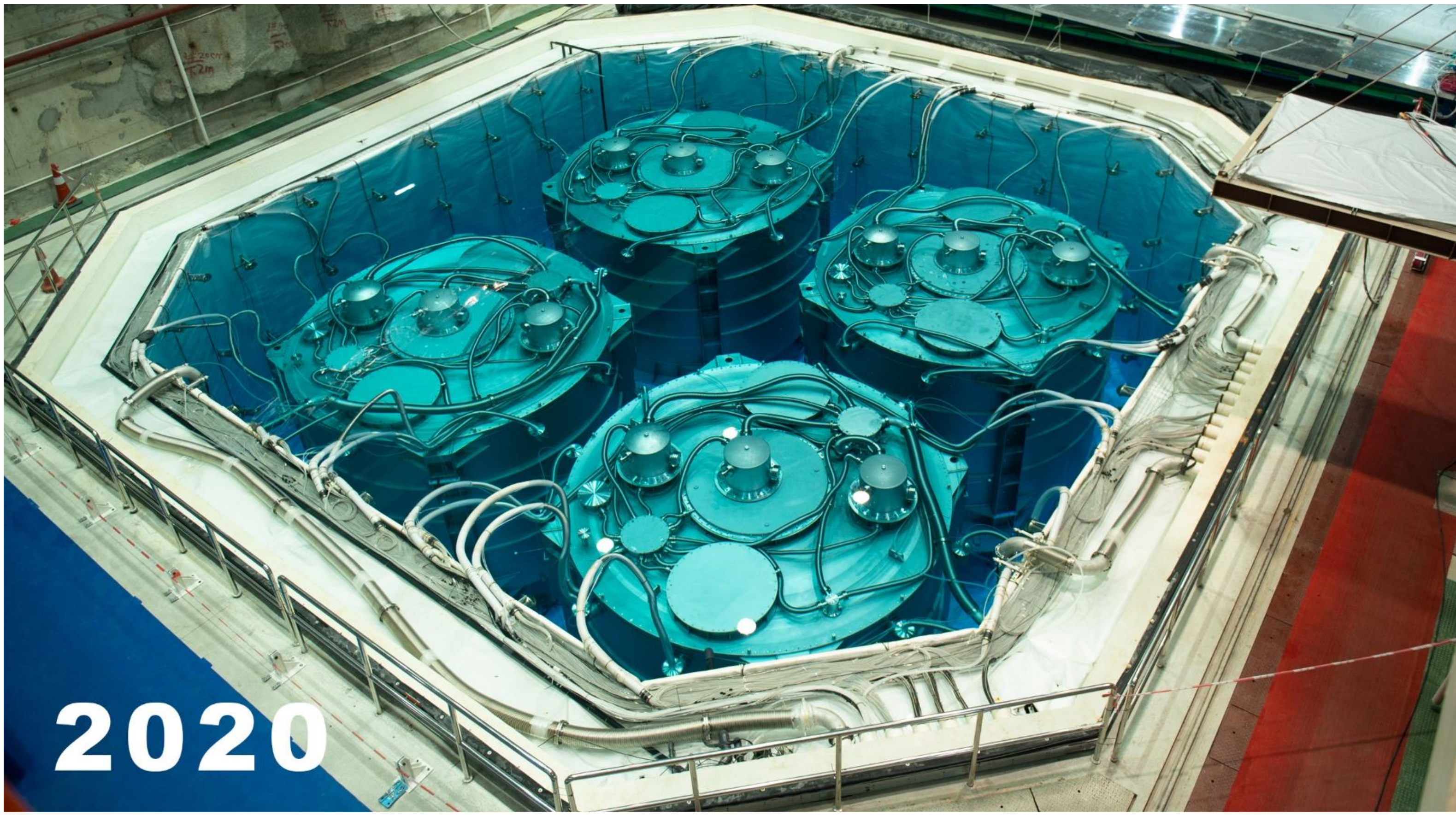
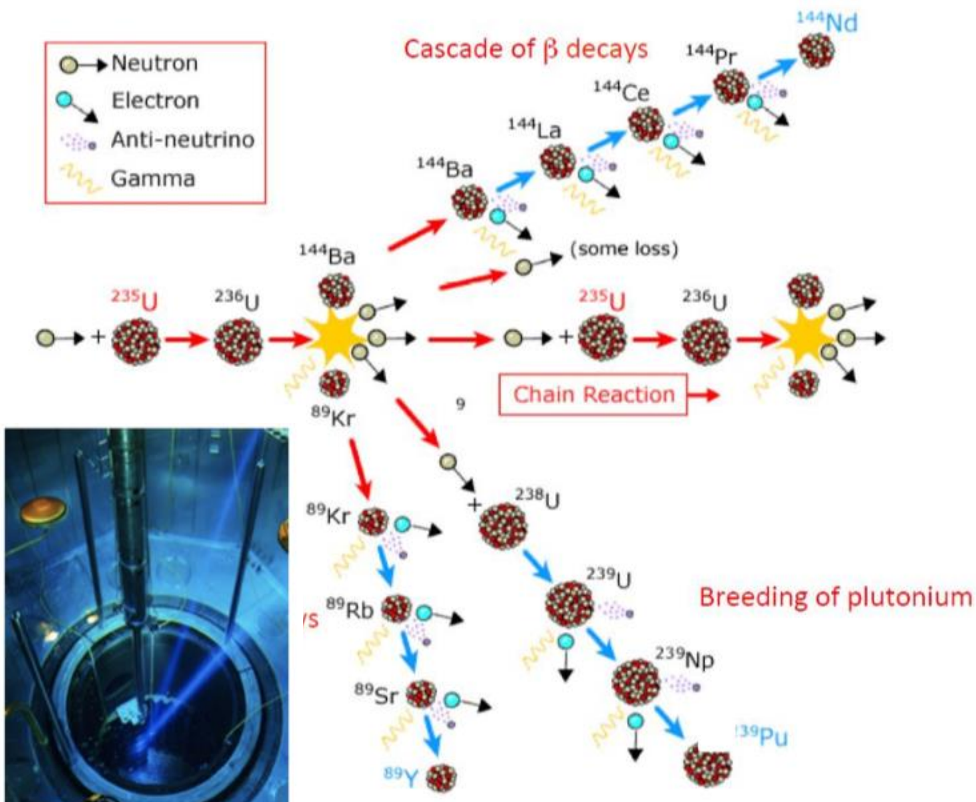
Reactor Antineutrino Measurement at Daya Bay

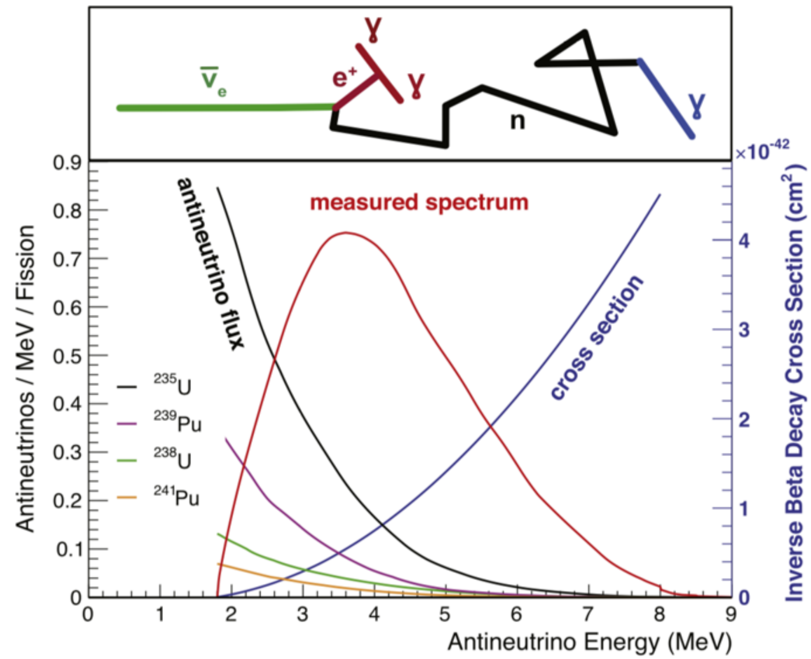


Jianrun Hu
On behalf of the Daya Bay Collaboration
Institute of High Energy Physics, China
ICHEP, 8th July 2022

Reactor Antineutrinos

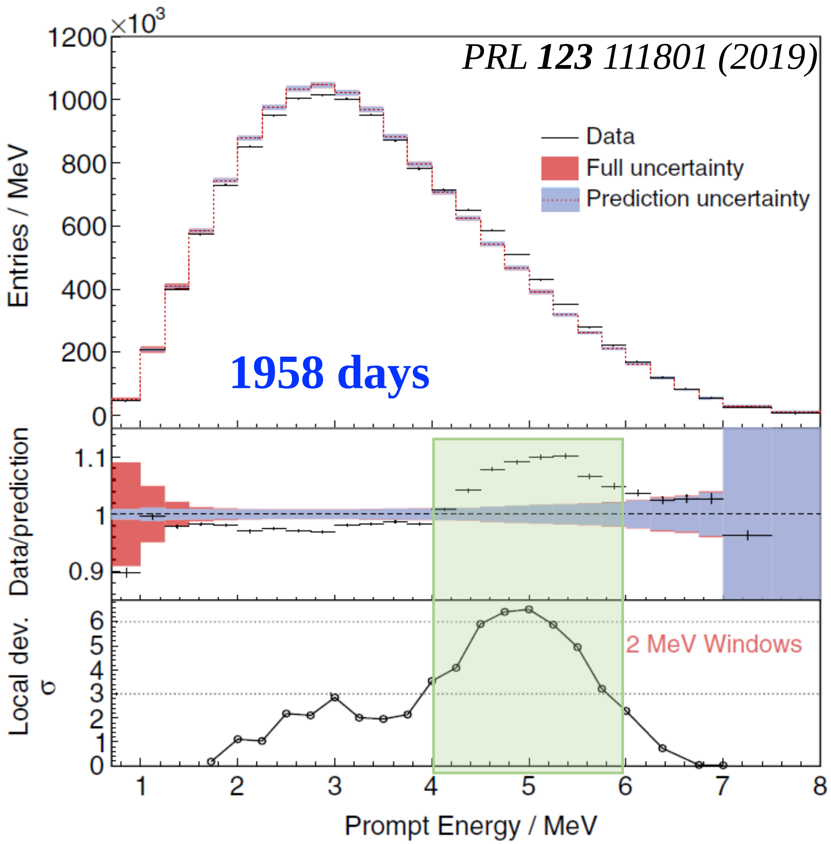
- Electron antineutrinos are produced in commercial nuclear reactor cores.
- Mainly from fission fragments of the 4 fissile isotopes ^{235}U, ^{238}U, ^{239}Pu, and ^{241}Pu.





Inverse β decay (IBD):
- Prompt: $E_{\mathrm{prompt}} \approx E_{\nu} - 0.8$ MeV
- Delayed: nGd (~8 MeV)
  nH (~2.2 MeV)

Antineutrino Flux and Spectrum

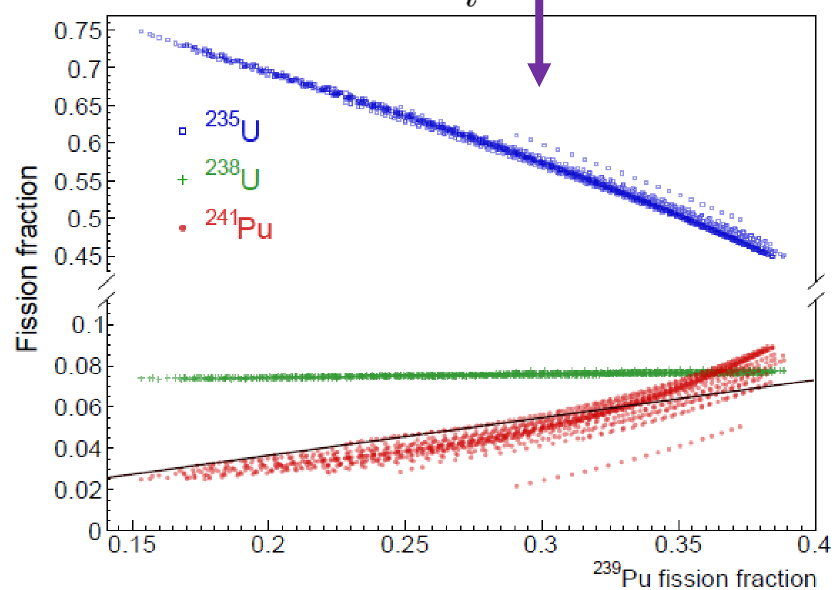


$$R = \frac{data}{Model\ (Huber + Mueller)}$$

$$= 0.953 \pm 0.014(exp) \pm 0.023(model)$$

As the fuel burns in the reactors, the fission fractions and the antineutrino flux also evolve.

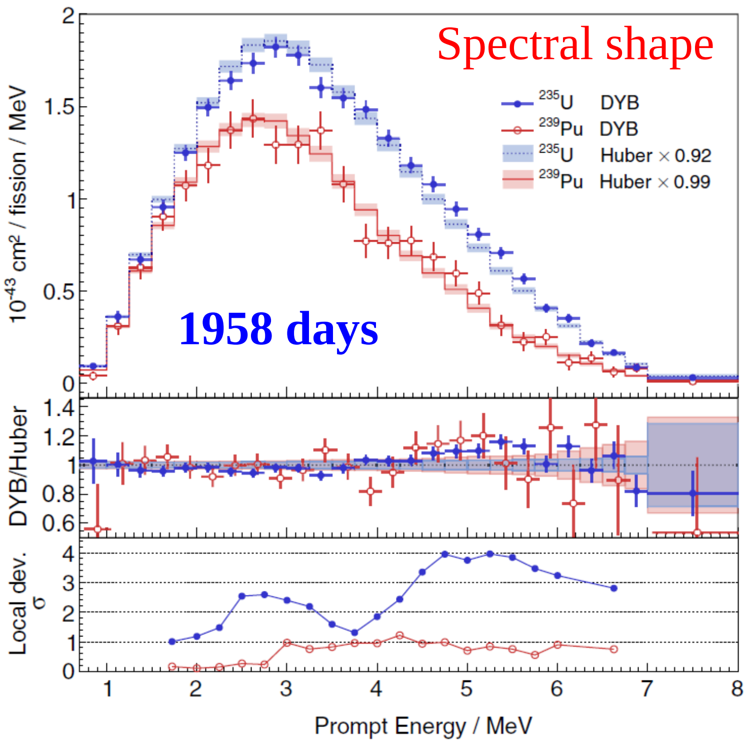
$$\sigma_f(t) = \sum_i \boxed{F_i(t)}\sigma_i$$



- Data/prediction spectrum shows an overall >5σ deviation, local deviation >6σ at maximum.
- Spectral shape uncertainty (detector + background + statistic): ~0.5%

PRL ***123*** *111801 (2019)*

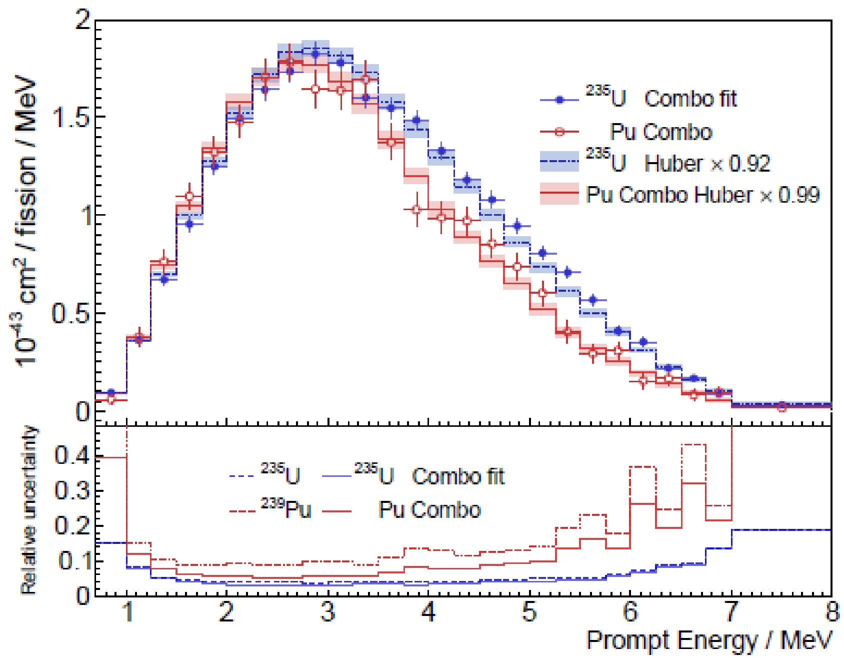
Isotopic Spectra



- First measurement of ^{235}U and ^{239}Pu spectra from commercial reactors.
- Similar bump excess for ^{235}U and ^{239}Pu in 4~6 MeV.
- Local spectral deviation from prediction: ^{235}U (4σ) and ^{239}Pu (1.2σ).

- Reduce the Pu spectrum uncertainty by combining ^{239}Pu and ^{241}Pu according to their fission fraction ratio

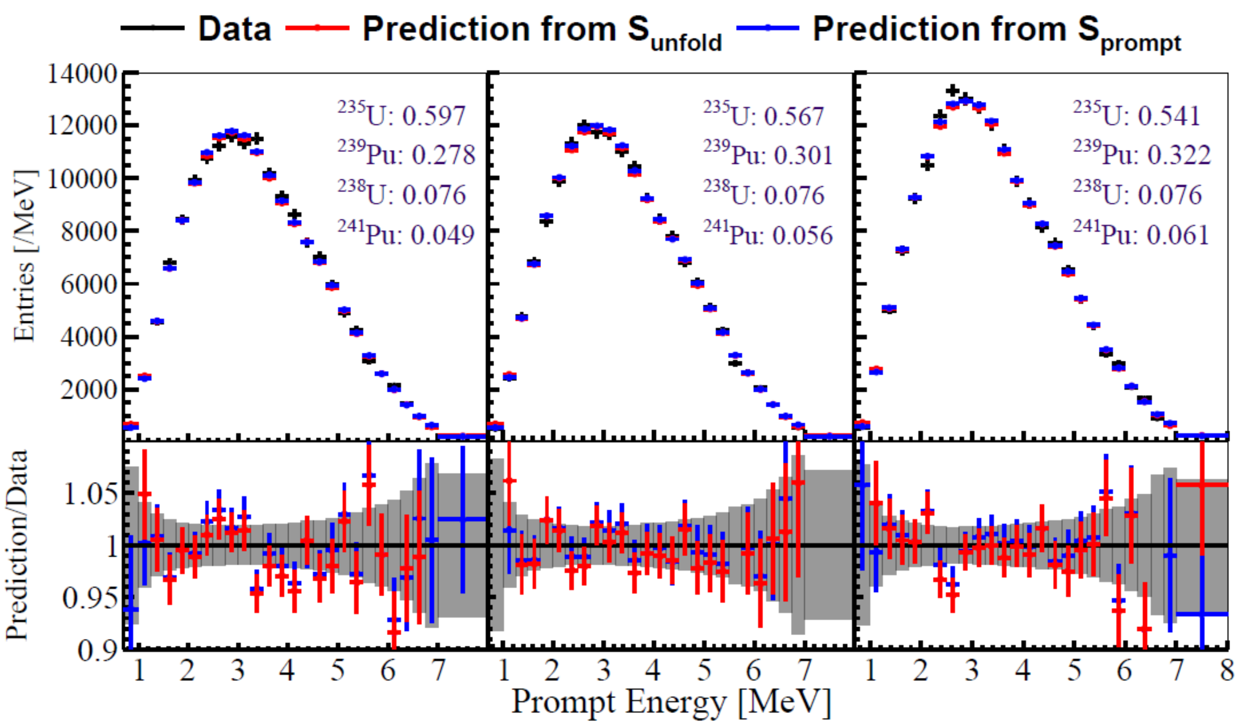
$$s_{\text{combo}} = s_{239} + 0.183 \times s_{241}$$



- Dependence on the input of ^{241}Pu largely removed.
- Combined Pu spectrum uncertainty: 6% (9% for Pu239-only).

Data-based Prediction for Other Experiments

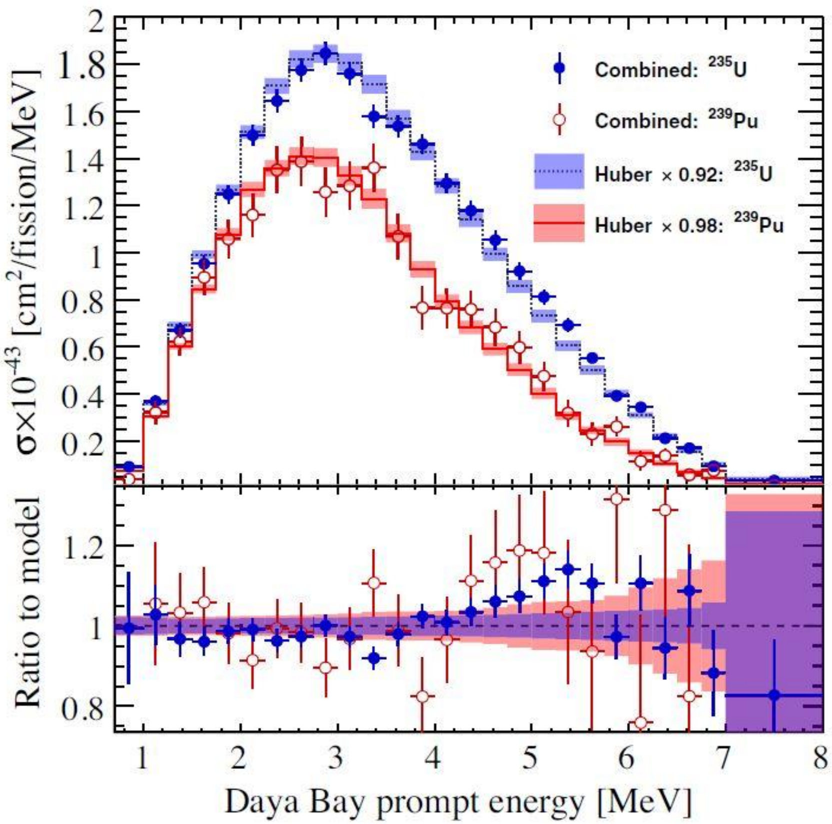
- Total and isotopic antineutrino energy spectra is unfolded by Wiener-SVD method.
- Provide a data-based prediction for other reactor antineutrino experiments.
    - With known reactor fission fractions, the technique can predict the energy spectrum to a 2% precision.



[Chinese Phys. C 45 073001 (2021)] Supplemental materials provided in arXiv:2102.04614.

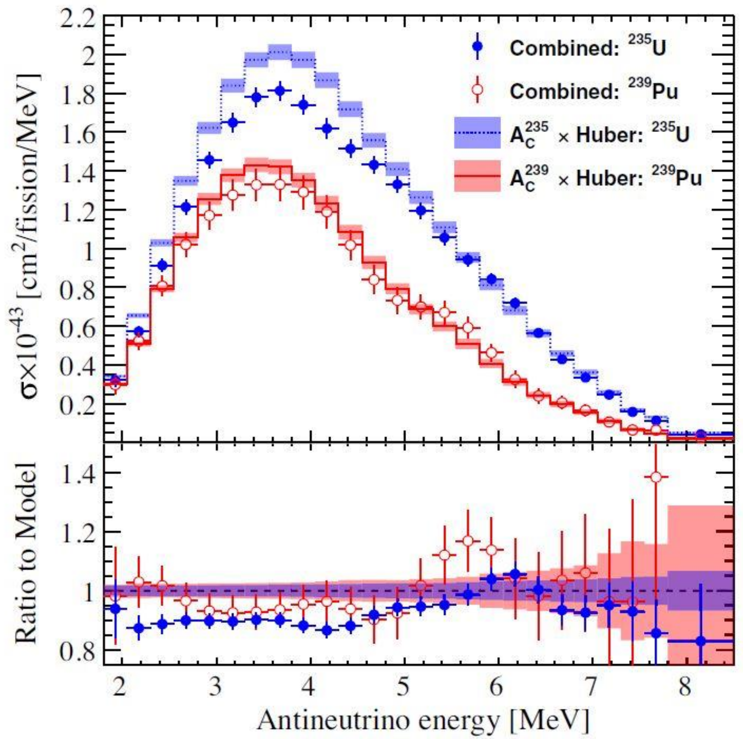
Joint Analysis by Daya Bay and PROSPECT

- Compared with Daya Bay-only result, ^{235}U spectral shape err: 3.5% → 3%
- Reduce the degeneracy between ^{235}U and ^{239}Pu (by 20%).
- Central values change within 2% (consistent within uncertainties).



[Phys. Rev. Lett. 128, 081801 (2022)]

- Unfold the $\bar{\nu}_e$ spectrum with Wiener-SVD method
- More precise prediction for other Exps

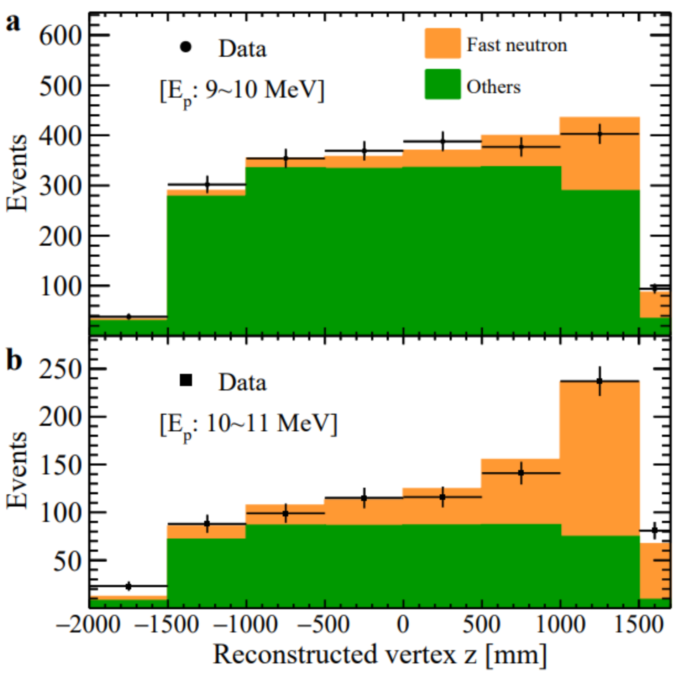


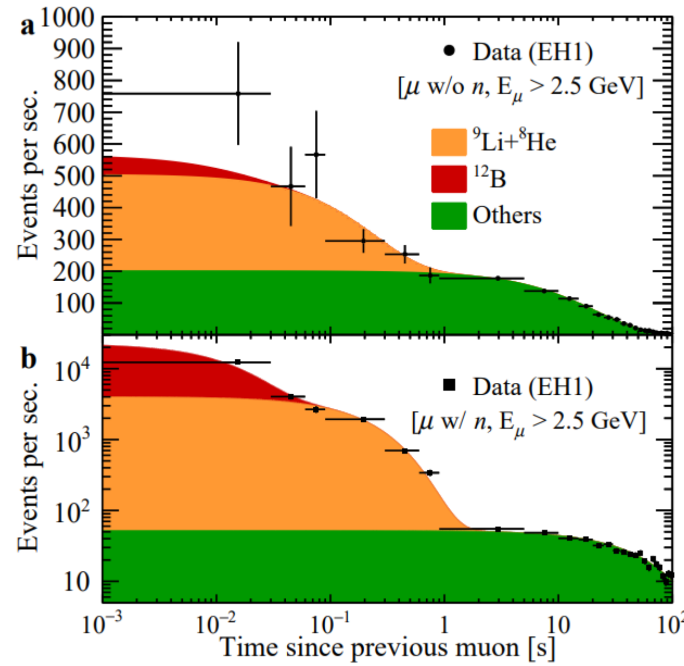
High-energy Reactor Antineutrinos

- No evidence of reactor antineutrinos with $E_\nu > 9$ MeV before this work.
- Generated by only a handful of short-lived β-decay nuclei with high Q_β
- Main backgrounds:
  1. Muon decays (excluded by a vertex cut).
  2. Cosmogenic fast neutrons: vertices near the top of the AD.
  3. Cosmogenic isotope decays: shorter time to the preceding muons.

$$f(\Delta t) = \kappa \cdot e^{-\kappa \Delta t}$$

- μ uncorrelated: $\kappa = R_\mu$
- μ correlated: $\kappa = R_\mu + \frac{n}{\tau}$

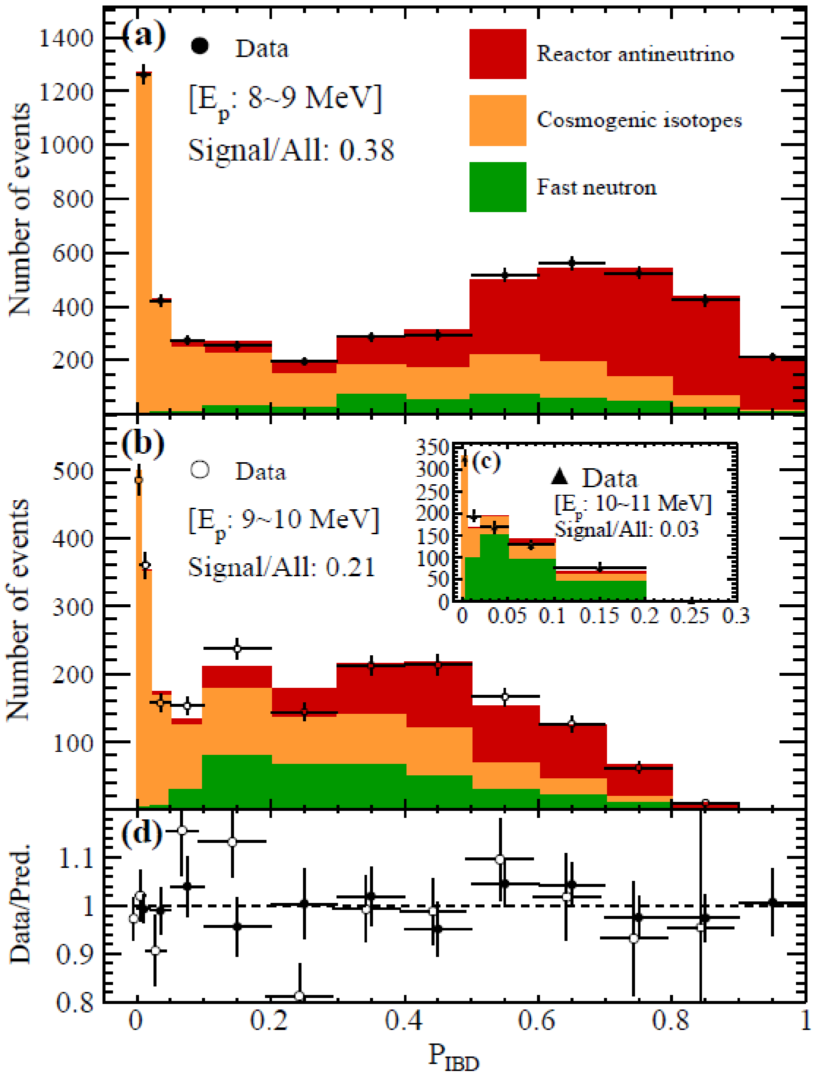




High-energy Reactor Antineutrinos

- Multivariate analysis: event-by-event fitter with above information:
  - Vertex z_p, time to preceding muons, reactor power
- Separate 2500 signal events from background in $E_p > 8$ MeV statistically.

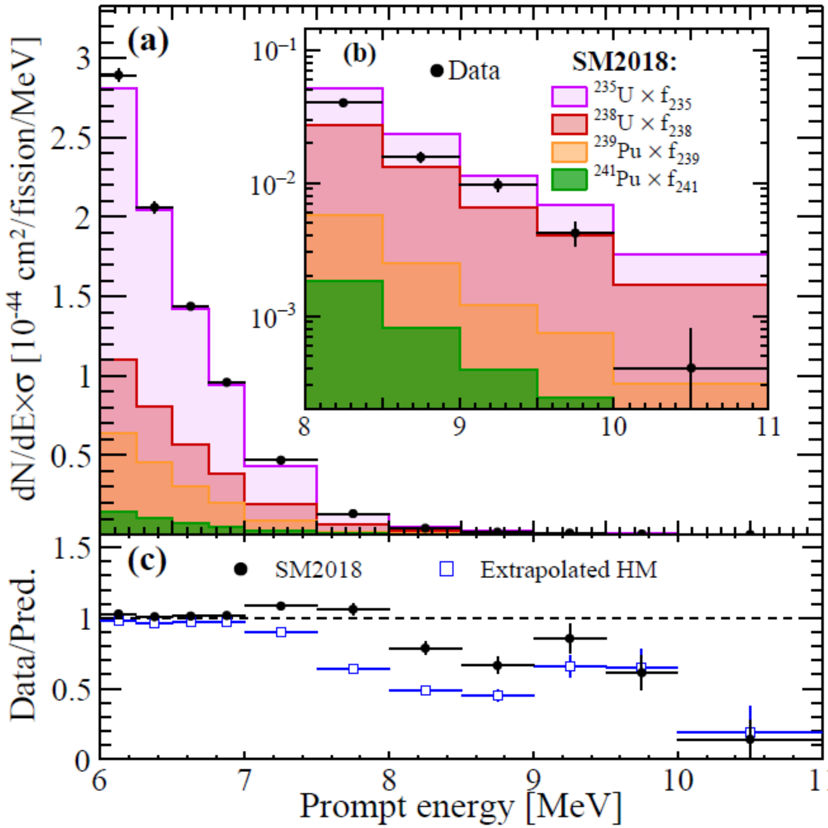
- Calculate the probability of being an IBD signal (PIBD) for each event with the best-fit values.
- PIBD distributions from data and fitting model are consistent within statistical uncertainty.

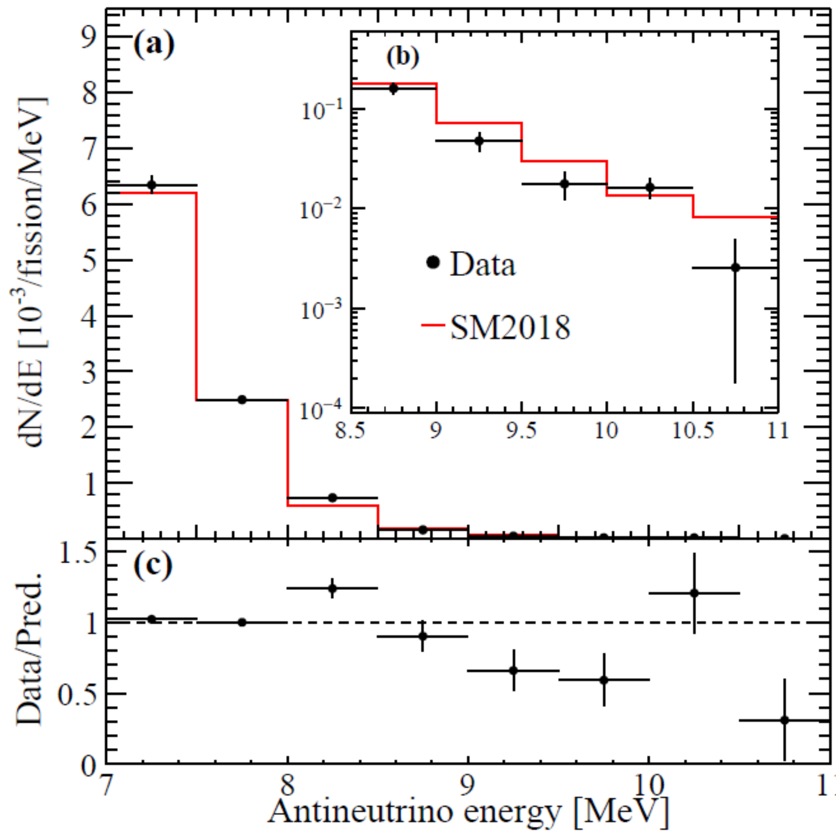


[arXiv:2203.06686]

High Energy Spectrum

- Measured IBD yield compared w/ SM2018: 3% larger for 6-8 MeV (E_p), but 29% smaller for 8-11 MeV (E_p). (Pandemonium-effect?)
- Unfolded $\bar{\nu}_e$ energy spectrum for better application.
- Significance in rejecting the hypothesis of no reactor antineutrinos above 10 MeV (E_ν) is determined to be 6.2σ.

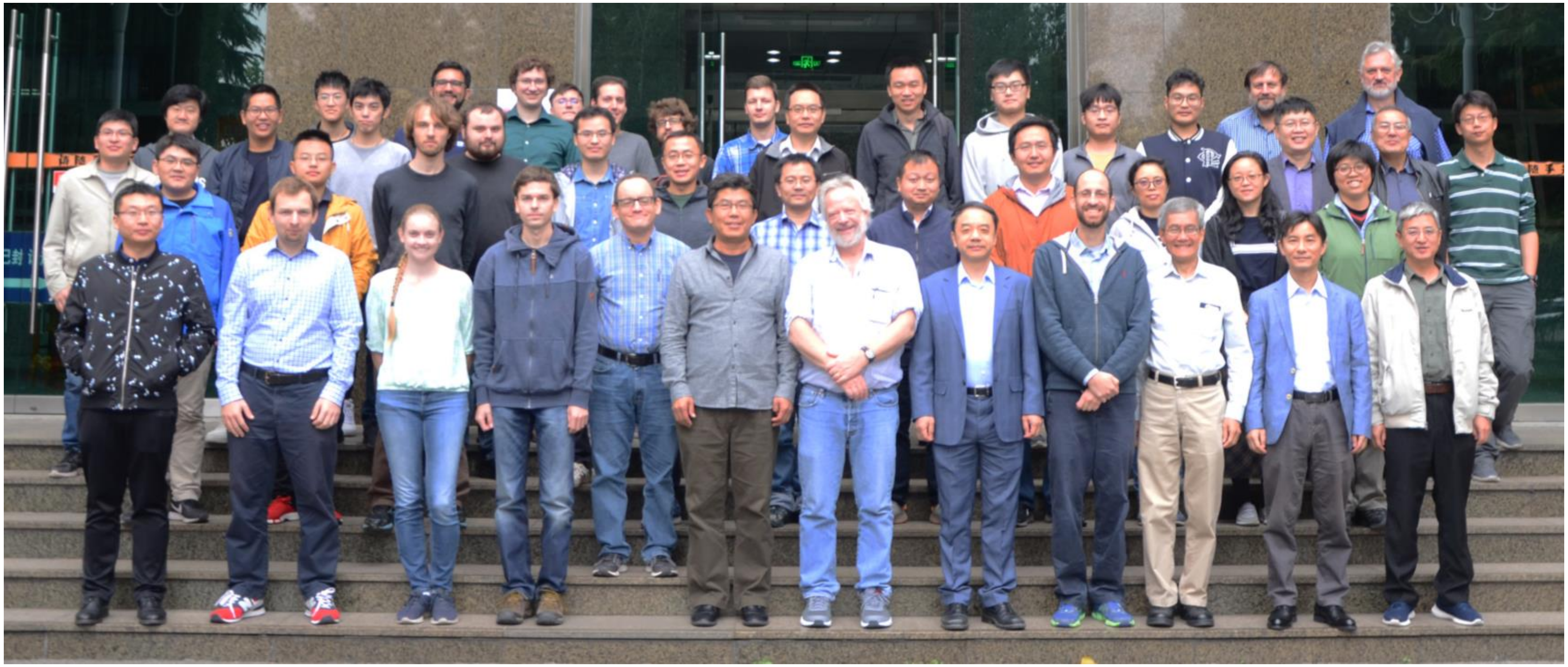




Summary

- Flux and spectral shape are both inconsistent with Huber-Mueller model.
- First measurement of ^{235}U and ^{239}Pu spectra from commercial reactor by reactor fuel evolution.
- Antineutrino energy spectra are unfolded to provide data-based prediction for other experiments.
- First combination between Daya Bay and PROSPECT to reduce the uncertainty of ^{235}U spectrum.
- First measurement of high-energy reactor antineutrinos.
  - Rejecting the hypothesis of no reactor antineutrinos above 10 MeV (E_ν) with 6.2σ.
- Final Daya Bay results are expected with full data set.

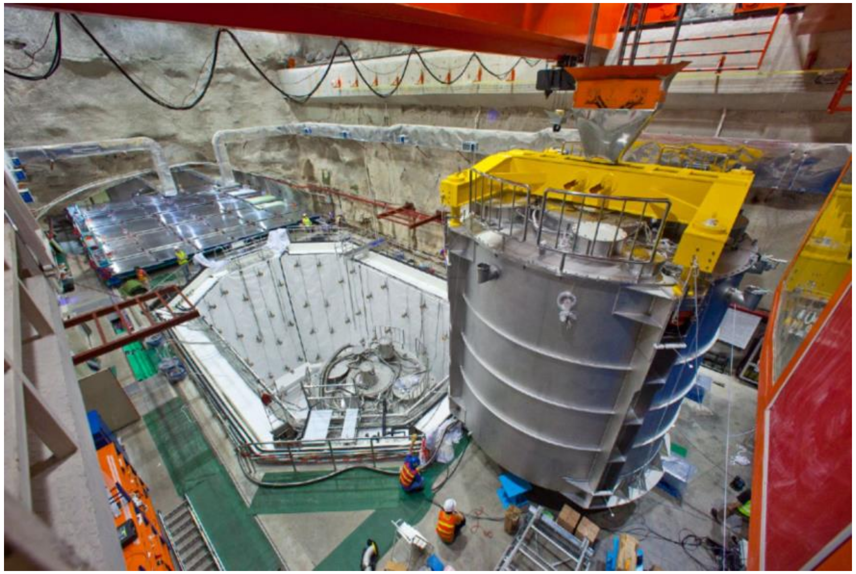
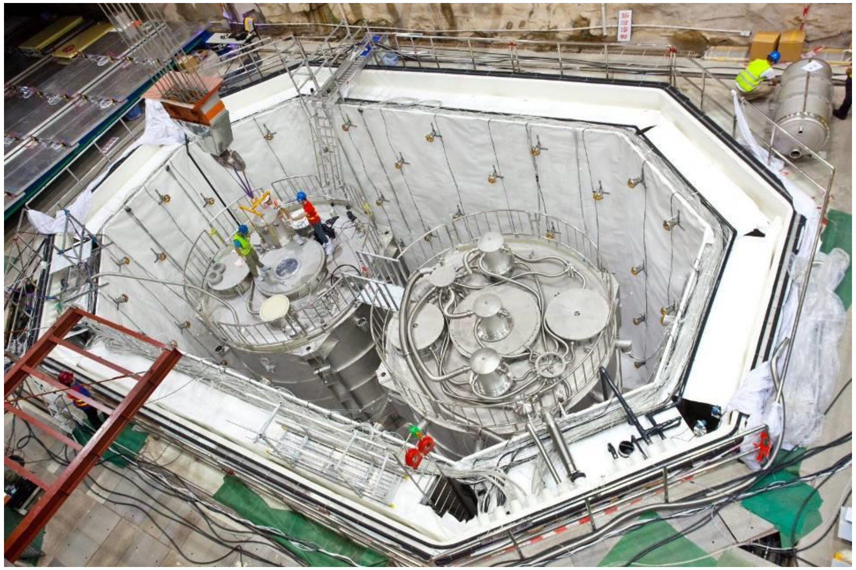
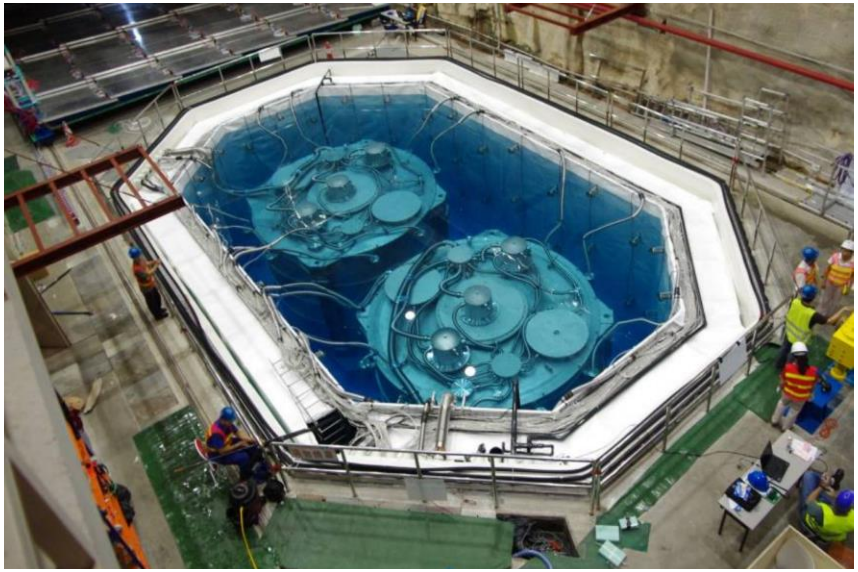
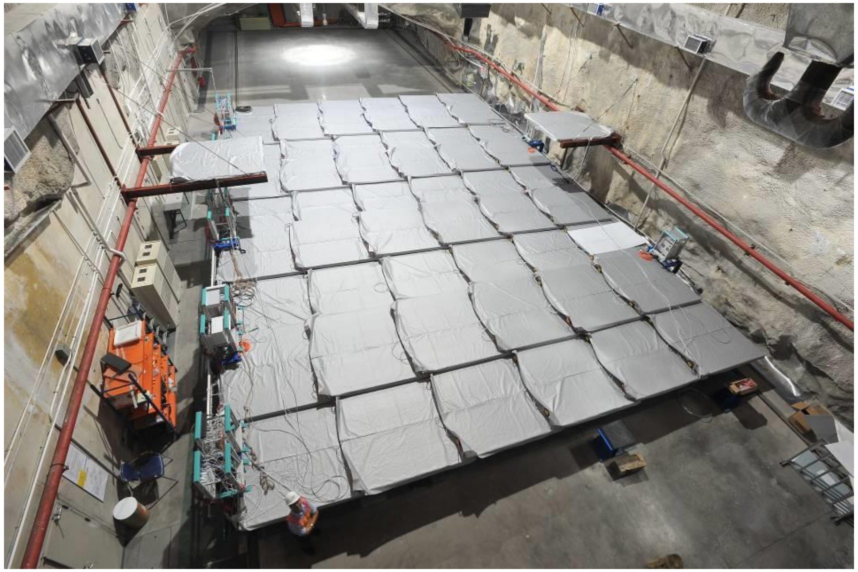
Thank you for your attention!



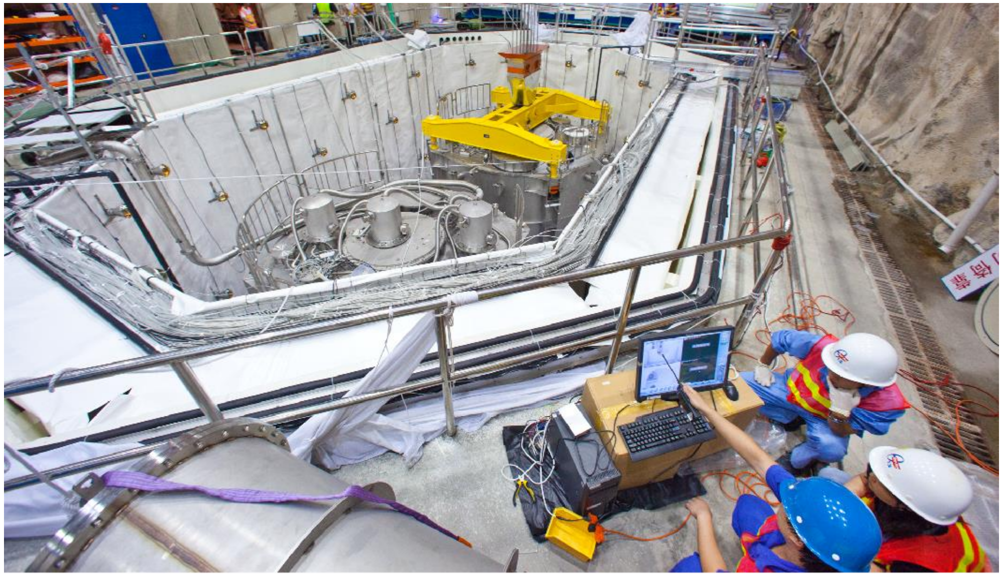
The Daya Bay Collaboration

Backup

A Selection of Pictures

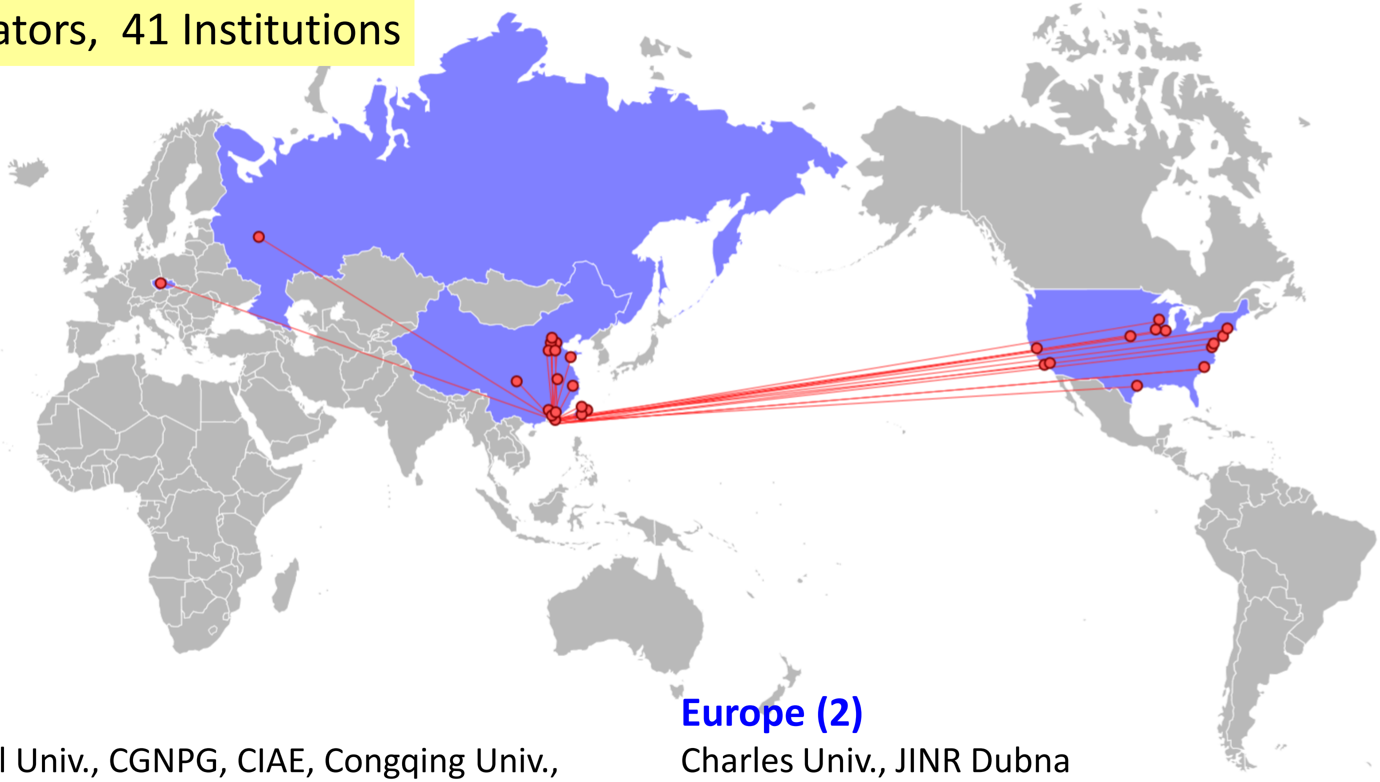





A Selection of Pictures



The Daya Bay Collaboration

191 Collaborators, 41 Institutions



Asia (24)

Beijing Normal Univ., CGNPG, CIAE, Congqing Univ., Dongguan Univ. Tech., ECUST, GXU, IHEP, Nanjing Univ., Nankai Univ., NCEPU, NUDT, Shandong Univ., Shanghai Jiao Tong Univ., Shenzhen Univ., Tsinghua Univ., USTC, Xian Jiaotong Univ., Zhongshan (Sun Yat-sen) Univ., Chinese Univ. of Hong Kong, Univ. of Hong Kong, National Chiao Tung Univ., National Taiwan Univ., National United Univ.

Europe (2)

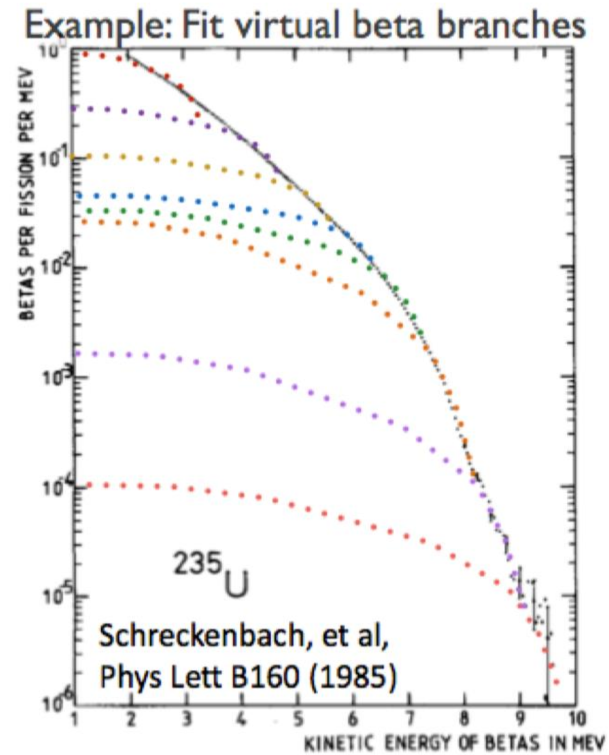
Charles Univ., JINR Dubna

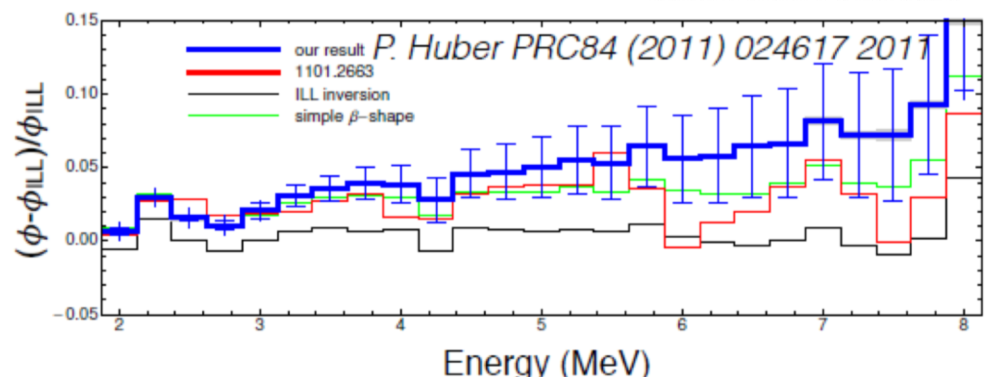
North America (15)

Brookhaven Natl Lab, Illinois Institute of Technology, Iowa State, Lawrence Berkeley Natl Lab, Princeton, Siena College, Temple University, UC Berkeley, Univ. of Cincinnati, Univ. of California Irvine, UIUC, Univ. of Wisconsin, Virginia Tech, William & Mary, Yale

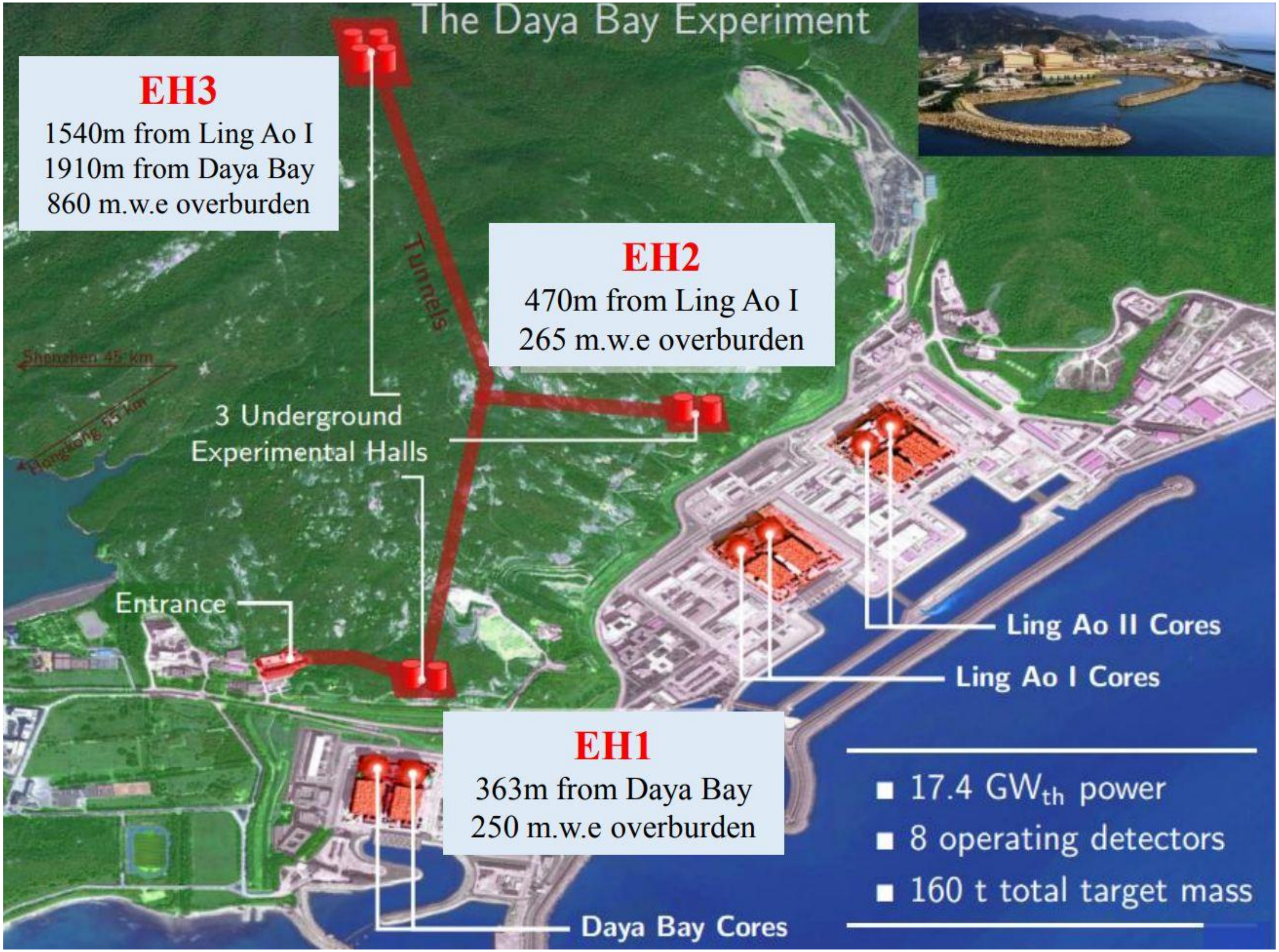
Reactor $\bar{\nu}_e$ Flux Prediction

- Summation (ab initio) method
  - > 6000 decay branches
  - Missing data in the nuclear database
  - ~30% forbidden decays
  - ~ 10% uncertainty
- Conversion method
  - Convert ILL measured ^{235}U, ^{239}Pu and ^{241}Pu β spectra to $\bar{\nu}_e$ with >30 virtual β-decay branches
  - Old: ILL + Vogel (^{238}U) model (1980s)
  - New: Huber + Mueller (^{238}U) model (2011)
  - ~ 2.4% uncertainty





Daya Bay Layout

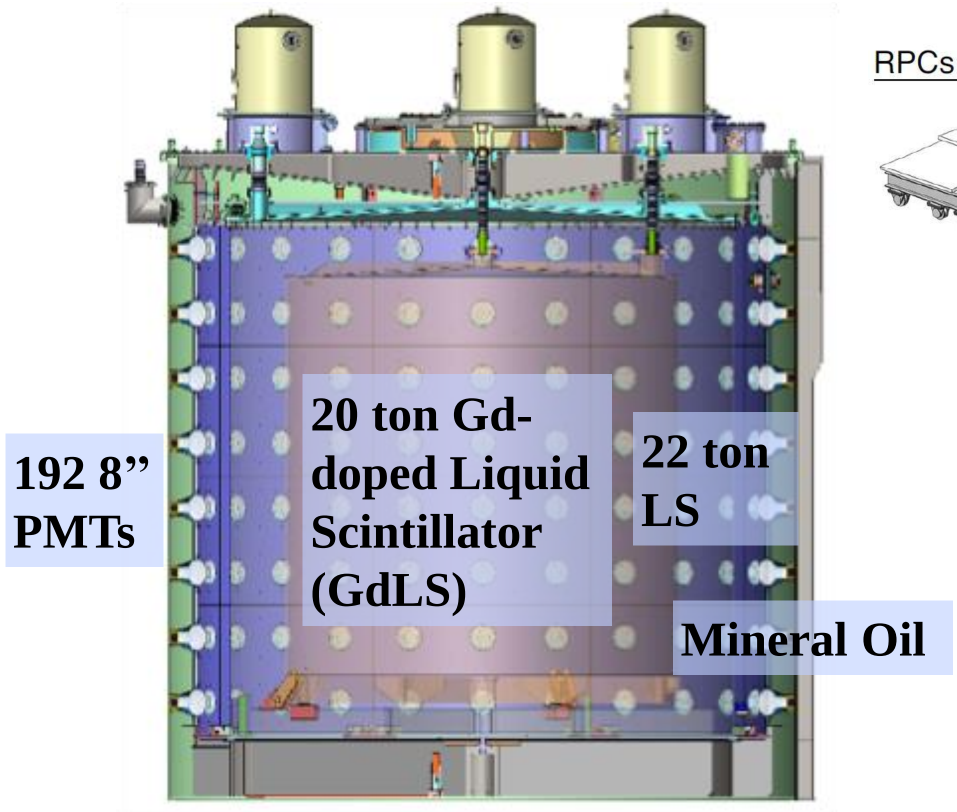


Detector System

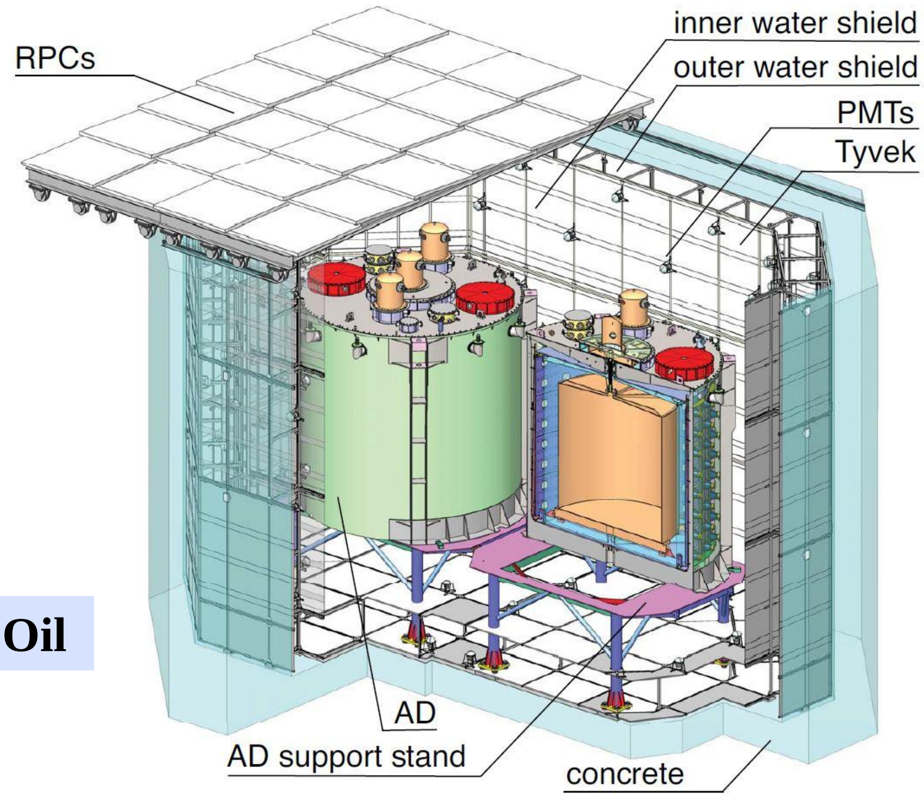
- Antineutrino Detectors (ADs):
  - "Three-zone" cylindrical modules

Energy resolution: $\sigma_E/E \cong 8.5\%/\sqrt{E[\mathrm{MeV}]}$

- Water Cherenkov Detector and RPCs:
  - Shield the ADs from natural radioactivity and neutrons
  - Veto cosmic-ray muons



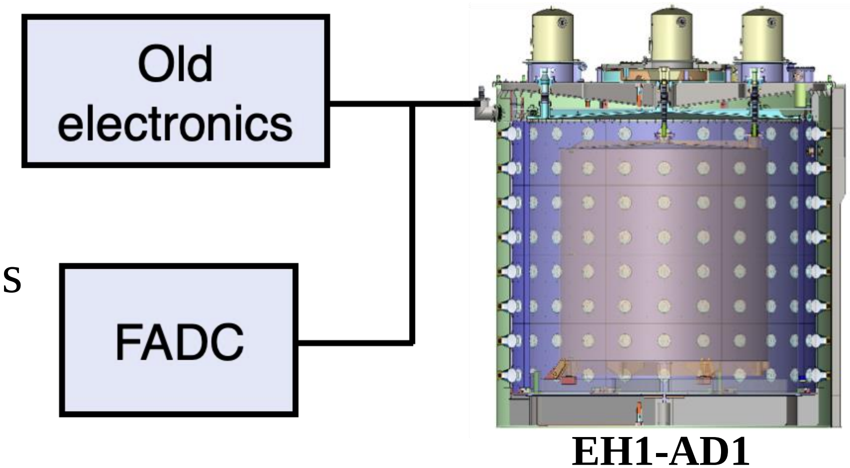
NIM A ***811****, 133 (2016)*



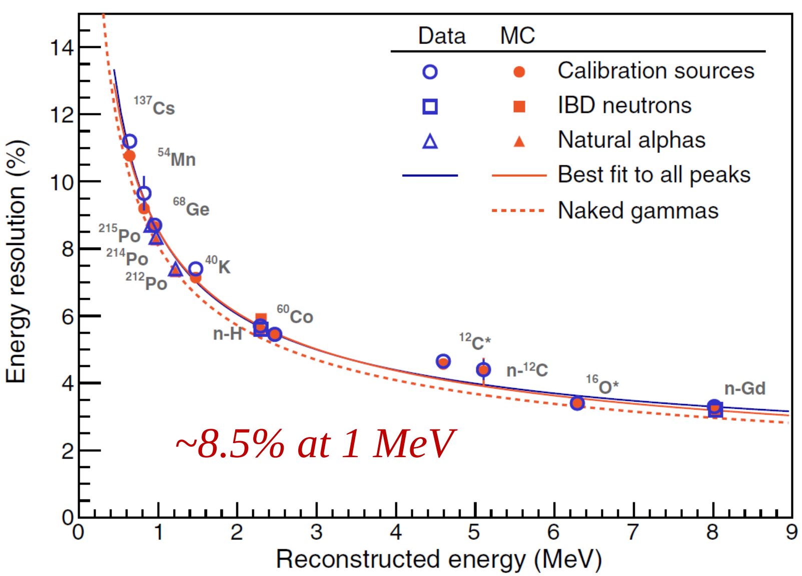
NIM A ***773****, 8 (2015)*

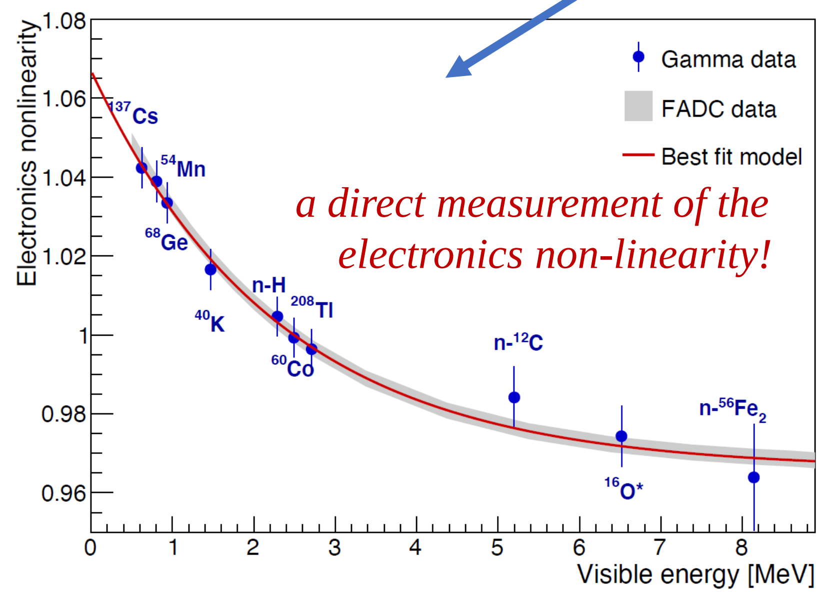
Energy Response

- End of 2015: installation of a full FADC readout system in EH1-AD1



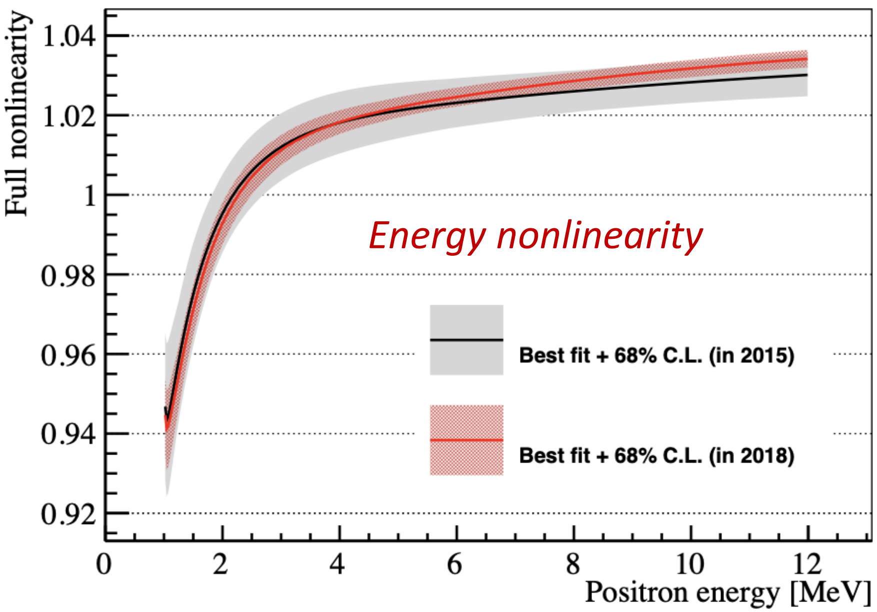
- Weekly calibration
  - ^{68}Ge, $^{241}Am^{13}C$, ^{60}Co
- Special calibration campaign
  - ^{137}Cs, ^{54}Mn, $^{241}Am^{9}Be$, $^{239}Pu^{13}C$
- Special calibration in 2017: ^{60}Co sources with different enclosures
  - ➢ Optical shadowing effect
- Lead to improvement on energy nonlinearity model



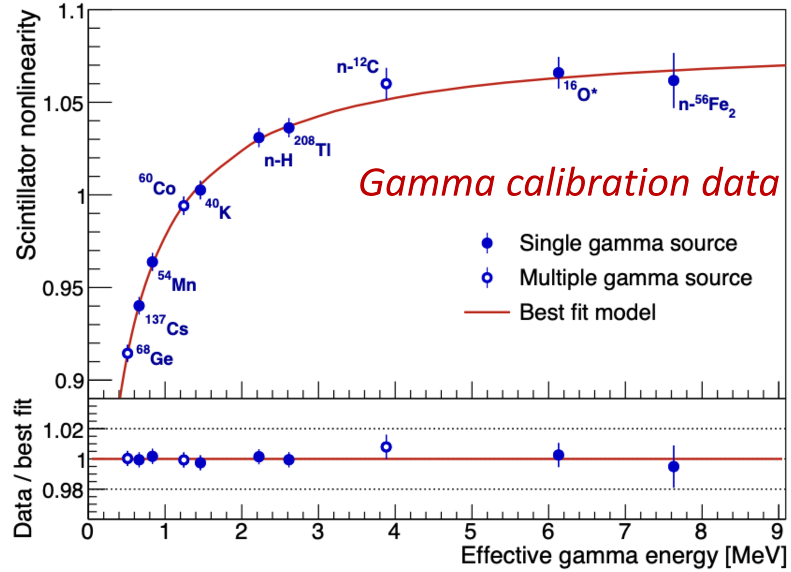


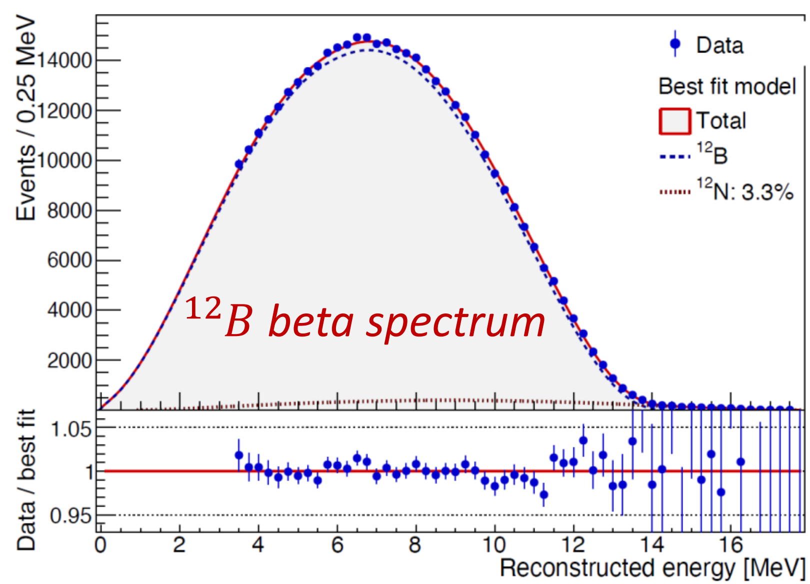
Energy Nonlinearity Model

- Model built by a combined fit to mono-energetic gamma lines and ^{12}B beta-decay spectrum
- Improved uncertainty of nonlinearity energy model: ~1% → ~0.5% since 2018.



NIMA 230-242,940(2019)



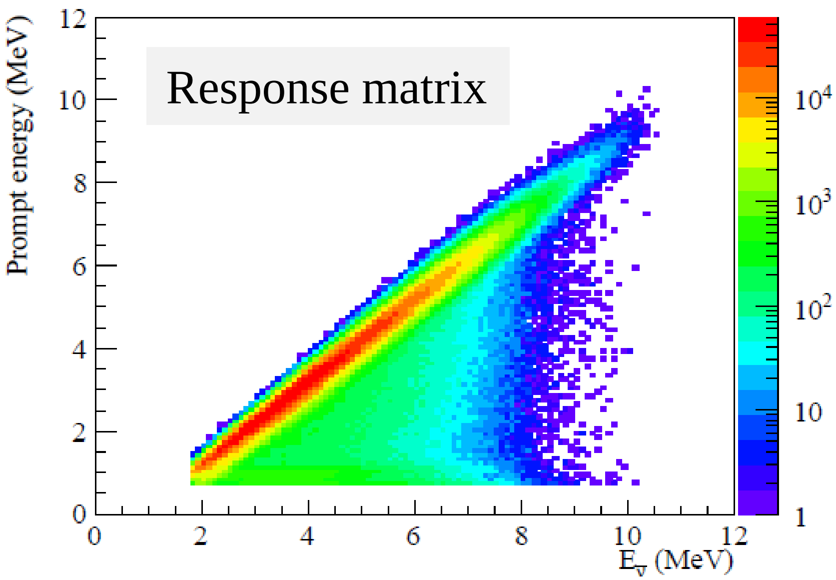


Detector Response

- Detector response includes effects of
  - IBD neutron recoiling
  - IAV effect: energy loss in inner acrylic vessel
  - Nonlinearity (scintillation quenching, electronics response)
  - Energy Resolution: ~8.5% at 1 MeV

Detection efficiency

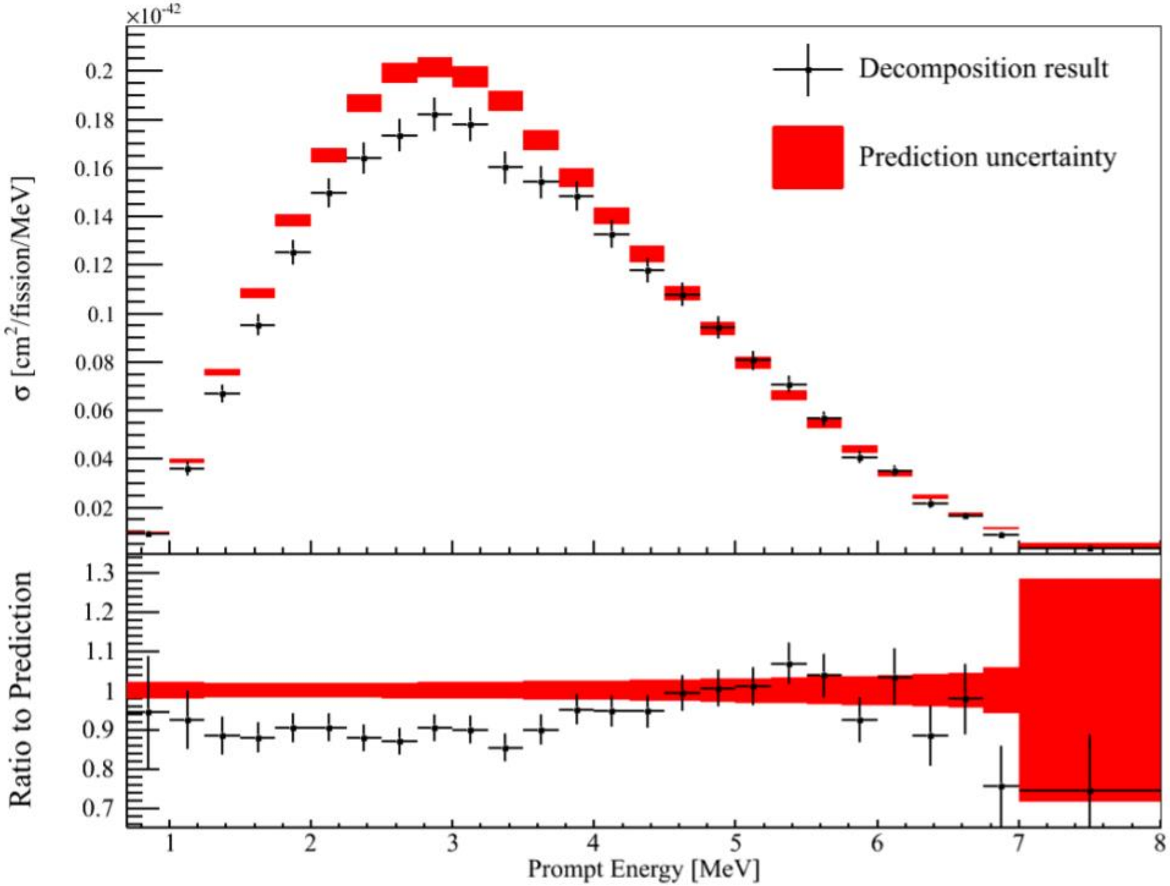
	Efficiency	Uncertainty	
		Correlated	Uncorrelated
Target protons	-	0.92%	0.03%
Flasher cut	99.98%	0.01%	0.01%
Prompt Energy cut	99.8%	0.10%	0.01%
Multiplicity cut	-	0.02%	0.01%
Capture time cut	98.7%	0.12%	0.01%
Delayed neutron cut	81.48%	0.74%	0.13%
Live time	-	0.002%	0.01%
Combined	80.2%	1.2%	0.13%



Absolute Spectrum Comparison for ^{235}U

Compare the spectrum without normalization

- The 8% deficit of ^{235}U depends on the energy
- 11% deficit below 4 MeV for ^{235}U spectrum → 8% overall rate deficit



IBD Candidate Rate $\boxed{R} = \boxed{R_{\mathrm{IBD}}} P_{\mathrm{reactor}} + \boxed{R_{\mathrm{bkg}}}$

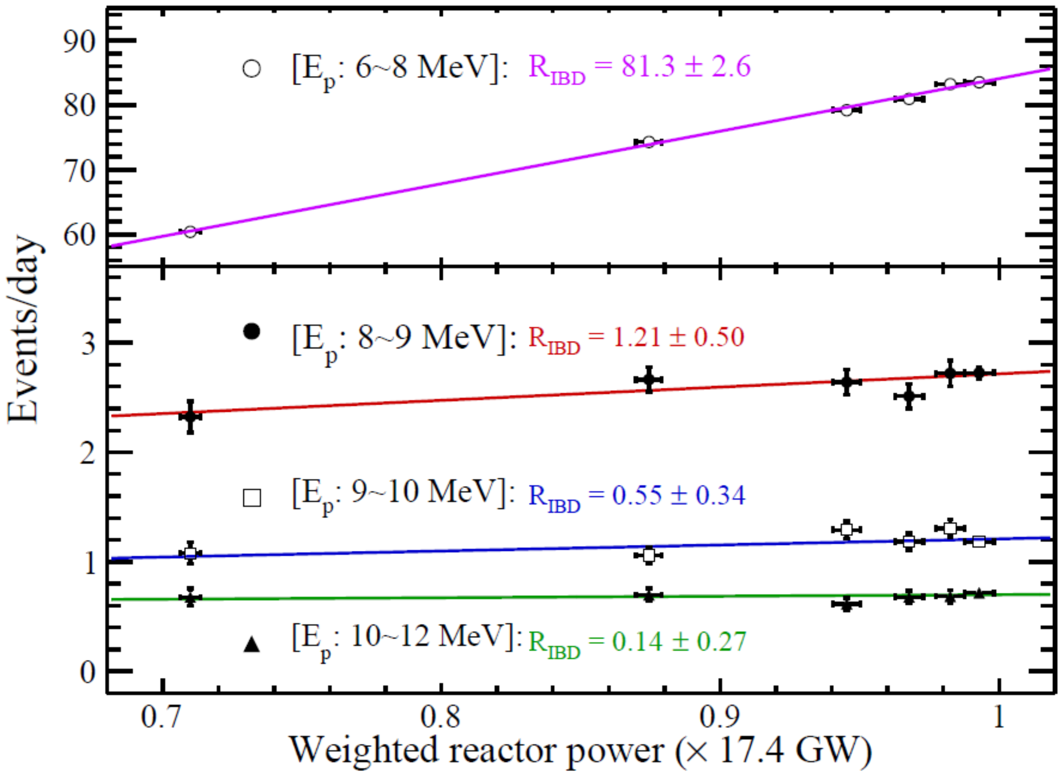
weighted reactor power

reactor antineutrino event rate per unit of reactor power

Background rate

- Clear correlation between R and P_{reactor} for prompt energy from 6 to 8 MeV

Relationship between the IBD candidate event rate per day and the weighted reactor power



- By decomposing R into two parts:
- Significance of the correlation decreases to below 2.5 standard deviations above 8 MeV,
- Much larger background to signal ratio

- Main backgrounds:
  1. Muon decays (excluded by a vertex cut)
  2. Cosmogenic fast neutrons
  3. Cosmogenic isotope decays

Fitting Method

Ratio of event type *p*

Reactor power information

$$\text{PDF:}\quad F(\boldsymbol{r};\boldsymbol{\Delta t},z,w)=\sum_p \boxed{r_p} f_p(\boldsymbol{\Delta t})h_p(z)\boxed{k_p(w)}$$

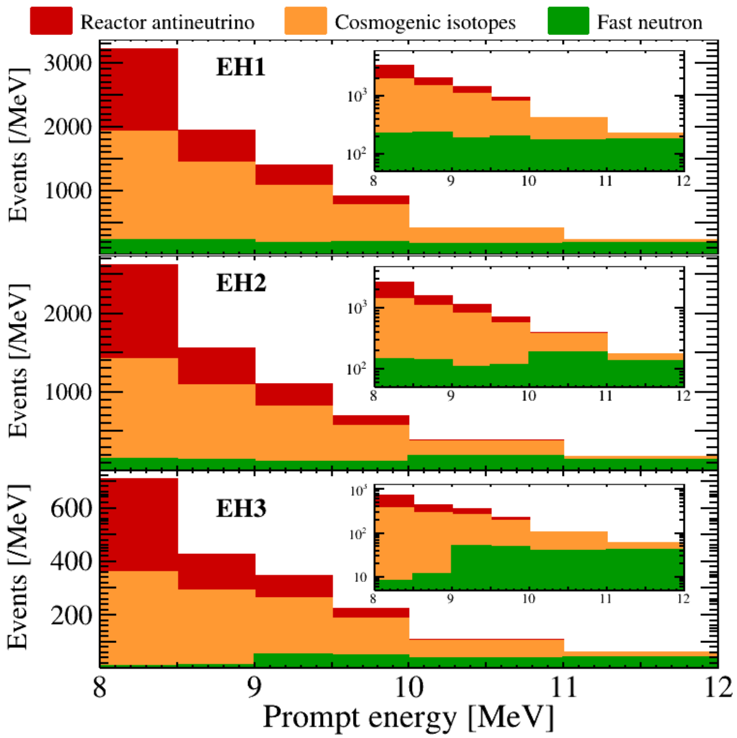
Δt distr. *z distr.*

$$\boxed{\chi^2(\boldsymbol{r})}=-2\sum\left[\log F(\boldsymbol{r};\boldsymbol{\Delta t},z,w)\right]+\boxed{g(\boldsymbol{\epsilon})}$$

multivariate analysis with event-by-event fitter

constrains the nuisance parameters describing $f_p(t)$, $h_p(z)$ and $k_p(w)$

Fitting results for 3 EHs



Probability of being an IBD signal for each event with the best-fit values:

$$P_{\mathrm{IBD}}=\frac{r_{\mathrm{IBD}}f_{\mathrm{IBD}}(\boldsymbol{\Delta t})h_{\mathrm{IBD}}(z)k_{\mathrm{IBD}}(w)}{F(\boldsymbol{r};\boldsymbol{\Delta t},z,w)}$$

P_{IBD} distributions from data and fitting model are consistent within statistical uncertainty