The Latest Results From Daya Bay

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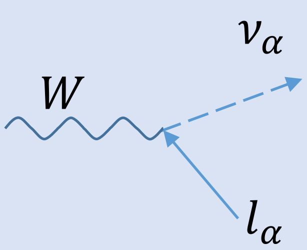
On Behalf of the Daya Bay Collaboration

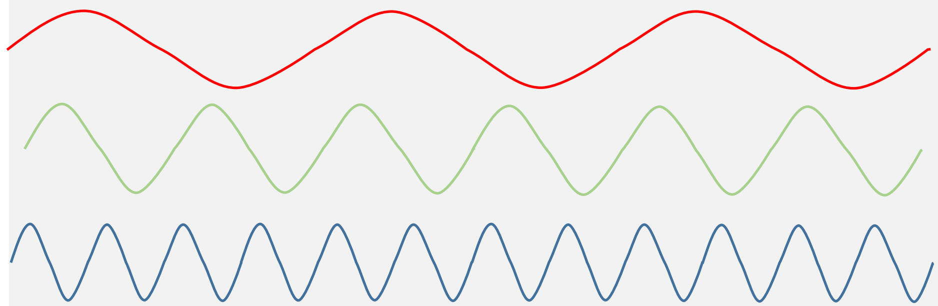
Neutrino Oscillations

Creation via weak Interaction



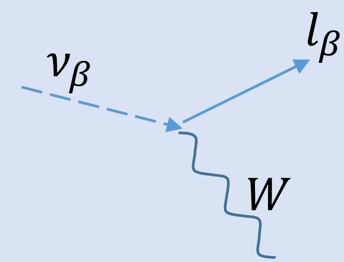
Flavor State $|\nu_\alpha\rangle$

Propagation determined by mass-eigenstates $|\nu_i; p\rangle$



$$\omega_i = E_i = \sqrt{p^2 + m_i^2}$$

Detection via weak interaction



Flavor State $|\nu_\beta\rangle$

$$|\nu_\alpha\rangle = \sum_{\alpha i} U^*_{\alpha i} |\nu_i; p\rangle$$

Different neutrino masses will create phase differences

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

Three Neutrinos Framework

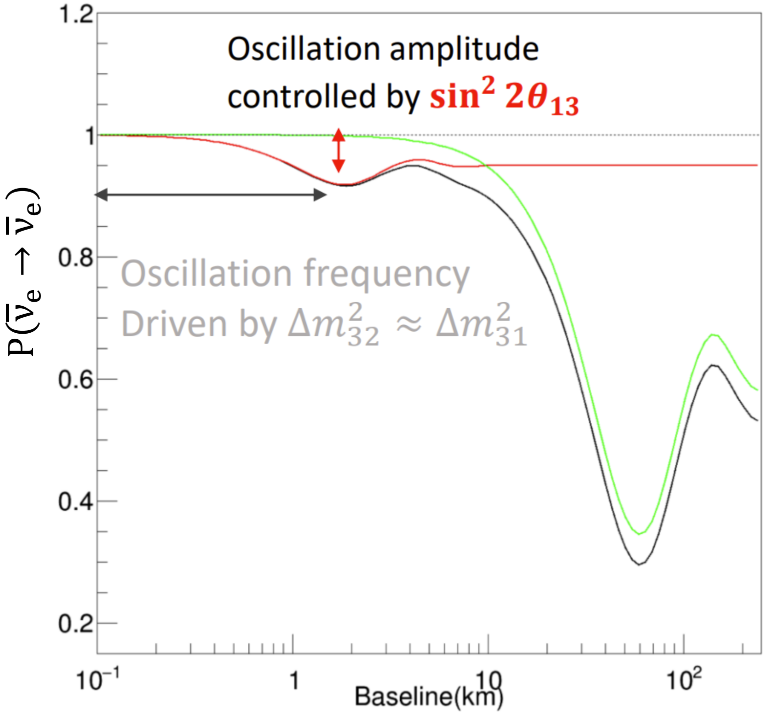
$$U_{PMNS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

atmospheric /accelerator

short-baseline reactor accelerator

Solar/ long-baseline reactor

Measuring θ_{13} with nearby reactors



Detecting neutrinos in **km** away from reactors :

A clean measurement of θ_{13} with no CP phase and negligible matter effects

High precision:

- High statistics
- Optimize baseline
- Reduce systematics uncertainties
- Reduce backgrounds

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$

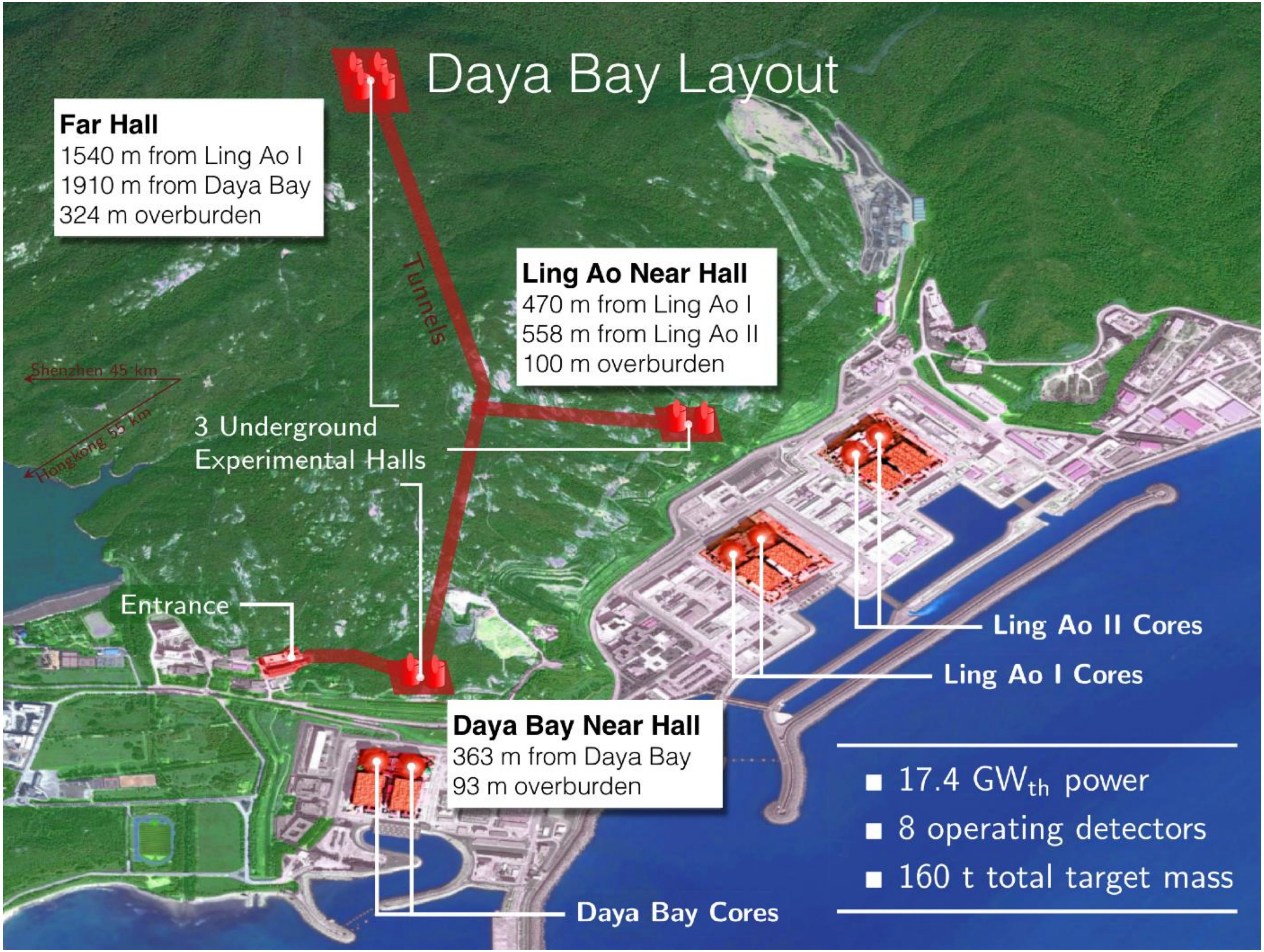
$$\Delta_{ij} \equiv \Delta m^2_{ij} L/4E$$

$$-\sin^2 2\theta_{13}\,(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32})$$

Observables: Total rate deficit (Rate-Analysis) : $\sin^2 2\theta_{13}$

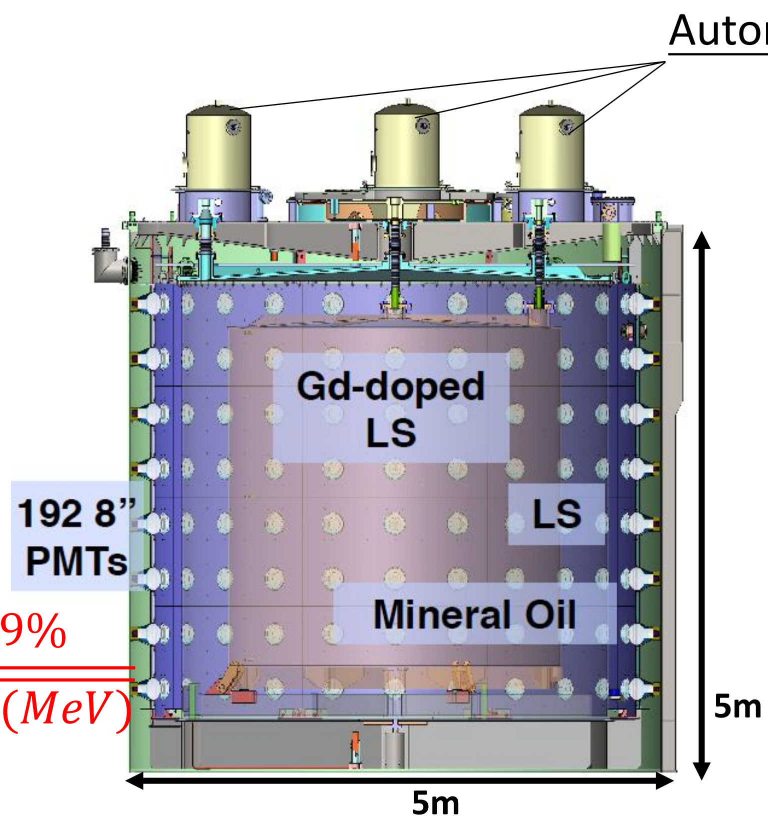
Energy dependent rate deficit (Spectra-Analysis) : $(\sin^2 2\theta_{13}, \Delta m^2_{32})$

- need energy nonlinearity well

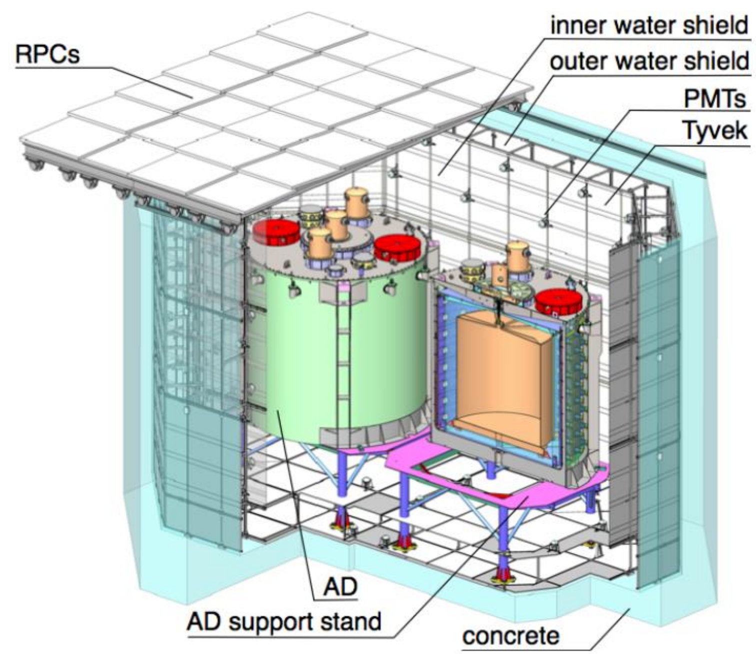

Daya Bay Layout
Far Hall
1540 m from Ling Ao I
1910 m from Daya Bay
324 m overburden
Tunnels
Ling Ao Near Hall
470 m from Ling Ao I
558 m from Ling Ao II
100 m overburden
Shenzhen 45 km
Hongkong 55 km
3 Underground
Experimental Halls
Entrance
Ling Ao II Cores
Ling Ao I Cores
Daya Bay Near Hall
363 m from Daya Bay
93 m overburden
17.4 GW_{th} power
8 operating detectors
160 t total target mass
Daya Bay Cores

Detector System

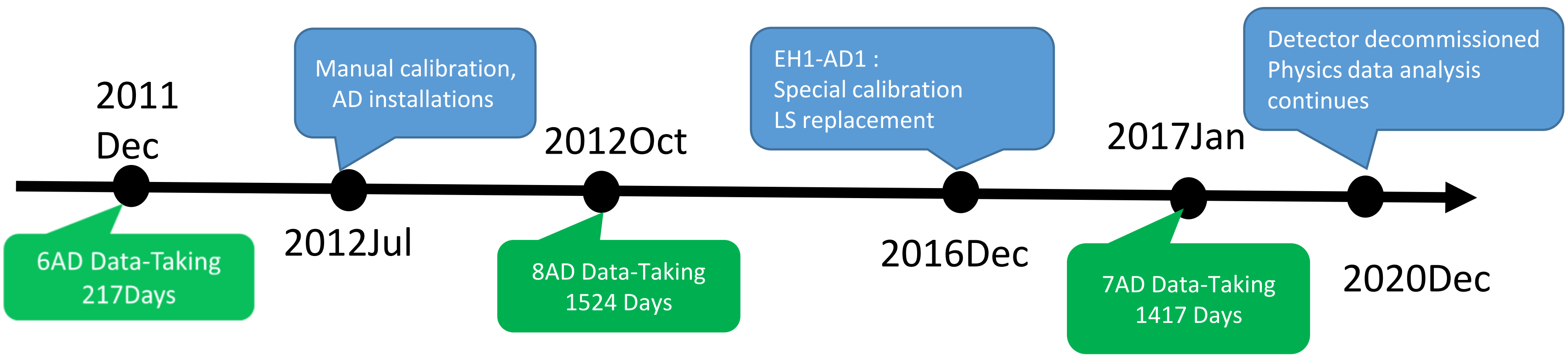
- Functionally identical Antineutrino Dectors (ADs)
  - 3-zone detector module : naturally define fiducial volume and good shielding
- Immersed in water pool segmented and instrumented with PMTs
  - shielding and muon tagging



$$\frac{\sigma_E}{E} \approx \frac{9\%}{\sqrt{E(MeV)}}$$

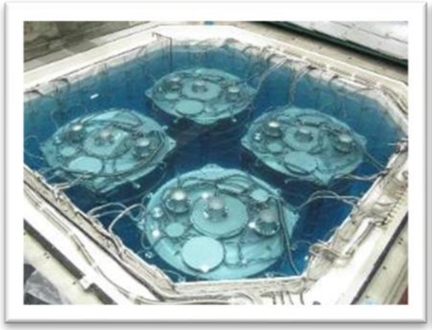


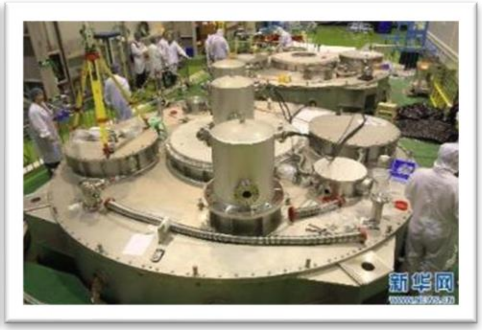
Daya Bay Neutrino Experiment

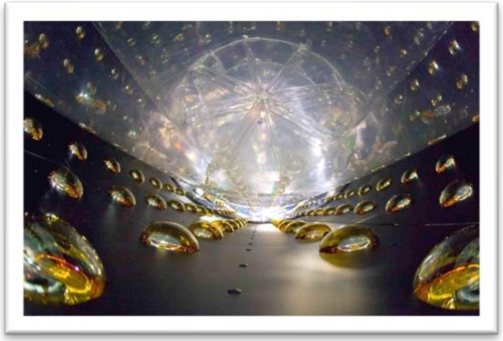


Lastest results :

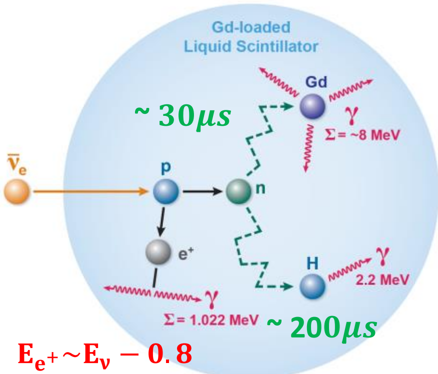
- nGd neutrino oscillation with **full dataset (3158 days)** Phys.Rev.Lett.130,161802(2023)
- nH neutrino oscillation with **sub dataset (1958 days)** Phys.Rev.Lett 133,151801(2024)
- Sterile neutrino search with **full dataset** Phys.Rev.Lett 133, 051801(2024)
- Reactor flux and spectra measurement with **full dataset** ICHEP2024,Neutrino2024







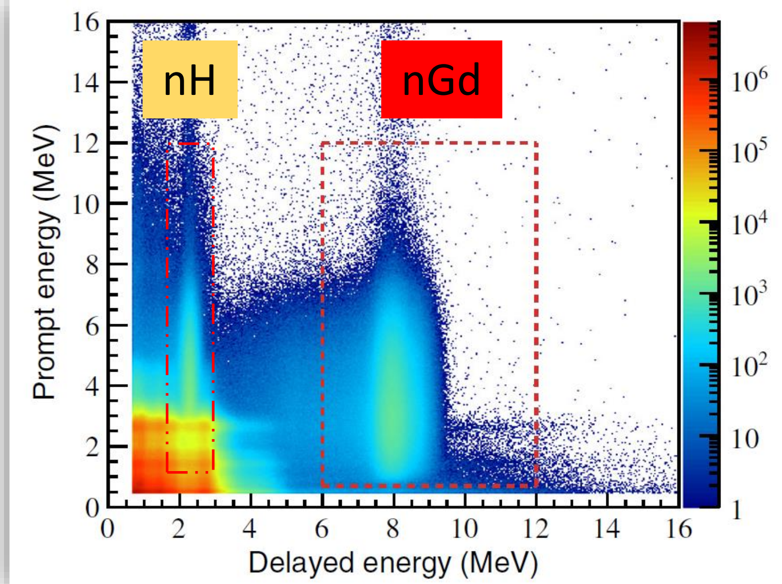
Signal Selection



$\overline{\nu}_e$ are detected via Inverse Beta Decays (IBDs) :

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

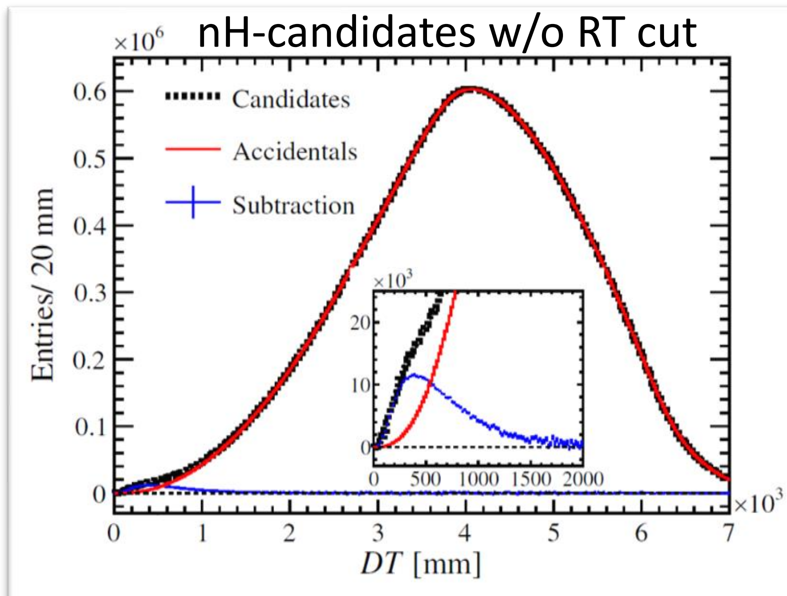
Correlated signals from e^+ (prompt) and neutron captures (delayed)



Daya Bay, Phys. Rev.D 95,072006(2017)

nGd- IBD: in GdLS
- $\mathrm{Ep: [0.7,12]MeV}$ $\mathrm{Ed: [6,12]MeV}$
- Time separation dT < 200μs

nH-IBD : in GdLS + LS
- Large accidental contaminations
  Optimized cuts
  - $\mathrm{Ep > 1.5MeV}$
  - $\mathrm{DT(= dR + dT * \frac{1000mm}{600\mu s}) < 1m}$
- More energy leakage: **Fine calibration**



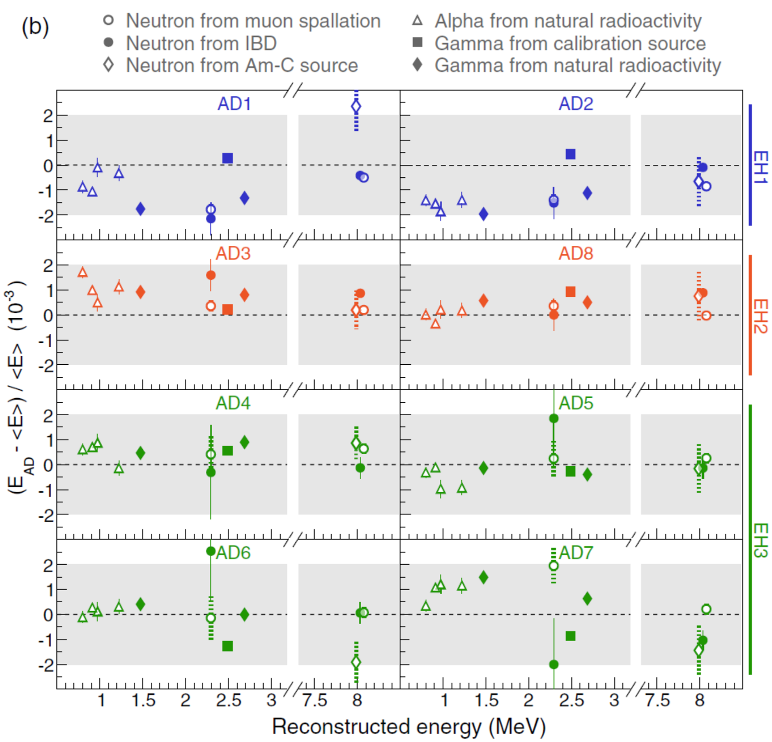
Signal and Background Summary

Sample	Signal and Backgrounds		Near	Far
nGd (3158 Days)	Signal		~ 650/Day	~75/Day
	B/S	Accidentals	~ 1.0%	~1.0%
		Muon-induced	~ 0.5%	0.5%
		Other	~0.04%	~ 0.1%
nH (1958 days)	Signal		~ 500/Day	~ 60/Day
	B/S	Accidentals	~25%	~180%
		Muon_induced	~1.0%	~0.7%
		Others	~0.05%	~0.4%

nGd Sample: Clean sample with very **low backgrounds B/S < 1.5 %**

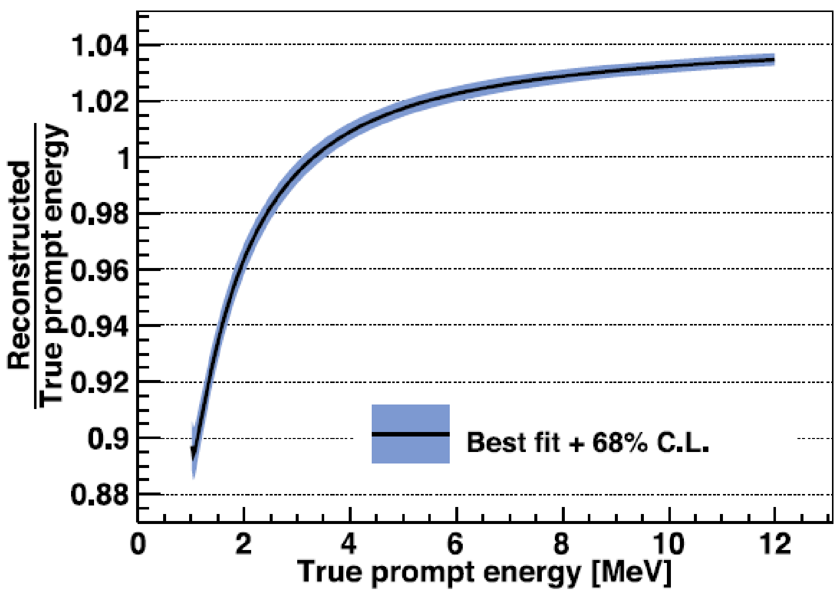
nH Sample:
- Comparable statistics
- suffer large accidental background contamination
- **Good news: accidentals are measured precisely**

Detector Calibration



Phys.Rev.D 95, 072006 (2007)

Energy Nonlinearity



NIM A 940(2019)230 − 242

Relative energy scale : < 0.2% variation in reconstructed energy among ADs

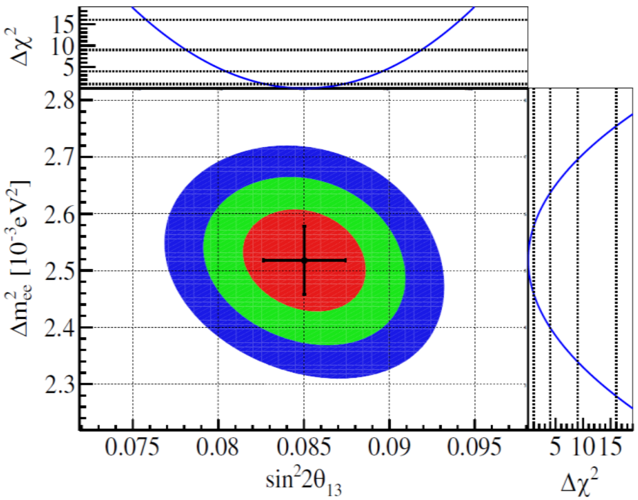
Energy nonlinearity: < 0.5% uncertainty (**correlated among all ADs**) is achieved for Positrons with kinematic energy greater than 1 MeV

nGd – full dataset

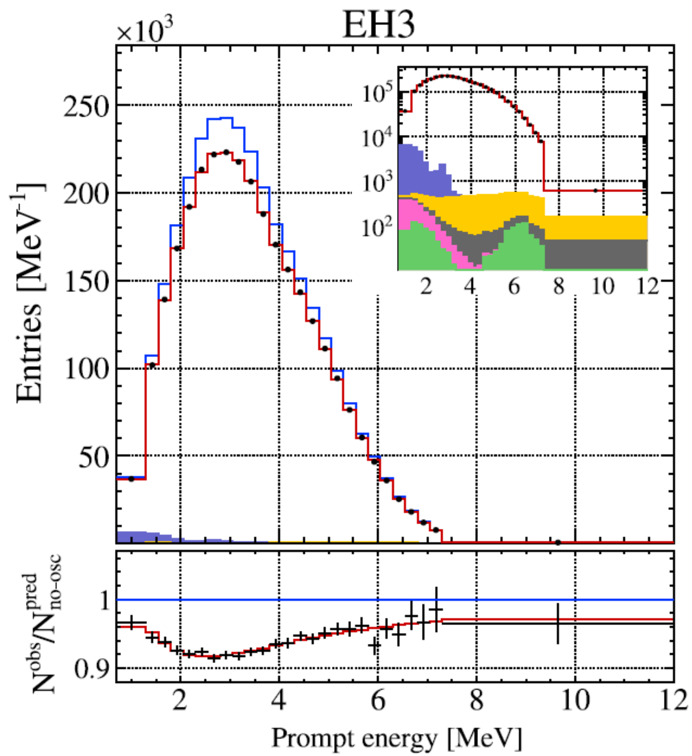
$\sin^2 2\theta_{13} = 0.0851 \pm 0.0024$: precision 2.8%

$$\Delta m^2_{32} = \begin{cases} (2.466 \pm 0.060) \times 10^{-3} \ \mathrm{eV}^2 & \mathrm{NO} \\ (-2.571 \pm 0.060) \times 10^{-3} \ \mathrm{eV}^2 & \mathrm{IO} \end{cases}$$ precision 2.4%

Systematics (mainly from detector difference) contributes ~ 50% of the total error



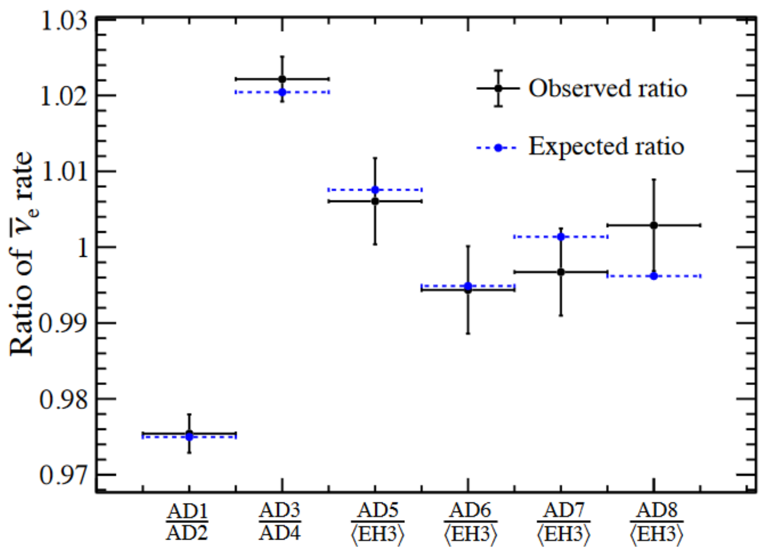
Phys.Rev.Lett.130,161802(2023)

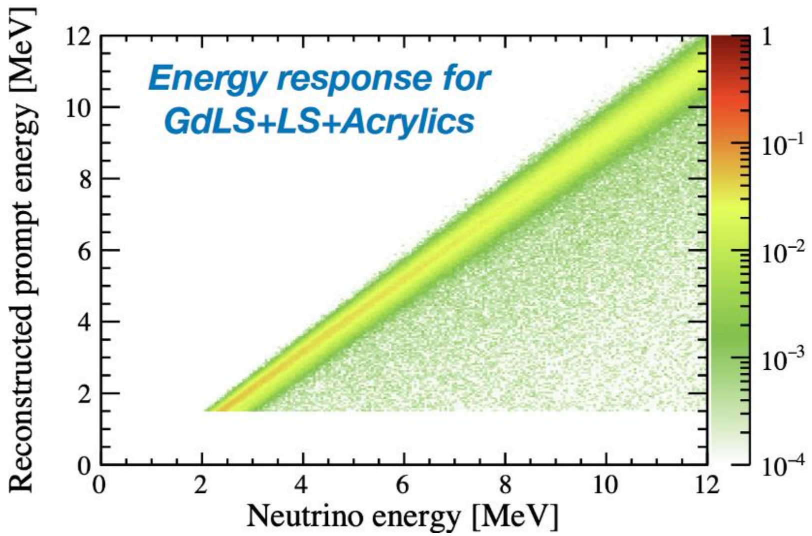


Parametrazation : $P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \cos^4\theta_{13} \sin^2 2\theta_{12} - \sin^2 2\theta_{13} \sin^2 \Delta_{ee}$ $\Delta_{ee} \equiv \Delta m^2_{ee} L/4E$

nH: 1958 Days

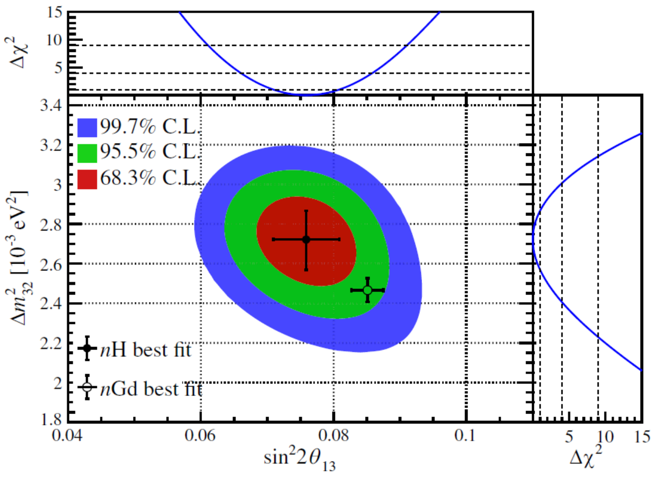
- An update on the previous rate-only result based 621 Days of data: a rate and shape study
  - Identification of radiogenic background
  - Multiple detectors at the same site provides a check on detector identicalness
  - Fine energy calibration: Relative energy scale ≤0.3%
  - Development of energy response model for using energy spectrum to extract oscillation parameters

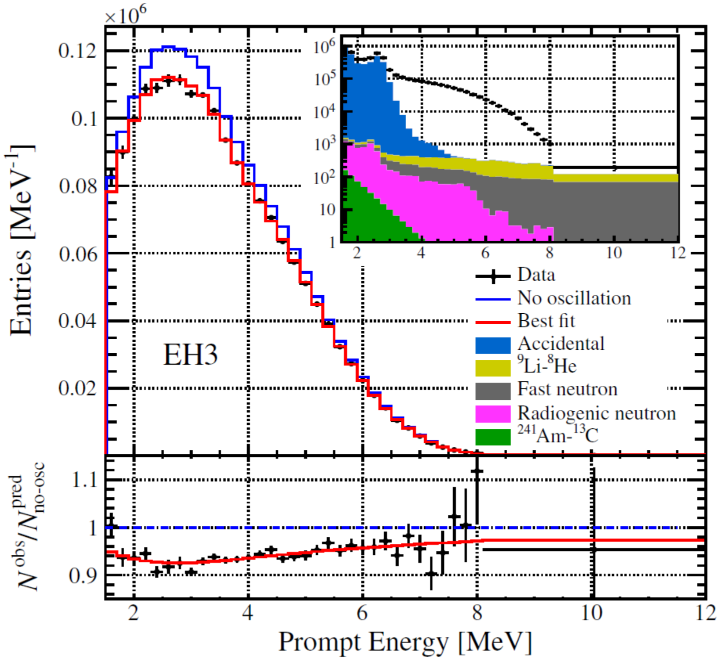




nH-Oscillation Results

Phys.Rev.Lett 133,151801(2024)





$\sin^2 2\theta_{13} = 0.0759^{+0.0050}_{-0.0049}$ precision 6.5%

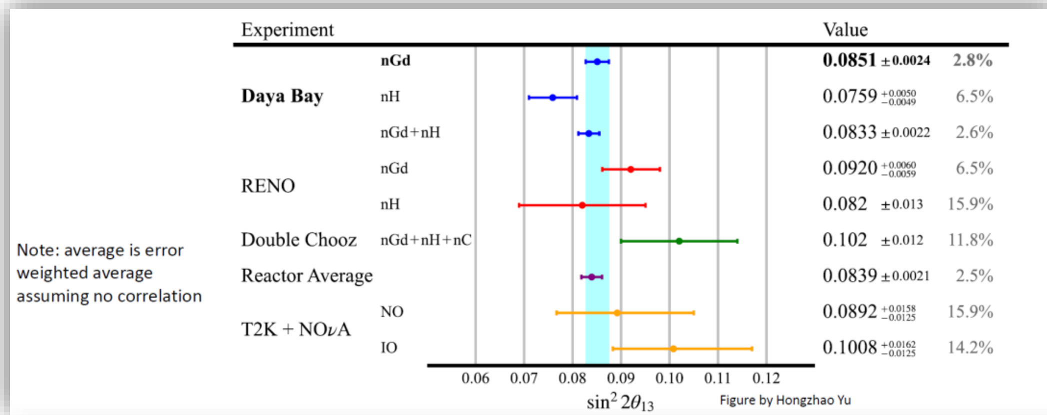
$$\Delta m^2_{32} = \begin{cases} (2.72^{+0.14}_{-0.15}) \times 10^{-3}\mathrm{eV}^2 & \mathrm{NO} \\ (-2.83^{+0.15}_{-0.14}) \times 10^{-3}\mathrm{eV}^2 & \mathrm{IO} \end{cases}$$ precision 5.3%

Consistent with nGd result within 2σ

Statistics contribute 47% and 64% of the total error of $\sin^2 2\theta_{13}$ and Δm^2_{32} respectively

Global Comparison

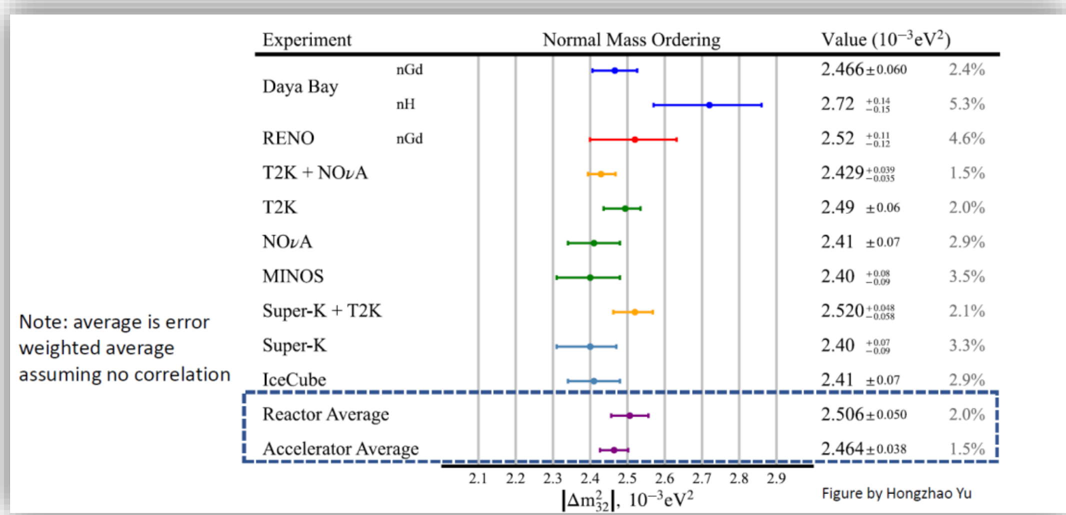
$sin^2 2\theta_{13}$



Daya Bay leads the precision

- nGd+nH : 2.6%
- nGd: 2.8%

Δm^2_{32} (NO)



Consistant with ν_μ, ν_e Measurements

Zeyuan Yu Neutrino 2024

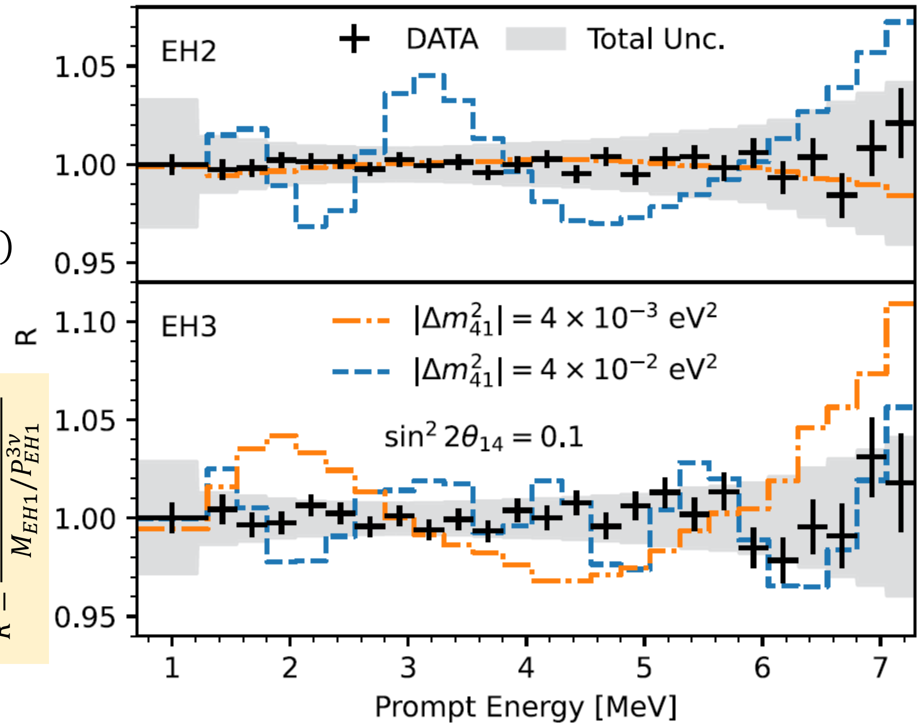
Search For Sterile Neutrinos

- Minimal "3+1" extension of the 3-neutrino mixing

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

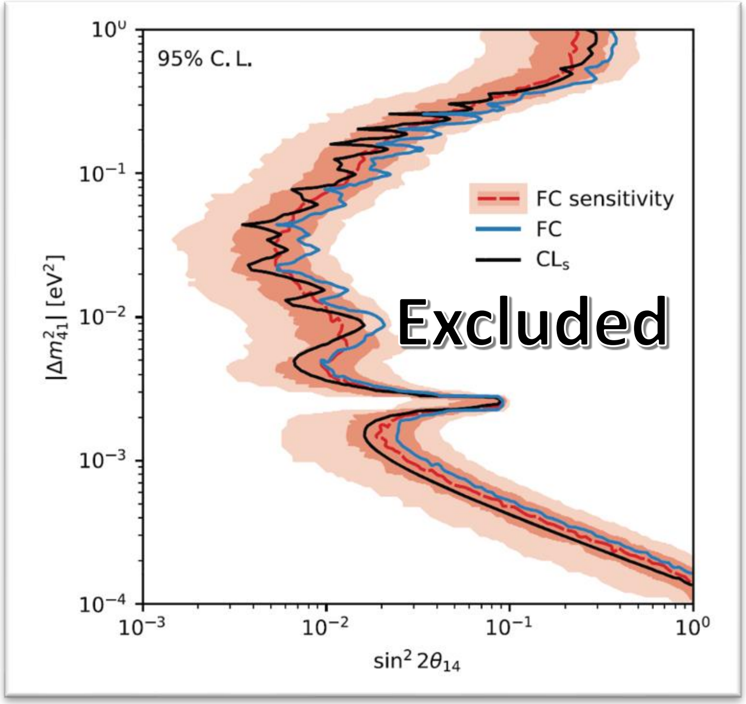
- Looking for deficit of the $\bar{\nu}_e$ Rate and energy spectrum distorsion

$$R = \frac{M_{EH2/3}/P^{3\nu}_{EH2/3}}{M_{EH1}/P^{3\nu}_{EH1}}$$

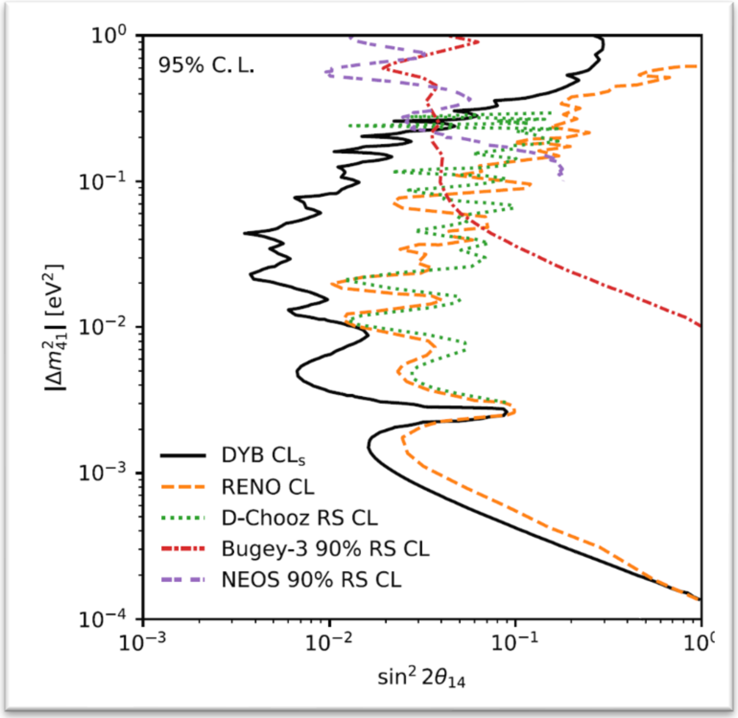


Statistical Test of "3+1" neutrino mixing hypothesis using Daya Bay nGd full data sample

Search for Sterile Neutrinos



Phys.Rev.Lett 133, 051801(2024)

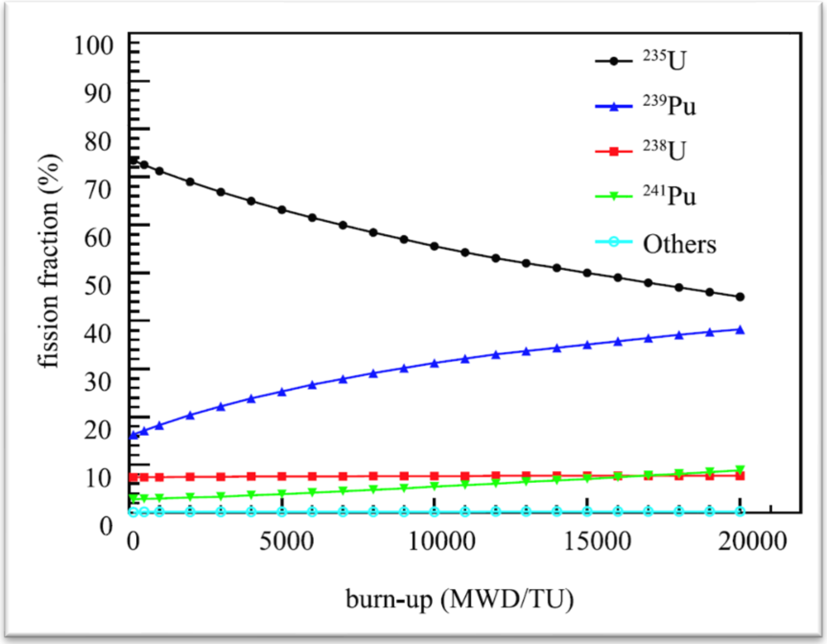


Comparison with other experiments

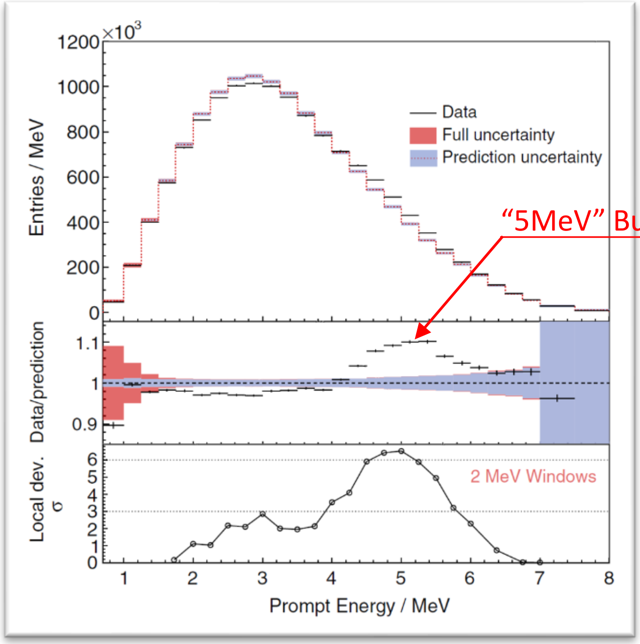
No evidence of a light sterile neutrino

The world's most stringent limits on the sterile-active neutrino mixing parameter $\sin^2 2\theta_{14}$ in the region of $2 \times 10^{-4} \mathrm{eV}^2 \leq \Delta m^2_{41} \leq 0.1\ \mathrm{eV}^2$

Reactor Flux and Spectrum Measurement



Chys.Phys. C 41,1(2017) 013002



Phys.Rev.Lett,123 ,111801(2019)

- More than 99% $\bar{\nu}_e$ ogrinate from βdecays of fission fragments of ^{235}U, ^{238}U,^{239}Pu, ^{241}Pu
-In one burning cycle:

$$^{235}\mathrm{U}\downarrow\ ^{238}\mathrm{U} -\ ^{239}\mathrm{Pu}\uparrow\ ^{241}\mathrm{Pu}\uparrow$$

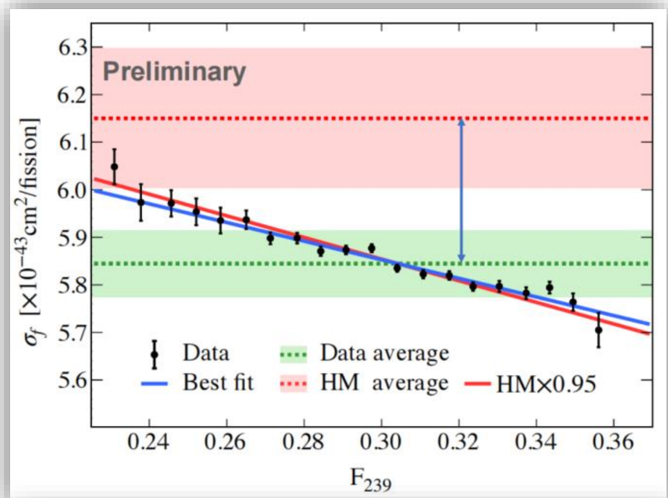
Data-Model Discrepancy

- Rate Discrepancy wrt Huber-Mueller model
- Shape Discrepancy w.r.t conversion and cummation models

Reactor Flux Measurement

- **Fuel evolution** can be viewed effective fission fractions F:
  - Fraction of fission isotopes viewed by detector in weekly basis
- IBD yield σ_f: number of $\bar{\nu}_e$ per fission * IBD cross section

$$\bar{\sigma}_f = (5.84 \pm 0.07) \times 10^{-43} \frac{cm^2}{fission}$$



Extract $\sigma_{235}, \sigma_{239}$:

$$\chi^2 = \chi^2(\sigma_f, F, \sigma_i, \epsilon) + \chi^2(\sigma_{238}, \sigma_{241})$$

Constrain with HM (10%)

ϵ : systematics

σ_f : Measured IBD yield

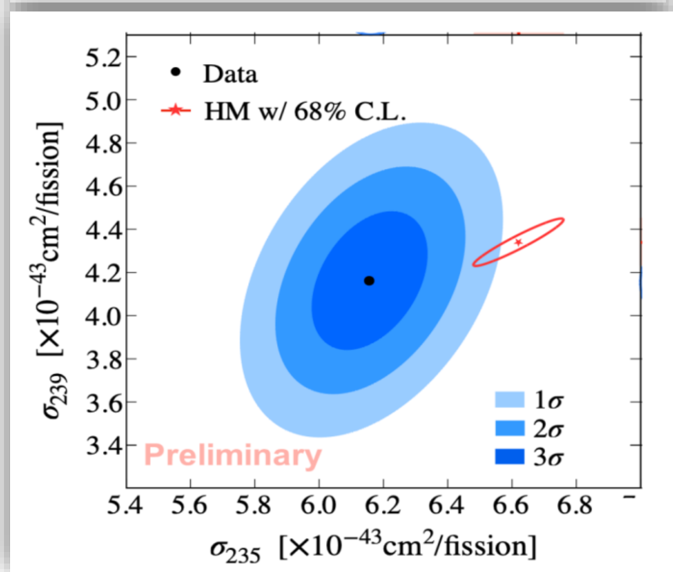
F: effective fission fraction

σ_i: $\sigma_{235}, \sigma_{239}$ Fitting parameter

$$\sigma_{235} = [6.16 \pm 0.12] \times 10^{-43}$$

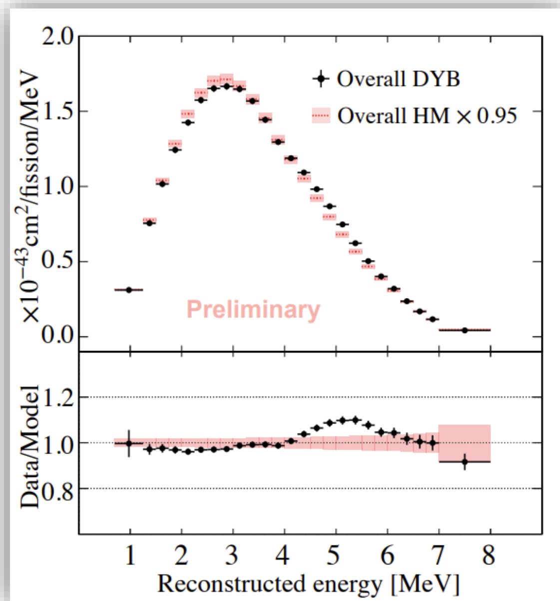
$$\sigma_{239} = [4.16 \pm 0.21] \times 10^{-43}$$

(unit: cm^2/fission)

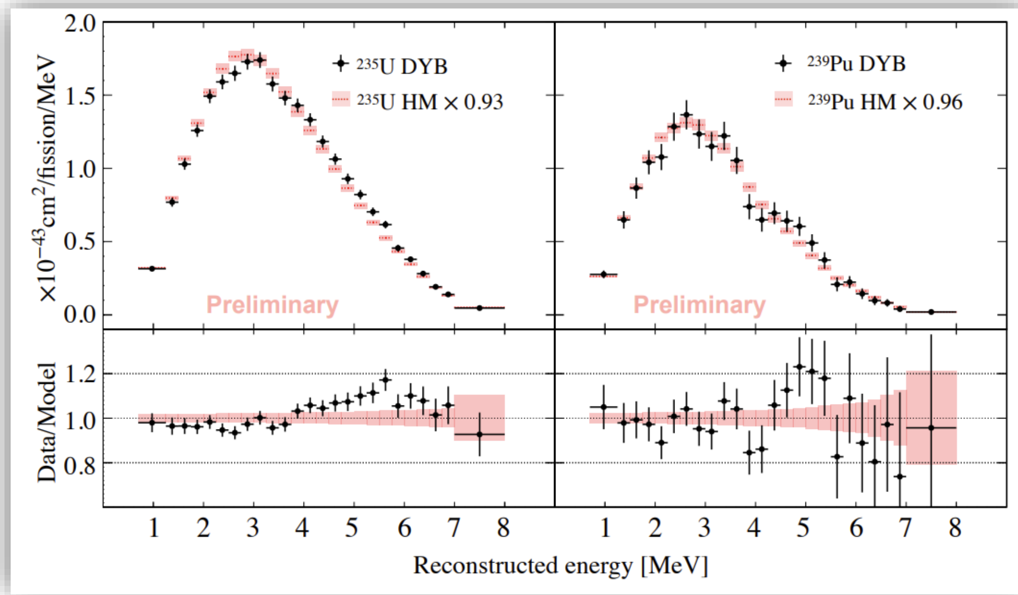


Yang HAN Neutrino 2024

Reactor $\bar{\nu}_e$ spectrum measurement



Overall Spectrum



$\bar{\nu}_e$ flux spectrum from ^{235}U and ^{239}Pu

- ~ 1.4% precision in 2-5 MeV
- Shape discrepancy w.r.t HM : ~ 10σ in 4-6 MeV (systematic dominant)

^{235}U: ~3% in 2-5 MeV
Shape discrepancy w.r.t HM: ~4σ in 4-6MeV

^{239}Pu: ~8% in 2-5 MeV
Shape discrepancy w.r.t HM: ~1σ in 4-6MeV
(statistical error dominant)

Summary

- Daya Bay has been providing the most precise measurement of $\sin^2 2\theta$
- Various topics are addressed using full dataset
  - Sterile neutrinos search yields null results
  - Precise measurement of reactor flux and spectra
  - Extraction of spectra and yield of individual isotope of ^{235}U and ^{239}Pu.
- Data analysis is still on-going, stay tuned for more results to come
  - Final results on reactor flux and spectrum measurement will be released soon
  - Seasonal variation of comic muon intensity
  - nH-oscillation with full data set
- Other interesting topics not covered
  - First Measurement of ^{8}He isotopes produced in liquid scintillator by cosmic-ray muons at Daya Bay: Phys. Rev. D 110 (2024)

The Daya Bay Collaboration

Backup

Signal and Backgrounds

nGd-FullDataset	EH1		EH2		EH3			
	AD1	AD2	AD3	AD8	AD4	AD5	AD6	AD7
$\bar{\nu}_e$ candidates	794 335	144 247 5	132 830 1	121 659 3	194 949	195 369	193 334	180 762
DAQ live time [day]	1535.111	2686.110	2689.880	2502.816	2689.156	2689.156	2689.156	2501.531
$\varepsilon_\mu \times \varepsilon_m$	0.7743	0.7716	0.8127	0.8105	0.9513	0.9514	0.9512	0.9513
Accidentals [day^{-1}]	7.11 ± 0.01	6.76 ± 0.01	5.00 ± 0.00	4.85 ± 0.01	0.80 ± 0.00	0.77 ± 0.00	0.79 ± 0.00	0.66 ± 0.00
Fast n + muon-x [day^{-1}]	0.83 ± 0.17	0.96 ± 0.19	0.56 ± 0.11	0.56 ± 0.11	0.05 ± 0.01	0.05 ± 0.01	0.05 ± 0.01	0.05 ± 0.01
^{9}Li/^{8}He [AD^{-1} day^{-1}]	2.92 ± 0.78		2.45 ± 0.57		0.26 ± 0.04			
^{241}Am-^{13}C [day^{-1}]	0.16 ± 0.07	0.13 ± 0.06	0.12 ± 0.05	0.11 ± 0.05	0.04 ± 0.02	0.04 ± 0.02	0.04 ± 0.02	0.03 ± 0.01
^{13}C$(\alpha, n)^{16}$O [day^{-1}]	0.08 ± 0.04	0.06 ± 0.03	0.04 ± 0.02	0.06 ± 0.03	0.04 ± 0.02	0.04 ± 0.02	0.03 ± 0.02	0.04 ± 0.02
$\bar{\nu}_e$ rate [day^{-1}]	657.2 ± 1.1	685.1 ± 1.0	599.5 ± 0.8	591.7 ± 0.8	75.0 ± 0.2	75.2 ± 0.2	74.4 ± 0.2	74.9 ± 0.2

nH-Subset	EH1-AD1	EH1-AD2	EH2-AD1	EH2-AD2	EH3-AD1	EH3-AD2	EH3-AD3	EH3-AD4
DAQ live time (days)	1536.624	1737.620	1741.214	1554.046	1739.010	1739.010	1739.010	1551.381
				Analysis A				
IBD candidates	602 614	690 506	688 868	599 446	258 084	265 453	263 683	234 910
$\varepsilon_\mu \times \varepsilon_m$	0.6071	0.6044	0.6725	0.6724	0.9187	0.9179	0.9173	0.9186
Accidentals (day^{-1})	119.20 ± 0.04	117.58 ± 0.04	108.47 ± 0.03	104.17 ± 0.03	101.28 ± 0.03	106.73 ± 0.03	105.60 ± 0.03	104.78 ± 0.03
Fast neutron (AD^{-1} day^{-1})	2.78 ± 0.33		2.07 ± 0.23		0.18 ± 0.03			
^{9}Li/^{8}He (AD^{-1} day^{-1})	2.34 ± 1.01		2.83 ± 1.15		0.28 ± 0.10			
Am-C correlated (day^{-1})	0.05 ± 0.03	0.05 ± 0.03	0.04 ± 0.02	0.04 ± 0.02	0.02 ± 0.01	0.02 ± 0.01	0.02 ± 0.01	0.01 ± 0.01
Radiogenic neutron (day^{-1})	0.20 ± 0.04							
IBD rate (day^{-1})	521.36 ± 1.35	534.49 ± 1.33	474.64 ± 1.37	464.36 ± 1.39	59.57 ± 0.34	58.88 ± 0.34	59.02 ± 0.34	59.38 ± 0.36

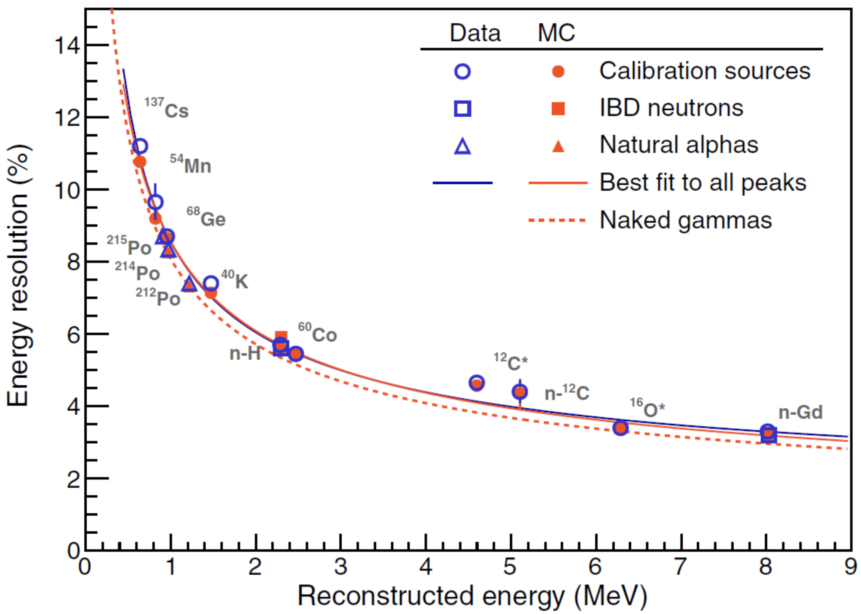
Backgrounds

- Uncorrelated : Accidentals
- Muon-induced correlated backgrounds
  - Fast Neutron: produced outside the AD but enters the active volume of the AD
  - "Muon-X": Associated with untagged muon due to equipment malfunction (become non-negligible at later days when some PMTs in water pool are dieing)
  - Li9/He8: Spallation product by cosmic muons inside AD
- Other Backgrounds
  - ^{241}Am-^{13}C: calibration neutron source reside the ACU
  - (nGd): $^{13}C(\alpha, n)^{16}O$
  - (nH) Radiogenic neutrons (Phys.Rev.D 104,092006(2021))

Calibration

Phys. Rev. D 95 072006(2017)

PMT calibration:
- Single PE from dark noise
- Weekly LED monitoring



Energy Calibration
- Weekly 68Ge, 60Co,241Am-13C
- Spallation neutrons
- Natural Radioactivity

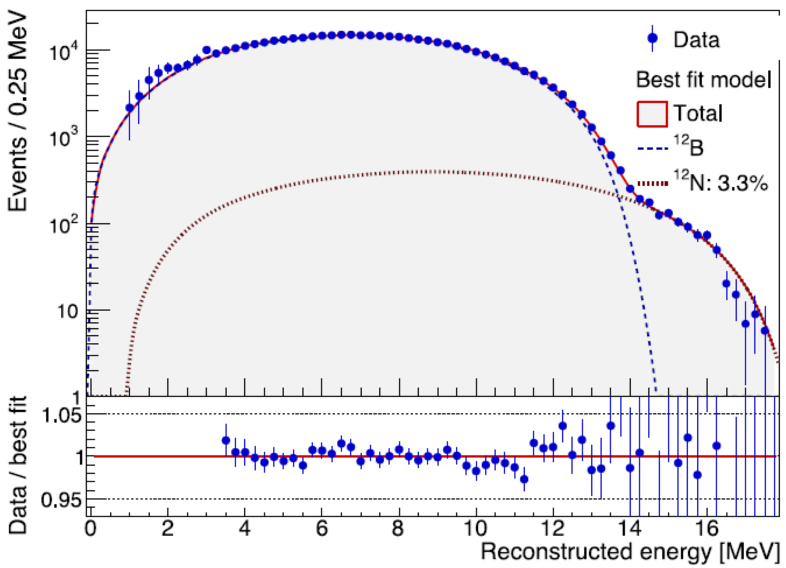
$$\frac{\sigma_E}{E_{rec}} = \sqrt{a^2 + \frac{b^2}{E_{rec}} + \frac{c^2}{E_{rec}}}$$

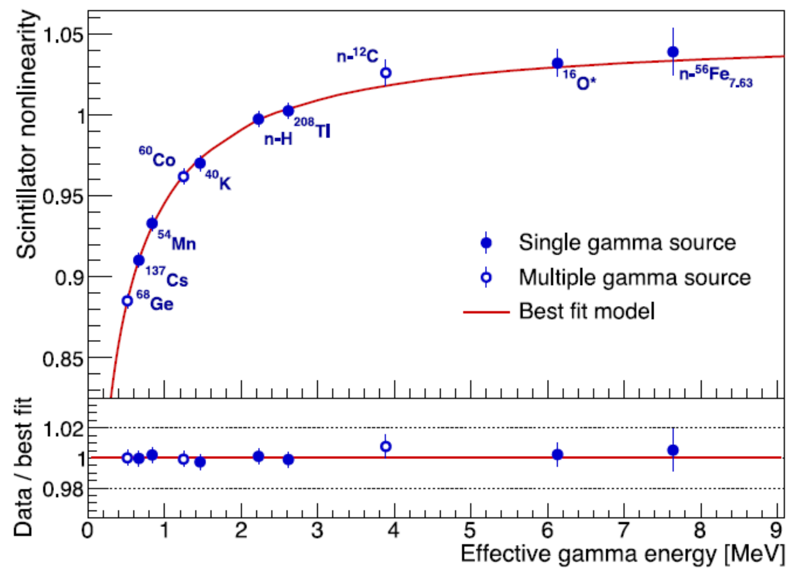
a = 0.016 : detector nonuniformity

b = 0.081$MeV^{1/2}$: p.e. statistics

c = 0.026MeV : noise

Nonlinearity Model Calibration

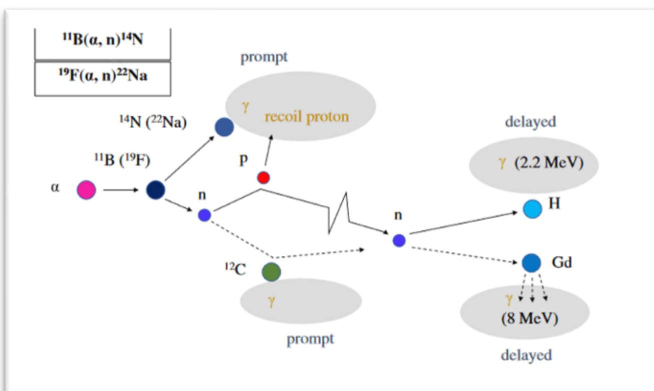


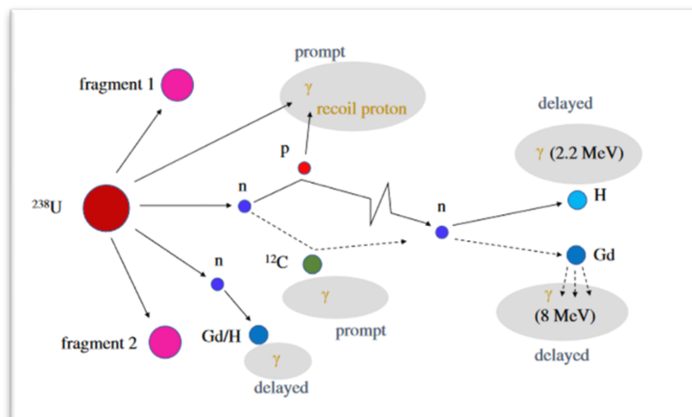


- FlashADC was install in EH1AD1 during specail calibration during end of 2016
- Less thatn 0.5% uncertainty in energy nonliearity is achieved for positrons with kinematic energy greater than 1MeV
  - constrains from data and removal of electronics nonlinearity with FADC

Radiogenic neutron Backgrounds

- Radiogenic neutron backgrounds
  - Spontaneous fission
  - (α, n) reactions in peripheral materials of the antineutrino detectors
- Good shielding is needed for removing the background





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Signal Selection

nGd

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%

nH

	Uncertainty (%)	
	Analysis A	Analysis B
Target protons	0.11	0.11
Prompt energy	0.13	0.13
[1, 1500] μs	0.10	0.10
Delayed energy	0.20	0.24
Coincidence *DT*	0.20	0.21
Combined (ε)	0.34	0.37

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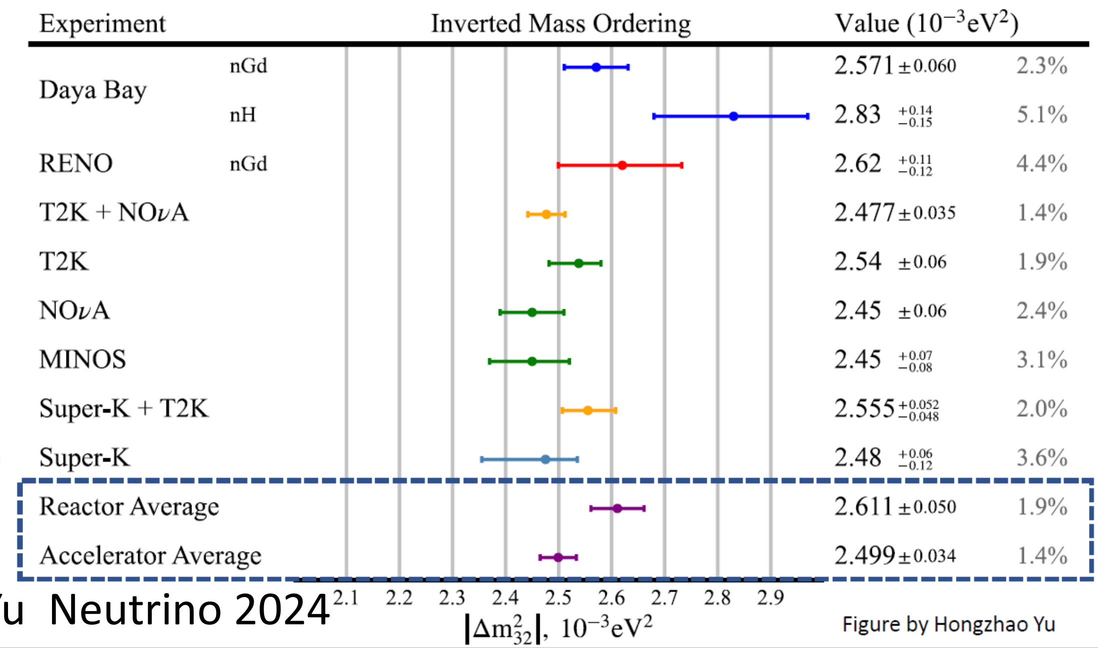
Compared with nGd analysis, nH analysis faces more challenging systematic uncertainties

Consistent results from reactor and accelerator experiments

Normal Ordering slightly preferred (<2σ) from reactor/accelerator averages

Note: average is error weighted average assuming no correlation



From Zeyuan Yu Neutrino 2024