Latest Oscillation Results from the Daya Bay Neutrino Experiment

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EPS-HEP 2021

Outline

- Daya Bay Experiment Overview
- Neutrino Oscillations
- Capture on Gd Oscillation Results
- Capture on H Oscillation Results
- Search for Sterile Neutrinos

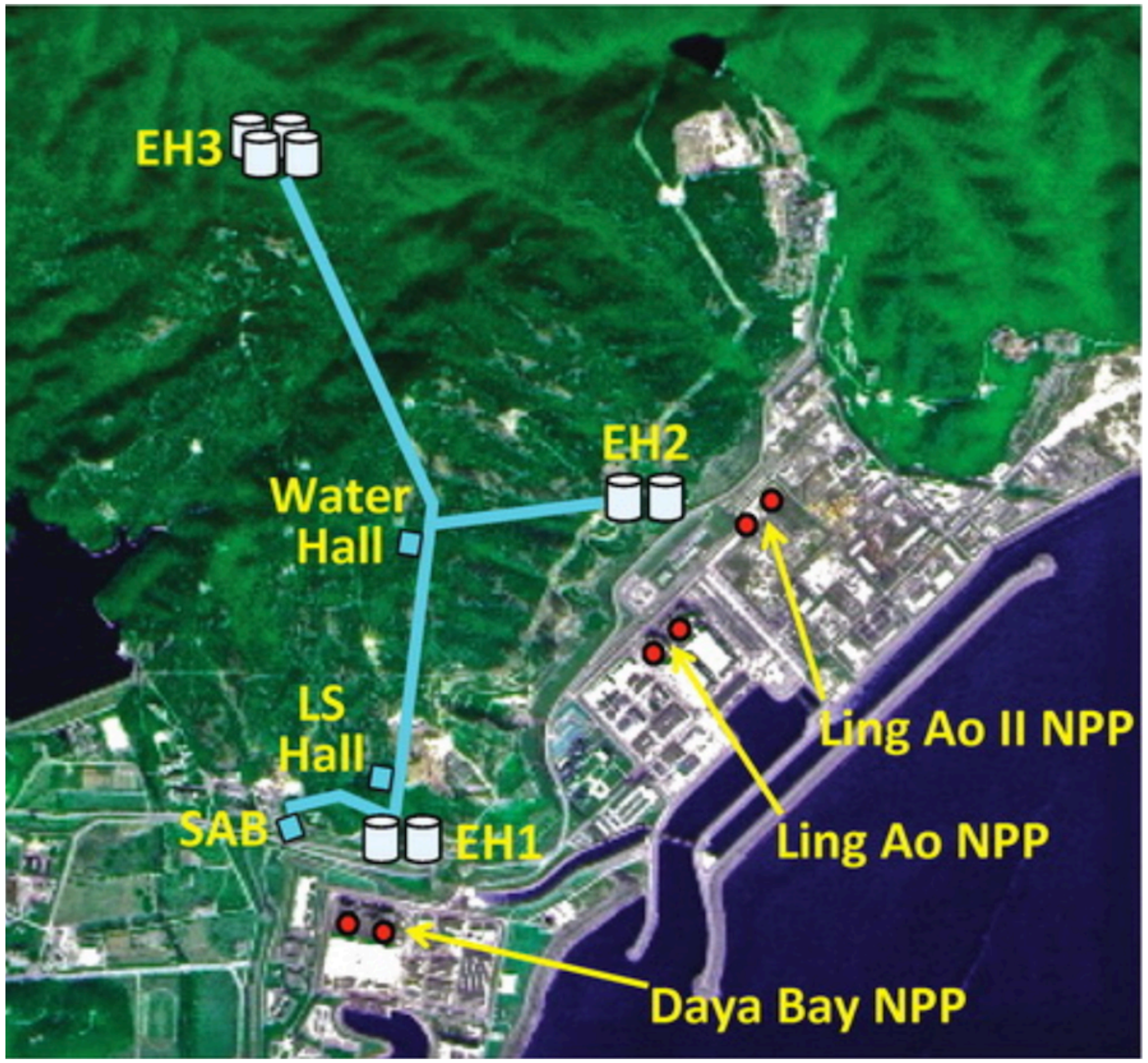
Daya Bay Experiment

- Eight antineutrino detectors (ADs) placed in three underground experimental halls (EHs)

- ADs placed at different baselines (~0.4-2 km) from six 2.9 GW_{th}
  - Among the most powerful nuclear power plant complexes in the world

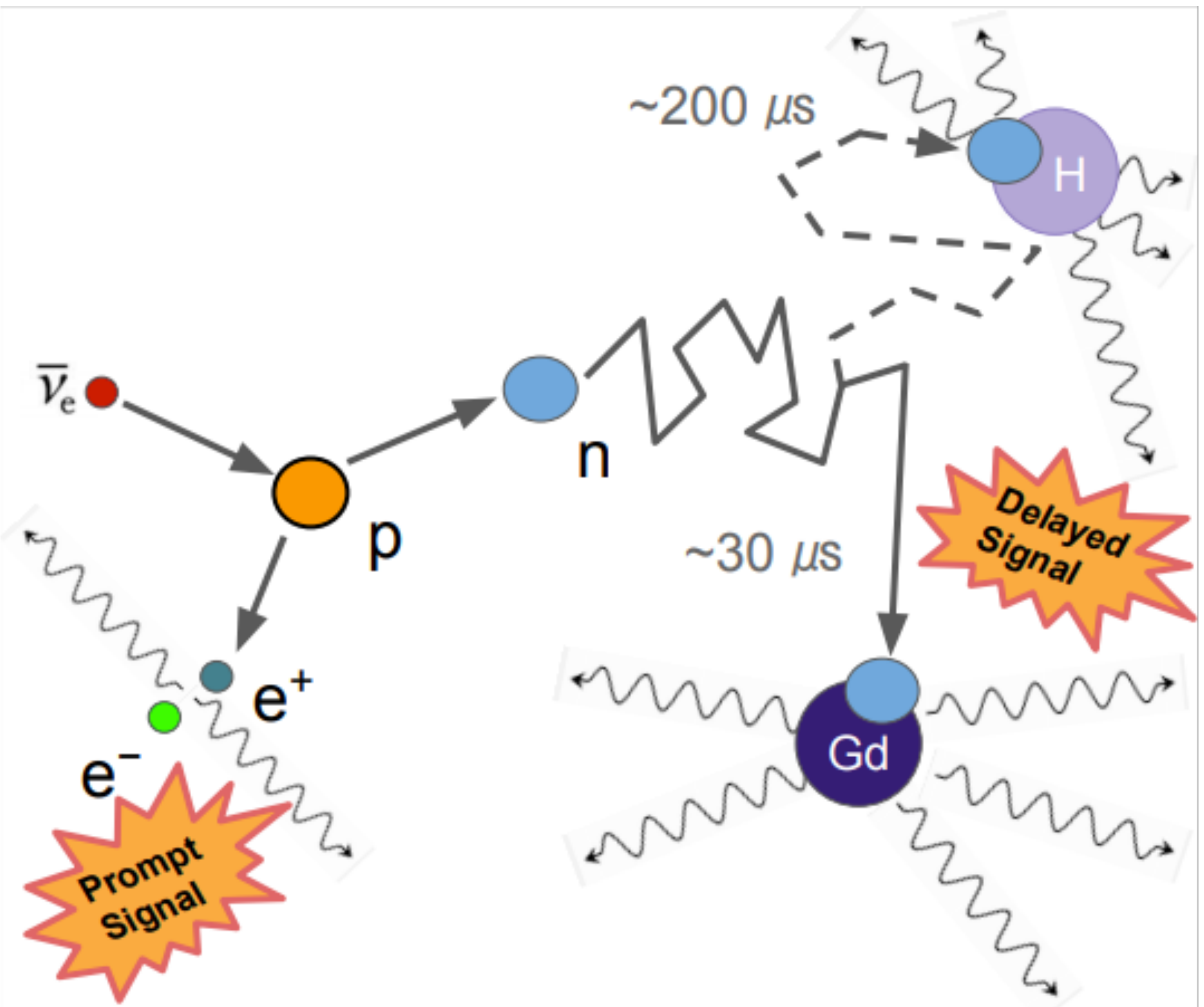
- **Strong, pure source** of electron antineutrinos: ~6x10^{20} $\bar{\nu}_e/s$ per reactor

- Discovered non-zero θ_{13} in 2012



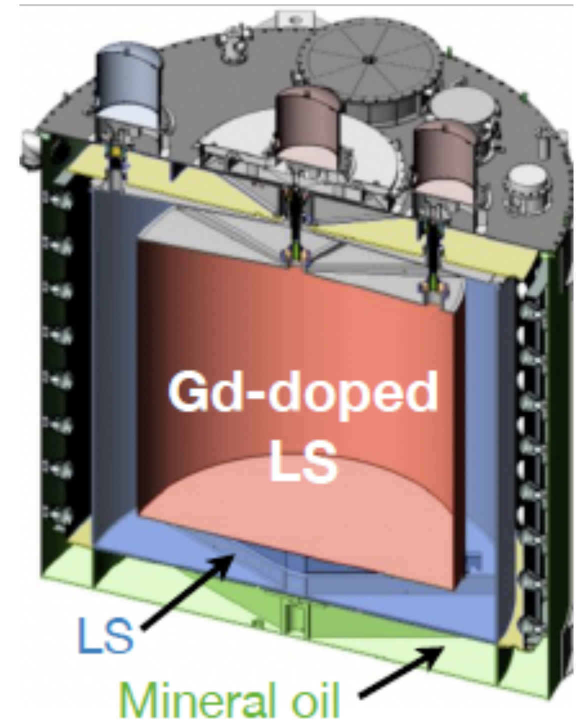
Inverse Beta Decay Detection

- $\bar{\nu}_e$ detected through Inverse Beta Decay (IBD): $\bar{\nu}_e + p \rightarrow e^+ + n$
- Fast e^+ ionization and annihilation with e^- provides prompt signal
  - e^+ preserves $\bar{\nu}_e$ energy information: $E_{\bar{\nu}_e} \approx E_{prompt} + 0.78\mathrm{MeV}$
- n gets captured on Gd (nGd) or on H (nH), de-excitation γ's provide delayed signal
- IBD signature is the time and space coincidence of the two signals: **strong background rejection**

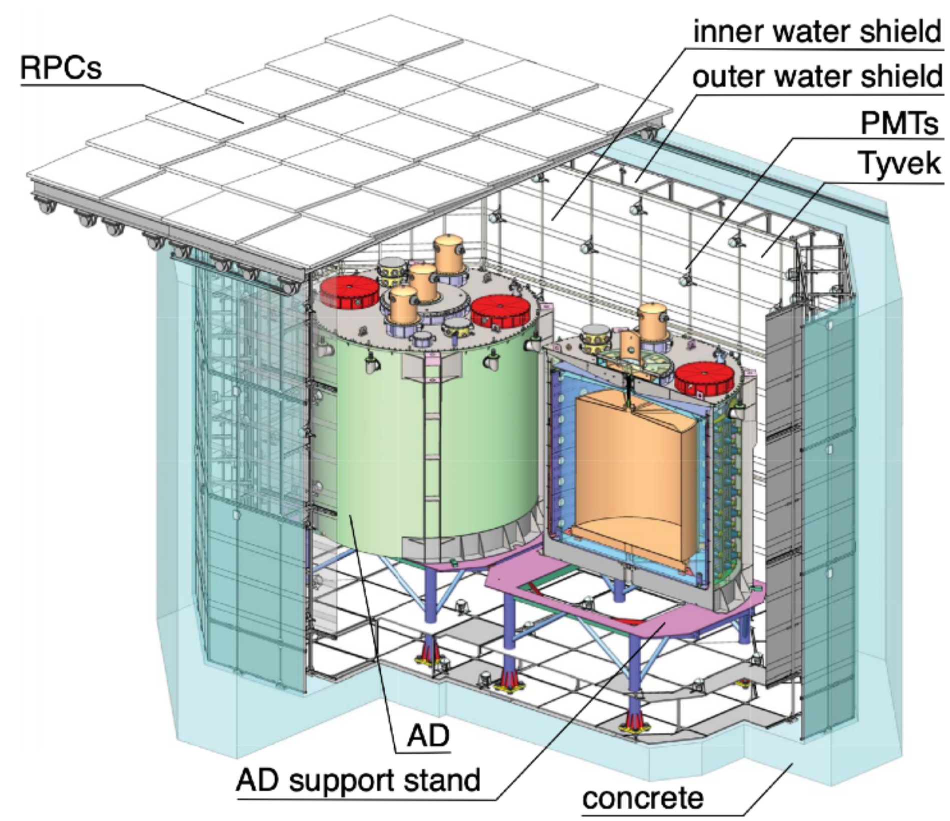


Daya Bay Detectors

- ADs consist of three cylindrical zones:
  - Gadolinium-doped liquid scintillator: target for nGd
  - Liquid Scintillator (LS): γ catcher and main target for nH
  - Mineral oil: buffer hosting PMTs
- Energy resolution of $8.5\,\%/\sqrt{E[\mathrm{MeV}]}$
- Submerged in instrumented ultra pure water pools for muon veto and radiation shielding



NIM A 773, 8 (2015)

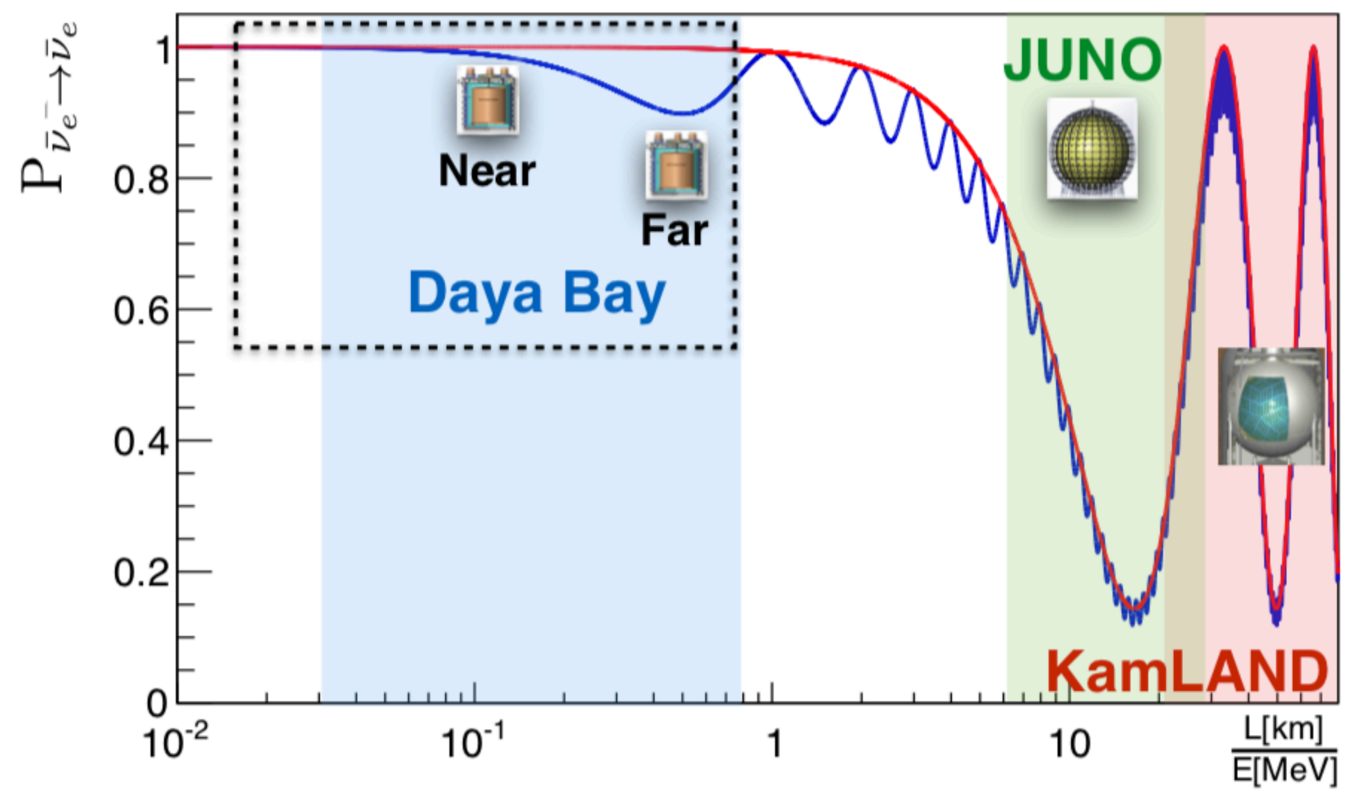


Neutrino Oscillations

Medium baseline | **Short baseline**

$$P_{\bar{\nu}_e\to\bar{\nu}_e}(L,E) = 1 - \boxed{\sin^2 2\theta_{12}\cos^4\theta_{13}\sin^2\frac{\Delta m^2_{21}L}{4E}} - \boxed{\sin^2 2\theta_{13}\left(\cos^2\theta_{12}\sin^2\frac{\Delta m^2_{31}L}{4E} + \sin^2\theta_{12}\sin^2\frac{\Delta m^2_{32}L}{4E}\right)}$$

- Neutrinos change flavor state as a function of distance and energy
- Daya Bay only detects $\bar{\nu}_e$: oscillations appear as flux deficit
- Far hall baseline chosen to maximize effect driven by short baseline oscillation
- Relative near/far measurement greatly reduces impact of many systematic uncertainties



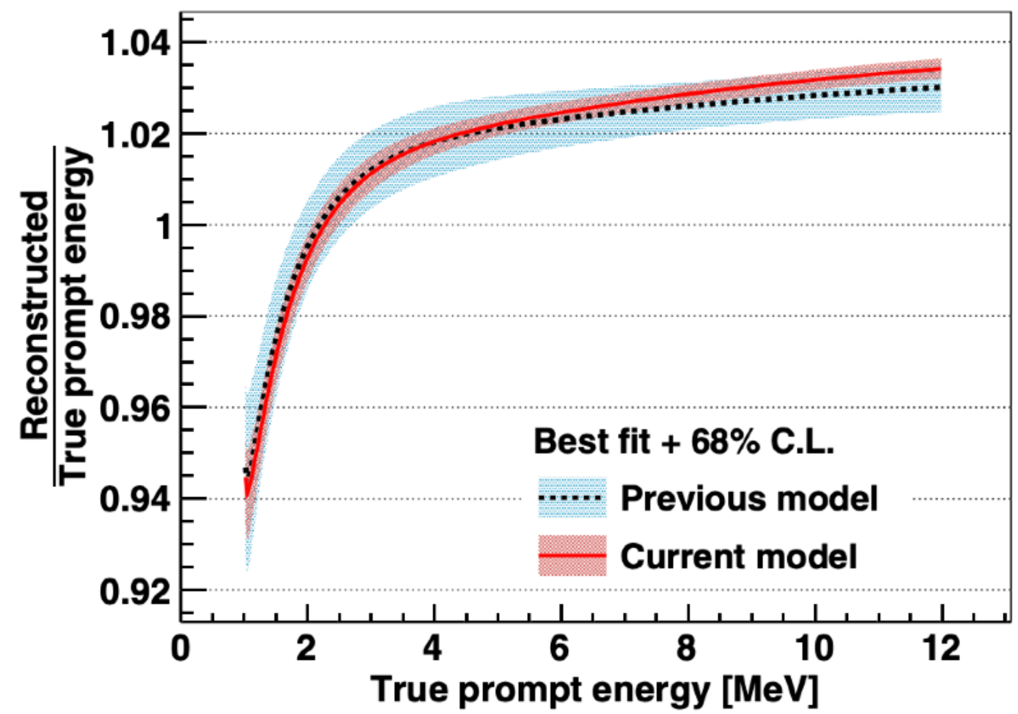
Improved Systematics

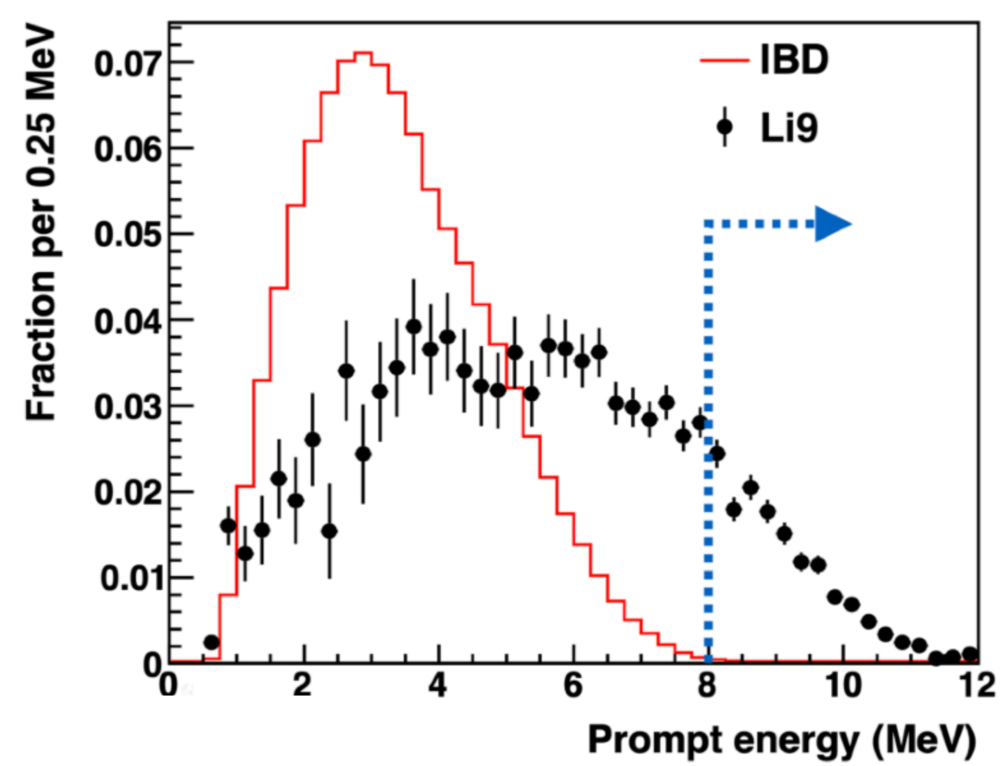
- Absolute energy scale uncertainty halved with respect to previous result: now <0.5%

- Improved detector non-linearity model
    - Strong neutron sources deployed in different areas of a near hall detector in a special calibration campaign

- Uncertainty in $^{9}\mathrm{Li}/^{8}\mathrm{He}$ background reduced
    - Dominant correlated background: $\beta - n$ decays indistinguishable from IBD
    - Prompt energy cut applied for a more pure sample of $^{9}\mathrm{Li}/^{8}\mathrm{He}$

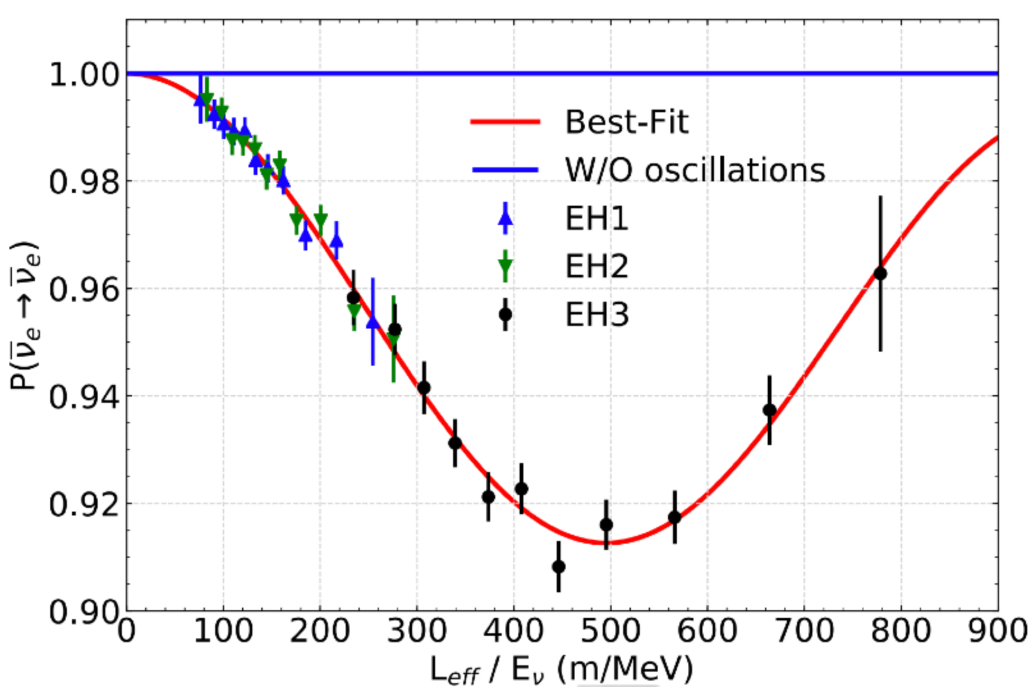
PRL 121, 241805 (2018)





Results with nGd

- Latest results from 1958 days of data with improved systematics
- 3.9 million antineutrino events collected: largest reactor antineutrino dataset in the world
- Consistent with 3-ν hypothesis: $\chi^2/\mathrm{ndf} = 148/154$



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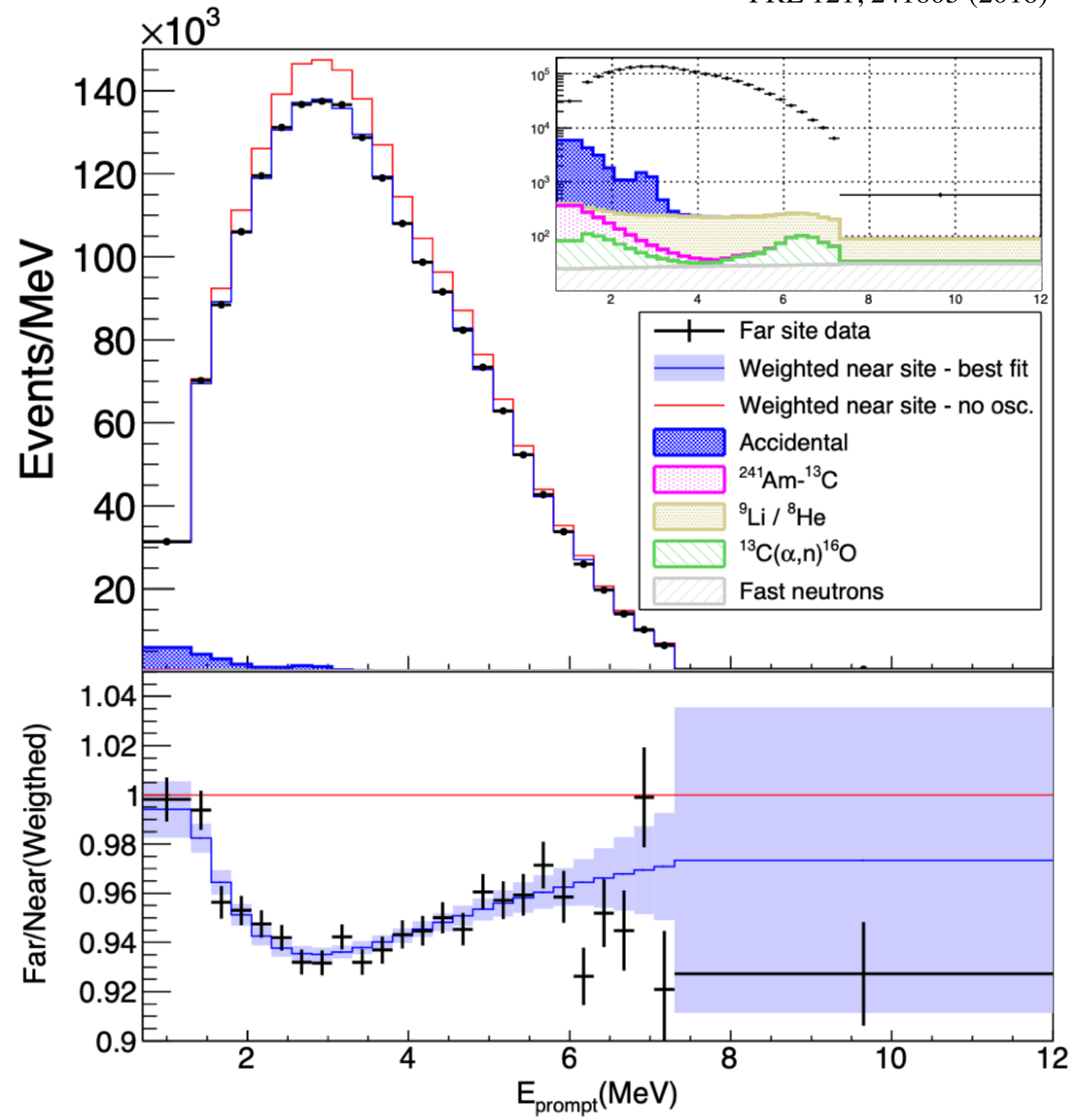
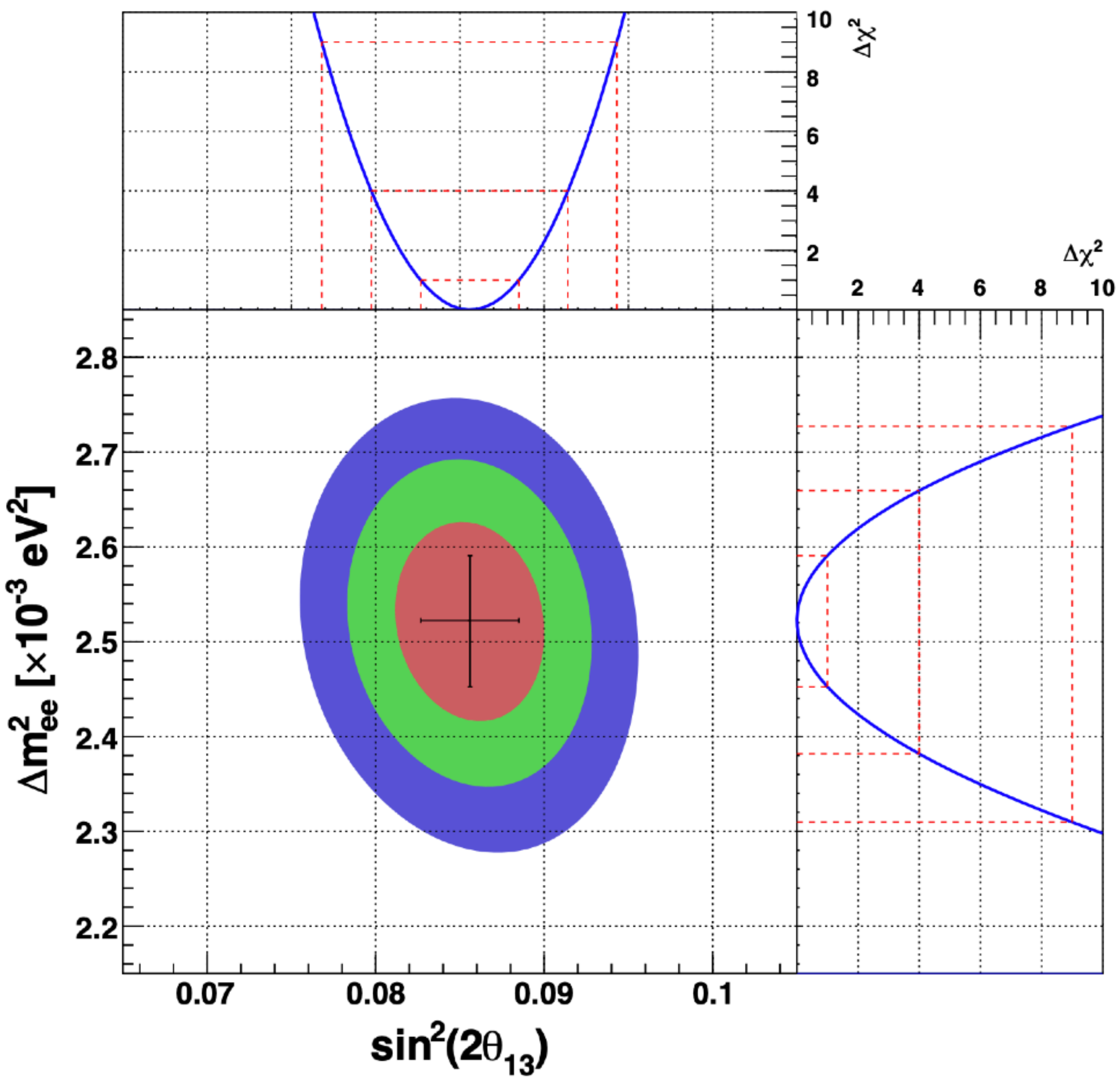


nGd Oscillations Results

- Measurement of $\sin^2 2\theta_{13}$ to 3.4% precision
  - Most precise measurement of θ_{13}: still slightly statistics dominated!
- Measurement of $|\Delta m^2_{32}|$ to 2.8% precision, comparable with accelerator experiments

PRL 121, 241805 (2018)



NO= Normal Ordering
IO = Inverted Ordering

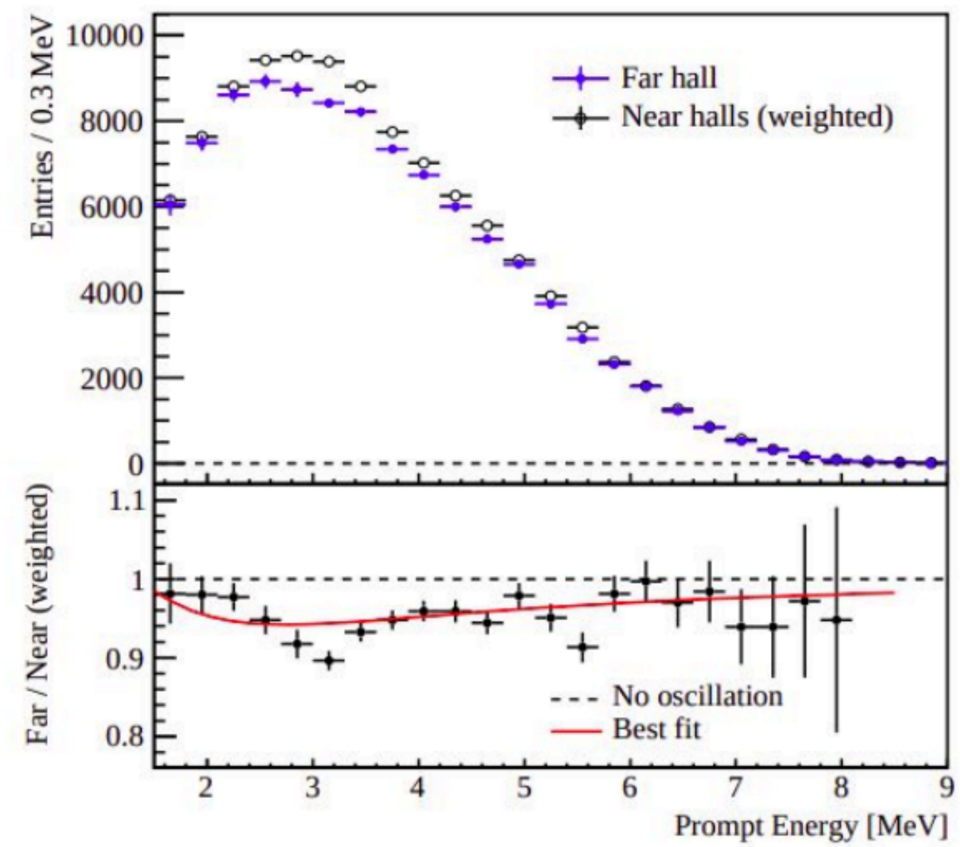
$$\sin^2 2\theta_{13} = 0.0856 \pm 0.0029 \qquad \Delta m^2_{32} = (2.471^{+0.068}_{-0.070}) \times 10^{-3}\ \mathrm{eV}^2\ (\mathrm{NO})$$

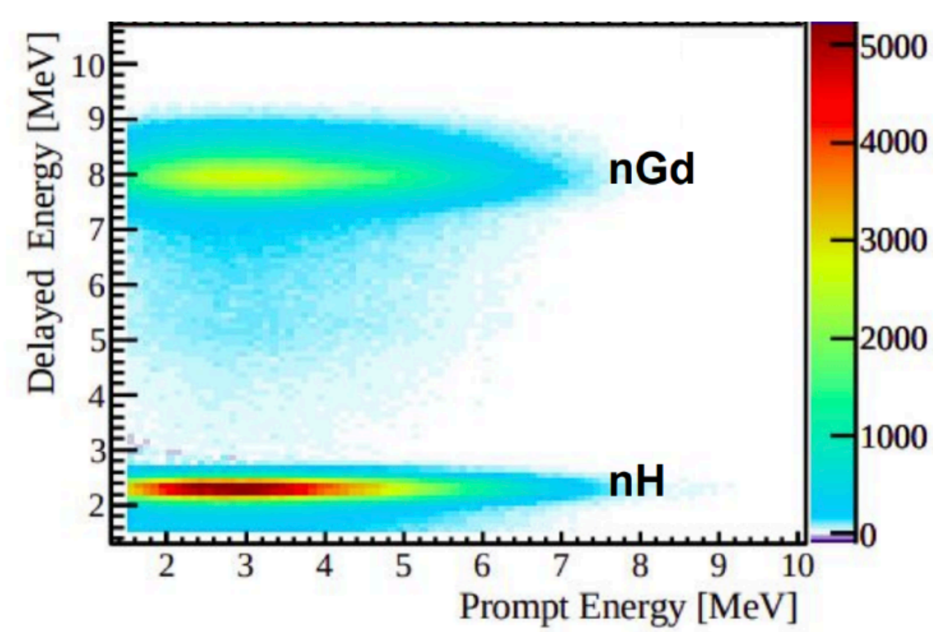
$$\Delta m^2_{ee} = (2.552^{+0.068}_{-0.070}) \times 10^{-3}\ \mathrm{eV}^2 \quad \Delta m^2_{32} = -(2.575^{+0.068}_{-0.070}) \times 10^{-3}\ \mathrm{eV}^2\ (\mathrm{IO})$$

nH Oscillations Results

PRD 93, 072011 (2016)

- Latest nH results from 621 days of data
- Statistically distinct sample with largely uncorrelated systematics to those of nGd, providing a nearly independent result
- Unique challenge due to larger background at lower energy
- Rate-only analysis: new rate+shape analysis in progress, anticipated to be released soon
- $\sin^2 2\theta_{13} = 0.071 \pm 0.011$



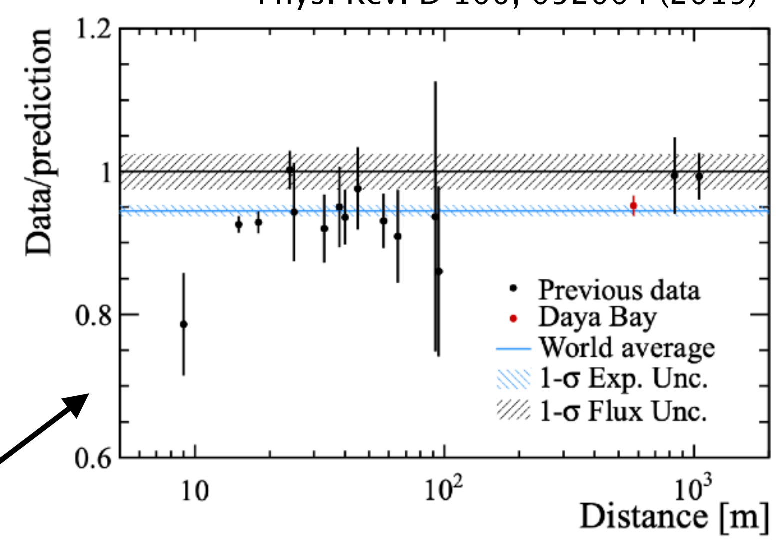


Sterile Neutrinos and Reactors

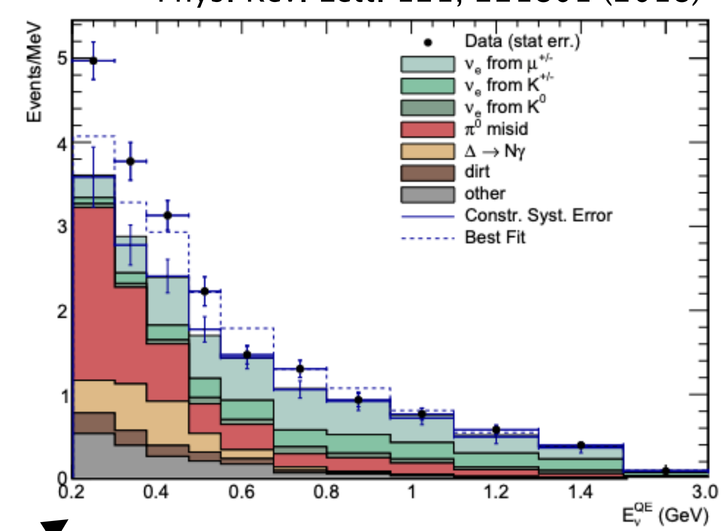
- Sterile neutrino is a proposed 4th neutrino that does not interact via Standard Model forces
- Sterile neutrino searches at short baselines motivated by various anomalous measurements
- Active neutrinos mixing with sterile would present as an additional oscillation distortion

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

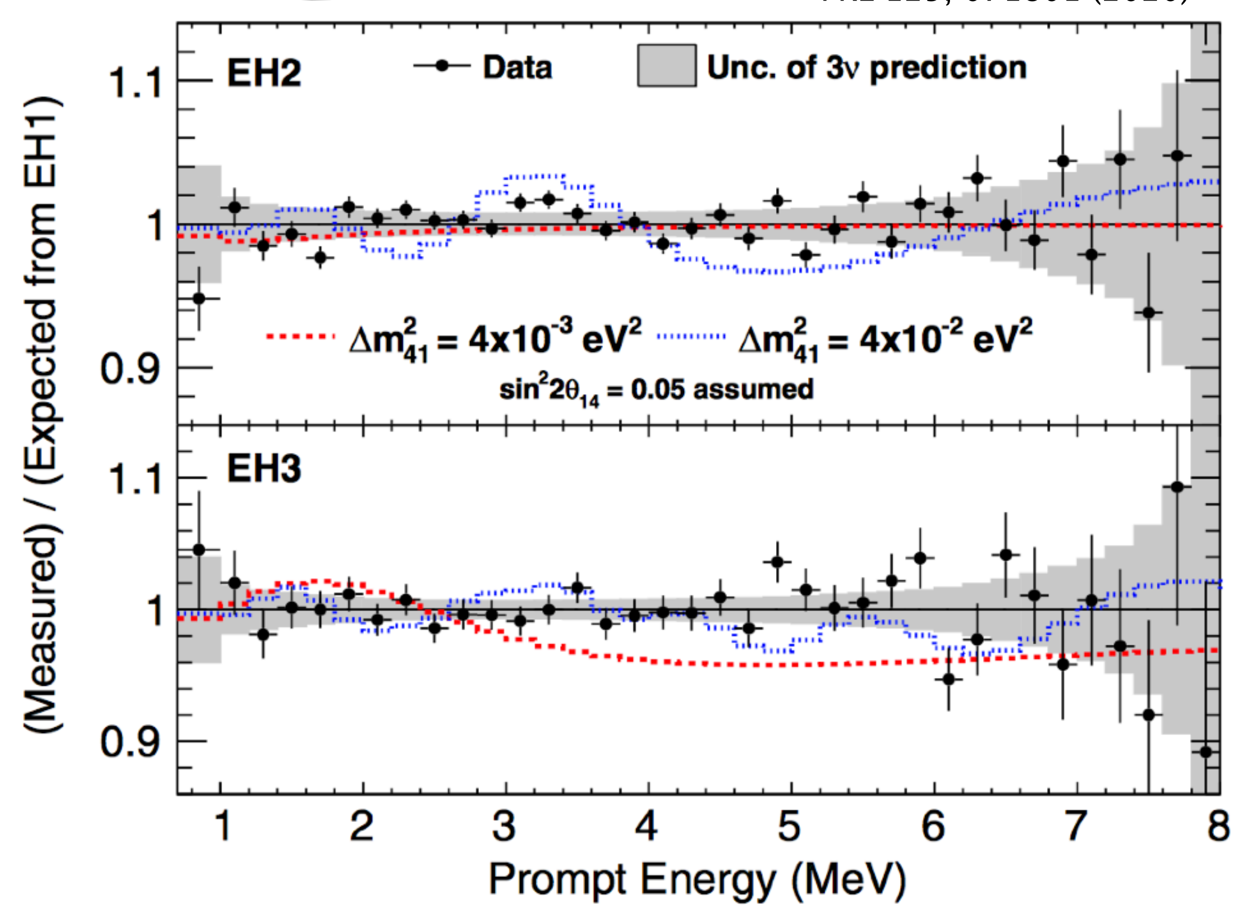
Phys. Rev. D 100, 052004 (2019)



Phys. Rev. Lett. 121, 221801 (2018)



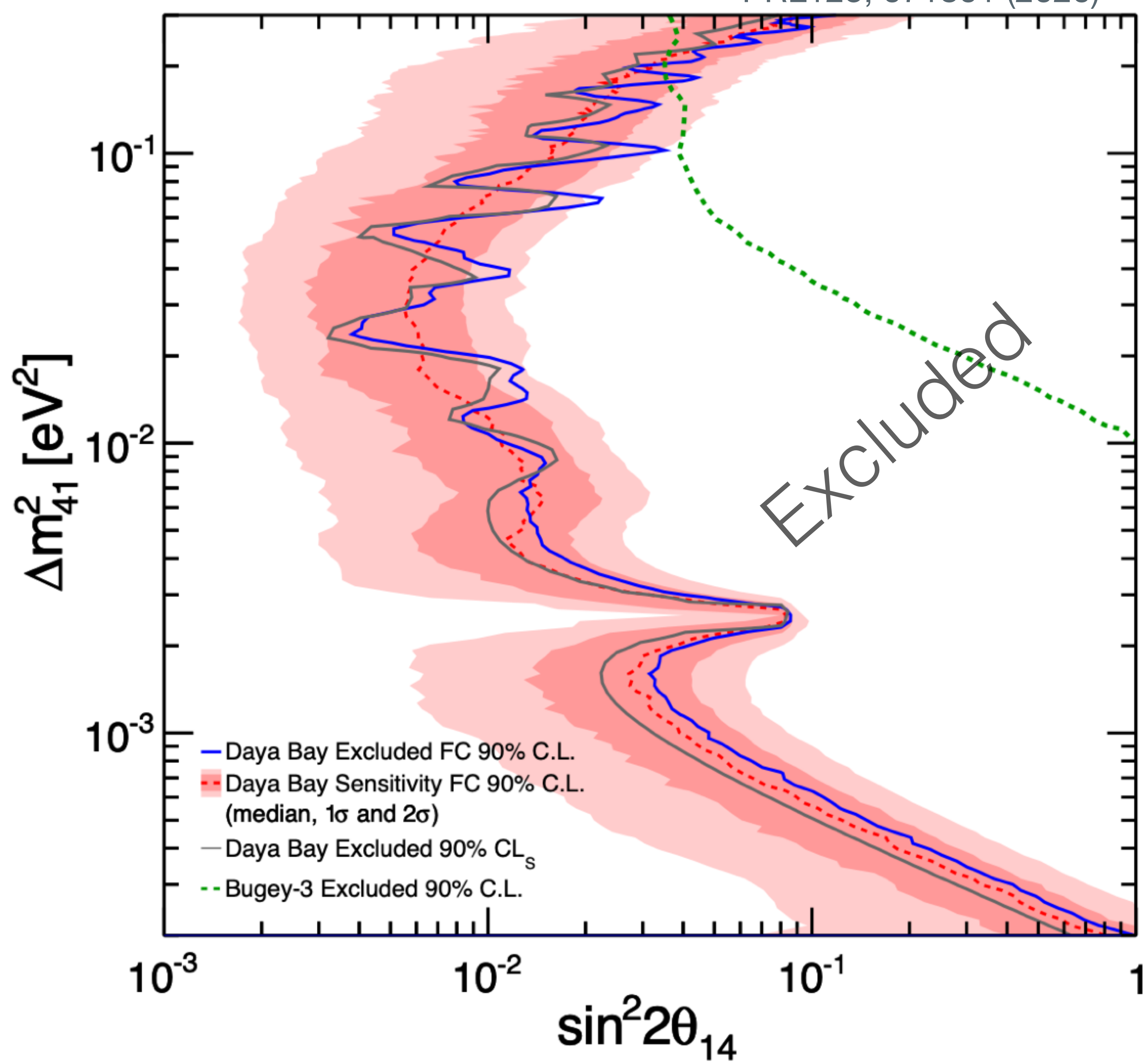
PRL 125, 071801 (2020)



Sterile Neutrinos at Daya Bay

- Relative measurement of rate and shape at different halls assuming 3+1 neutrino model
- θ_{13}, θ_{14} and Δm^2_{41} taken as free parameters
- Gaussian CLs and Feldman-Cousins methods used to set limits in $(\sin^2 2\theta_{14}, \Delta \mathrm{m}^2_{41})$ space
- No significant signal observed: world-leading limits set for $|\Delta m^2_{41}| \le 0.2\mathrm{eV}^2$

PRL125, 071801 (2020)



Check out O. Dalager's poster 804 in T04 for more!

Joint Sterile Neutrino Search

- Joined forces with Bugey-3 and MINOS/MINOS+ experiments
  - Combination with Bugey-3 allows to set limits on greater range of Δm^2_{41}
  - Combination with MINOS/MINOS+ allows to probe excess of $\nu_e, \bar{\nu}_e$ measured by LSND and MiniBooNE experiments

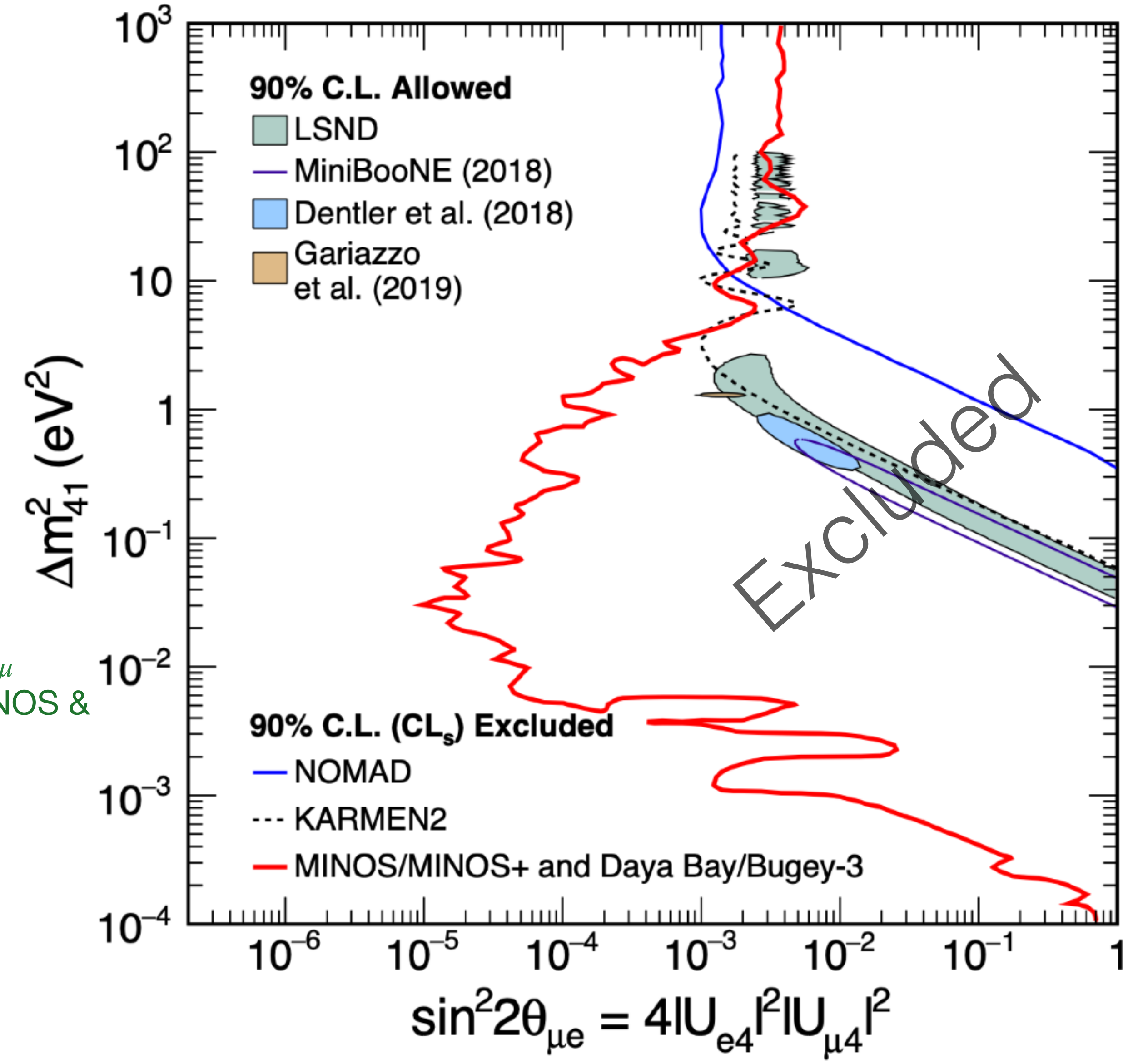
$$P^{SBL}_{\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e} = 4|U_{e4}|^2|U_{\mu 4}|^2 \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

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

Constrained by $\bar{\nu}_e$ disappearance (Daya Bay and Bugey-3)

Constrained by $\overset{(-)}{\nu}_\mu$ disappearance (MINOS & MINOS+)

PRL 125,071801 (2020)



- LSND and MiniBooNE $\Delta m^2_{41} - \sin^2 2\theta_{\mu e}$ parameter space excluded at 90% C.L. for $\Delta m^2_{41} < 13 \text{ eV}^2$
- World-leading limits on $\theta_{\mu e}$ over 5 orders of magnitude on Δm^2_{41}

Summary

- Daya Bay has the leading measurement of reactor antineutrino disappearance at short-baselines

$$\sin^2 2\theta_{13} = 0.0856 \pm 0.0029$$
$$\Delta m^2_{32} = (2.471^{+0.068}_{-0.070}) \times 10^{-3}\ \mathrm{eV}^2\ (\mathrm{NO})$$
$$\Delta m^2_{32} = -\,(2.575^{+0.068}_{-0.070}) \times 10^{-3}\ \mathrm{eV}^2\ (\mathrm{IO})$$

- Independent oscillation analysis using neutron capture on hydrogen performed, with updated result in preparation

- Search for sterile neutrinos in conjunction with Bugey-3 and MINOS/MINOS+ found no significant signal and set stringent limits over 5 orders of magnitude in Δm^2_{41}

- Data-taking ended in Dec. 2020: final analyses by 2022

Daya Bay Posters in EPS-HEP

- Poster 738: Joint Determination of Reactor Antineutrino Spectra from ^{235}U and ^{239}Pu Fission using the Daya Bay and PROSPECT Experiments (J. Hu)
- Poster 804: Sterile Neutrinos in Daya Bay (O. Dalager)
- Poster 916: Daya Bay Reactor Neutrino Flux and Spectrum Measurement (R. Zhao and Y. Yang)

Stay Tuned and check out our posters!

Backup: Effective Mass Difference

$$P_{ee} = 1 - \sin^2 2\theta_{13} \sin^2(\Delta m^2_{ee} \frac{L}{4E}) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2(\Delta m^2_{21} \frac{L}{4E})$$

- Dominant oscillation frequency at short baselines
- Model-independent parameter: invariant with mass ordering
- Independent fit from fundamental oscillation parameters: Daya Bay measures both