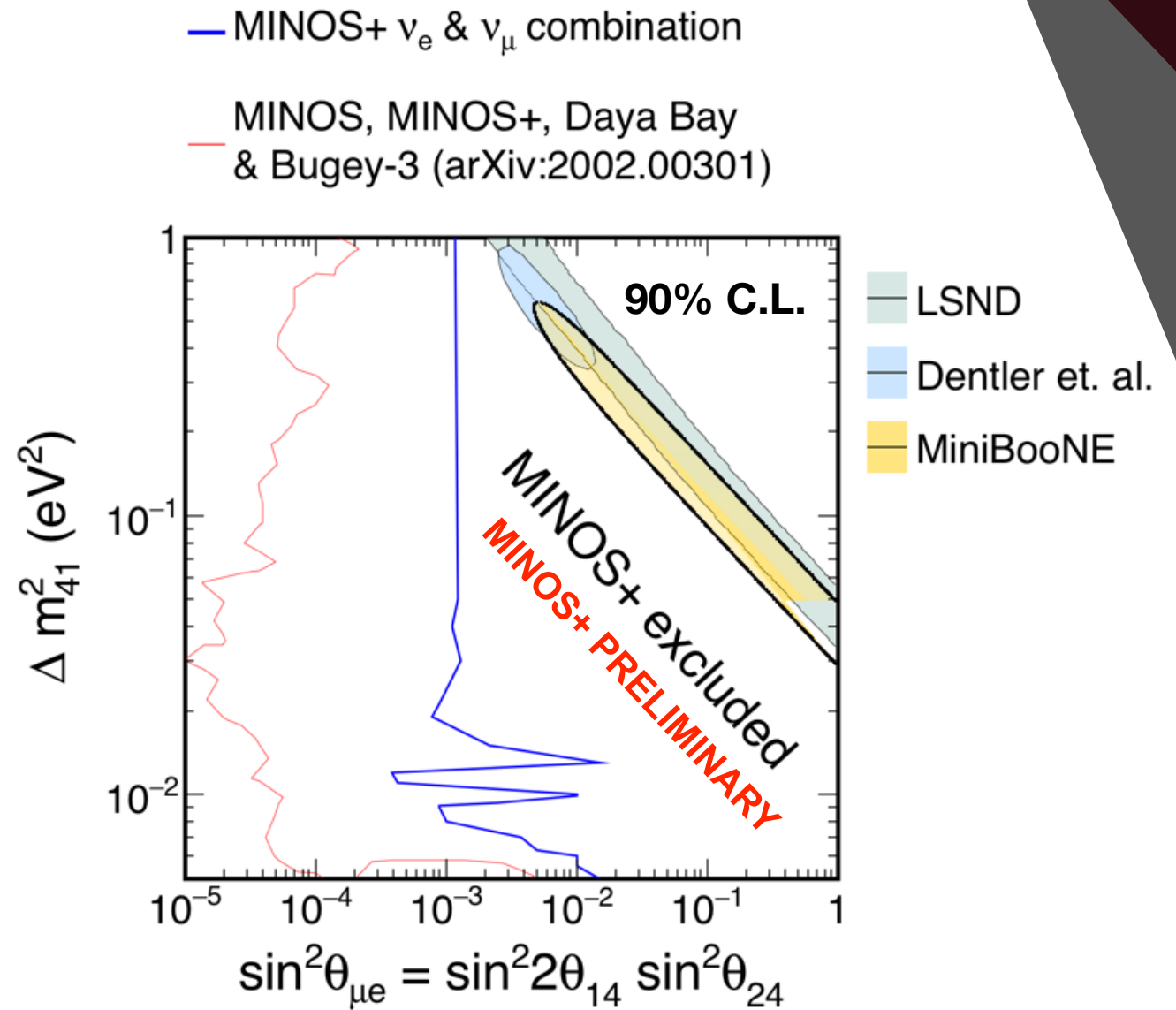
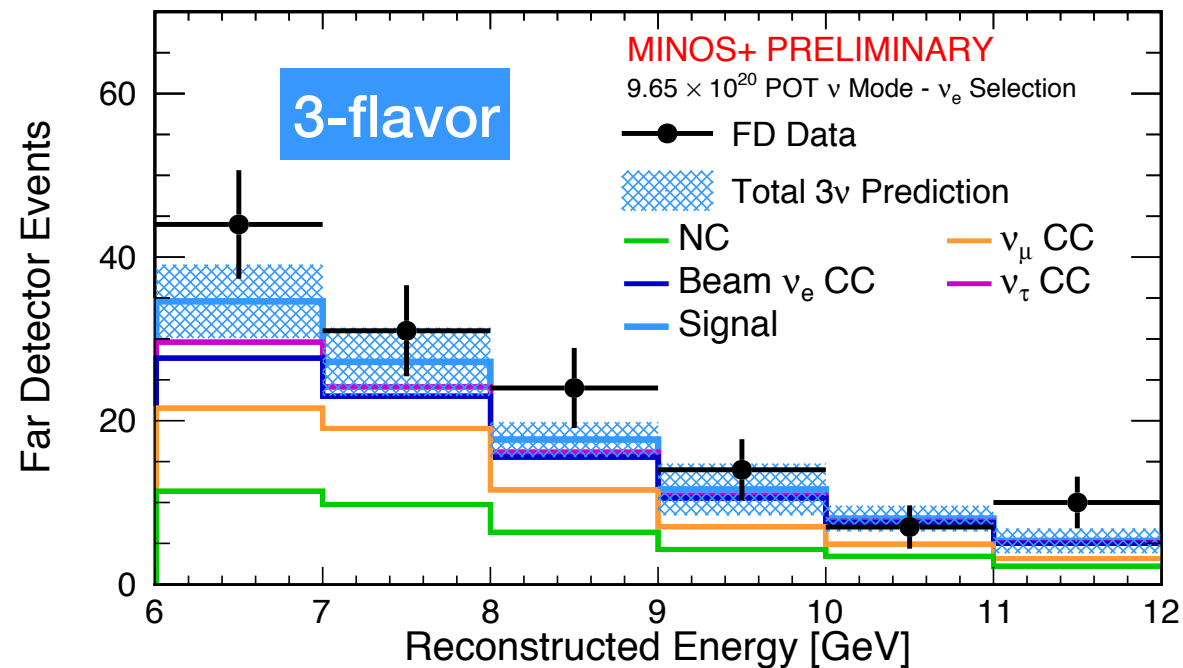
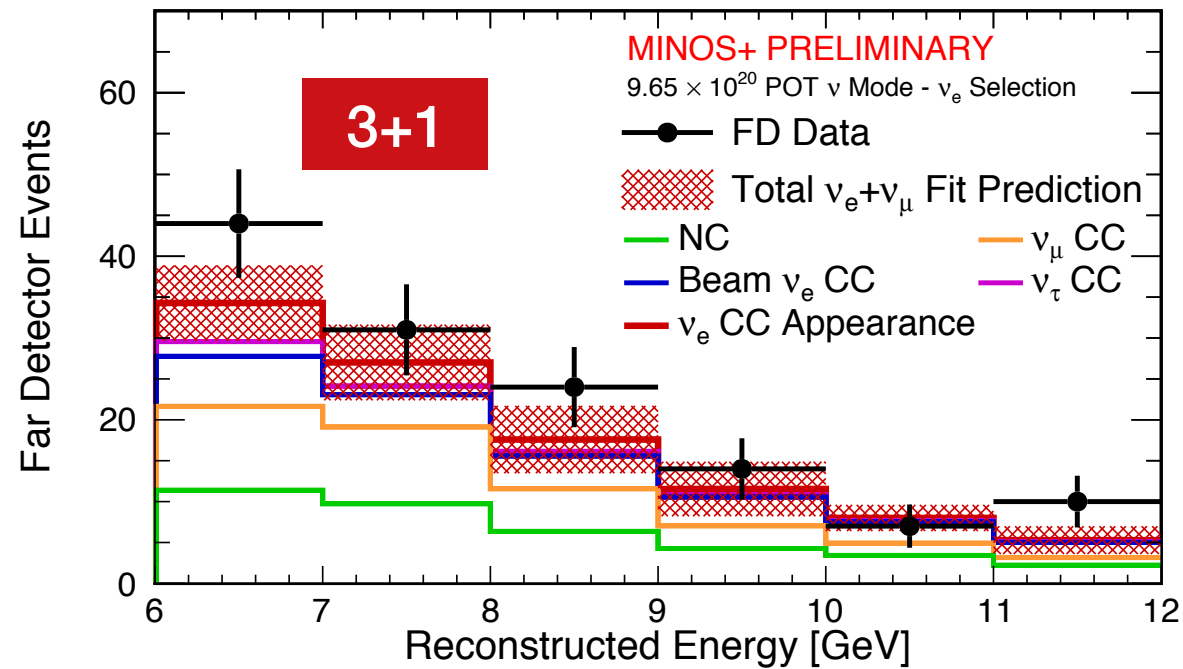


Background-like events



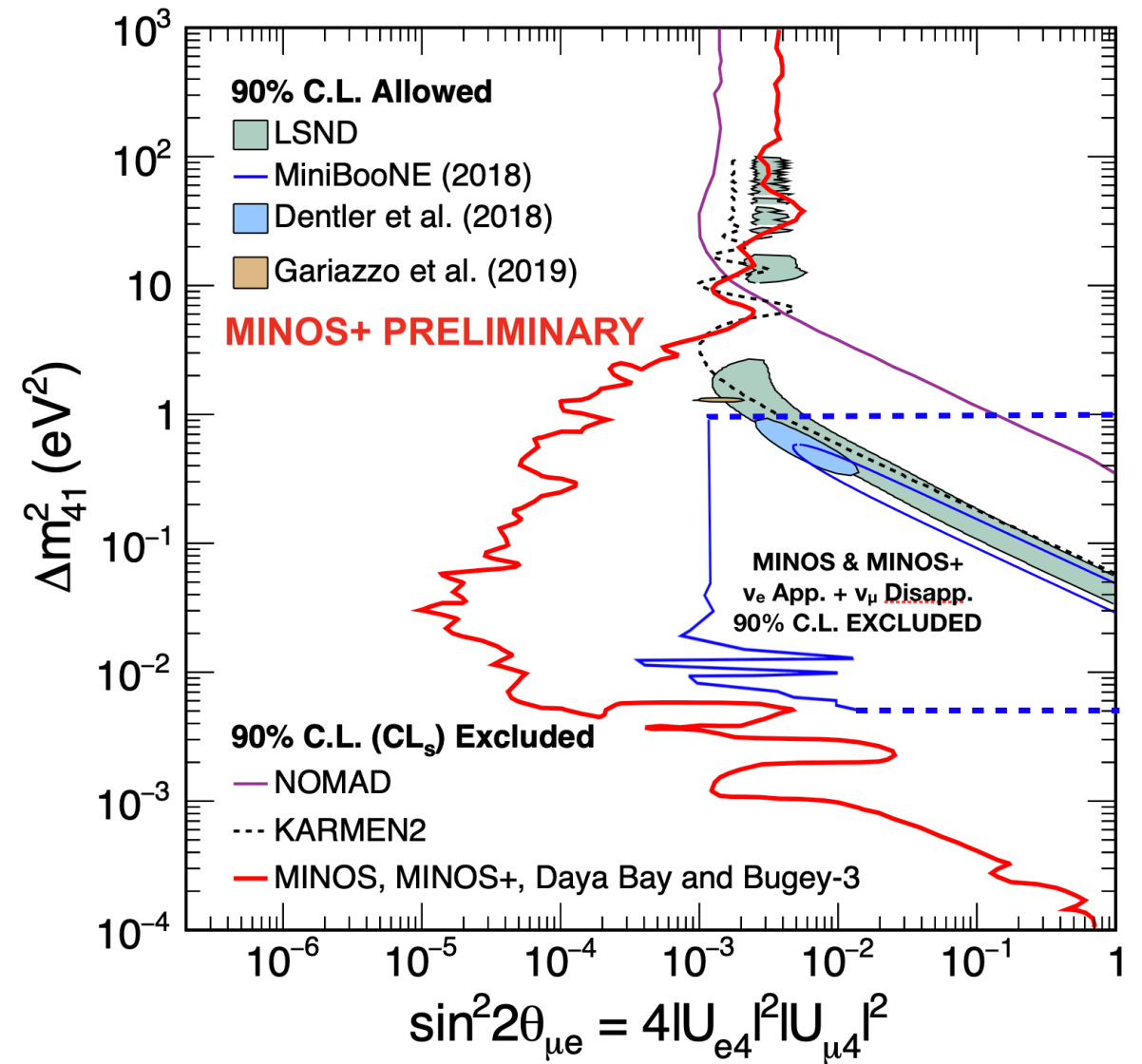
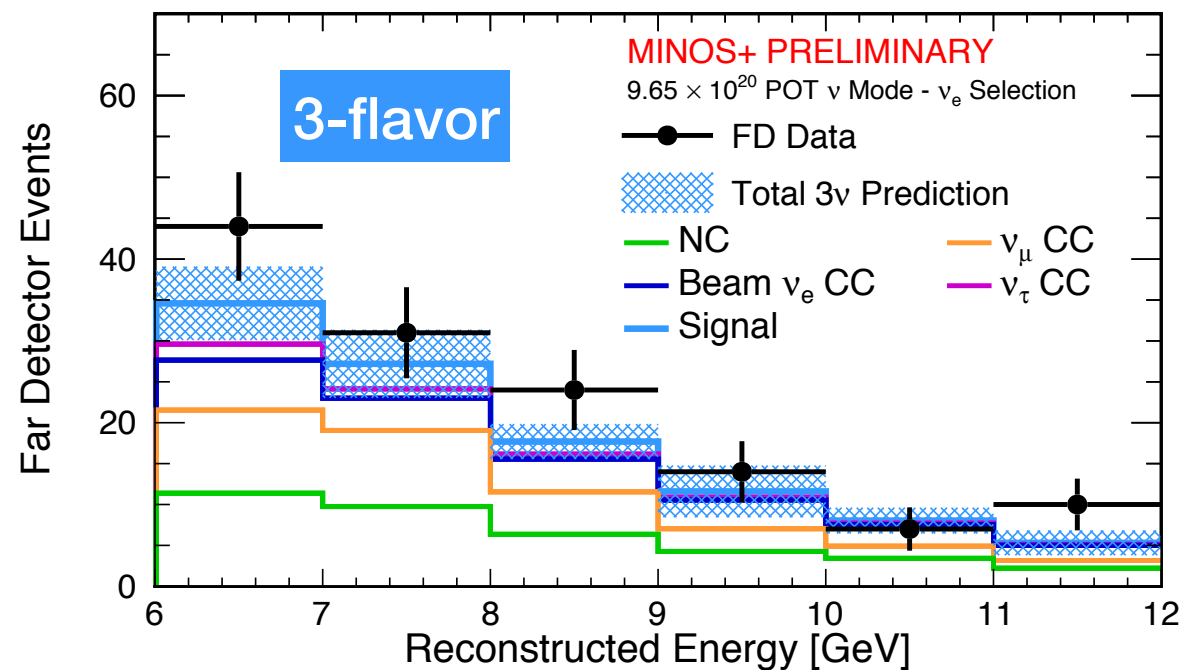
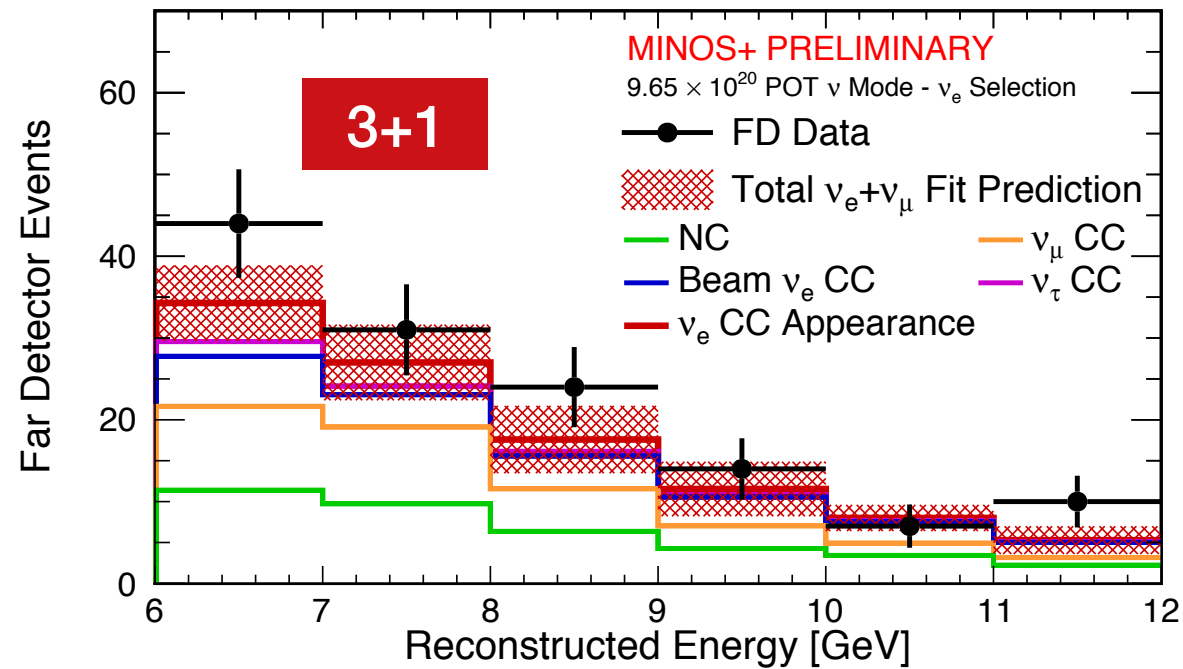
consistent with 3-flavor
oscillations

Joint $\nu_\mu + \nu_e$ sterile search



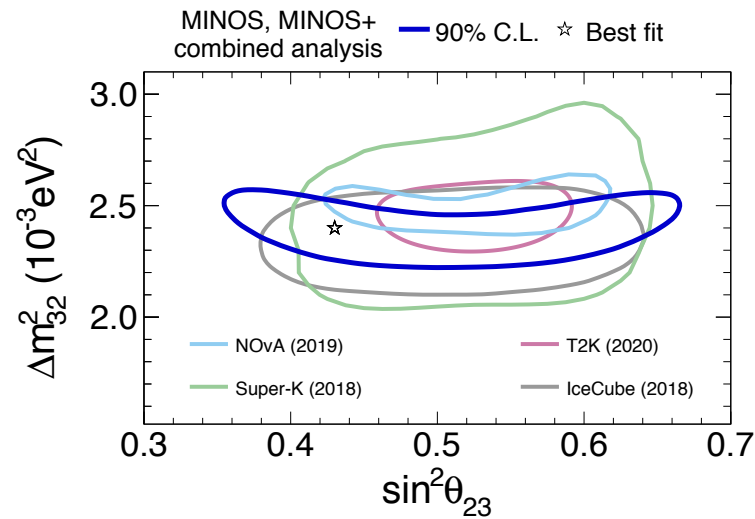
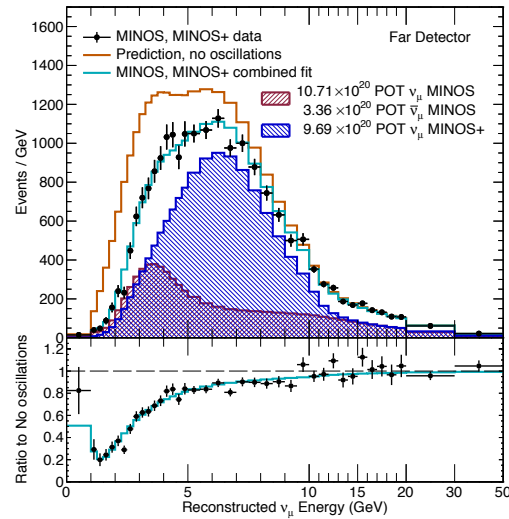
- * Complements the joint fit with Daya Bay
- * Using MINOS/MINOS+ appearance/disappearance

Joint $\nu_\mu + \nu_e$ sterile search



- * Complements the joint fit with Daya Bay
- * Using MINOS/MINOS+ appearance/disappearance

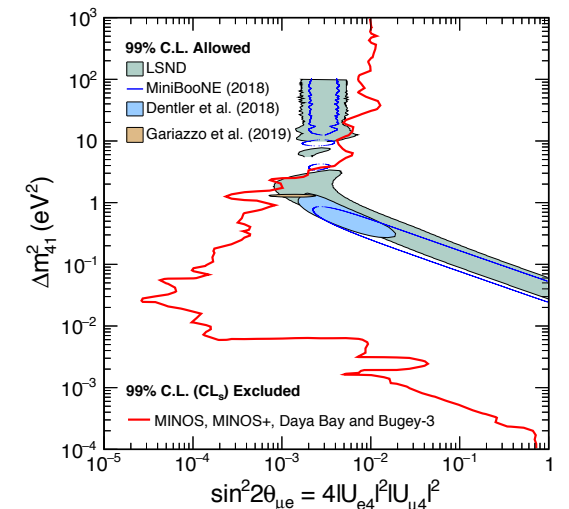
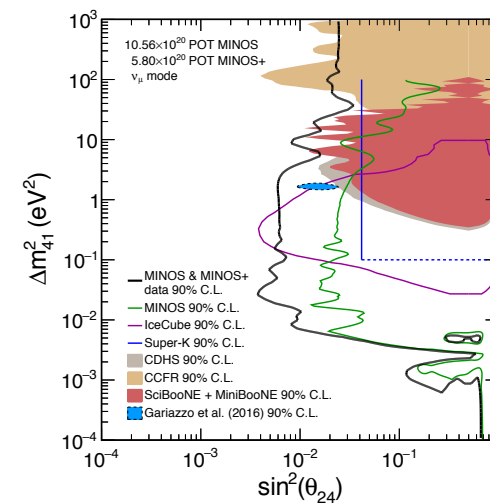
Conclusion



High stats long-baseline ν_μ disappearance:
tight constraints on 3 ν paradigm

Normal hierarchy, non-maximal mixing
 $\Delta m_{32}^2 = 2.40^{+0.08}_{-0.09} \times 10^{-3} \text{ eV}^2$
 $\sin^2 \theta_{23} = 0.43 (0.39 \leftrightarrow 0.63) \text{ 68 \% C.L.}$

High stats long-baseline ν_μ disappearance:
tight constraints on “3+1” ν paradigm
and in combination with Daya Bay and Bugey-3



Exclude large parameter space of “3+1” ν models
from MINOS/MINOS+
 ν_e appearance + ν_μ disappearance search

