Improved Limits on Sterile Neutrino Mixing from a Joint Search of the MINOS, MINOS+, Daya Bay, and Bugey-3 Experiments

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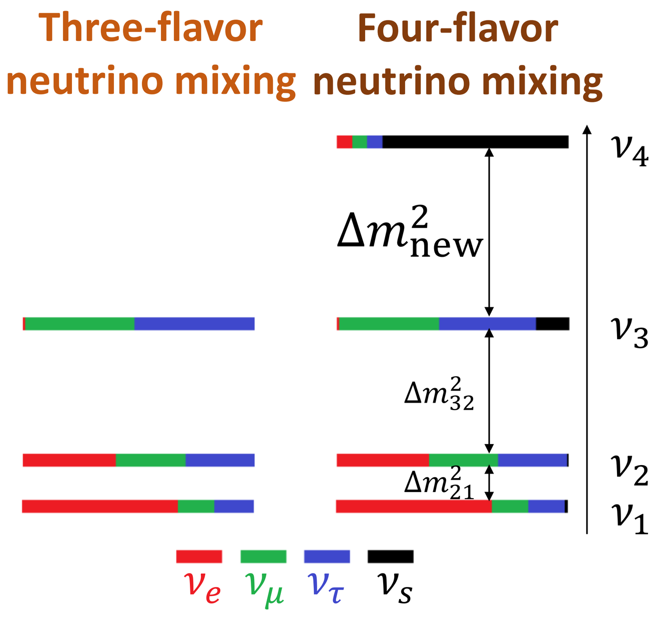
On behalf of the Daya Bay and MINOS/MINOS+ Collaborations

Introduction

Neutrino oscillation

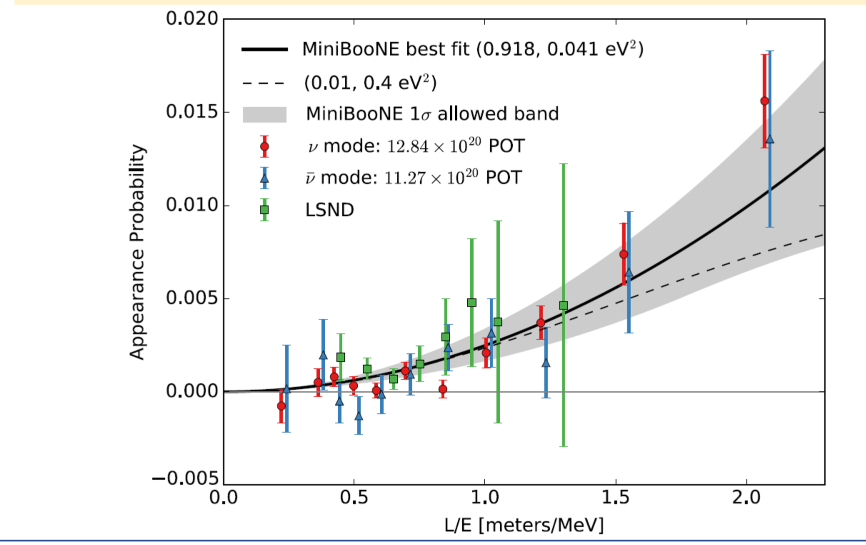
- A neutrino created as a certain flavor may be later measured as a different flavor
- Neutrino flavor eigenstates are superpositions of mass eigenstates
- Confirmed by a wealth of experimental data
- Most of the experimental data is consistent with the three-flavor neutrino mixing framework (ν_e, ν_μ, ν_τ)



Sterile neutrino (ν_s)

- Additional neutrino states may exist provided they do not interact through any of the interactions of the Standard Model
- Could mix with active neutrinos (ν_e, ν_μ, ν_τ)
- Well-motivated to explain the origin of neutrino masses
- Proposed as an explanation for the anomalous excess observed by the Liquid Scintillator Neutrino Detector (LSND) and MinoBooNE experiments [1]

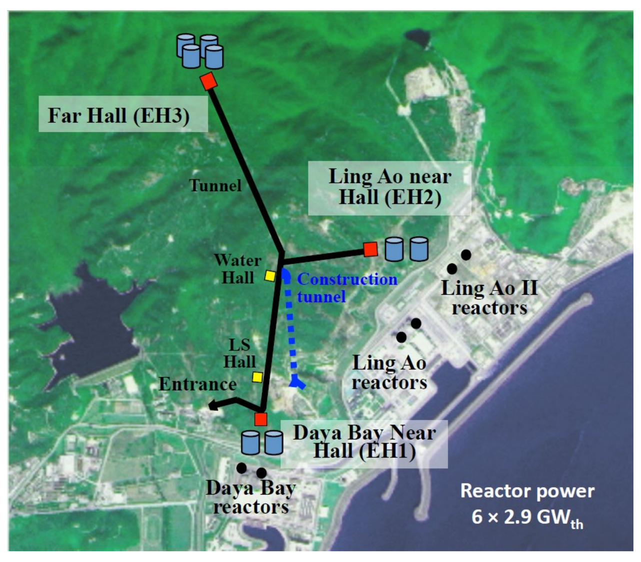
*LSND/MinoBooNE data and fits to data assuming the presence of a new sterile neutrino state. The $\overset{(-)}{\nu}_e$ appearance data indicates a sterile neutrino state with mixing parameter $\sin^2 2\theta_{\mu e} = 0.918$, and $\Delta m^2_{new} = 0.041$ eV^2.

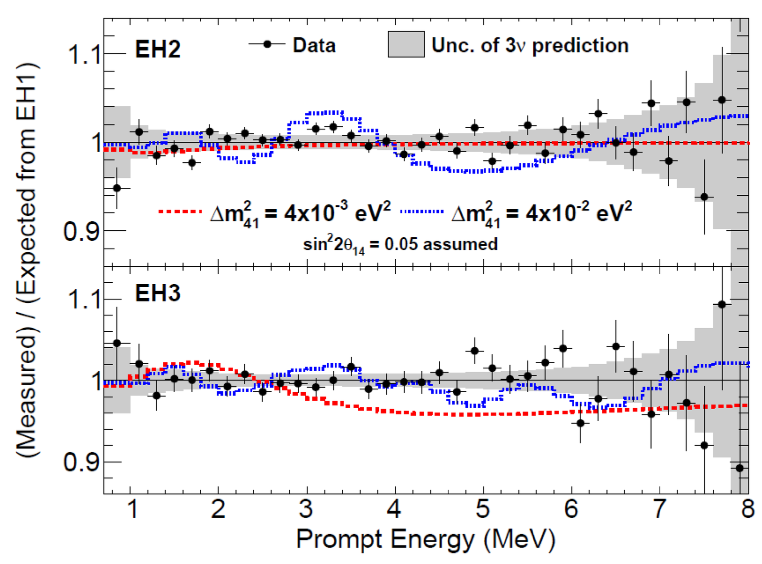


Search for light sterile neutrinos at Daya Bay

Daya Bay experiment

- Measures reactor $\bar{\nu}_e$ flux at multiple baselines (~300 m - ~2000 m)
- Search for an oscillation frequency different from those in the three-flavor framework





Improvements

- x2 more data than previous analysis
- Relative detection efficiency uncertainty reduced from 0.2% to 0.13%
- New time-dependent spatial non-uniformity correction
- More precise background assessment

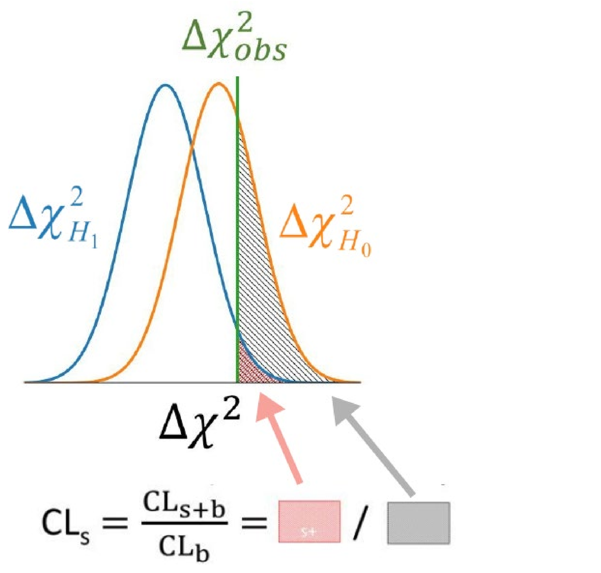
Gaussian CL$_s$ statistical method [2-3]

Two-hypothesis test

H$_1$: ($\sin^2 2\theta_{14} \neq 0, \Delta m^2_{41} \neq 0$), a specific point in the sterile neutrino mixing parameter space

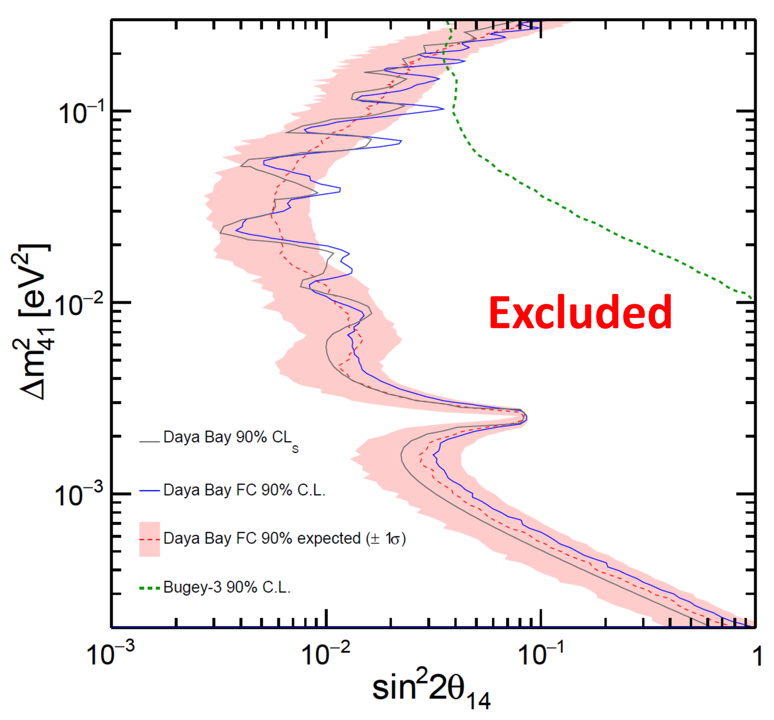
H$_0$: ($\sin^2 2\theta_{14} = 0$), standard three-flavor mixing framework

$$\Delta\chi^2 = \chi^2_{H_1} - \chi^2_{H_0}$$

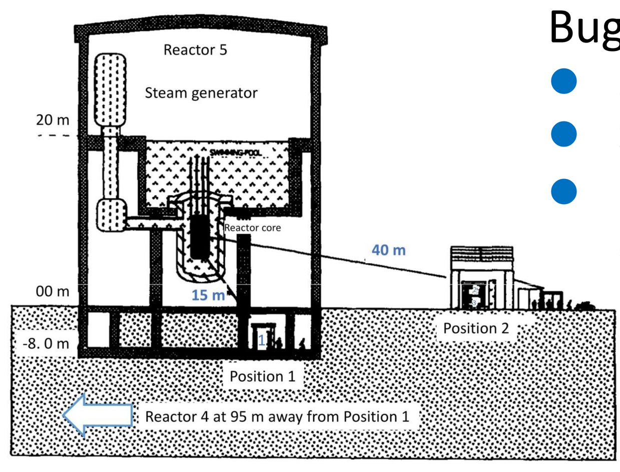


Results

- No evidence of light sterile neutrino observed
- Limits obtained using Gaussian CL$_s$ method
- Independent analyses by two groups yield consistent results
- Feldman-Cousins [4] contours consistent with CL$_s$ contours
- World-leading limits on $\sin^2 2\theta_{14}$ in the 2×10^{-4} eV^2 $\leq |\Delta m^2_{41}| \leq 0.2$ eV^2 regions

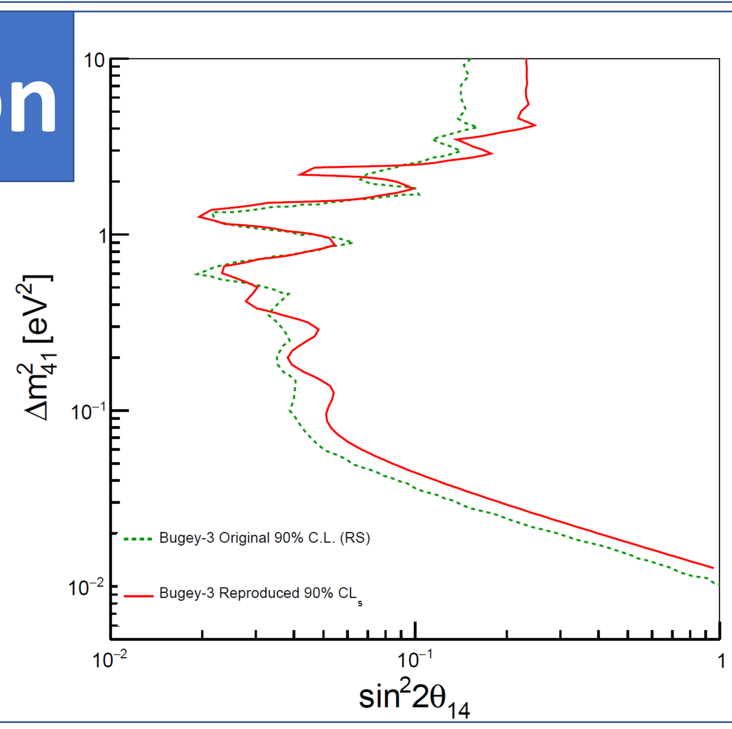


Daya Bay + Bugey-3 Combination



Bugey-3 experiment [5]

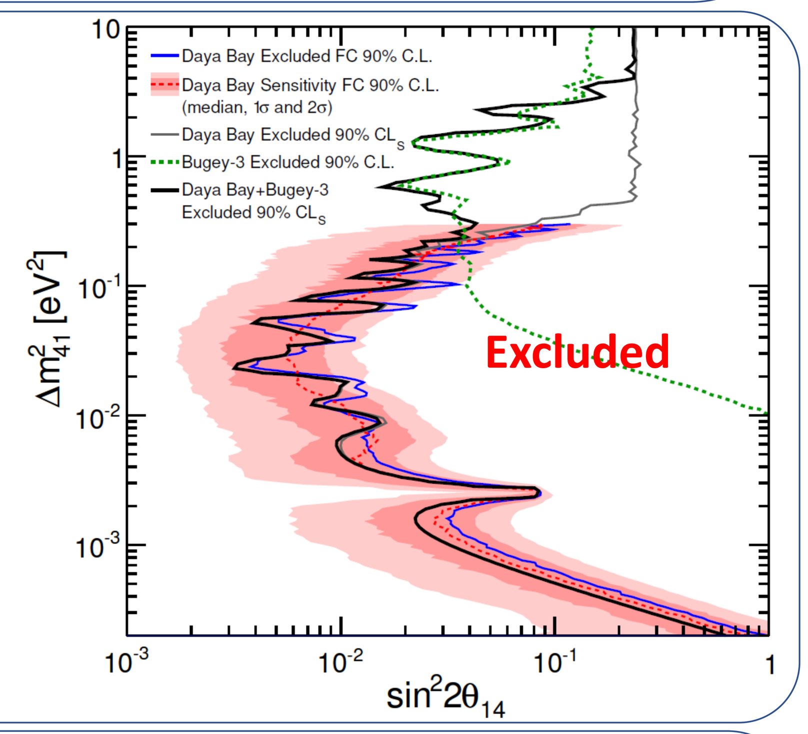
- 3 detectors at 2 positions
- Short baselines. (15 m, 40 m, 95 m)
- Probe higher $|\Delta m^2_{41}|$ than Daya Bay does



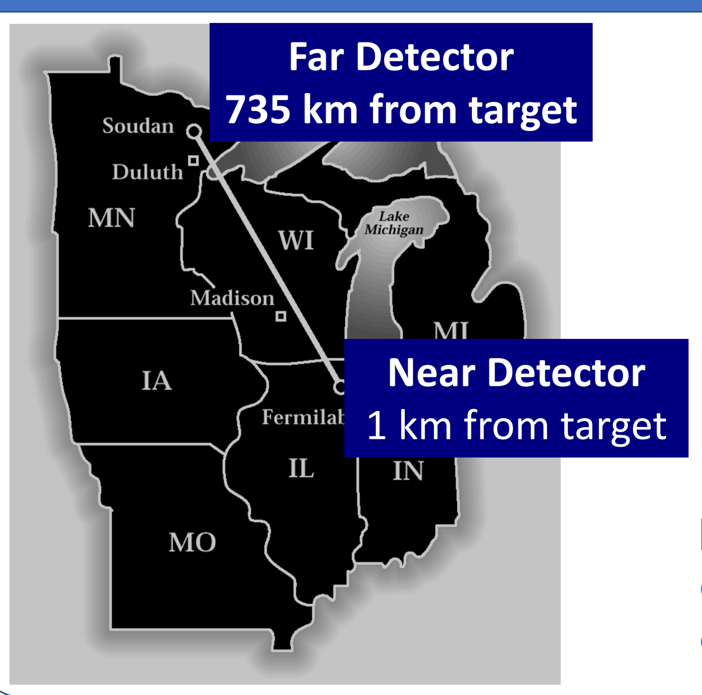
Data from Bugey-3 experiment are reanalyzed using the Gaussian CL$_s$ method

- Updated reactor neutrino model and neutron life time

Combine Daya Bay and Bugey-3 results to set the constraints for $\sin^2 2\theta_{14}$



Search for light sterile neutrinos at MINOS and MINOS+

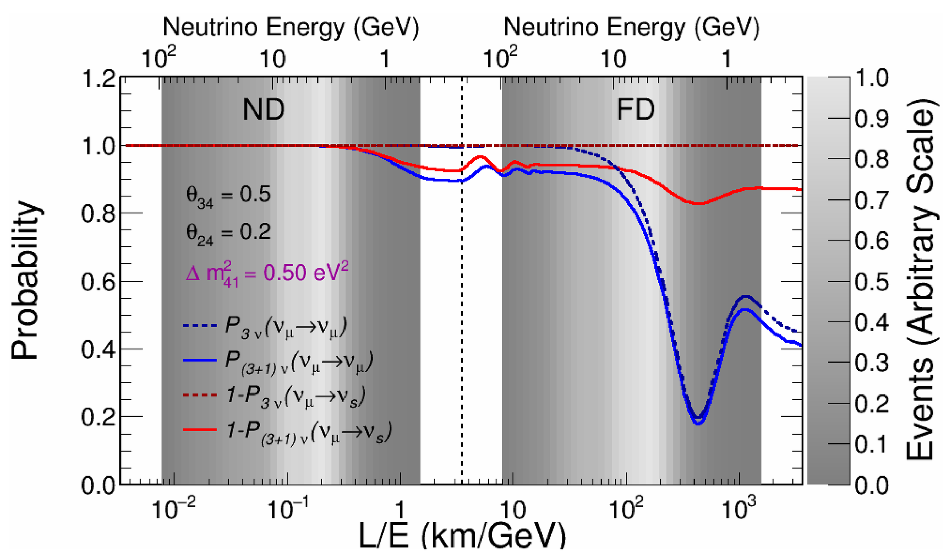


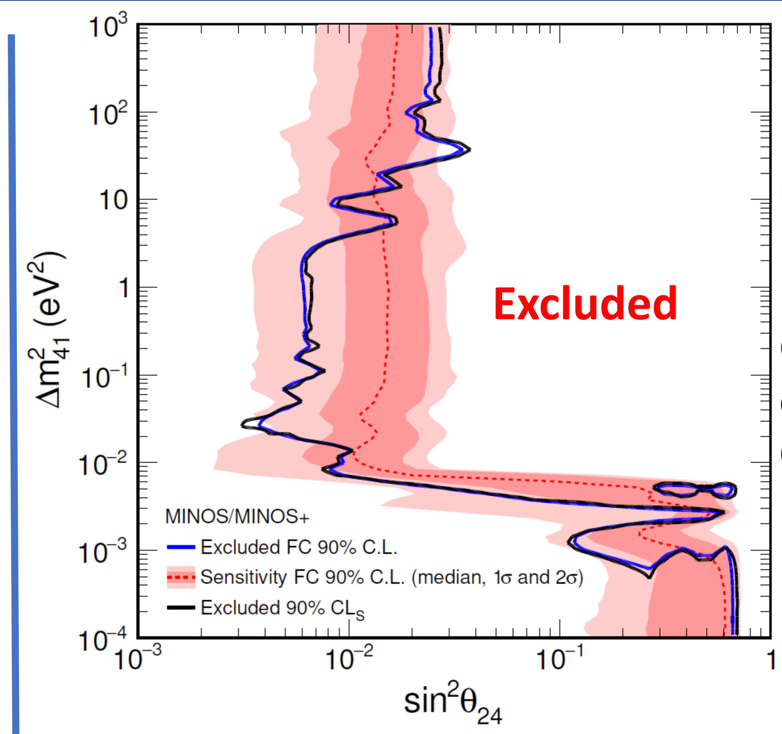
MINOS and MINOS+

- Measures accelerator neutrino flux with a long baseline
- Two functionally identical iron-scintillator sampling calorimeters
- Search for oscillation signature in both near and far detectors

Improvement

- +5.8 × 10^{20} POT from MINOS+ runs
- New two-detector fit method (fit near and far spectra simultaneously)





*No sterile neutrino is found

**Feldman-Cousins contours consistent with CL$_s$ contours

Most stringent limits on $\sin^2\theta_{24}$ to date for most values of $\Delta m^2_{41} > 10^{-4}$ eV^2 [6]

Joint Analysis

In presence of a light sterile neutrino (3 active + 1 sterile)

$\bar{\nu}_e$ disappearance (reactor)

$$P_{\bar{\nu}_e \to \bar{\nu}_e} \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{31} L}{4E} - \sin^2 2\theta_{14} \sin^2 \frac{\Delta m^2_{41} L}{4E}$$

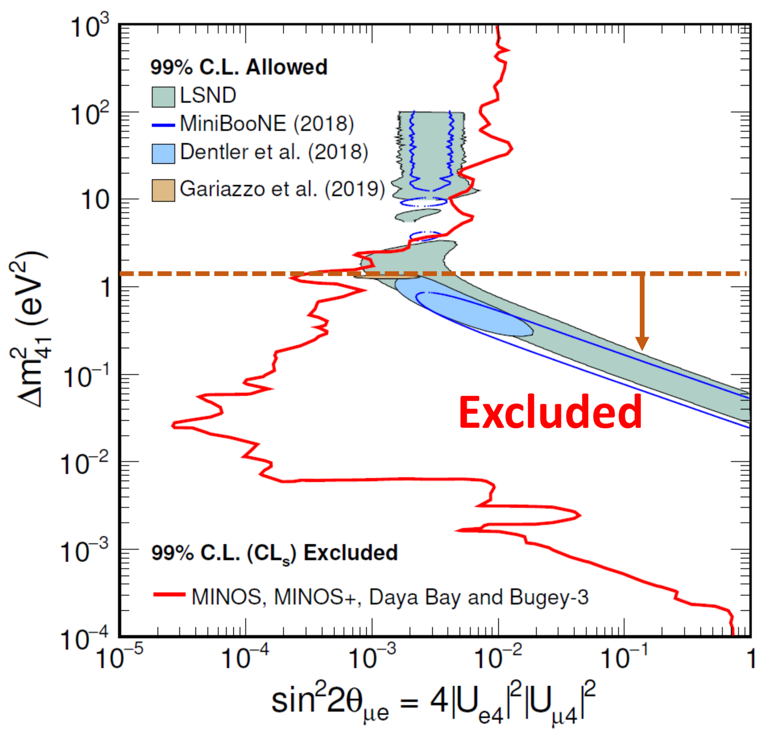
$\nu_\mu(\bar{\nu}_\mu)$ disappearance (accelerator)

$$P_{\nu_\mu \to \nu_\mu} \approx 1 - \sin^2 2\theta_{23} \cos 2\theta_{24} \sin^2 \frac{\Delta m^2_{31} L}{4E} - \sin^2 2\theta_{24} \sin^2 \frac{\Delta m^2_{41} L}{4E}$$

Combination of two disappearance channels can constrain

The LSND and MinoBooNE **appearance** probability

$$P^{SBL}_{\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e} = \sin^2 2\theta_{\mu e} \sin^2 \frac{\Delta m^2_{41} L}{4E}, \text{ where } \sin^2 2\theta_{\mu e} \equiv \sin^2 2\theta_{14} \sin^2 \theta_{24}$$



The CL$_s$ contours from the MINOS, MINOS+, Daya Bay, and Bugey-3 experiments are combined

- $\Delta\chi^2$ surfaces from two disappearance channels are summed up
- Appearance allowed regions with $\Delta m^2_{41} < 1.2$ eV^2 are excluded at 99% C.L., including two sterile neutrino global fits [7-8]

Conclusions

PRL accepted

- Daya Bay and MINOS+ collaborated to combine the measurements from $\bar{\nu}_e$ and $\nu_\mu(\bar{\nu}_\mu)$ disappearance channels, using the CL$_s$ statistical method
- Stringent limits are placed on $\sin^2 2\theta_{\mu e}$ over 7 orders of magnitude in Δm^2_{41}
- Tension between the $\overset{(-)}{\nu}_e$ appearance indications and the null results from disappearance channels is increased

Reference

[1] A. A. Aguilar-Arevalo et al. (MiniBooNE Collaboration), Phys. Rev. Lett. **121**, 221801 (2018).
[2] A. L. Read, J. Phys. G **28**, 2693 (2002).
[3] X. Qian, A. Tan, J. J. Ling, Y. Nakajima, and C. Zhang, Nucl. Instrum. Meth. A **827**, 63 (2016).
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[5] B. Achkar et al. (Bugey-3 Collaboration), Nucl. Phys. B **434**, 503 (1995).
[6] P. Adamson et al. (MINOS+ Collaboration), Phys. Rev. Lett. **122**, 091803 (2019).
[7] S. Gariazzo, C. Giunti, M. Laveder, and Y. F. Li, Phys. Lett. B **782**, 13 (2018).
[8] M. Dentler, A. Hernández-Cabezudo, J. Kopp, P. A. N. Machado, M. Maltoni, I. Martinez-Soler, and T. Schwetz, JHEP **08**, 010 (2018).