Latest Neutrino Oscillation Results from Daya Bay

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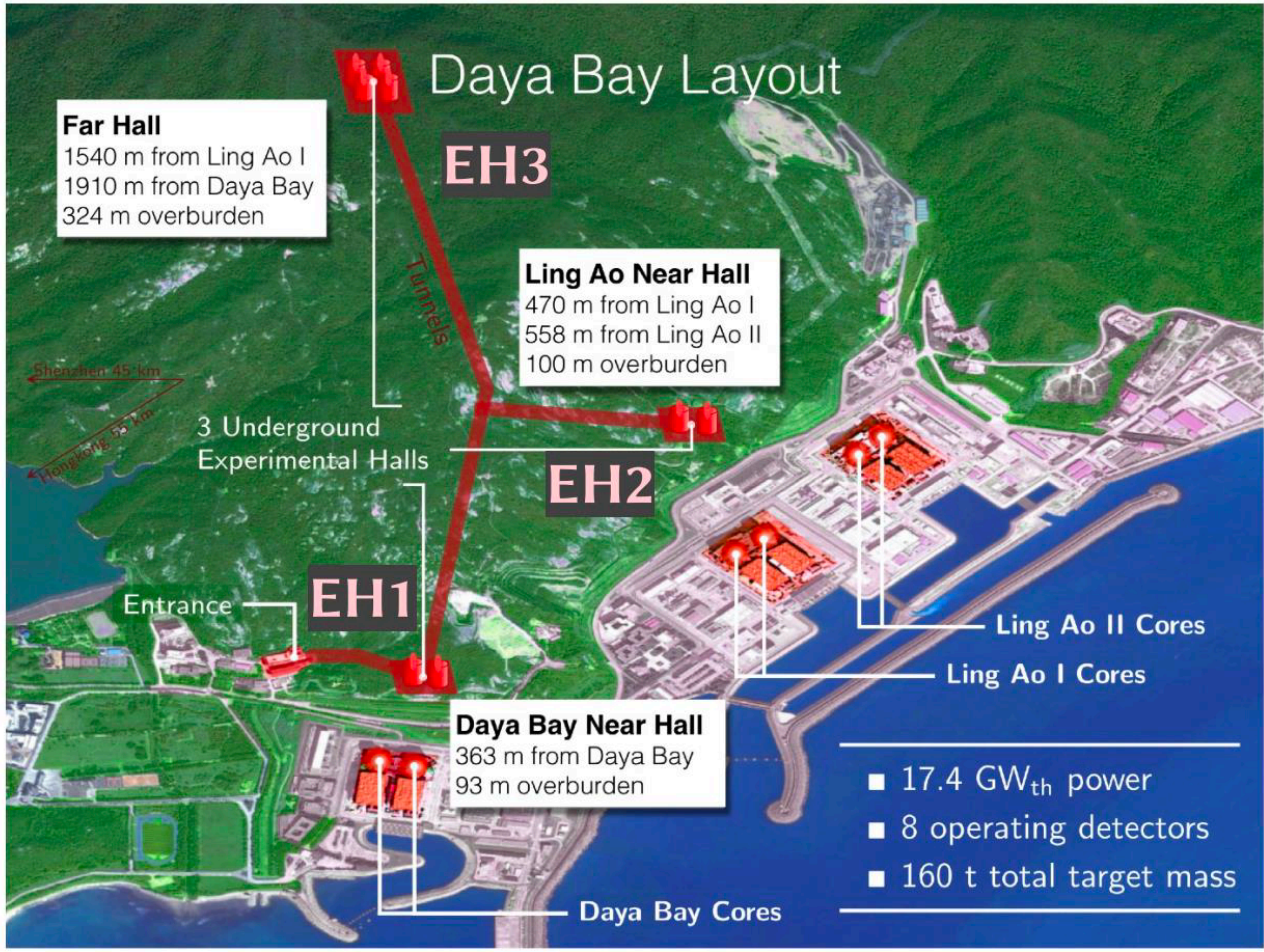
Outline

- Overview of the Daya Bay Experiment
- Neutrino Oscillation
- Oscillation Results with Gadolinium-capture Sample
  Final result: Phys. Rev. Lett. 130, 161802 (2023)
- Oscillation Results with Hydrogen-capture Sample
  New result! [arXiv:2406.01007]
- Search for Sterile Neutrinos
  New result! [arXiv:2404.01687]
- Summary and Prospects

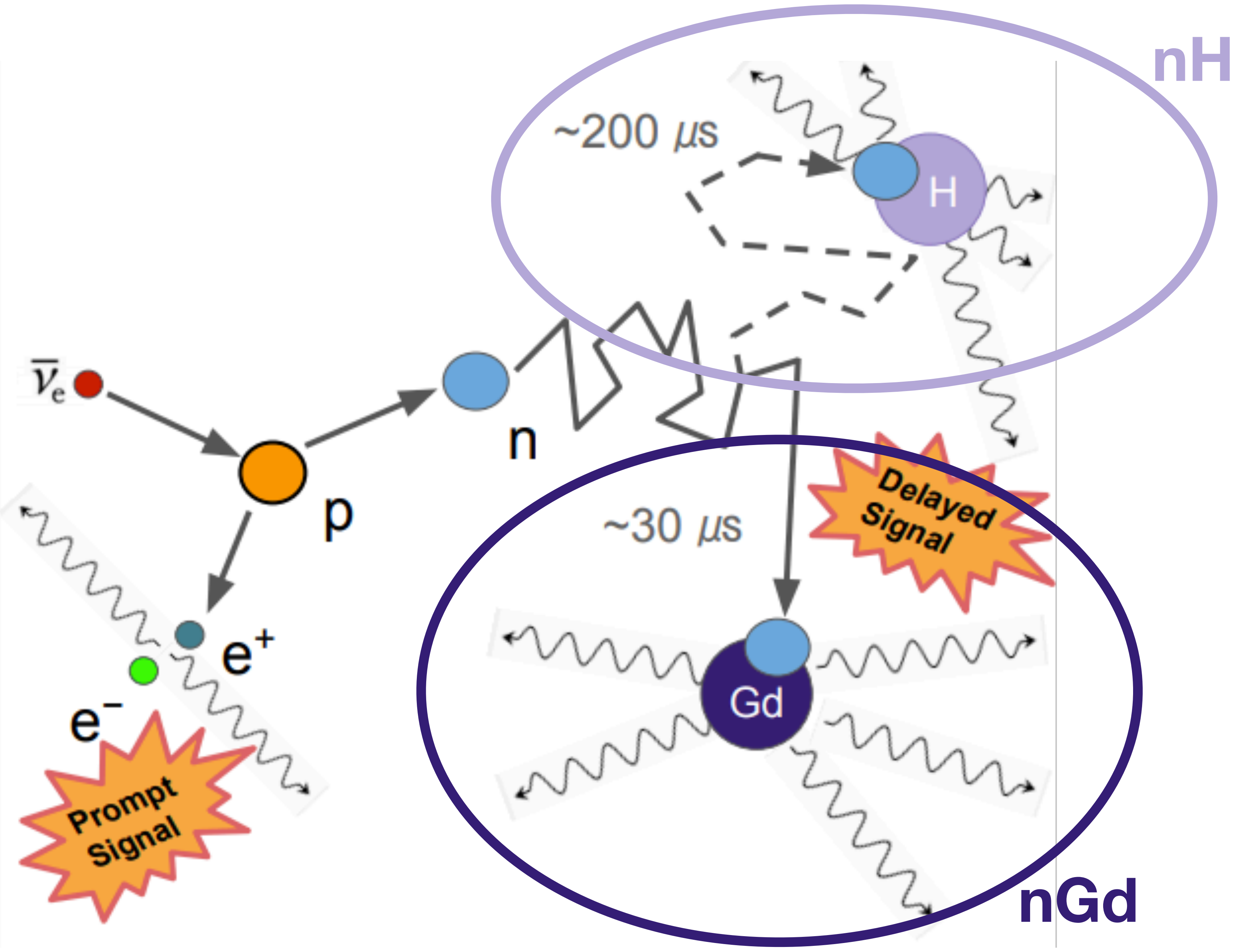
Daya Bay Experiment

- Six 2.9 GW_{th} reactors as very strong antineutrino sources(~6×10^{20} per reactor per second)
- Eight antineutrino detectors (ADs) deployed in three experimental halls (EHs)
  - Near 4 ADs: sample the flux precisely with minor oscillation effect
  - The other 4 ADs: measure the oscillated flux and spectrum due to non-zero θ_{13}
- Highly reduced systematic uncertainties thanks to the near/far measurements
- Collecting data from Dec. 24, 2011 to Dec. 12, 2020

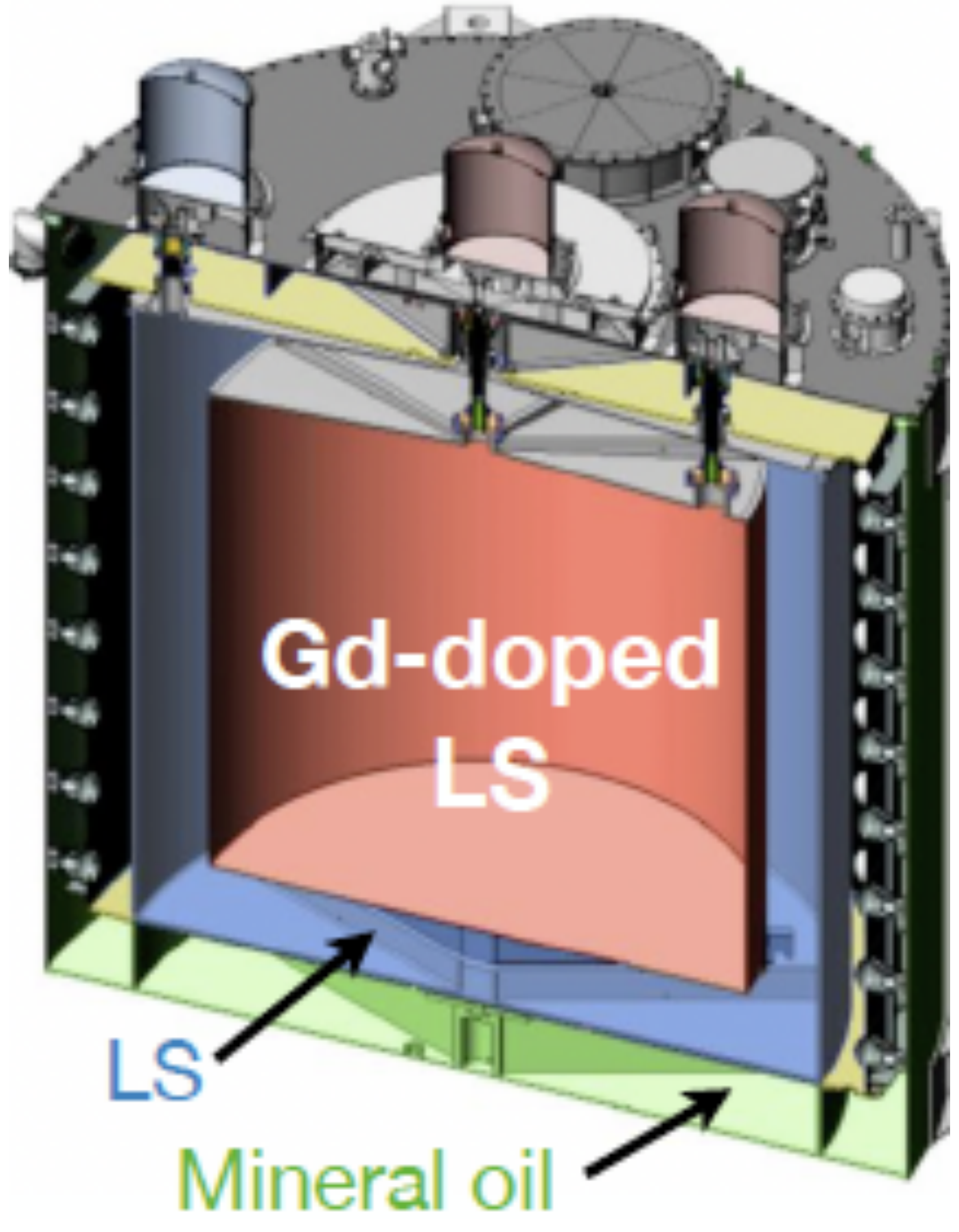


Neutrino Detection

- Inverse beta decay (IBD)
  - $\overline{\nu}_e + p \rightarrow e^+ + n$
- Featured prompt-delayed pairs
  - **Prompt** positron ionization and annihilation
  - **Delayed** γ('s) of ~8 MeV for nGd or 2.2 MeV for nH
- Allows for strong background suppression



NIM A773 (2015) 8
NIM A811 (2016) 133

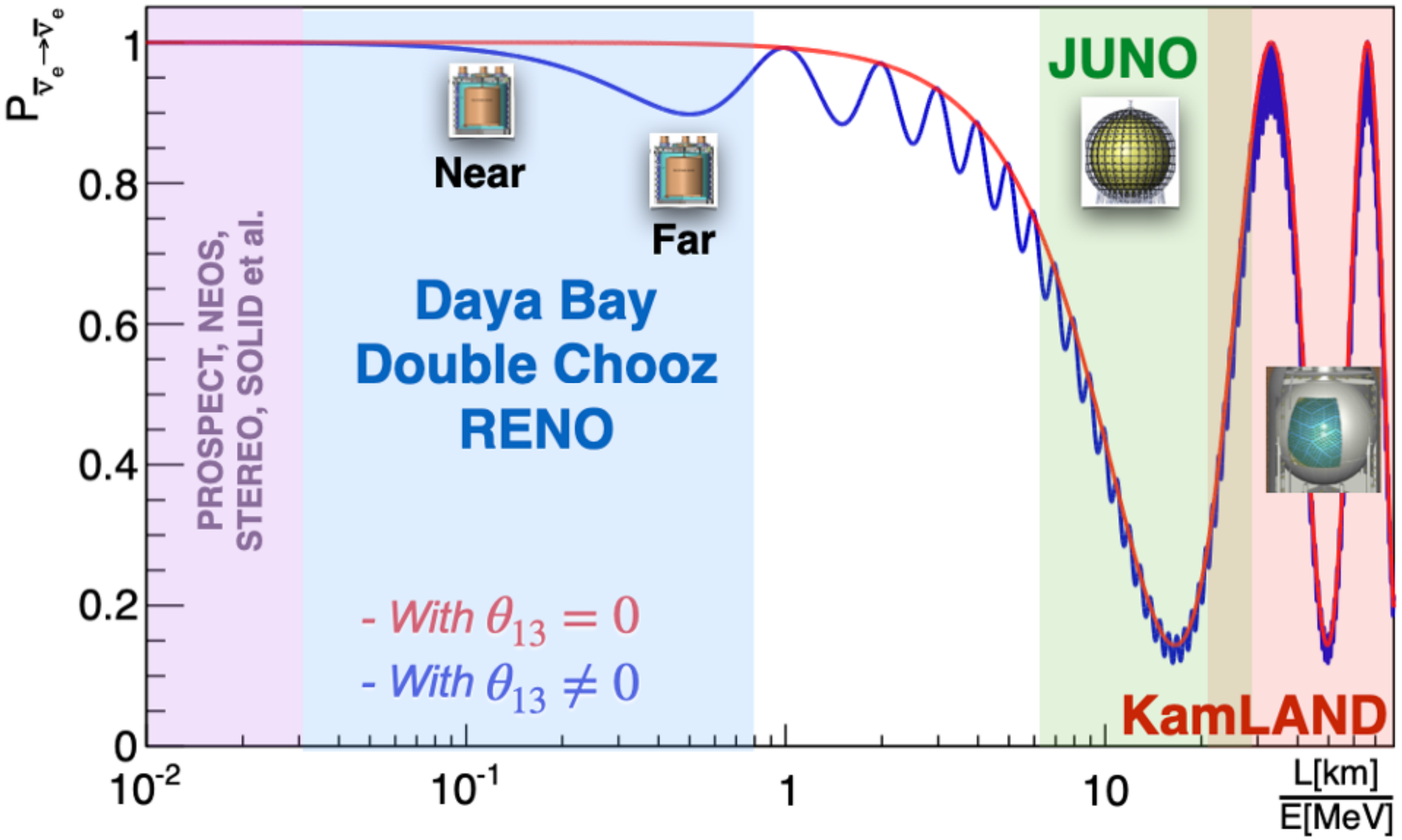


- 20 tons of 0.1% Gd-loaded liquid scintillator (GdLS) as target for nGd
- 21 tons of liquid scintillator (LS) as gamma catcher and main target for nH
- 40 tons of mineral oil as shielding

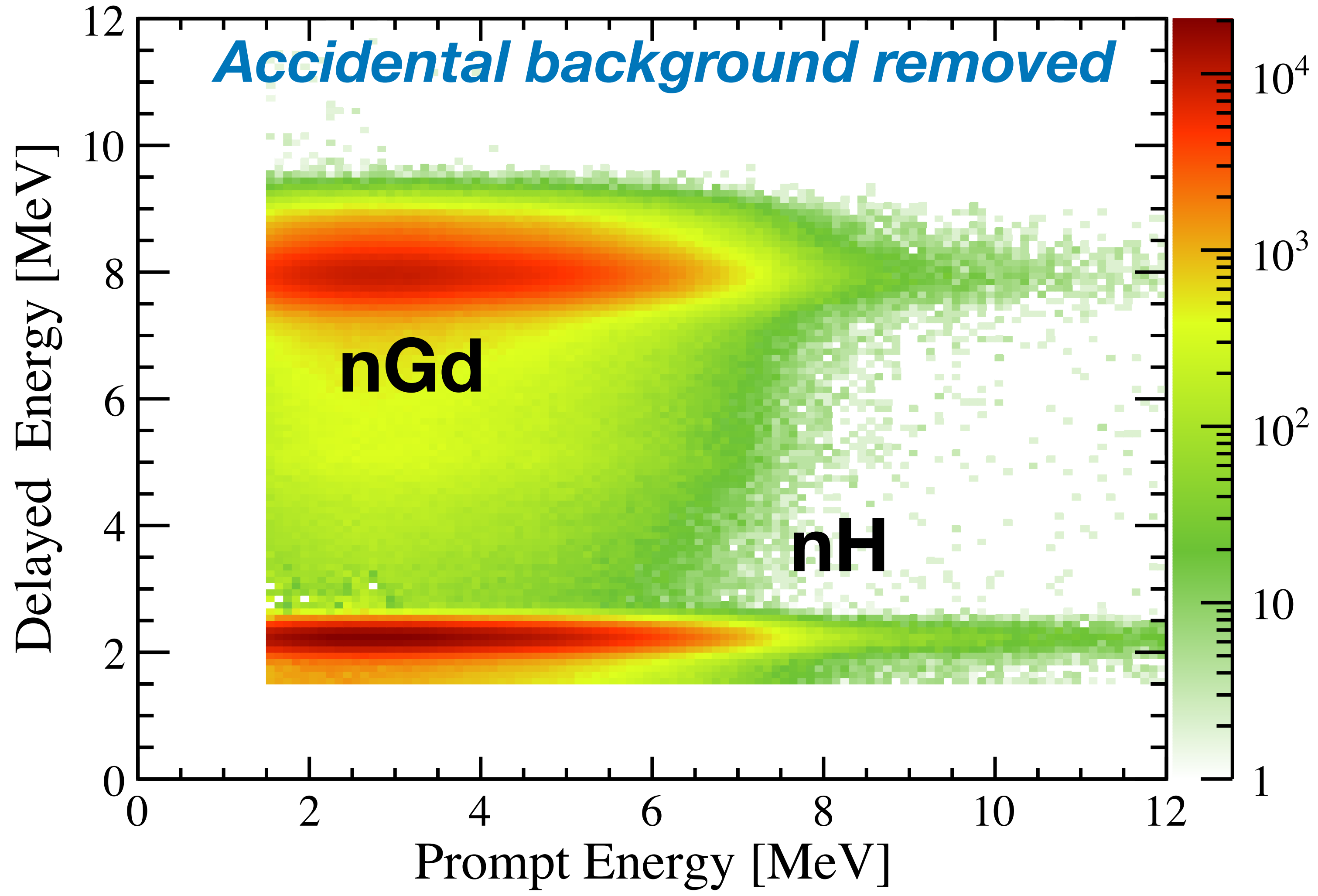
Neutrino Oscillation

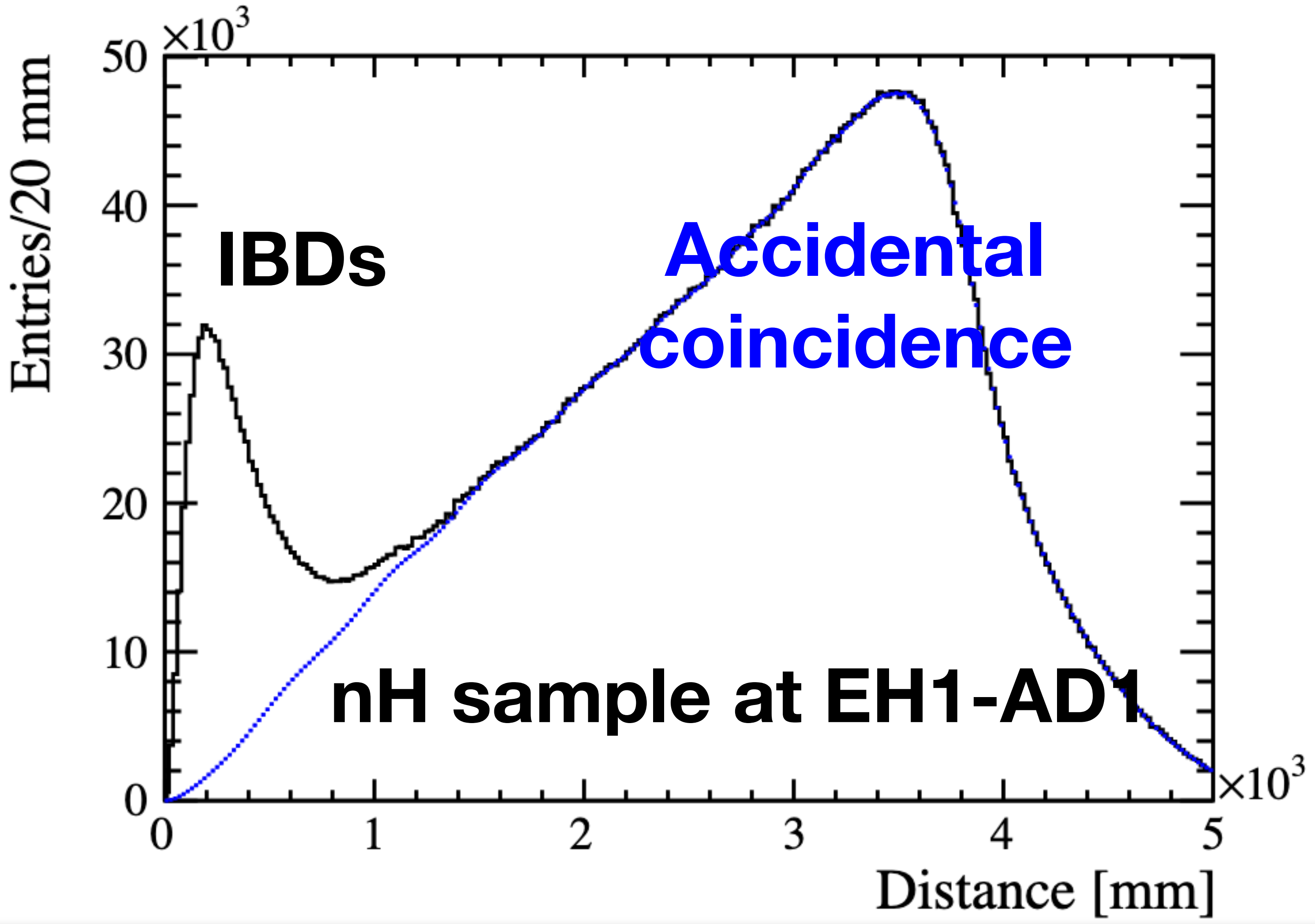
$$P_{\bar{\nu}_e\to\bar{\nu}_e}(L,E) = 1 - \sin^2 2\theta_{12}\cos^4\theta_{13}\sin^2\frac{\Delta m^2_{21}L}{4E} - \sin^2 2\theta_{13}\left(\cos^2\theta_{12}\sin^2\frac{\Delta m^2_{31}L}{4E} + \sin^2\theta_{12}\sin^2\frac{\Delta m^2_{32}L}{4E}\right)$$

- Neutrinos change flavor state as a function of distance (*L*) and energy (*E*)
- Daya Bay observes $\bar{\nu}_e$ disappearance at a baseline around the first maximum of oscillation term modulated by $\sin^2 2\theta_{13}$



Selection of IBD Candidates

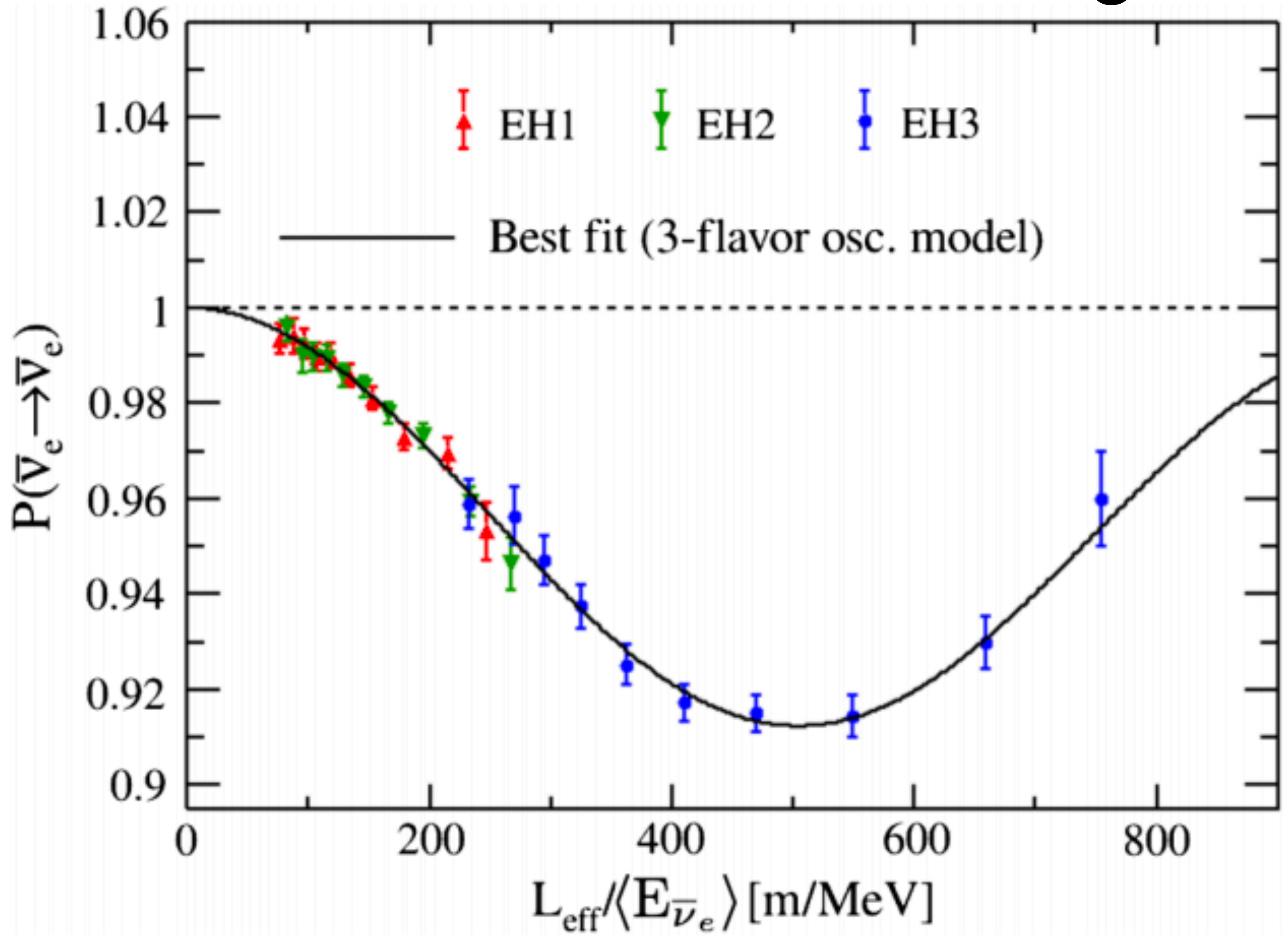


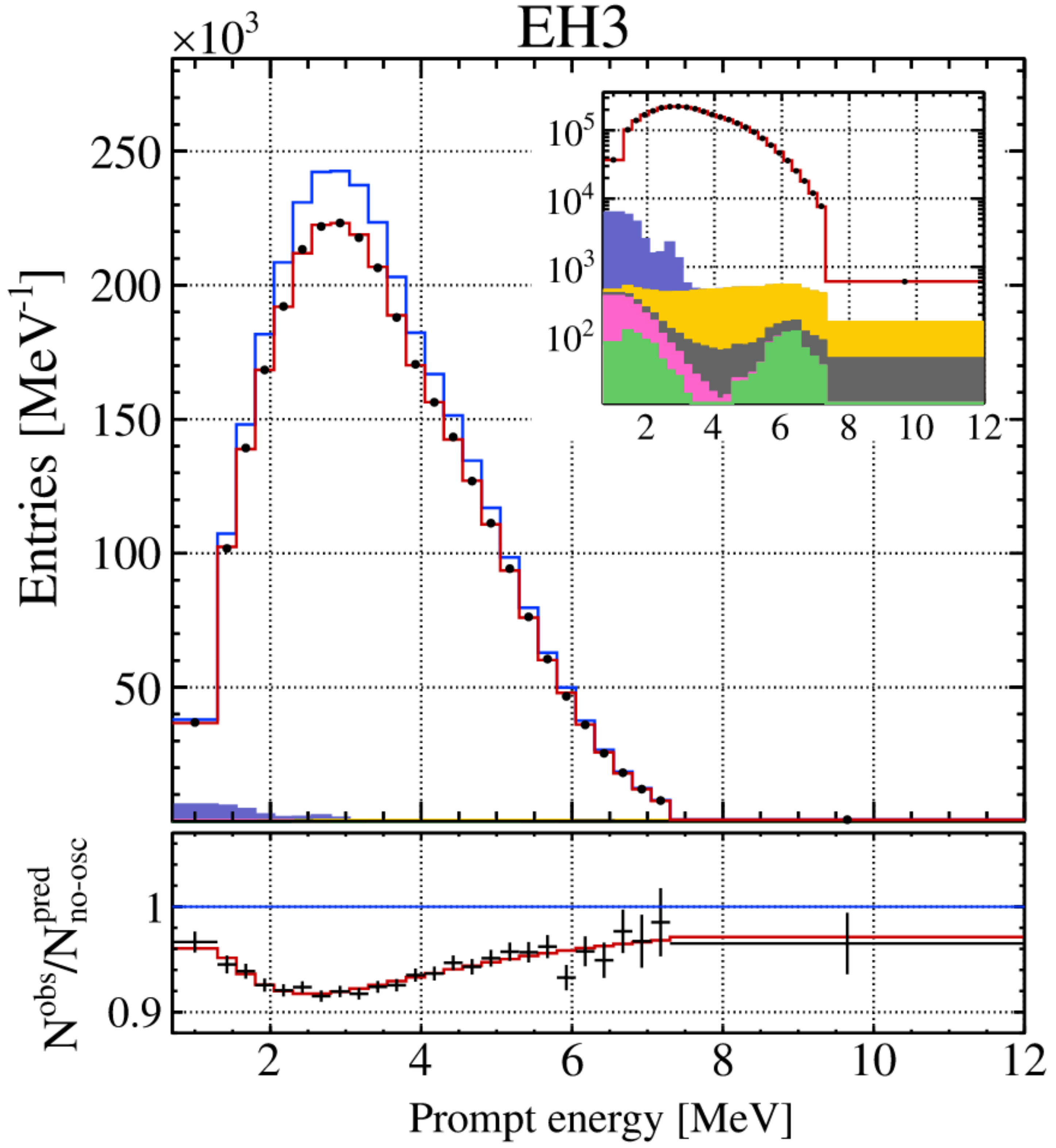


- Remove spontaneous flashing from PMTs
- Veto events that are close in time to muons
- Energy criteria
- Temporal and spatial coincidence
  - nGd: 1 μs < Δt < 200 μs
  - nH: Δt > 1 μs, $\Delta r + \Delta t$/[600 μs/m] < 1 m
- Multiplicity cut: time-isolated event pairs

Oscillation Results Based on nGd

Normal mass ordering





Best fit results:

χ^2/NDF = 559/518

$\sin^2 2\theta_{13}$ = 0.0851±0.0024 (2.8% precision)

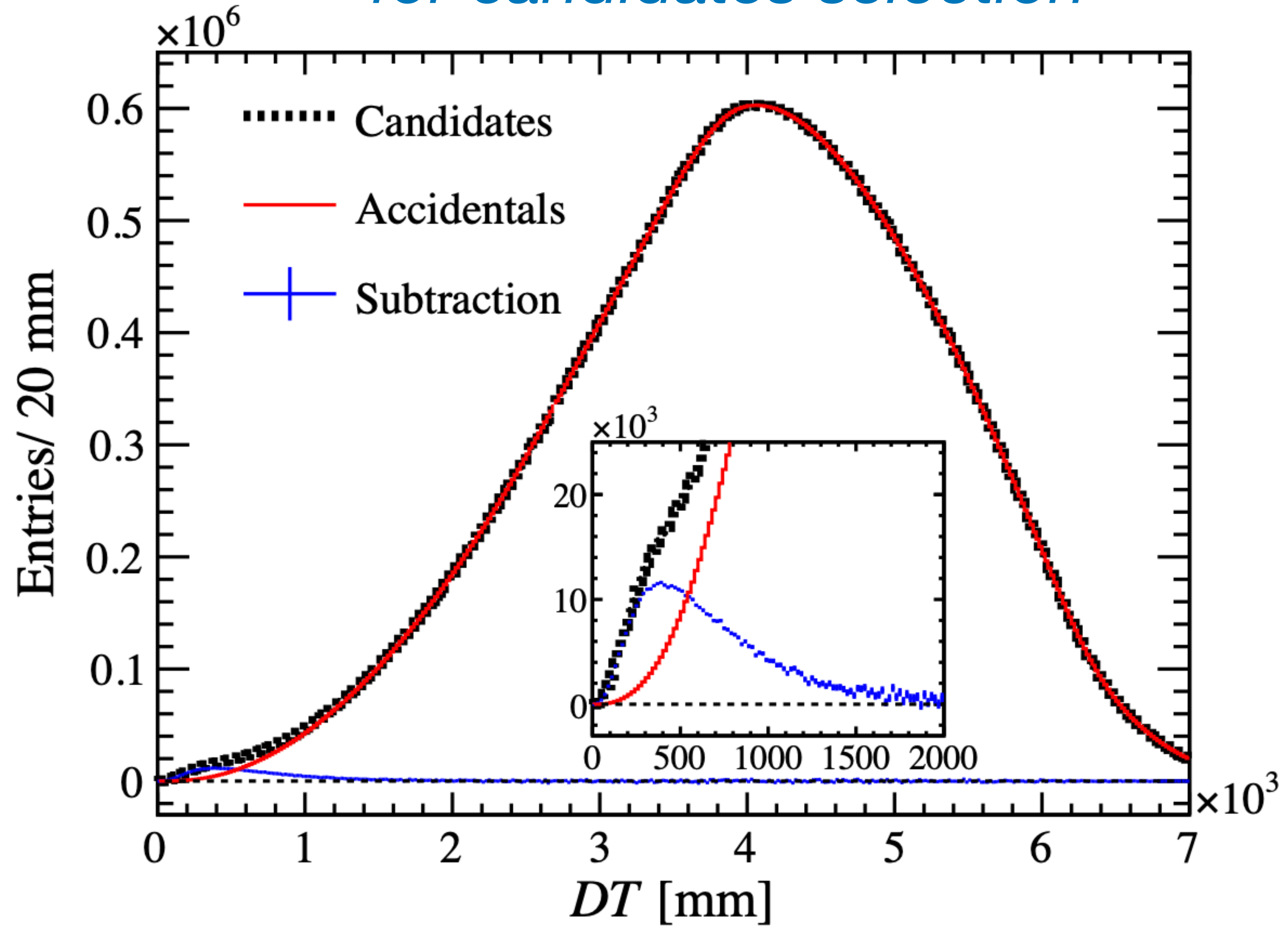
Normal mass ordering : Δm^2_{32} = (2.466±0.060)×10^{-3} eV^2 (2.4% precision)

Inverted mass ordering : Δm^2_{32} = -(2.571±0.060)×10^{-3} eV^2 (2.3% precision)

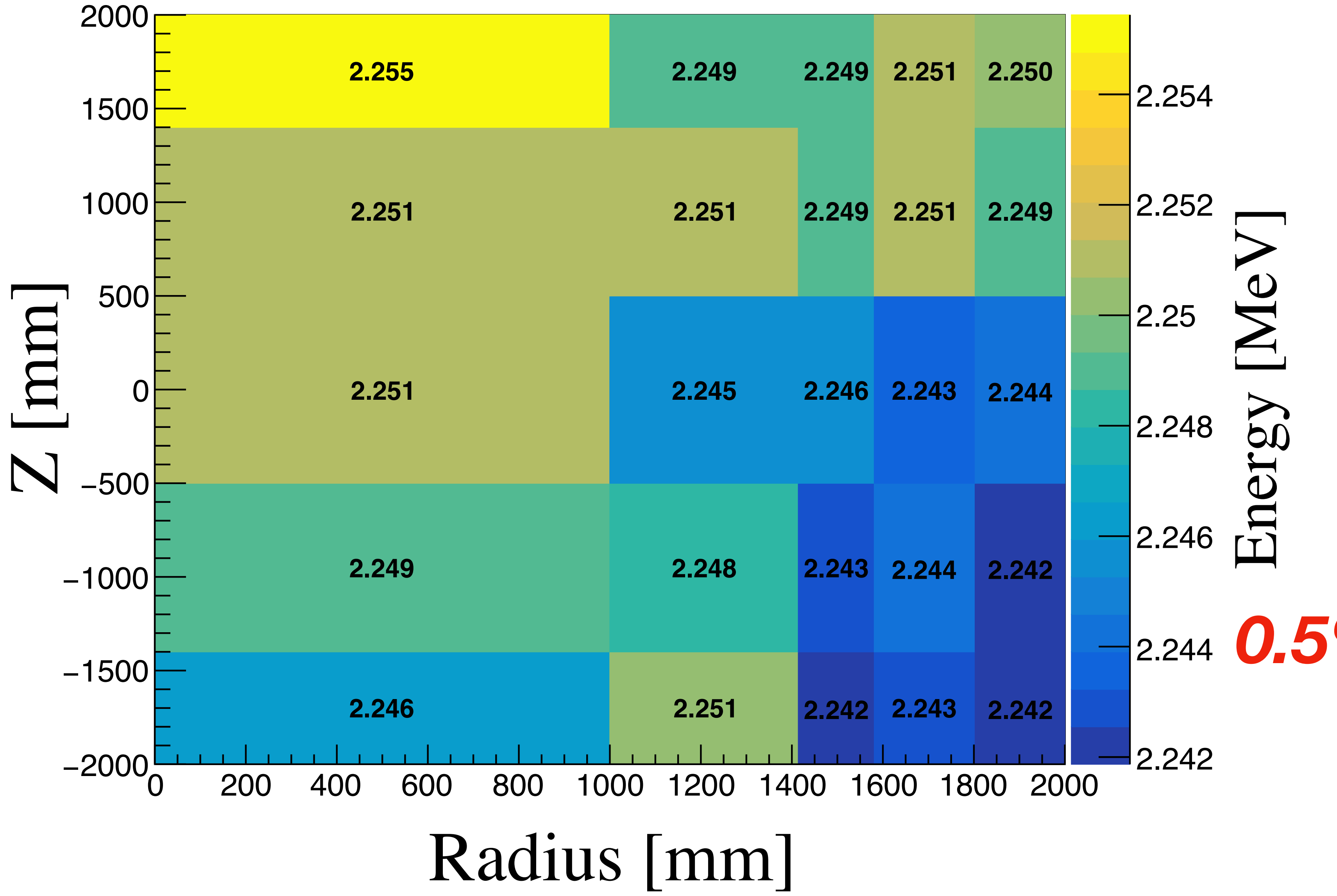
New Oscillation Results Based on nH

- New nH oscillation result with 1958 days of data in **arXiv:2406.01007** released on June 3, 2024
  [Previous DYB nH result: PRD 93, 072011 (2016)]
  - **Two independent analyses: consistent**
  - **3.1 times more statistics** (2/3 of the full data set)
  - **Significant improvements in candidate selection, backgrounds and efficiencies, energy calibration…**

Combining distance and time
for candidates selection



- *Energy scale difference among ADs ≲ 0.3%*
- *… among voxels ≲ 0.5%*

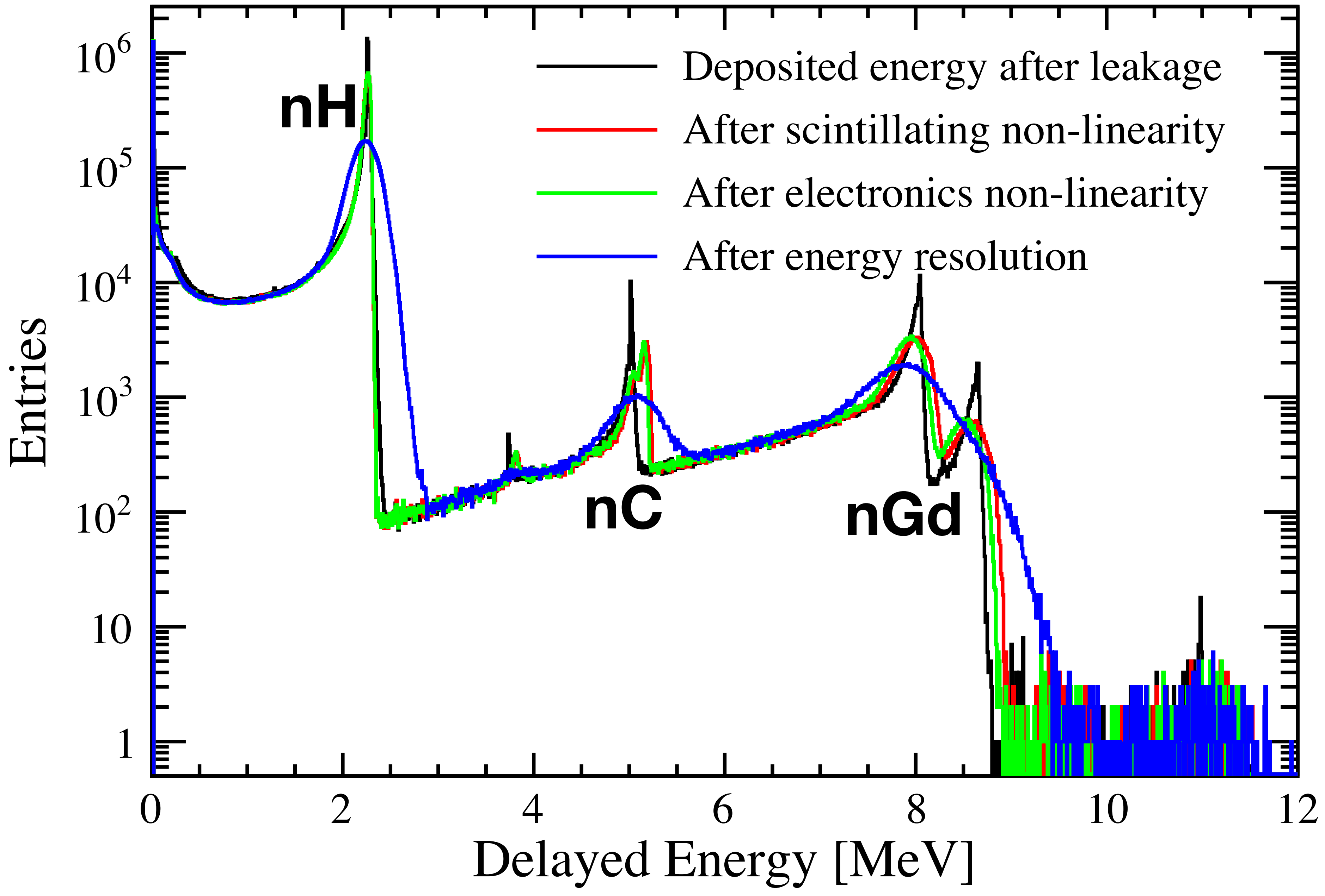


0.5% Z-axis range

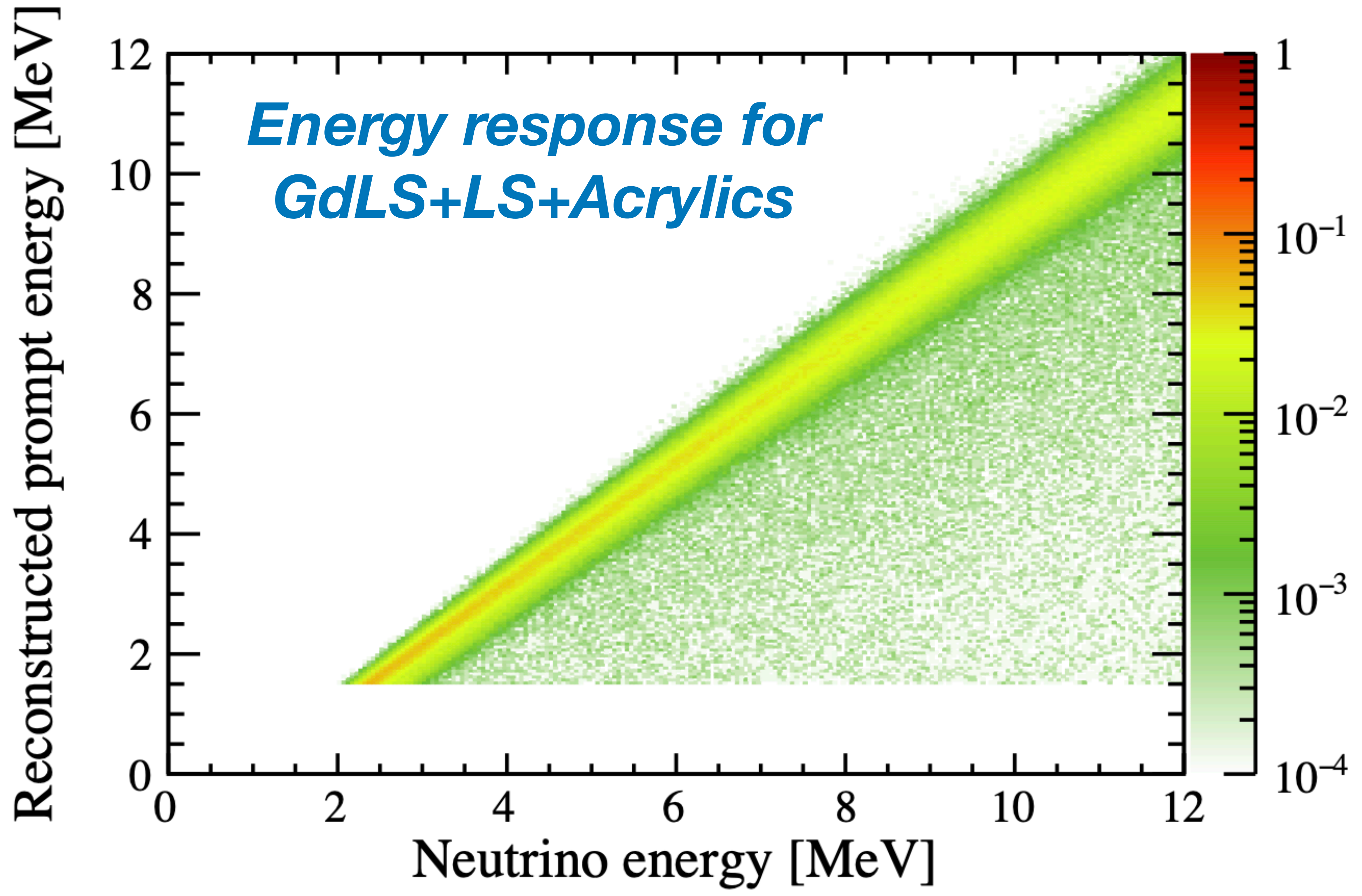
New Oscillation Results Based on nH

- **New energy response model -> First rate+shape analysis with nH-only sample**
  - Adding the non-linearities on deposited energy on step-by-step basis
  - Able to decouple leakage for data with Calorimeter function: *Nucl. Instrum. Meth. A 827 (2016), 165-170*
  - Able to adjust each effect and study the resulted uncertainty on the measured prompt spectrum

Simulated IBDs in LS volume

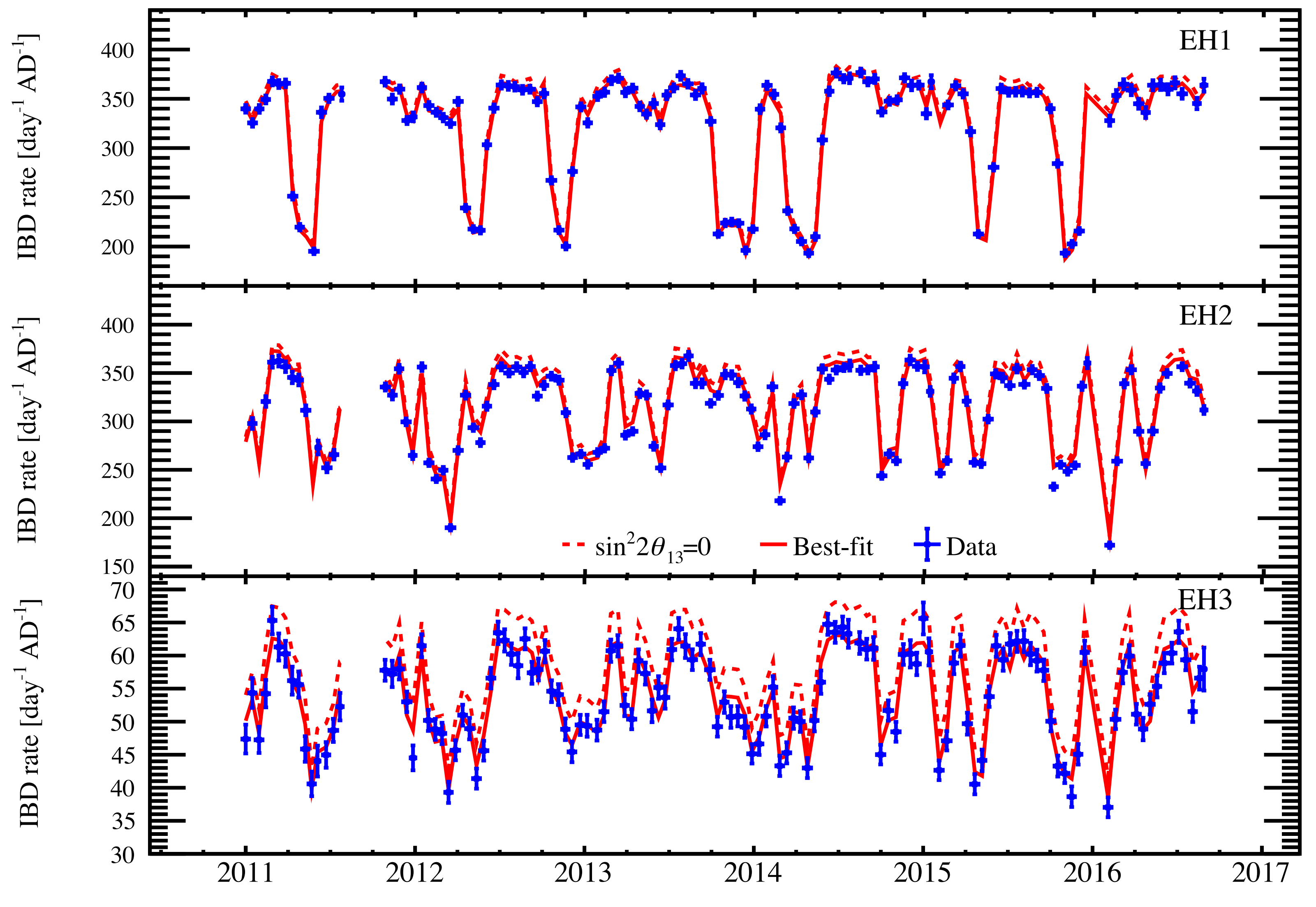


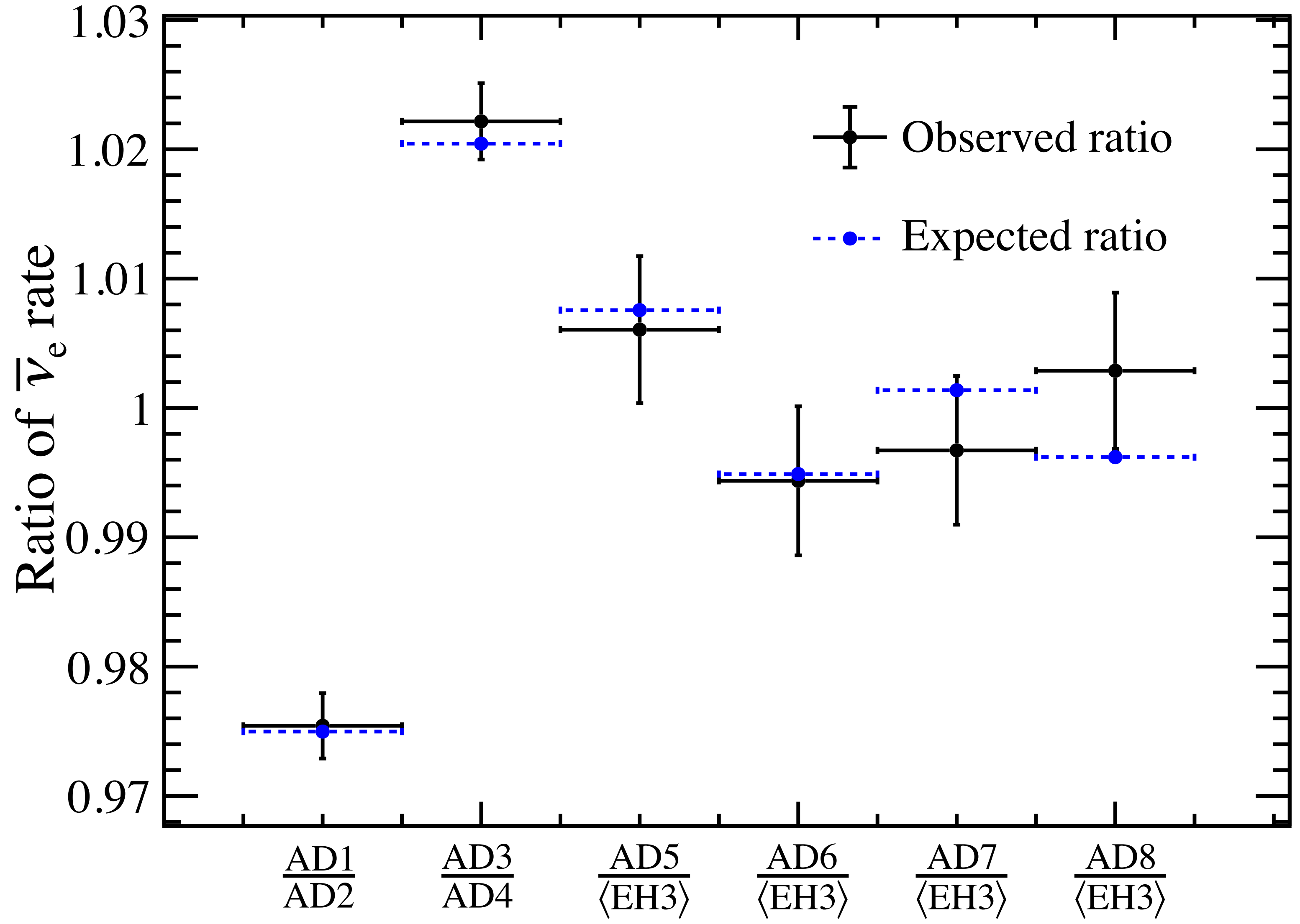
Adjusting Non-uniformities in Monte-Carlo according to Data

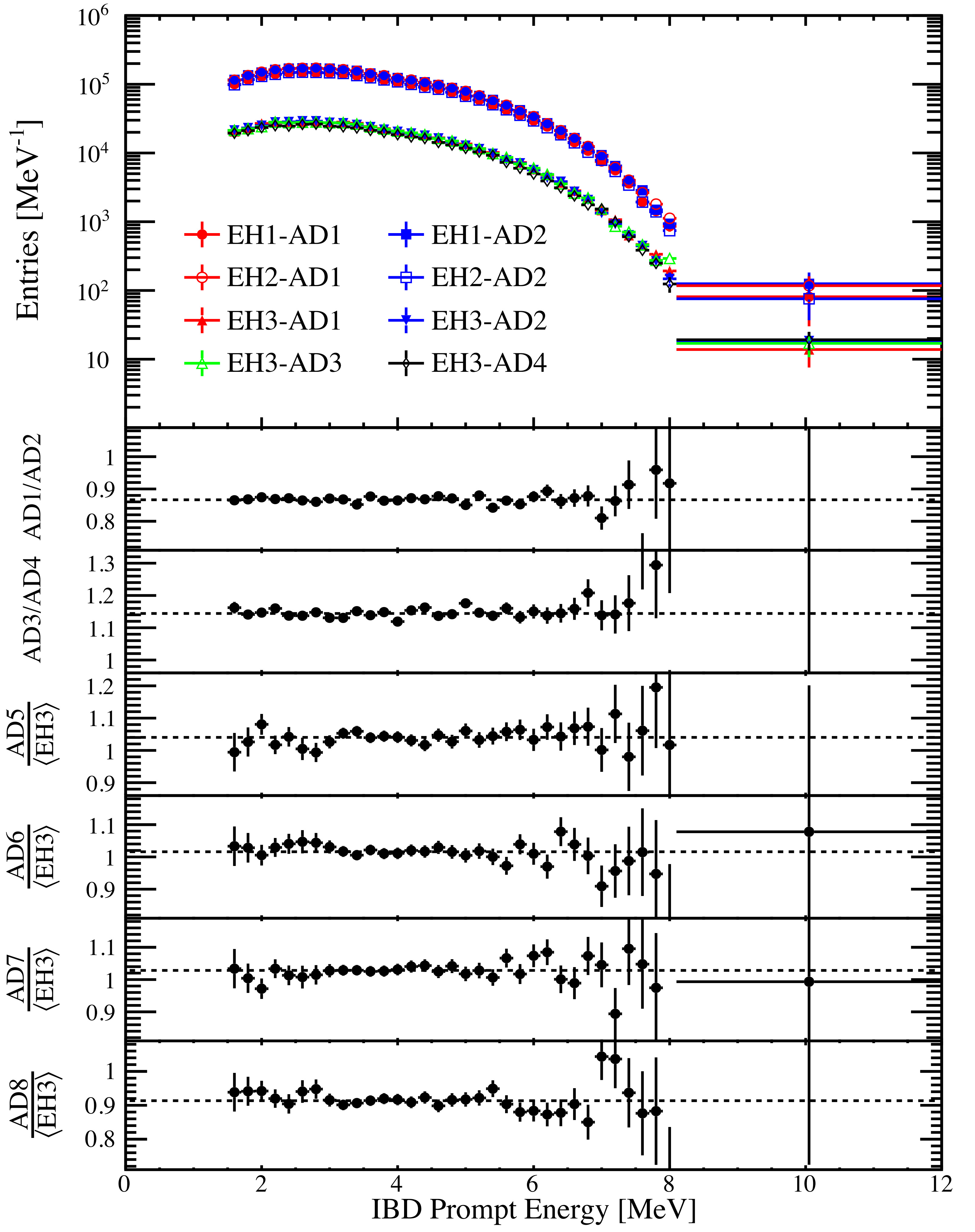


New Oscillation Results Based on nH

- The identicalness among ADs is examined and used to evaluate the AD-uncorrelated uncertainties
- The total systematic uncertainty benefits from the larger statistics and new control techniques
  - Reduced from 0.57% to 0.34% in this result







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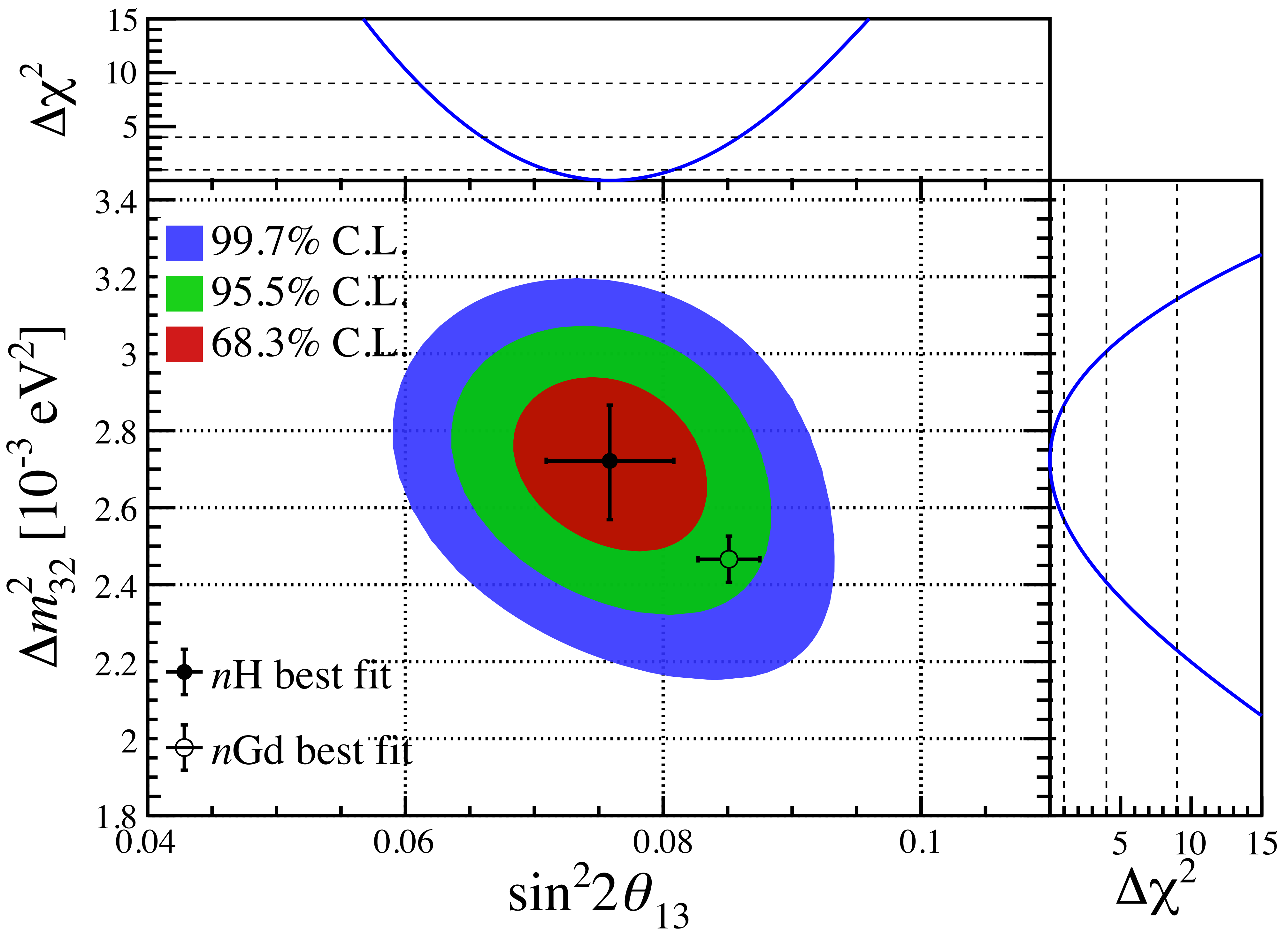
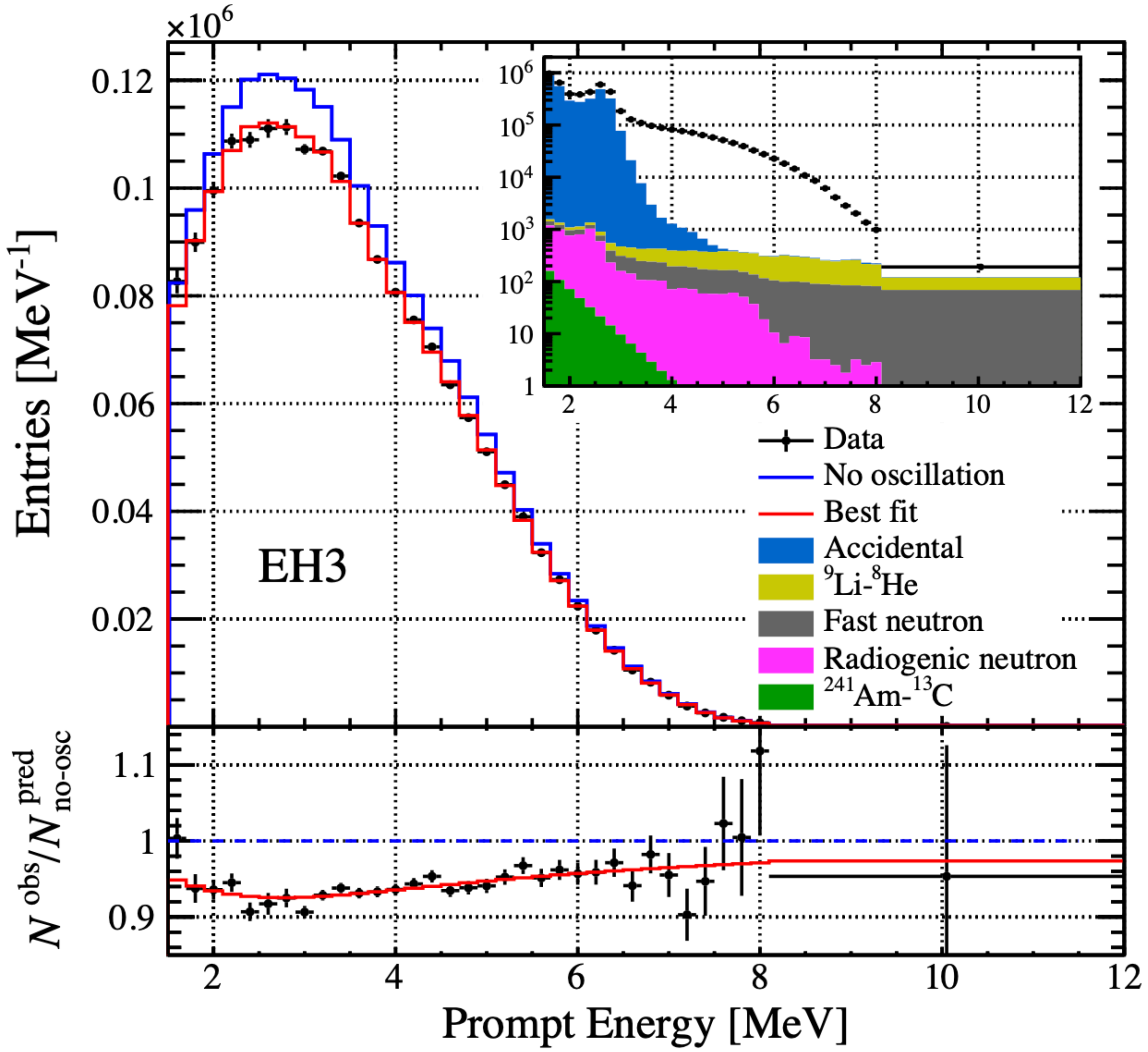




- The results with rate+shape analysis yield:

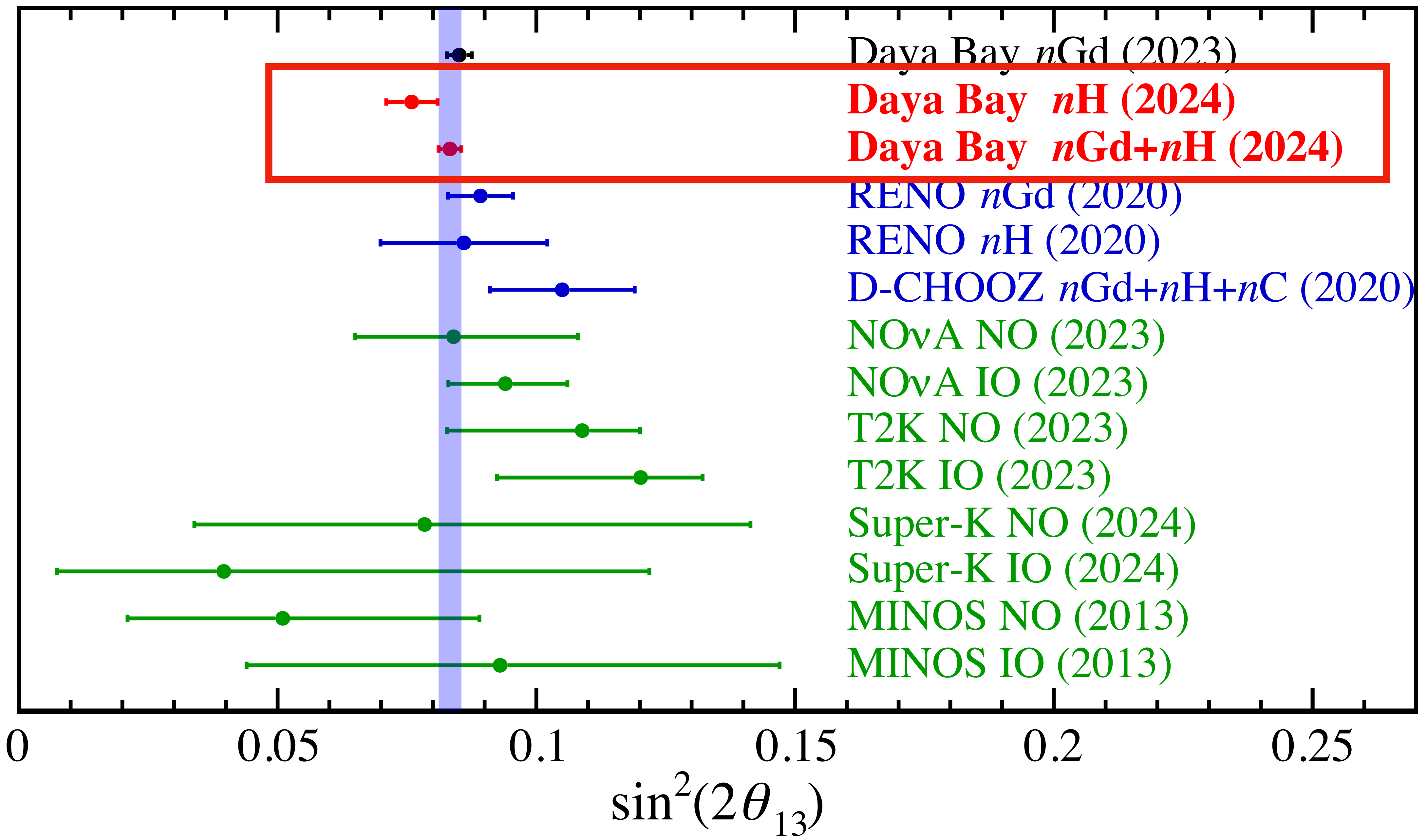
$$\sin^2 2\theta_{13} = 0.0759^{+0.0050}_{-0.0049}$$

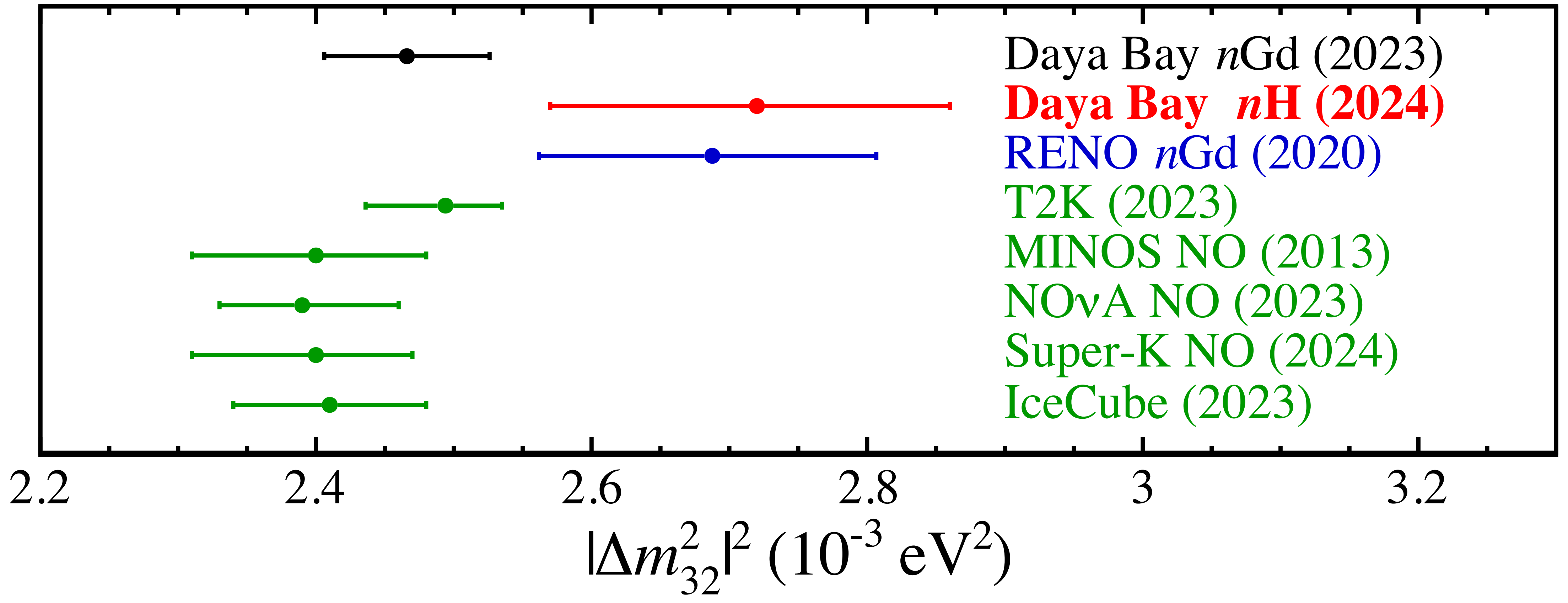
$$\Delta m^2_{32} = 2.72^{+0.14}_{-0.15} \times 10^{-3}\ \text{eV}^2\ \ [\text{NO}], \quad -2.83^{+0.15}_{-0.14} \times 10^{-3}\ \text{eV}^2\ \ [\text{IO}]$$

- nGd+nH combined result: 0.0833 ± 0.0022

Global Comparison

- **Daya Bay's nH measurement provides a $\sin^2 2\theta_{13}$ precision surpassed only by Daya Bay's nGd result**
  - Statistical uncertainty accounts for about 46% of the total
  - 8% improvement in nGd+nH result compared to nGd-only
- **nGd+nH leads to a precision measurement of $\sin^2 2\theta_{13}$, 2.6% precision**





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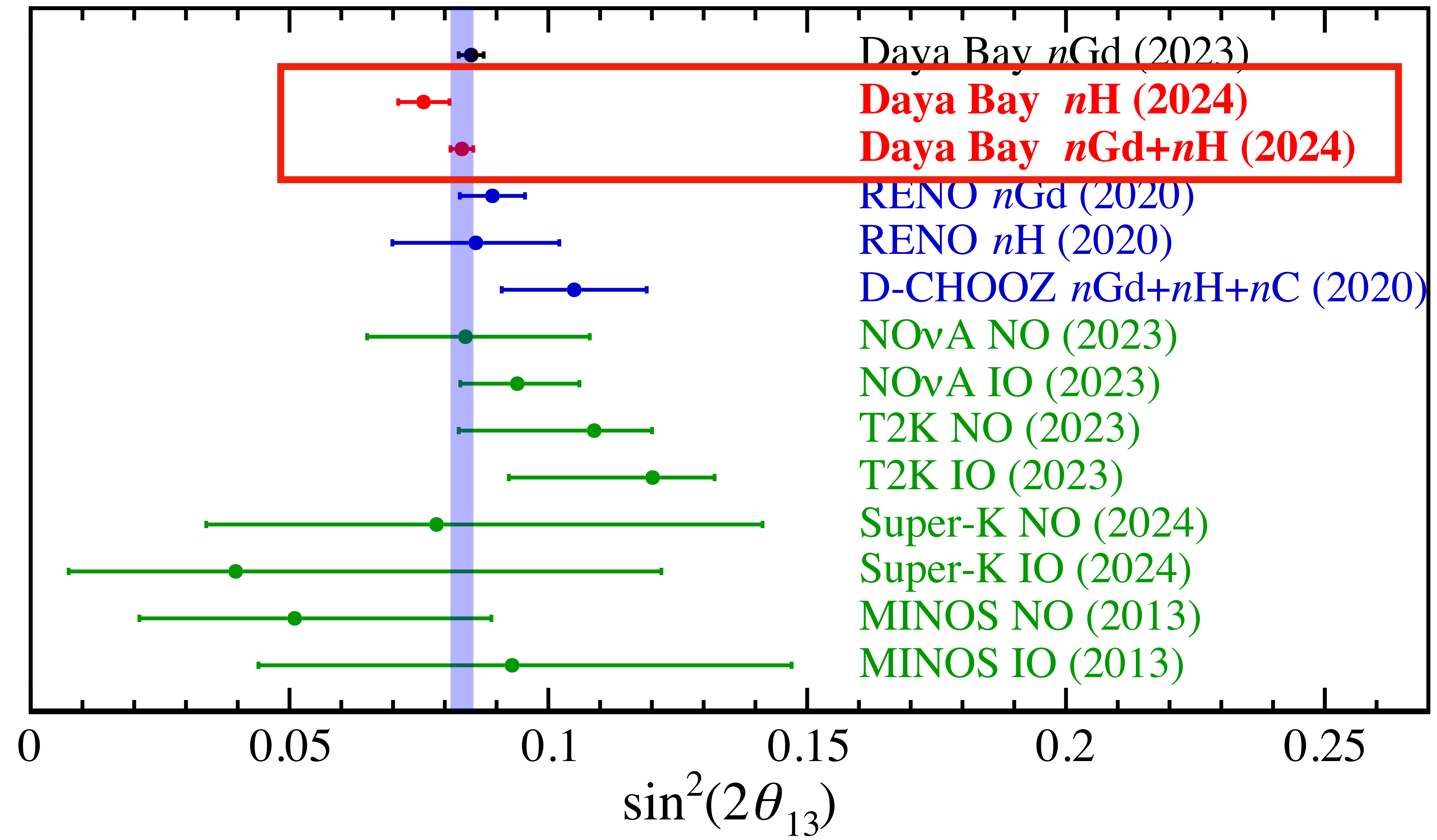
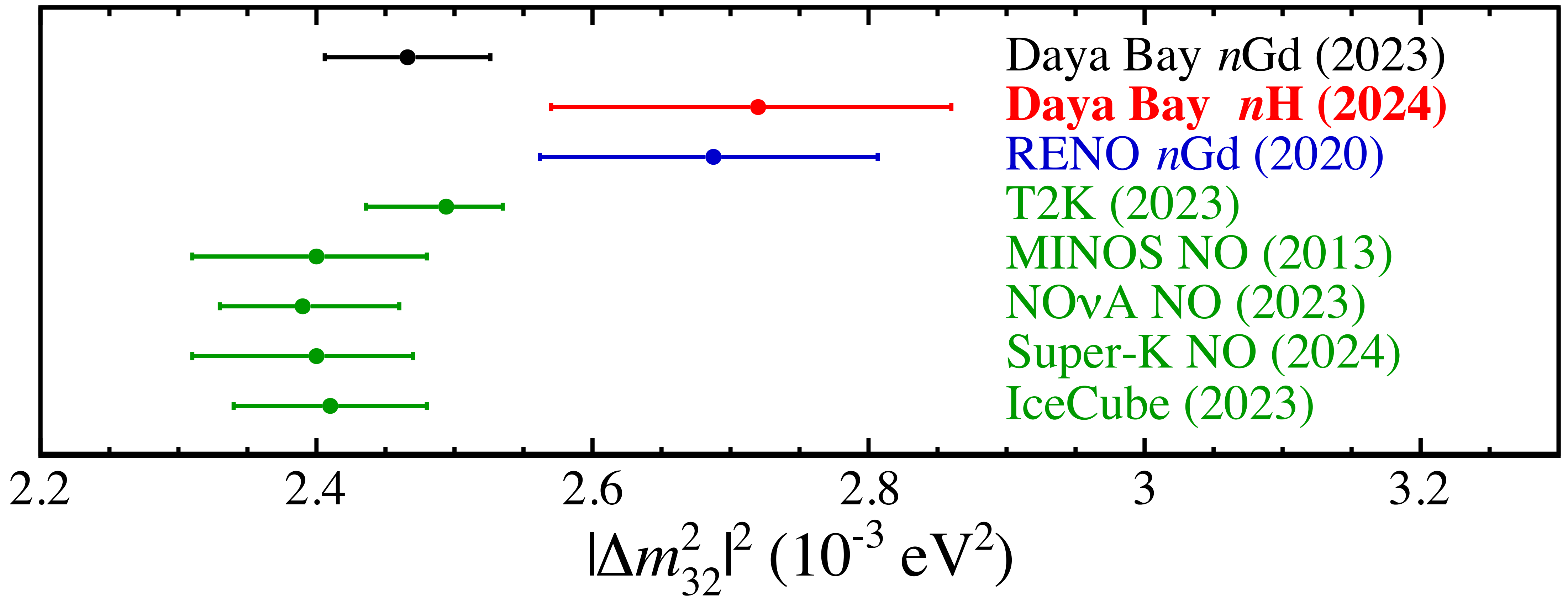
Consistent results from reactor and accelerator experiments

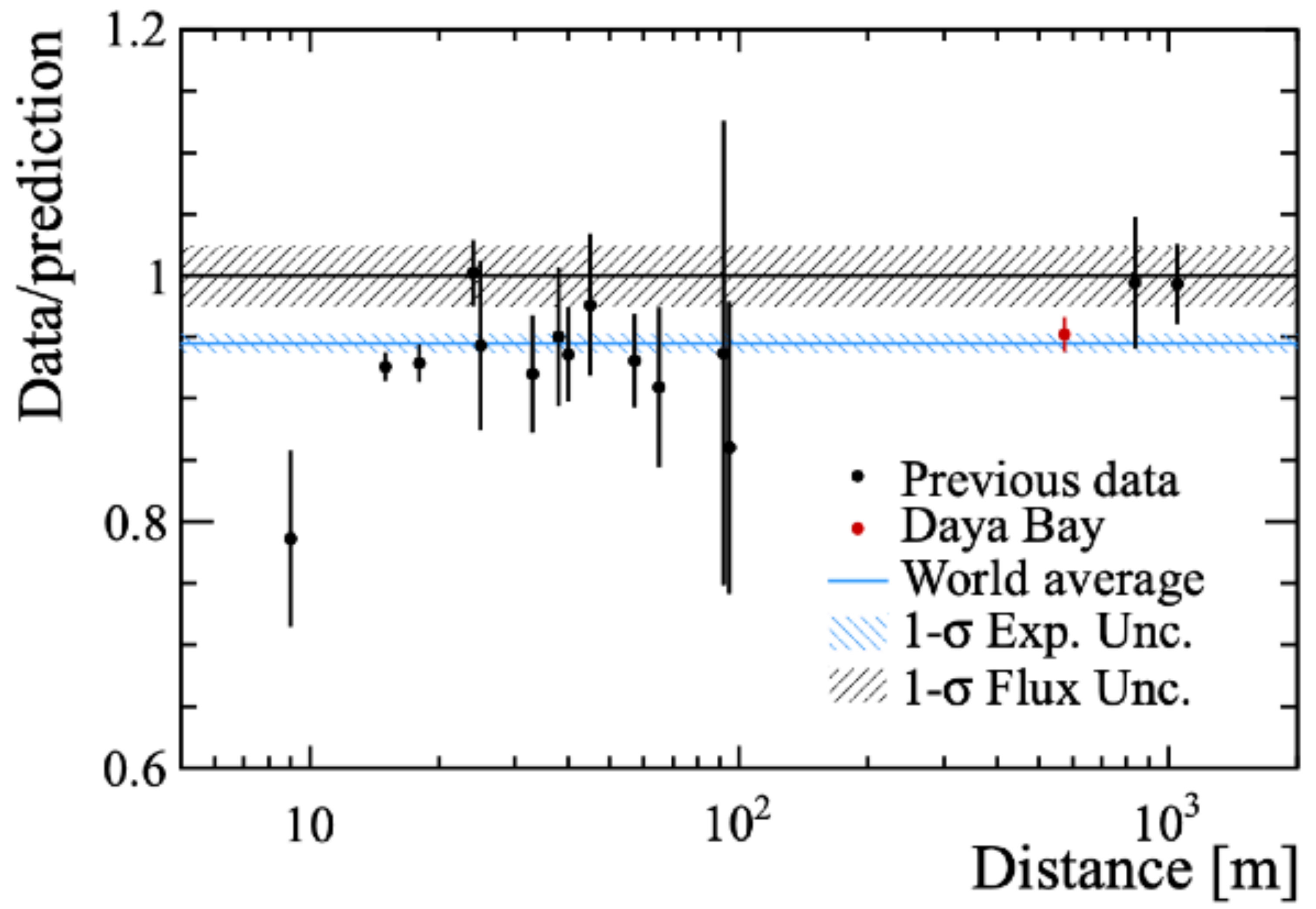




Sterile Neutrinos

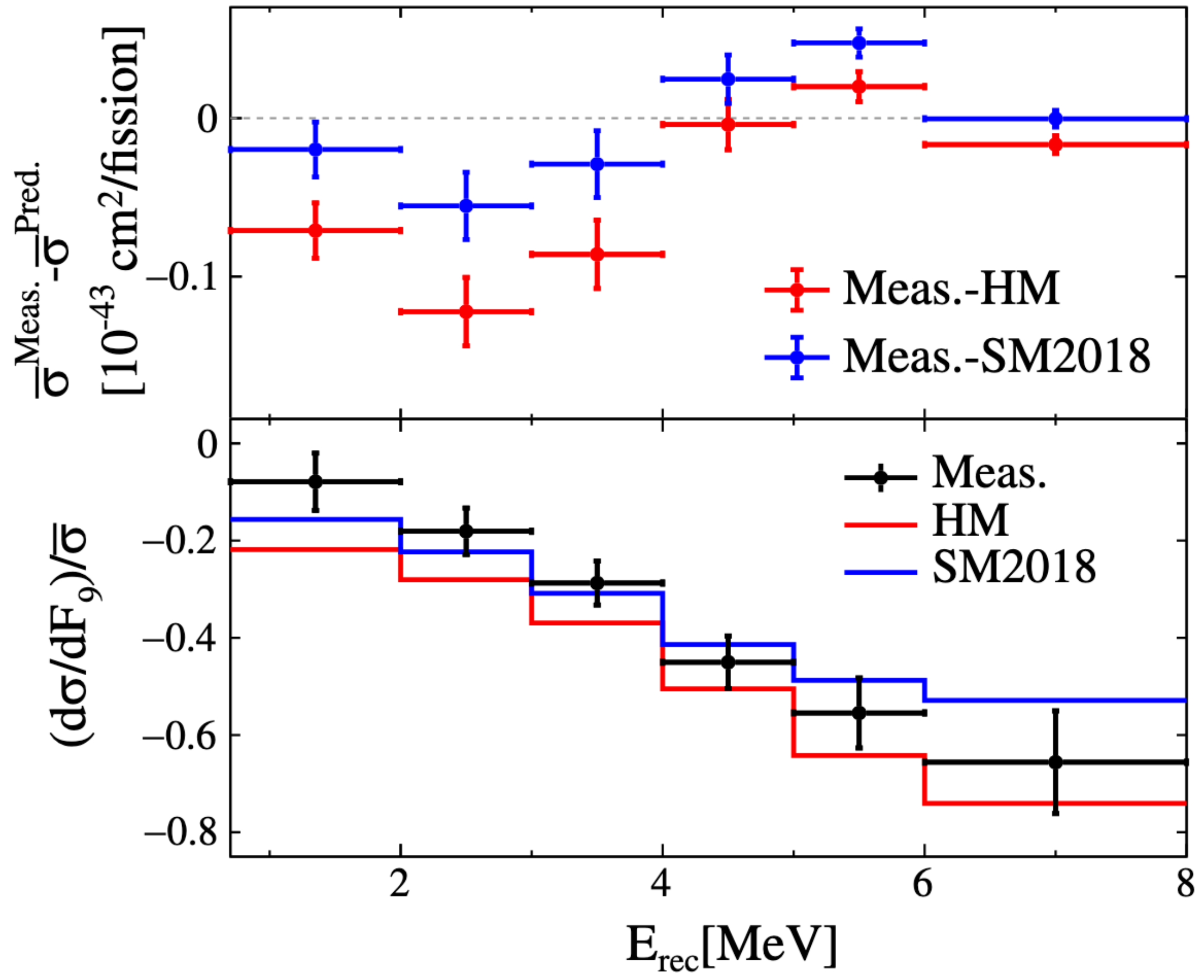
- Sterile neutrino searches at short baselines motivated by various oscillation anomalies
- Additional deficit due to sterile neutrino mixing can be visible with $|\Delta m^2_{41}| < 0.2\ \mathrm{eV}^2$
  - Able to provide world-leading constraint in this region at Daya Bay
- Modified the $\bar{\nu}_e$ survival probability: $P_{\bar{\nu}_e\to\bar{\nu}_e} \approx 1 - \sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{31}L}{4E} - \sin^2 2\theta_{14}\sin^2\frac{\Delta m^2_{41}L}{4E}$

Phys. Rev. D 100 (2019) 5, 052004

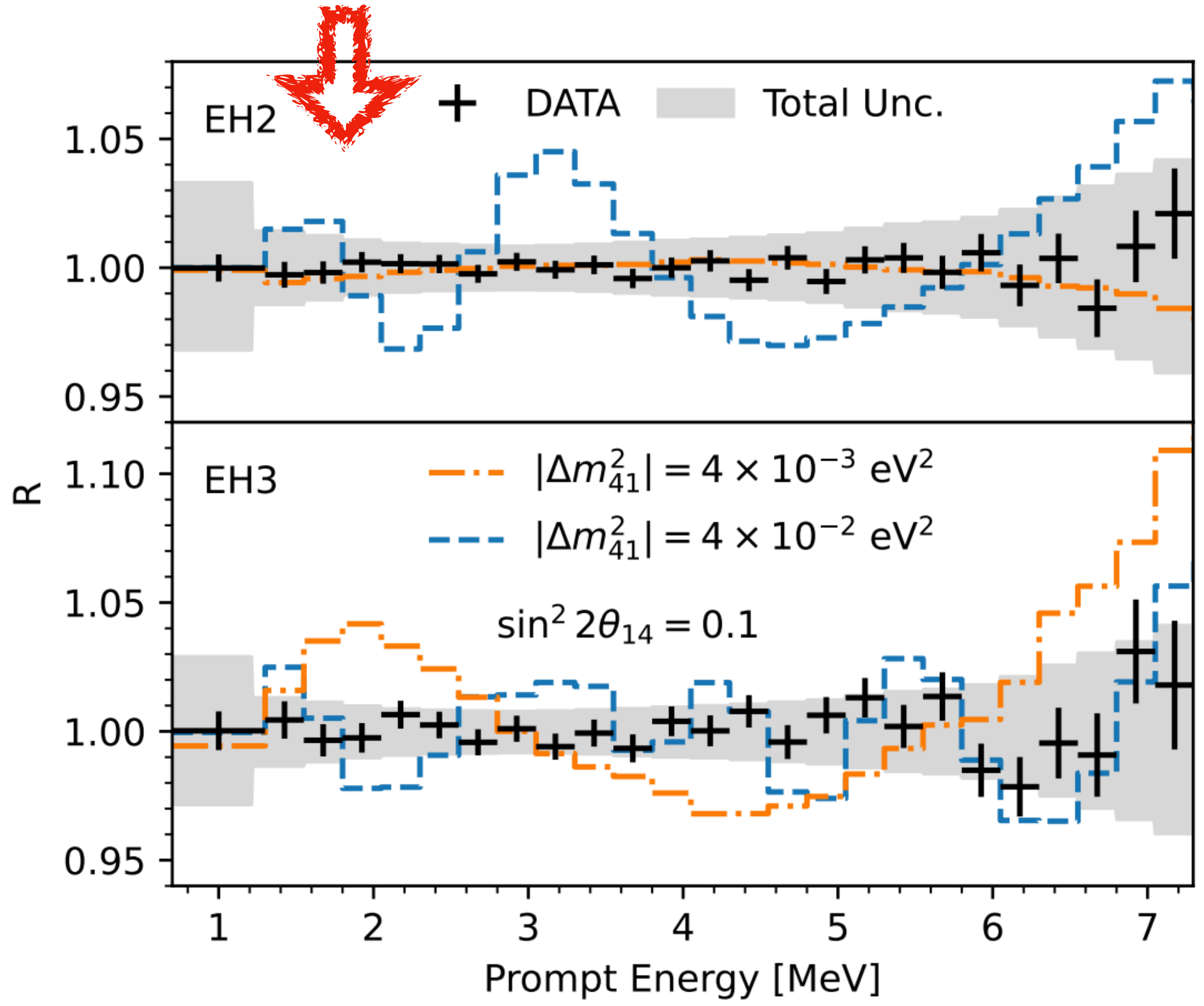


Reactor $\bar{\nu}_e$ flux deficit

Phys. Rev. Lett. 130, 211801 (2023)



Spectrum difference of Reactor $\bar{\nu}_e$

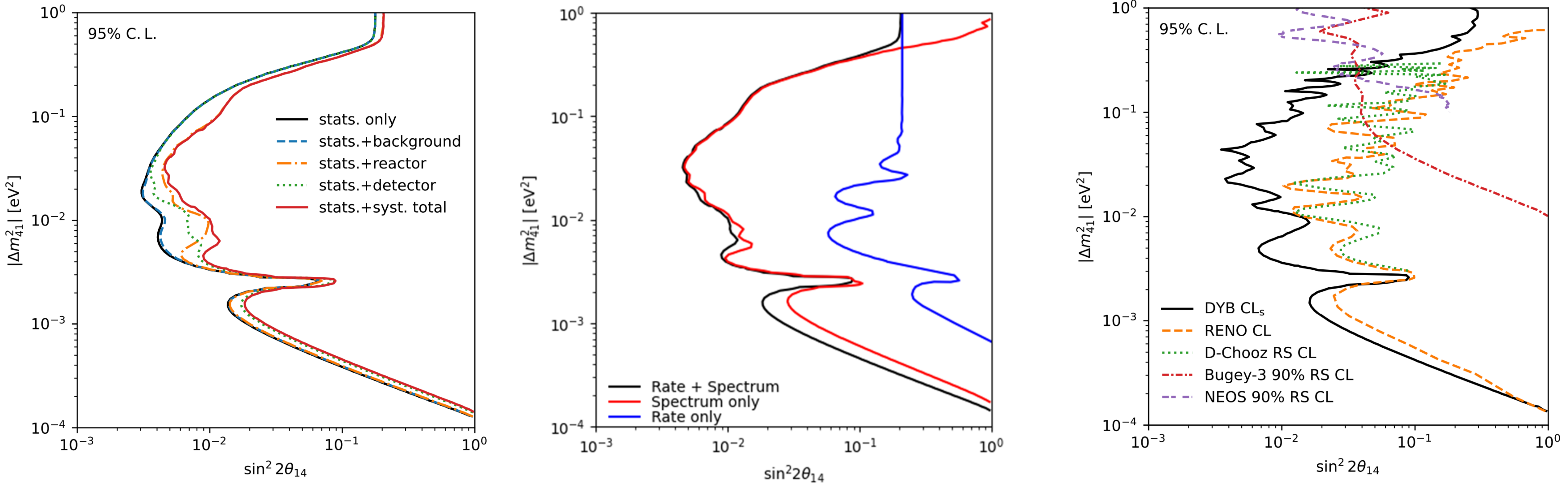


Poster from Shiqi Zhang, ID-594, arXiv:2404.01687 [Accepted by Phys. Rev. Lett.]

Search for Sterile Neutrinos

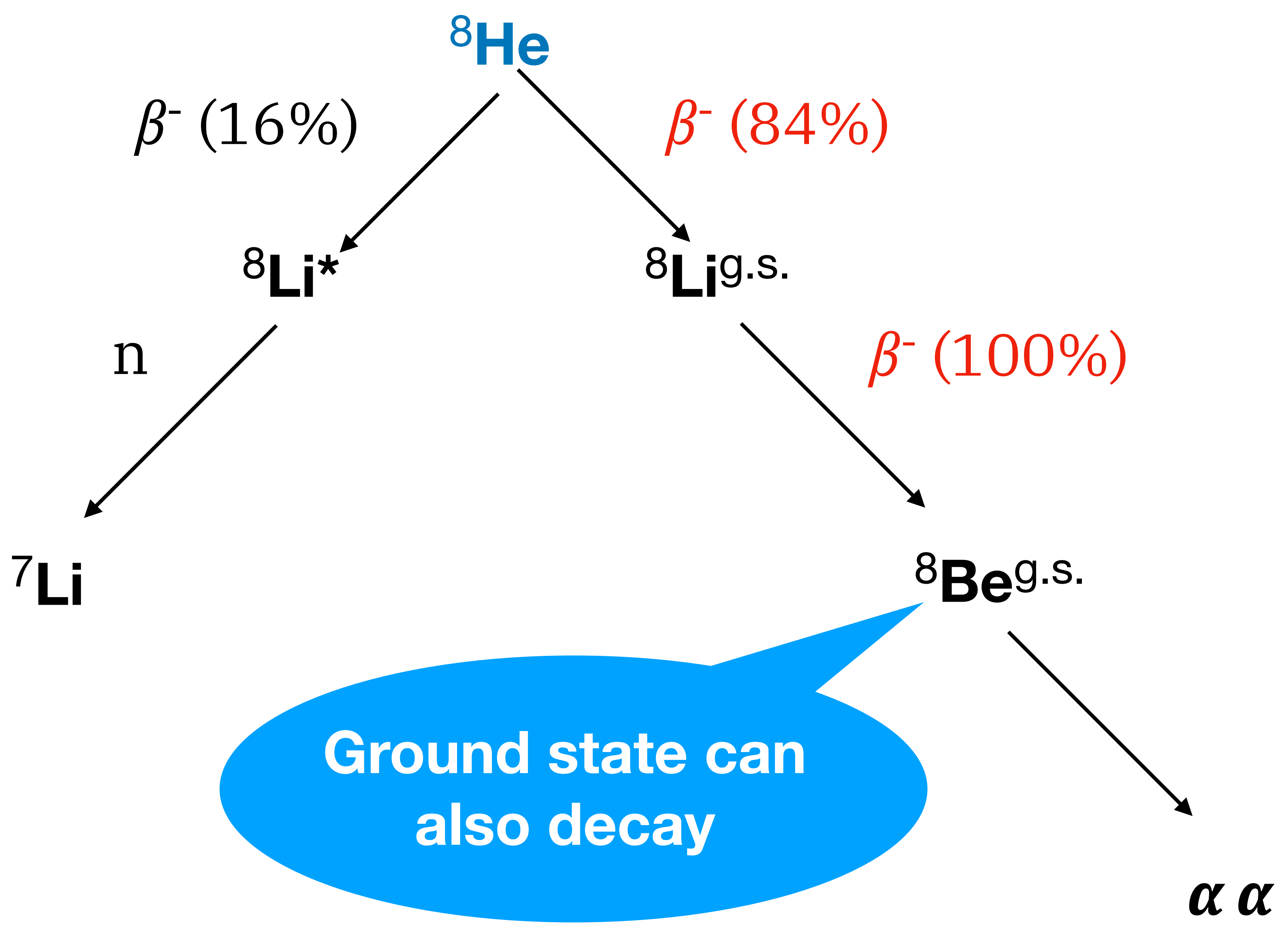
- Minimal "3+1" extension of the three-neutrino mixing scenario is considered
- No evidence of a light sterile neutrino was found
  - Set limits in ($\sin^2 2\theta_{14}$, Δm^2_{41}) space: Gaussian CL_s and Feldman-Cousins methods
- The world's most stringent limits on the sterile-active neutrino mixing parameter $\sin^2 2\theta_{14}$ were obtained in the region of 2×10^{-4} eV^2 $\lesssim \Delta m^2_{41} \lesssim$ 0.2 eV^2

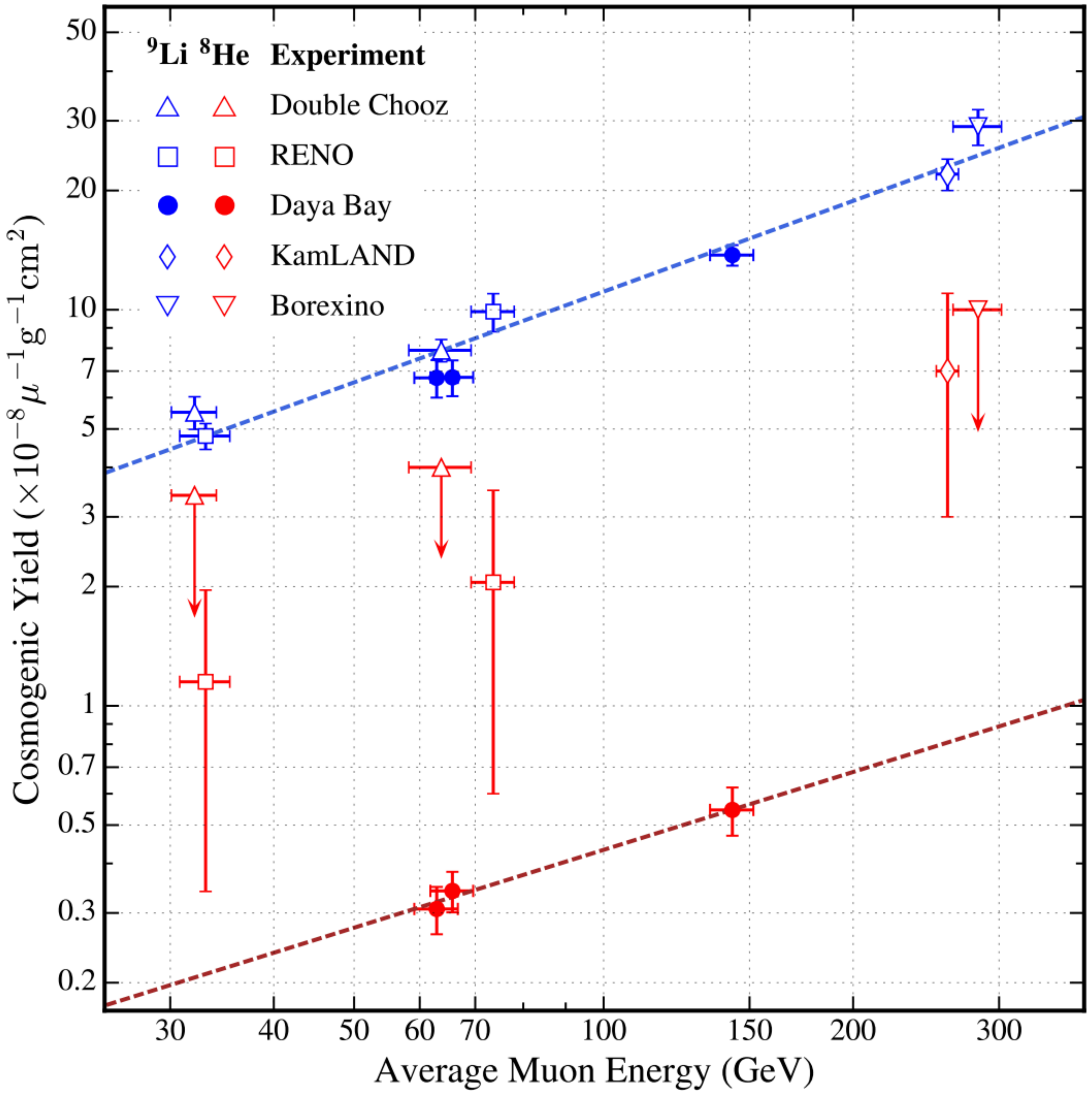
Different error components | ***Different fitting strategies*** | ***Comparisons with different experiments***



Cosmogenic 9Li/8He Background

- First observation of ^{8}He at Daya Bay
  - using β cascade decays of ^{8}He-^{8}Li$^{g.s.}$
- The smallest production yield isotope in LS
- Valuable inputs for future experiments





arXiv: 2402.05383, accepted as a PRD Letter

Summary

- **Daya Bay leads the precision measurement for $\boldsymbol{\theta_{13}}$**
  - Giving the most precise measurement of $\sin^2 2\theta_{13}$
  - And one of the best measurements of Δm^2_{32}
  - Providing an high-precision independent cross-validation via nH sample
  - And world-leading constraints on light sterile neutrino mixing
- **Still more results are expected to be released**
  - nH oscillation results with the full data set
  - Joint sterile neutrino analysis with other experiments
  - Other non-oscillation results

Stay Tuned!

Daya Bay collaboration

Thank
You

谢谢!