Recent Results from Daya Bay

Ming-chung Chu
The Chinese University of Hong Kong, Hong Kong
On behalf of the Daya Bay Collaboration

Partial support: CUHK VC Discretionary Fund, RGC CUHK3/CRF/10R

The International Workshops on Weak Interactions and Neutrinos (WIN2023)
July 3 – 8, 2019, Zhuhai, China

Recent results from Daya Bay

- The Daya Bay Reactor Neutrino Experiment
- Measuring neutrino mixing parameters
- Absolute reactor antineutrino flux, spectrum, and fuel evolution

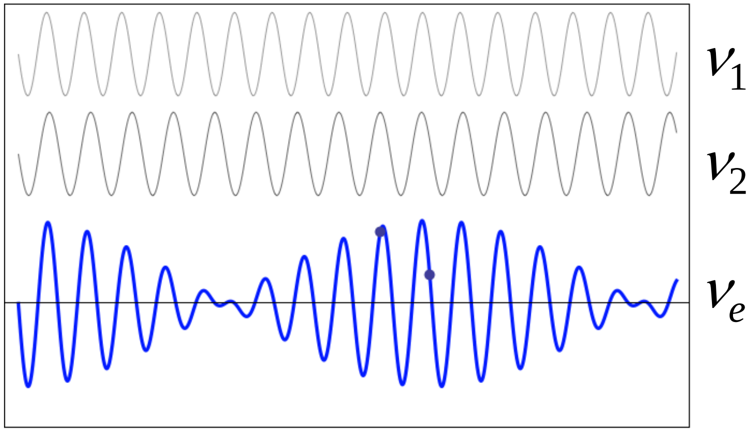
The Daya Bay Reactor Neutrino Experiment

F. P. An et al., Daya Bay Collaboration, NIM A **811**, 133 (2016);
PRD **95**, 072006 (2017).

Neutrino Oscillations

- Free particles: $E^2 = p^2 + m^2 \quad \lambda \propto 1/p$
- 1 ν_e with 1 E = mixture of 3 mass states → 3 p's → 3 λ's
- Interference of 3 wavelength components → beats = oscillation

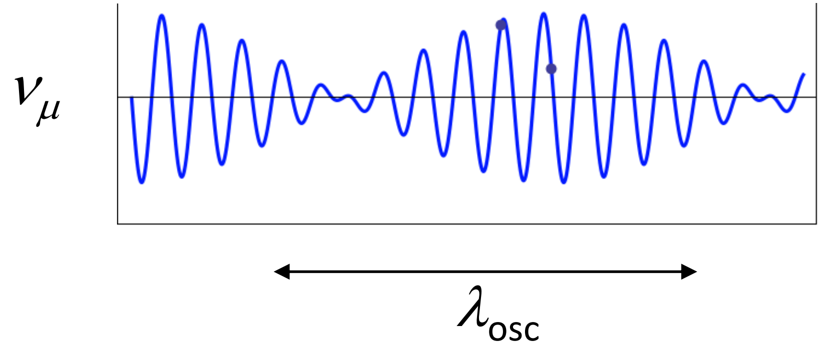
Eg. 2-state mixing:



$p \approx E(1 - m^2/2E^2)$ if $m << E$

$\therefore \Delta k \approx (m_2^2 - m_1^2)/4E$

$\lambda_{osc} = 4E/\Delta m_{21}^2$



$P_{ee} = |<\nu_e(t)|\nu_e(0)>|^2$
$= 1 - \sin^2 2\theta_{12} \sin^2(\pi L/\lambda_{osc})$
Survival probability $\quad L \approx t$

http://www.acs.psu.edu/drussell/Demos/superposition/superposition.html

Reactor expt.: a clean way to measure θ_{13}

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{ee} L}{4E_\nu} - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2 \frac{\Delta m^2_{21} L}{4E_\nu}$$

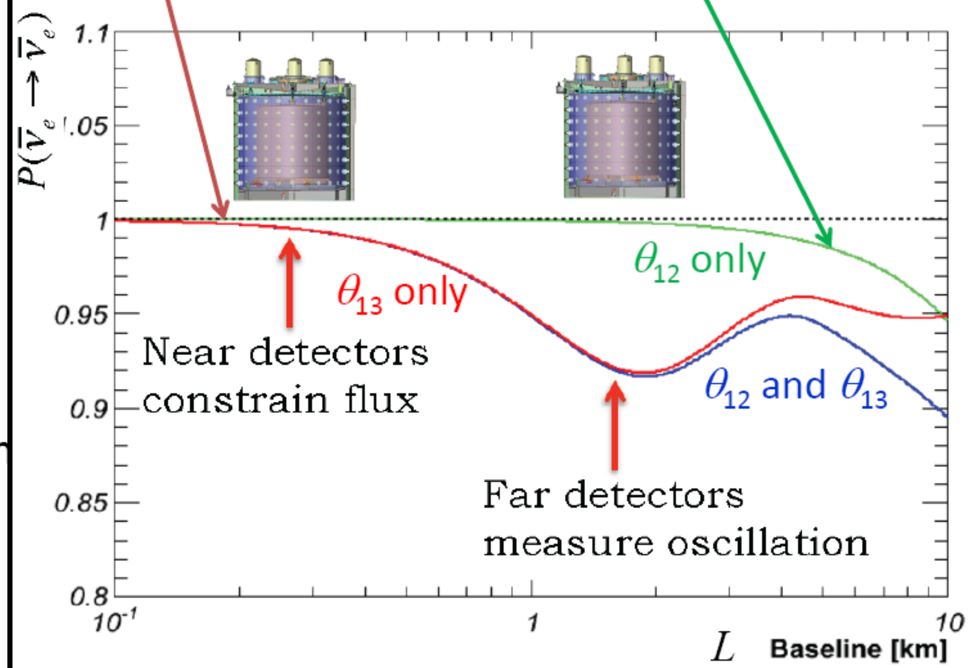
- Reactor: abundant, free, pure source of $\bar{\nu}_e$
- disappearance of $\bar{\nu}_e$ at small L depends only on θ_{13}

Near-far configuration

Near detectors: $\bar{\nu}_e$ flux and spectrum for normalization

Far detectors: near oscillation maximum for best sensitivity

Relative measurement: cancel out most systematics



Minimize systematics:
Reactor-related: near-far ratio
Detector-related: 'identical' detectors, careful calibration

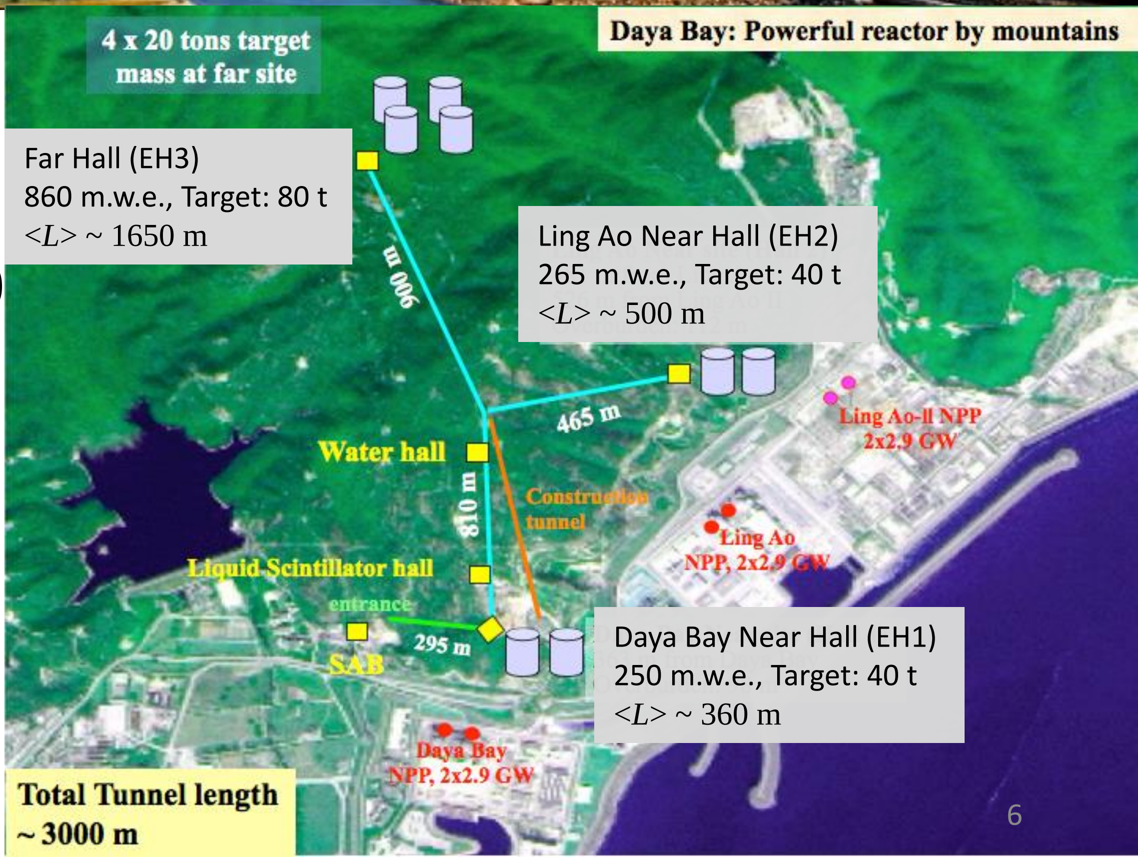
$$\frac{R_{\rm Far}}{R_{\rm Near}} = \left(\frac{L_{\rm Near}}{L_{\rm Far}}\right)^2 \frac{N_{\rm Far}}{N_{\rm Near}} \frac{\varepsilon_{\rm Far}}{\varepsilon_{\rm Near}} \left(\frac{P_{\rm surv}(L_{\rm Far})}{P_{\rm surv}(L_{\rm Near})}\right)$$

$\bar{\nu}_e$ detection ratio | $1/r^2$ | number of protons | detector efficiency | Survival prob. $\rightarrow \sin^2(2\theta_{13})$

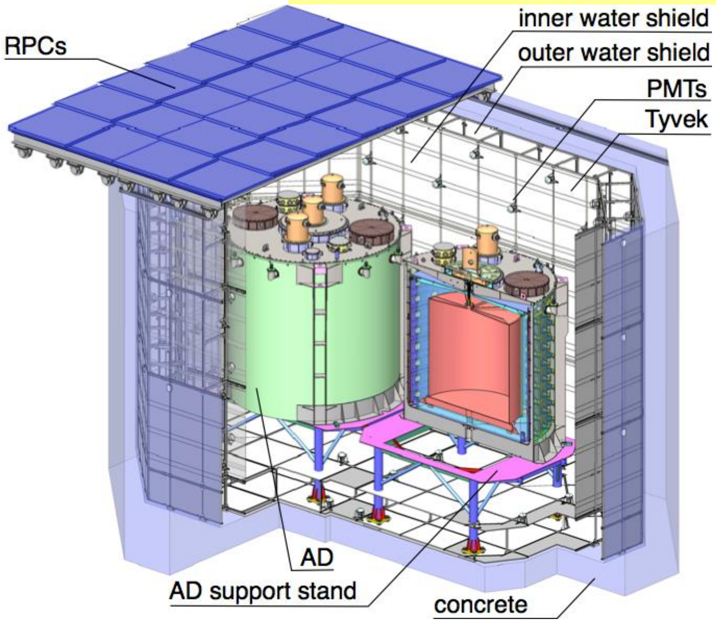
$\sin^2\Delta_{ee} = \cos^2\theta_{12} \sin^2\Delta_{31} + \sin^2\theta_{12} \sin^2\Delta_{32}$, $\Delta_{ji} \equiv \Delta m^2_{ji} L/4E$

Daya Bay Experiment

- Top five most powerful nuclear plants (17.4 GW_{th})
→ large number of $\bar{\nu}_e$ ($3x10^{21}/s$)
- Adjacent mountains shield cosmic rays



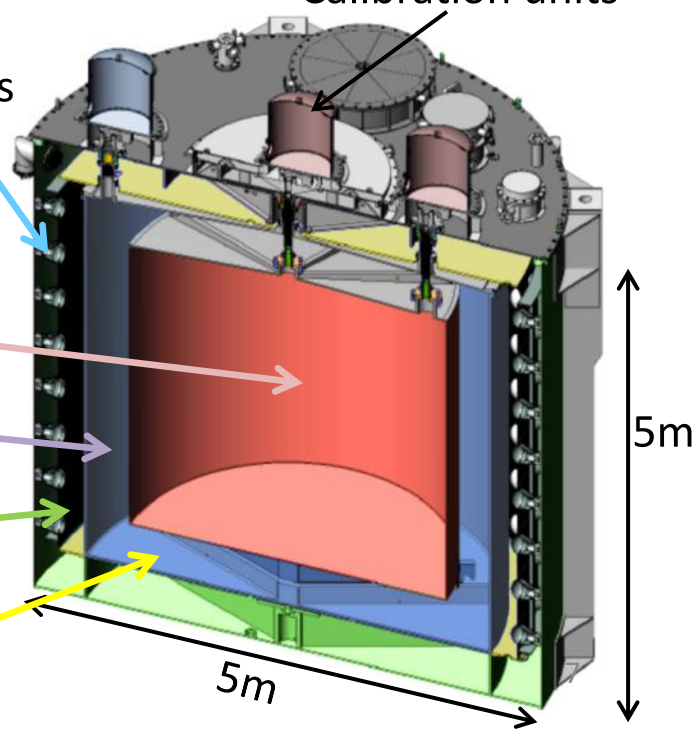
Daya Bay detectors



RPC : muon veto
Water pool: muon veto + shielding from environmental radiations (2.5m water)

8 functionally identical anti-neutrino detectors (AD) to suppress systematic uncertainties

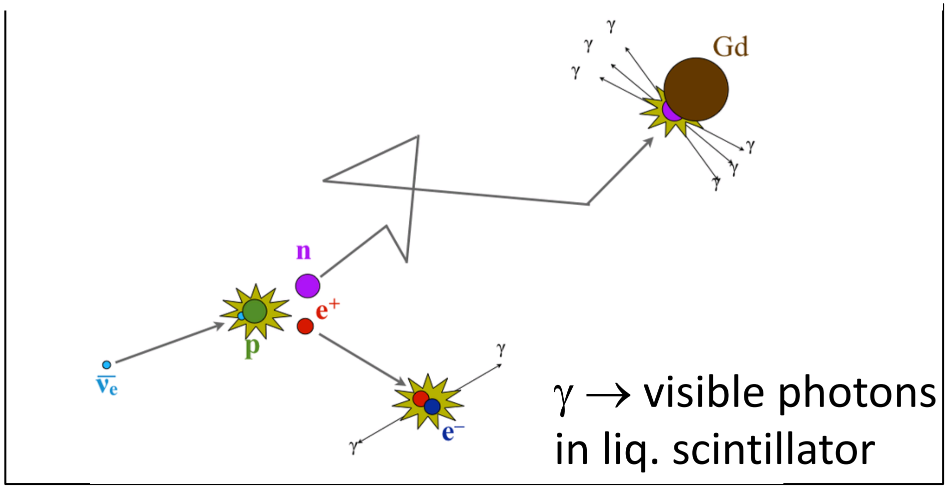
3 zone cylindrical vessels			
	Liquid	Mass	Function
Inner acrylic	Gd-doped liquid scint.	20 t	Antineutrino target
Outer acrylic	Liquid scintillator	20 t	Gamma catcher
Stainless steel	Mineral oil	40 t	Radiation shielding



Top and bottom reflectors: more light, more uniform detector response

Antineutrino detection

$\overline{\nu}_e$ detected via inverse beta-decay (IBD):



$\overline{\nu}_e + p \rightarrow e^+ + n$ (prompt signal)

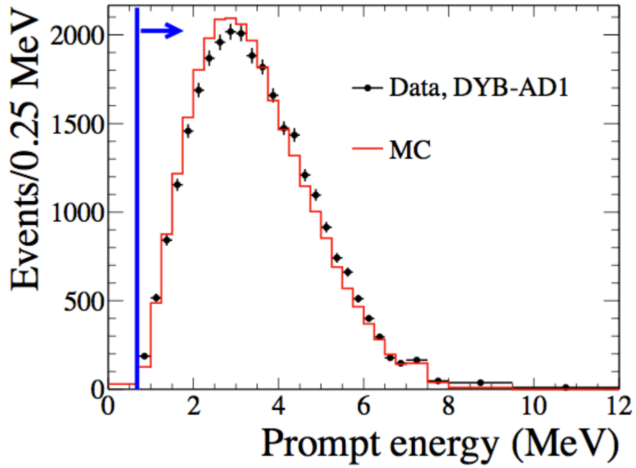
- ~180μs → + p → D + γ (2.2 MeV)
- → + Gd → Gd* (~30μs for 0.1% Gd)
  - → Gd + γ's (8 MeV)

(delayed signal)

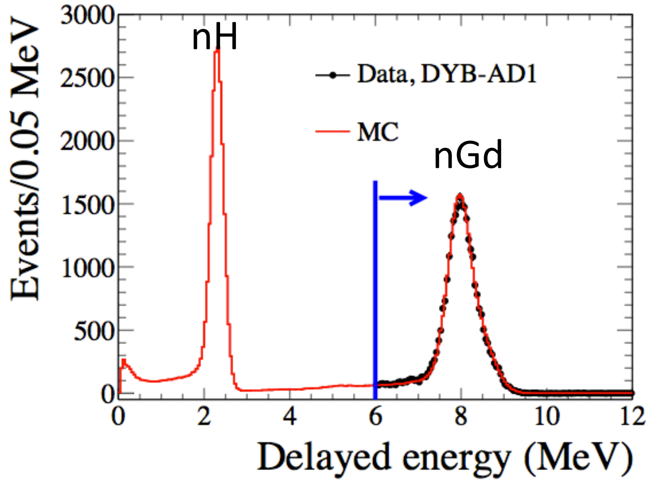
Powerful background rejection!

$$E_\nu \approx T_{e+} + 1.8\ \text{MeV} = E_{prompt} + 0.78\ \text{MeV}$$

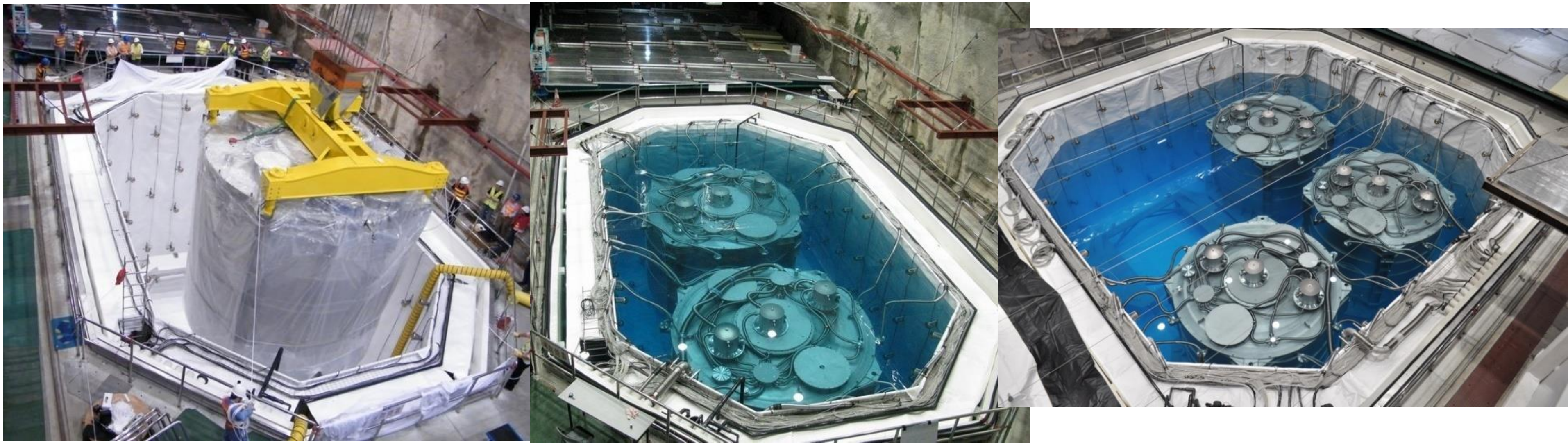
Prompt Signal



Delayed Signal



Operation history



3 Physics runs:
6-AD: 217 days (12/11 – 07/12)
8-AD: 1524 days (10/12 - 12/16)
7-AD: 1417 days (01/17 - 12/20)
~ 2700 days of data (good run list)

Statistics of nGd data:

Year	Calendar days	EH1	EH2	EH3	Total IBD's
2018 (PRL 121, 241805)	1958	1,794,417	1,673,907	495,421	3,963,745
2022	3158	2,236,810	2,544,894	764,414	5,546,118

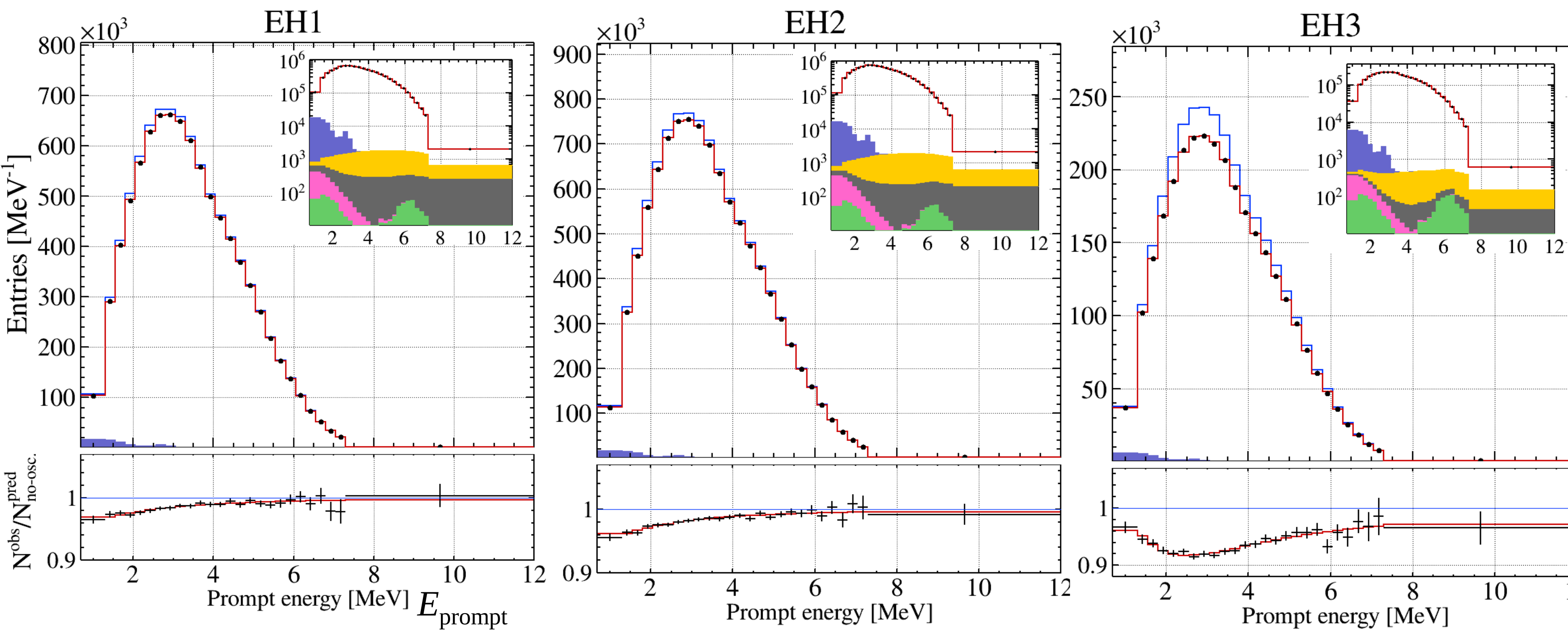
The Daya Bay Collaboration

About 200 members, 41 institutions from Chile, China, Czech Republic, Hong Kong, Russia, Taiwan, and USA

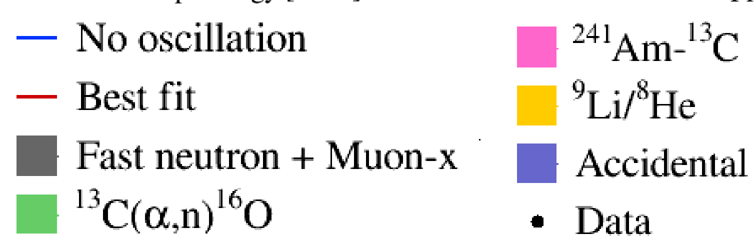
Prompt energy spectra

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2(\Delta m_{ee}^2 L/4E_\nu) - \sin^2 2\theta_{12} \cos^4\theta_{13} \sin^2(\Delta m_{21}^2 L/4E_\nu)$$

Daya Bay Collaboration, PRL **130**, 161802 (2023).



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

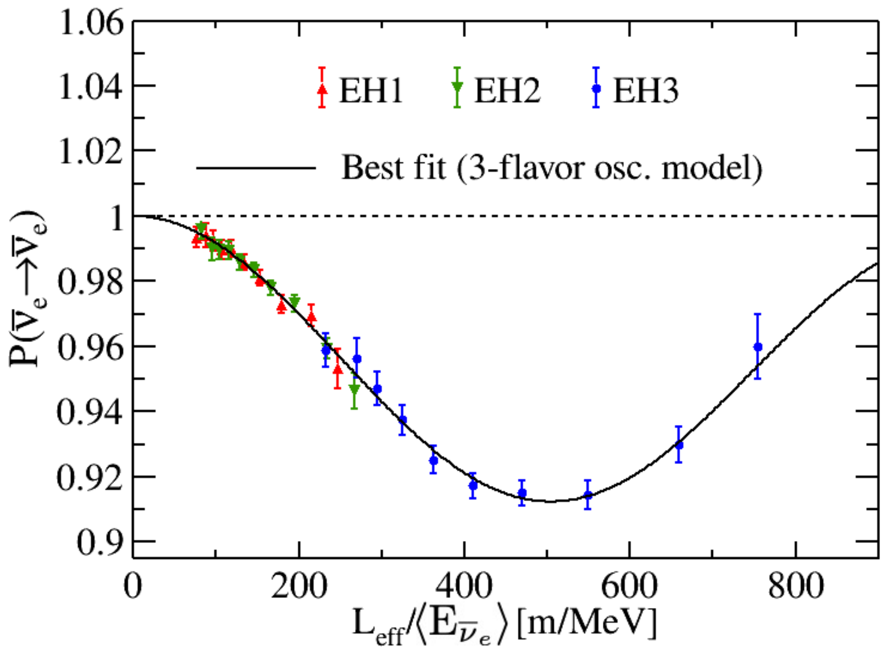


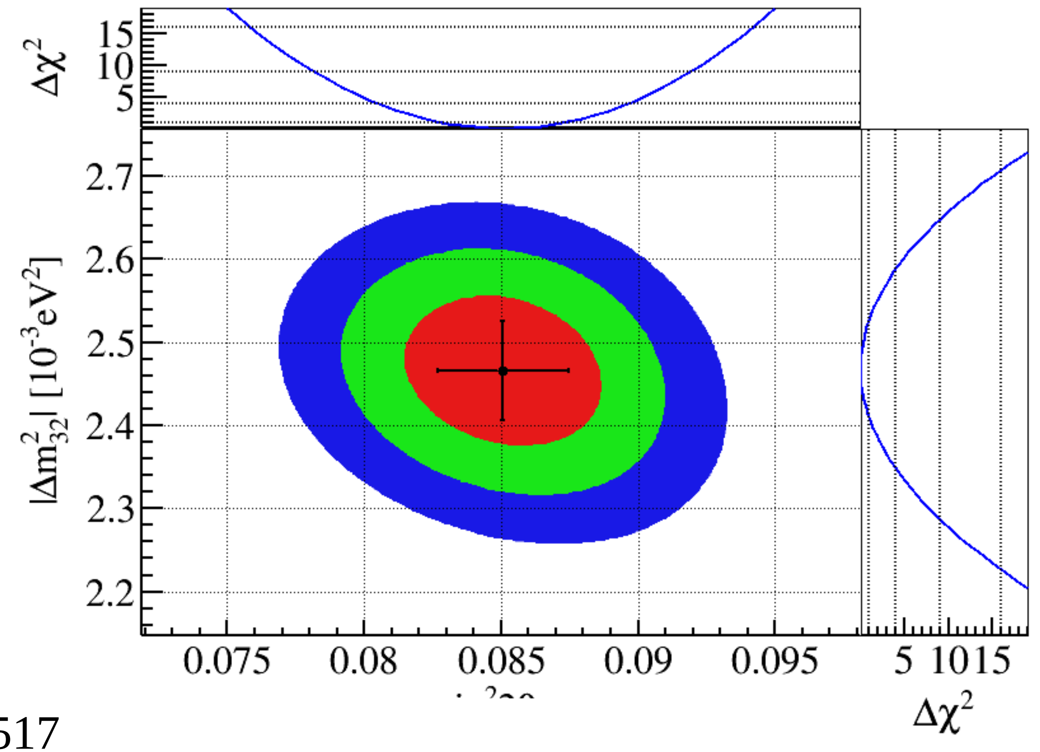
$$\sin^2\Delta_{ee} = \cos^2\theta_{12} \sin^2\Delta_{31} + \sin^2\theta_{12} \sin^2\Delta_{32}, \quad \Delta_{ji} \equiv \Delta m^2_{ji} L/4E$$

Oscillation results

PRL **130**, 161802 (2023).

- Oscillation parameters measured with rate + spectral distortion
- Both consistent with neutrino oscillation interpretation





Best-fit results: χ^2/ndf = 559/517

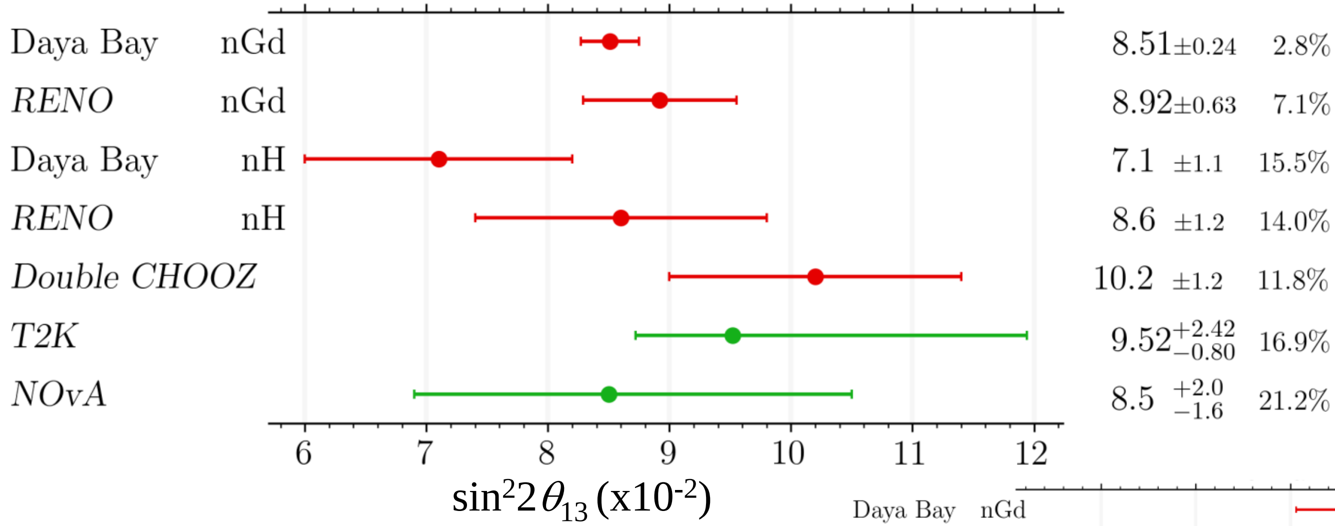
$\sin^2 2\theta_{13} = 0.0851^{+0.0024}_{-0.0024}$ (2.8% precision)

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

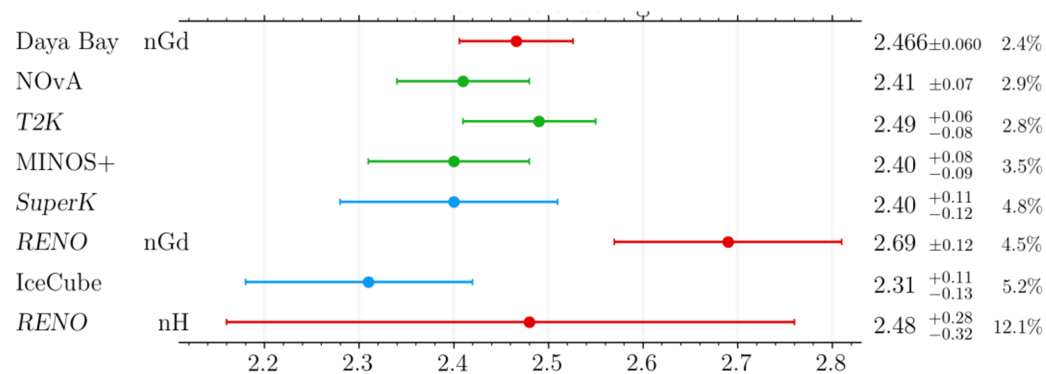
Inverted hierarchy: $\Delta m^2_{32} = -\left(2.571^{+0.060}_{-0.060}\right) \times 10^{-3}\mathrm{eV}^2$ (2.3% precision)

Oscillation results

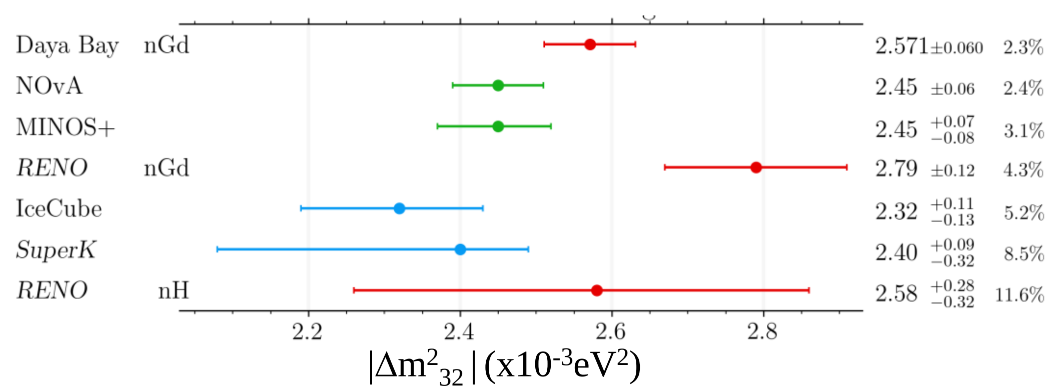
PRL **130**, 161802 (2023).



Normal mass ordering



Inverted mass ordering



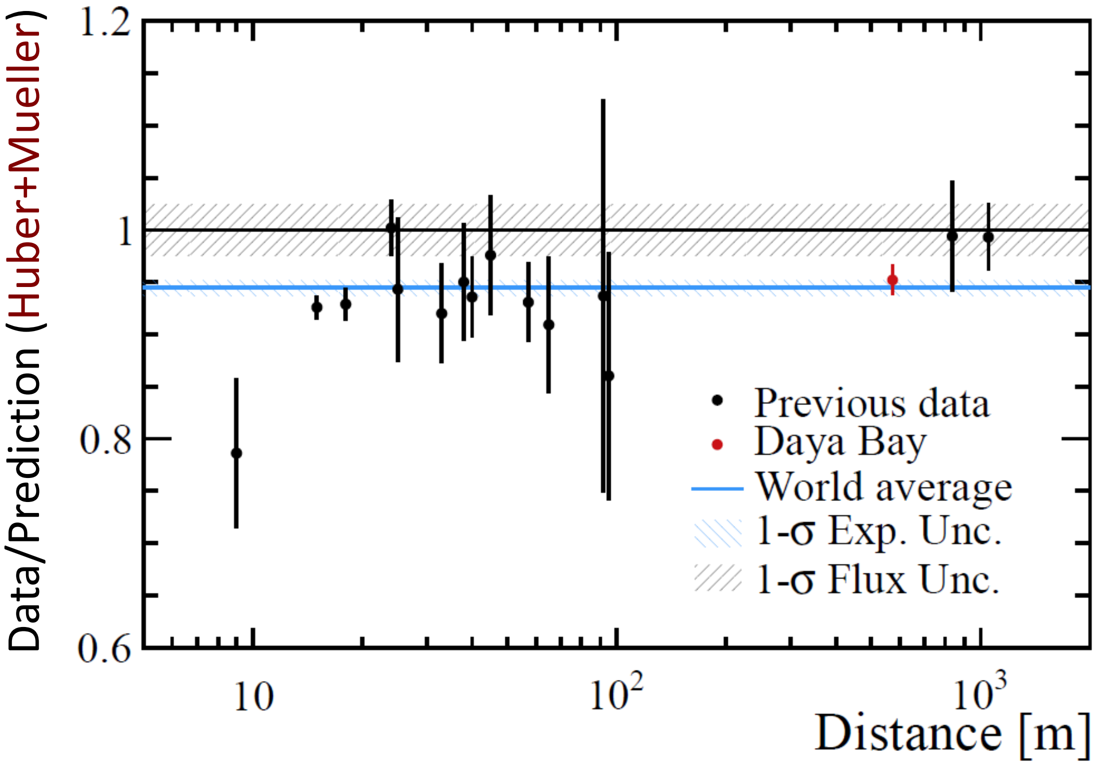
Absolute reactor antineutrino flux, spectrum, and fuel evolution

F. P. An et al., Daya Bay Collaboration, PRL **116**, 061801 (2016); Chinese Physics C **41**, 13002 (2017); PRL **118**, 251801 (2017); PRD **100**, 052004 (2019); PRL **128**, 081801 (2022); PRL **130**, 211801 (2023).

Reactor antineutrino flux

PRL **130**, 211801 (2023); PRD **100**, 052004 (2019); Chin. Phys. C **45**, 073001 (2021).

- Precise measurement of reactor antineutrino flux using 3.5 M inverse beta decay (IBD) events collected with the Daya Bay near detectors in 1958 days
- IBD yield = (5.89±0.07)x 10^{-43} cm^2/fission, consistent with Summation method (SM2018), but rejects Huber-Mueller model (HM) prediction by 3.6 σ



Mean fission fractions:

^{235}U	^{238}U	^{239}Pu	^{241}Pu
0.564	0.076	0.304	0.056

Reactor antineutrino flux evolution

Effective fission fraction for i^{th} isotope changes in time as fuel evolves:

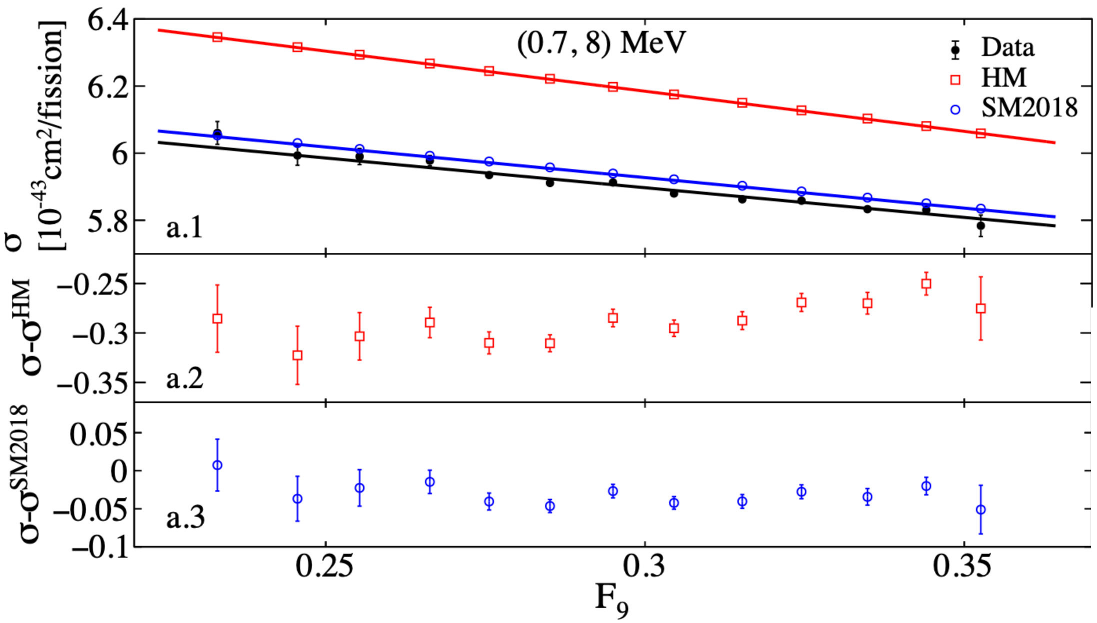
$$F_i(t) = \sum_{r=1}^{6} \frac{W_{\text{th},r}(t)\overline{p}_r f_{i,r}(t)}{L_r^2 \overline{E}_r(t)} \Big/ \sum_{r=1}^{6} \frac{W_{\text{th},r}(t)\overline{p}_r}{L_r^2 \overline{E}_r(t)}$$

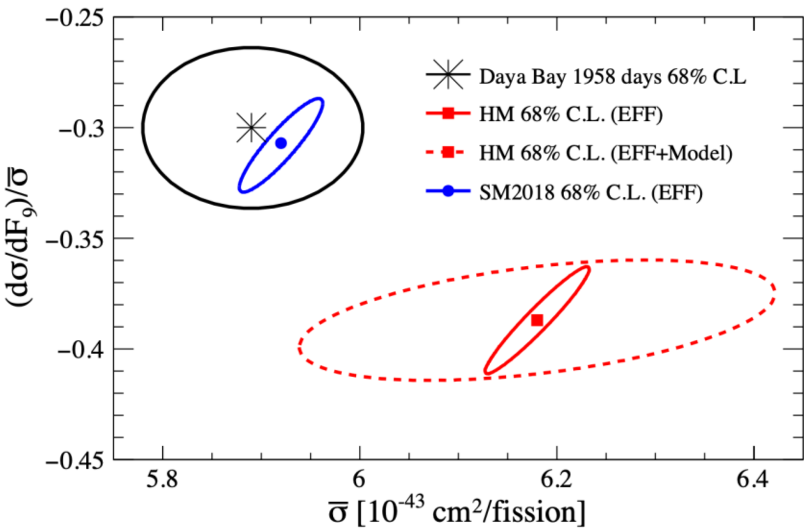
$f_{i,r}(t)$ (fission fraction for i^{th} isotope in reactor r) and $W_{\text{th},r}(t)$ (thermal power) obtained from reactor data, validated with MC.

$\overline{p_r}$ = survival probability

L_r = baseline

$\overline{E_r}$ = average energy per fission





$\sigma(t) = \Sigma_i\ \sigma_i F_i(t)$ also evolves

IBD yield $\quad$ i^{th} isotope

Flux evolution: agrees with SM2018, disagrees with Hubert-Mueller

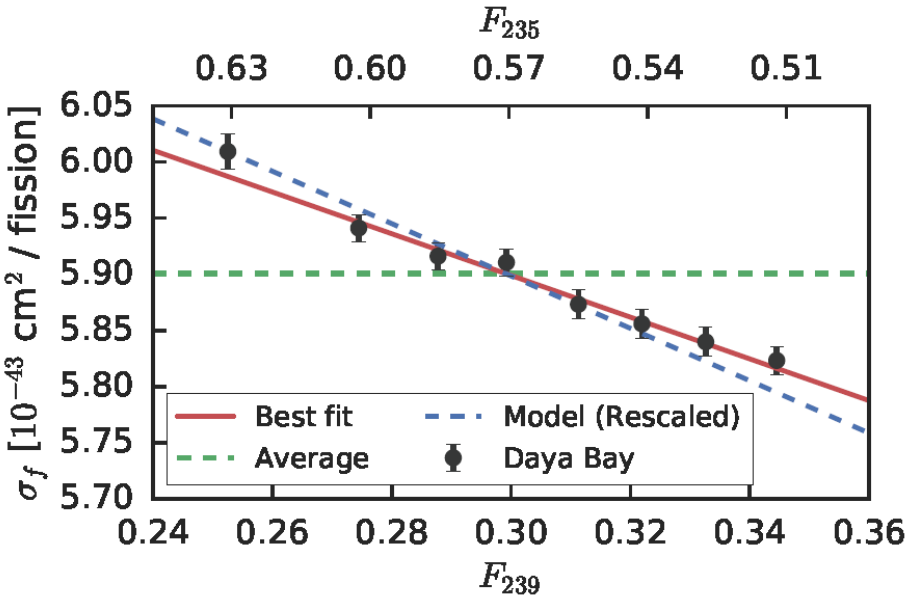
PRL **130**, 211801 (2023); PRL **118**, 251801 (2017).

Reactor antineutrino flux evolution

PRL **118**, 251801 (2017).

$\sigma_f(t) = \Sigma_i \ \sigma_i F_i(t)$ also evolves

IBD yield i^{th} isotope

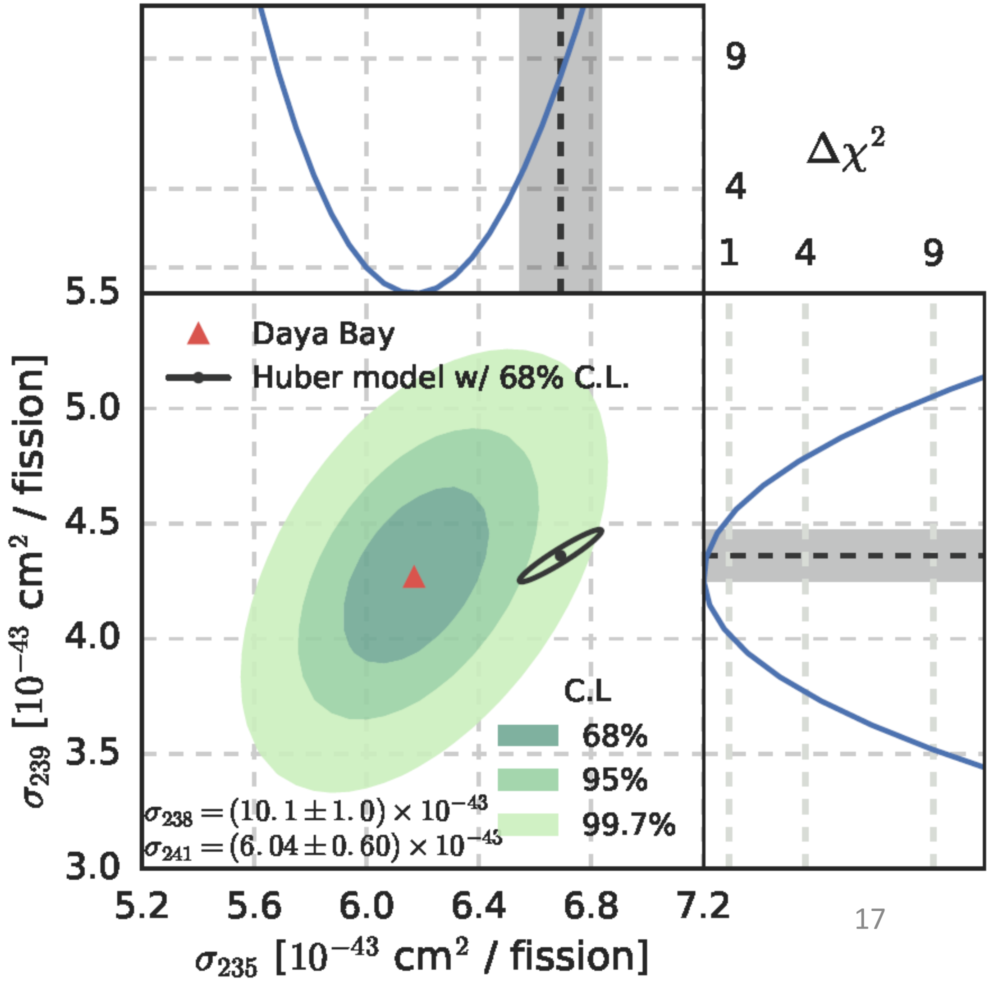


Slope differs from HM by 3.1σ

Sterile ν only ⇒ same fractional flux deficit for all isotopes: $(d\sigma_f/dF_{239})/\langle\sigma_f\rangle$ = theory incompatible with data at 2.6σ

Best fit of $\sigma_f(t) = \Sigma_i \ \sigma_i F_i(t)$ to get σ_i

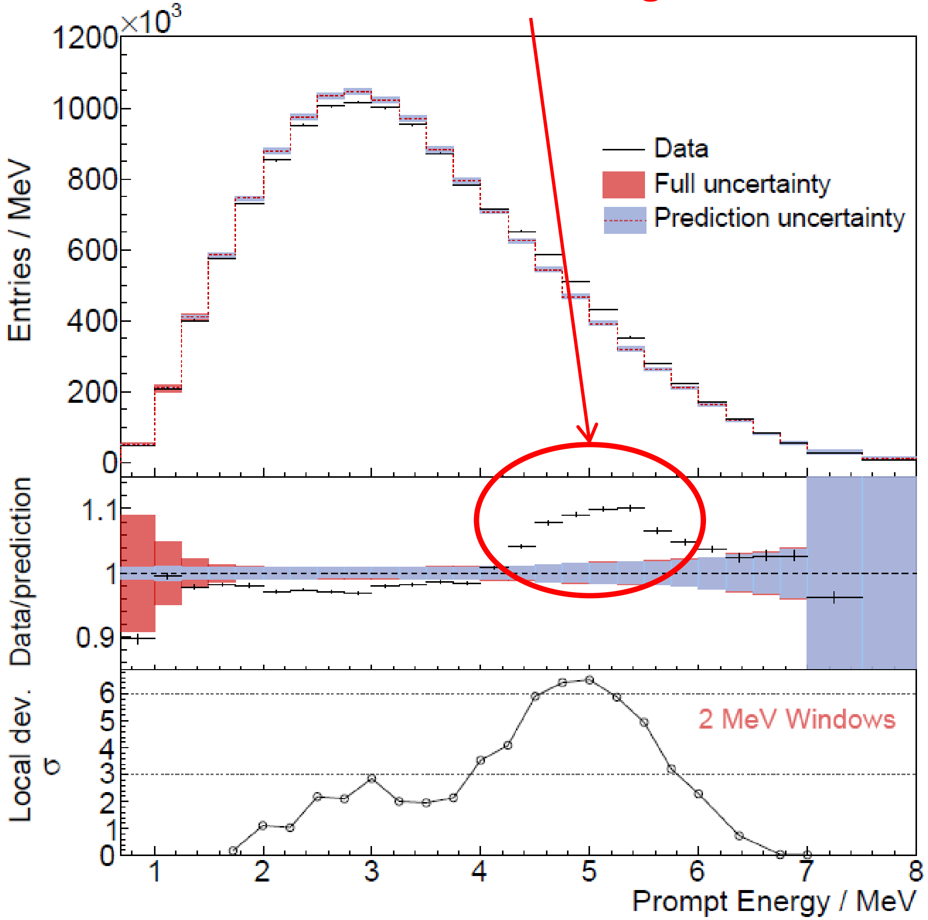
Favors: overestimation of ^{235}U yield



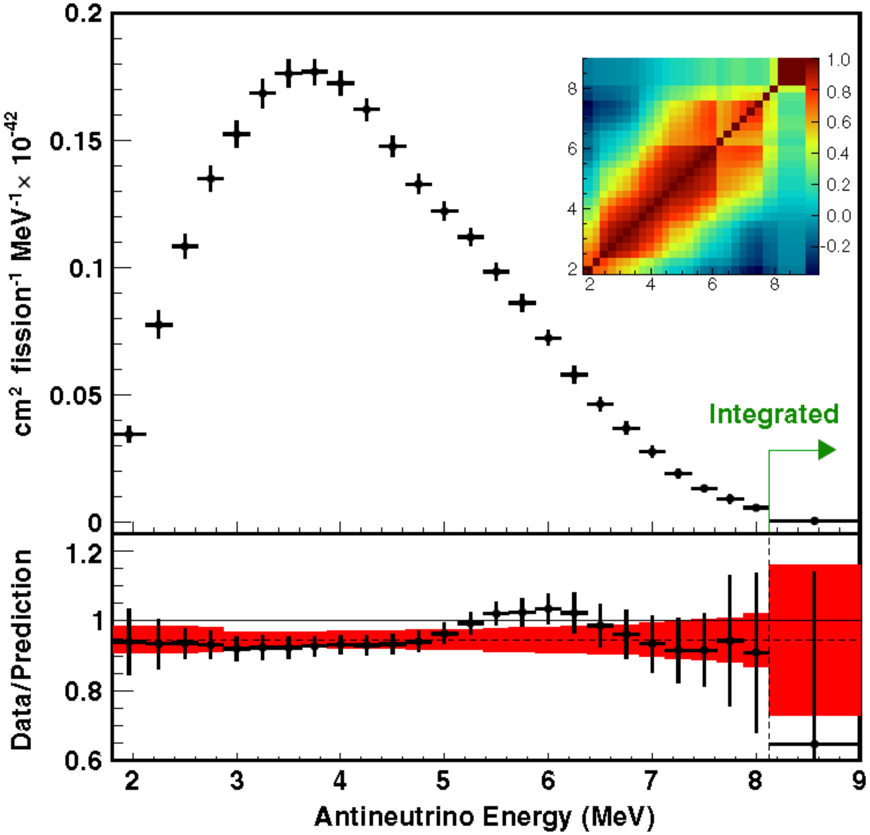
Reactor antineutrino spectrum

PRD **100**, 052004 (2019)

- 1958 days of data, 3.5M IBD events
- Measured prompt spectrum vs. Huber+Mueller:
- Global discrepancy at 5.3 σ
- Local deviation in 4-6 MeV region: 6.3 σ

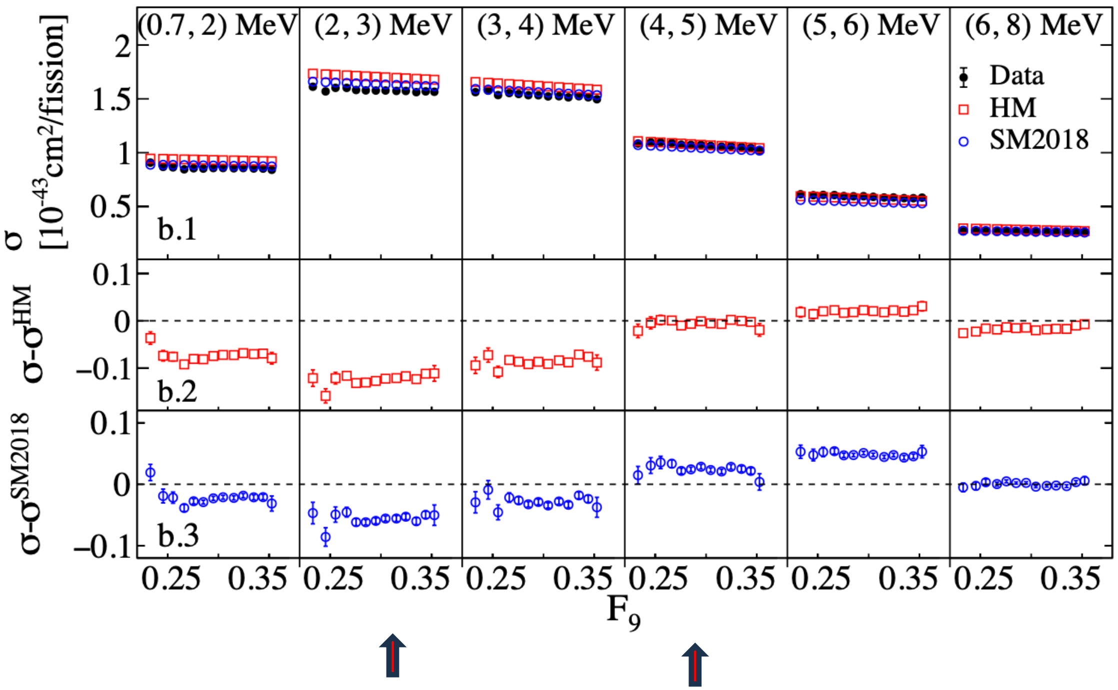


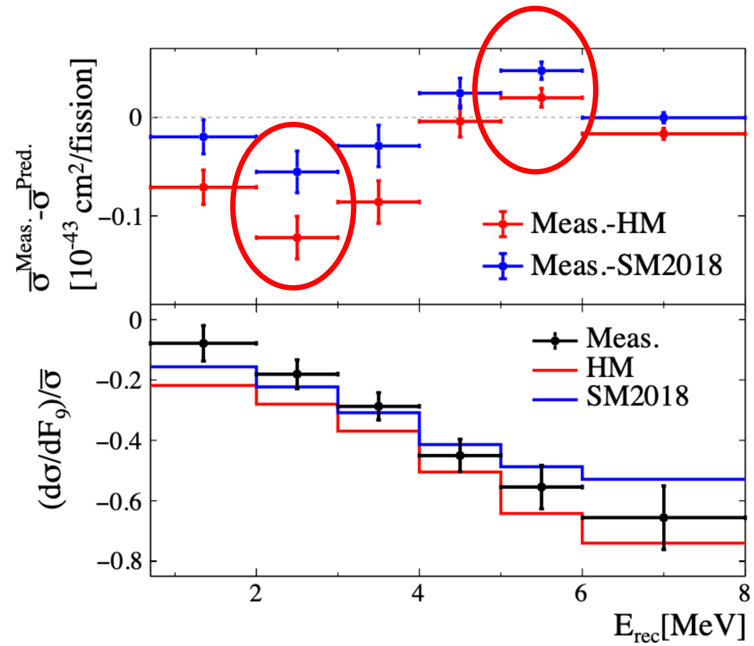
Extracted a generic observable reactor antineutrino spectrum by removing the detector response



Reactor antineutrino spectrum evolution

PRL **130**, 211801 (2023); PRL **118**, 251801 (2017).

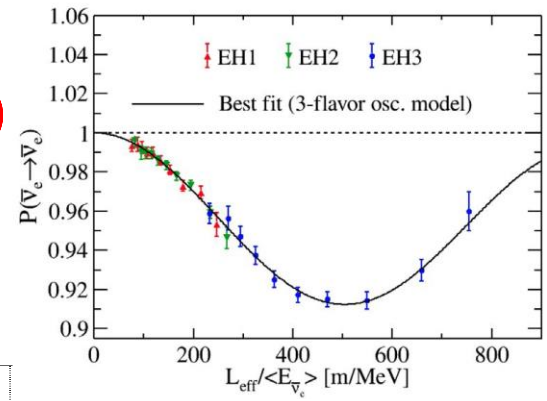


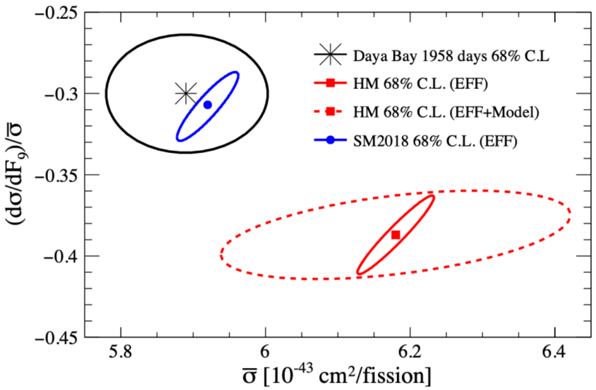


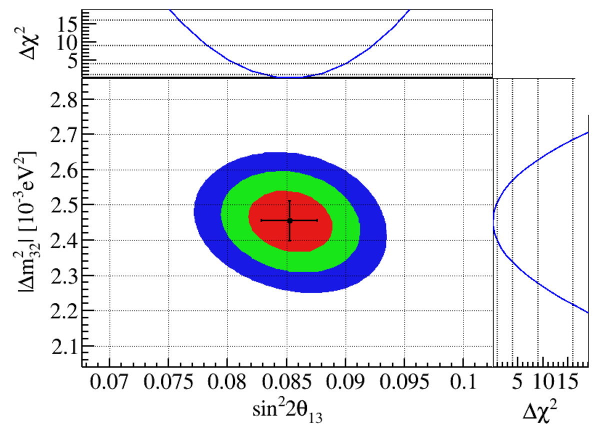
- Both SM2018 and HM have large disagreement with data particularly at ~ 3 MeV and 5 MeV → 27 (25) σ
- Both SM2018 and HM show much better agreement with data for normalized evolution slope $(d\sigma/dF_9)/\bar{\sigma}$: 0.7 (1.8) σ

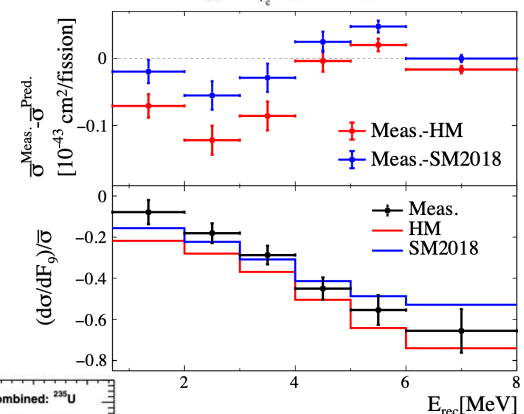
Summary

- Daya Bay Neutrino Oscillation Measurement:
  - Largest sample of reactor antineutrinos to date (5.5M nGd IBD)
  - $\sin^2 2\theta_{13} = 0.0851 \pm 0.0024$ (2.8% precision)
  - $\Delta m^2_{32} = 2.466\ (-2.571) \pm 0.060 \times 10^{-3}\ \mathrm{eV}^2$ (2.3% precision)

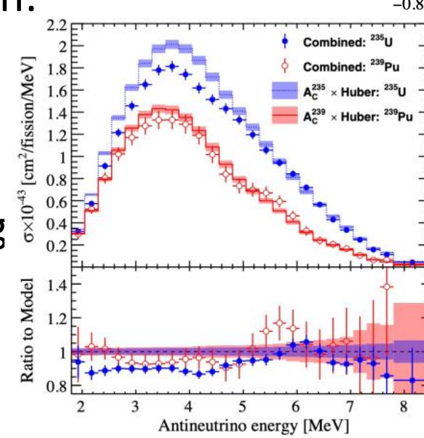


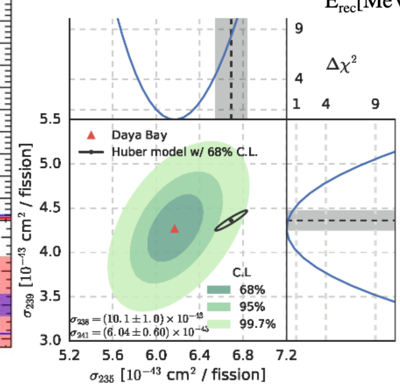






- Reactor antineutrino flux, spectrum and evolution:
  - **Flux and evolution**: SM2018 ok, not with HM
  - **Prompt Spectrum**: ^{235}U and ^{239}Pu spectra extracted, similar excess in [4, 6] MeV
  - **Spectrum evolution**: SM2018, HM both wrong
  - Favors σ_{235} wrong





- Much more to come!

Recent Results from Daya Bay

Ming-chung Chu
The Chinese University of Hong Kong, Hong Kong
On behalf of the Daya Bay Collaboration

Thank you!

Partial support: CUHK VC Discretionary Fund, RGC CUHK3/CRF/10R

The International Workshops on Weak Interactions and Neutrinos (WIN2023)
July 3 – 8, 2019, Zhuhai, China

backup

Neutrino Oscillations

- Each flavor state is a mixture of mass eigenstates
- Described by a neutrino mixing matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}$$

The Maki-Nakagawa-Sakata-Pontecorvo Matrix

- A freely propagating ν_e will oscillate into other types

$P_{ee} = |<\nu_e(t)|\nu_e(0)>|^2$ Survival probability for ν_e

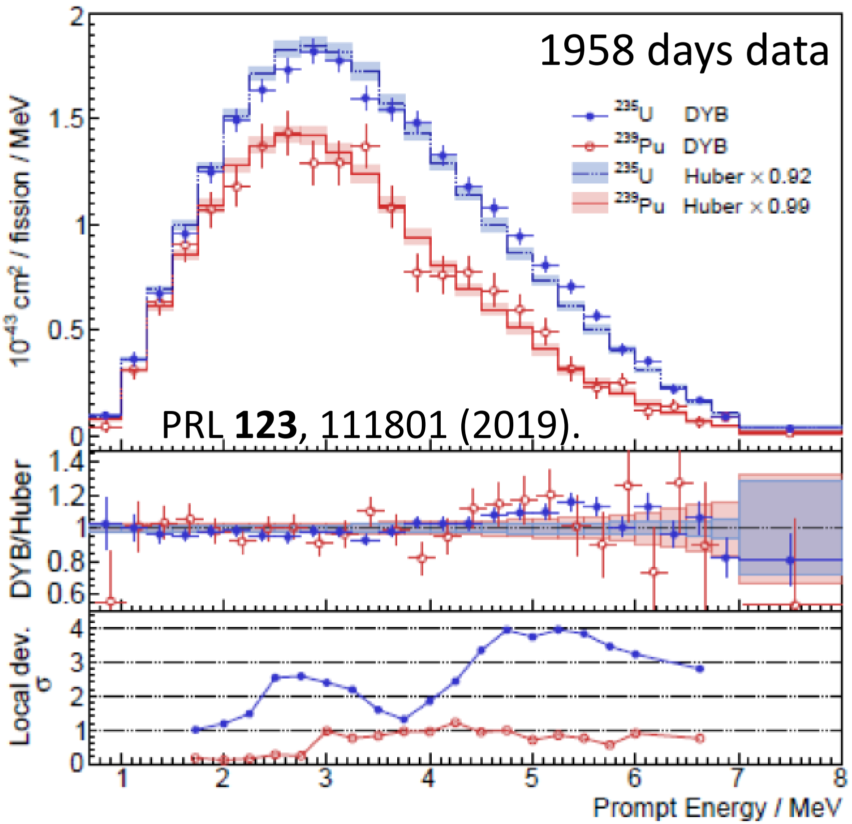
$$= 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} - \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32})$$

$$\simeq 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} - \sin^2 2\theta_{13}\sin^2\Delta_{ee}$$ for Daya Bay

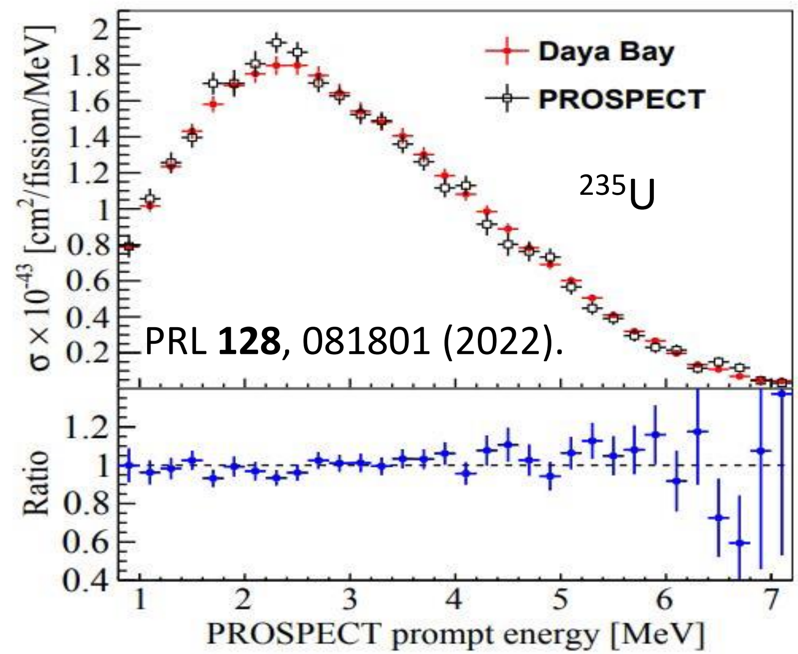
$$\sin^2\Delta_{ee} = \cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32},\ \ \Delta_{ji} \equiv \Delta m^2_{ji}L/4E,\ \ \Delta m^2_{ji} \equiv m_j^2 - m_i^2$$

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

Fuel evolution allows to extract ^{235}U and ^{239}Pu spectra



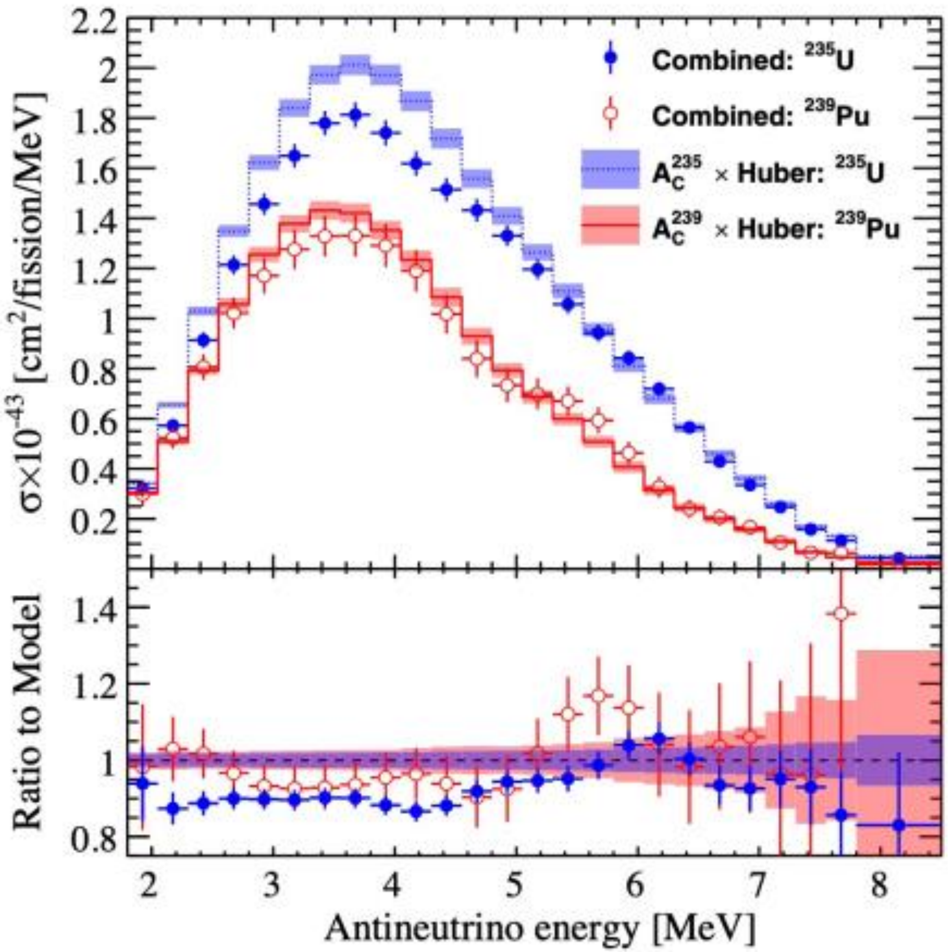
Joint analysis with PROSPECT



Daya Bay ^{235}U spectrum agrees well with PROSPECT (pure ^{235}U)

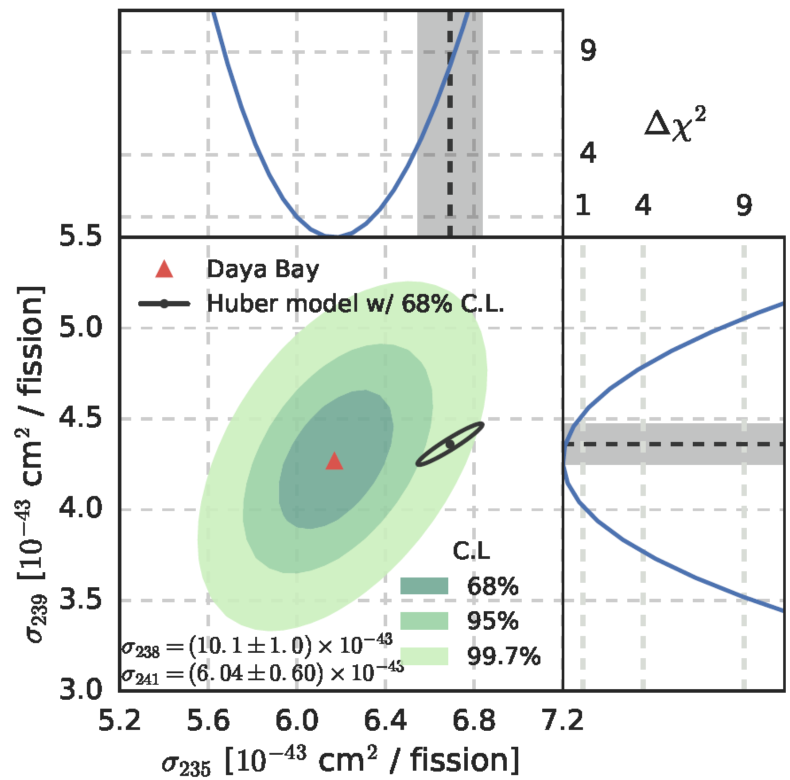
^{235}U and ^{239}Pu Spectra

PRL **128**, 081801 (2022).



Use PROSPECT prompt-energy spectrum as constraint in Daya Bay's fit to extract ^{235}U and ^{239}Pu spectra

PRL **118**, 251801 (2017).



Compare spectra, yield with HM:

- Reasonable agreement for ^{239}Pu
- Significant deviation for ^{235}U