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

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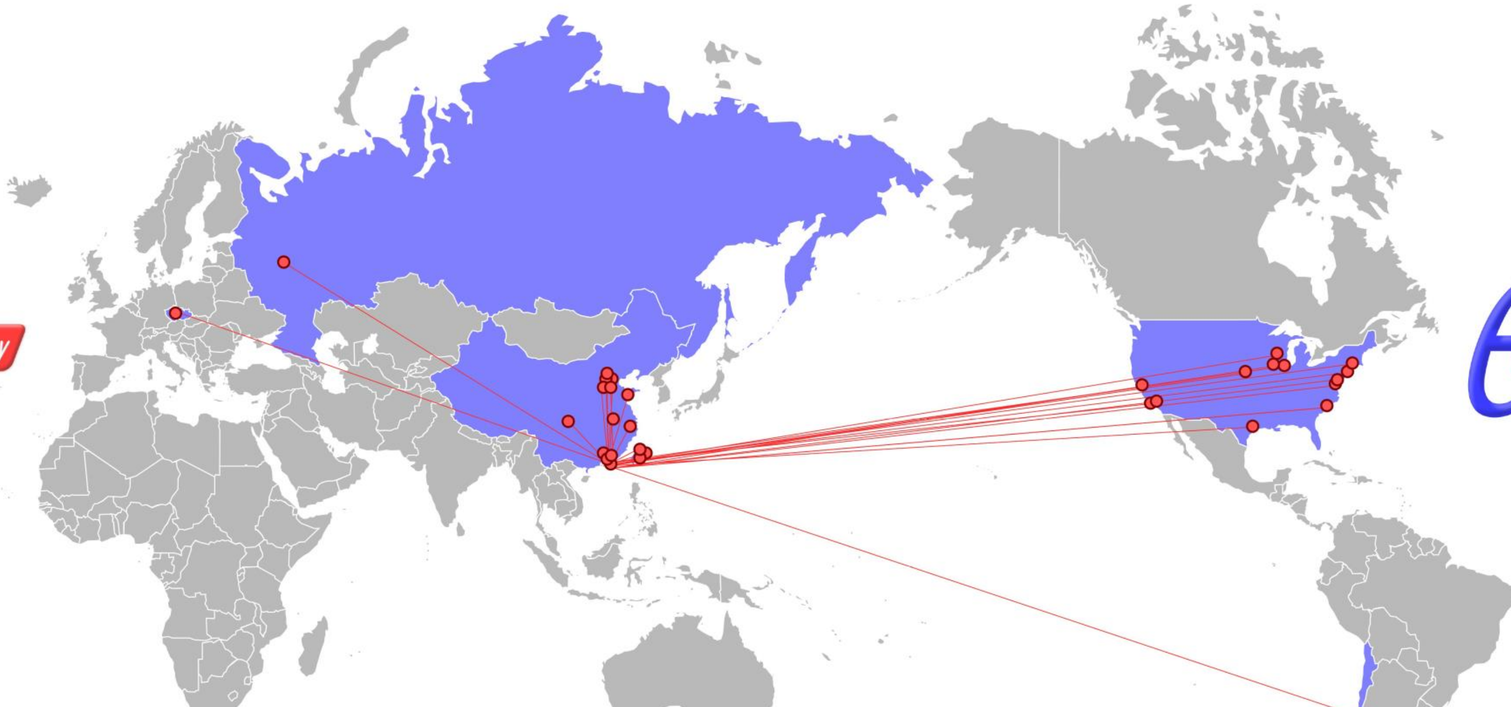
(On behalf of the Daya Bay Collaboration)

October 25, 2023 @ XX International Workshop on Neutrino Telescopes

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

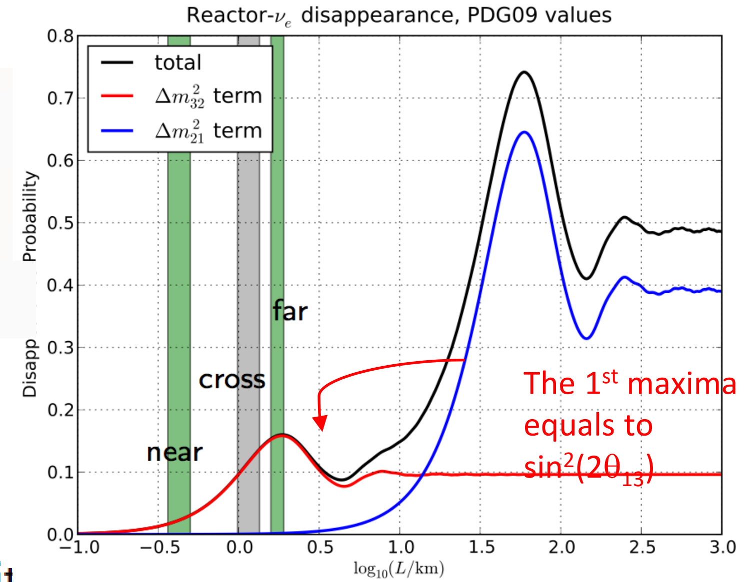
Reactor Neutrino Oscillation and Measurement

- Detection of anti-electron-neutrino

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

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

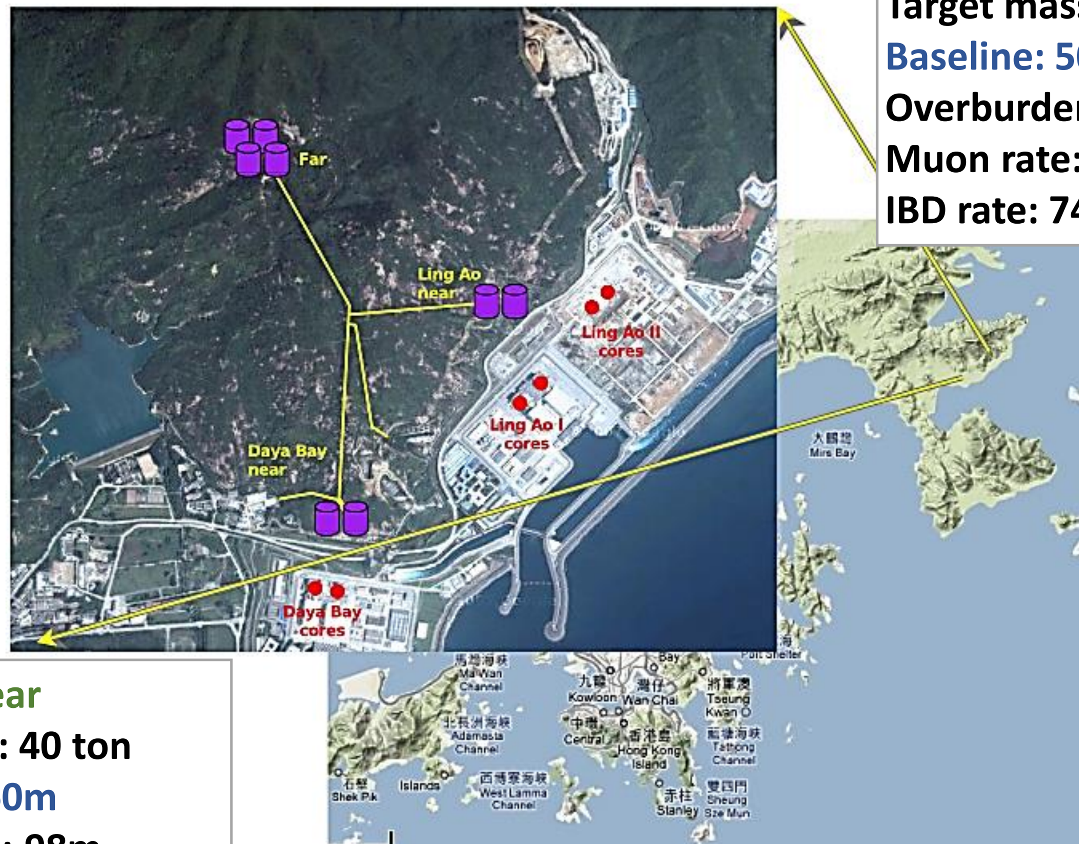
$$P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} = 1 - \sin^2 2\theta_{13} \sin^2\left(\Delta m^2_{ee} \frac{L}{4E}\right) - \sin^2 2\theta_{12} \cos^4\theta_{13} \sin^2\left(\Delta m^2_{21} \frac{L}{4E}\right)$$

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

- 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

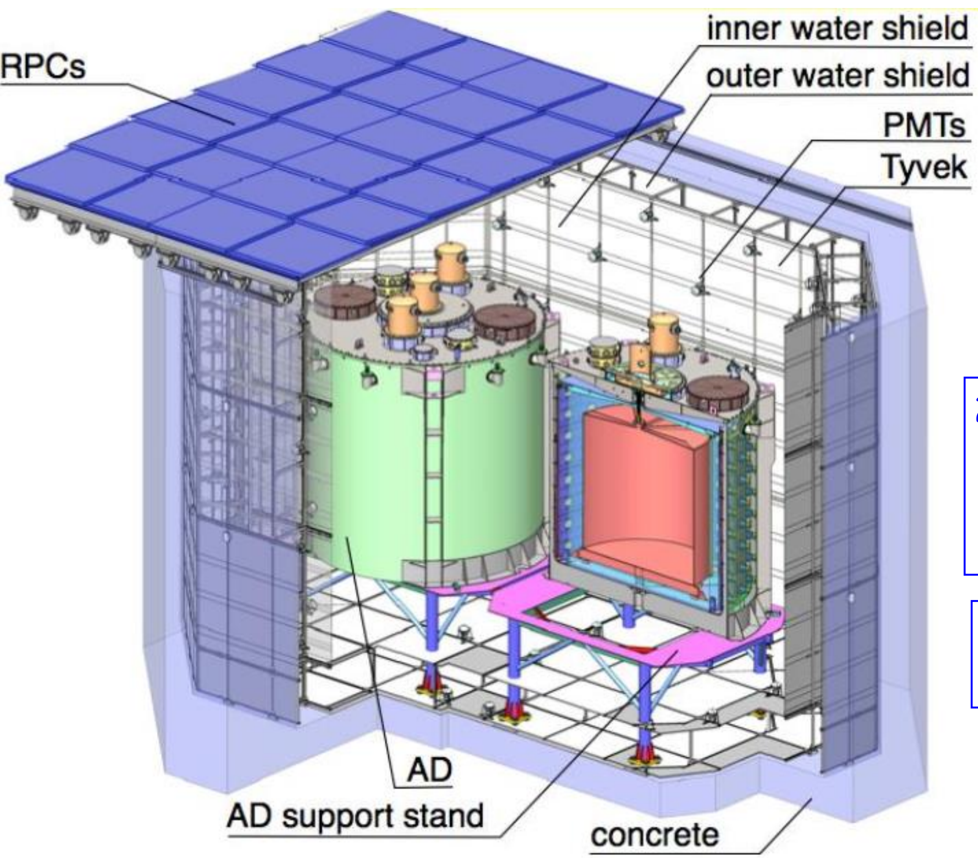


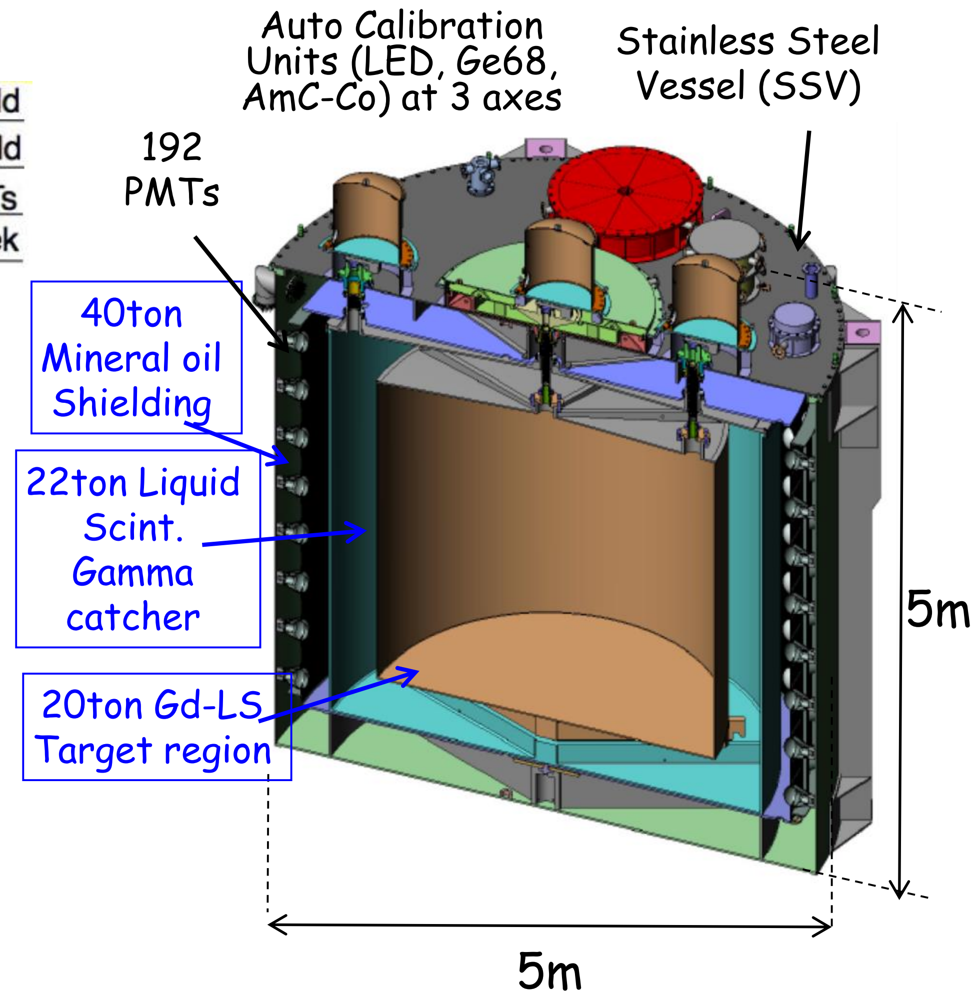
Ling Ao near
Target mass: 40 ton
Baseline: 500m
Overburden: 112m
Muon rate: 0.73Hz/m^2
IBD rate: 740/day/AD

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)

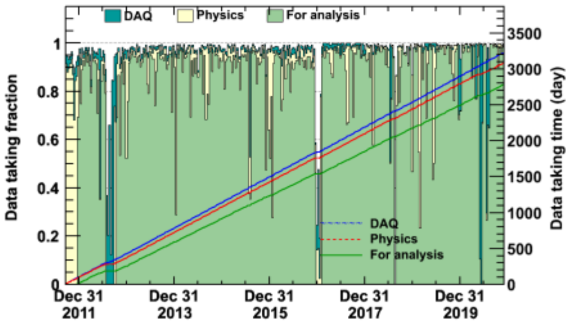




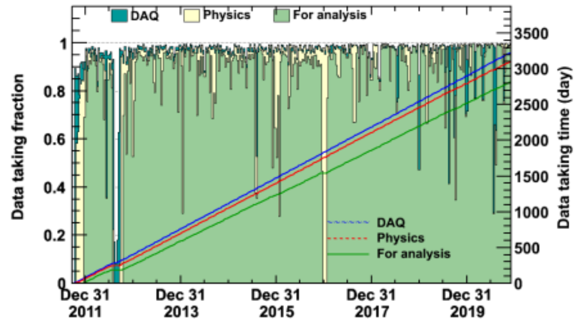
Data Collection

- Operational statistics:

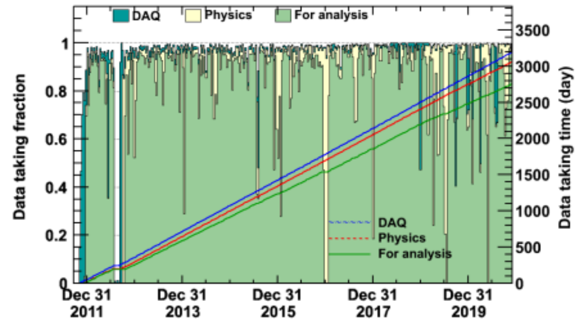
EH1



EH2



EH3



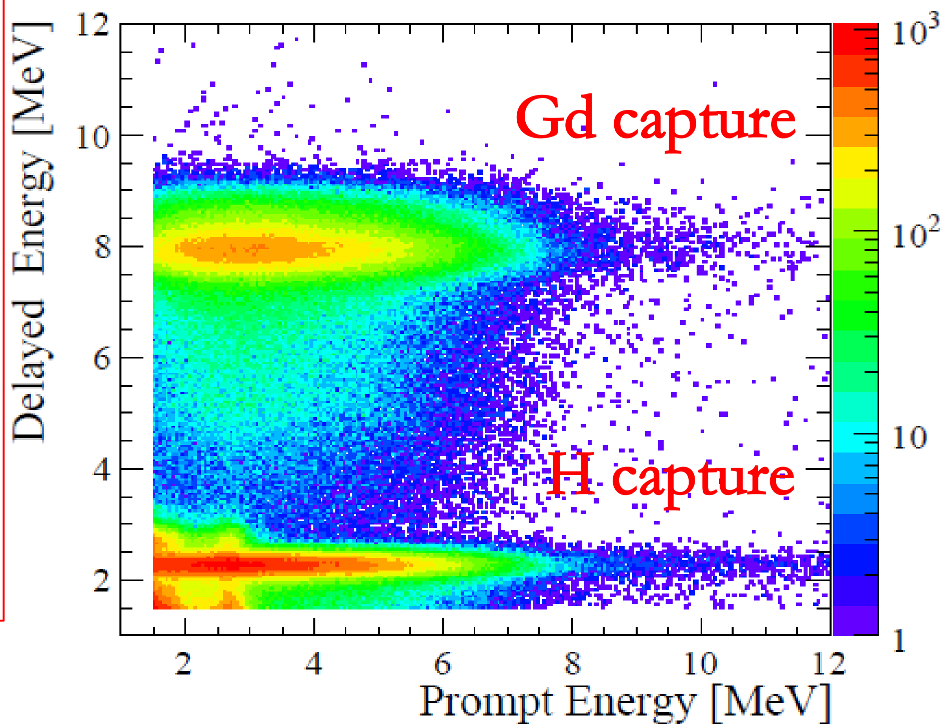
- Three physics runs:

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

Candidates and Background

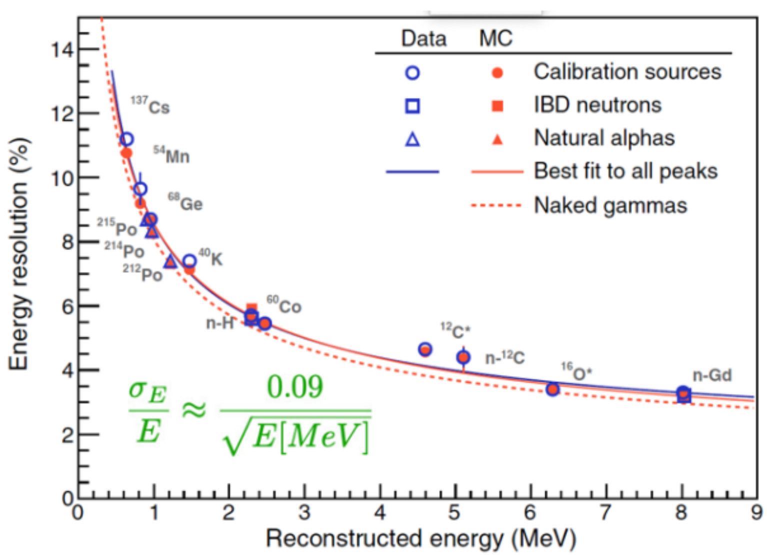
- Remove flashing PMT events
- Veto muon events
- Require 0.7 MeV < E_{prompt} < 12 MeV, 6 MeV < $E_{delayed}$ < 12 MeV
- Neutron capture time: 1 μs < Δt < 200 μs
- Multiplicity cut: select time-isolated energy pairs



- 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)

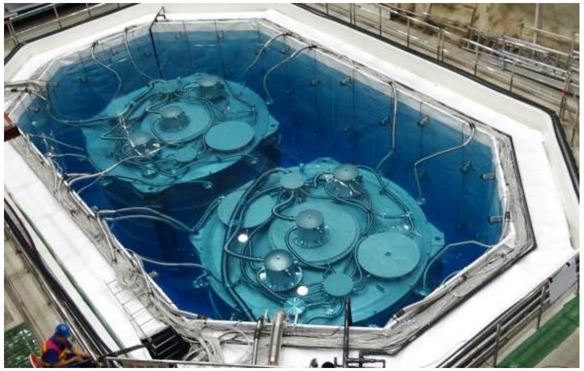
Energy Scale and Systematics

- 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:

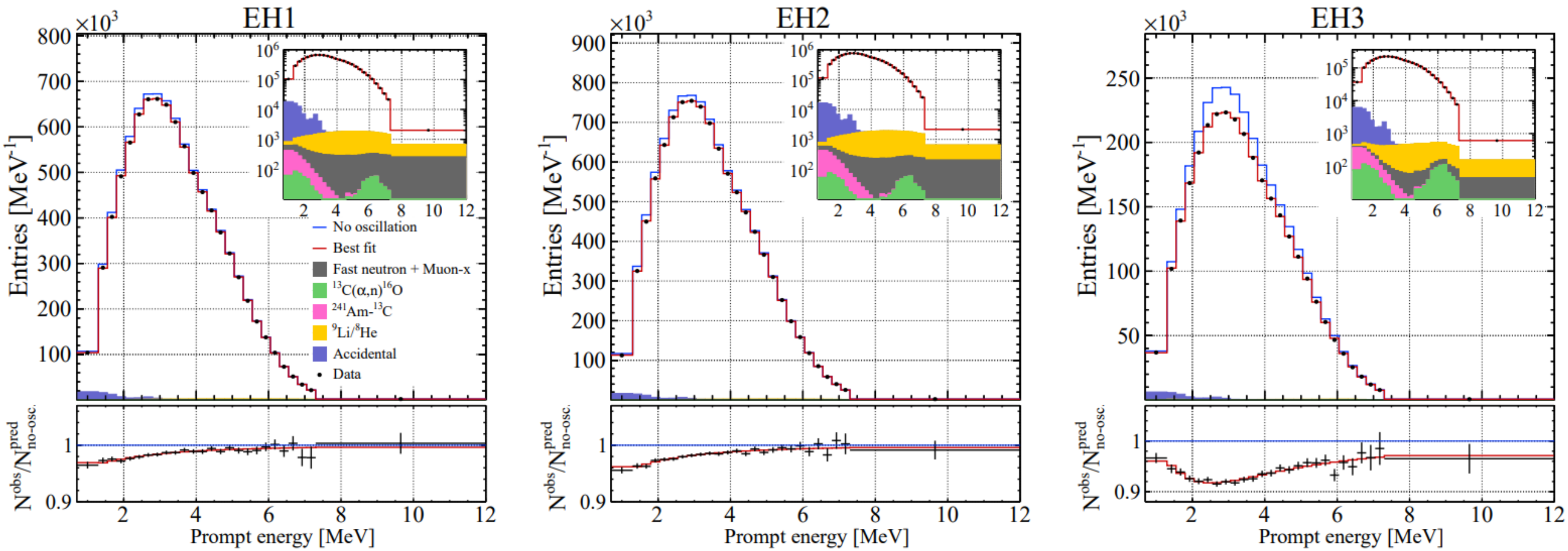
R(AD1/AD2) = 0.982

Measurement:

0.987 ± 0.004(stat) ± 0.003(syst)

Prompt energy spectra

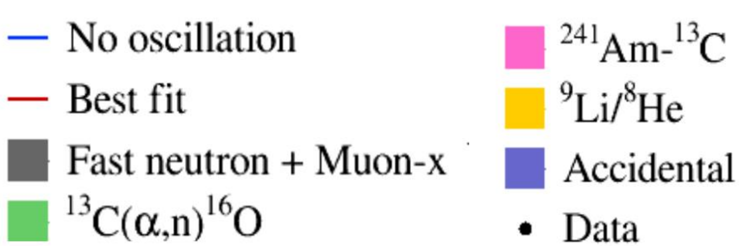
$$E_\nu \approx E_{\text{prompt}} + 0.78\ \text{MeV}$$



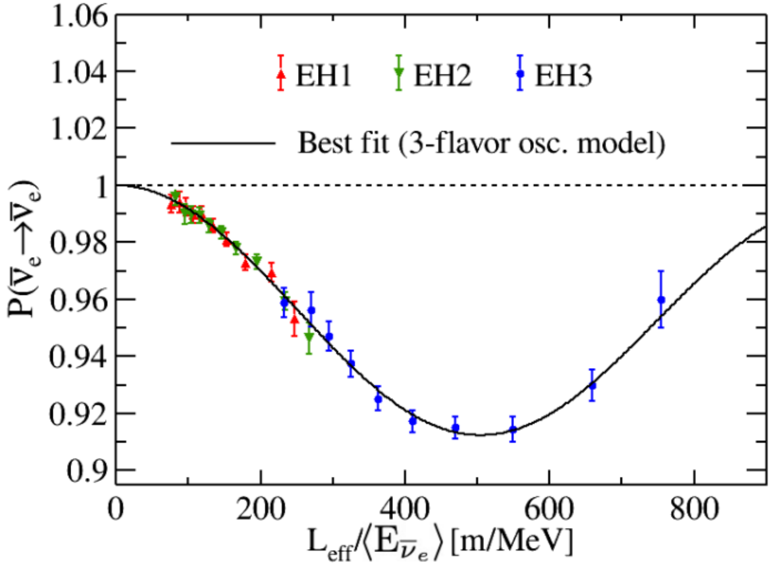
2,236,810 IBD events

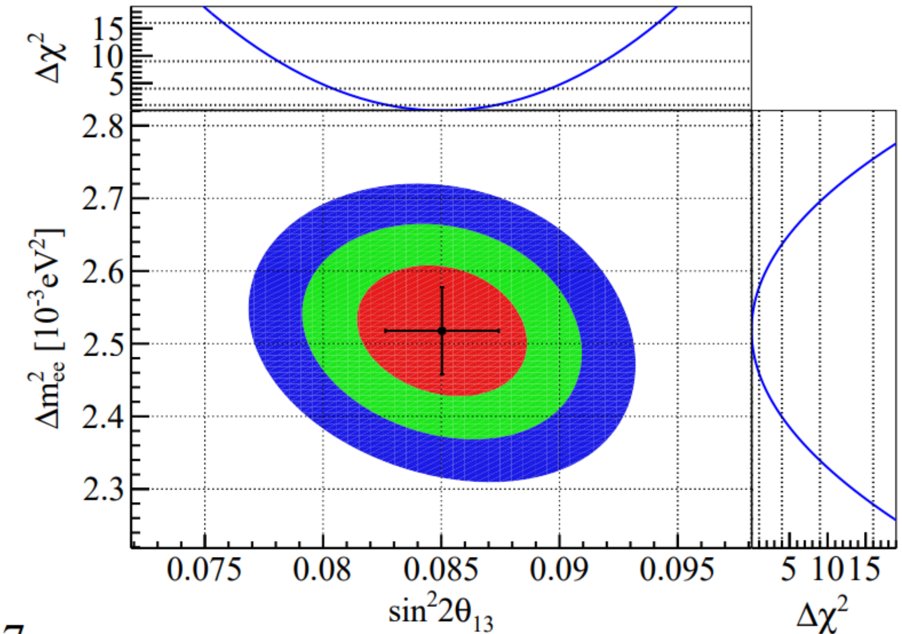
2,544,894 IBD events

2,544,894 IBD events



Improved $\sin^2 2\theta_{13}$ and Δm^2_{32}





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

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

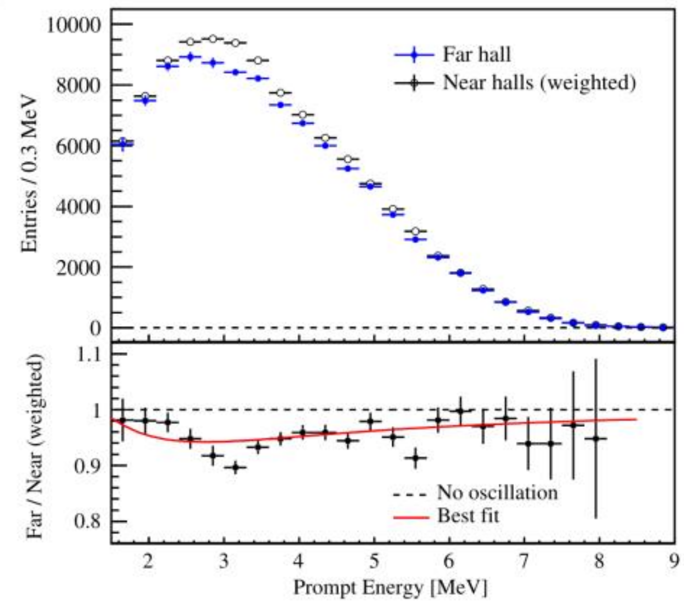
Normal hierarchy: $$\Delta m^2_{32} = +\left(2.466^{+0.060}_{-0.060}\right) \times 10^{-3}\mathrm{eV}^2$$ (2.4% precision)

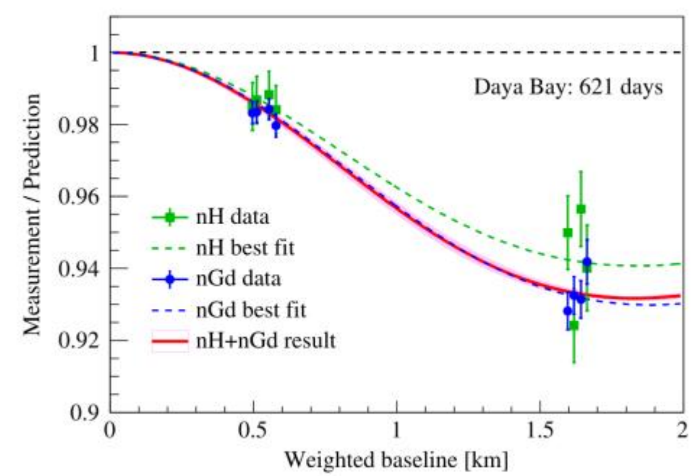
Inverted hierarchy: $$\Delta m^2_{32} = -\left(2.571^{+0.060}_{-0.060}\right) \times 10^{-3}\mathrm{eV}^2$$ (2.3% precision)

PRL **130**, 161802 (2023)

Measurement with nH

- Daya Bay's latest nH results still from 2016
  - Phys. Rev. D **93**, 072011 (2016)
- 621 days of data were used to perform an analysis on rate deficit due to oscillation effect
- Statistically distinct sample with largely uncorrelated systematics to that of nGd, providing a nearly independent result
- Unique challenge due to more low energy background
- Result: $\sin^2 2\theta_{13} = 0.071 \pm 0.011$
  - with $\chi^2/\mathrm{NDF} = 6.3/6$
- A new result exploiting rate deficit and shape distortion with larger sample is under preparation

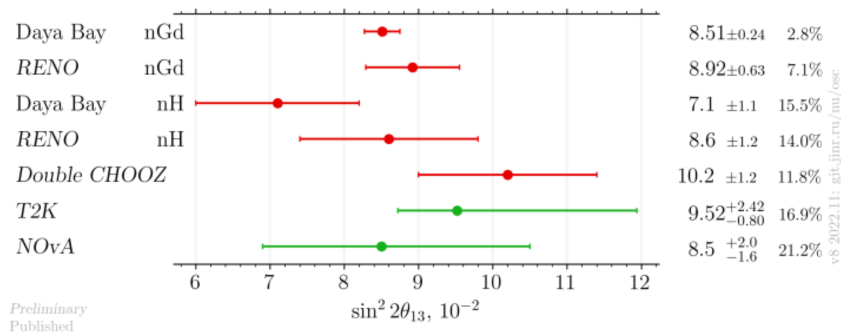




Present Global Landscape

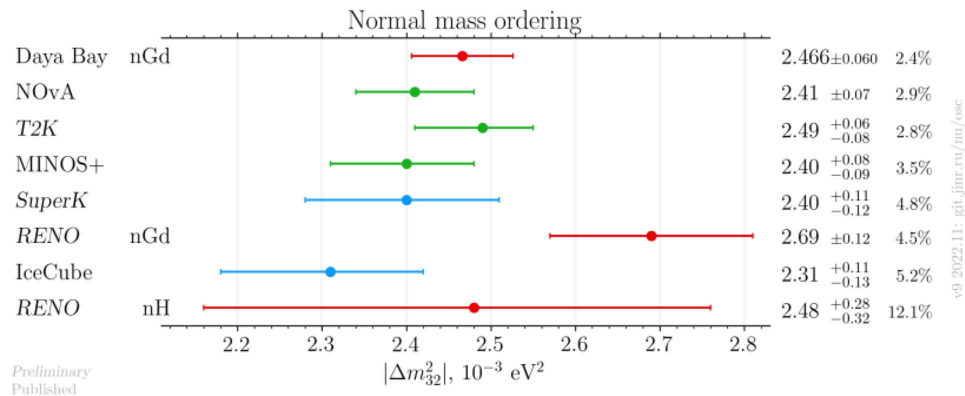
Compare Daya Bay's current results with other measurements

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



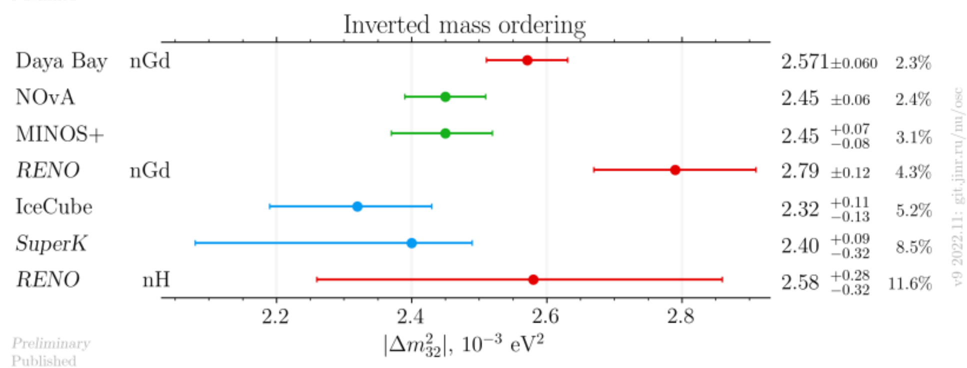
Probably the best measurement for a while

Δm^2_{32} (NO)



Consistent results from ν_e and ν_μ measurements strongly support 3-flavor framework

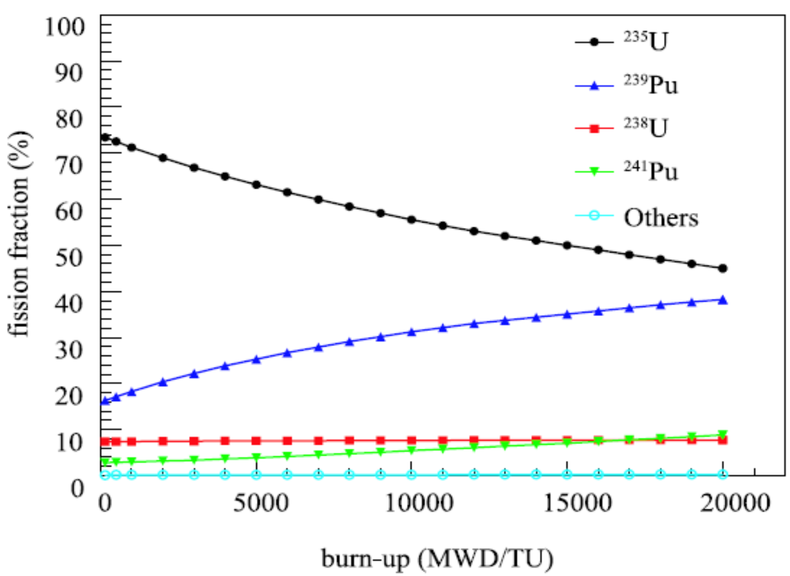
Δm^2_{32} (IO)



Evolution of Daya Bay Reactors

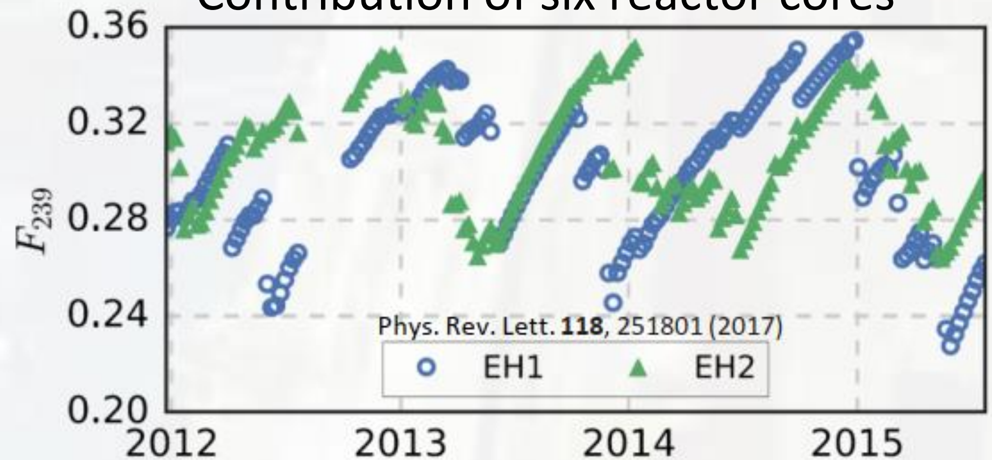
French Pressurized Water Reactor (PWR)

- 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

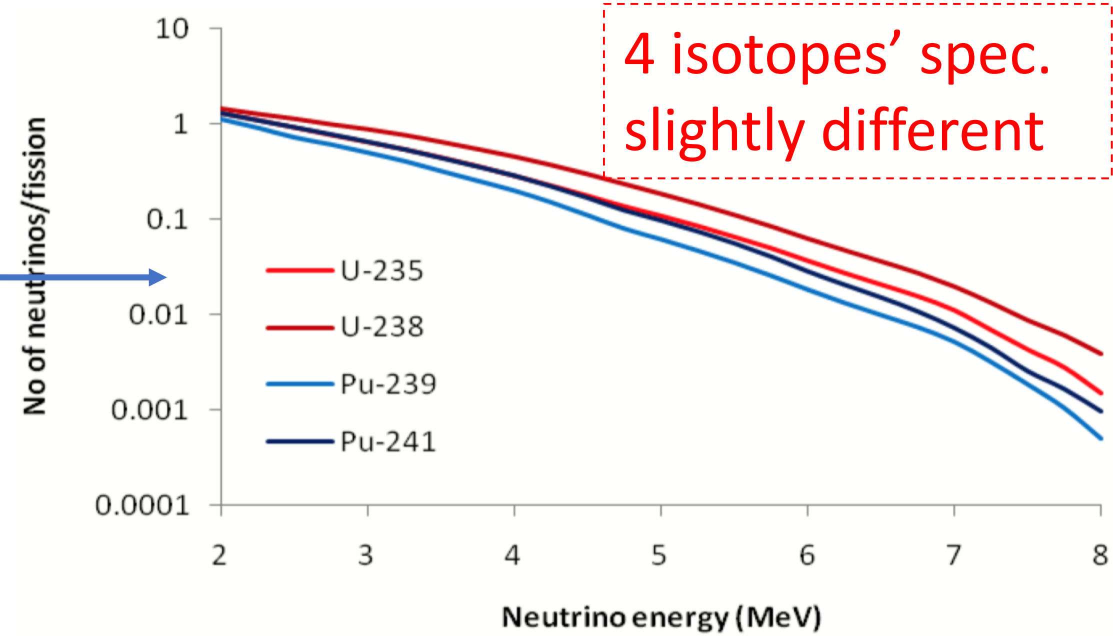
Dominant fission fuels	^{235}U:	50% ~ 65%	
	^{239}Pu:	24% ~ 35%	

Reactor Neutrino Flux and Spectrum

- Evolution of Flux and spectrum

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

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



4 isotopes' spec. slightly different

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, comparison with models, <u>HM and SM2018</u>, are made.

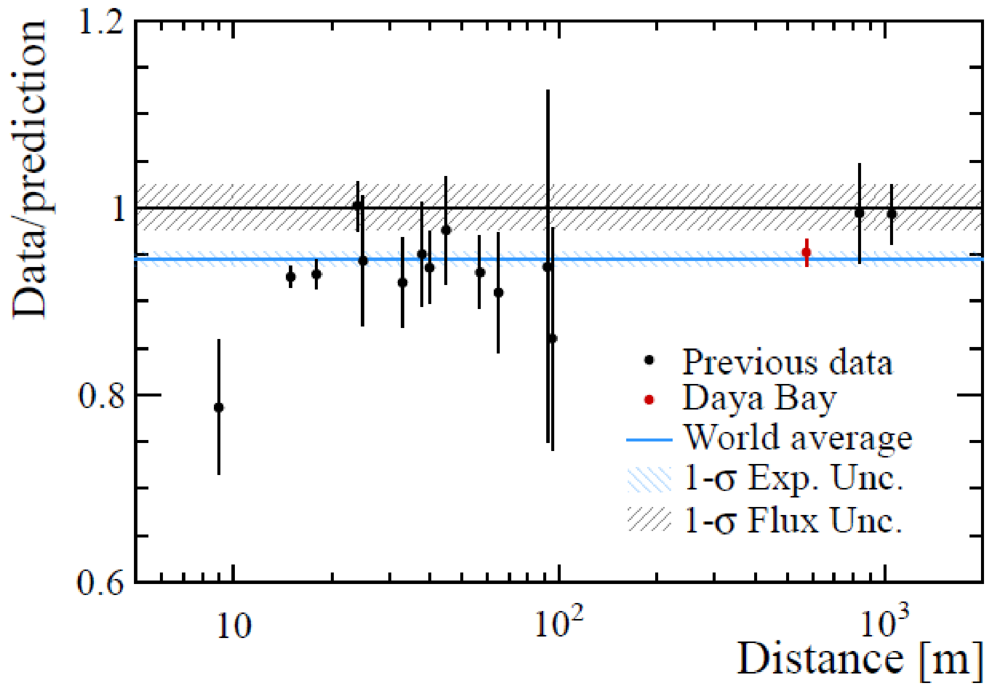
Reactor Neutrino Flux

Flux (yield at average fission status):

$$\sigma_f = (5.91 \pm 0.09) \times 10^{43}\ \mathrm{cm}^2/\mathrm{fission}$$

Ratio with respect to predicted reactor neutrino yield:

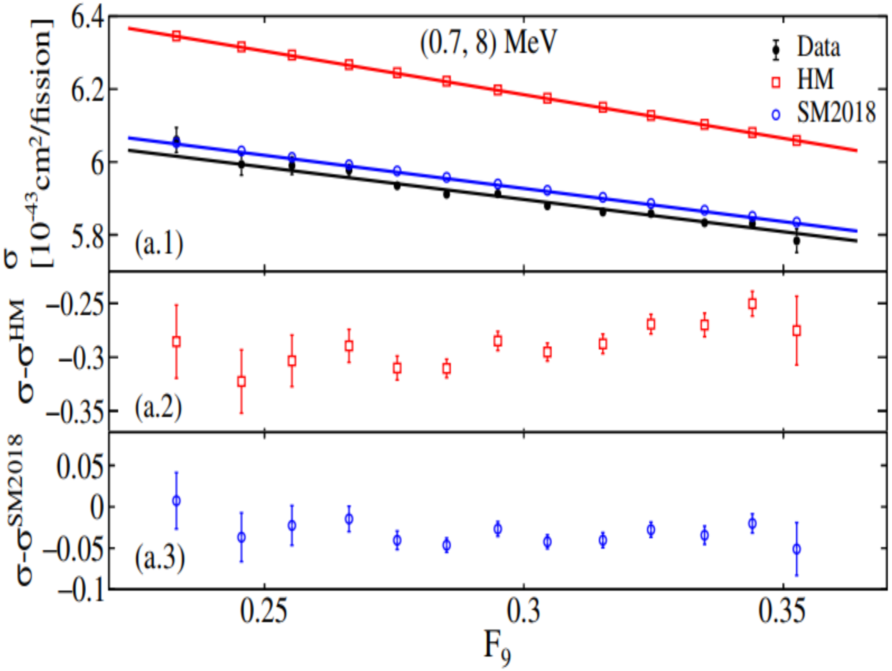
R = 0.952±0.014 (Exp.)±0.023 (Huber-Mueller)

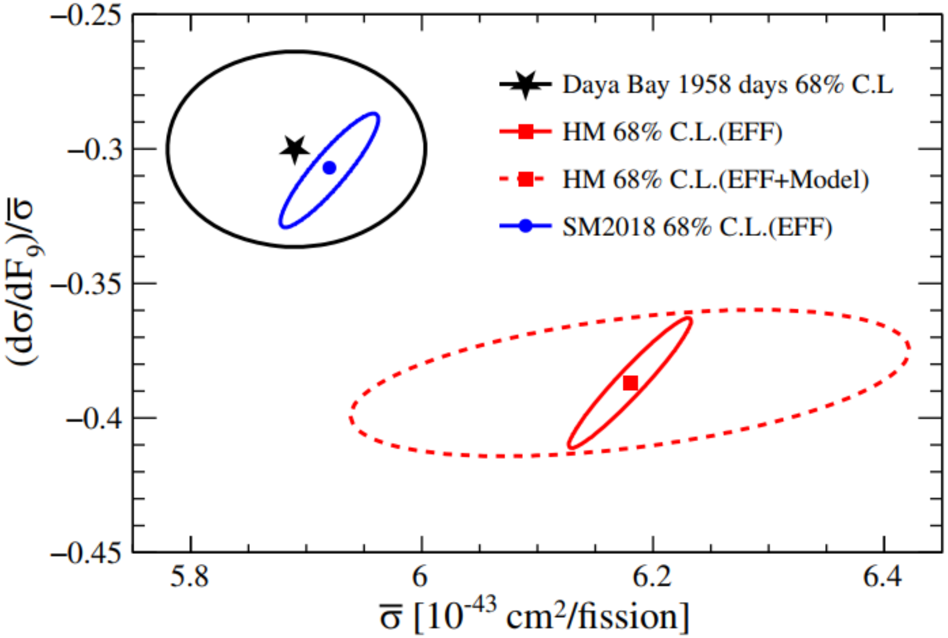


Phys. Rev. D 100 (2019) 052004

Reactor Neutrino Flux Evolution

Data are grouped into 13 fission groups according to their F_9.





$$\sigma^{\mathrm{Lin},g} = \bar{\sigma}\{1 + [(d\sigma/dF_9)/\bar{\sigma}](F_9^g - \bar{F}_9)\}$$

The HM predictions:

Rejected at 3.6 standard deviations in $\bar{\sigma}$

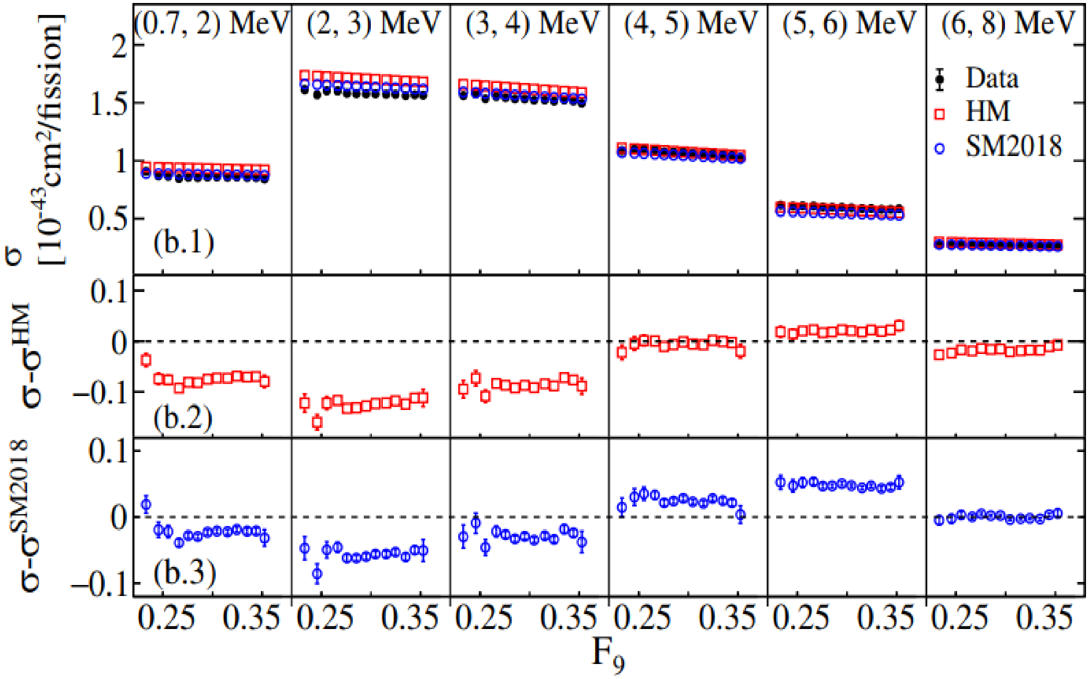
Rejected at 3.0 standard deviations in $(d\sigma/dF_9)/\bar{\sigma}$

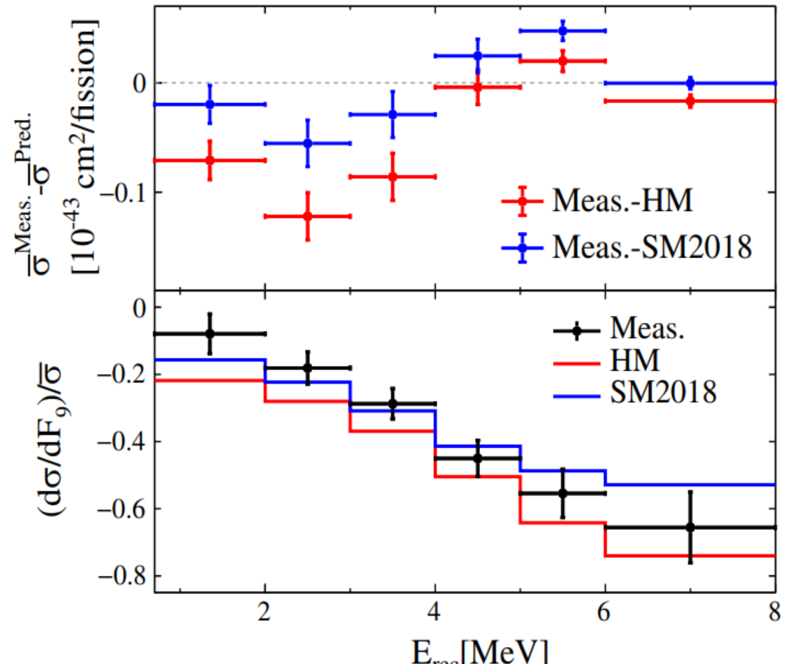
The normalized evolution slope is free of any normalization issue

The SM2018 predictions:

Consistent

Reactor Neutrino Spectrum (Fluxes in 6 energy bins) Evolution





$$\sigma^{\mathrm{Lin},eg} = \bar{\sigma}^e\{1 + [(d\sigma/dF_9)/\bar{\sigma}]^e(F_9^g - \bar{F}_9)\}$$

Shape $\bar{\sigma}^e$:

Reject HM and SM2018 predictions at 27 and 25 σ

Normalized slope $[(d\sigma/dF_9)/\bar{\sigma}]^e$:

Consistent within uncertainty

More significant than 5 MeV the bump itself. Reason: High positive correlation between data points

Hints for Models

Predictions of the HM or SM2018 models:

$$\sigma^{\mathrm{Pred},eg} \equiv F_5^g \sigma_5^e + F_8^g \sigma_8^e + F_9^g \sigma_9^e + F_1^g \sigma_1^e$$

Introduce U, Pu spectrum distortions, f_5^e or f_9^e, or a global normalization factor η (motivated by large-mass sterile neutrinos or by a global uncertainty, e.g., from the detection efficiency) to improve data HM/SM2018 agreement

$$\sigma^{\mathrm{model},eg} = \eta[F_5^g \sigma_5^e (1 + f_5^e) + F_8^g \sigma_8^e + F_9^g \sigma_9^e + F_1^g \sigma_1^e]$$

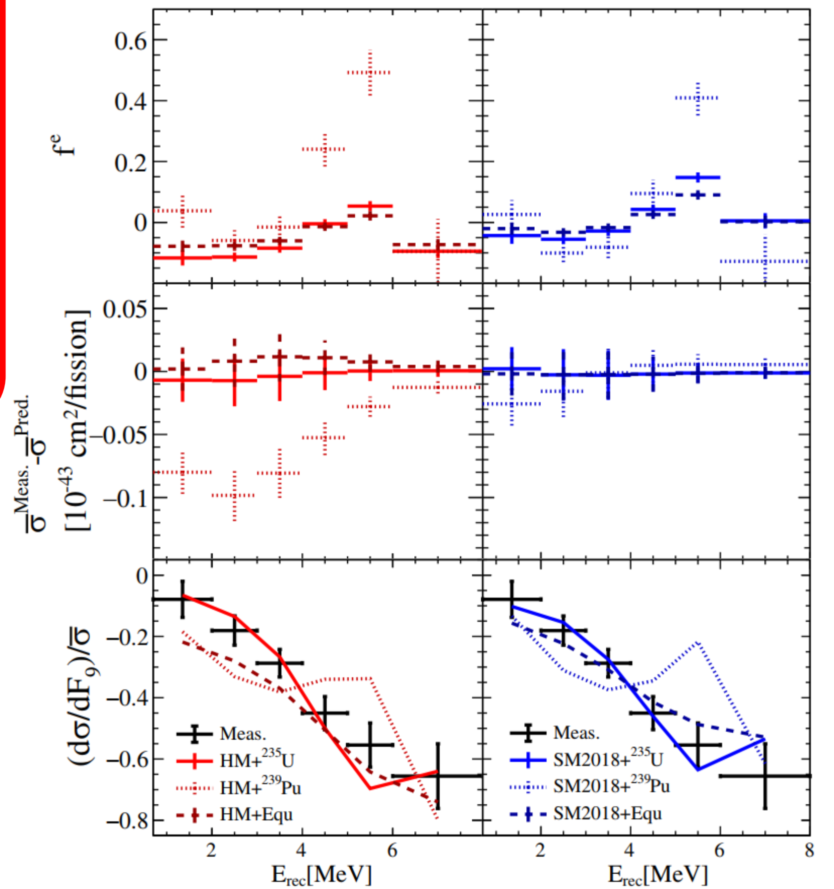
$$\sigma^{\mathrm{model},eg} = \eta[F_5^g \sigma_5^e + F_8^g \sigma_8^e + F_9^g \sigma_9^e (1 + f_9^e) + F_1^g \sigma_1^e]$$

$$\sigma^{\mathrm{model},eg} = (1 + f_{\mathrm{E}}^e)[F_5^g \sigma_5^e + F_8^g \sigma_8^e + F_9^g \sigma_9^e + F_1^g \sigma_1^e]$$

Hints for Models

Model	η	χ^2/NDF	N_σ	χ^2/NDF $(\eta=1)$	N_σ $(\eta=1)$
HM + ^{235}U	0.985 ± 0.021	83/71	1.4σ	83/72	1.4σ
SM2018 + ^{235}U	0.997 ± 0.021	80/71	1.2σ	80/72	1.2σ
HM + ^{239}Pu	0.935 ± 0.014	116/71	3.4σ	136/72	4.5σ
SM2018 + ^{239}Pu	0.995 ± 0.014	126/71	4.0σ	127/72	4.0σ
HM + Equ	NA	89/72	1.7σ	NA	NA
SM2018 + Equ	NA	82/72	1.3σ	NA	NA

Solutions



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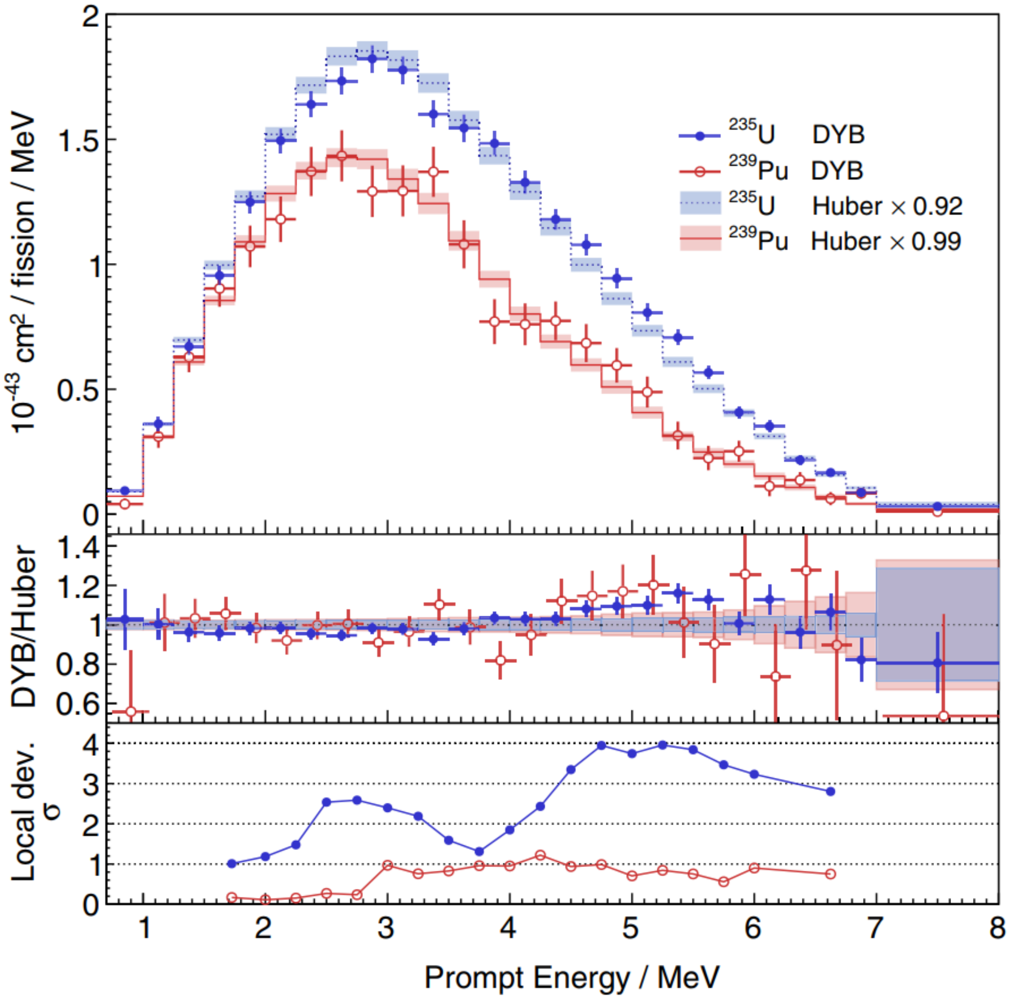
1. Fixing ^{235}U fission spectrum helps
2. Fixing ^{239}Pu fission spectrum: No (No matter what η is), unphysical
3. Changing the predicted ^{235}U, ^{238}U, ^{239}Pu, and ^{241}Pu in equal measure helps

^{235}U and ^{239}Pu Spectra Measurement



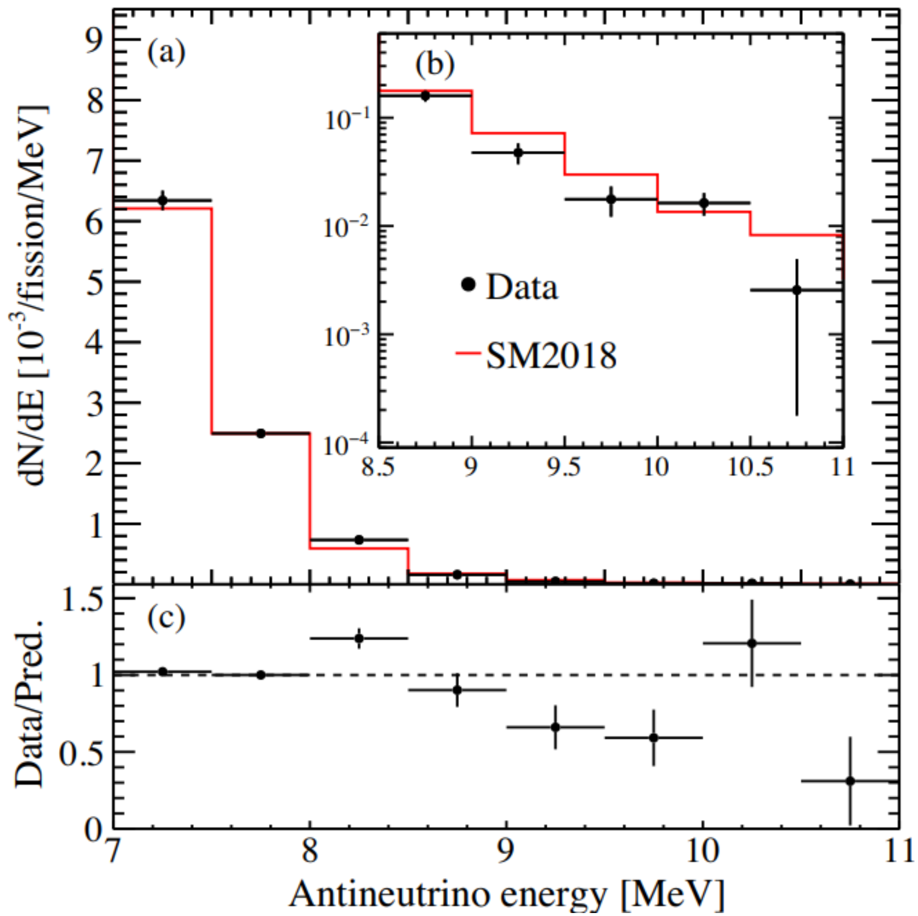
- First extraction of the ^{235}U spectrum from commercial reactors and the first measurement of the ^{239}Pu spectrum.
- In the 4~6 MeV energy range (bump), the ^{235}U and ^{239}Pu spectra might have a similar bump structure to the total spectrum.
- Joint Determination of Reactor Antineutrino Spectra by Daya Bay and PROSPECT,

Phys. Rev. Lett. 123 (2019) 111801 Phys. Rev. Lett. 128 (2022) 081801

High-Energy Reactor Antineutrinos

- High-energy reactor antineutrinos in the prompt energy region of 8–12 MeV observed over 1958 days of data collection.

- The hypothesis of no reactor antineutrinos with neutrino energy above 10 MeV is rejected with a significance of 6.2 standard deviations.



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Summary

- Precise $\sin^2 2\theta_{13}$ measurement with neutron capture on Gd and H
- One of the best measurements of $|\Delta m^2_{32}|$
- One of the best reactor neutrino flux measurement
- Reactor model comparision:
  HM: Flux and spectrum both in conflict with Daya Bay
  SM2018: Flux agrees with Daya Bay, but not the spectrum
- ^{235}U and ^{239}Pu spectra measurement, high energy neutrino measurement
- More in the future, for example, updated results on oscillation parameters with neutron captured on H samples

Thank you. Stay tuned.