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

Vitalii Zavadskyi (Joint Institute for Nuclear Research), on behalf of the Daya Bay collaboration

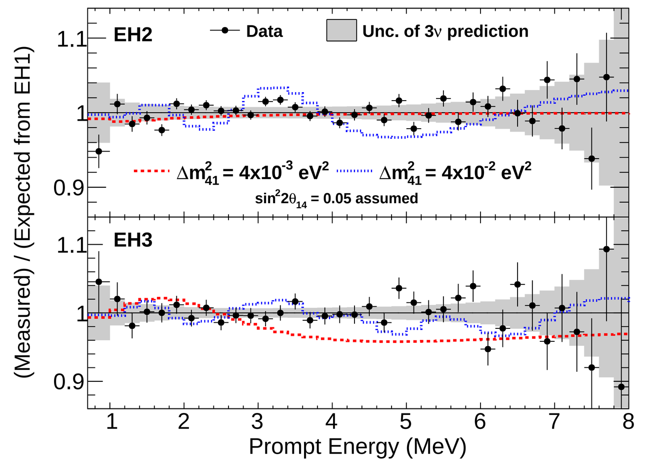
Introduction

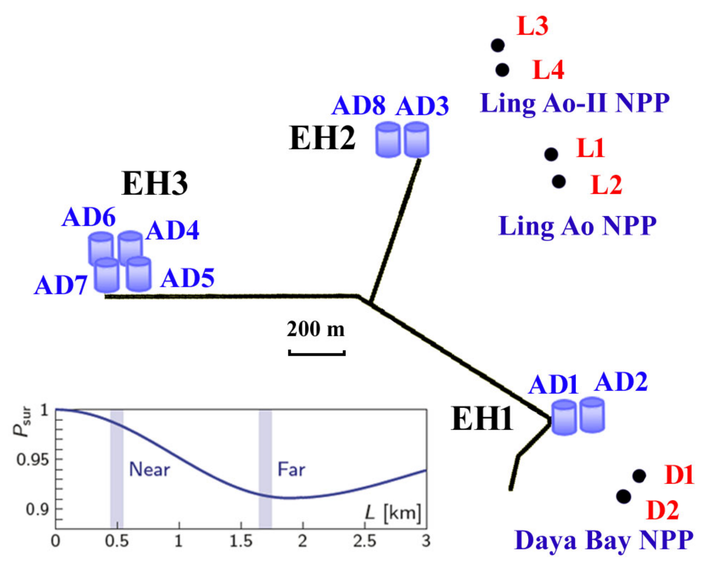
The LSND experiment [1] has detected a 3.8σ excess of the expected number of $\overline{\nu}_e$ events in a $\overline{\nu}_\mu$ beam. Similar effects were observed by the MiniBooNE [2]: a 4.7σ excess in a total number of ν_e and $\overline{\nu}_e$ events.
These excess could be explained with one or more sterile neutrinos, which interact only gravitationally.

The Daya Bay Experiment

A reactor antineutrino experiment [3]

- Measures $\overline{\nu}_e$ disappearance from six reactors at multiple baselines from ~ 0.4 km (near halls) to ~ 1.7 km (far hall) baselines.



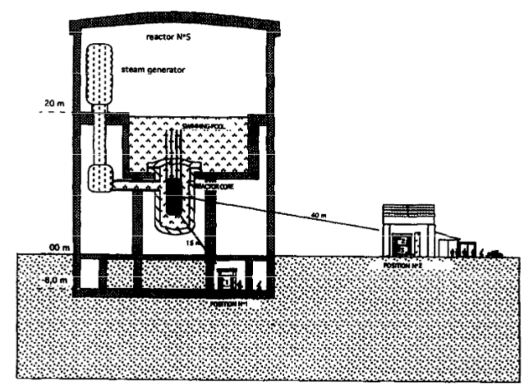


- Large statistics (more than $2.5 \cdot 10^6$ events).

The Bugey-3 Experiment

A reactor antineutrino experiment [4]

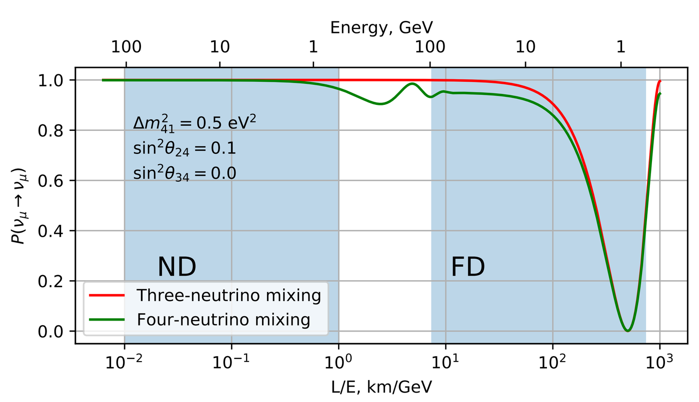
- Measures $\overline{\nu}_e$ disappearance.
- Three distances of measurement: 15, 40, 95 m.
- Nearly 120,000 $\overline{\nu}_e$ events.

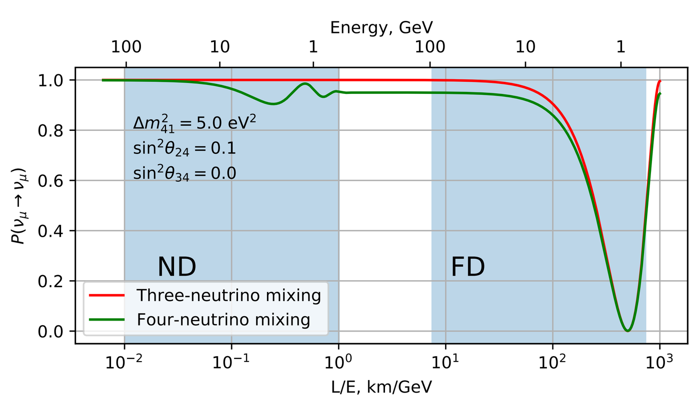


The MINOS/MINOS+ Experiment

An accelerator experiment [5]

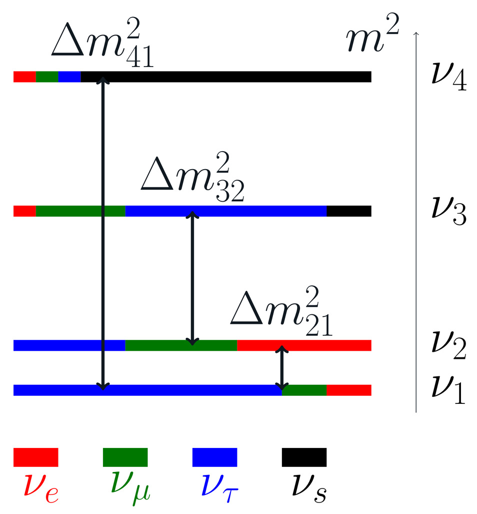
- Measures ν_μ and $\overline{\nu}_\mu$ disappearance.
- Two detectors: near (≈ 1 km) and far (≈ 735 km).
- Detectors are sensitive to different region of sterile mass splitting.
- $16.36 \cdot 10^{20}$ protons on target to yield the NuMI ν_μ ($\nu_{\overline{\mu}}$) beam.





Neutrino oscillation

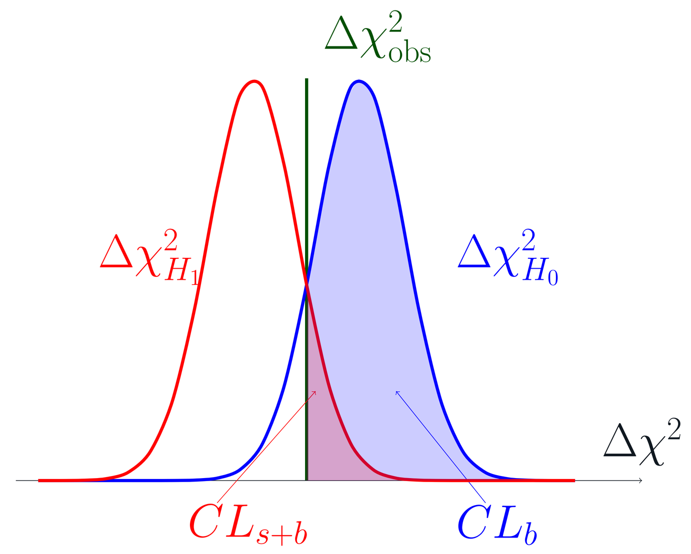
- Neutrino flavor eigenstates are superposition of mass eigenstates.
- Neutrino mixing can be parameterized by the Pontecorvo-Maki-Nakagawa-Sakata matrix.
- Commonly, neutrino oscillation is parameterized by three-neutrino mixing.
- An additional state (sterile) that does not interact through weak interaction but it could mix with active states.
- A sterile state may explain the anomalous excess observed by the LSND and MinoBooNE experiments.



Analysis Method

CL_s method [6] was used to produce exclusion region:

- $H_0 : \sin^2 2\theta_{14} = 0$ three neutrino mixing
- $H_1 : \sin^2 2\theta_{14} \neq 0$ four neutrino mixing
- $\Delta\chi^2 = \chi^2_{H_1} - \chi^2_{H_0}$
- $CL_s = \frac{CL_{s+b}}{CL_b}$
- Exclusion rule: $CL_s < \alpha$
- $\Delta\chi^2$ has Gaussian approximation [7] (*used only for the Daya Bay experiment*)



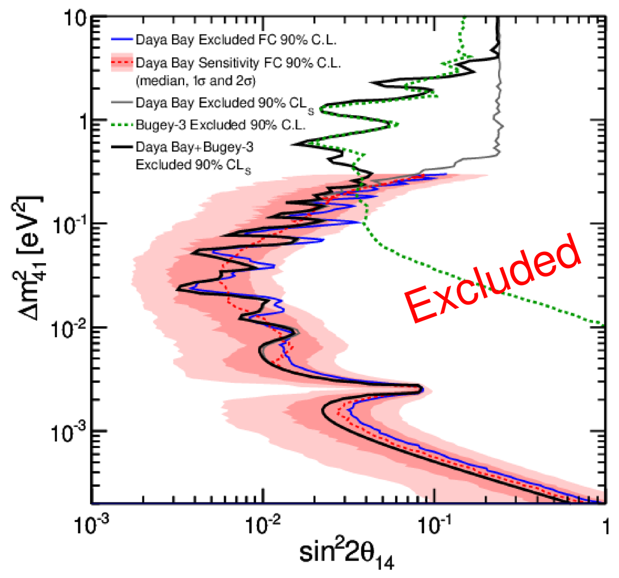
Daya Bay+Bugey-3 Combination

$$P(\overline{\nu}_e \to \overline{\nu}_e) \approx 1 - \sin^2 2\theta_{14} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right) - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$

- Using Huber-Mueller model of $\overline{\nu}_e$ energy spectrum [8], [9].
- Daya Bay exclusion region based on 1230 days of data.
- Combination of two experiments is sensitive to $\sin^2 2\theta_{14}$ in the region

$$2 \cdot 10^{-4}\ \text{eV}^2 < \Delta m^2_{41} < 3\ \text{eV}^2.$$

- No evidence of light sterile neutrino is observed.



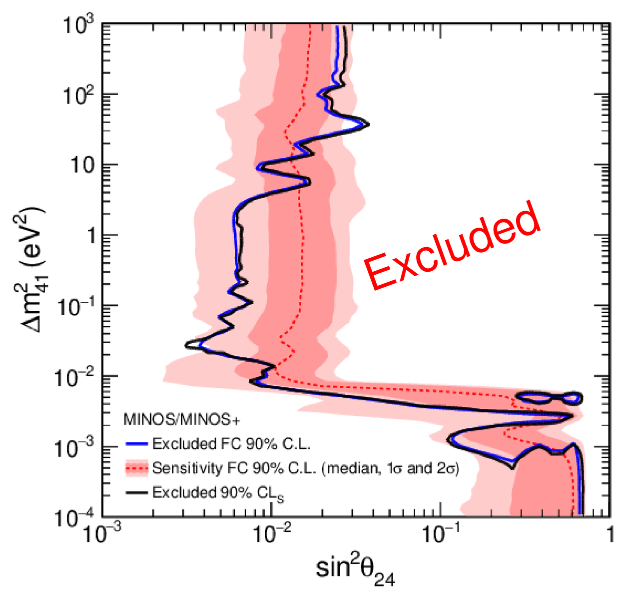
MINOS/MINOS+ Results

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

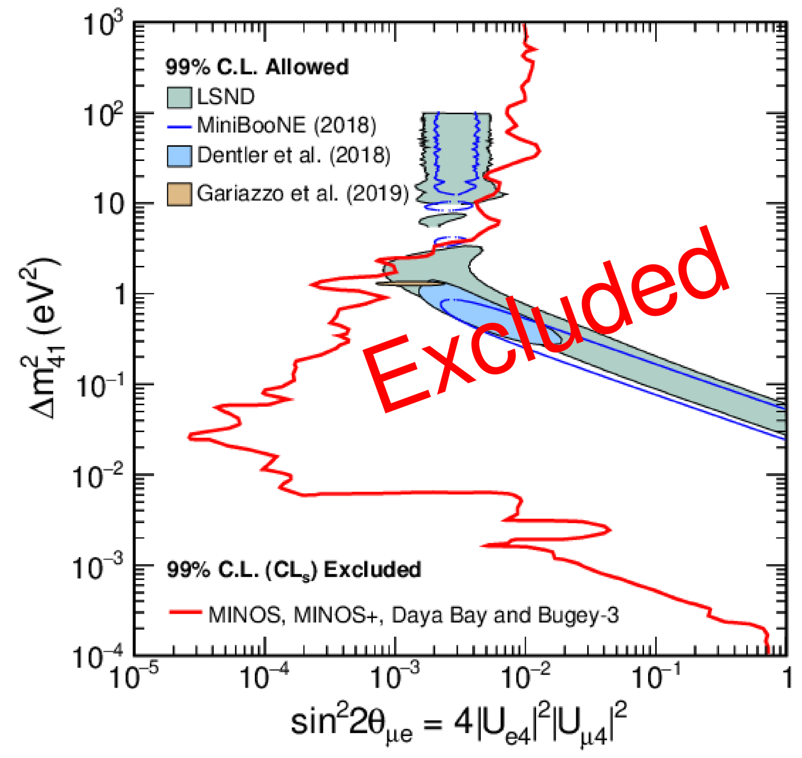
- Two-detector fit method (fit near and far spectra simultaneously).
- The experiment is sensitive to $\sin^2\theta_{24}$ in the region

$$10^{-4}\ \text{eV}^2 < \Delta m^2_{41} < 10^3\ \text{eV}^2.$$

- Feldman-Cousins contours are consistent with CL_s contours.



Daya Bay+Bugey-3+MINOS Combination



- An appearance probability for the short-baseline experiments

$$P(\nu_\mu \to \nu_e) = 4|U_{e4}|^2|U_{\mu 4}|^2 \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right).$$

- Combines constrains of $\sin^2 2\theta_{14}$ from Daya Bay+Bugey-3 and constrains of $\sin^2\theta_{24}$ from MINOS/MINOS+ into

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

- The largest CL_s value is taken for different combinations of $\sin^2 2\theta_{14}$, $\sin^2\theta_{24}$ that give the same value of $\sin^2 2\theta_{\mu e}$.

Conclusion

- No evidence of light sterile neutrino is found.
- Stringent limits are obtained on the $\sin^2 2\theta_{\mu e}$ in the region

$$10^{-4}\ \text{eV}^2 < \Delta m^2_{41} < 10^3\ \text{eV}^2.$$

- The LSND and MiniBooNE 99% C.L. allowed regions are excluded at 99% CL_s for $\Delta m^2_{41} < 1.2$ eV^2 [10].
- Tension between the ν_e appearance indications and the null results from disappearance channels is increased.

References

1. Aguilar, A. *et al. Phys. Rev. D* **64,** 112007 (2001).
2. Aguilar-Arevalo, A. A. *et al. Phys. Rev. Lett.* **121,** 221801 (2018).
3. Cao, J. & Luk, K.-B. *Nucl. Phys. B* **908,** 62–73 (2016).
4. Abbes, M. & et al. *Nucl. Instrum. Meth. A* **374,** 164–187 (1996).
5. Adamson, P. & et al. *Phys. Rev. Lett.* **122.** ISSN: 1079-7114 (2019).
6. Read, A. L. *J. of Phys. G* **28,** 2693–2704 (2002).
7. Qian, X. *et al. Nucl. Instrum. Meth. A* **827,** 63–78 (2016).
8. Huber, P. *Phys. Rev. C* **84,** 024617 (2 2011).
9. Mueller, T. A. *et al. Phys. Rev. C* **83,** 054615 (5 2011).
10. Adamson, P. & et al. *Phys. Rev. Lett.* **125,** 071801 (2020).