Reactor Antineutrino Flux and Spectrum Measurement at Daya Bay and Study of its High-Energy Component

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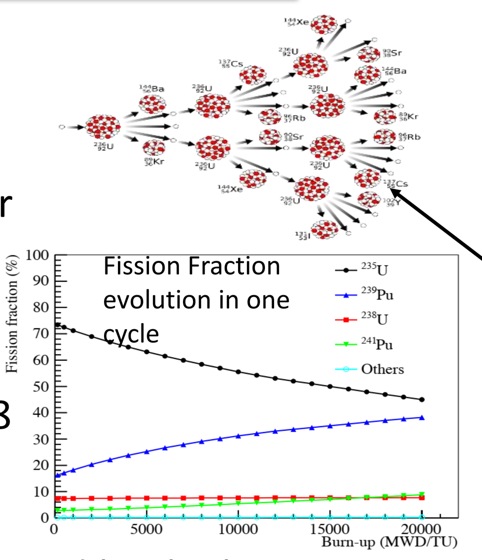
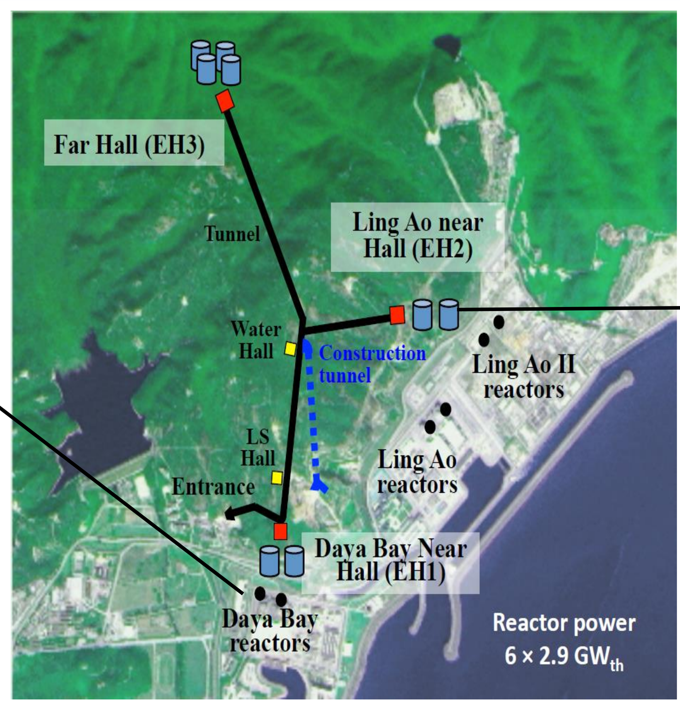
On behalf of the Daya Bay Collaboration

Daya Bay experiment

- **Six commercial reactors**
  - Pressurized-Water reactor
  - Thermal power of each reactor is 2.9 GW
  - The neutrino produce is ~$3.5\times10^{21}\ \bar{\nu}_e$/s.
  - Replace 1/3 (1/4) fuel every 18 (12) months

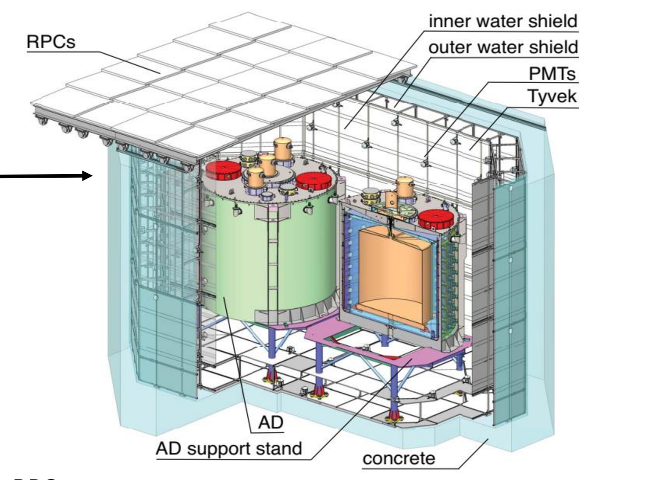




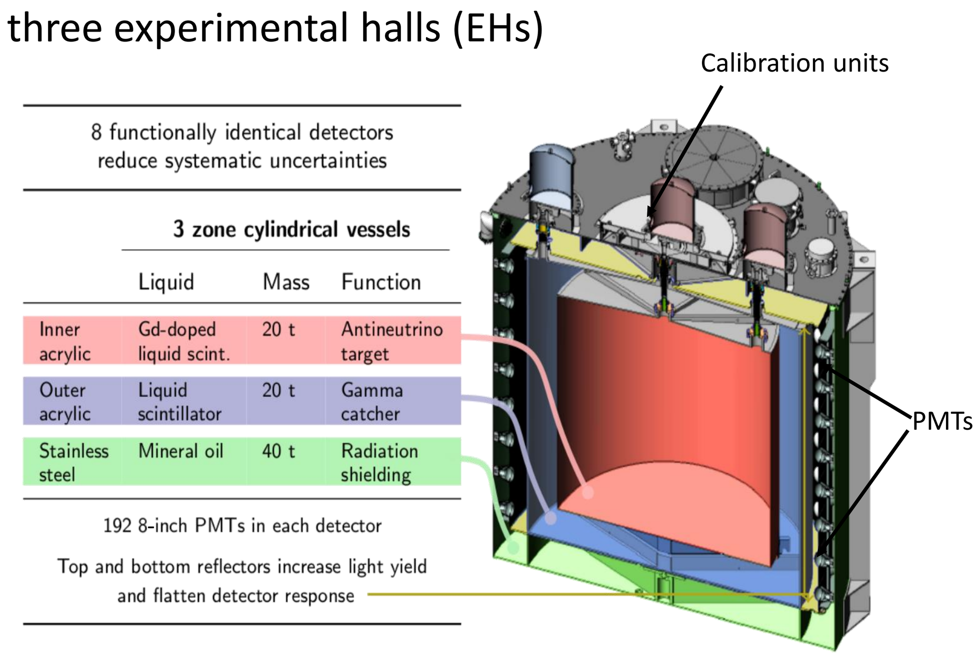
- Antineutrinos are mainly produced by the beta decay of fission products of ^{235}U, ^{239}Pu, ^{238}U, ^{241}Pu.
- The average fission fraction of ^{235}U, ^{239}Pu, ^{238}U, ^{241}Pu is :

Isotope	U235	U238	Pu239	Pu241
Fission fraction	0.564	0.076	0.304	0.056

- Eight antineutrino detectors (ADs) in three experimental halls (EHs)

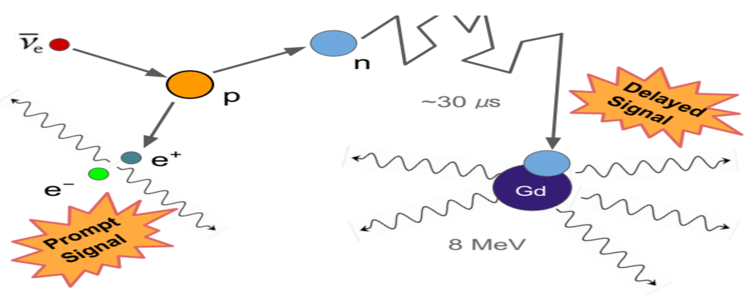


RPC: muon veto
Water pool: muon veto + shielding from environmental radiations (2.5m water)

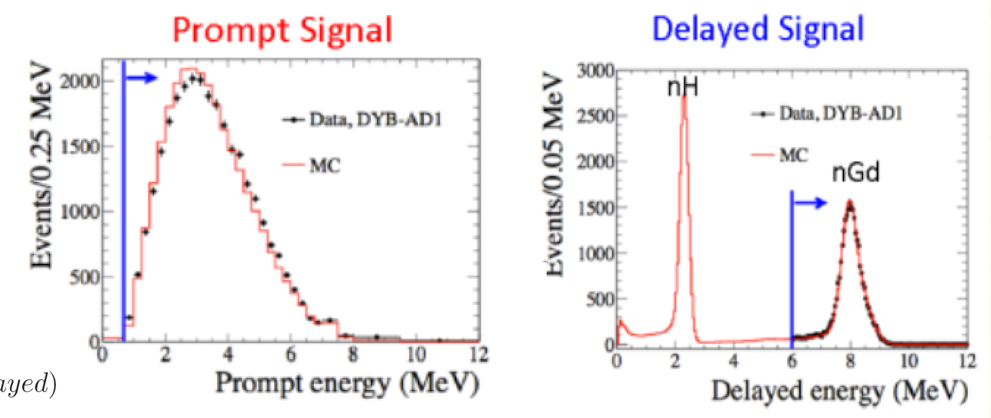


The most precise measurement of θ_{13} with 8 identically designed antineutrino detectors

- Antineutrinos are detected via inverse beta decay process:



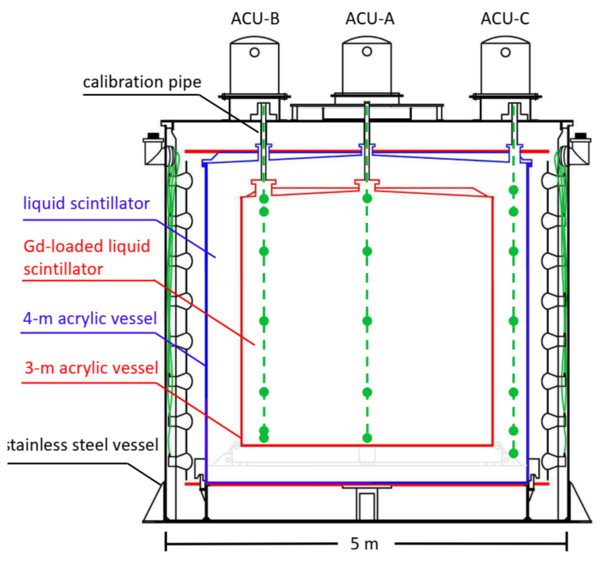
$$\bar{\nu}_e + p \to e^+ + n \ \ (prompt)$$
$$\hookrightarrow + p \to D + \gamma \ \ (2.2\ MeV\ delayed)$$
$$\hookrightarrow + Gd \to Gd^*$$
$$\hookrightarrow Gd + \gamma' s \ \ (8\ MeV\ delayed)$$



Powerful background rejection ! (BG <2% of antineutrino signals)

Neutron Detection Efficiency Improvement[1]

- The dominant uncertainty in the neutron detection efficiency is reduced by 56%.



Comprehensive neutron calibration and simulation analysis.

- Measurements taken with strong Am-C and Am-Be neutron sources.
- Automated Calibration Units (ACUs) deploy sources at different AD heights along three different along three different axes (19 locations total) .
- Benchmarked different neutron capture/scattering models with these measurement.

$$F = \frac{N([6,12]\ \text{MeV})}{N([1.5,12]\ \text{MeV})}$$ N([x,y]) MeV ≡ No. of events of in [x,y] MeV

$$\chi^2 = (F_{\text{data}} - F_{\text{MC}})^T \cdot V^{-1} \cdot (F_{\text{data}} - F_{\text{MC}})$$

- IBD neutron detection efficiency ε_n and χ^2 with 59 calibration points for 5 neutrino scattering model combinations (a-e)×4 gamma models (1-4):

ε_n, χ^2	1. Geant4 native	2. Geant4 Phot. Eva.	3. Nuclear Data Sheets	4. Caltech
a. water, free gas	82.23%, 76.0	82.35%, 86.4	80.56%, 316	82.55%, 156
b. water, poly	81.75%, 52.1	81.93%, 85.1	80.42%, 350	82.43%, 119
c. poly, poly	81.61%, 56.6	82.00%, 63.9	79.96%, 389	82.00%, 96.9
d. poly, free gas	82.01%, 57.7	82.28%, 79.9	80.28%, 371	82.36%, 115
e. free gas, free gas	84.76%, 1183	84.65%, 1273	82.70%, 576	85.37%, 1569

- Efficiency is estimated with the best fitting models and consider a shift from all ε_n.
- The uncertainty is determined from the spread between models.

	Previous		This work	
	Value	Rel. Error	Value	Rel. Error
ε_n	81.83%	1.69%	81.48%	0.74%
$\varepsilon_{\text{other}}$	98.49%	0.16%	98.49%	0.16%

Antineutrino yield[1][2]

- Measured IBD yield:

$$N_{\text{IBD}}(1 - c^{\text{SNF}}) = \sigma_f \sum_{d=1}^{4} \sum_{r=1}^{6} \frac{N_d^P \varepsilon_{\text{IBD}} P_{sur}^{rd} N_r^f}{4\pi L_{rd}^2}$$

Sum over 4 detectors and 6 reactors; Detection efficiency $\varepsilon_n \times \varepsilon_{other}$; Survival probability; Number of fission; IBD yield per nuclear fission; Number of protons; Distance to detector

- Predicted IBD yield:

$$\sigma_f = \sum_{iso=1}^{4} f_{iso} \int (S_{iso}(E_\nu) + k_{iso}^{\text{NE}}(E_\nu))\sigma_{\text{IBD}}(E_\nu)\text{d}E_\nu$$

Huber-Mueller model; Non-equilibrium effect; Average fission fraction; IBD cross-section

source	Previous value	Previous rel. err.	This work value	This work rel. err.
statistic	-	0.1%	-	0.1%
oscillation	-	0.1%	-	0.1%
target proton	-	0.92%	-	0.92%
reactor				
power	-	0.5%	-	0.5%
energy/fission	-	0.2%	-	0.2%
IBD cross section	-	0.12%	-	0.12%
fission fraction	-	0.6%	-	0.6%
spent fuel	-	0.3%	-	0.3%
non-equilibrium	-	0.2%	-	0.2%
ε_{IBD}				
ε_n	81.83%	1.69%	81.48%	0.74%
$\varepsilon_{\text{other}}$	98.49%	0.16%	98.49%	0.16%
total	-	2.1%	-	1.5%

- The total systematic uncertainty is improved by 29%.

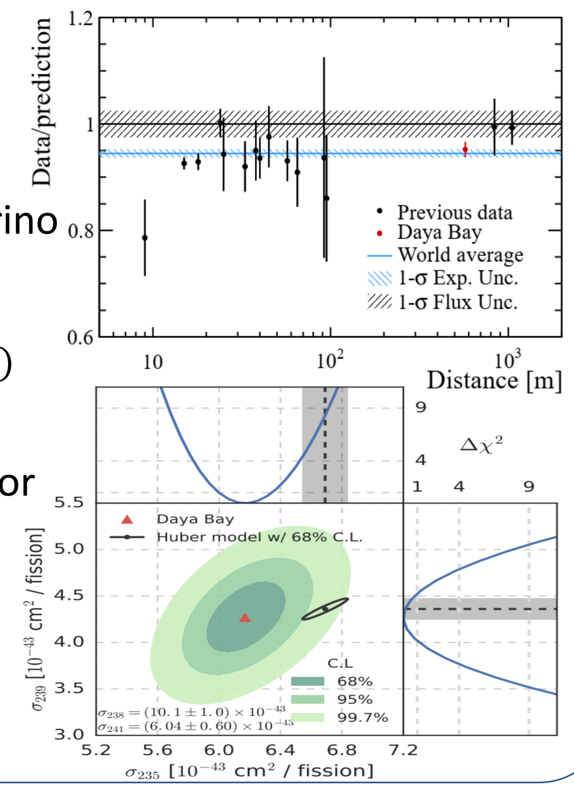
- The new reactor antineutrino flux measured by Daya Bay from 1230 days data is:

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

- The ratio of measured to predicted antineutrino yield is found to be:

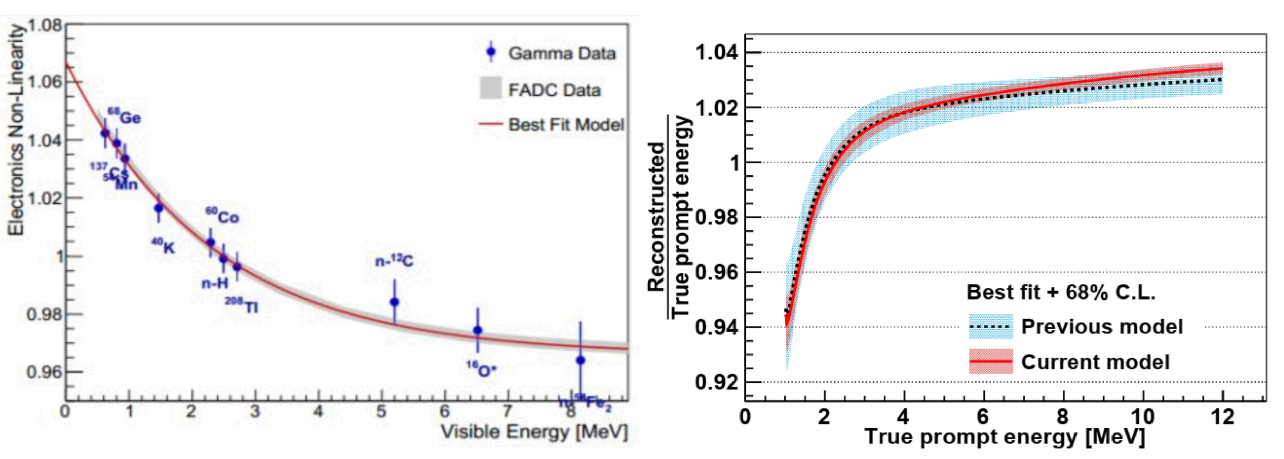
$$\frac{Data}{Predcition} = 0.952 \pm 0.014(exp) \pm 0.023(model)$$

- Data favors ^{235}U as main contributor to reactor antineutrino anomaly.
- Equal isotope deficit hypothesis, needed for sterile neutrino, is disfavored at 2.8σ.

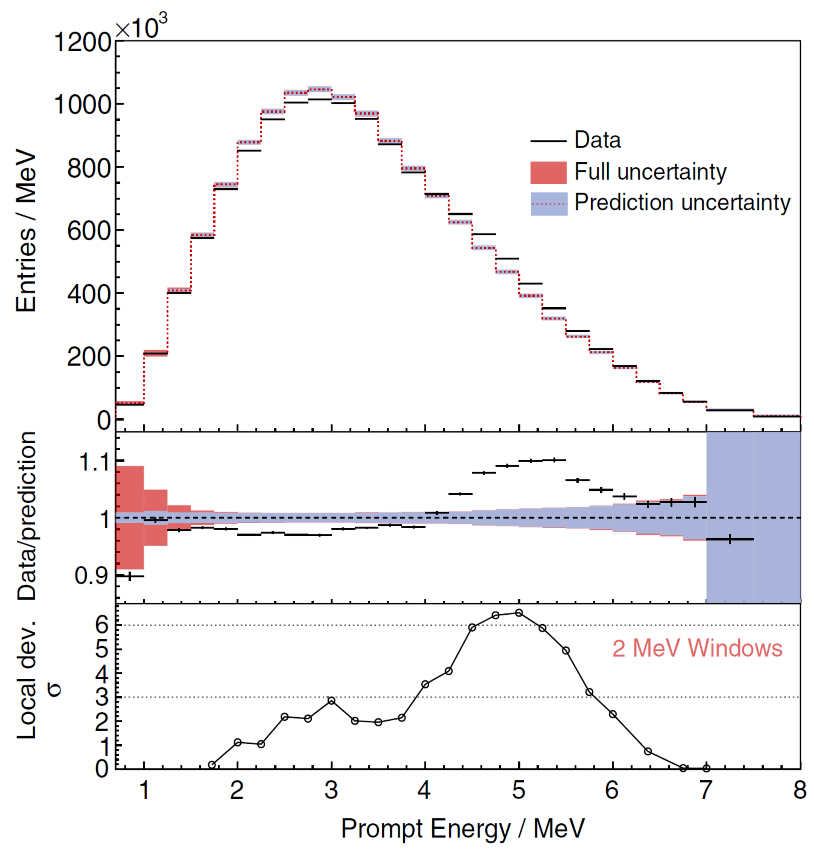


Antineutrino spectrum[3][4]

- FADC data and new calibration campaign in 2017 help to reduced the energy nonlinearity uncertainty.



- Uncertainties in the absolute energy calibration is reduced to less than 0.5% from previous 1.0% for visible energies larger than 2MeV.



- Measured spectrum shape is from 1958 days data of Daya Bay.
- The prediction is based on the Huber-Mueller model and normalized to the number of measured events.
- Effects of IBD kinetics, energy leakage, and energy resolution are considered.

$$\chi^2 = \sum_{i,j} (N_i^{\text{obs}} - N_i^{\text{pred}})(V^{-1})_{ij}(N_j^{\text{obs}} - N_j^{\text{pred}}),$$

Observed No. of events; Predicted No. of events; $i(j)$ –th energy bin

- The spectral shape disagrees with the Huber-Mueller model at 5.2 σ from 0.7 to 8 MeV.
- An excess in the 4-6 MeV range is observed with 6.3 σ discrepancy.
- The energy spectra of antineutrinos from ^{235}U and ^{239}Pu are extracted also.

High-energy reactor antineutrino study

- In all previous papers, we limited the energy range to lower than 8 MeV.
- High energy reactor antineutrino (HERA) are predicted by some theoretical model.
- HERA may help the nuclear physics in reactors.
- HERA is background for DSNB (Diffuse supernova neutrino background) study.
- How many candidates from HERA at Daya Bay?

Reference

[1] F. P. An et al. Phys. Rev. D 100 (2019) 052004
[2] F. P. An et al. Phys. Rev. Lett 118 (2017) 251801
[3] F. P. An et al. Phys. Rev. Lett 121 (2018) 241805
[4] F. P. An et al. Phys. Rev. Lett 123 (2019) 111801