清華大學
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Latest θ_{13} Results from Daya Bay

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On Behalf of the Daya Bay Collaboration

2024年11月9日于洛阳，第六届粒子物理天问论坛

Outline

- Neutrino Mixing and Oscillation
- Overview of the Daya Bay Experiment
- Oscillation Results with Gadolinium-capture Sample
  Final result: Phys. Rev. Lett. 130, 161802 (2023)
- Oscillation Results with Hydrogen-capture Sample
  New result: Phys. Rev. Lett. 133, 151801 (2024)
- Summary and Prospects

Neutrino Mixing and Oscillation

Three-Neutrino Mixing Framework

Atmospheric, accelerator ν

Solar, reactor L~60 km ν

$$\text{Flavor States} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \text{Mass States}$$

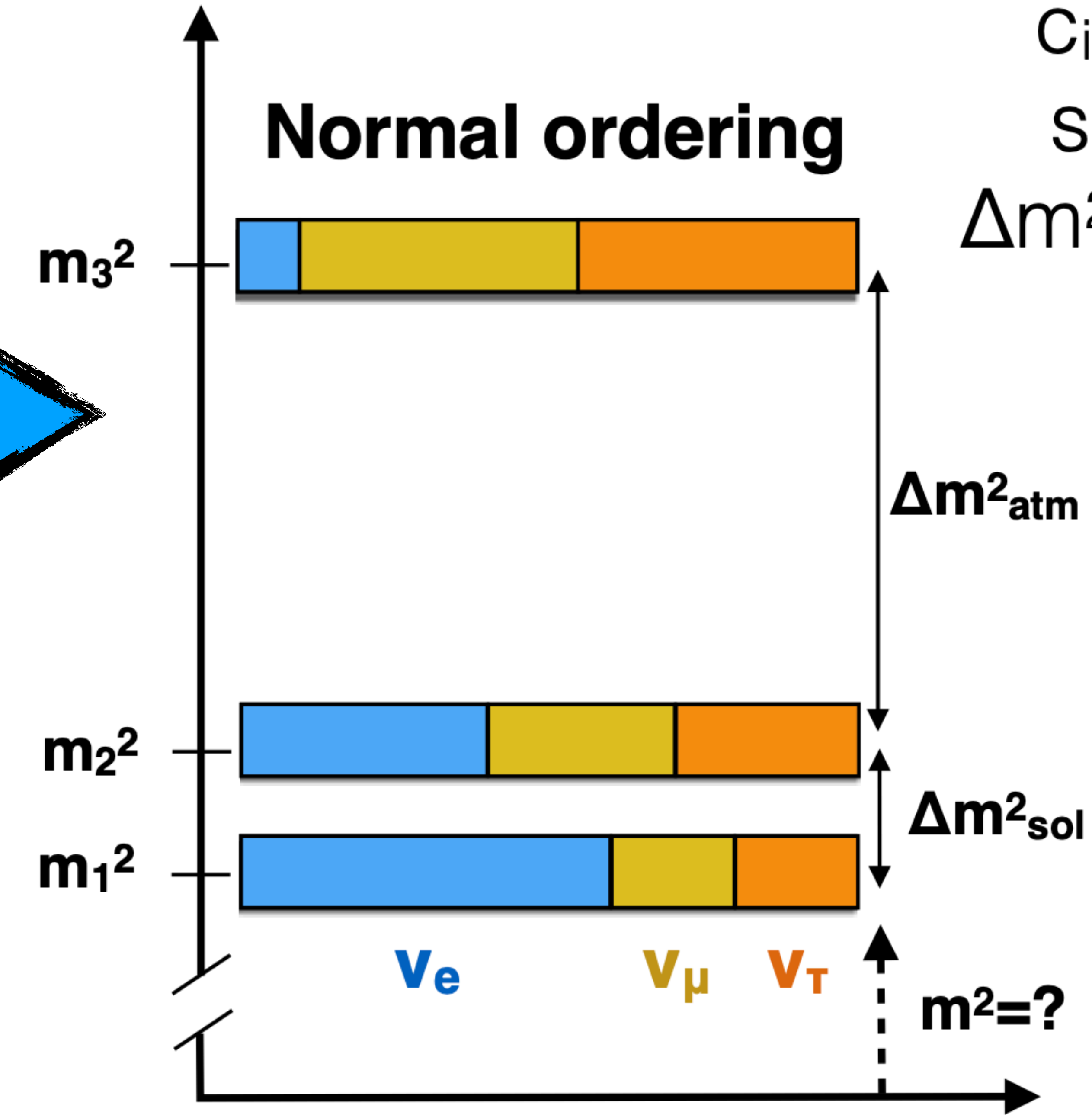
Reactor L~2 km, accelerator ν

Parameter	Value	Open questions
Δm^2_{21}	7.5×10^{-5} eV^2	–
$\|\Delta m^2_{31}\| \approx \|\Delta m^2_{32}\|$	2.5×10^{-3} eV^2	Ordering? $\Leftrightarrow \Delta m^2_{31} \gtrless 0$
θ_{12}	33°	–
θ_{23}	45°	Maximal? $\Leftrightarrow \theta_{23} \gtreqless 45°$
θ_{13}	8.5°	–
δ_{CP}	?°	Unknown

$c_{ij}=\cos\theta_{ij}$

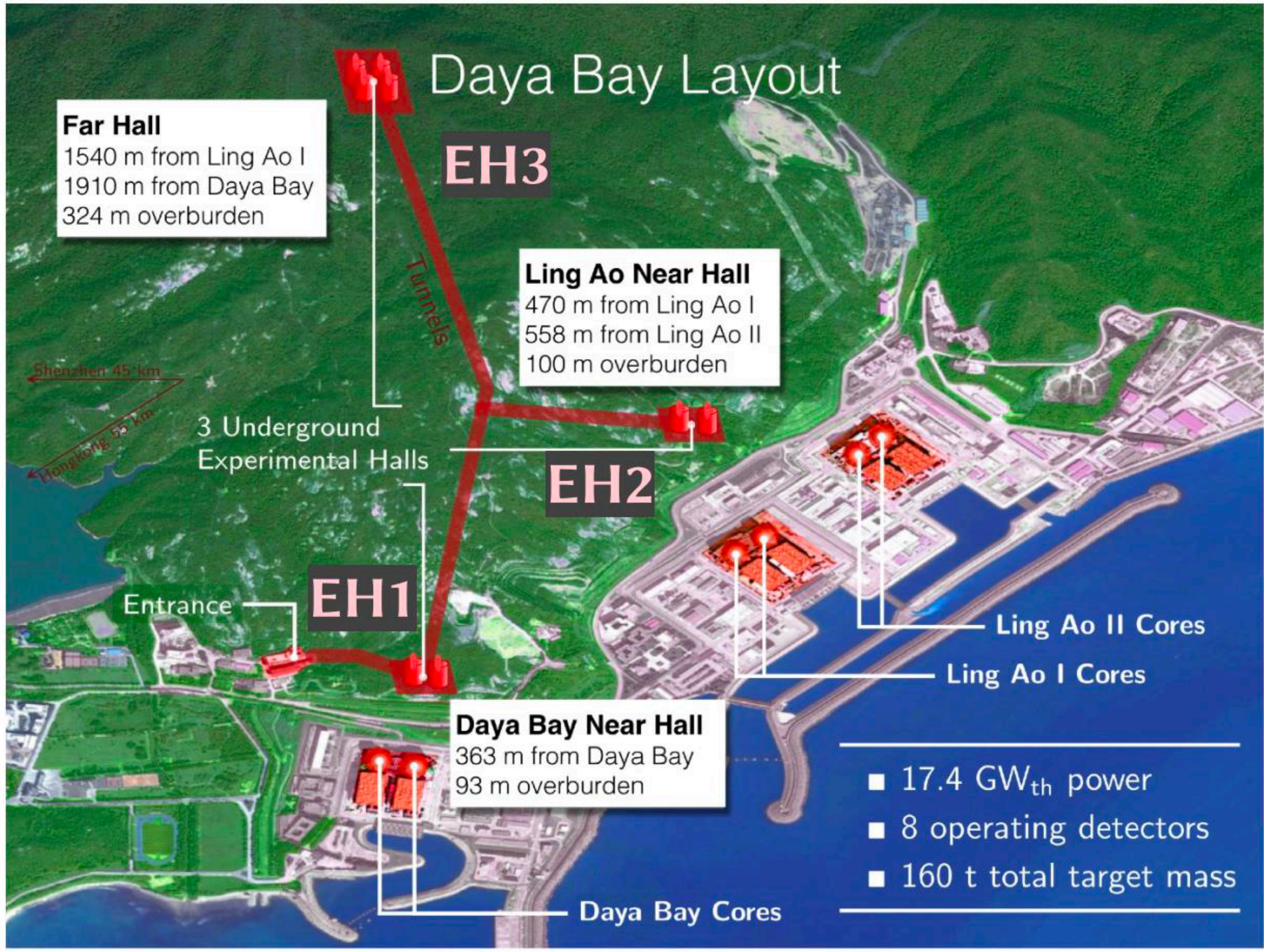
$s_{ij}=\sin\theta_{ij}$

$\Delta m^2_{ij} \equiv m^2_i - m^2_j$



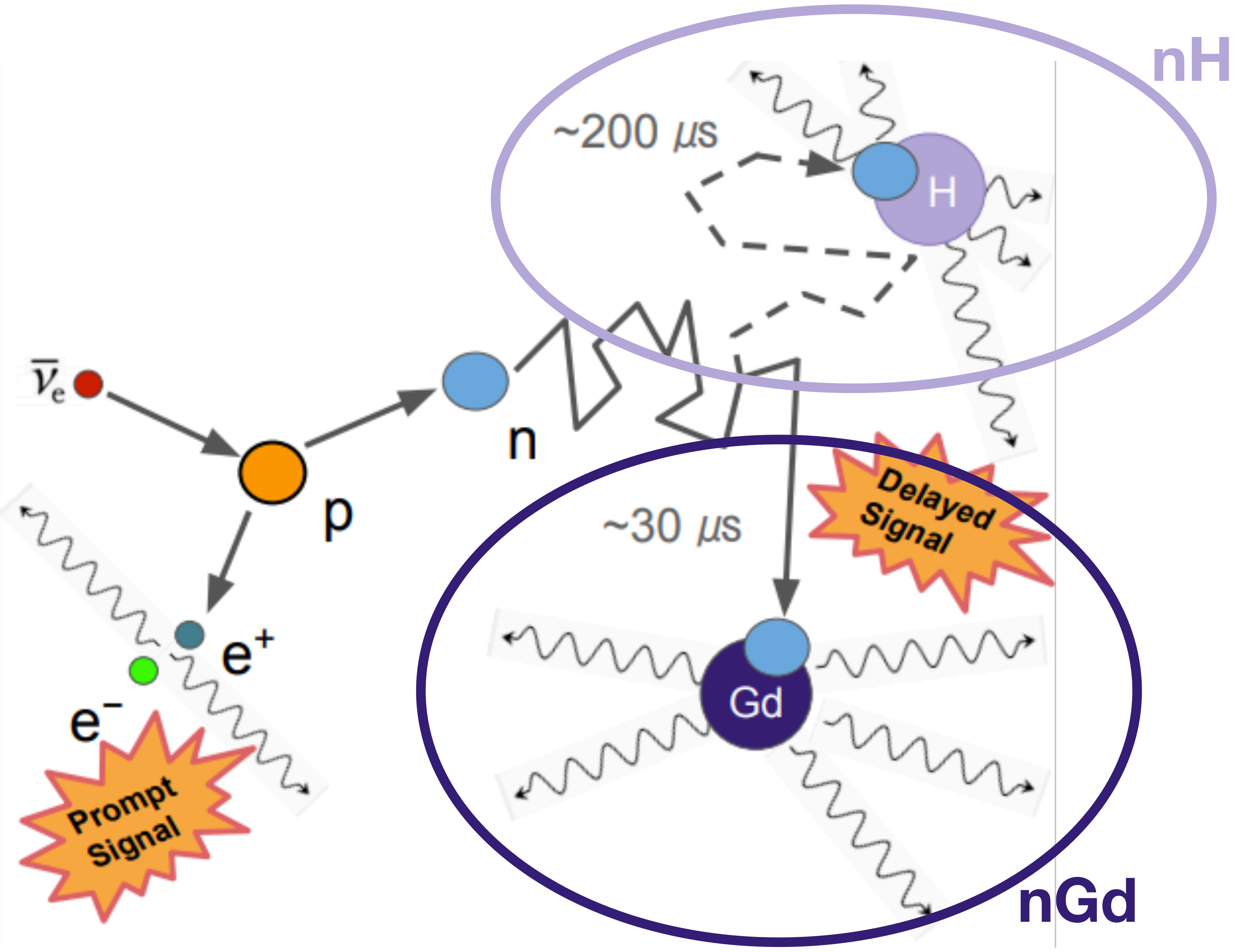
Daya Bay Experiment

- Six 2.9 GW_{th} reactors as very strong antineutrino sources(~6x10^{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}
- Collecting data from Dec. 24, 2011 to Dec. 12, 2020

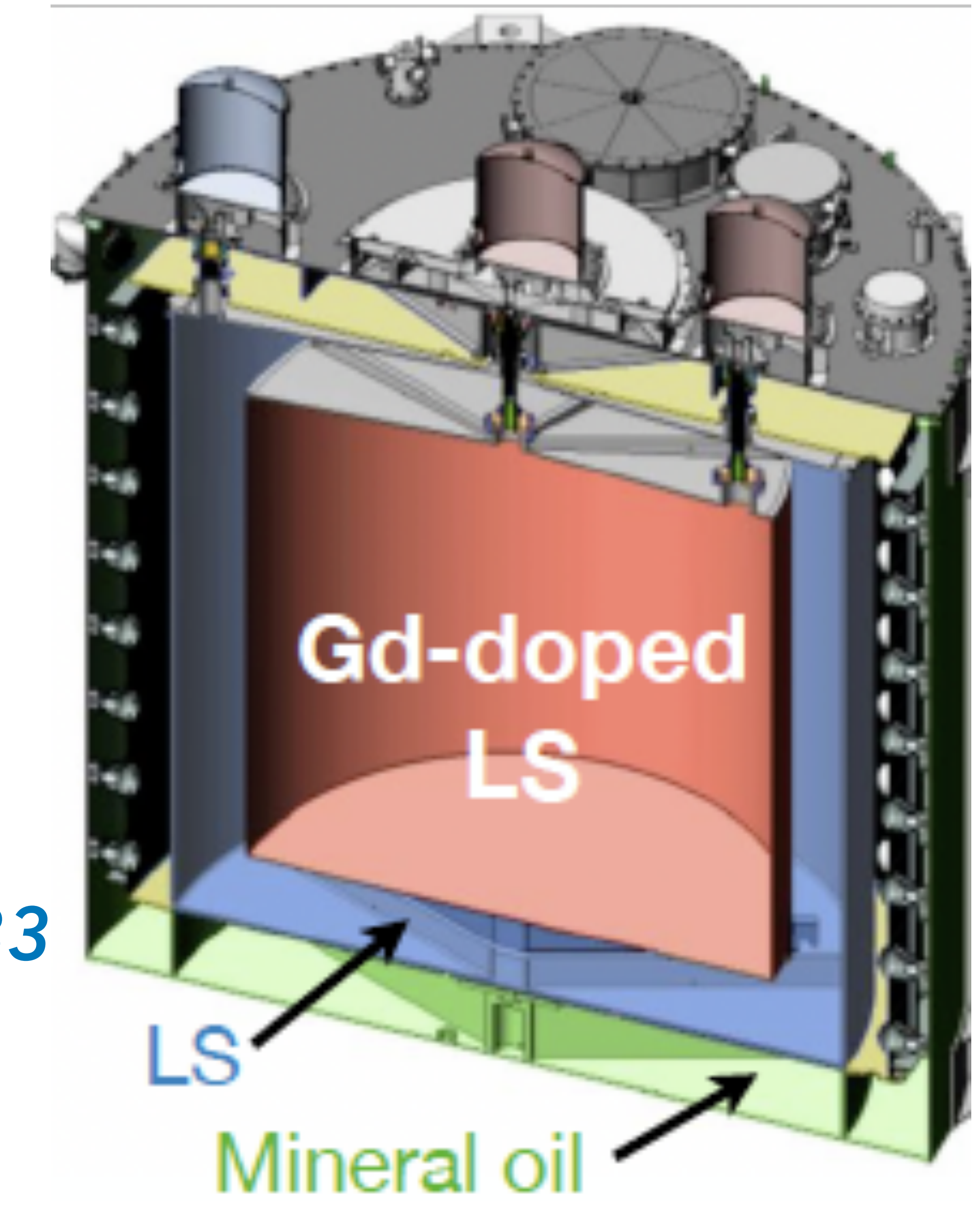


Neutrino Detection

- Inverse beta decay (IBD)
  - $\bar{\nu}_e + p \rightarrow e^+ + n$
- Featured prompt-delayed pairs
  - Prompt positron
  - Delayed γ('s) from nGd or nH



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

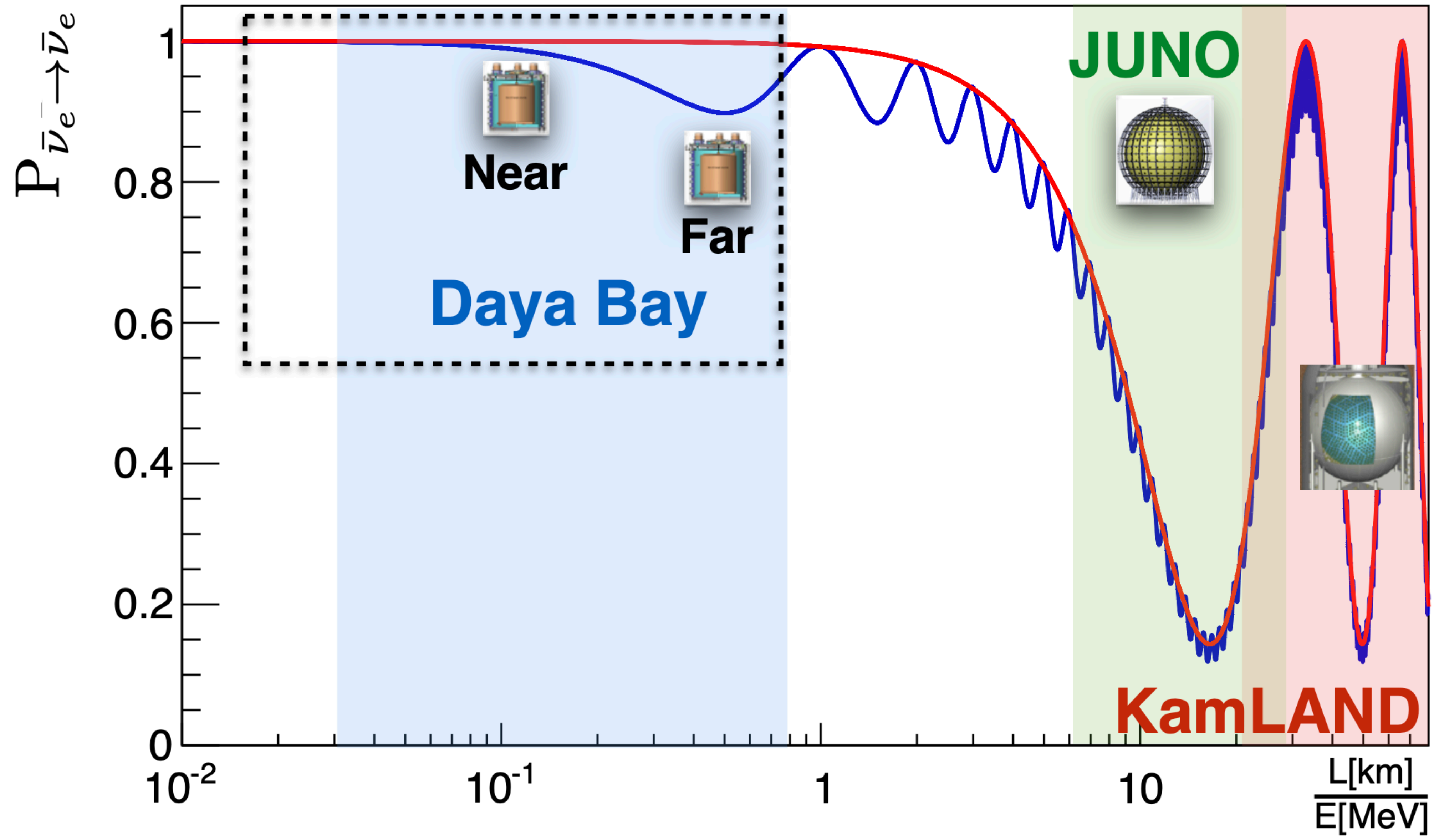
Measuring the Oscillation

- **Observing the $\bar{\nu}_e$ flux of as a function of distance and energy**
- **Some $\bar{\nu}_e's$ disappear due to neutrino oscillation**

Short Baseline

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

Medium Baseline



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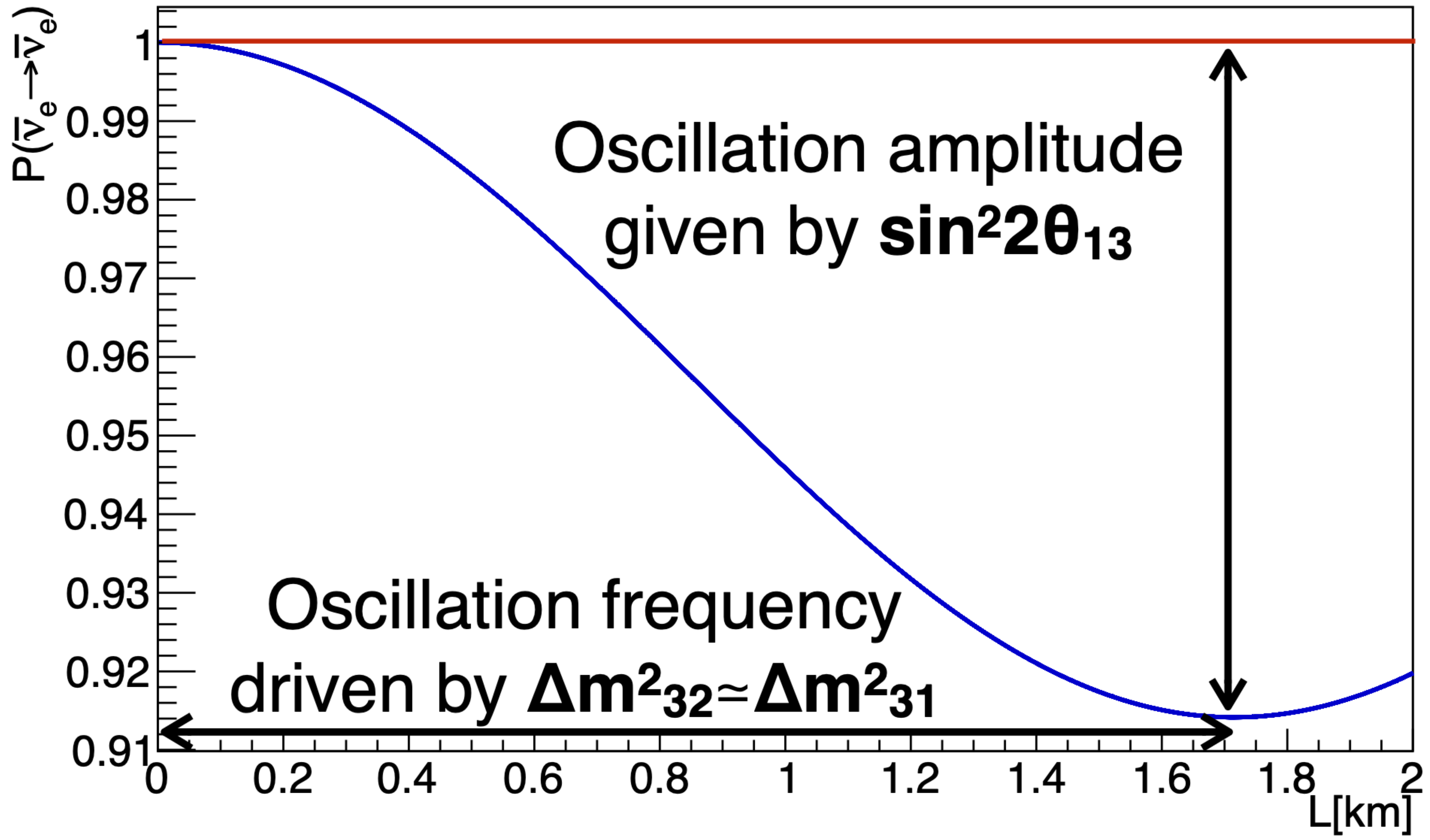

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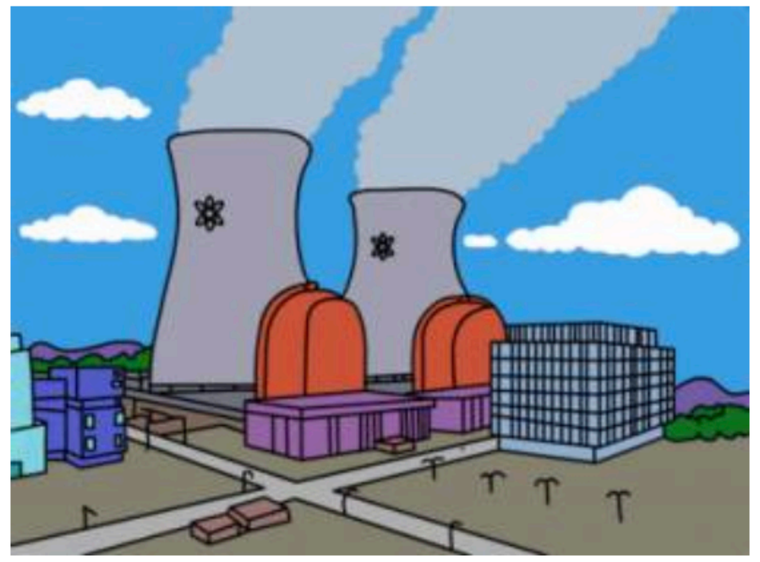
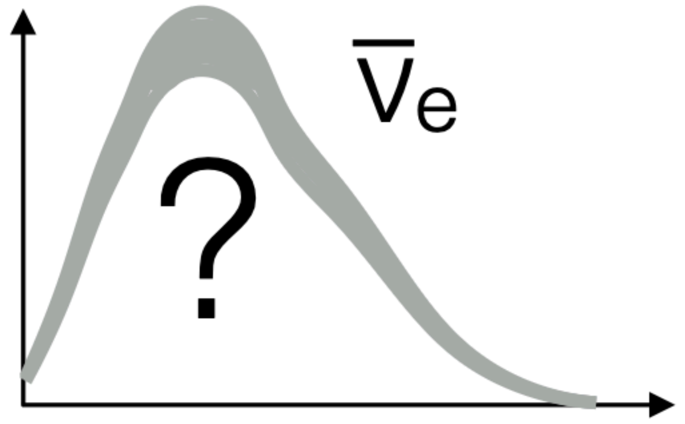
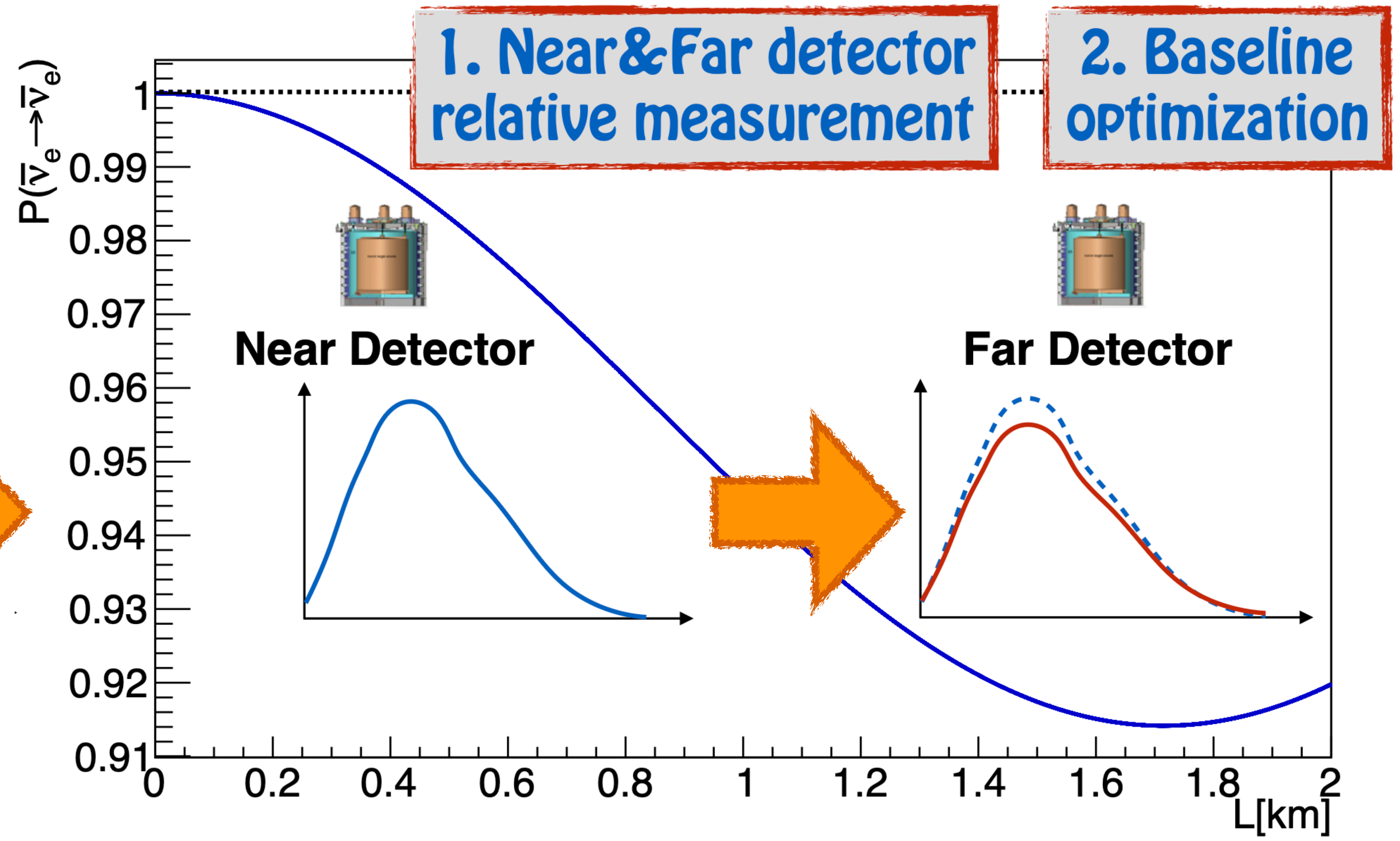
Medium Baseline

3. Powerful source, large detector(s)

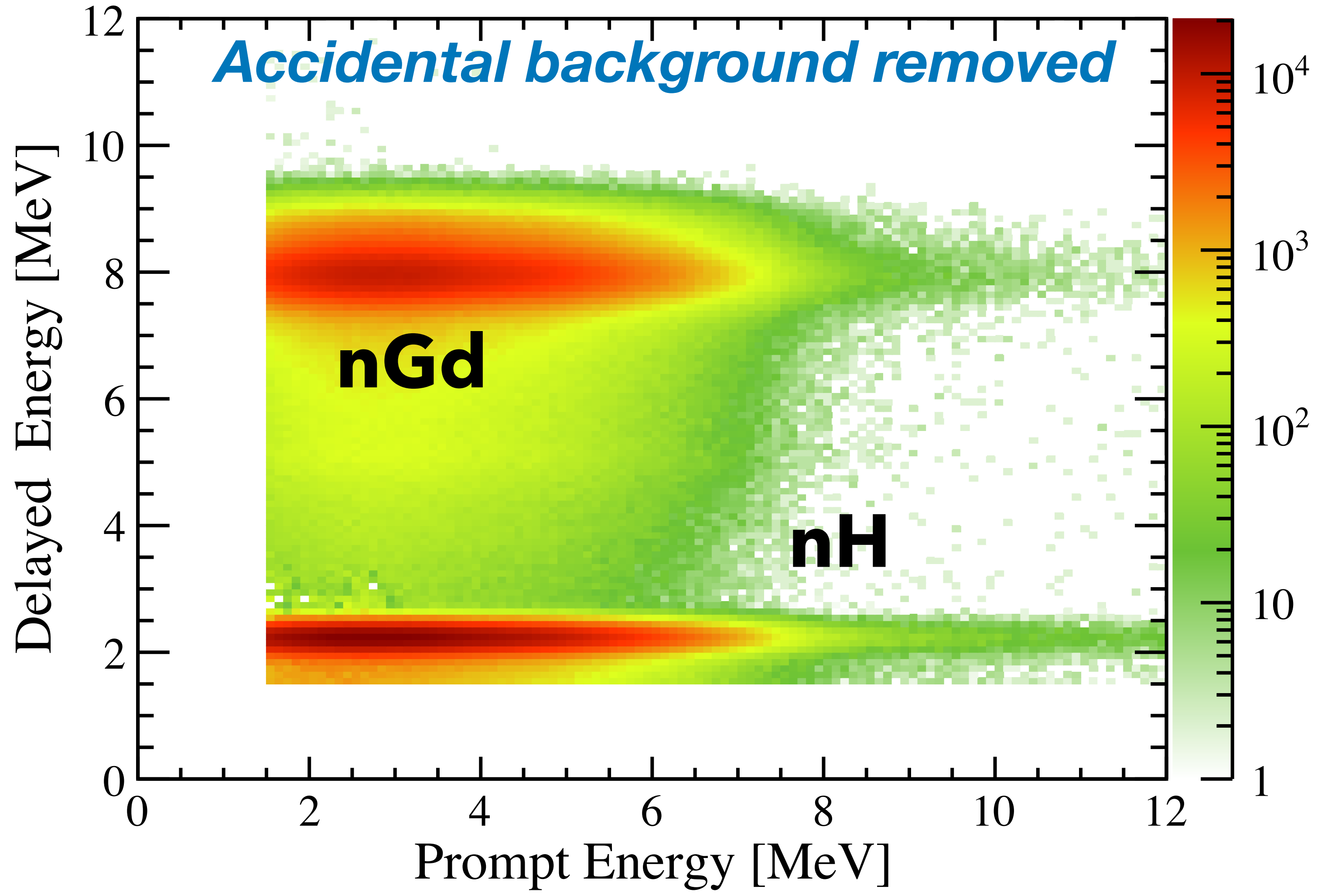


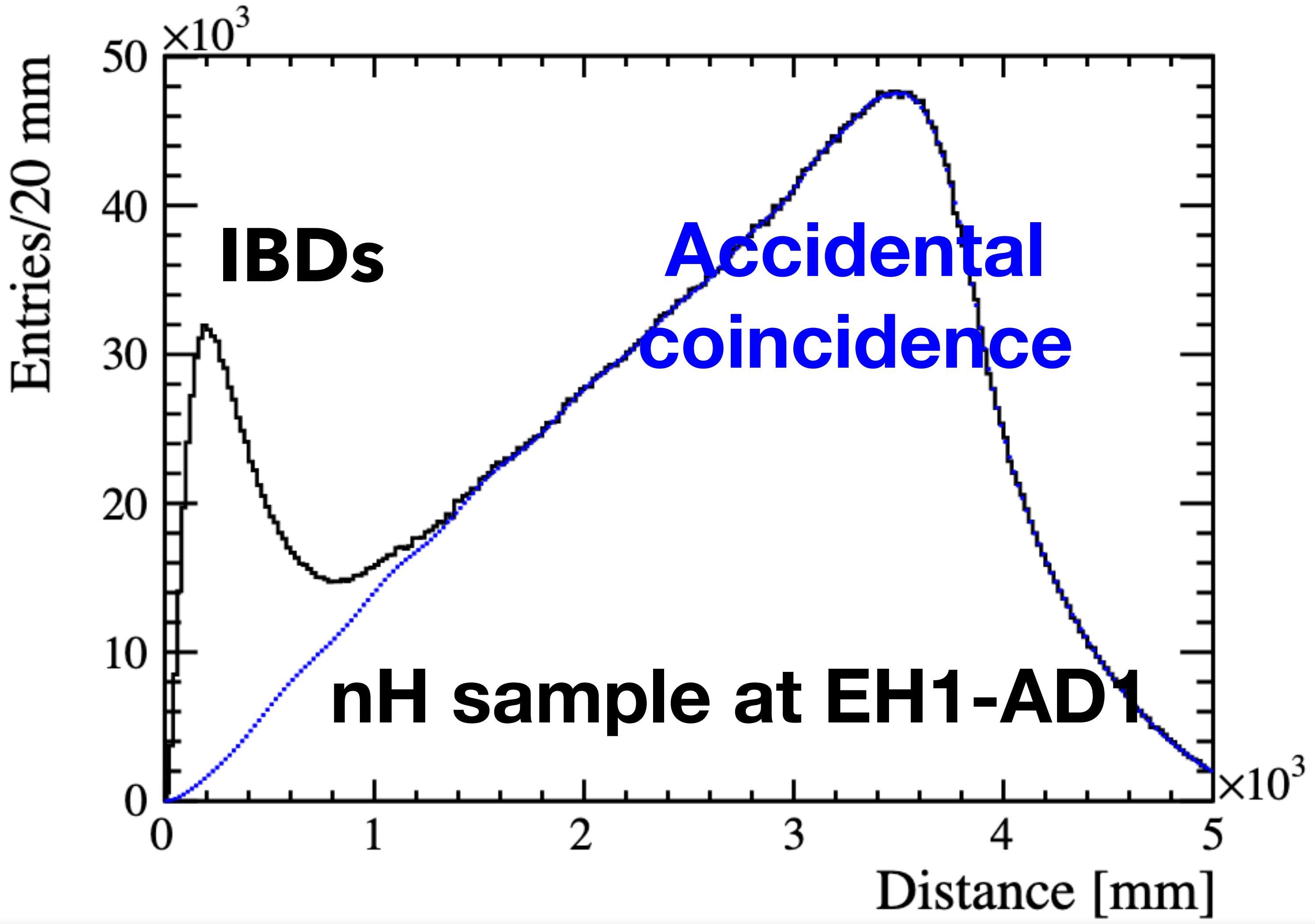




+4. Low background

Selection of IBD Candidates

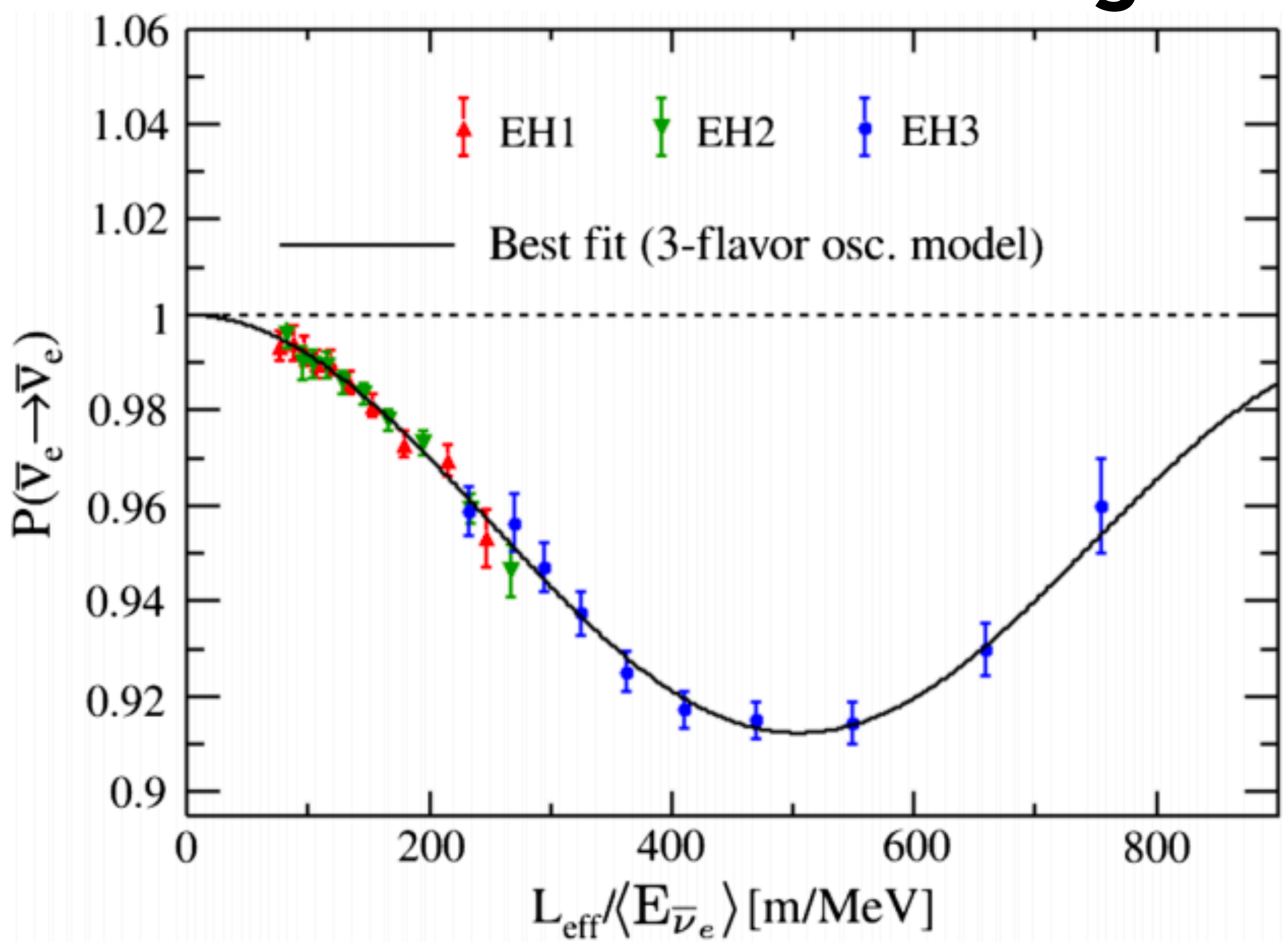


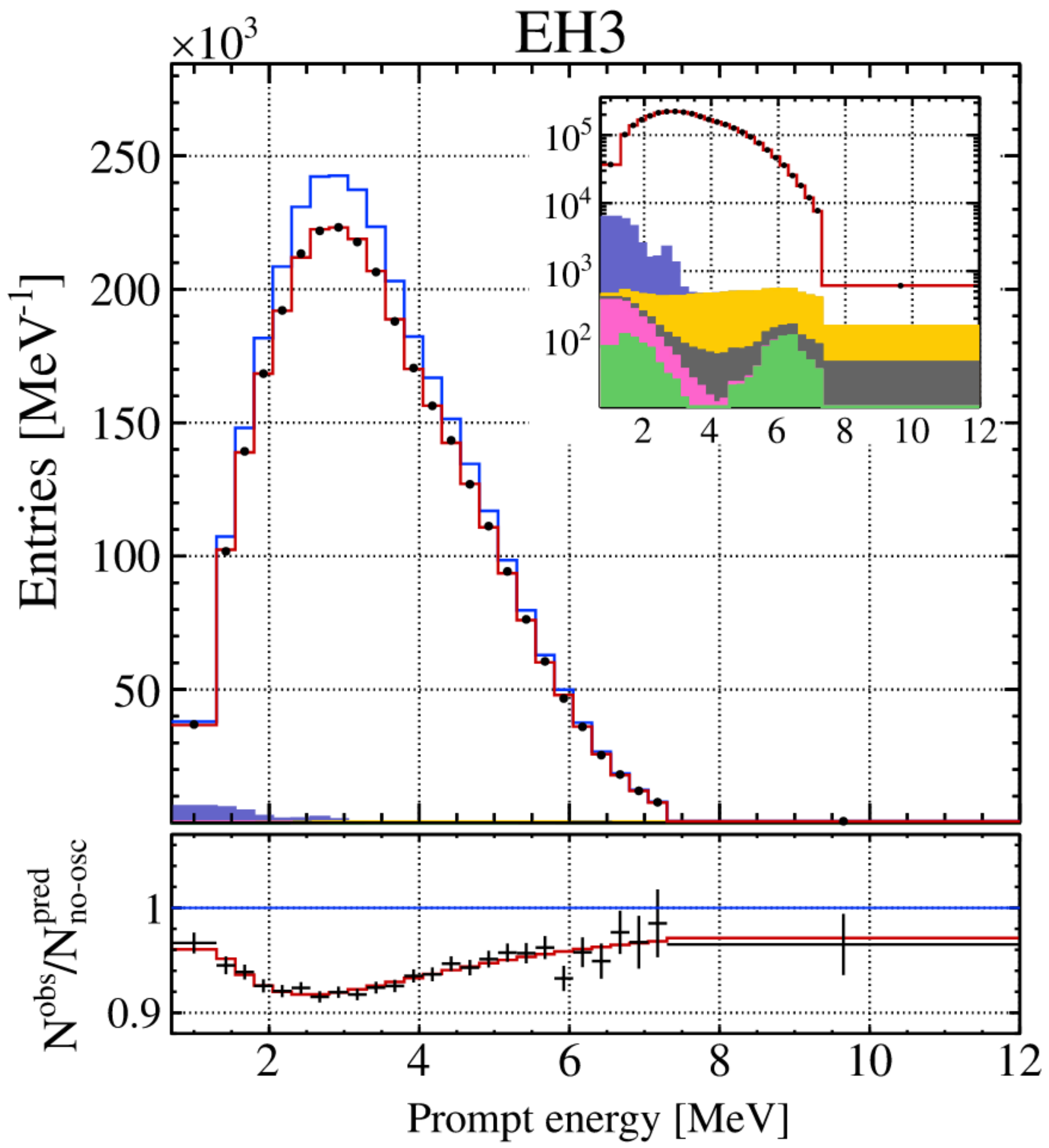


- Remove spontaneous flashing from PMTs
- Veto events that are close in time to muons
- Energy criteria
- Temporal and spatial coincidence
  - nGd: 1 μs < Δ*t* < 200 μs
  - nH: Δ*t* > 1 μs, Δ*r*+ Δ*t*/[600 μs/m] < 1 m
- Multiplicity cut: time-isolated event pairs

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)**

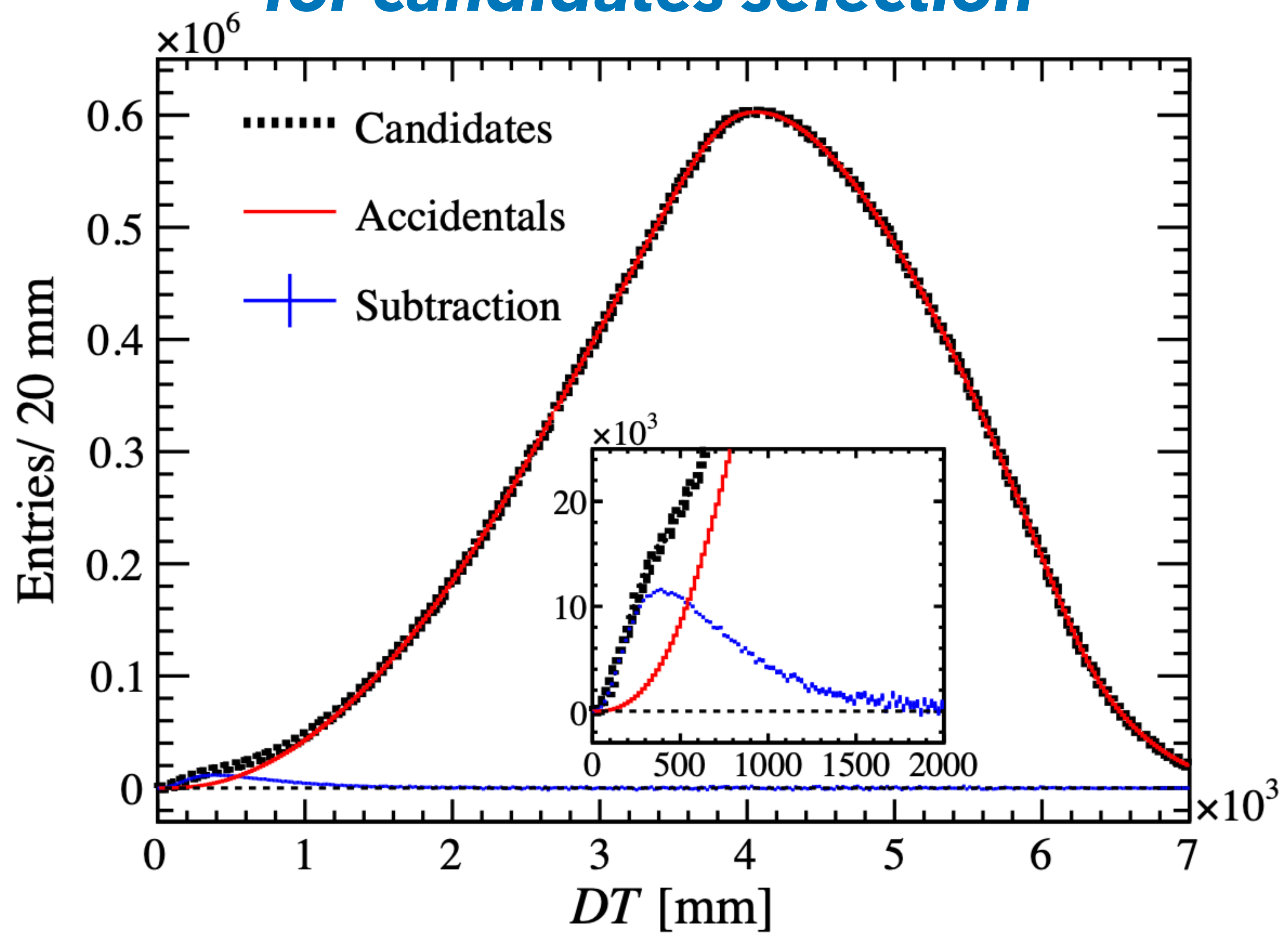
Normal mass ordering : Δm^2_{32} = (2.466±0.060)×10^{-3} eV^2 **(2.4% precision)**

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

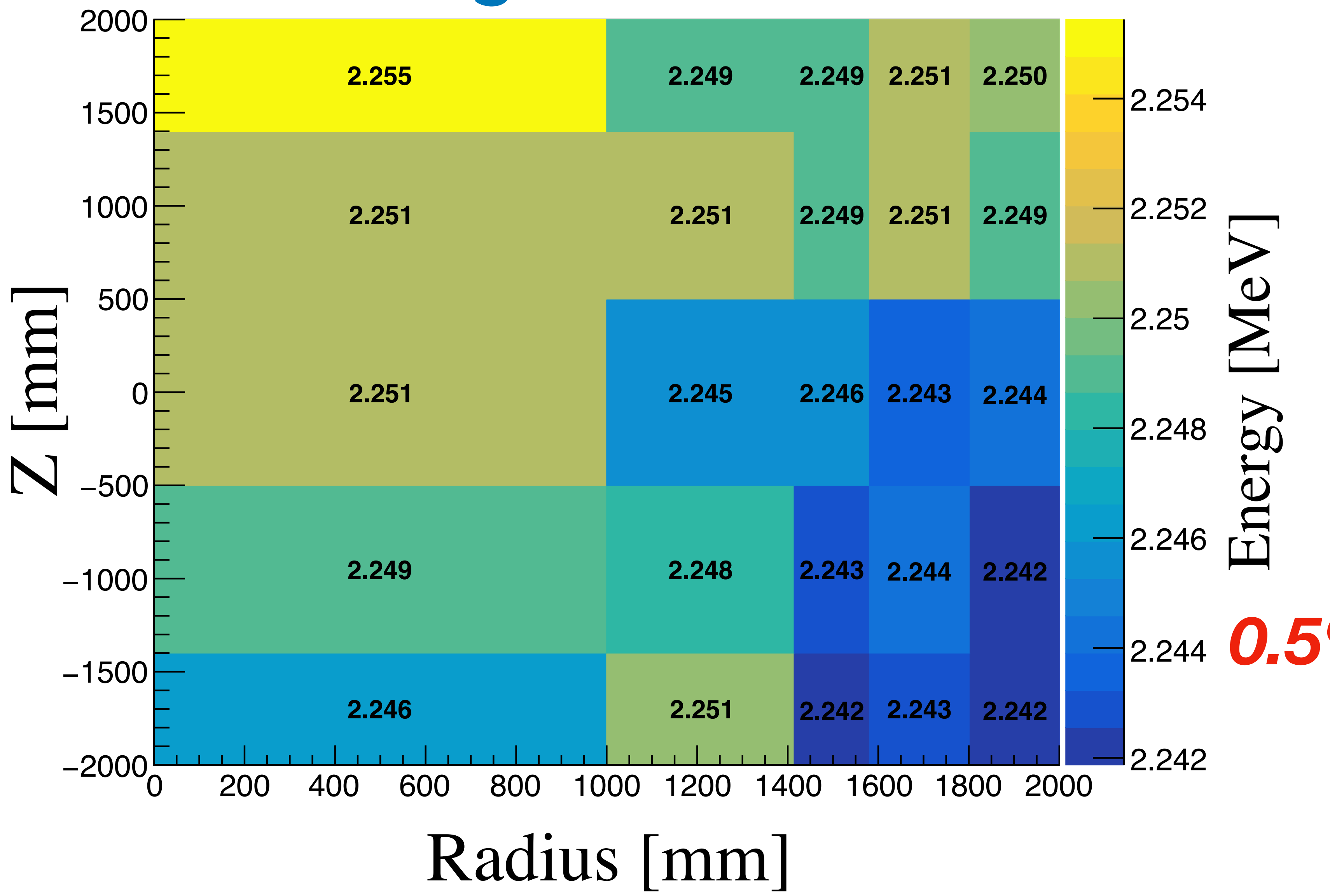
New Oscillation Results Based on nH

- **New nH oscillation result with 1958 days of data released on June 3, 2024**
  - **Already published: Phys. Rev. Lett. 133, 151801 (2024)**
  - **3.1 times more statistics (2/3 of the full data set) than that in 2016**
  - **The dominant accidental background is estimated with negligible uncertainty**
  - **New energy calibration, new candidate selection, and new background, etc…**

Combining distance and time for candidates selection

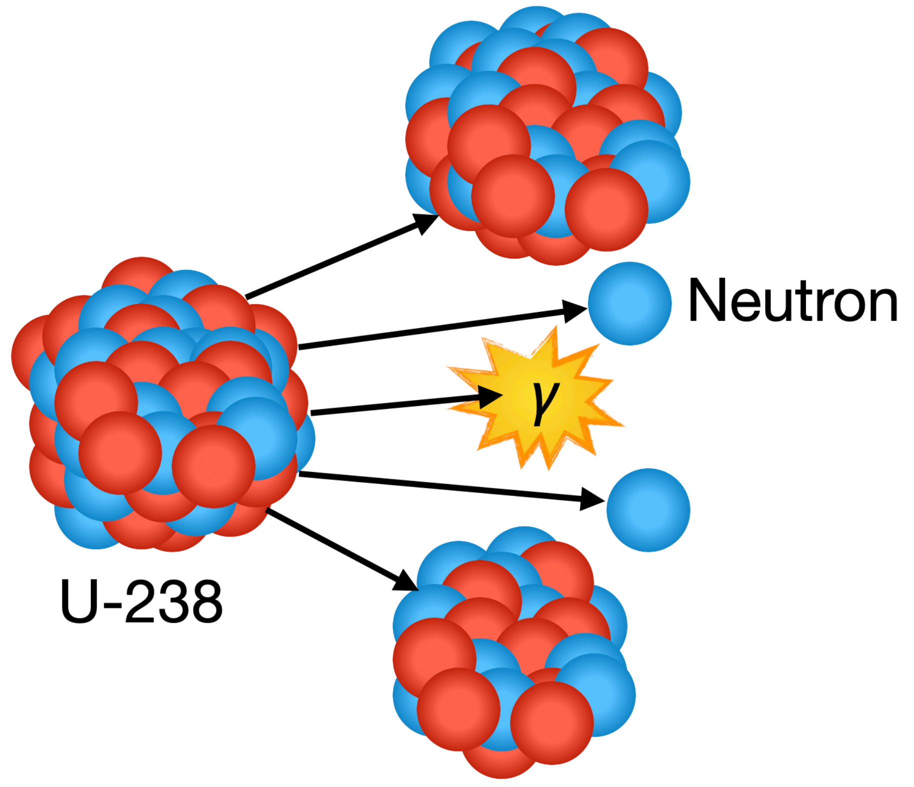


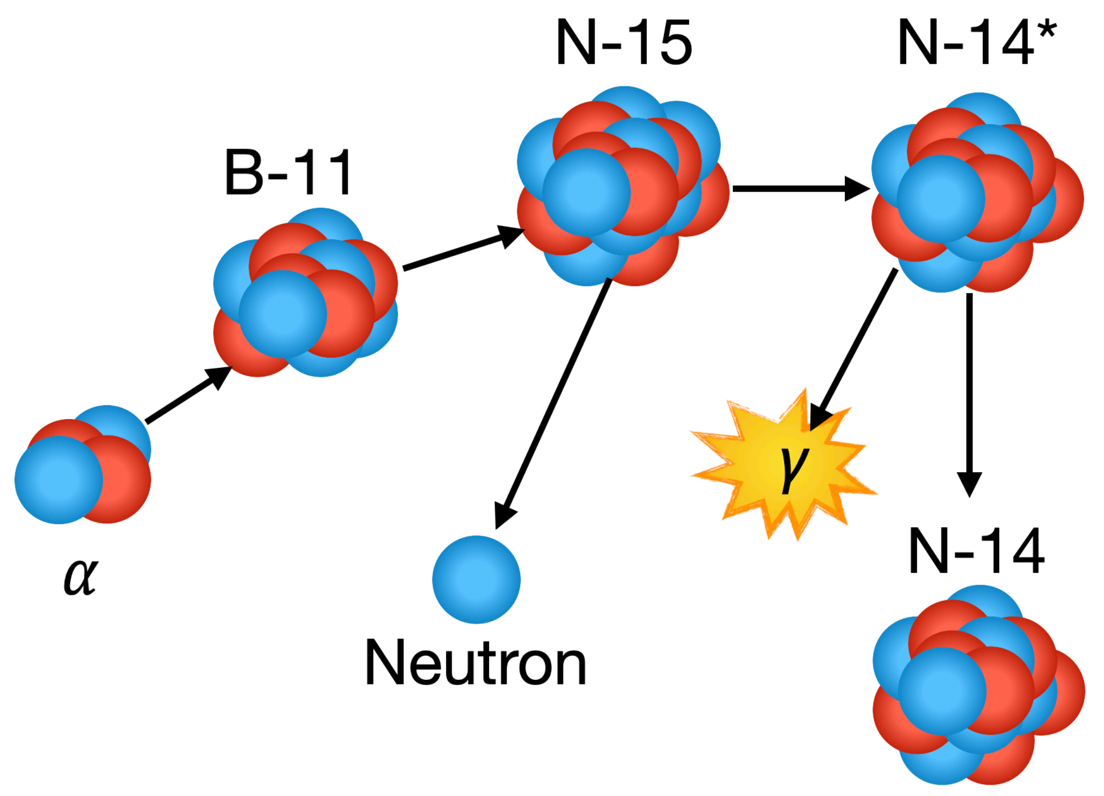
- ***Energy scale difference among ADs ≲ 0.3%***
- ***… among voxels ≲ 0.5%***



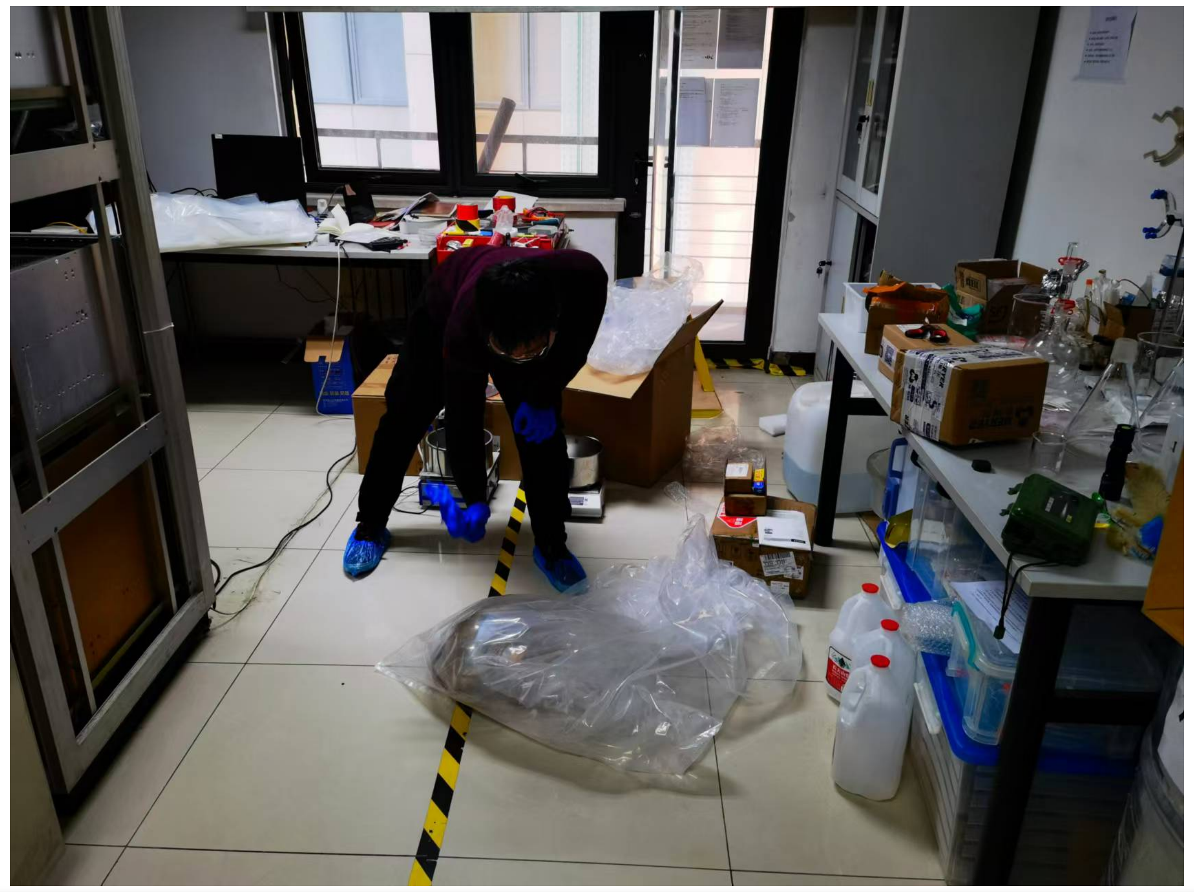
0.5% Z-axis range

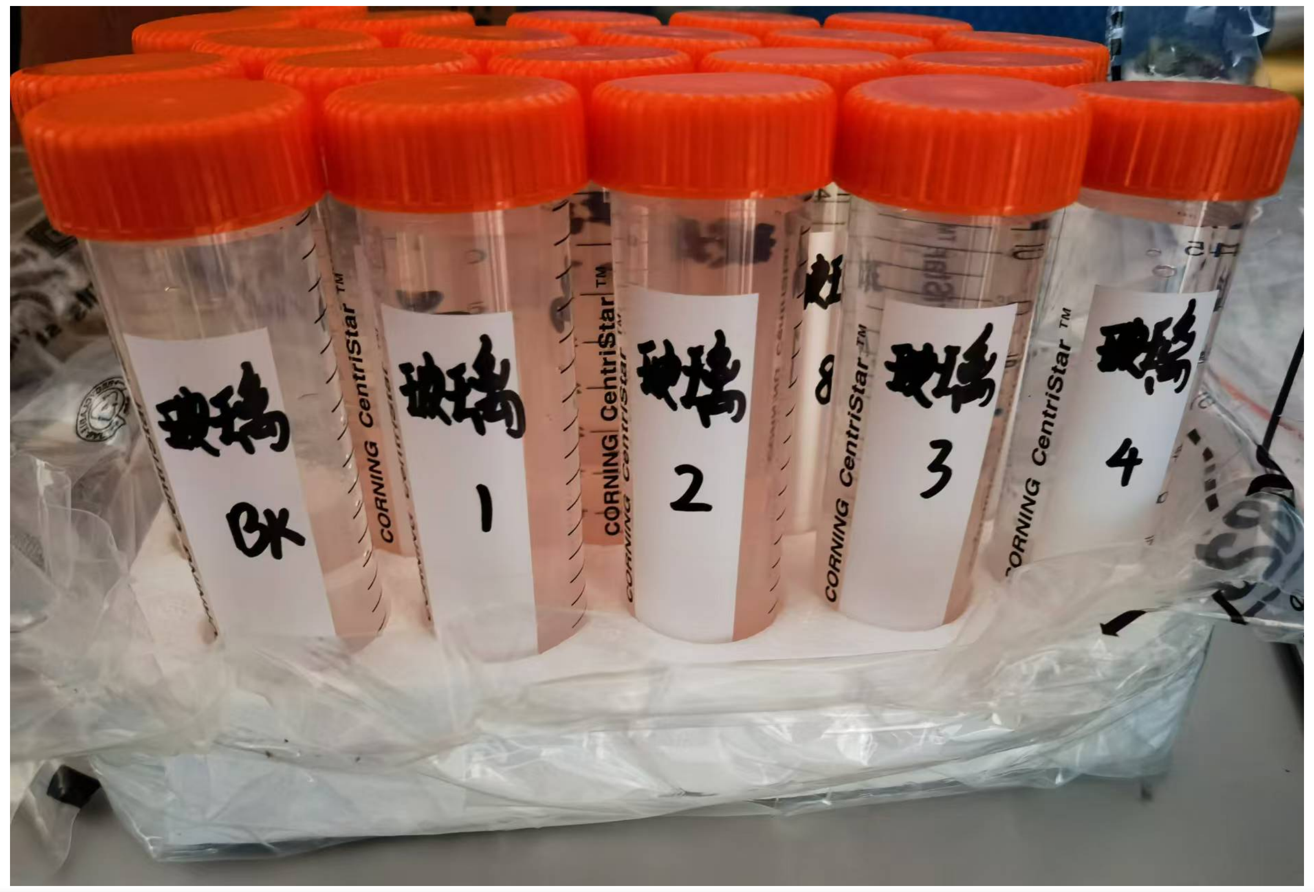
New Oscillation Results Based on nH



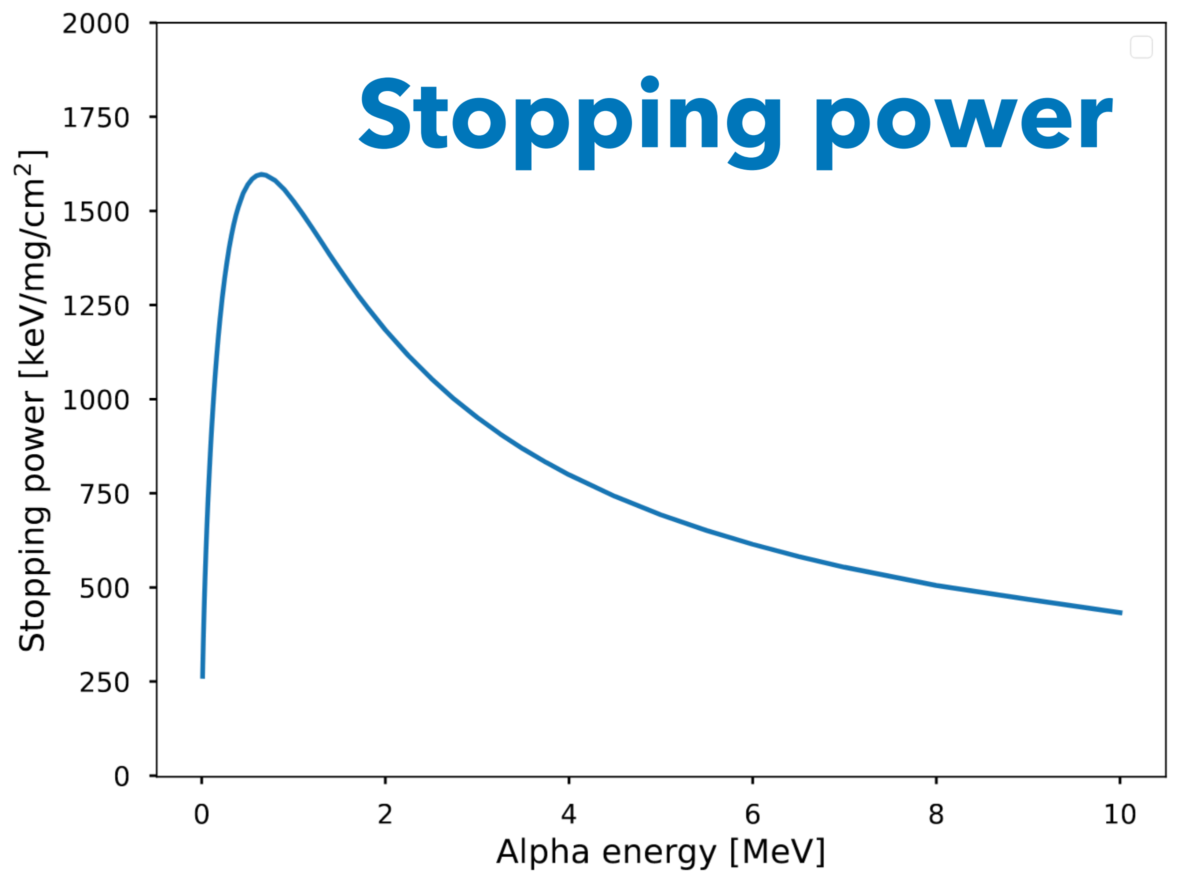


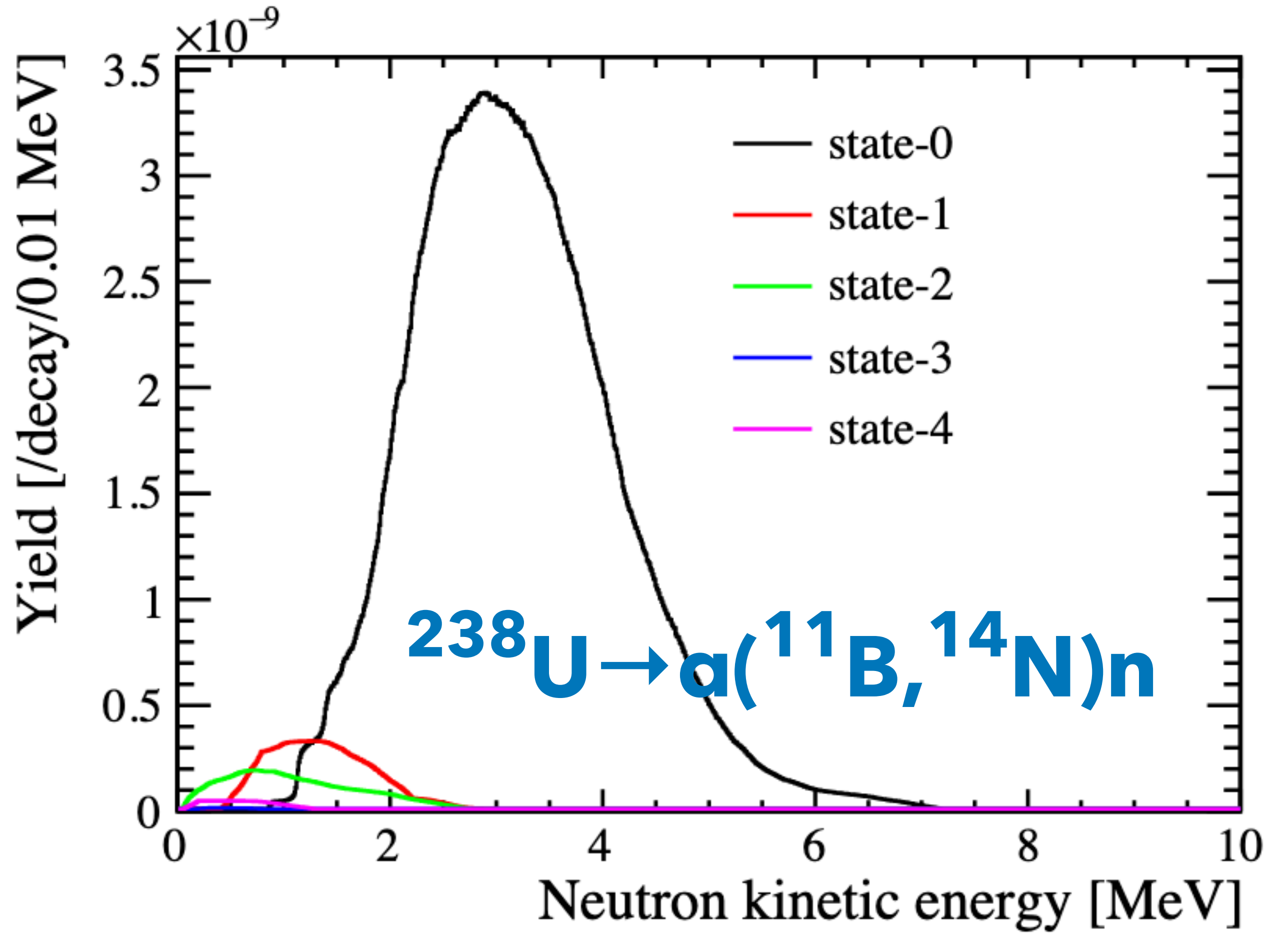
- **Two new neutron sources were found:**
  - ^{238}U spontaneous: 12.9 fission/day, ~2 neutrons/fission
  - (α,n): 367 neutrons/day
- **Dominant source → PMT glass with a high U/Th level and boron fraction**
  - ^{11}B fraction was measured to be ~17.35%
- Background rate was estimated to be 0.20±0.04 /AD/day

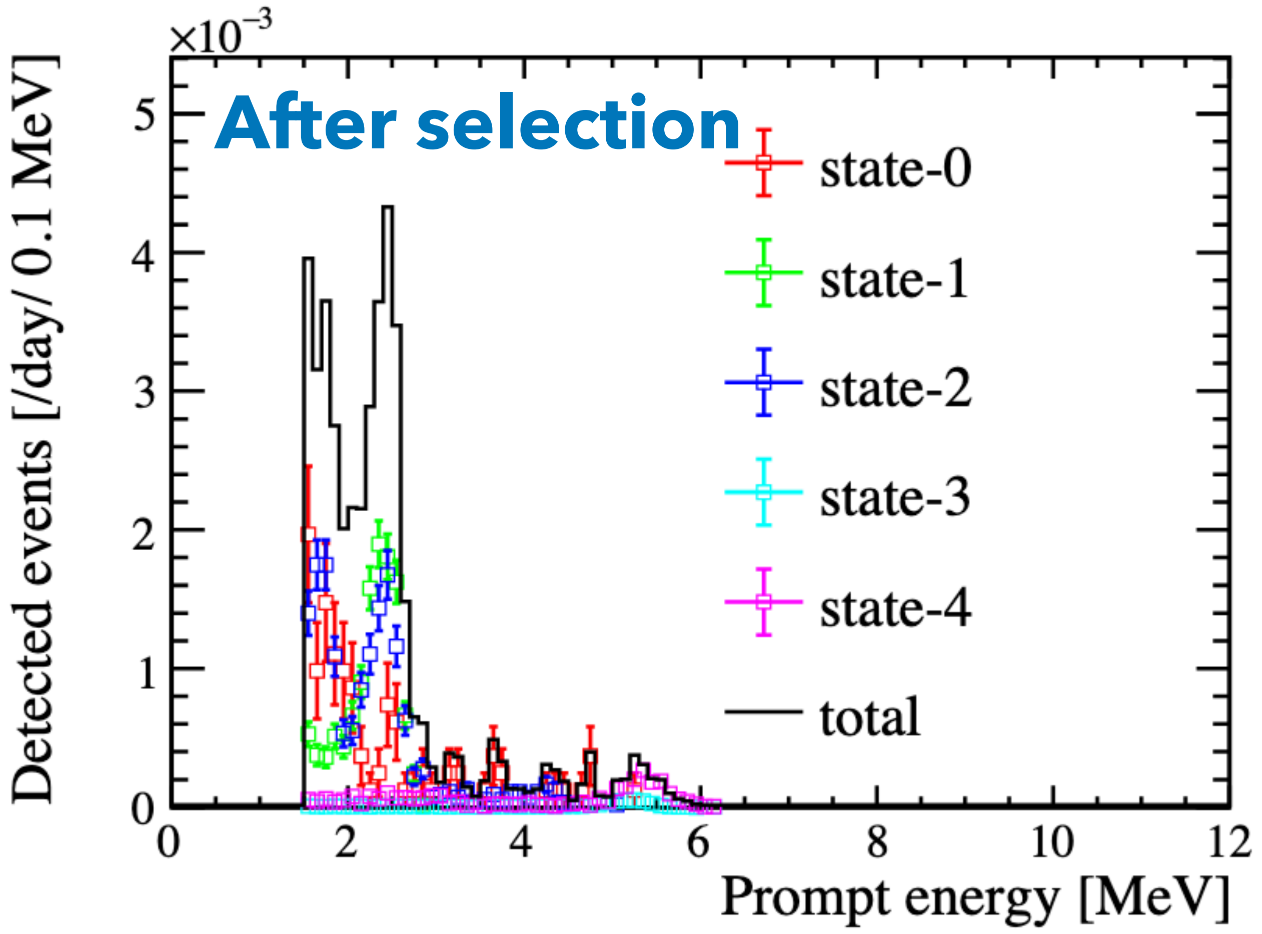




Evaluation of (α,n) Background

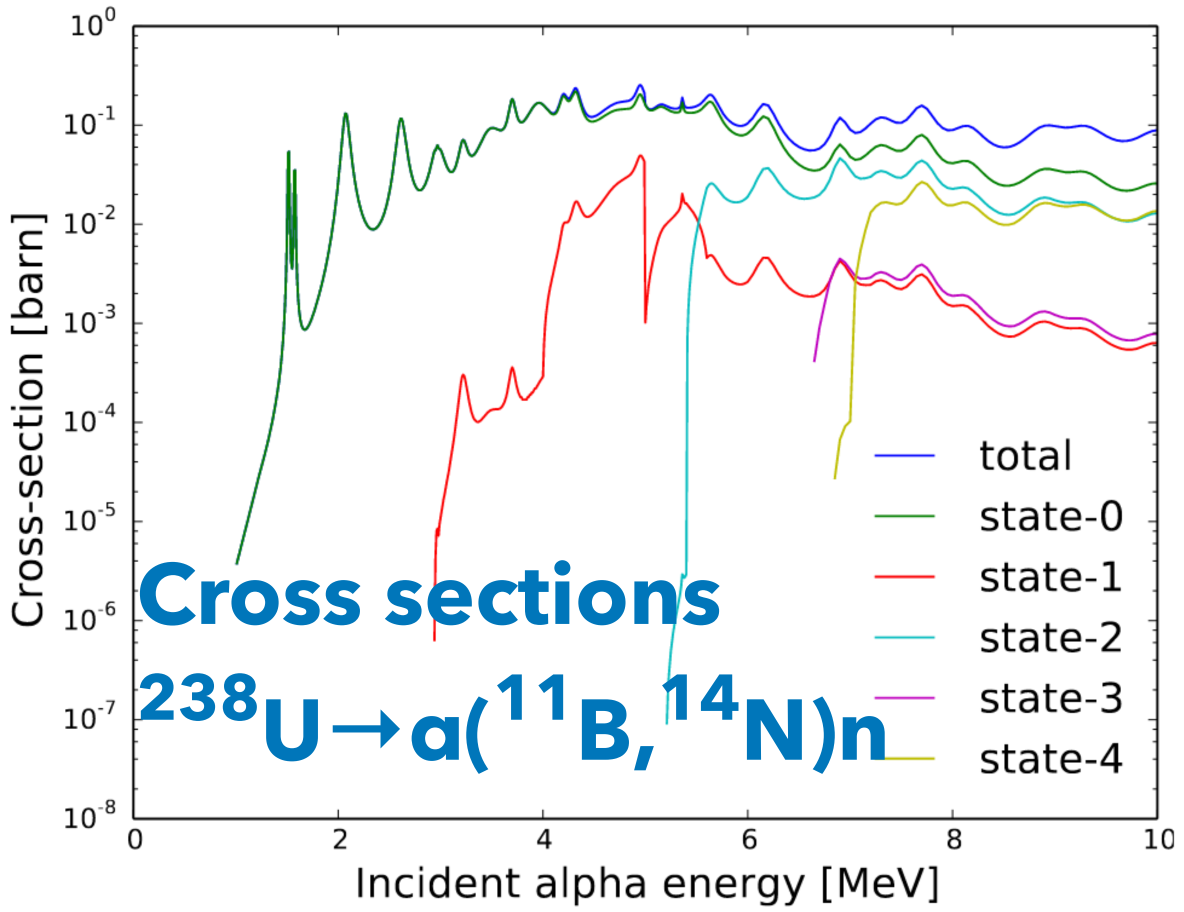


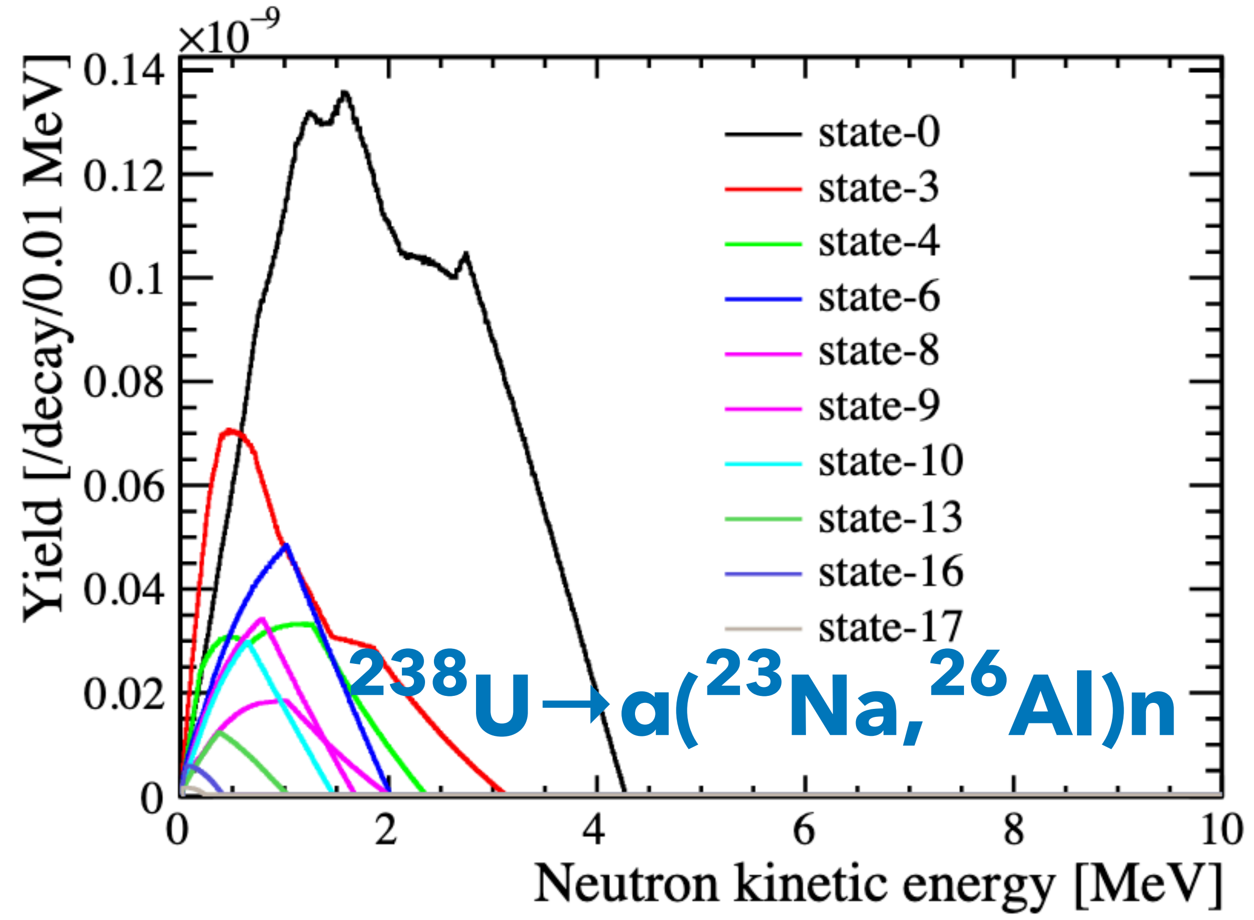


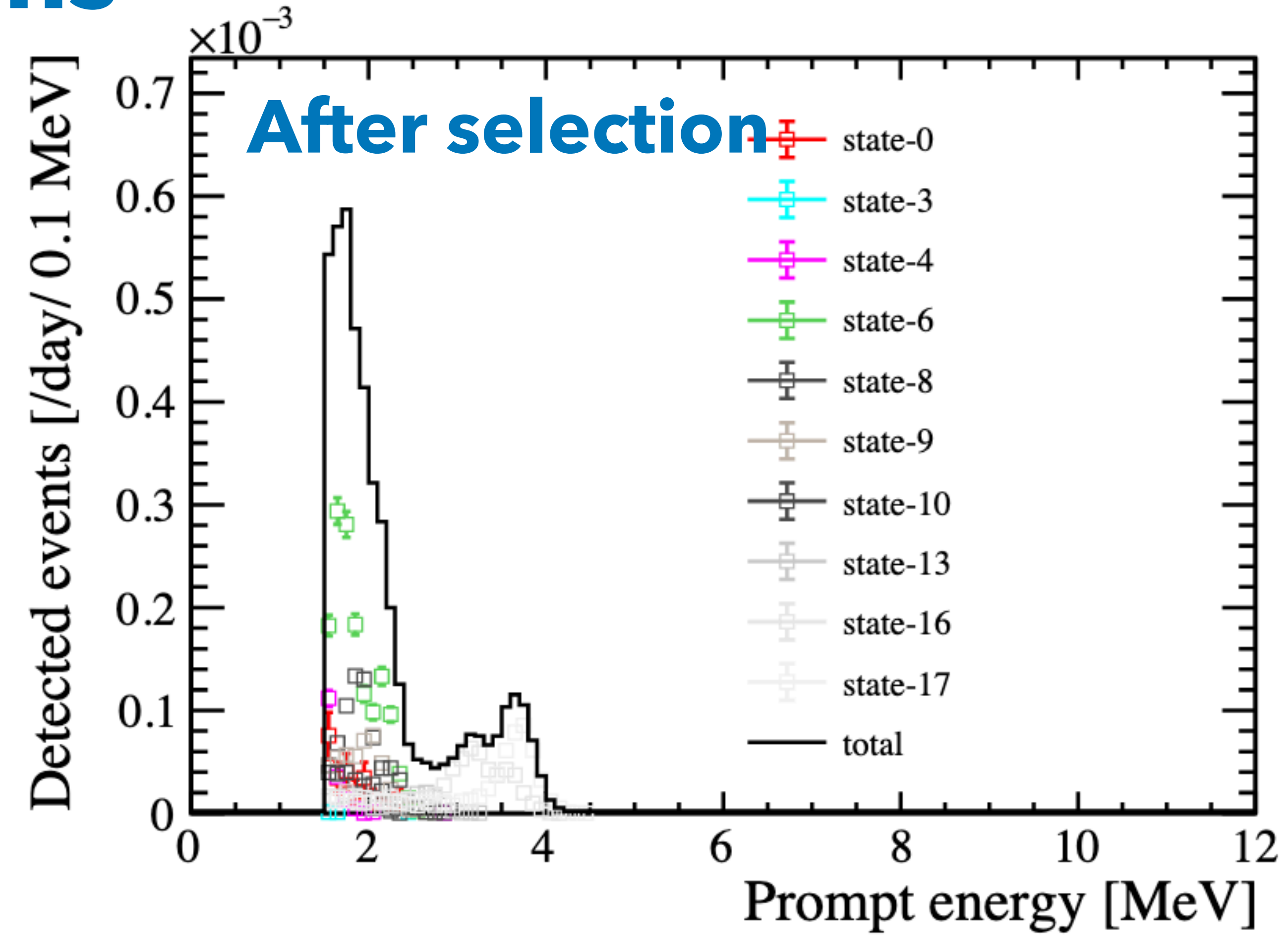


Simulation

Selections



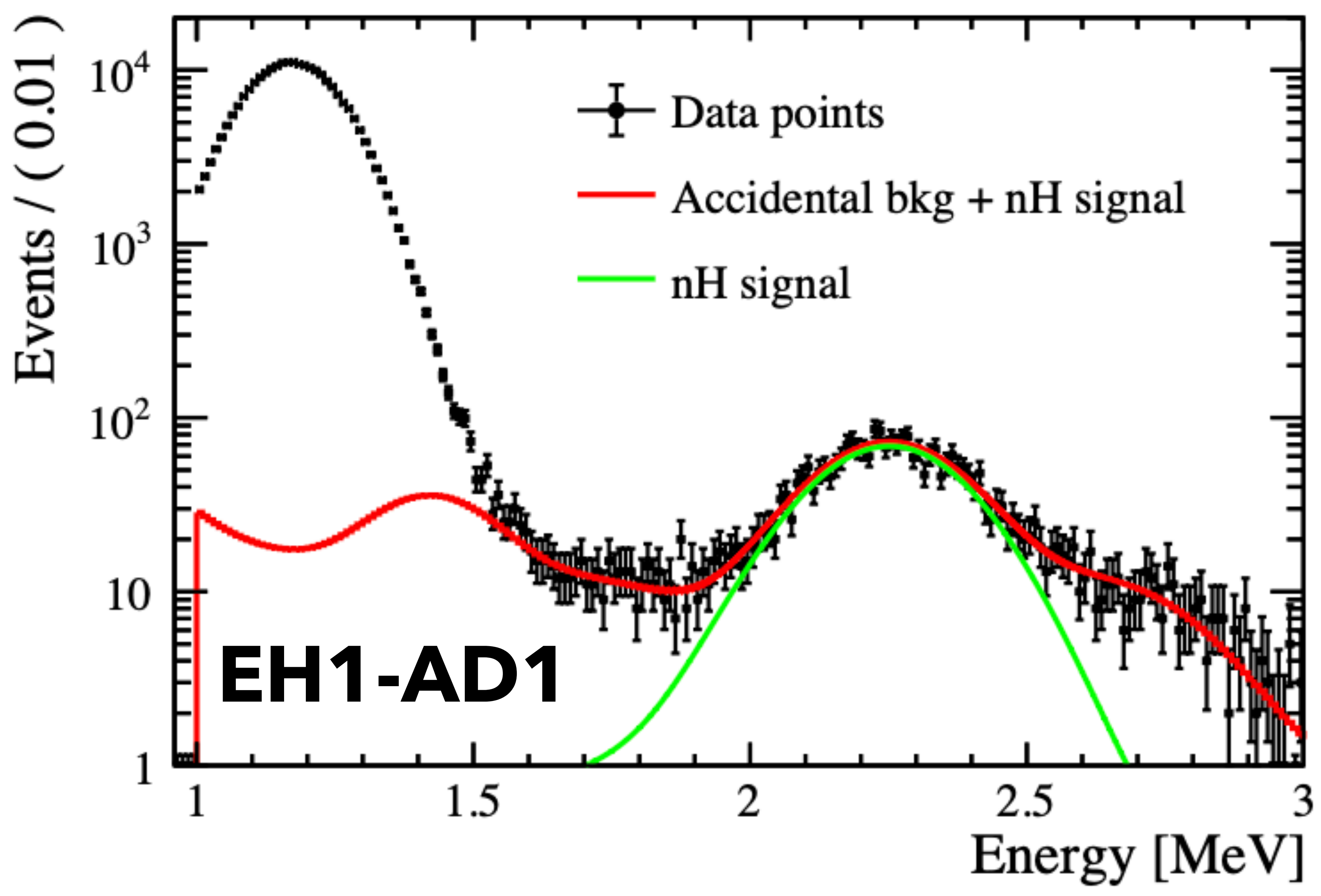


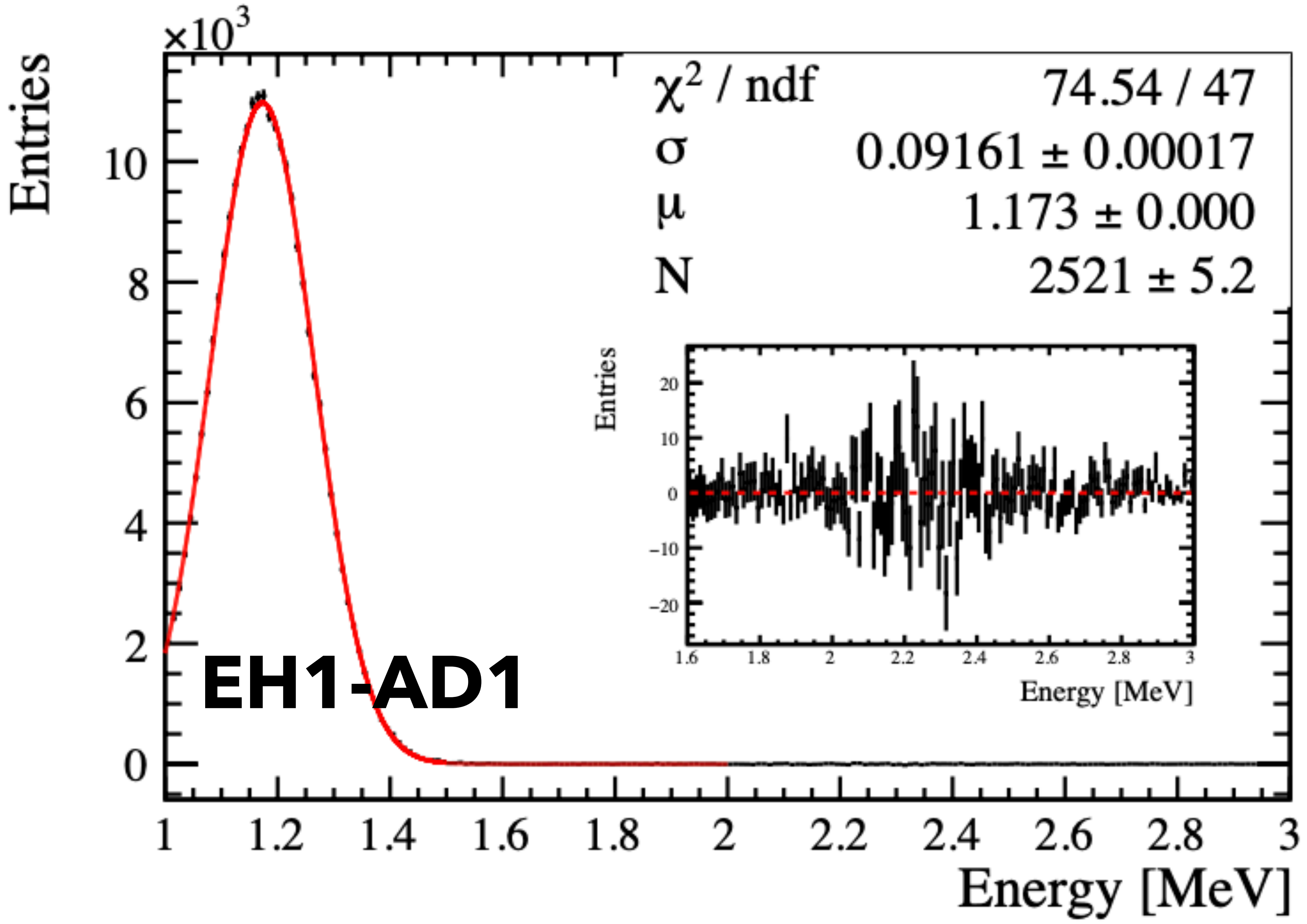


Potential β-α cascade decay background

➡Subtracting accidentals and nH-IBDs

- Select ^{212}Bi-^{212}Po-^{208}Pb sample, to see if there is a residual tail the nH-IBD region
  - Removing accidentals and nH-IBDs to get a clean α energy spectrum
- Confirmed that the α energy tail is consistent with 0 in nH-IBD region

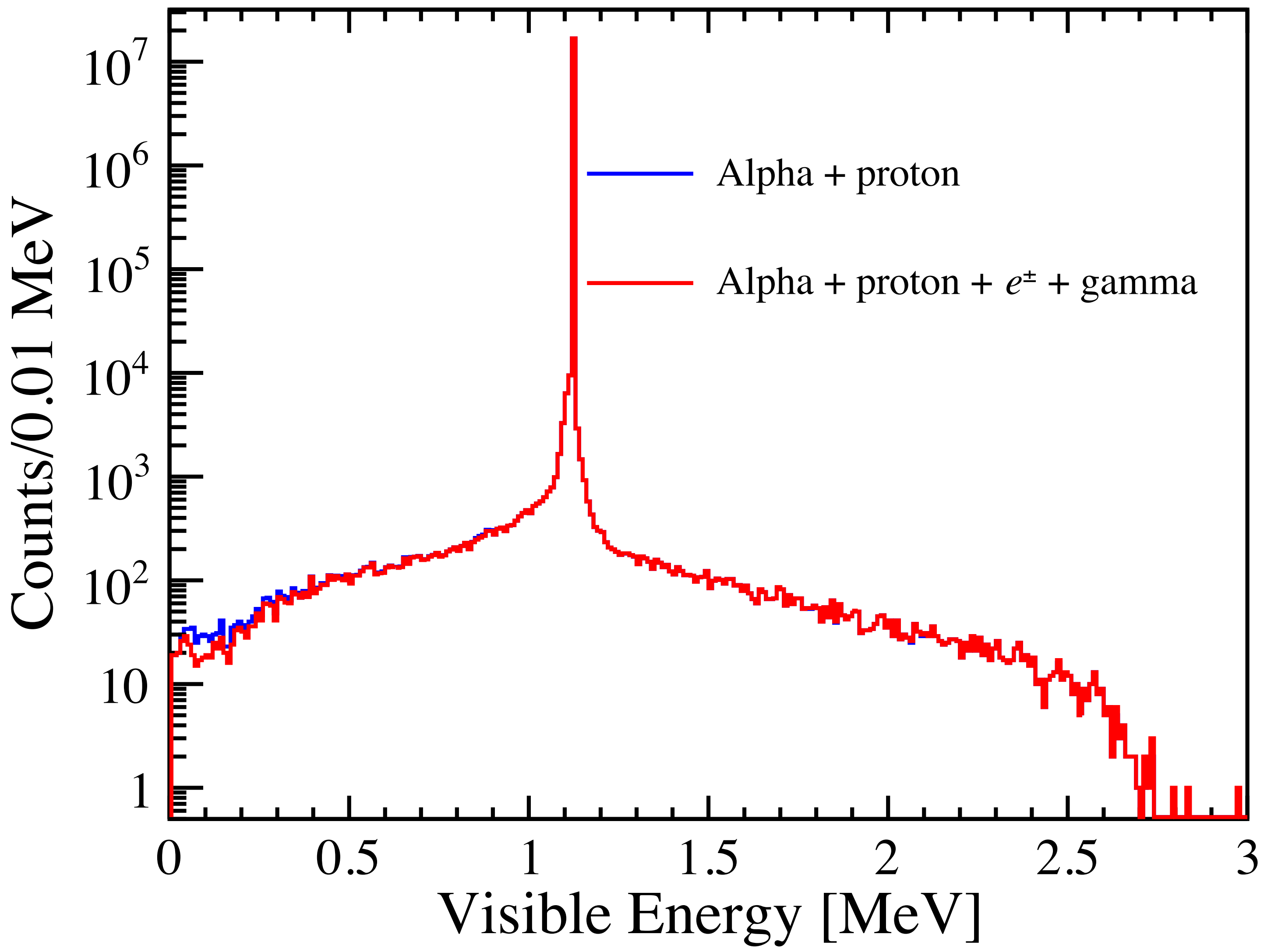


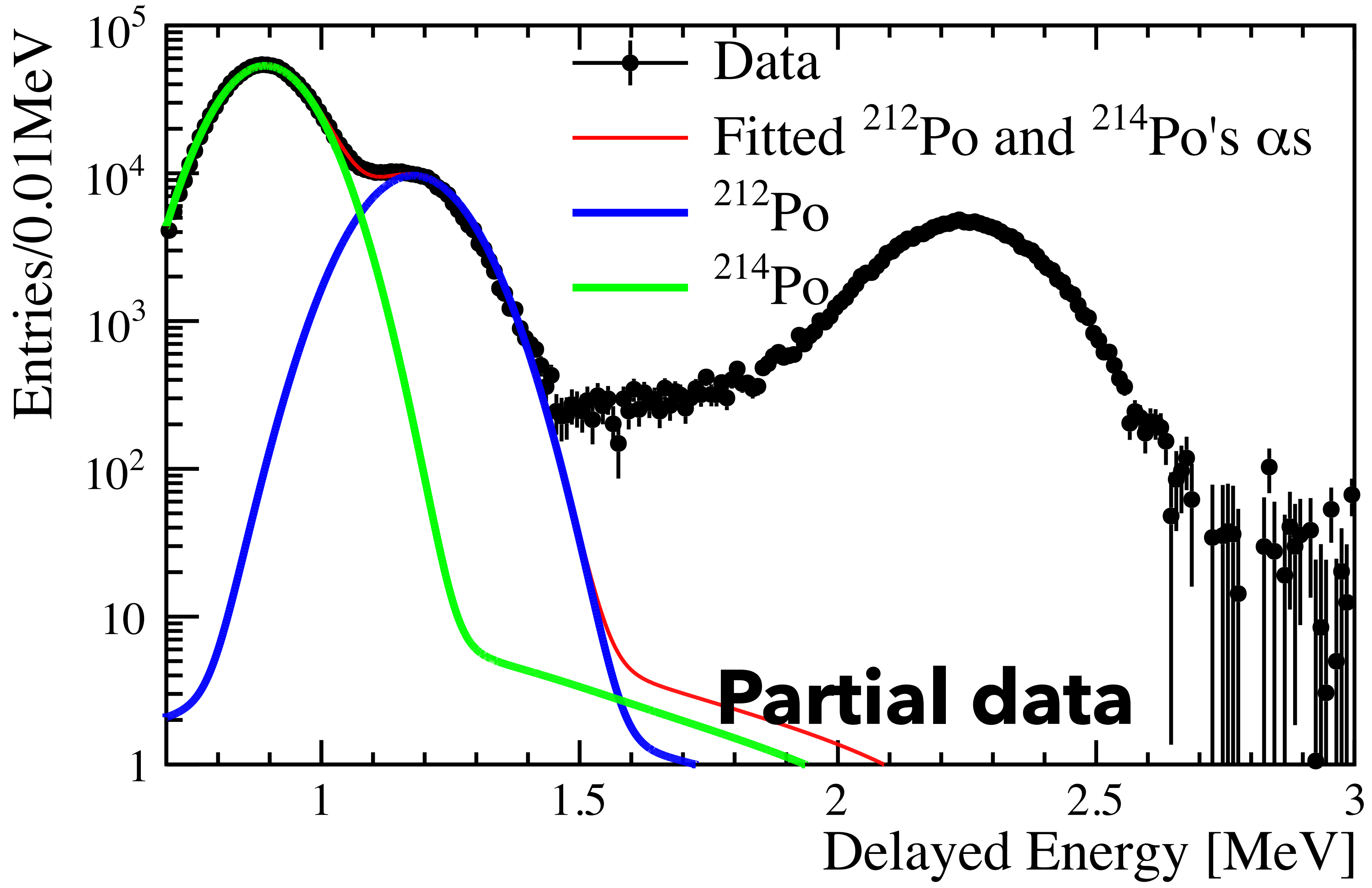


Potential β-α cascade decay background

➡Determining α-tails

- Change the low energy cut in nH-IBD: 1.5 MeV to 0.7 MeV
  - Able to see two peaks in nH-IBD candidate (before delayed energy cut)
- Determine the α tails in GEANT4 simulation, then fit it to data
- Evaluated background rate ≲ 0.01 /day/AD, negligible

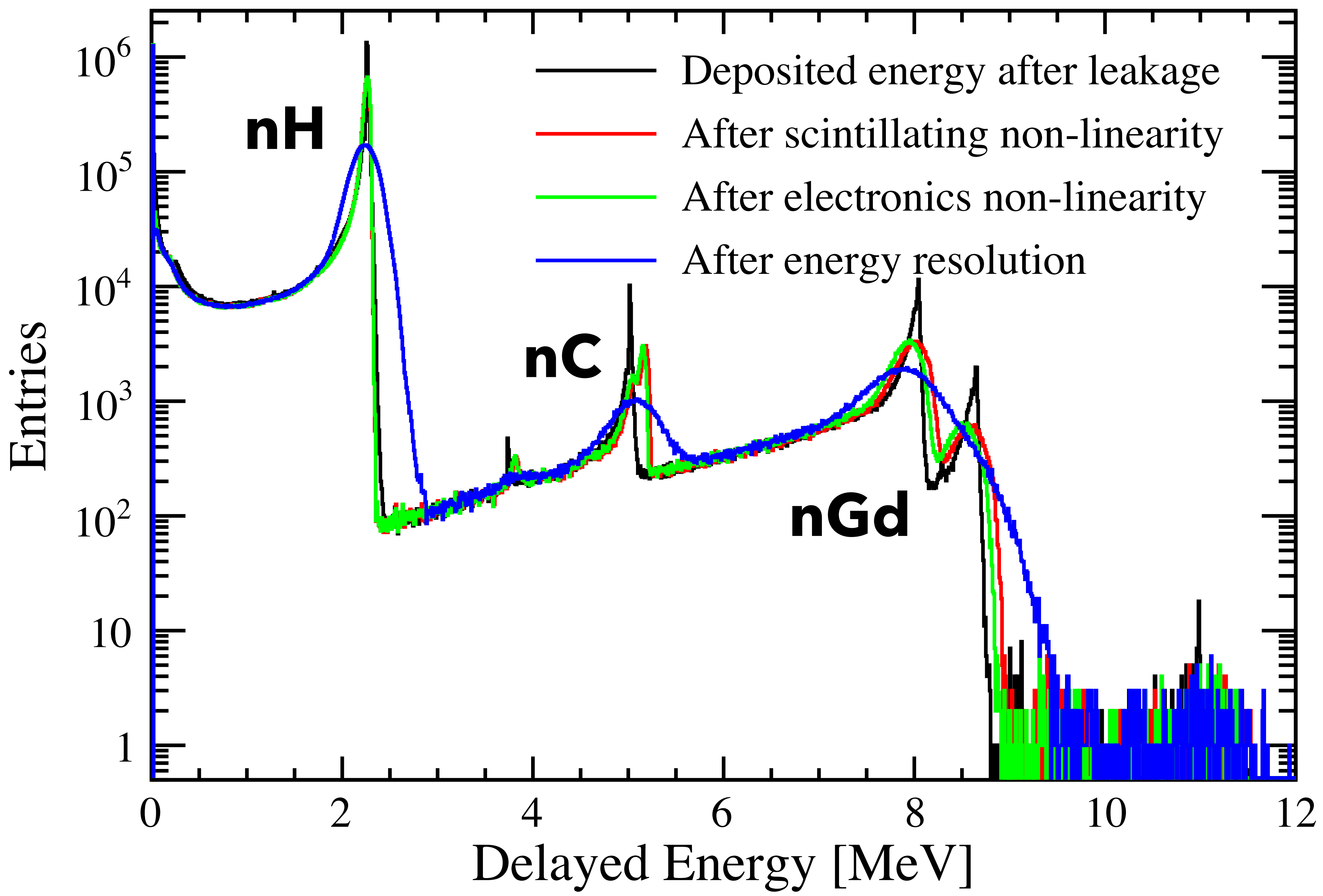




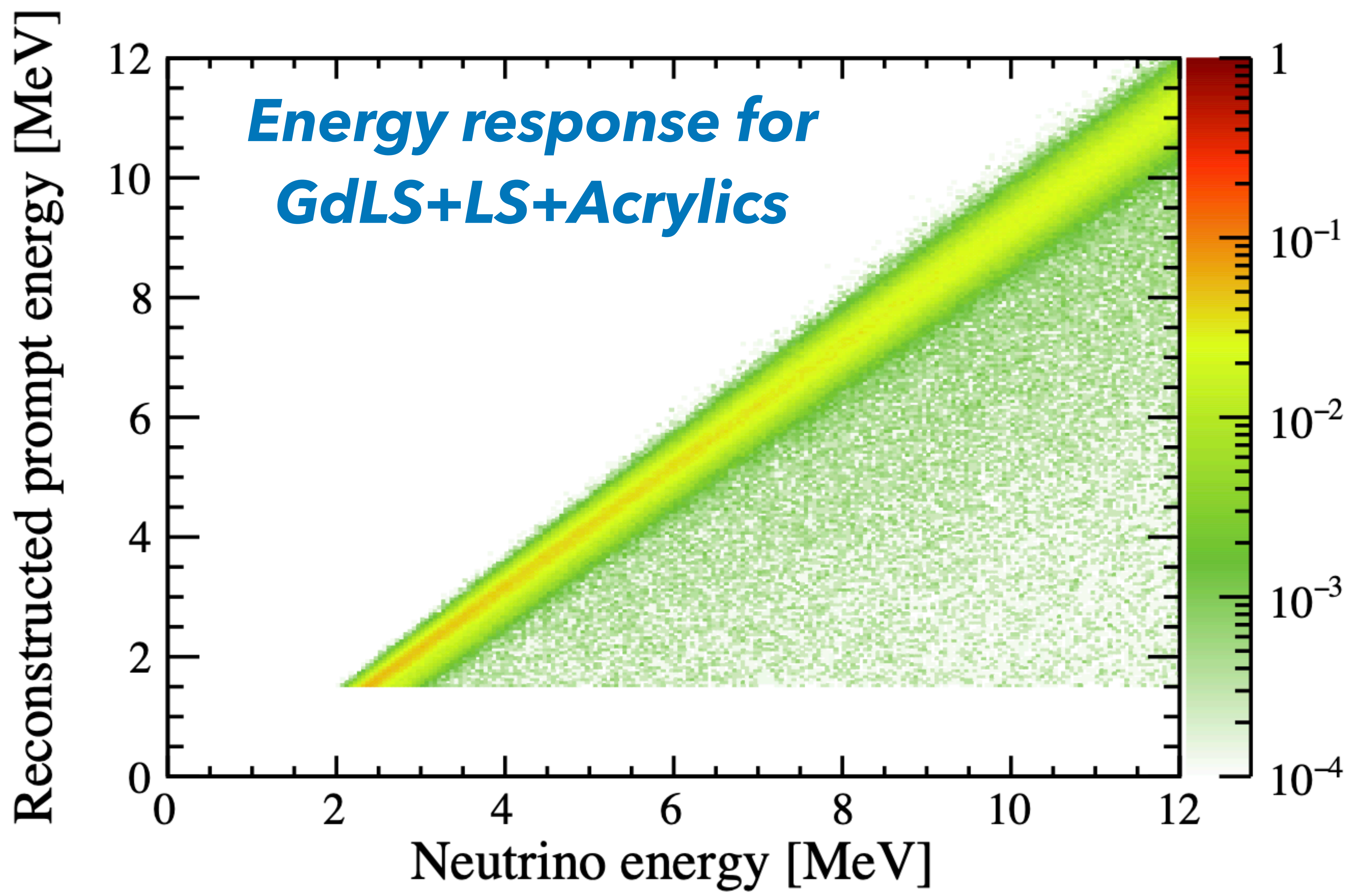
New Oscillation Results Based on nH

- **New energy response model -> First rate+shape analysis with nH-only sample**
  - **Add the non-linearities on deposited energy on a step-by-step basis**
  - **Decouple energy leakage with the Calorimeter function: *NIM A 827, 165-170***
  - **Study each effect and their uncertainties on the measured prompt spectrum**

Simulated IBDs in LS volume

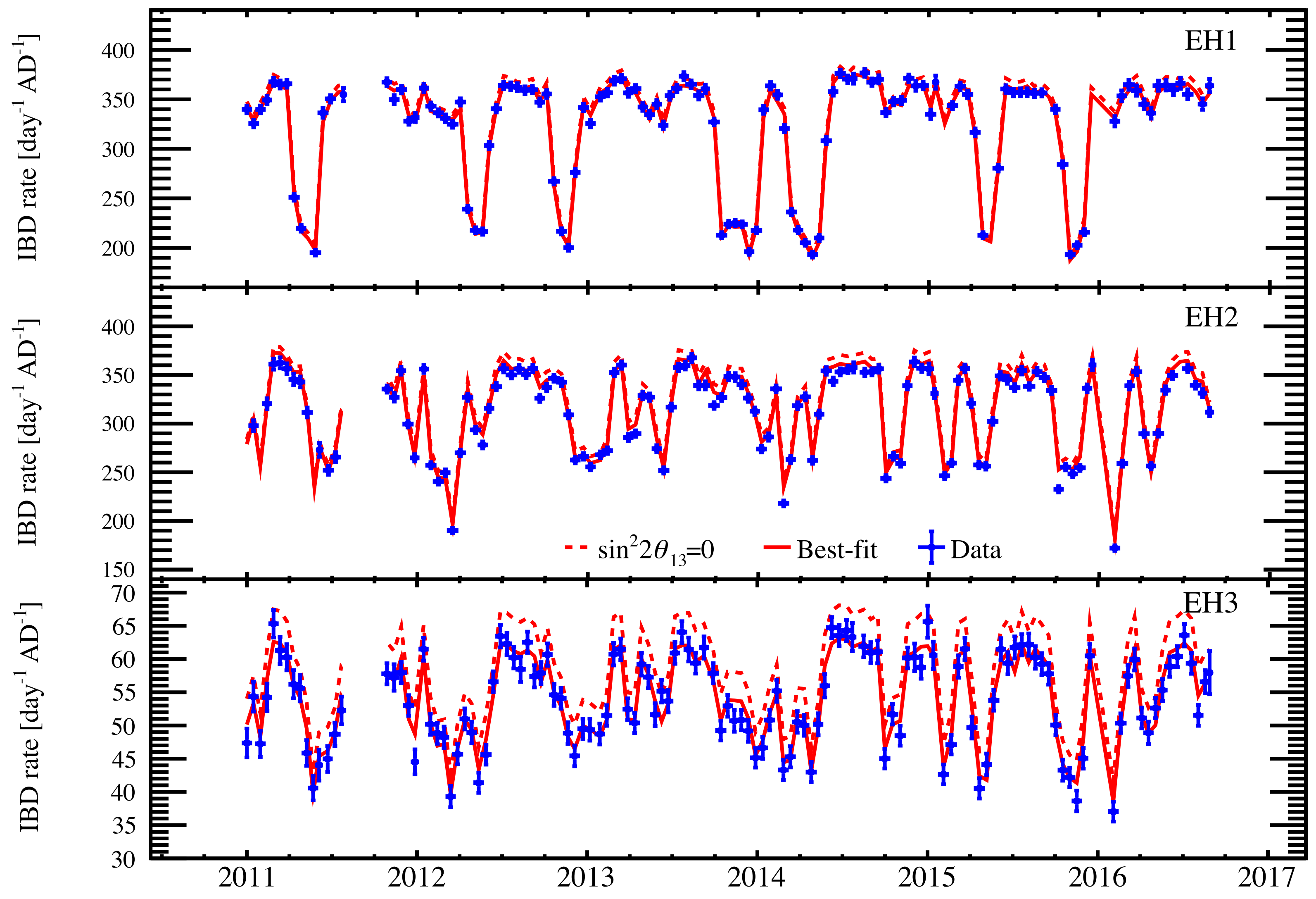


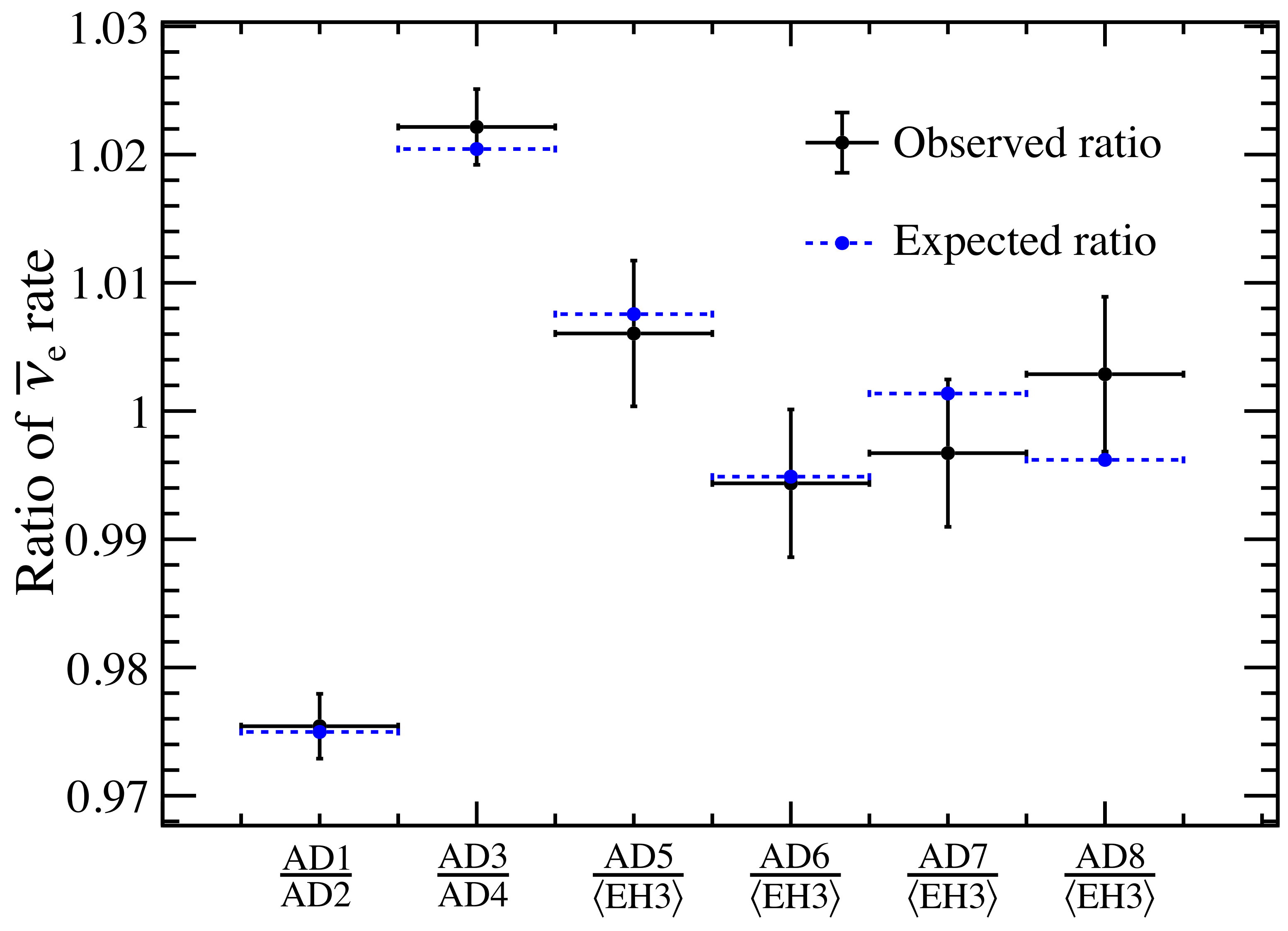
Adjusting Non-uniformities in Monte-Carlo according to Data

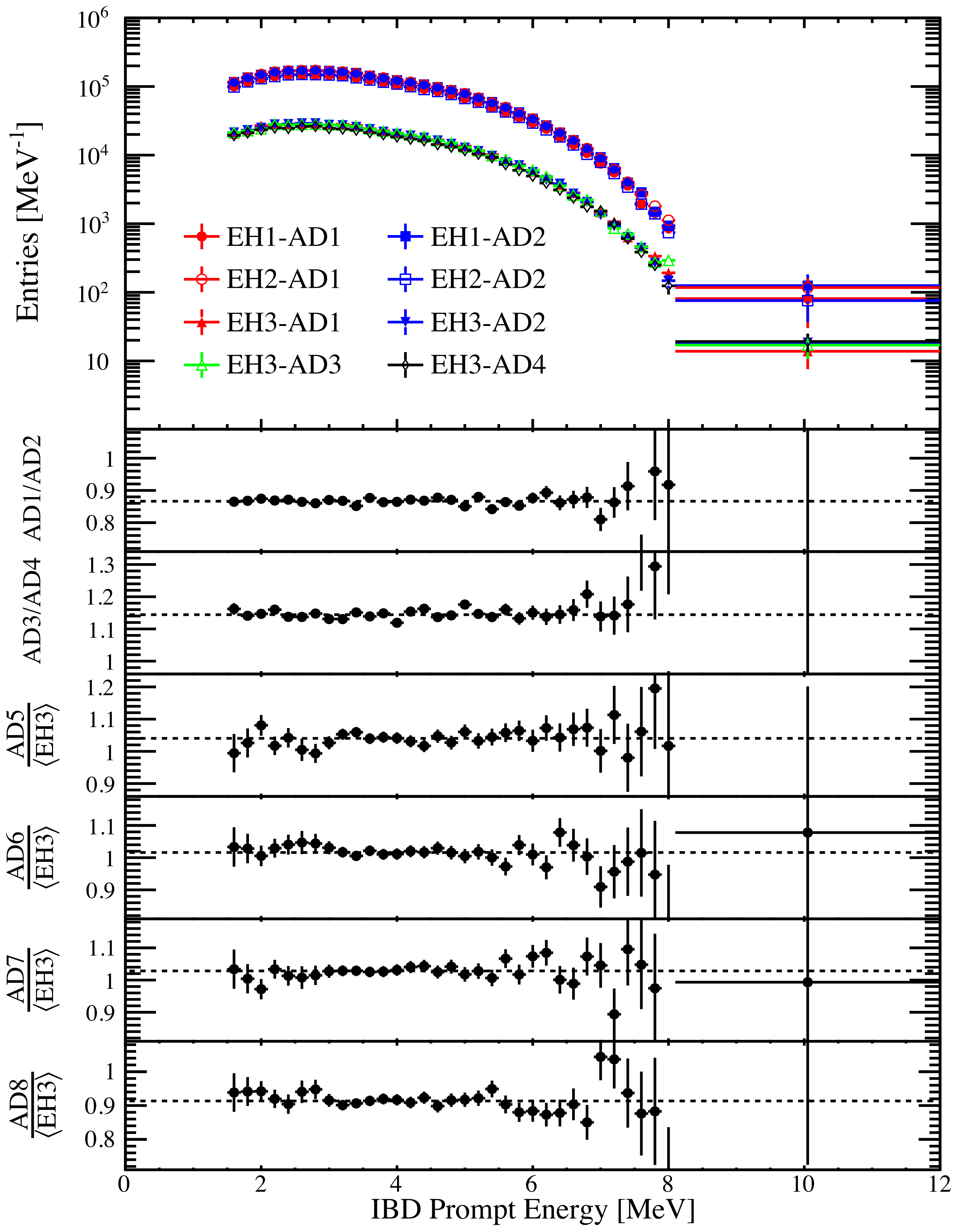


New Oscillation Results Based on nH

- 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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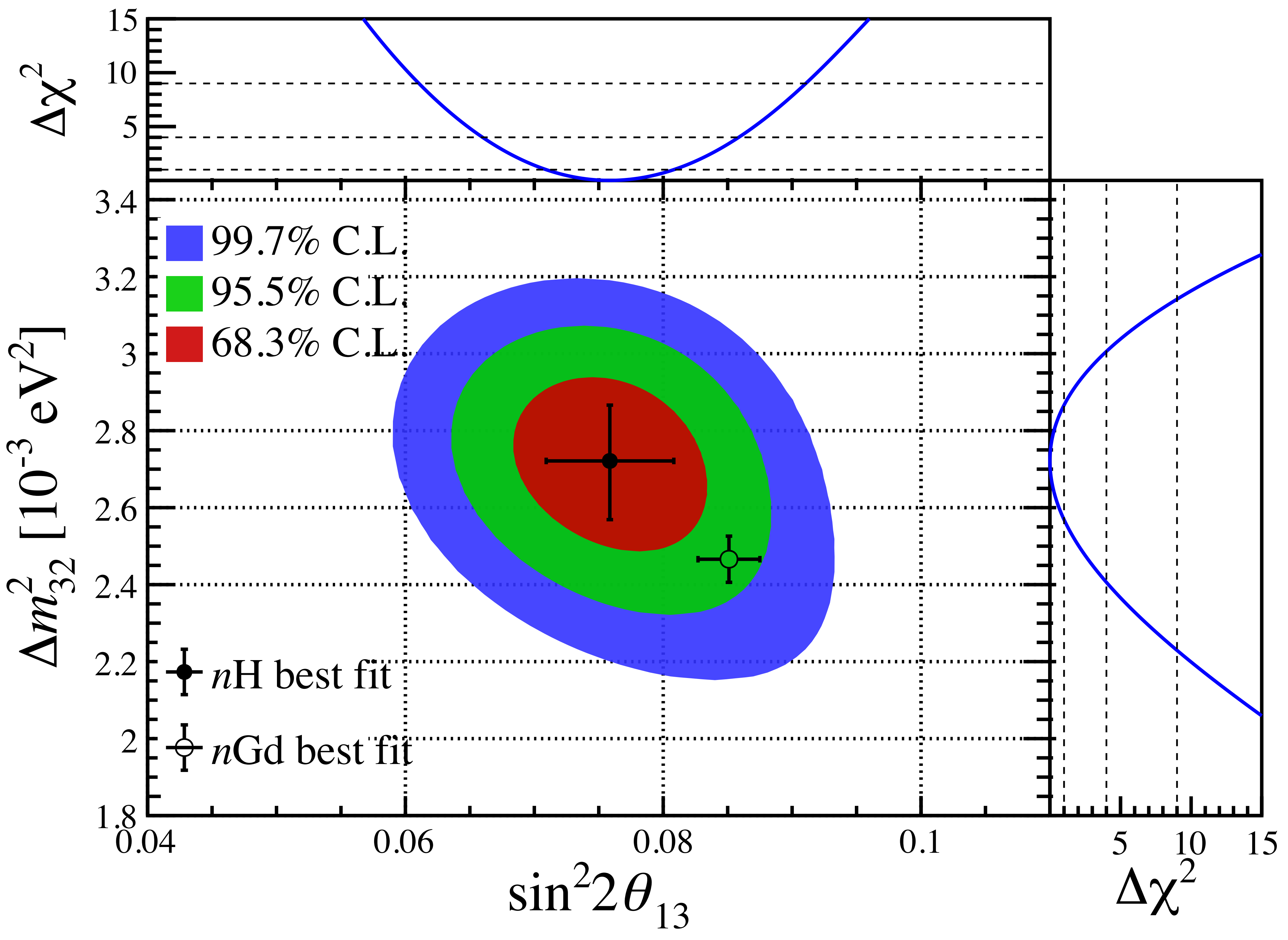
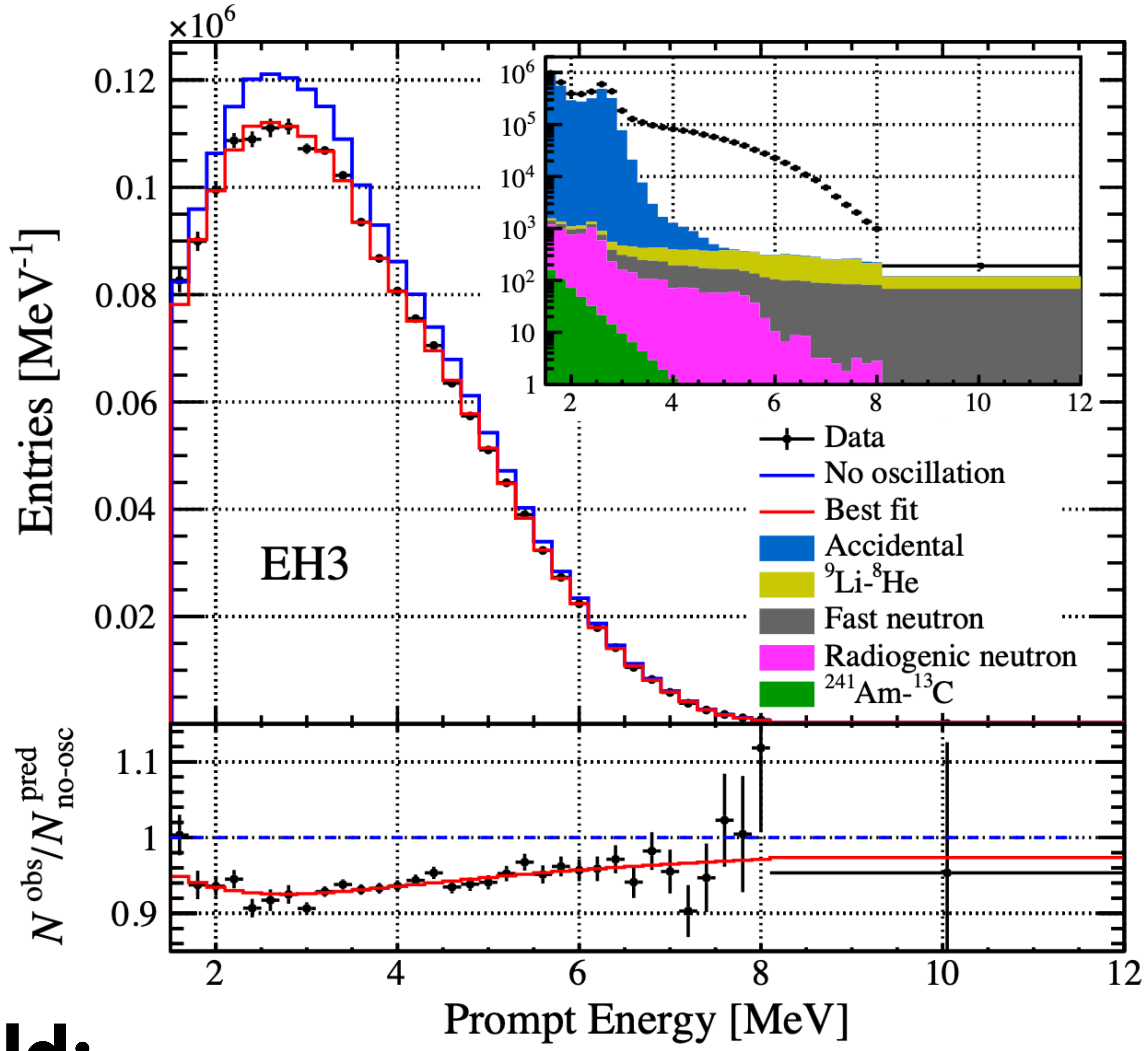




- **The results with rate+shape analysis yield:**

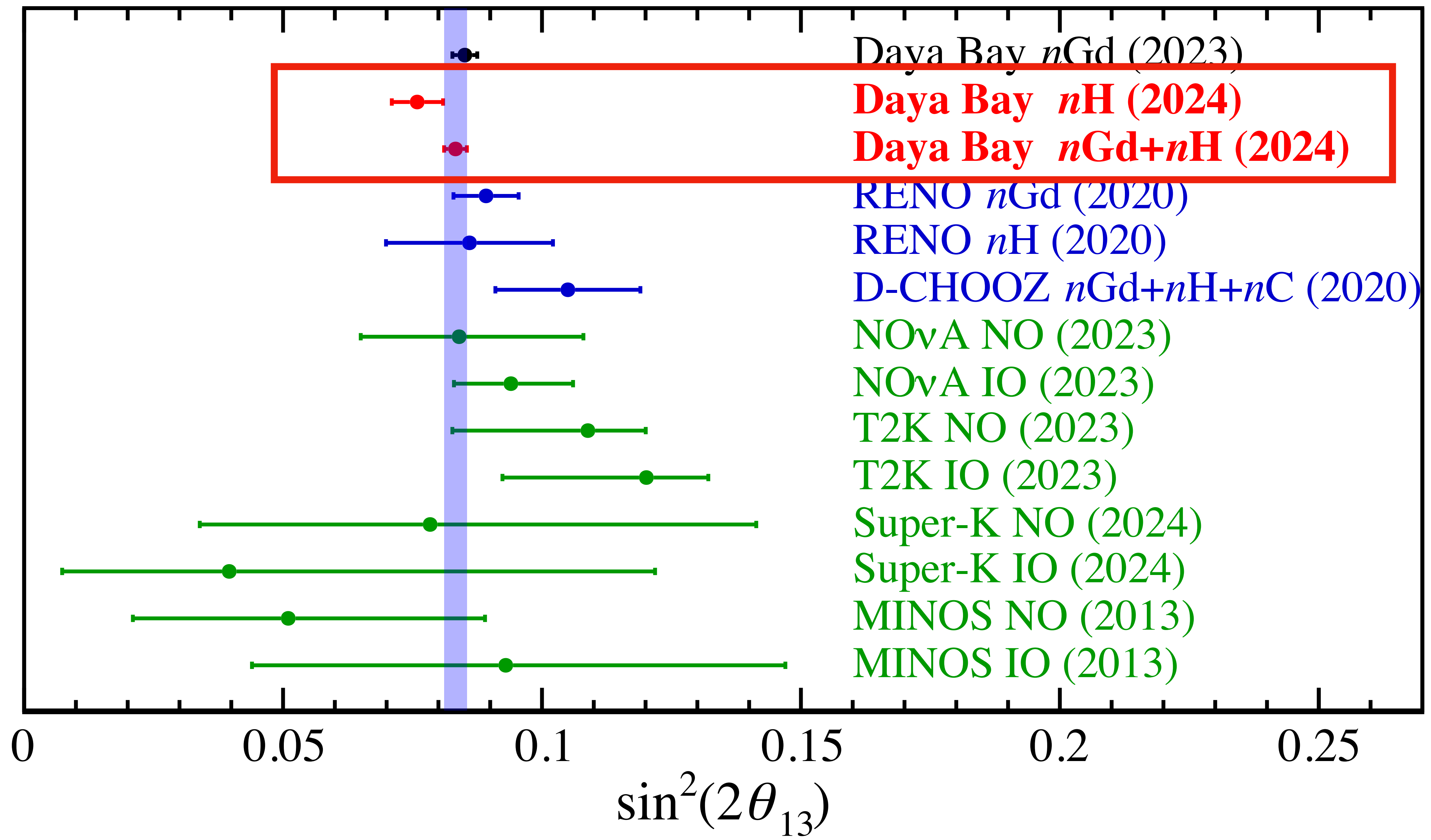
$$\sin^2 2\theta_{13} = 0.0759^{+0.0050}_{-0.0049}$$

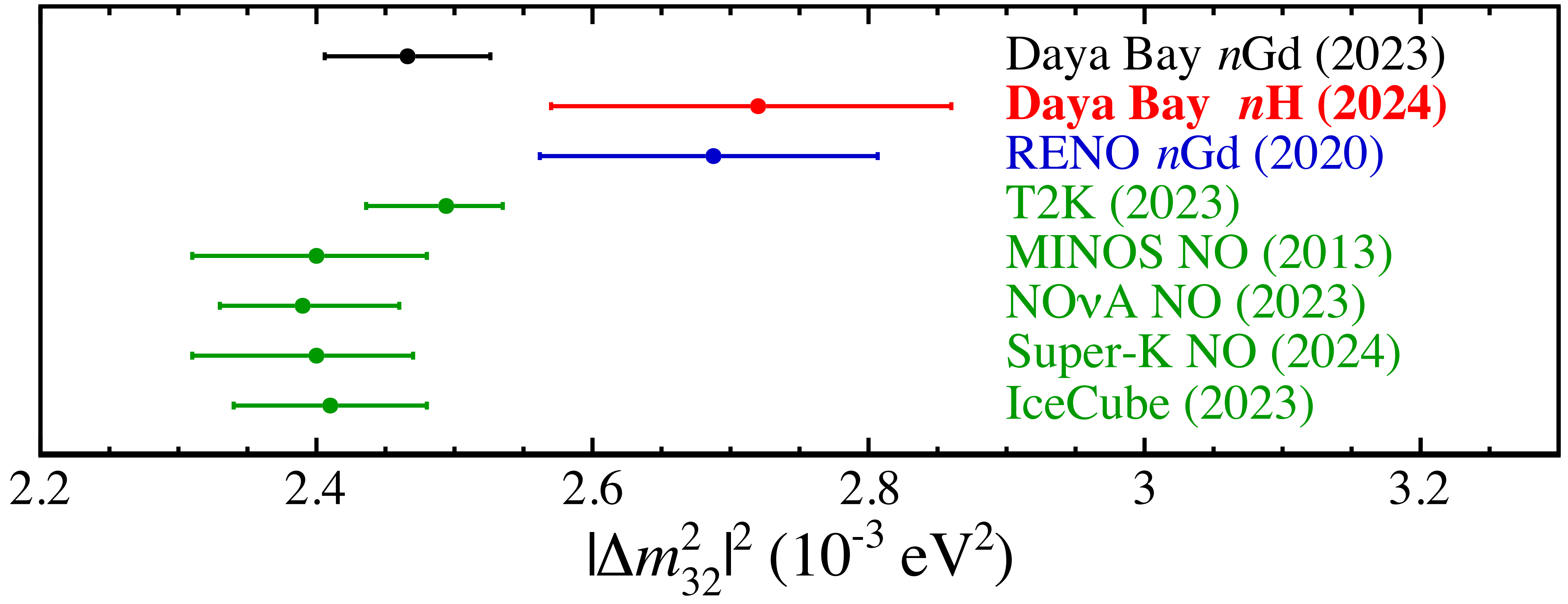
$$\Delta m^2_{32} = 2.72^{+0.14}_{-0.15} \times 10^{-3}\ \text{eV}^2\ \ \textbf{[NO]},\qquad -2.83^{+0.15}_{-0.14} \times 10^{-3}\ \text{eV}^2\ \ \textbf{[IO]}$$

- **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 $\sin^2 2\theta_{13}$, <u>2.6%</u> precision**





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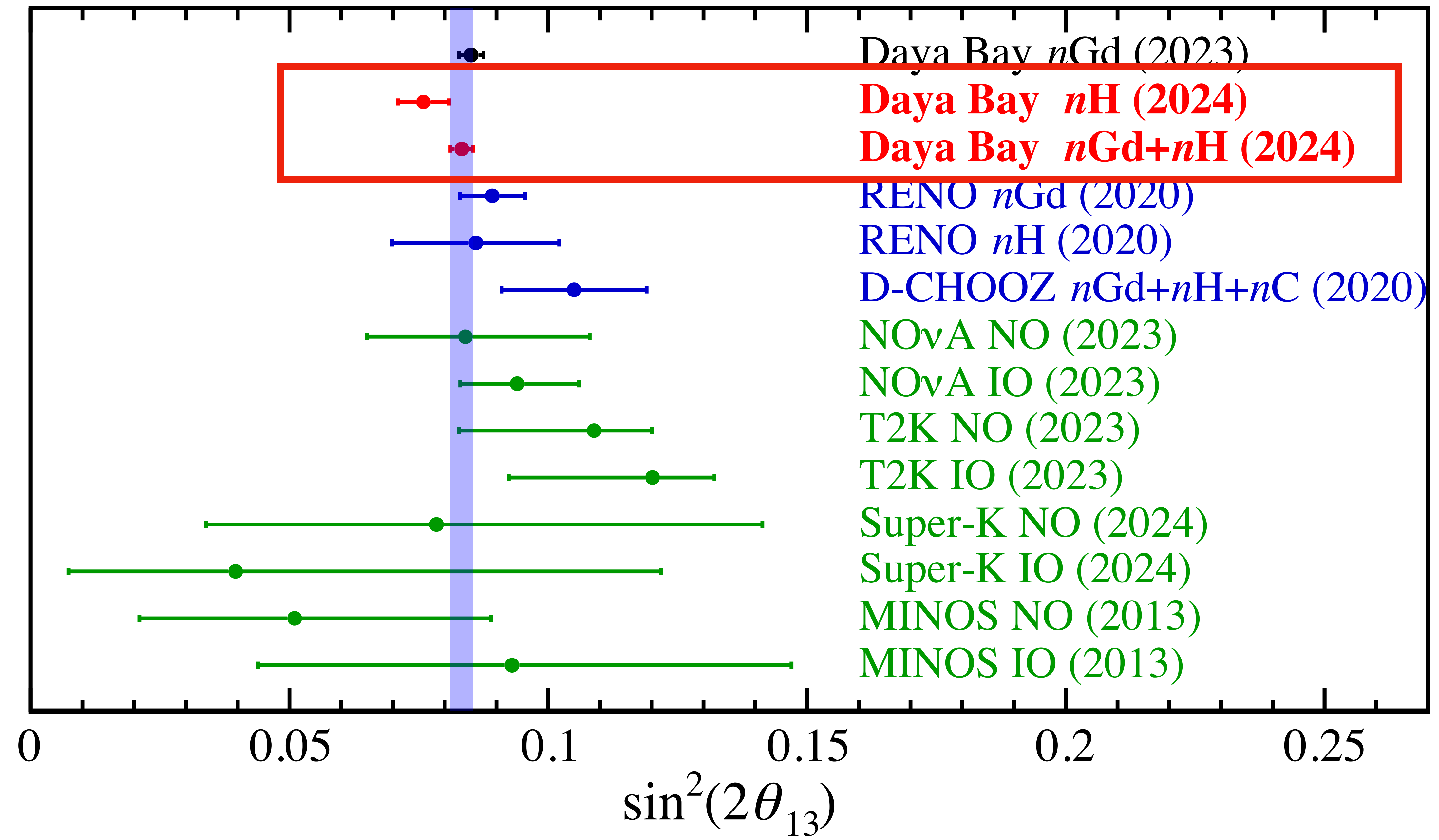
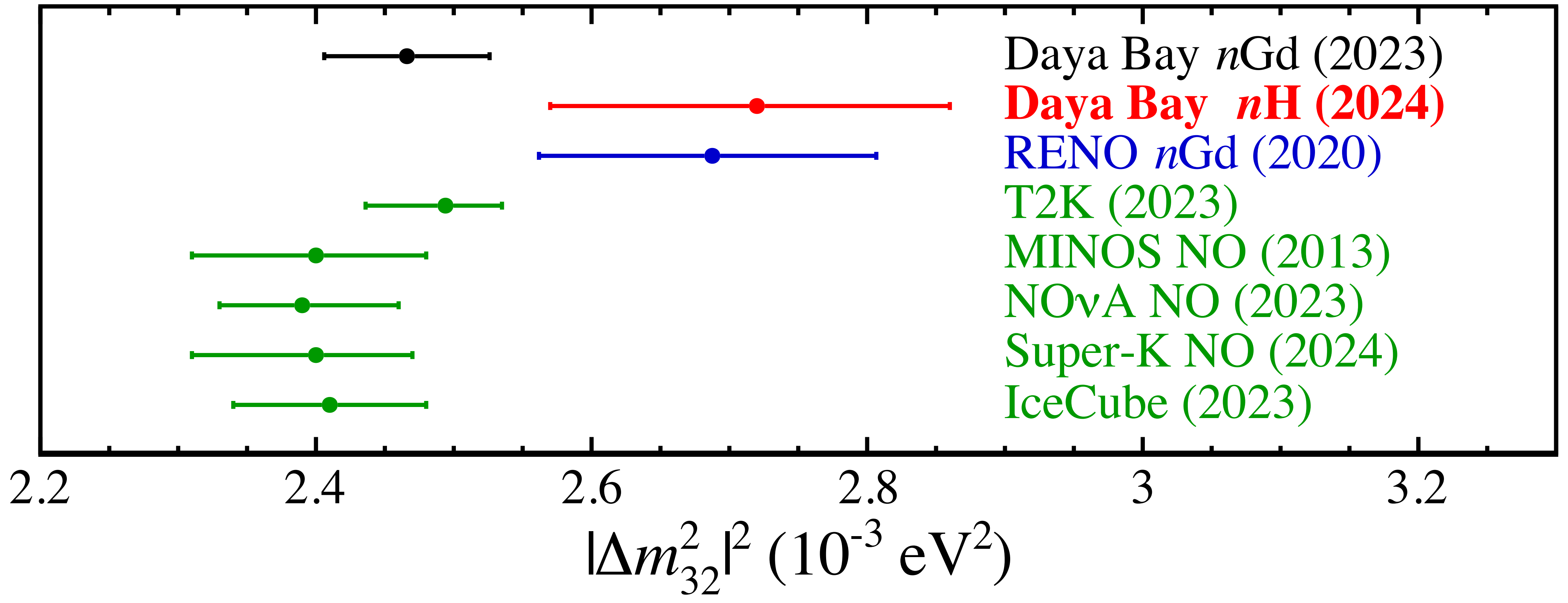
Consistent results from reactor and accelerator experiments





Precision Measurement of θ_{13}

- **Help to determine the unknown parameters**
  - Lepton charge-parity violation phase
  - Neutrino mass ordering
  - θ_{23}'s octant
  - New physics, non-unitarity of PMNS matrix
- **θ_{13} will become the least precise neutrino mixing angle after JUNO's measurements**
- **Currently, no running experiments aim to increase the precision of θ_{13}**
- **nH analysis → JUNO**

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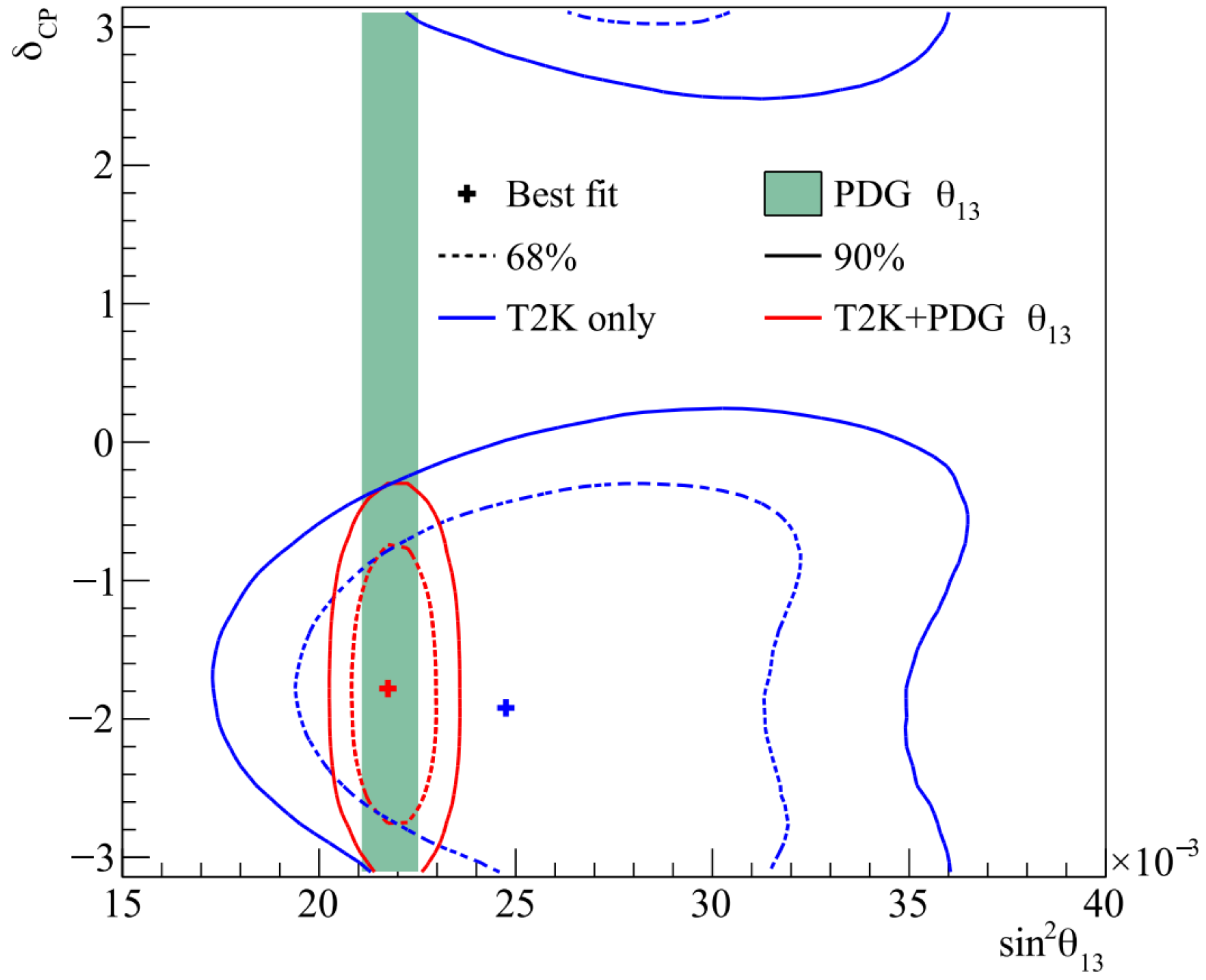

Summary

- **Daya Bay leads the precision measurement for θ_{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 measurement via nH sample
  - Combination of nH and nGd has been reported as the most precise result
- **nH results with the full data set is expected to be released soon**

Stay Tuned!

Thank You