Tests of three-neutrino paradigm by the MINOS and MINOS+ experiments

Our story:
+ Beams and experiments
+ Results on standard oscillations
+ Search for sterile neutrinos

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University of Texas at Austin

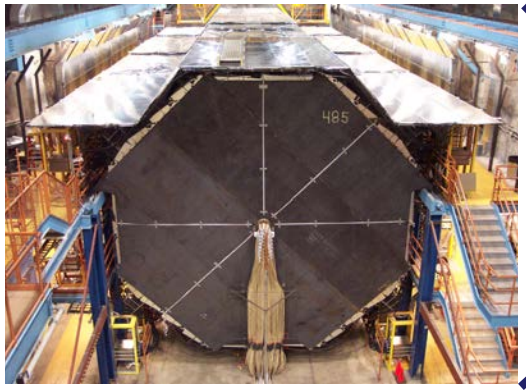
On behalf of the MINOS+ Collaboration

Conference on Neutrino and Nuclear Physics (CNNP2020)
Arabella Hotel and Spa, South Africa, 24-28 February 2020

MINOS & MINOS+

BEAMS AND DETECTORS

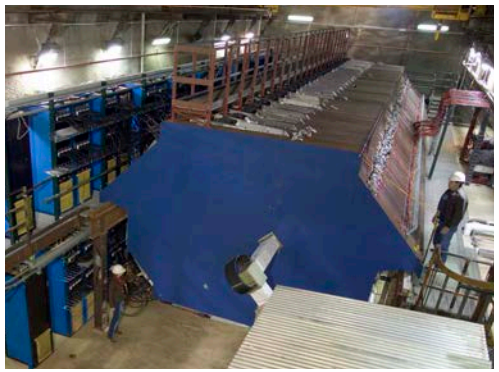
MINOS, MINOS+, and NuMI



- Far Detector (FD) on axis
- 735 km from target
- 5.4 kt, 8m octagon
- ~1.2 T B field
- Segmented, sampling, iron/scint. tracking calorimeter

- MINOS Proposed 1995
- Main Injector 2000
- Beam data 2005-2012
- NuMI reconfigured for NOvA 2013
- MINOS+ 2013-2016

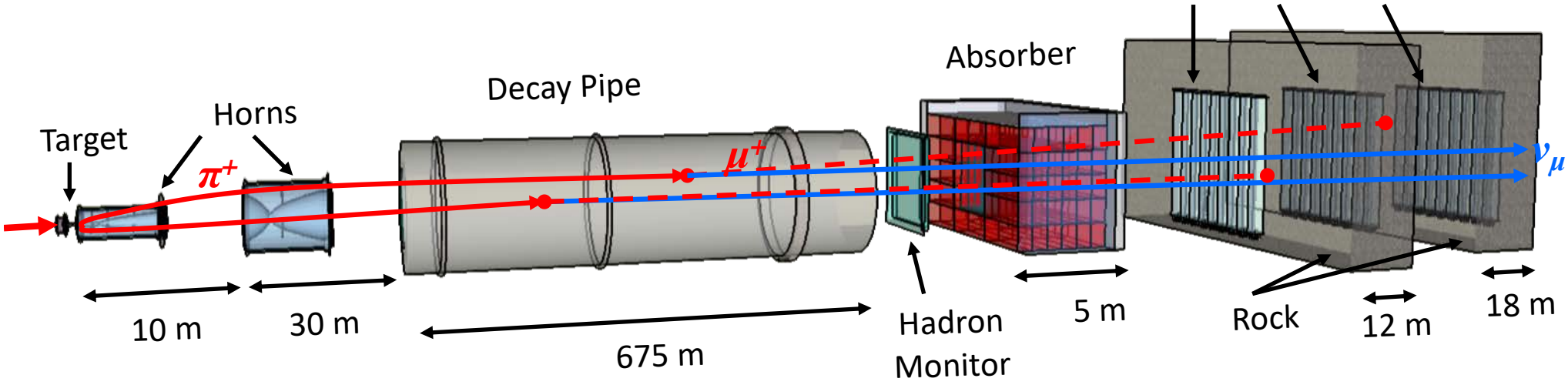
- Near Detector (ND) on axis
- 1,040 m from target
- 1kt, 4m `squeezed' octagon
- ~1.2 T B field
- Same technology as FD

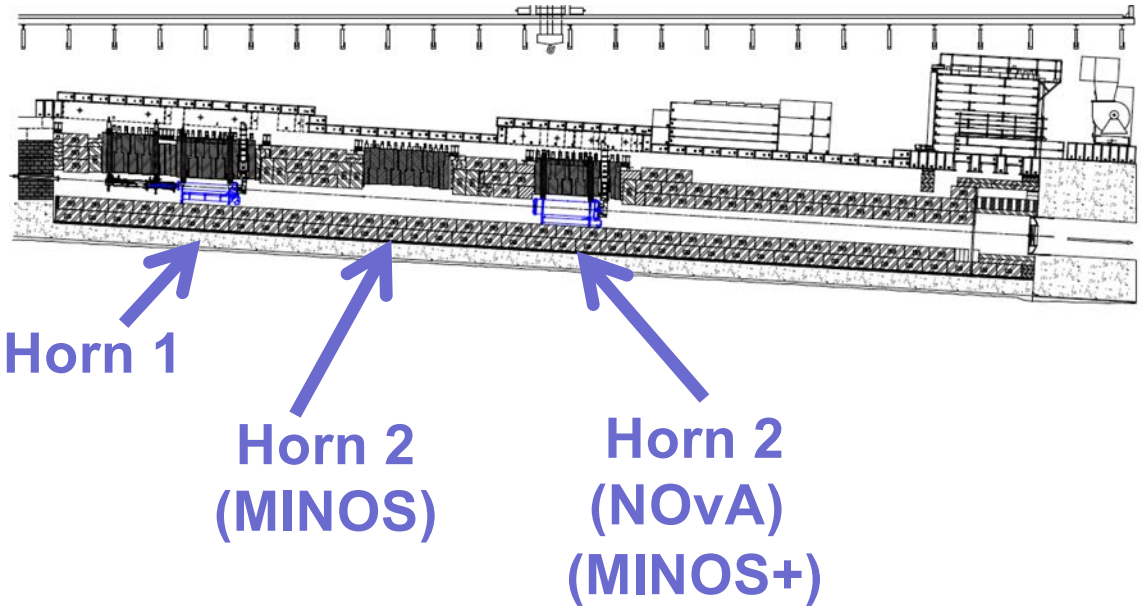


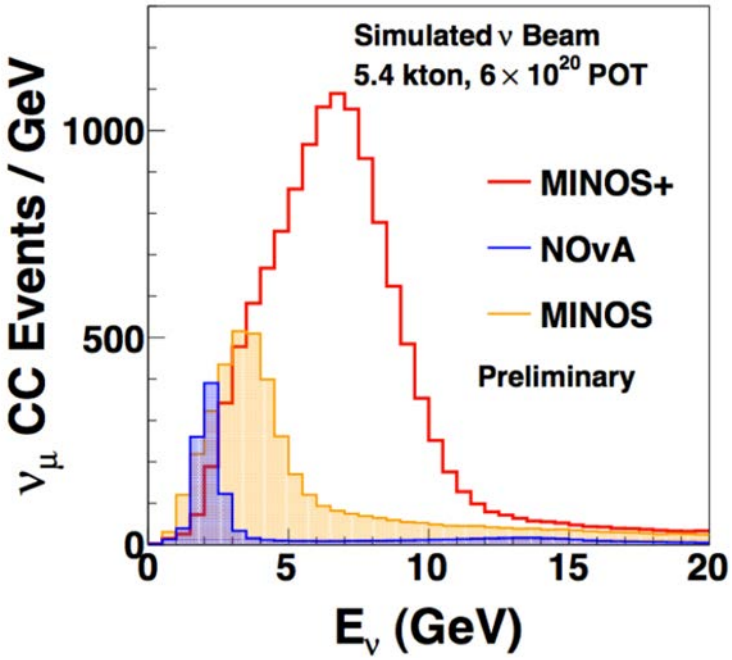
- 2-horn focusing 185 kA
- 2λ graphite target (movable)
- Up to ~600 kW beam
- 3.5×10^{13} ppp
- 1.33 s cycle time

NuMI Neutrino Beams

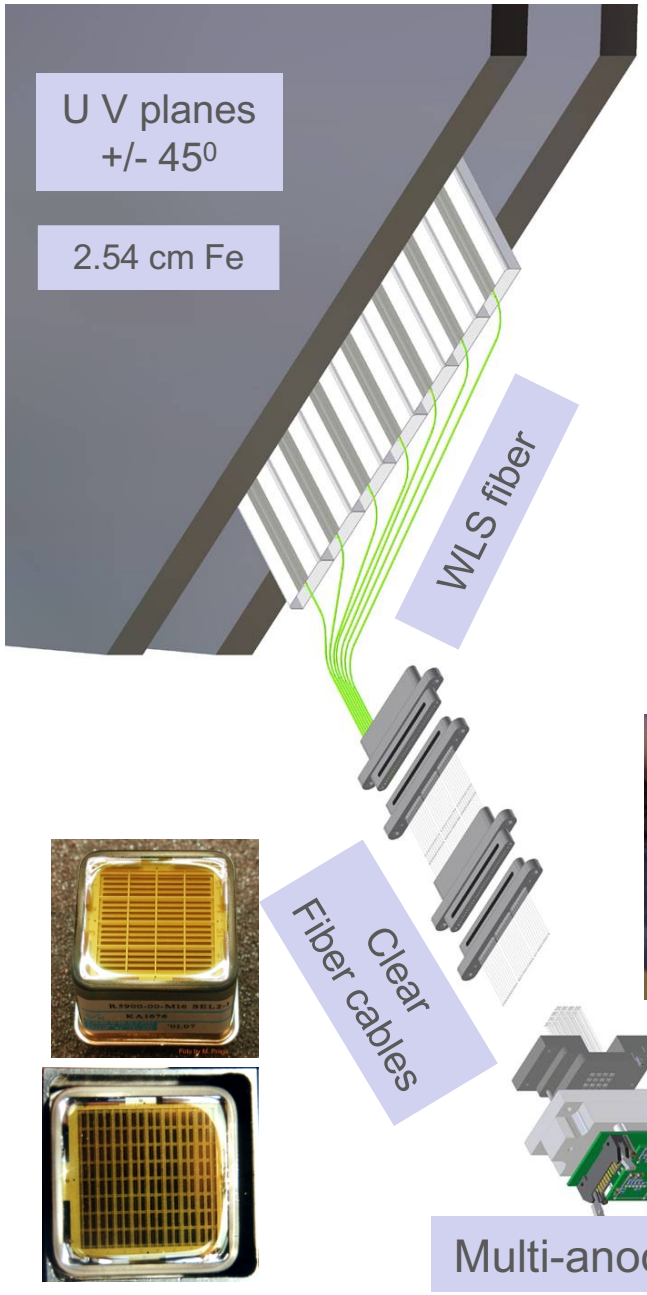
(Neutrinos from the Main Injector)

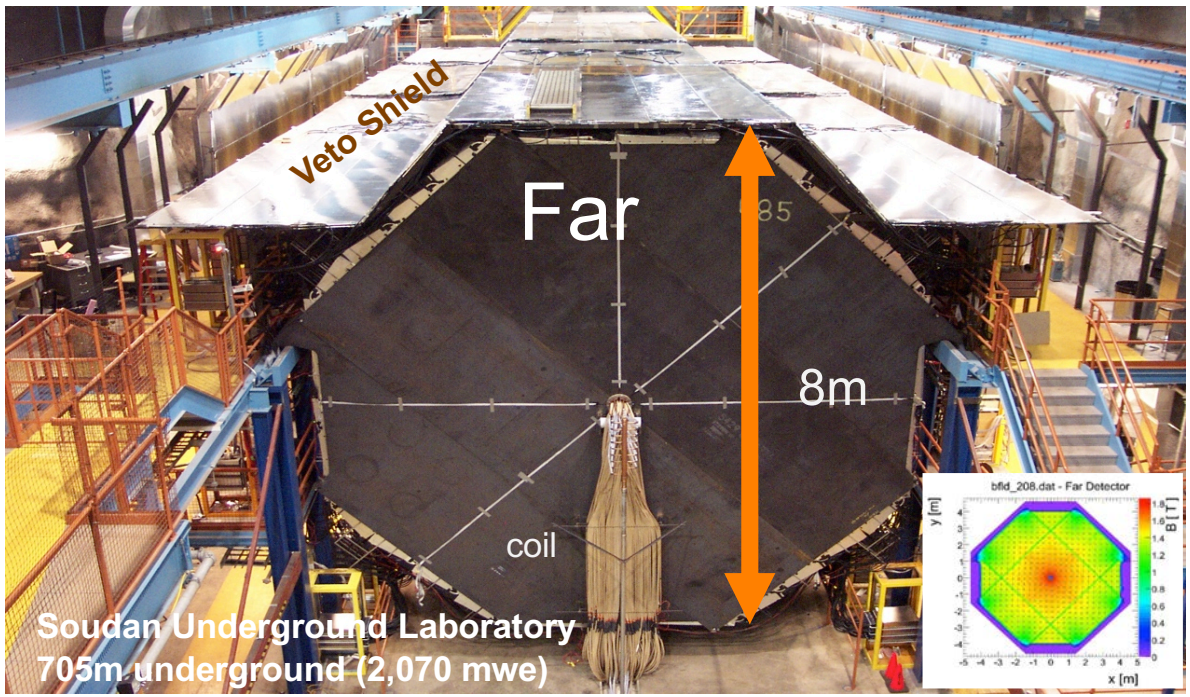


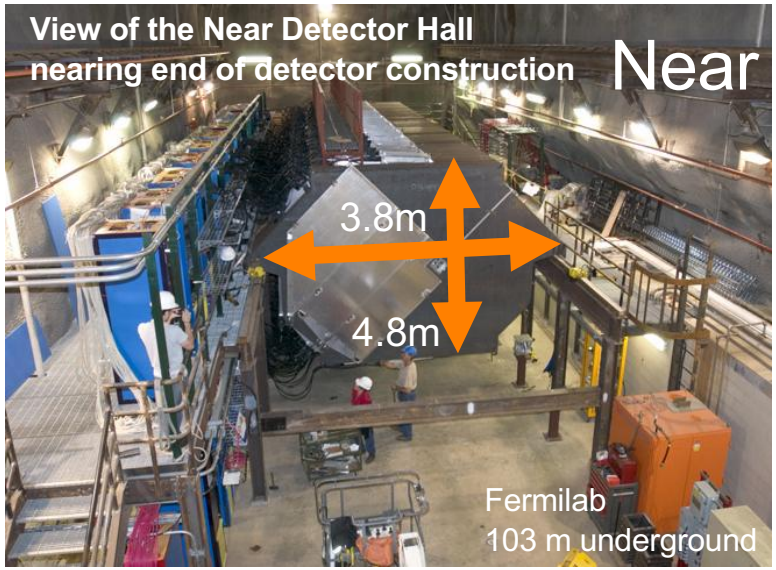




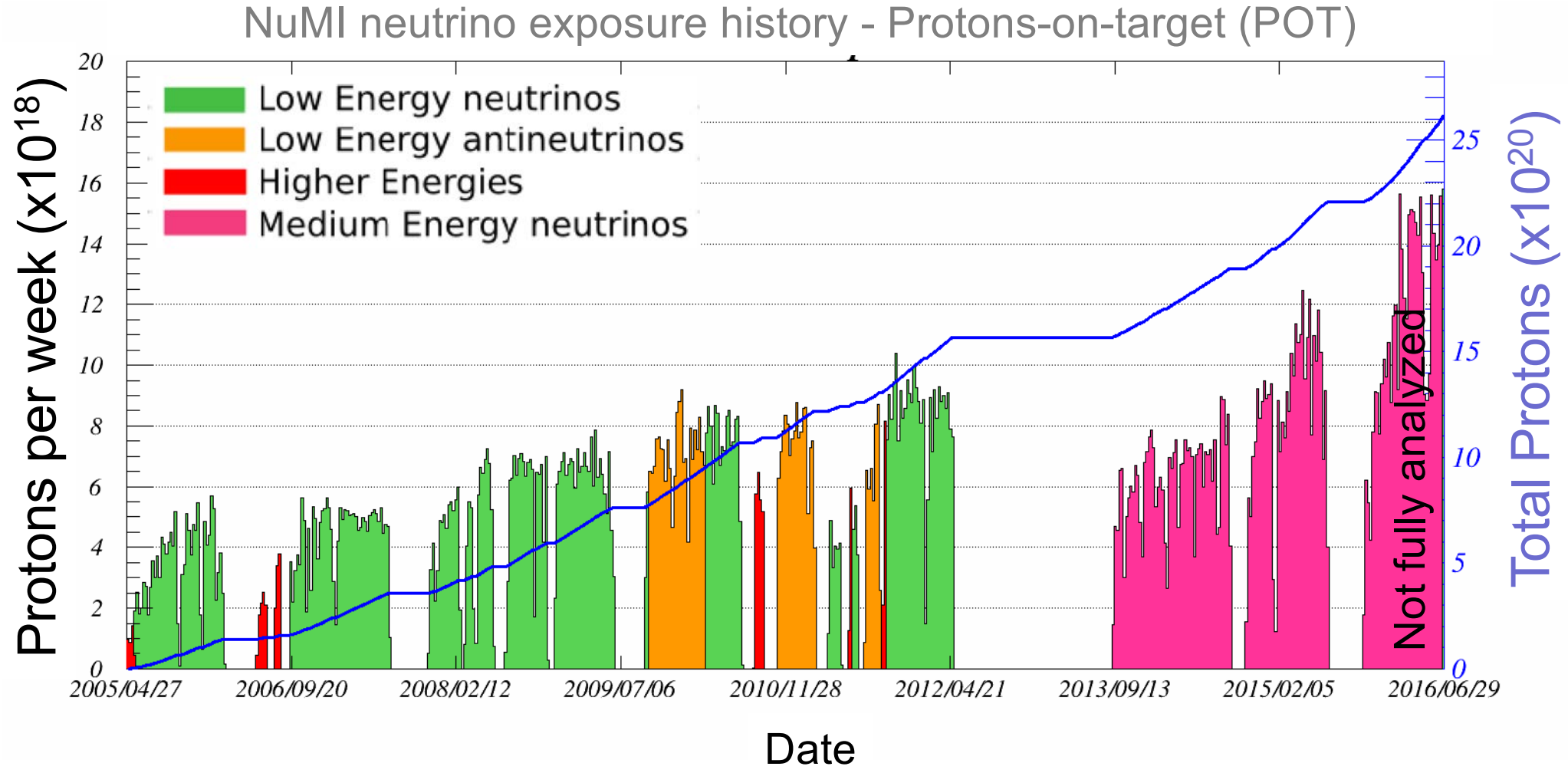
MINOS: Near and Far Detectors







MINOS and MINOS+ exposures
2005 → 2016



MINOS (2005-2012)

10.56x10^20 POT

3.36x10^20 POT

MINOS+ (2013-2016)

9.69x10^20 POT

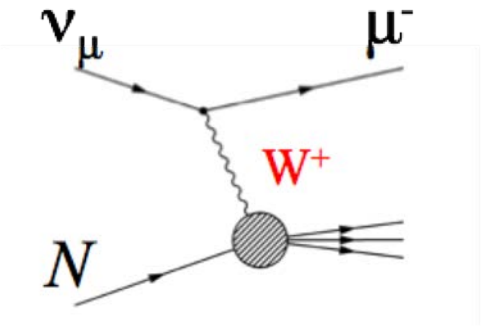
(5.80 x10^20 POT in "sterile analysis)

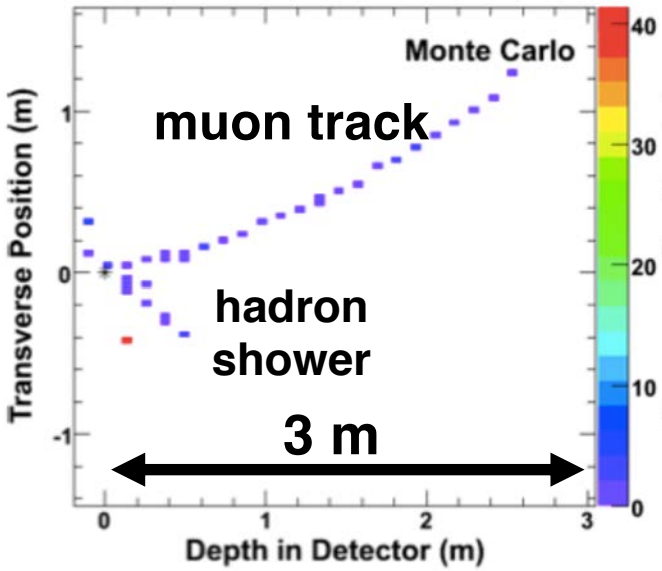
MINOS & MINOS+

STANDARD OSCILLATIONS

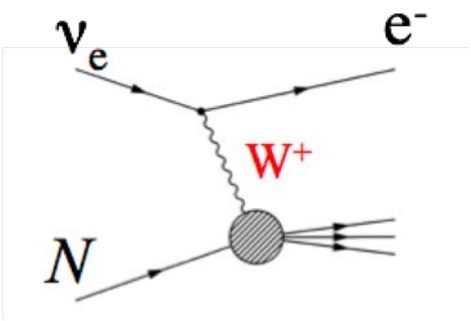
Event types in MINOS

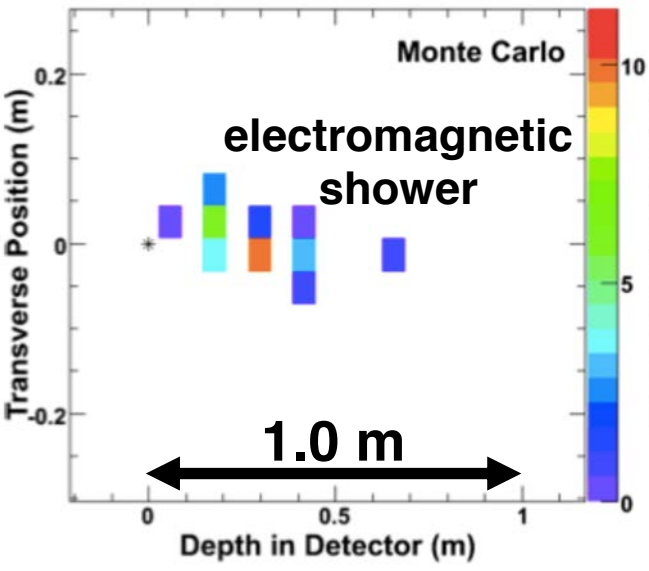
ν_μ Charged Current (ν_μ CC)



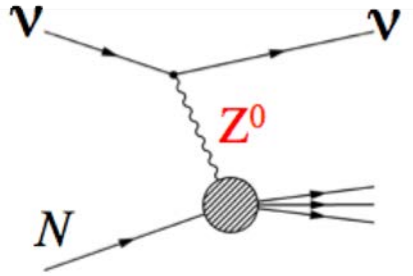


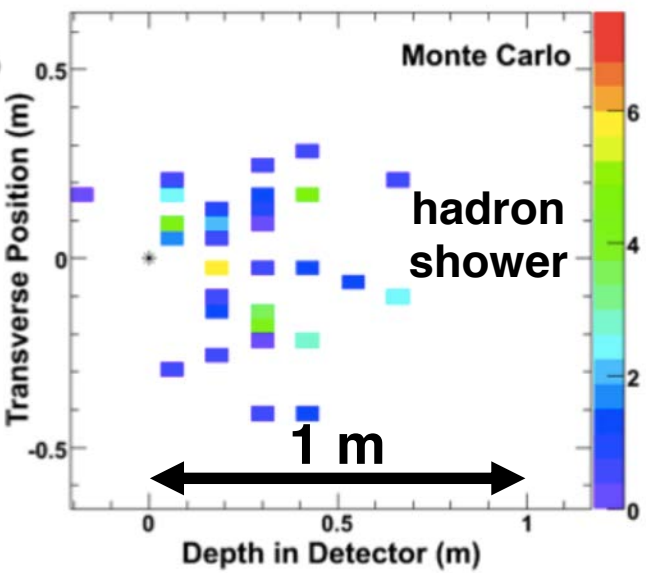
ν_e Charged Current (ν_e CC)





ν_x Neutral Current (NC)

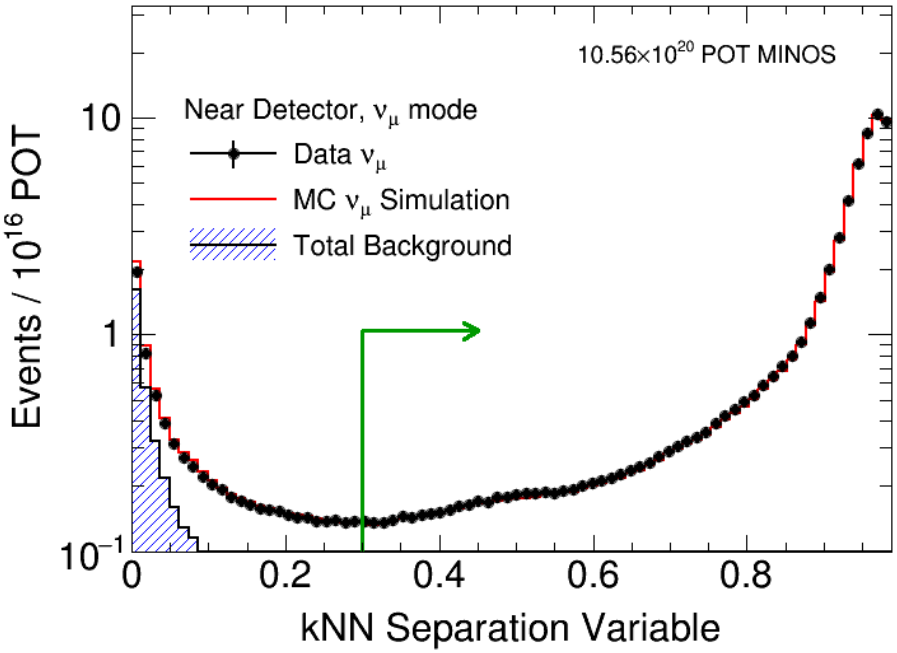




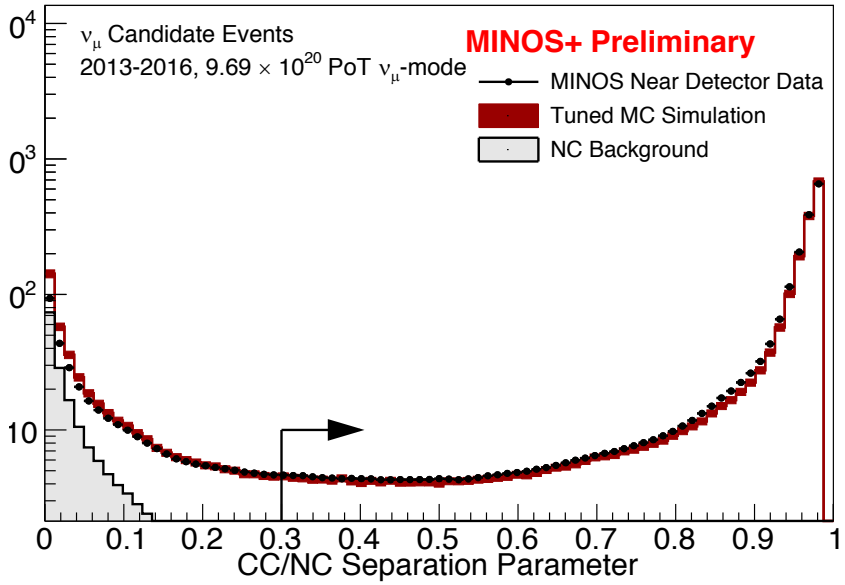
MINOS and MINOS+
Charged current **(CC)** vs Neutral current **(NC)** classification

Event classification:
k Nearest-Neighbors (kNN)

MINOS



MINOS+

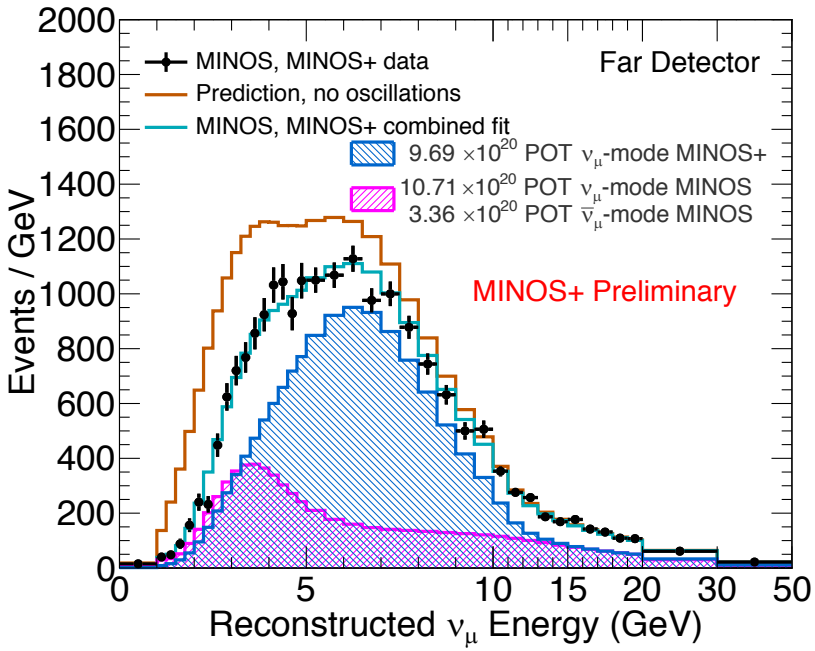


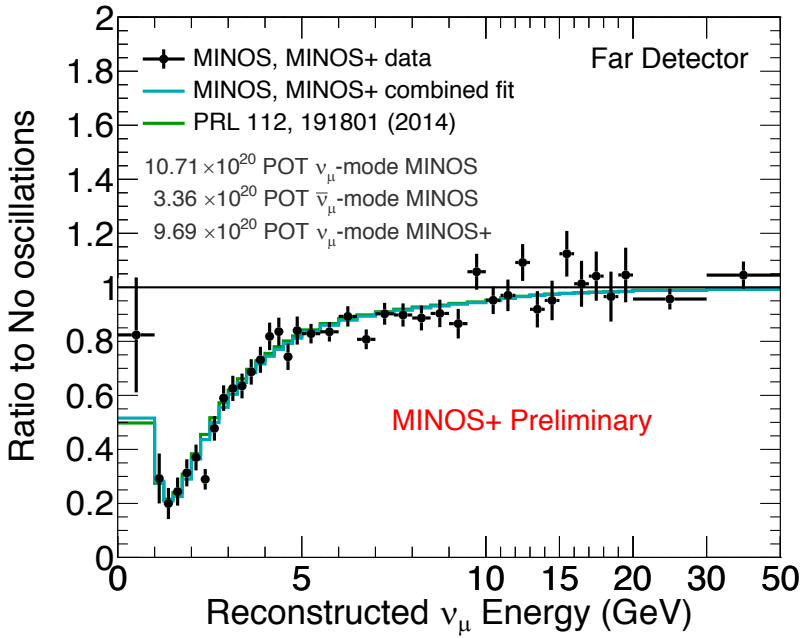
MINOS+ Far Detector (complete data set)

efficiency 84.2%

purity 99.3%

MINOS & MINOS+
Standard Oscillations Results (complete data set)





Best fits and uncertainties 68% C.L.

Normal

$$\Delta m^2_{32} = +2.41\ ^{+0.08}_{-0.08} \quad (\times 10^{-3} eV^2)$$

$$sin^2\theta_{23} = 0.42 \ \ (0.38 \leftrightarrow 0.48)$$

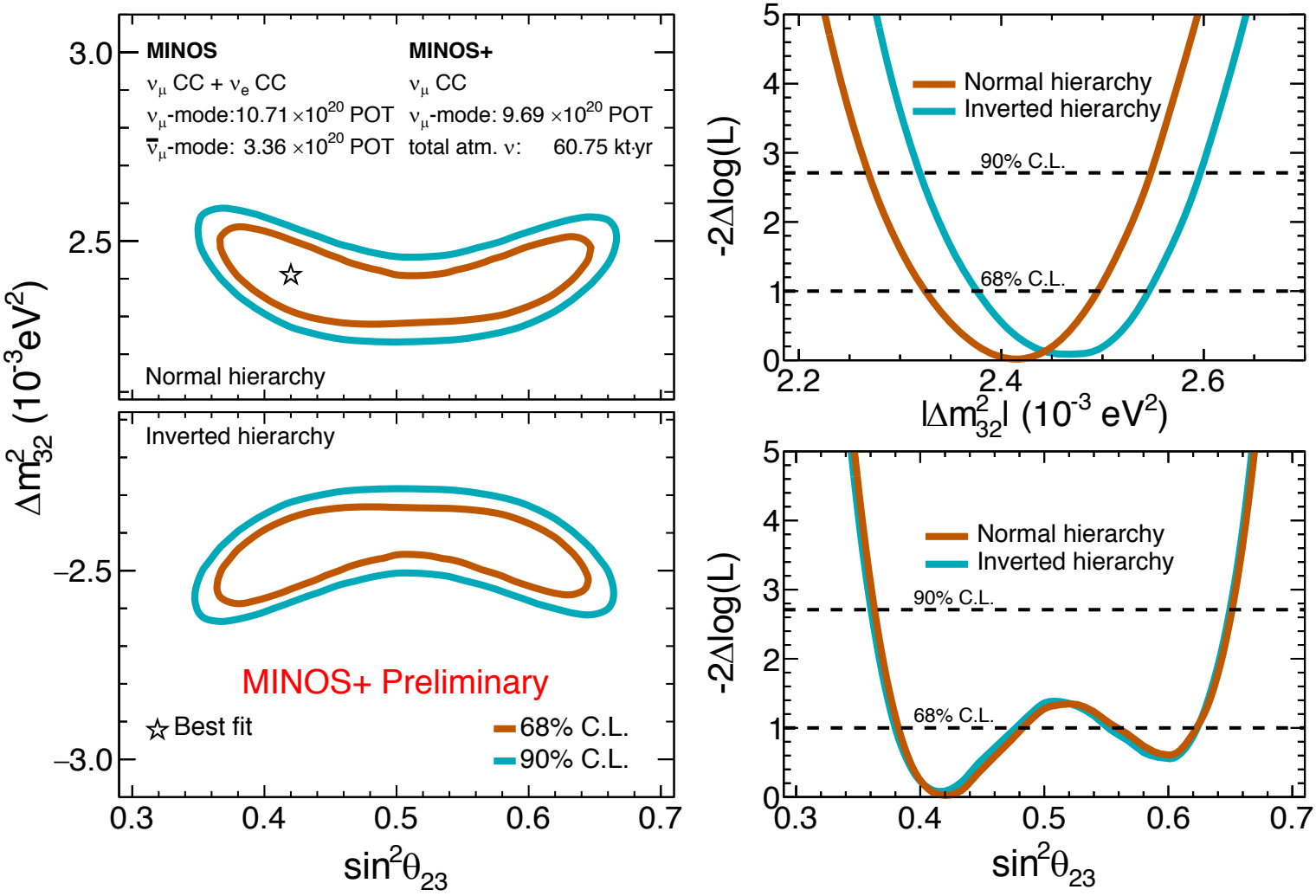
Inverted

$$\Delta m^2_{32} = -2.47\ ^{+0.09}_{-0.07} \quad (\times 10^{-3} eV^2)$$

$$sin^2\theta_{23} = 0.42 \ \ (0.38 \leftrightarrow 0.48)$$

No. of data events	Beam ν_μ	Beam $\bar{\nu}_\mu$	Beam ν_e	Beam $\bar{\nu}_e$	Atmospheric
MINOS (2005-2012)	2579	538	152	20	2072
MINOS+ (2013-2016)	6280	293	-	-	1165

MINOS contours bounds
(complete data set)



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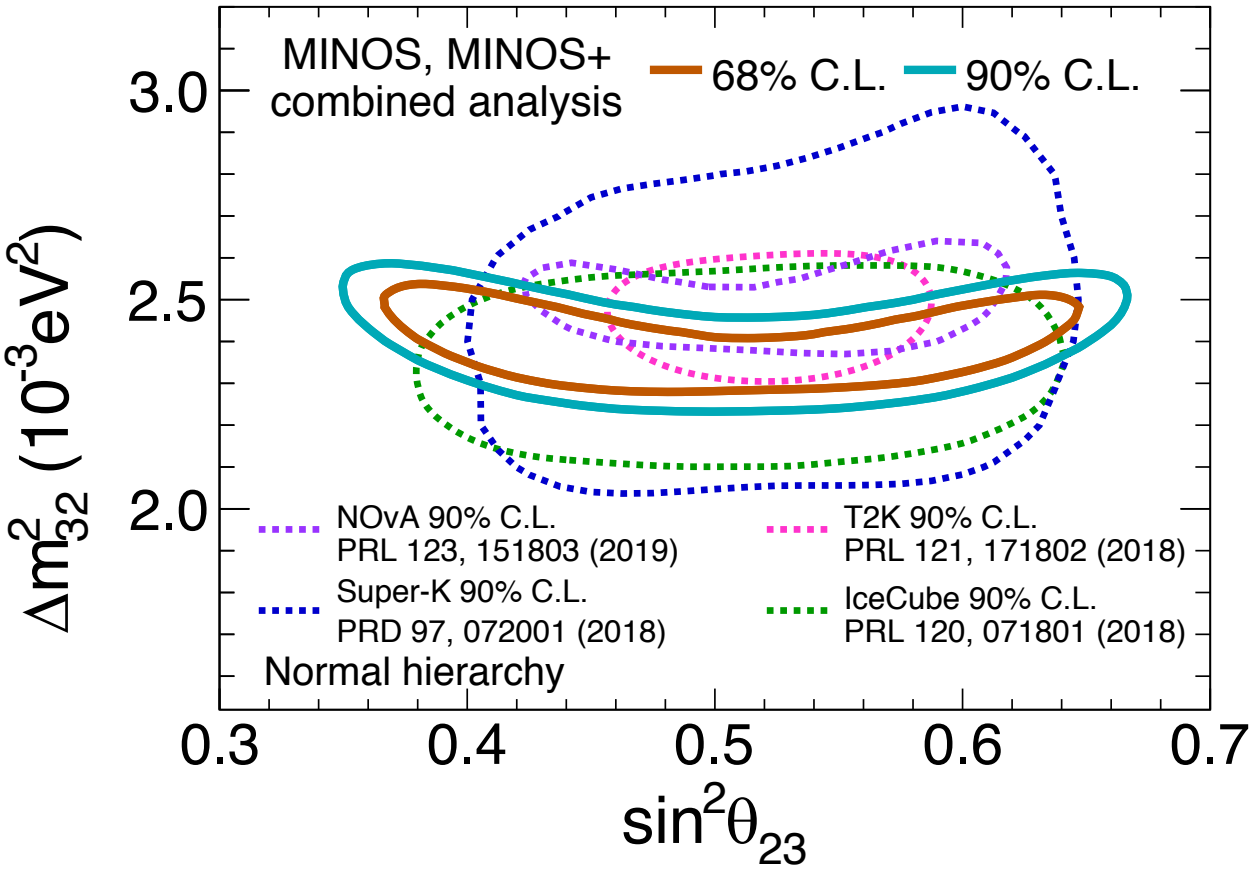
Compare to other experiments:

NOvA, T2K, Super-K, IceCube



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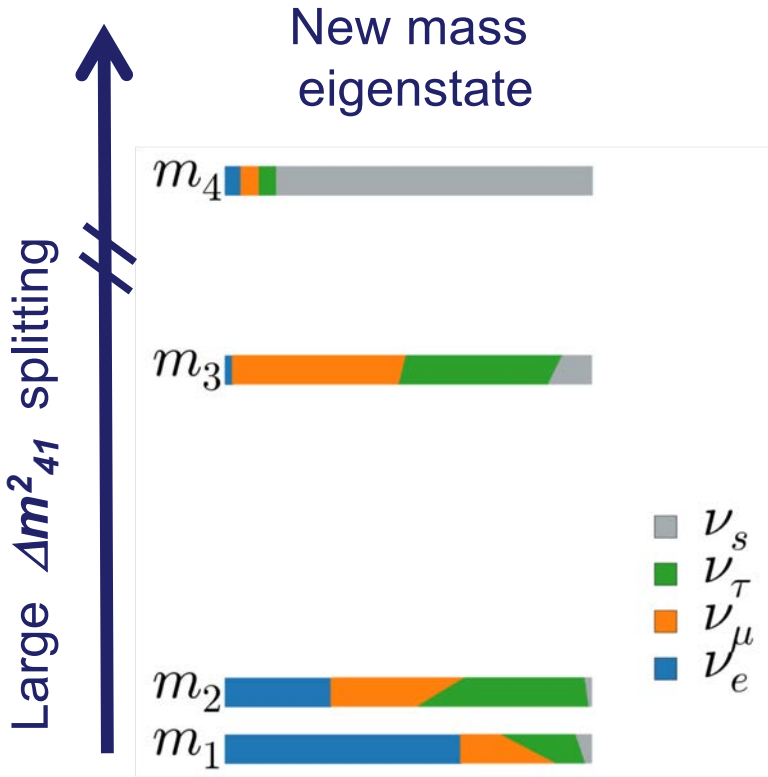
	$sin^2\theta_{23} = 0.42\ (0.38 \leftrightarrow 0.48)$		$sin^2\theta_{23} = 0.42\ (0.38 \leftrightarrow 0.48)$

MINOS & MINOS+

ARE THERE MORE NEUTRINOS?
→SEARCH FOR STERILE NEUTRINOS

The “3+1” mixing

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

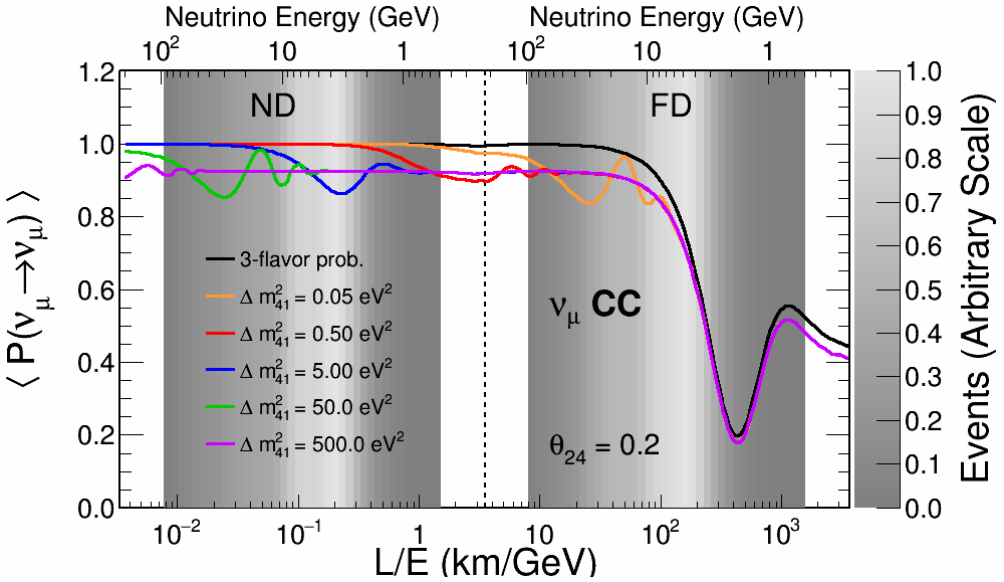


- ”3+1” oscillation parameters:
  - ⇨ 3 mass scales: Δm^2_{21}, Δm^2_{32}, Δm^2_{41}
  - ⇨ 6 mixing angles: θ_{12}, θ_{23}, θ_{13}, θ_{14}, θ_{24}, θ_{34}
  - ⇨ 3 CP-violating phases: δ_{13}, δ_{14}, δ_{24}

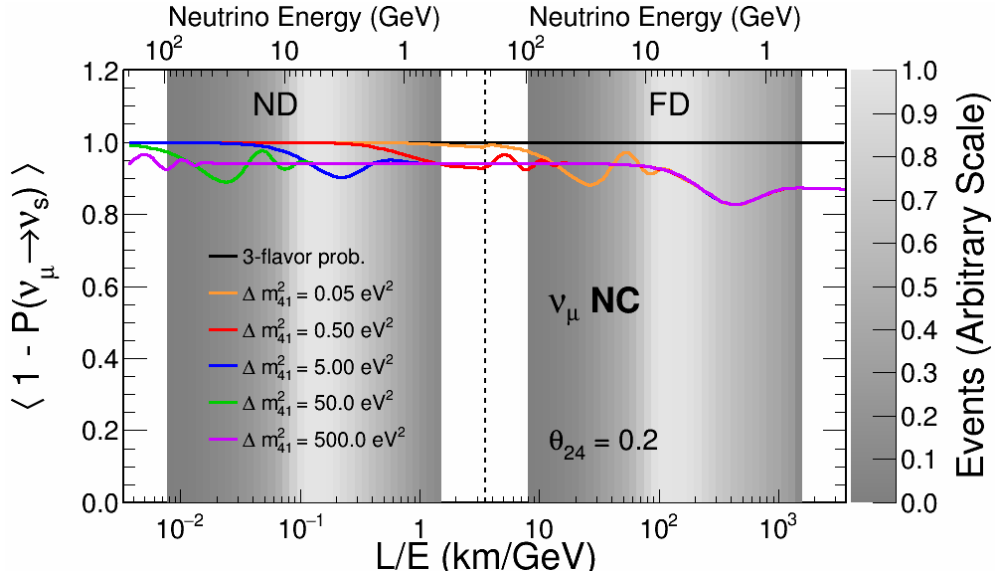
4-flavor oscillations in MINOS & MINOS+

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \cos 2\theta_{24} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) - \sin^2 2\theta_{24} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right).$$

Charged current: $P(\nu_\mu \to \nu_\mu)$



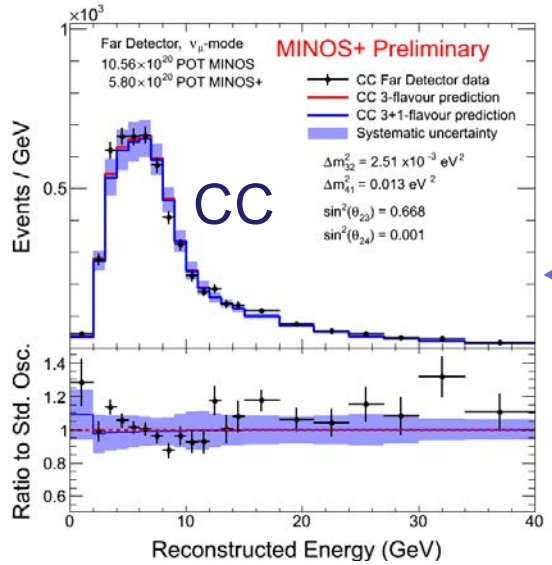
Neutral current: $1 - P(\nu_\mu \to \nu_s)$



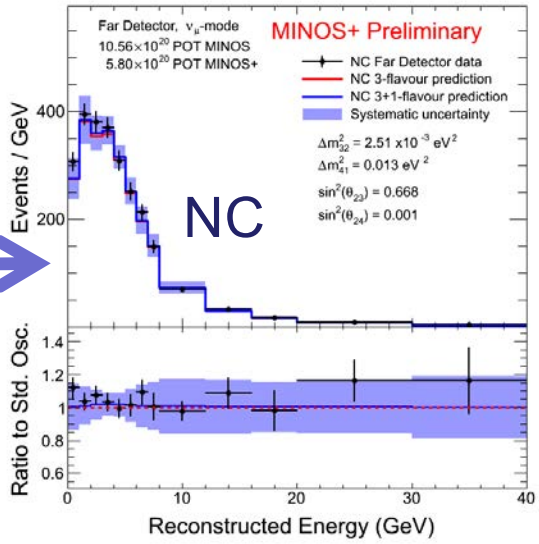
- Fit the CC and NC spectra simultaneously to determine θ_{23}, θ_{24}, θ_{34}, Δm^2_{32}, and Δm^2_{41}
- Fix δ_{13}, δ_{14}, δ_{24}, and $\theta_{14} = 0$ (insensitive to these terms)

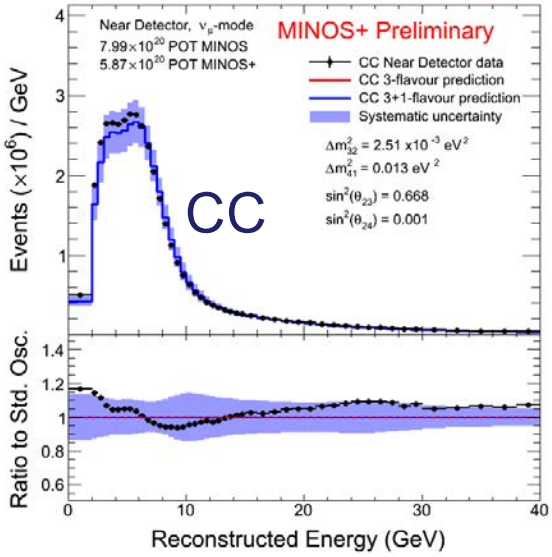
Sterile Search - new method – two-detector fit

- Far and Near Detectors, CC and NC energy spectra directly rather than their ratios
- Systematics through the covariance matrix

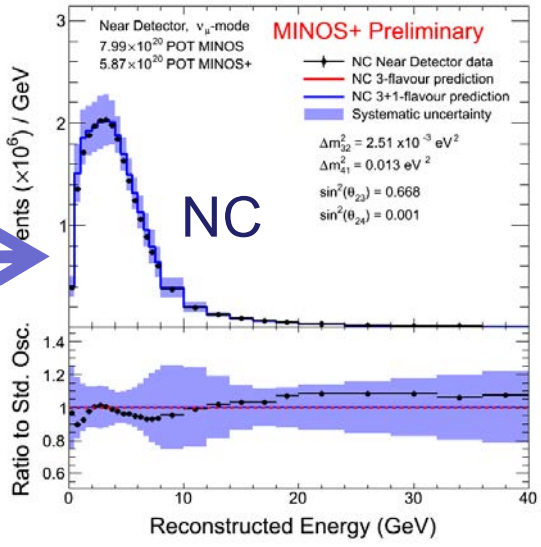


Far Det.





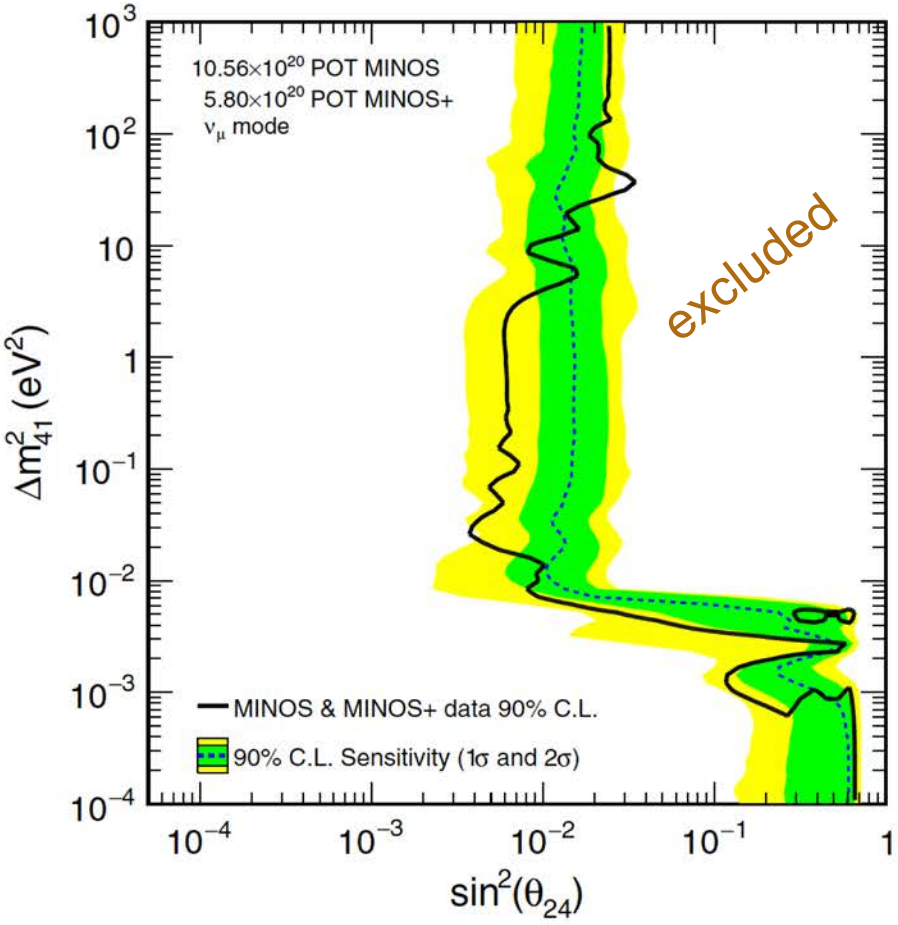
Near Det.



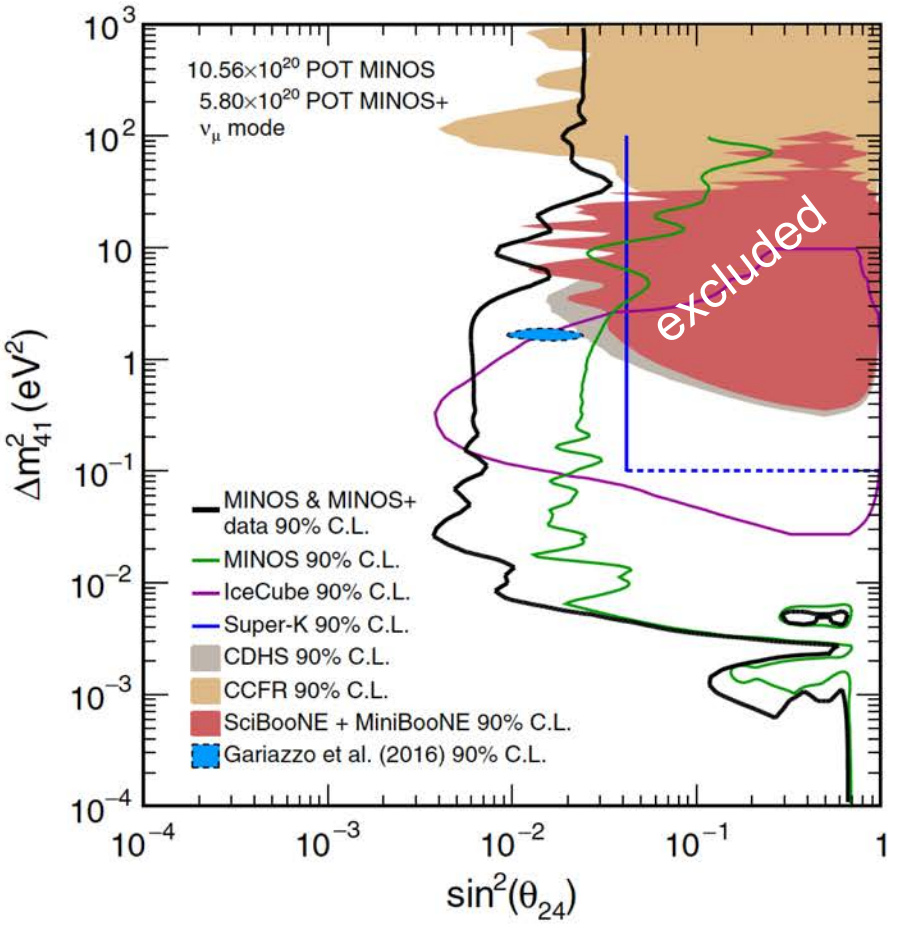
MINOS and MINOS+ constraints on Δm^2_{41} – $\sin^2\theta_{24}$

P. Adamson *et al.,* PRL 122, 091803 (2019)

MINOS & MINOS+

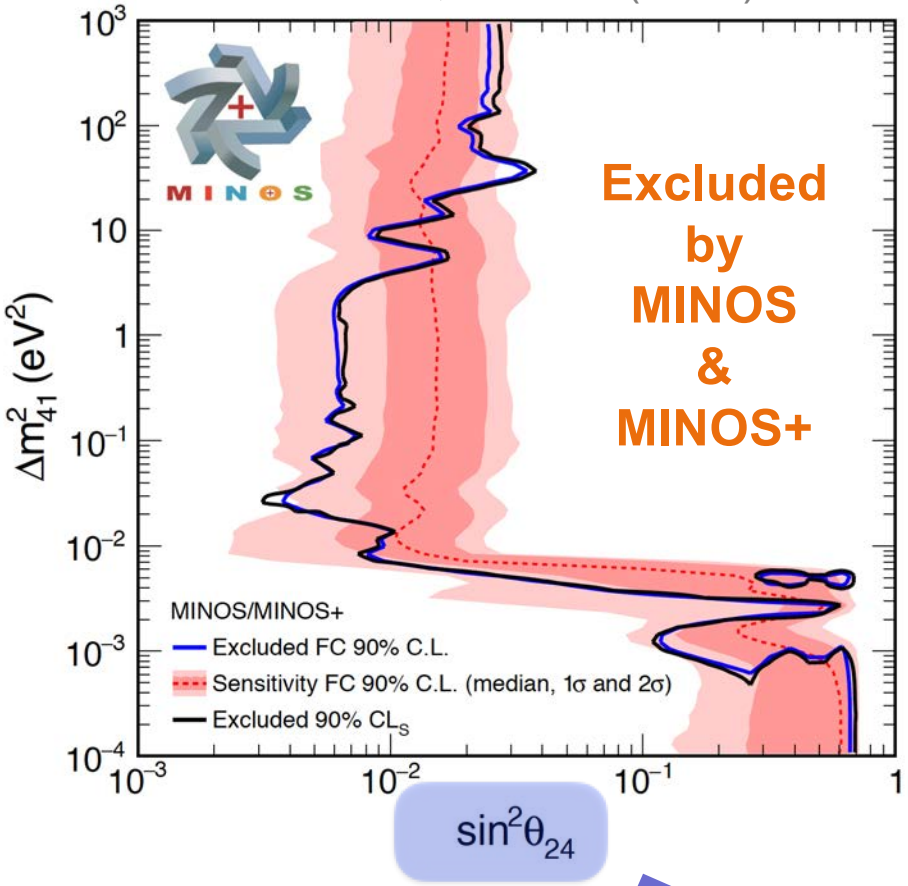


Compare to others

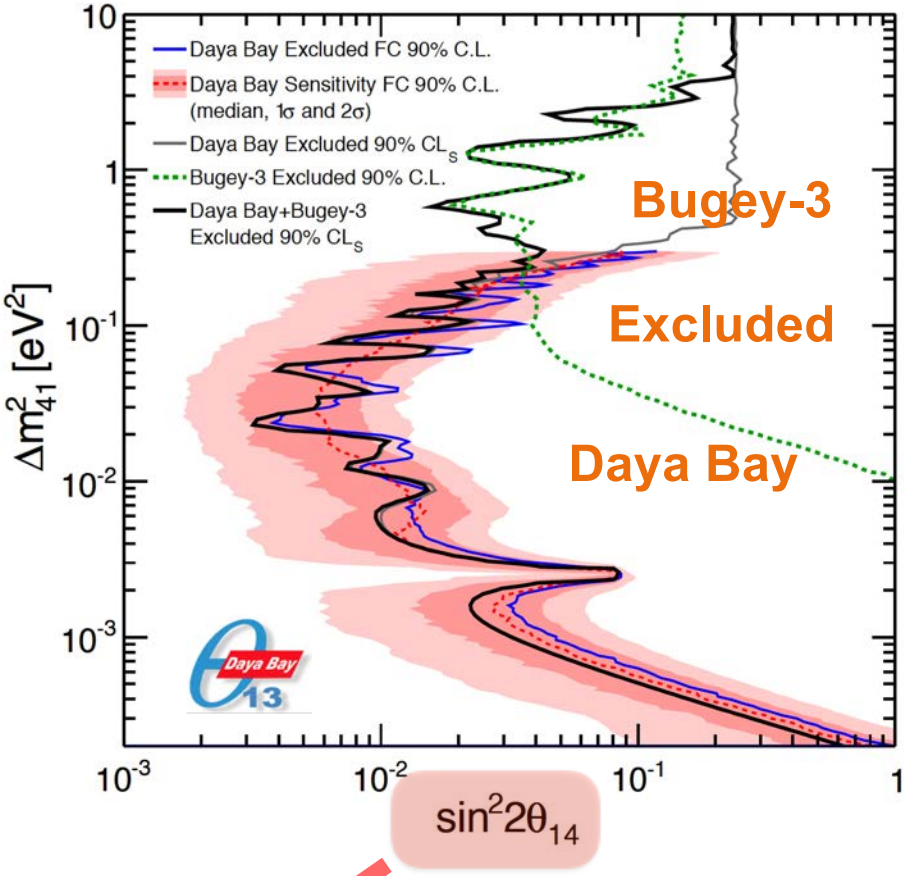


MINOS, MINOS+, Daya Bay, Bugey-3

PRL 122, 091803 (2019)



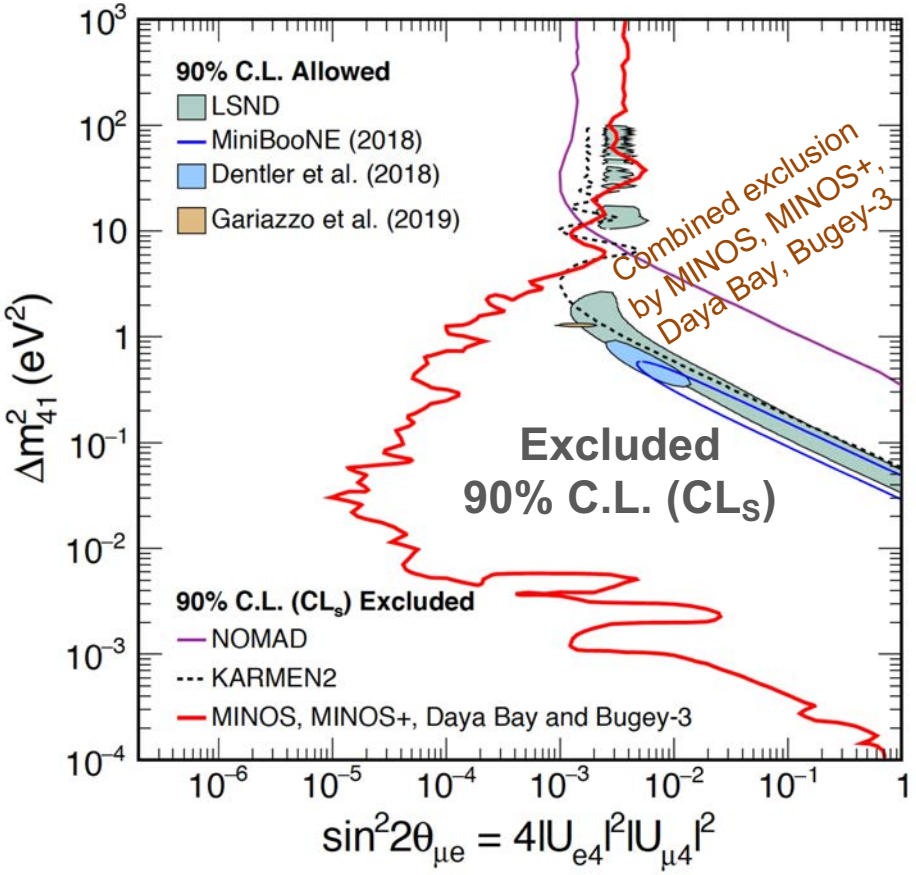
Daya Bay 1230 days (2019) + Bugey-3

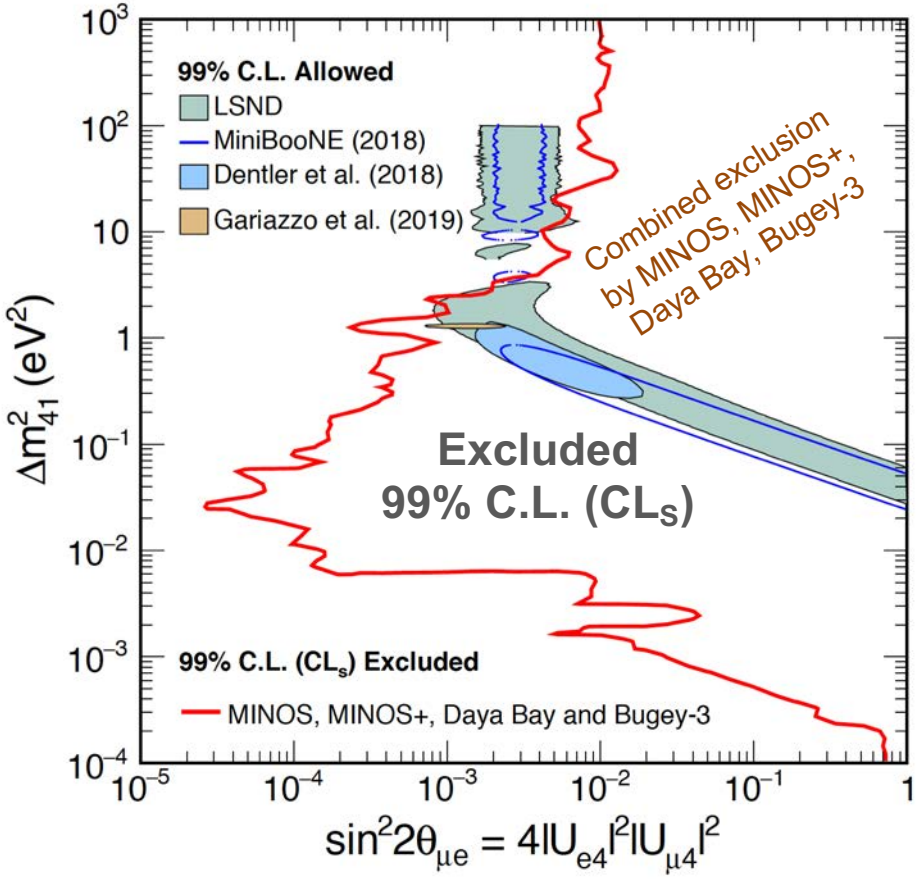


$$4|U_{e4}|^2|U_{\mu 4}|^2 = \sin^2\theta_{24}\sin^2 2\theta_{14} \equiv \sin^2 2\theta_{\mu e}$$

Combined constraints of MINOS, MINOS+, Daya Bay, Bugey-3

P. Adamson *et al.,* arXiv:2002.00301v1 [hep-ex] 2 Feb 2020





Dentler *et al.* – global fit includes MiniBoonE
Gariazzo *et al.* – global fit excludes MINOS, MINOS+, Daya Bay, Bugey-3

Previous results (using ratios of energy spectra:
Combined : Phys. Rev. Lett. 117, 151801 (2016)
MINOS : Phys. Rev. Lett. 117, 151803 (2016)
Daya Bay : Phys. Rev. Lett. 117, 151802 (2016)

MINOS & MINOS+

- 11 years of operations, 25 POT exposure, up to 600 kW beam

- Best to date Δm^2_{32} (68% CL), no octant preference at 90%CL for θ_{23}

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- Some of the most stringent bounds on "3+1" sterile neutrinos
  - ⇨ Muon disappearance
  - ⇨ Joint analysis with Daya Bay for $\nu_\mu \rightarrow \nu_e$ appearance bounds
  - ⇨ Increased tension with global fits


Ely, MN, June 2012 (the proposal era)

- Bounds on LED and NSI
  (not discussed here)

- MINOS+ data still being analyzed
  - ⇨ $\nu_\mu \rightarrow \nu_e$ appearance
  - ⇨ Final papers on all the above still to come …

MINOS & MINOS+