The Latest Reactor Neutrino Oscillation and Reactor Neutrino Flux and Spectrum Results from Daya Bay

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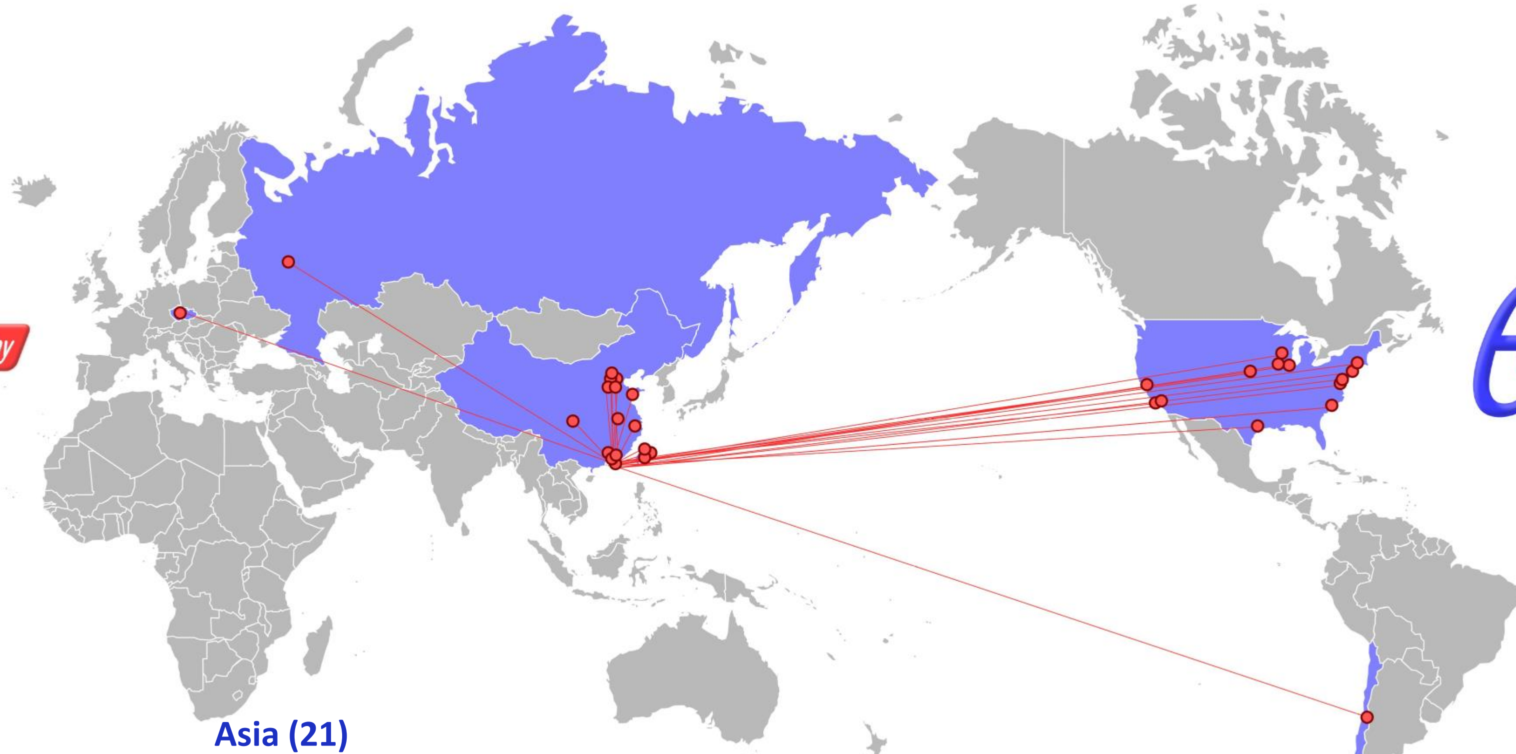
(On behalf of the Daya Bay Collaboration)

August 25, 2025 @ TAUP2025

The Daya Bay Collaboration

About 250 collaborators



Asia (21)

Beijing Normal Univ., CNG, CIAE, Dongguan Polytechnic, ECUST, IHEP, Nanjing Univ., Nankai Univ., NCEPU, Shandong Univ., Shanghai Jiao Tong Univ., Shenzhen Univ., Tsinghua Univ., USTC, Xian Jiaotong Univ., Zhongshan Univ., Chinese Univ. of Hong Kong, Univ. of Hong Kong, National Chiao Tung Univ., National Taiwan Univ., National United Univ.

Europe (2)

Charles University, JINR Dubna

North America (17)

Brookhaven Natl Lab, CalTech, Illinois Institute of Technology, Iowa State, Lawrence Berkeley Natl Lab, Princeton, Rensselaer Polytechnic, Siena College, UC Berkeley, UCLA, Univ. of Cincinnati, Univ. of Houston, UIUC, Univ. of Wisconsin, Virginia Tech, William & Mary, Yale

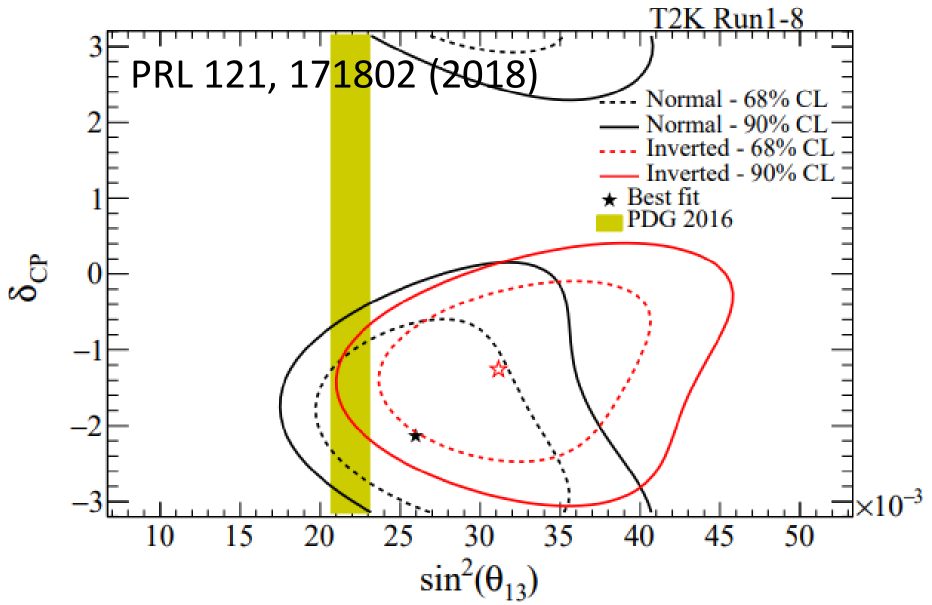
South America (1)

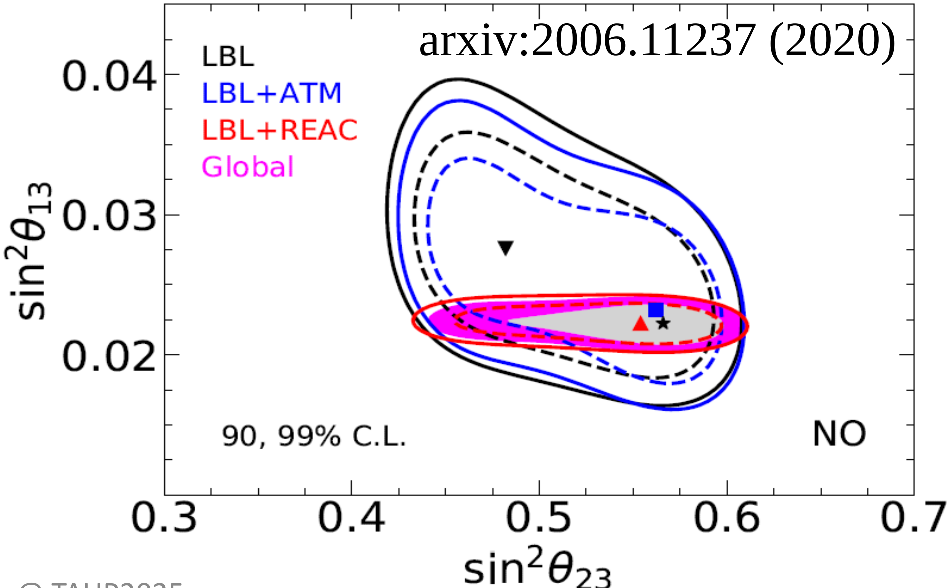
Catholic Univ. of Chile

θ_{13} Measurement and Reactor Neutrino Physics

Motivation:

1. Leptonic CP violation phase and neutrino mass hierarchy
2. θ_{23} octant determination
3. Sterile neutrino
4. Reactor and nuclear physics





Reactor Neutrino Oscillation and Measurement

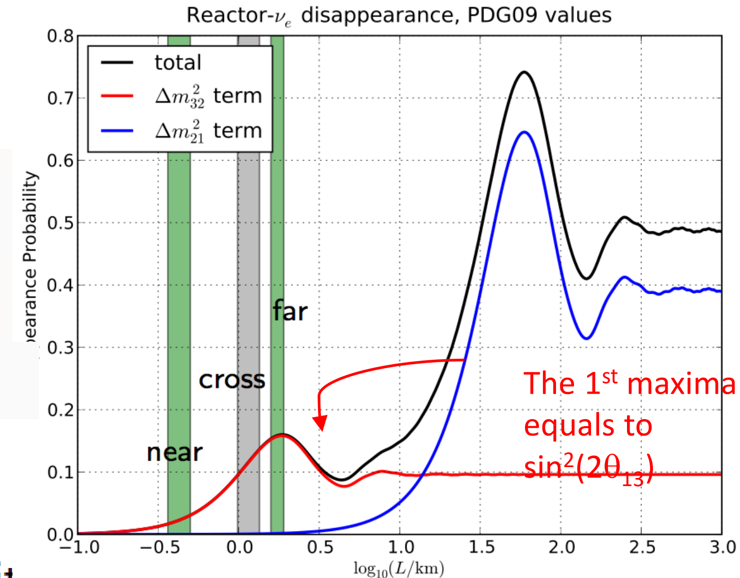
- Detection of anti-electron-neutrino

Inverse beta decay: IBD

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

$\rightarrow + p \rightarrow D + \gamma\ (2.2\ MeV)$ (200 μs)

$\rightarrow + Gd \rightarrow Gd^* \rightarrow Gd + \gamma\text{'s}\ (8\ MeV)$ (30 μs)



- Extraction of θ_{13}
  1. Mixing angle θ_{13} governs overall size of $\bar{\nu}_e$ deficit
  2. Effective mass squared difference $|\Delta m^2_{ee}|$ determines deficit dependence on L/E

Short Baseline | Long Baseline

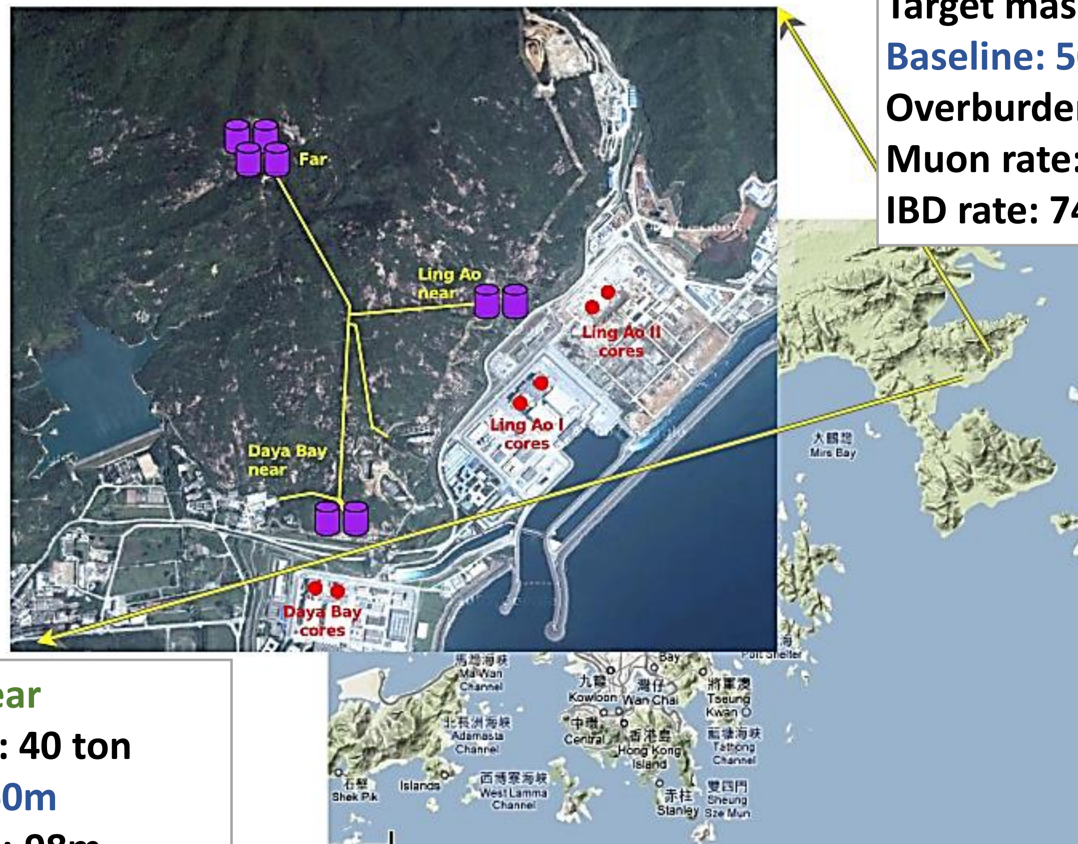
$$P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} = 1 - \sin^2 2\theta_{13} \sin^2\left(\Delta m^2_{ee} \frac{L}{4E}\right) - \sin^2 2\theta_{12} \cos^4\theta_{13} \sin^2\left(\Delta m^2_{21} \frac{L}{4E}\right)$$

$$\sin^2(\Delta m^2_{ee} \tfrac{L}{4E}) \equiv \cos^2\theta_{12} \sin^2(\Delta m^2_{31} \tfrac{L}{4E}) + \sin^2\theta_{12} \sin^2(\Delta m^2_{32} \tfrac{L}{4E})$$

- Near and far cancellation

Power Plant and Three Experimental Sites

Far
Target mass: 80 ton
1600m to LA, 1900m to DYB
Overburden: 350m
Muon rate: 0.04Hz/m^2
IBD rate: 90/day/AD

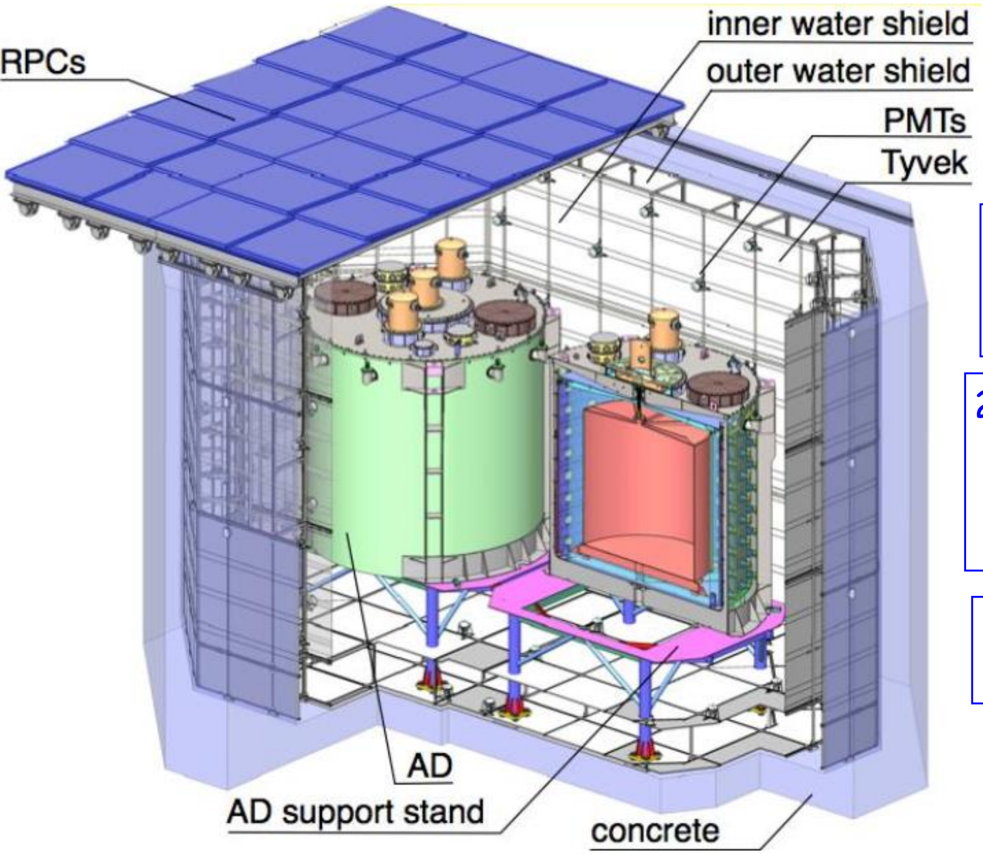


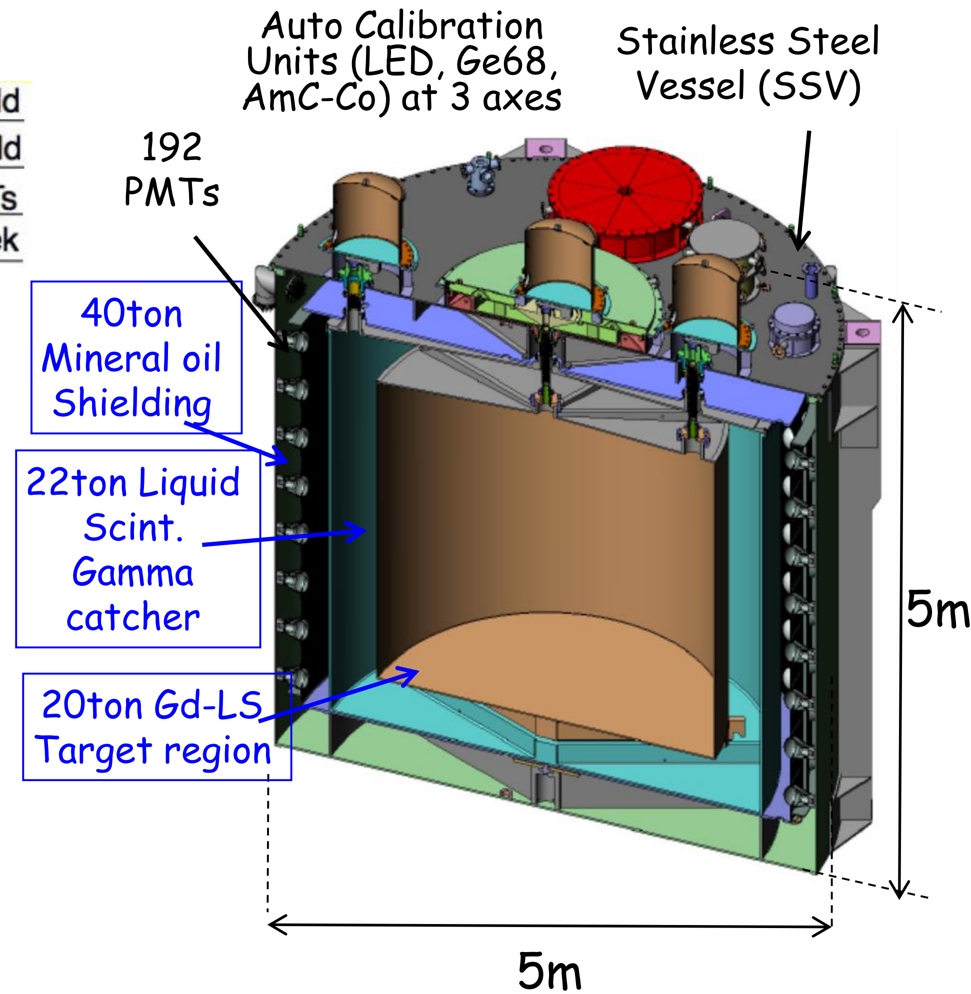
Ling Ao near
Target mass: 40 ton
Baseline: 500m
Overburden: 112m
Muon rate: 0.73Hz/m^2
IBD rate: 740/day/AD

Daya Bay near
Target mass: 40 ton
Baseline: 360m
Overburden: 98m
Muon rate: 1.2Hz/m^2
IBD rate: 840/day/AD

The total power 6x2.9 GW_{th}.

Antineutrino Detector (AD)

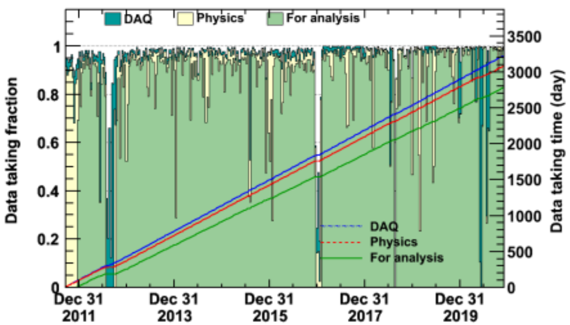




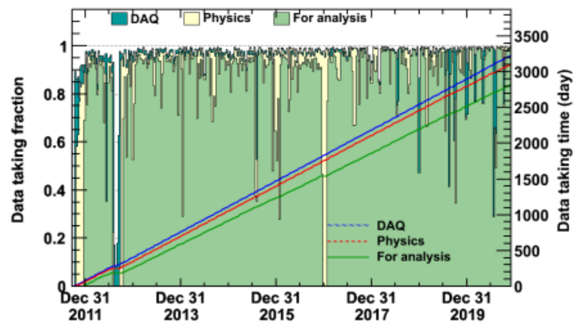
Data Collection

- Operational statistics:

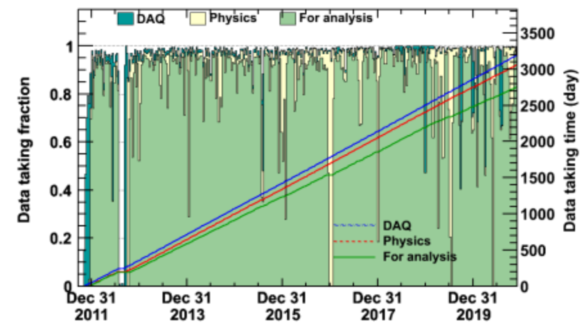
EH1



EH2



EH3



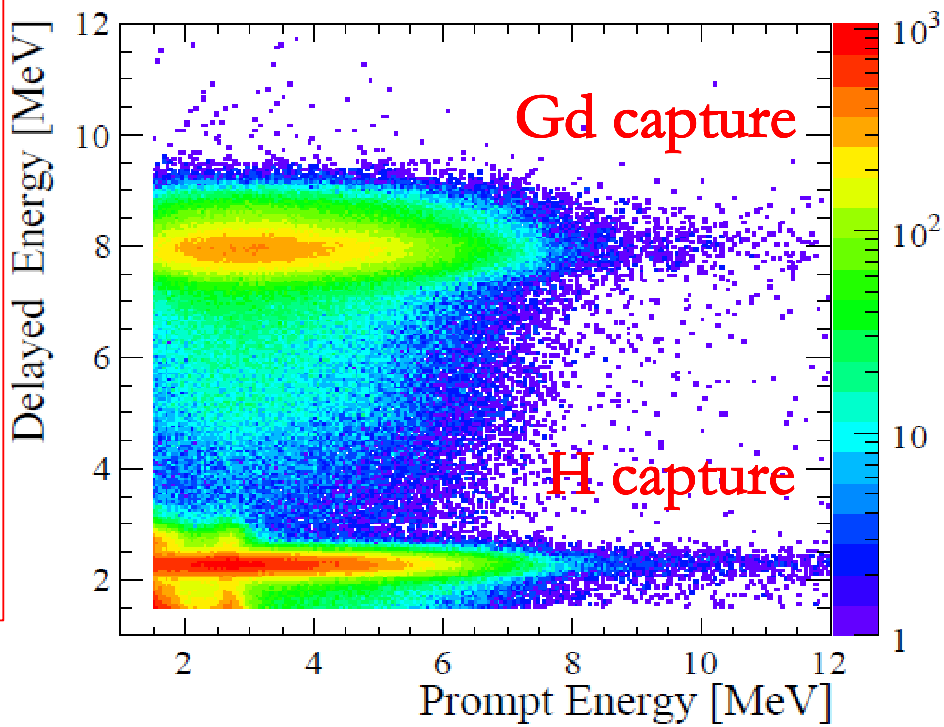
- Three physics runs:

Configuration	EH1	EH2	EH3	Start date – End date	Duration (Days)
6-AD	2	1	3	24 Dec 2011 – 28 July 2012	217
8-AD	2	2	4	19 Oct 2012 – 20 Dec 2016	1524
7-AD	1	2	4	26 Jan 2017 – 12 Dec 2020	1417
Total					**3158**

- Data available for analyses: ~2700 days

Neutron Gd Capture IBD Sample

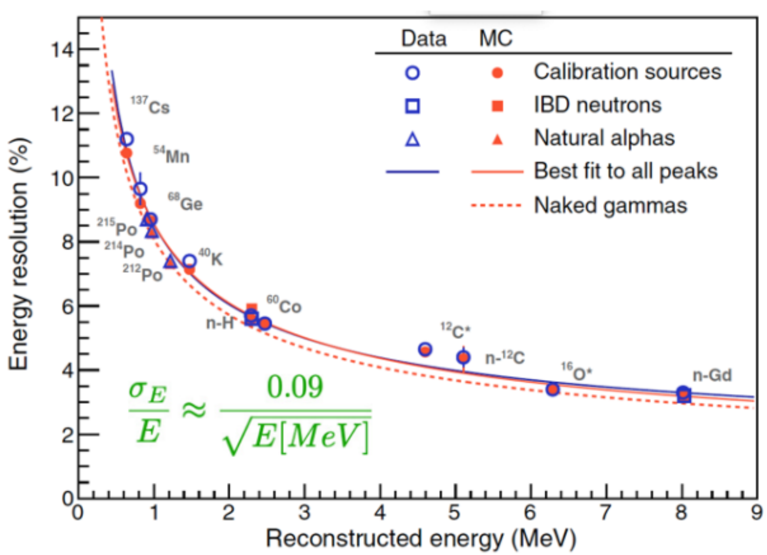
- Remove flashing PMT events
- Veto muon events
- Require 0.7 MeV < E_{prompt} < 12 MeV, 6 MeV < $E_{delayed}$ < 12 MeV
- Neutron capture time: 1 μs < Δt < 200 μs
- Multiplicity cut: select time-isolated energy pairs



- Uncorrelated background
  - Accidental
- Correlated background
  - Fast neutron (produced outside of the AD but enters the active volume of the AD)
  - 'Muon-x' (associated with untagged muons due to equipment malfunction)
  - $^{9}Li/^{8}He$ (spallation product produced by cosmic-ray muons inside the AD)
  - ^{241}Am-^{13}C (neutron calibration source resides inside the ACU)
  - $^{13}C(\alpha,n)^{16}O$ (α from decay of natural radioactive isotope in the liquid scintillator)

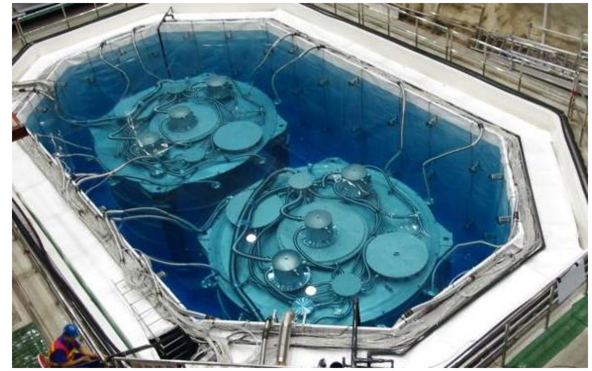
Energy Scale and Systematics

- Gain of photomultiplier tubes
  - Single-photoelectron dark noise
  - Weekly LED monitoring
- Energy calibration
  - Weekly ^{68}Ge, ^{60}Co, ^{241}Am-^{13}C
  - Spallation neutrons
  - Natural radioactivity



Relative uncertainty in energy scale: ~0.2%

Side-by-side comparison in 2012



Detection efficiencies

	Efficiency	Correlated	Uncorrelated
Target protons	-	0.92%	0.03%
Flasher cut	99.98%	0.01%	0.01%
Delayed energy cut	92.7%	0.97%	0.08%
Prompt energy cut	99.8%	0.10%	0.01%
Multiplicity cut		0.02%	0.01%
Capture time cut	98.7%	0.12%	0.01%
Gd capture fraction	84.2%	0.95%	0.10%
Spill-in	104.9%	1.00%	0.02%
Livetime	-	0.002%	0.01%
Combined	80.6%	1.93%	0.13%

Expectation:

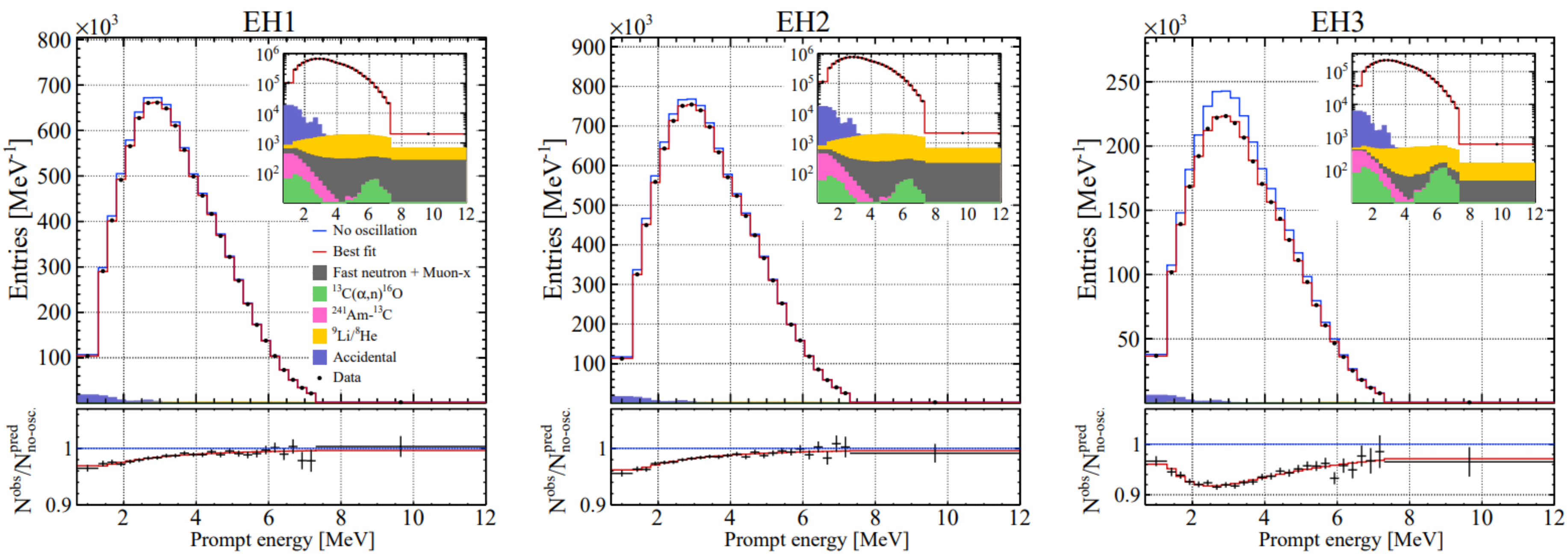
R(AD1/AD2) = 0.982

Measurement:

0.987 ± 0.004(stat) ± 0.003(syst)

nGd IBD Prompt Energy Spectra

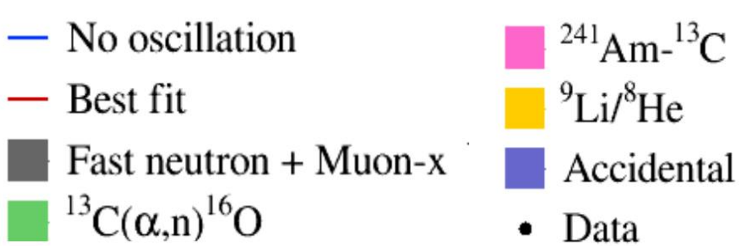
$$E_{\nu} \approx E_{\text{prompt}} + 0.78\ \text{MeV}$$



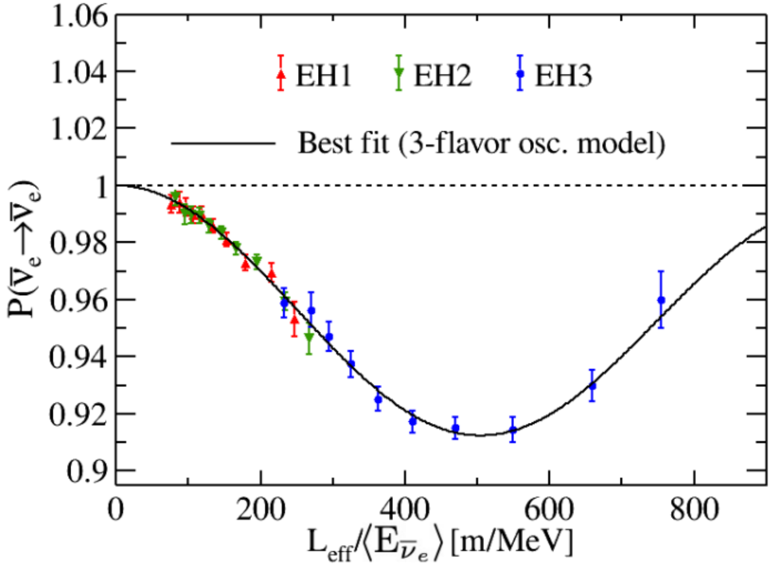
2,236,810 IBD events

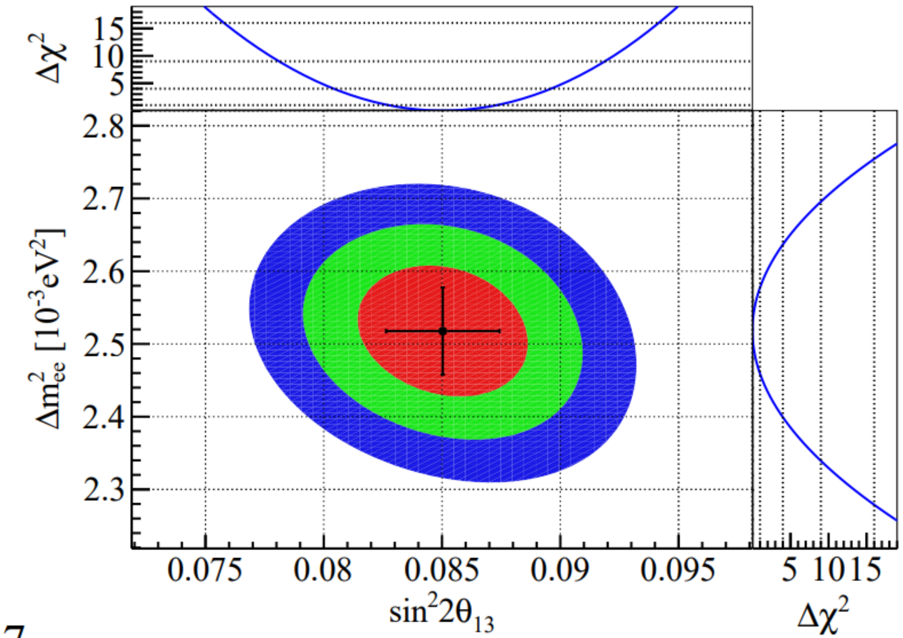
2,544,894 IBD events

2,544,894 IBD events



$\sin^2 2\theta_{13}$ and Δm^2_{32} with nGd IBD sample





Best-fit results: $\chi^2/\text{ndf} = 559/517$

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

Normal hierarchy: $$\Delta m^2_{32} = +\left(2.466^{+0.060}_{-0.060}\right) \times 10^{-3}\text{eV}^2$$ (2.4% precision)

Inverted hierarchy: $$\Delta m^2_{32} = -\left(2.571^{+0.060}_{-0.060}\right) \times 10^{-3}\text{eV}^2$$ (2.3% precision)

PRL **130**, 161802 (2023)

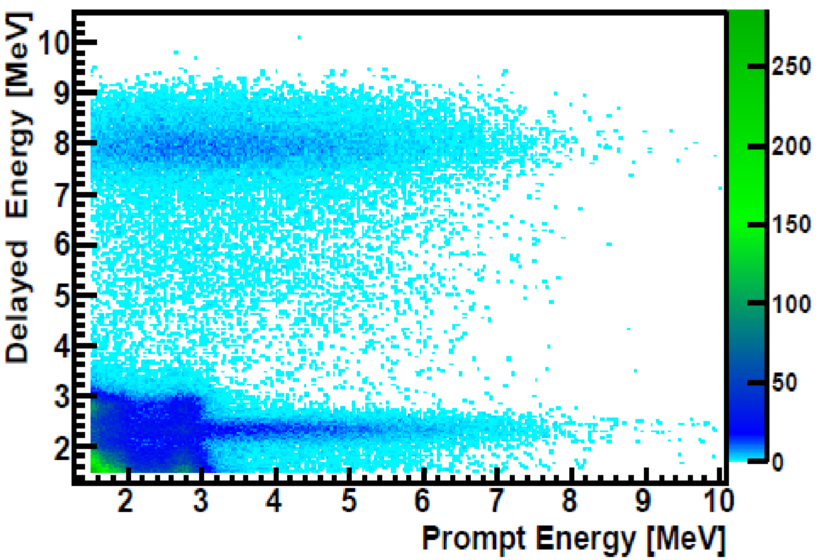
Neutron H Capture IBD Sample

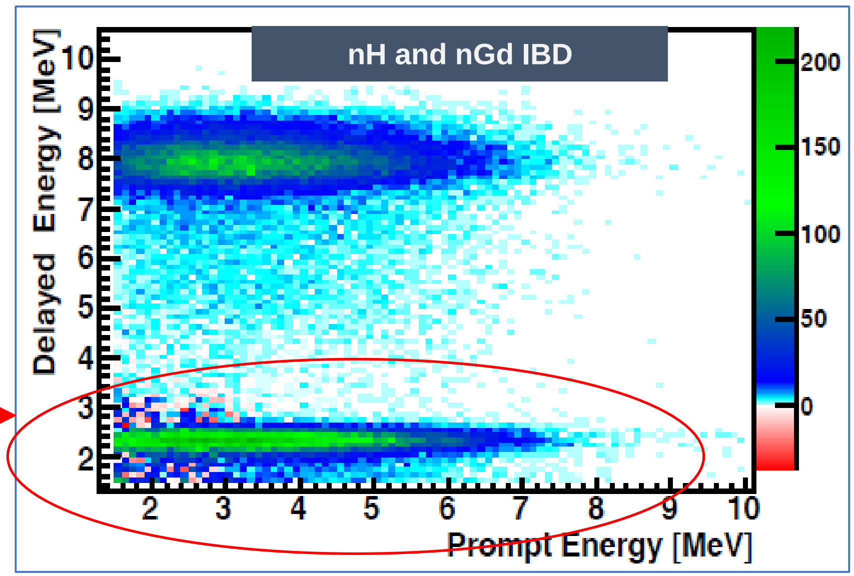
nH sample selected with 1958-day data

Different procedure for the nH sample:

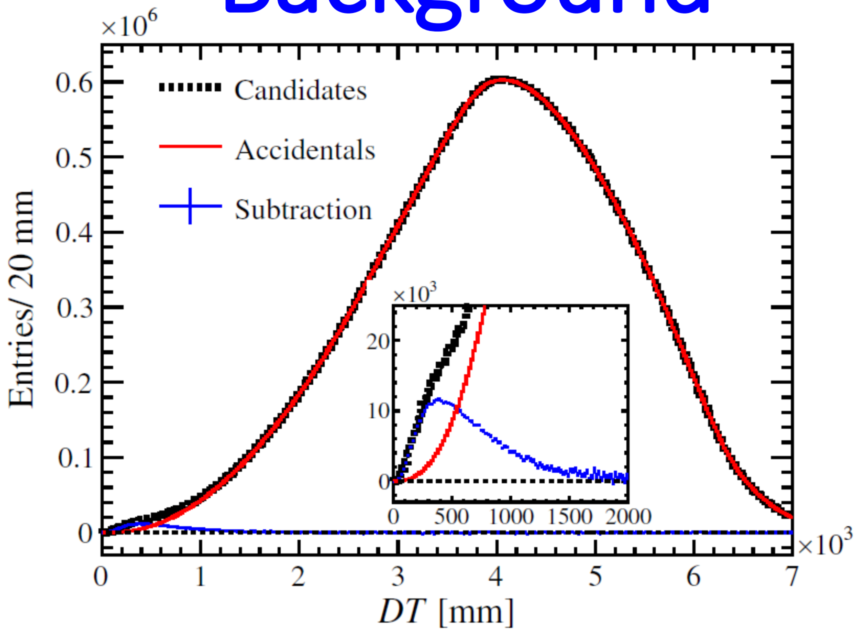
- Require 0.7 MeV < E_{prompt} < 12 MeV, $E_{delayed}$ in 3σ of nH peak
- Neutron capture time and distance:

  DT < 1 m (DT=D+ T/[600 μs/m])





Accidental Background



• Prediction and verification

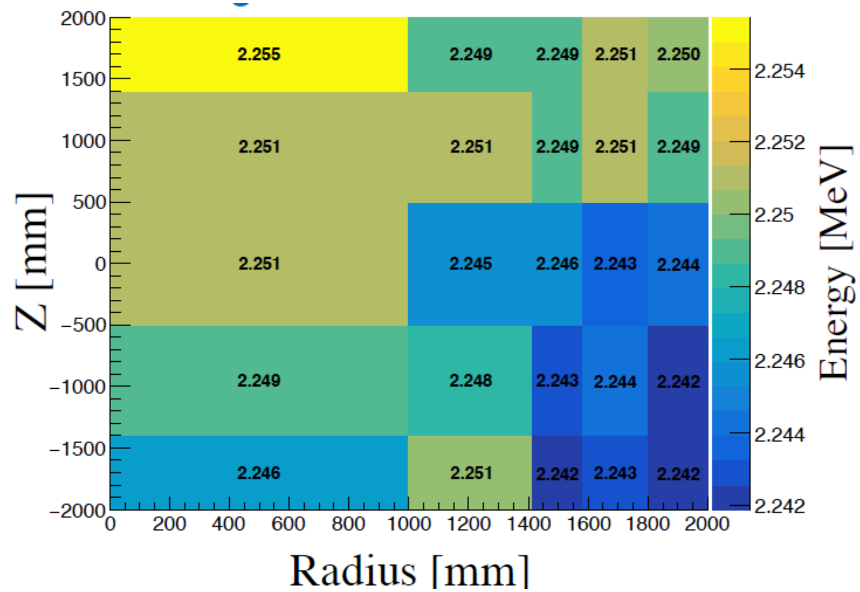
*Precise background prediction

*High statistic MC verification

*Verification with delta distance distribution

* with delta time distribution

Spatial Energy Scale Correction



• Energy scale in unloaded LS region

Energy scale difference among ADs < 0.3%

among voxels < 0.5%

New nH Energy Response Model

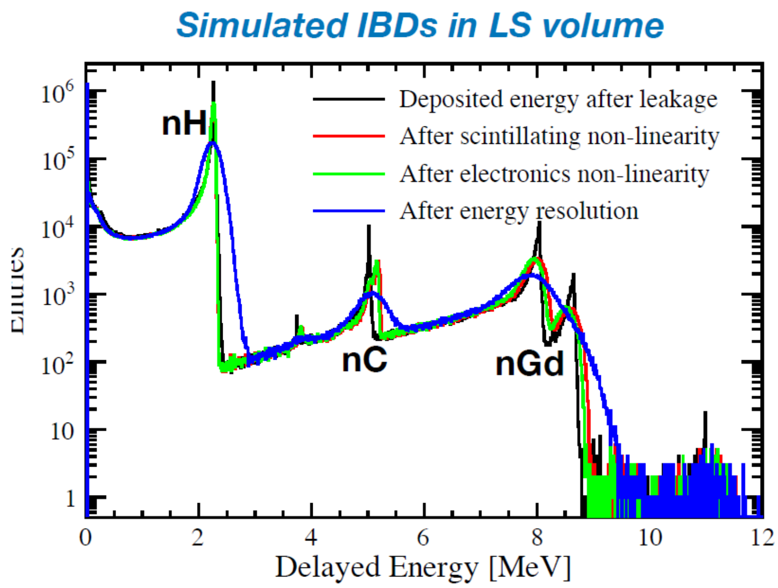
- First rate+shape analysis with nH-only sample

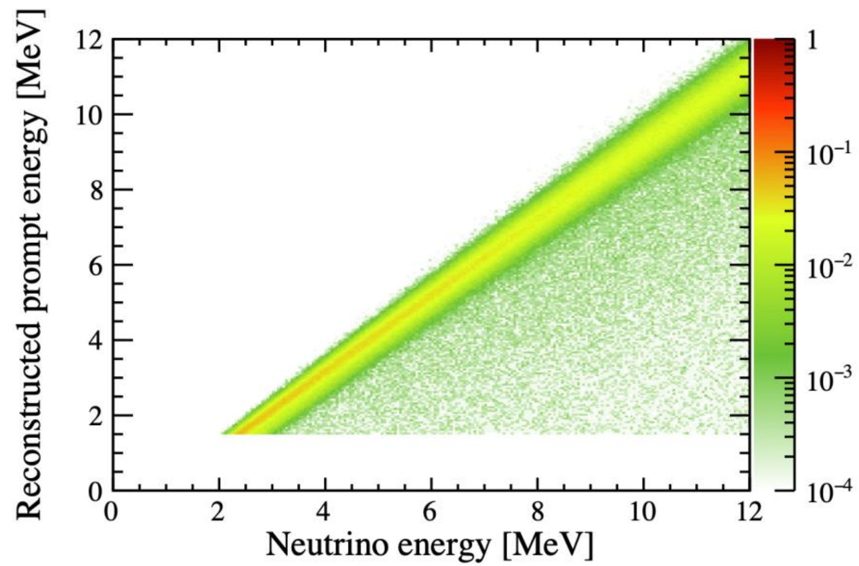
- Add the non-linearities on deposited energy on step-by-step basis

- Decouple leakage for data with Calorimeter function:

Nucl. Instrum. Meth. A 827 (2016), 165-170

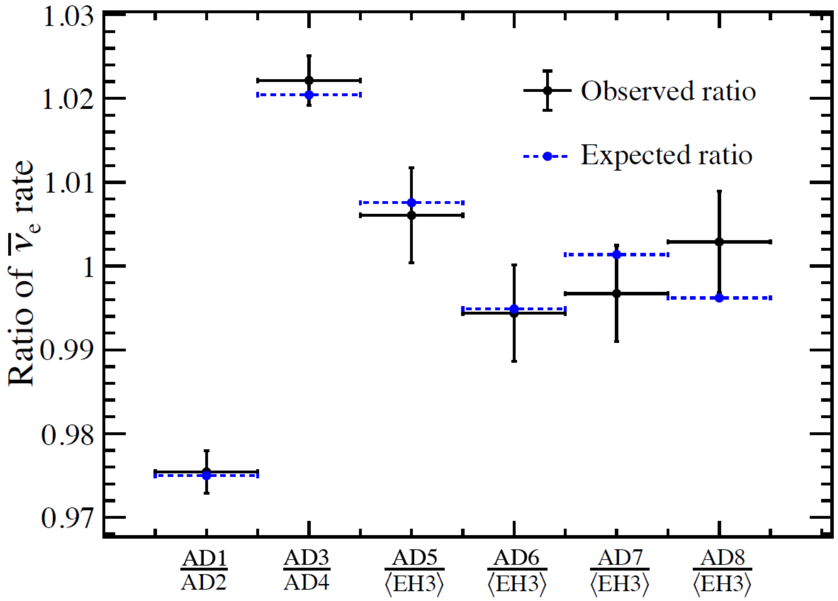
- Adjust each effect and study the resulted uncertainty on the measured prompt spectrum

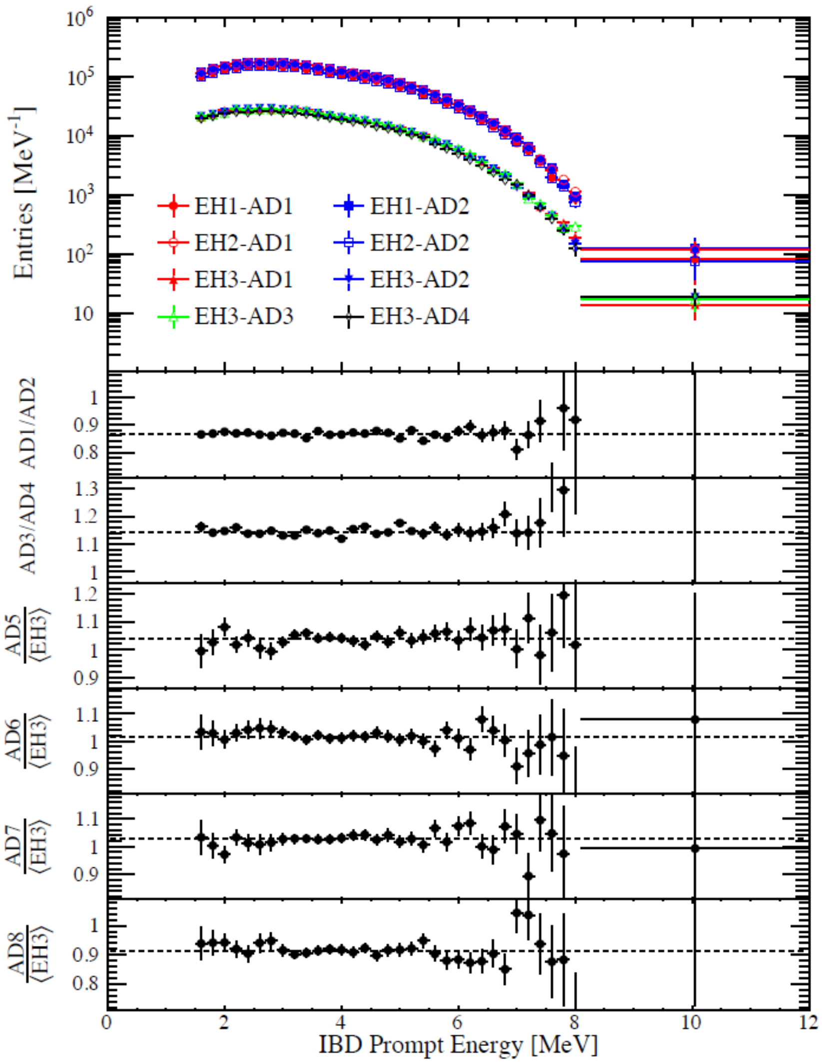




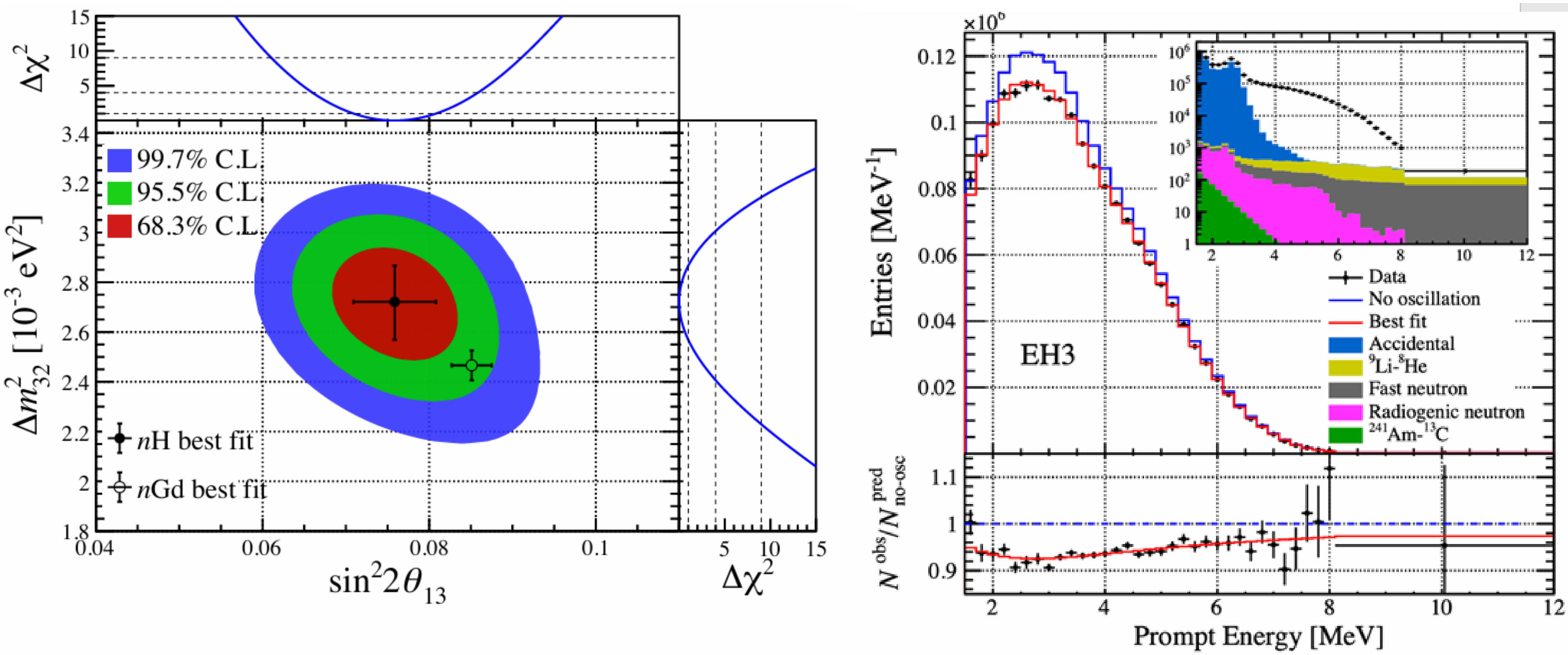
Systematic and Sanity Checks

- Identicalness among ADs in the same site. Rate and spectrum.
- Systematic uncertainty reduced from 0.57% to 0.34%
(Energy cut and DT cut)





$\sin^2 2\theta_{13}$ and Δm^2_{32} with nH IBD Sample

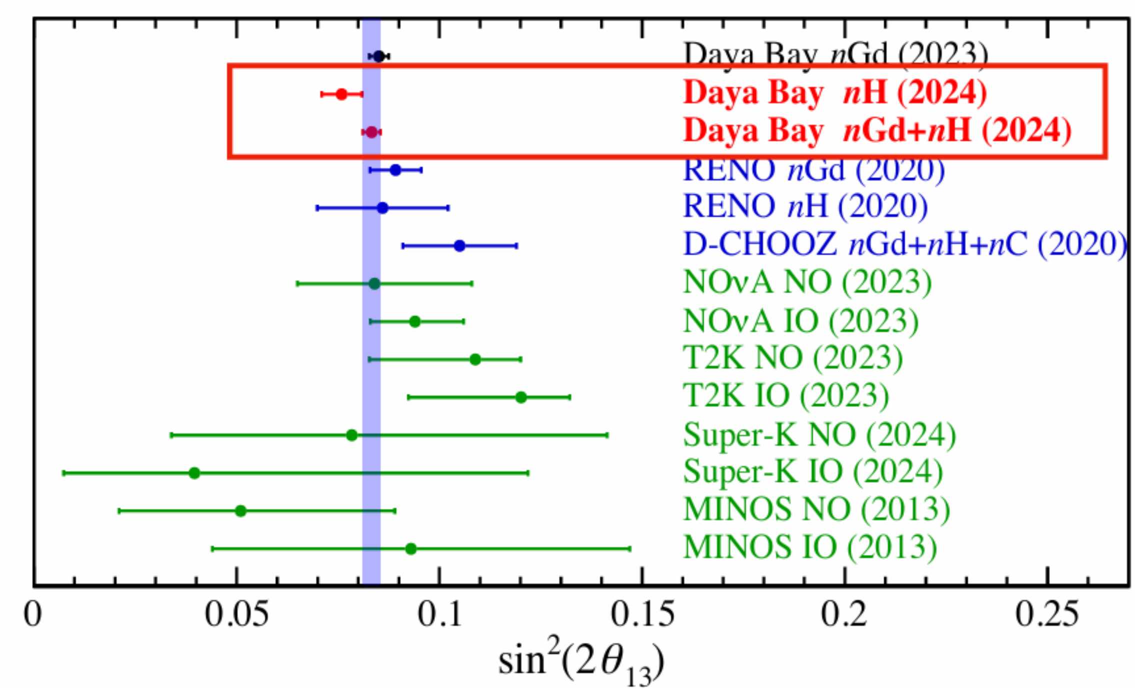


- The results with rate+shape analysis yield.

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

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

Combined $\sin^2 2\theta_{13}$ Measurement

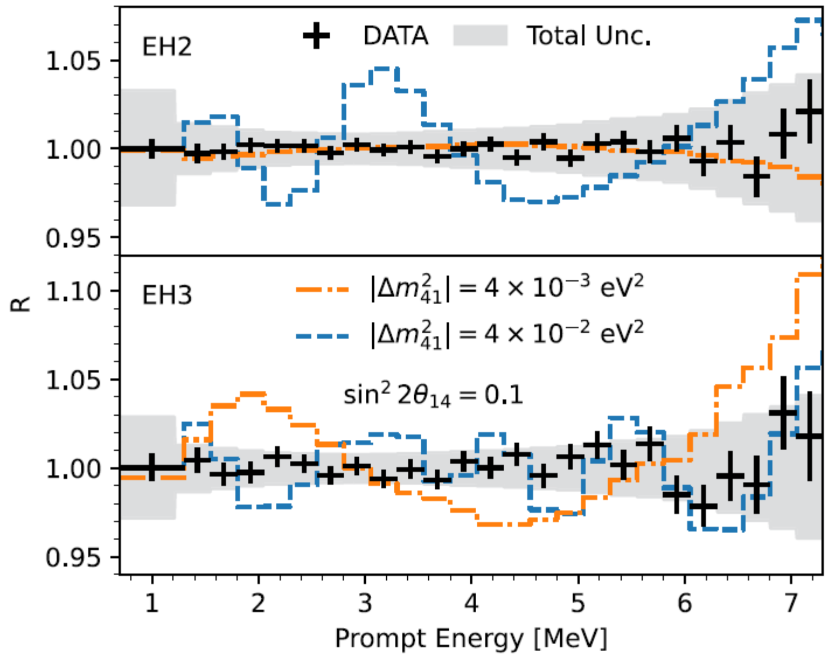


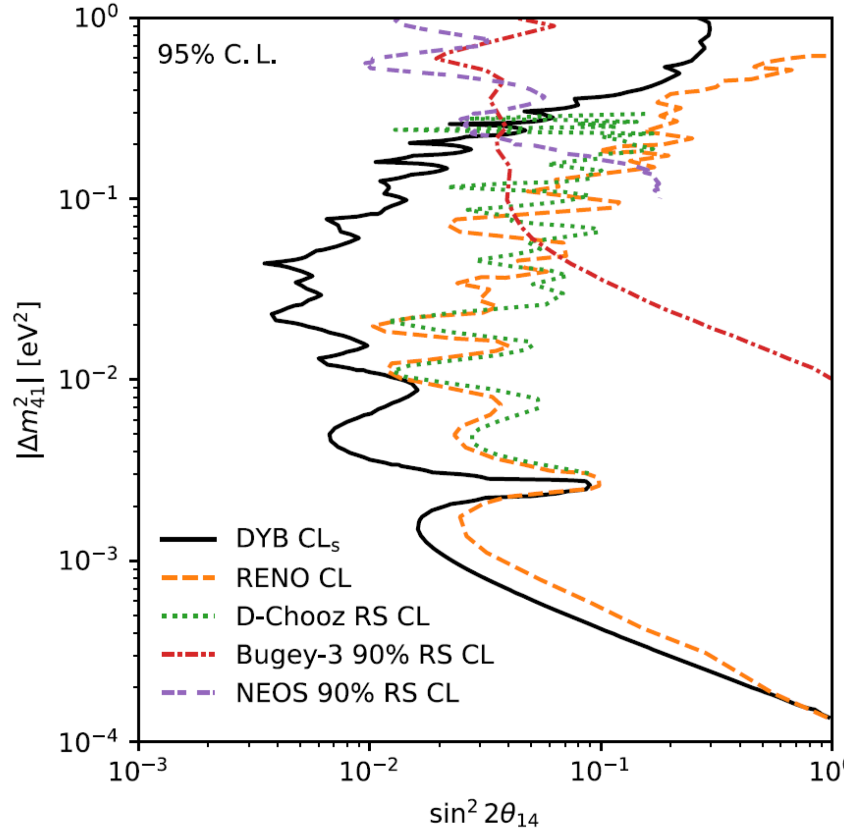
$\sin^2 2\theta_{13} = 0.0833 \pm 0.0022$

Daya Bay collaboration
PRL 133, 151801 (2024)

1. Independently measured θ_{13} by nGd and nH samples
2. nH sample improves the Daya Bay total $\sin^2 2\theta_{13}$ precision by 8%
3. Total precision of $\sin^2 2\theta_{13}$ is 2.6%

Sterile Neutrino Search





$$P_{\bar{\nu}_e\to\bar{\nu}_e} = 1 - 4\sum_{j>i}^{4} |U_{ei}|^2 |U_{ej}|^2 \sin^2\Delta_{ji}$$

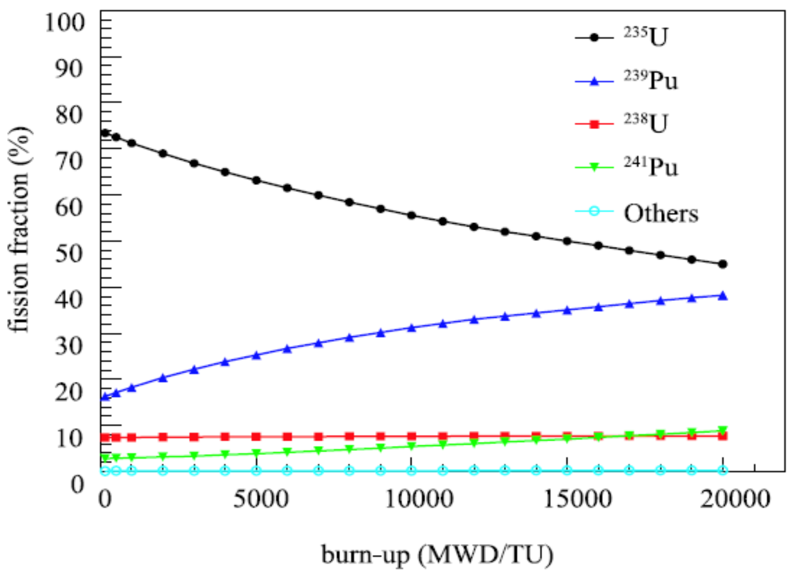
$$P_{\bar{\nu}_e\to\bar{\nu}_e} \approx 1 - \sin^2 2\theta_{14}(\cos^2\theta_{13}\sin^2\Delta_{41} + \sin^2\theta_{13}\sin^2\Delta_{43}) - \cos^4\theta_{14}\sin^2 2\theta_{13}\sin^2\Delta_{32}.$$

- Best constrain in 2×10^{-4} eV^2 $\lesssim |\Delta m^2_{41}| \lesssim 0.2$ eV^2 PRL 133, 051801 (2024)

Evolution of Daya Bay Reactors

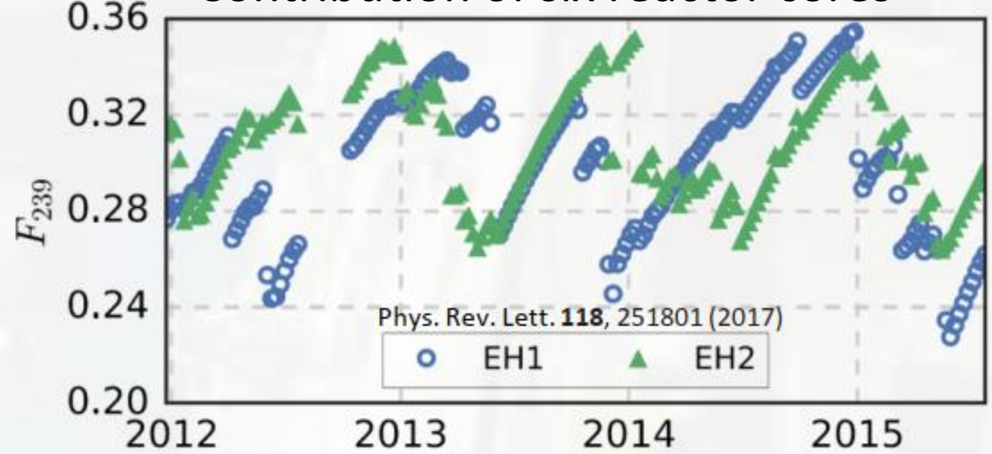
Daya Bay reactors: French Pressurized Water Reactor (PWR)

- Running cycle:
  - Replace 1/3 (1/4) fuel every 18 (12) months
- Fuel evolution in a cycle
  - U-235 and Pu-239 dominant



Fission fractions in one running cycle

Contribution of six reactor cores



Effective fission fraction of ^{239}Pu of near sites

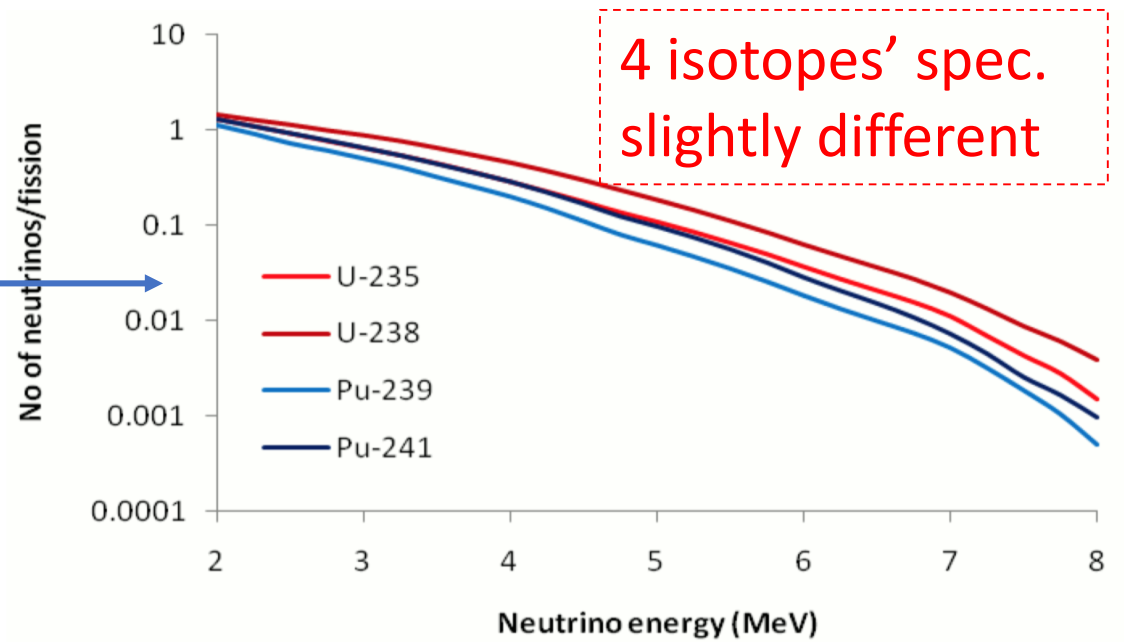
Dominant fission fuels	^{235}U:	50% ~ 65%
	^{239}Pu:	24% ~ 35%

Reactor Neutrino Flux and Spectrum

- Evolution of Flux and spectrum

$$S(E) = \sum_i F_i S_i(E)$$

$$F_i = \frac{W_{\rm th} f_i}{\sum_k f_k E_k}$$



F_i: Fission rate of isotope i

W_{th}: thermal power

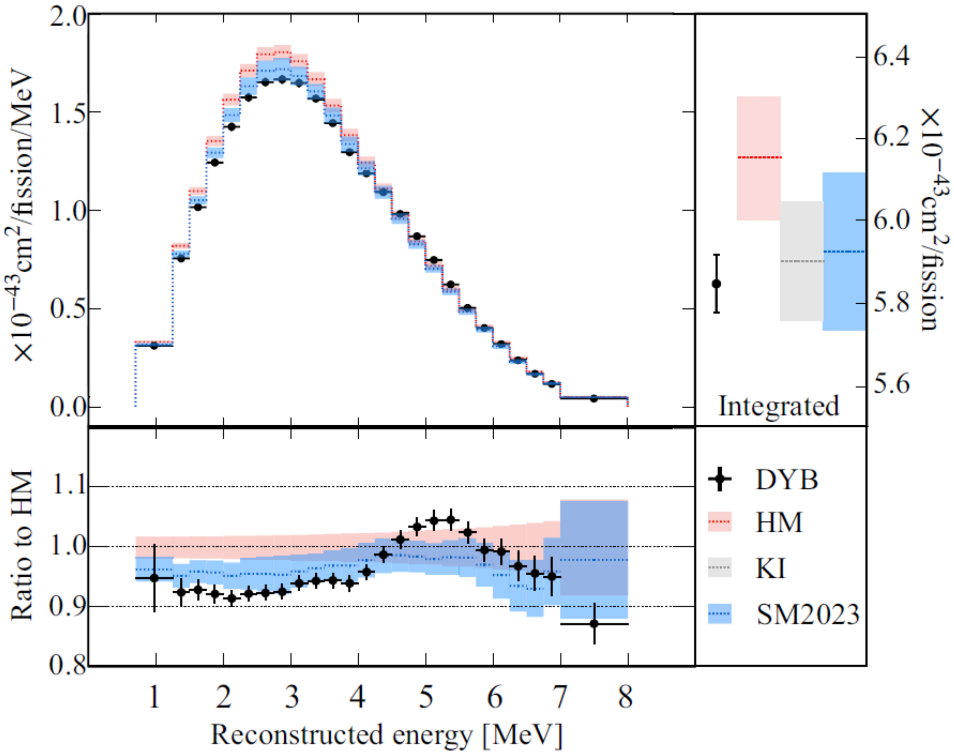
f_i: fission fraction of i

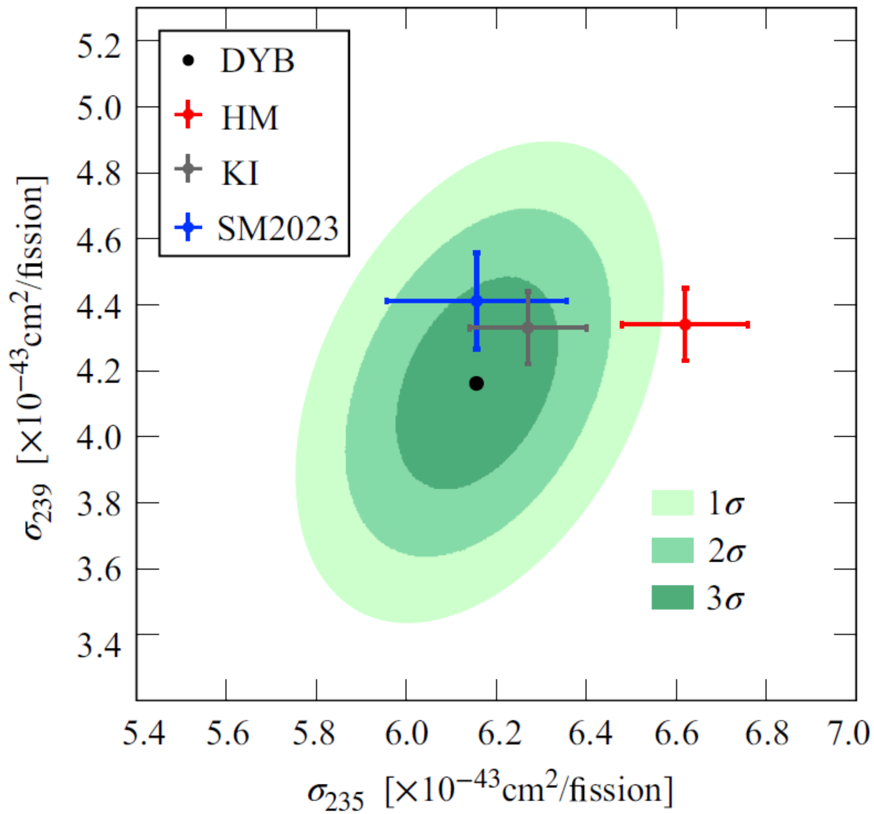
E_k: Energy release/fission

i, k: four fission isotopes

With the evolution information, U and Pu spectra extraction, and comparison with models, HM and Summation, are made.

Total and U235 and Pu239 Neutrino Flux

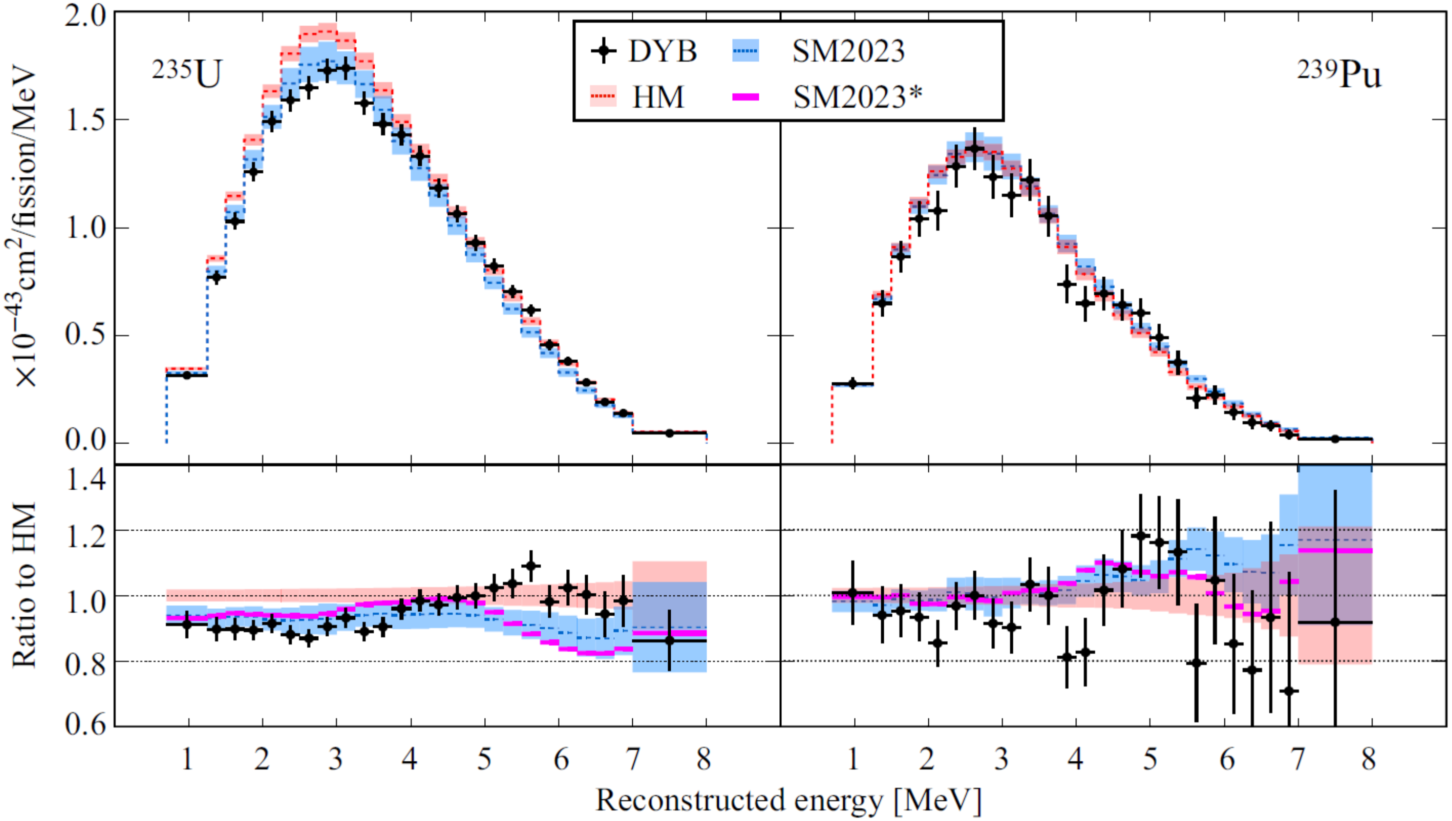




Total, U235, and Pu239 flux are measured to be 5.84±0.07, 6.16±0.12, and 4.16±0.21 [10^{-43}cm^2/fission], respectively.

PRL 134, 201802 (2025)

Comparison with Models



- The flux shows good consistency with the Kurchatov Institute and SM2023 models but disagrees with the Huber-Mueller model.
- The spectrum, however, disagrees with all model predictions.

Another detailed comparison can be found in PRL 130 (2023) 211801

Summary

- Precise $\sin^2 2\theta_{13}$ measurement with neutron capture on Gd and H IBD samples

- Sterile neutrino exclusion in $2\times10^{-4}\ \mathrm{eV}^2 \lesssim |\Delta m^2_{41}| \lesssim 0.2\ \mathrm{eV}^2$

- Comprehensive measurement of the reactor antineutrino spectrum and flux

Thank you.