Precise measurement of absolute flux and spectrum of reactor neutrinos at Daya Bay

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on behalf of the Daya Bay collaboration

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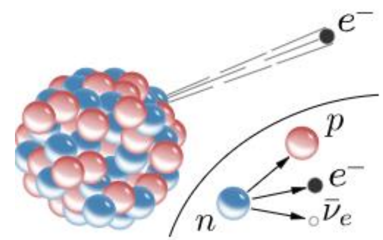
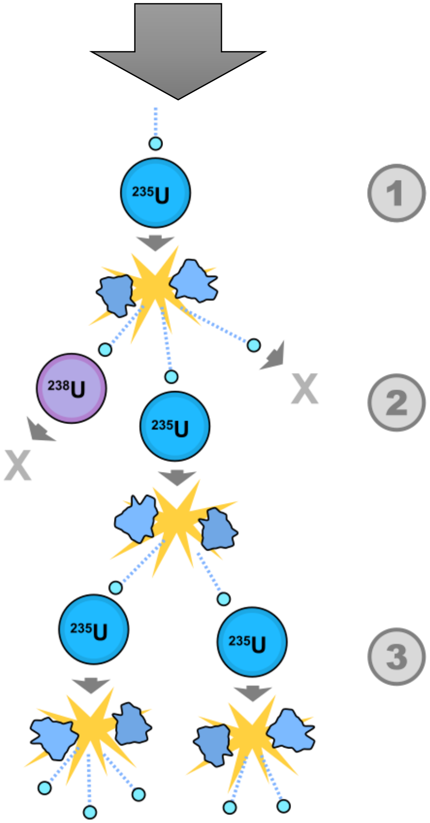
Reactor neutrinos and detection

- Nuclear power plants as powerful sources
  - Electron antineutrinos ($\bar{\nu}_e$) from β decays
  - Averaged 6 $\bar{\nu}_e$ per fission
  - 6×10^{20} $\bar{\nu}_e$/sec/3 GW_{th}



From wiki



From wiki

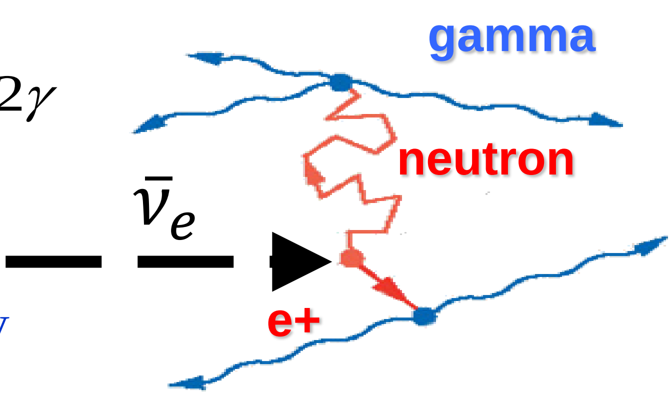
- Detected by inverse beta decay (IBD) with a pair of coincidence signals

Prompt signal

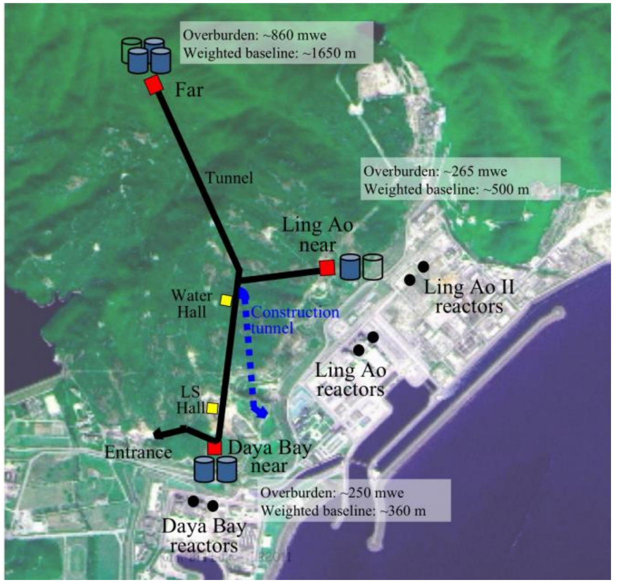
$$e^+ + e^- \rightarrow 2\gamma$$

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

Capture on H or **Gd**,
Delayed signal, 2.2 or 8 MeV

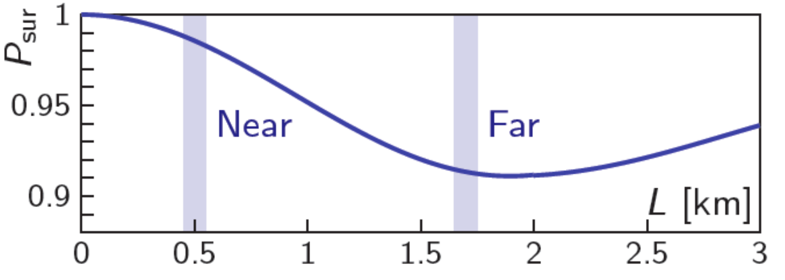


Daya Bay experiment



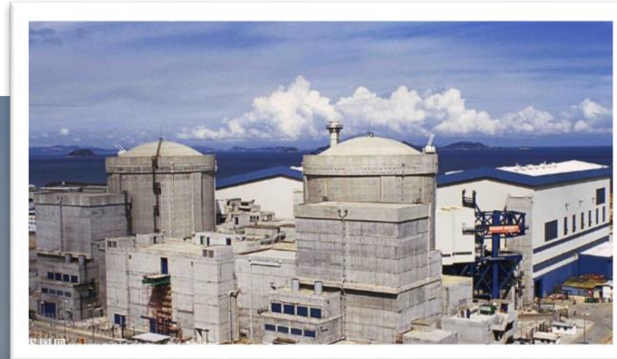
- Reactor thermal power: 2.9 GW×6=17.4 GW
- Detector target mass: 20 ton×8=160 ton
- Relative rate deficit and spectrum distortion between far and near detectors to extract θ_{13}
- Absolute efficiency and detector response with oscillation correction to measure reactor neutrino flux and spectrum

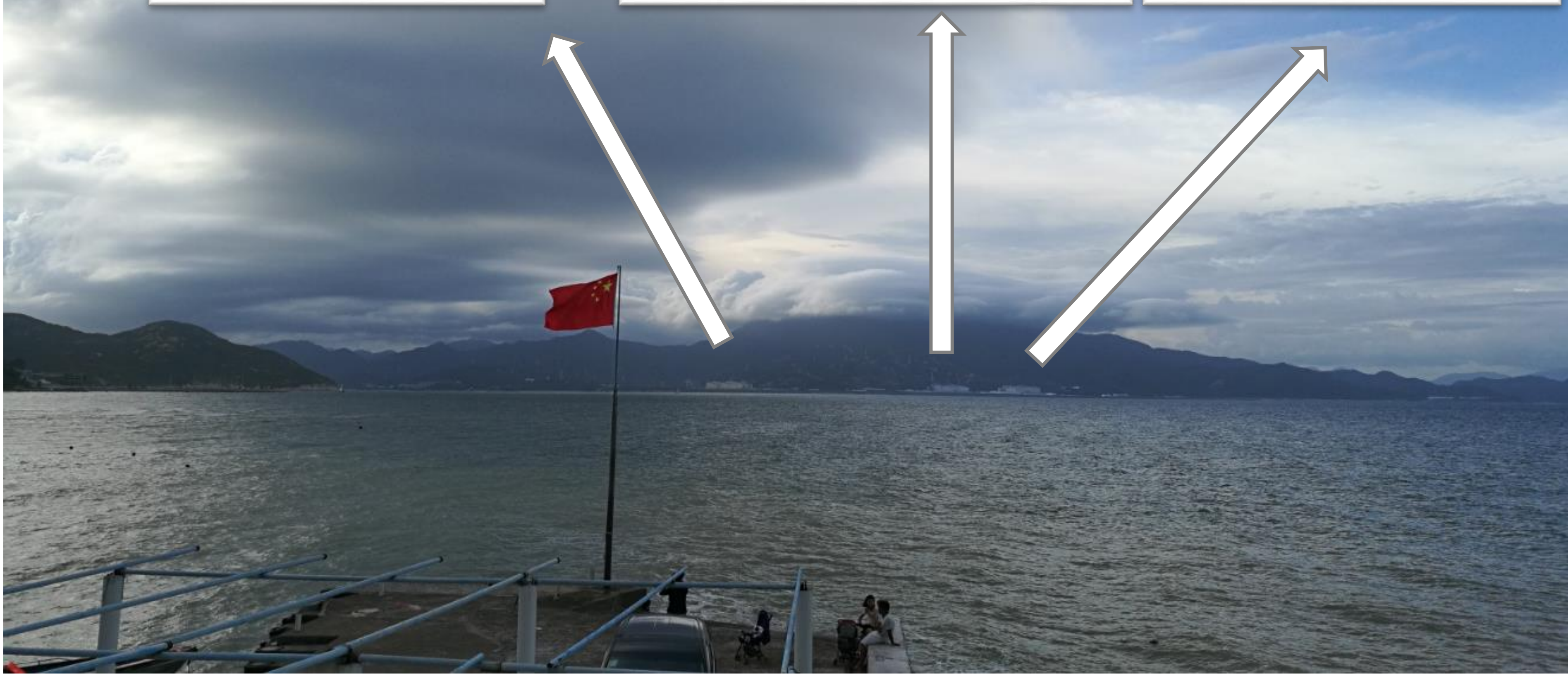
- **Measurement of the Reactor Antineutrino Flux and Spectrum at Daya Bay**
  PRL 116, 061801 (2016)
- **Improved measurement of the reactor antineutrino flux and spectrum at Daya Bay**
  CPC 41, 1, 013002 (2017)
- **Evolution of the Reactor Antineutrino Flux and Spectrum at Daya Bay**
  PRL 118, 251801 (2017)



- Flux-weighted baseline
  - Near detectors: 560m-600m
  - Far detectors: 1640m

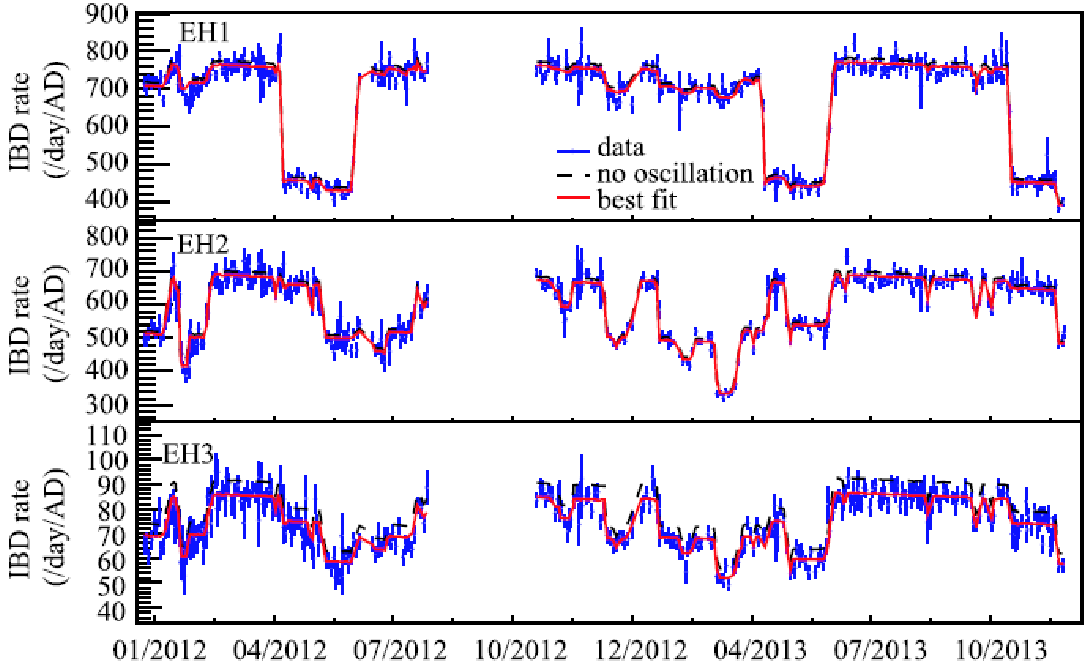
Daya Bay Ling Ao Ling Ao II



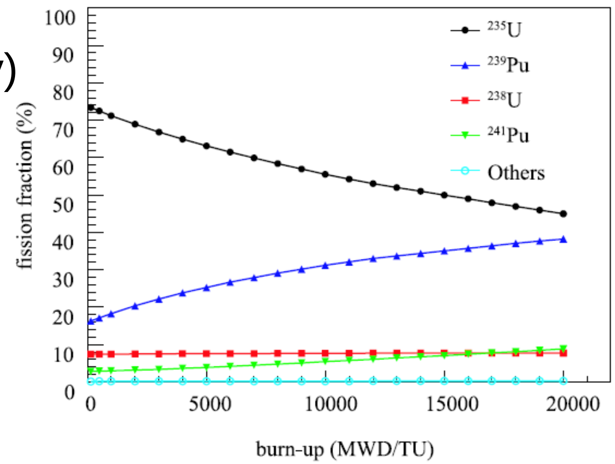


Prediction of flux and spectrum

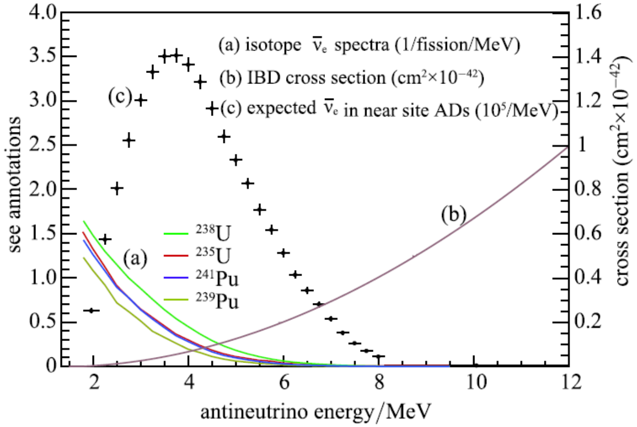
- Reactor: power, fission fraction, non-equilibrium, spent fuel
- Isotope neutrino spectrum:
  - ILL measurement and Vogel calculation (2.7% uncertainty)
  - Huber+Mueller's new calculation (2.4% uncertainty)
- Detector: cross section, efficiency, energy response



Measured and predicted daily neutrino rates are consistent with proper normalization



Nuclear fuel revolution



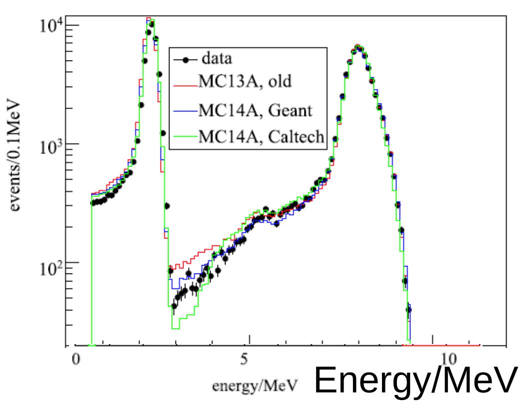
Expected $\bar{\nu}_e$ spectrum

Absolute efficiency

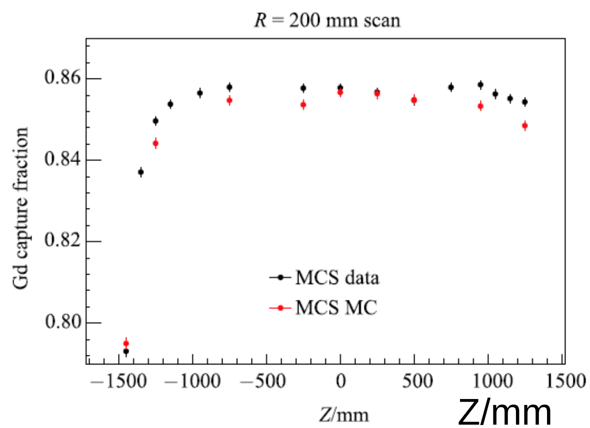
- Careful MC tuning, good agreement with data

source	ϵ	$\delta\epsilon/\epsilon$
target protons	—	0.92%
flasher cut	99.98%	0.01%
capture time cut	98.70%	0.12%
prompt energy cut	99.81%	0.10%
Gd capture fraction	84.17%	0.95%
nGd detection efficiency	92.71%	0.97%
spill-in correction	104.86%	1.00%
combined	80.60%	1.93%

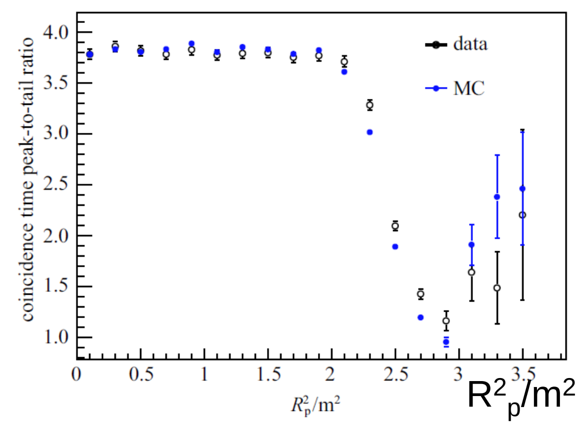
Related to Gd concentration, neutron propagation and neutron captured gamma spectrum



Neutron capture spectrum



Gd capture fraction



Capture time profile

Neutrino flux measurement

Near detectors measurement

$Y_0 = (1.53 \pm 0.03) \times 10^{-18} cm^2/GW/day$
$\sigma_f = (5.91 \pm 0.12) \times 10^{-43}\ cm^2/fission$

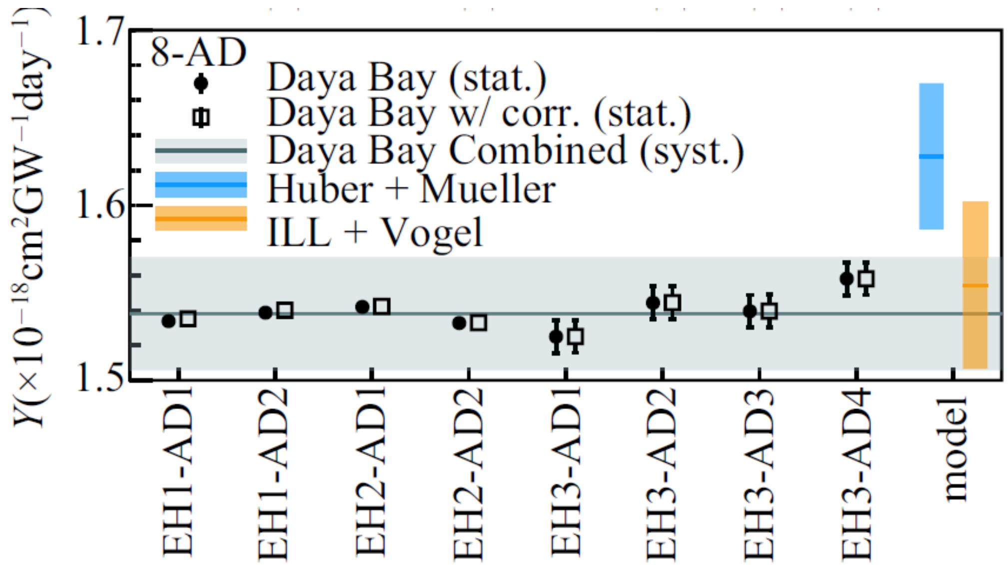
Comparison to flux models

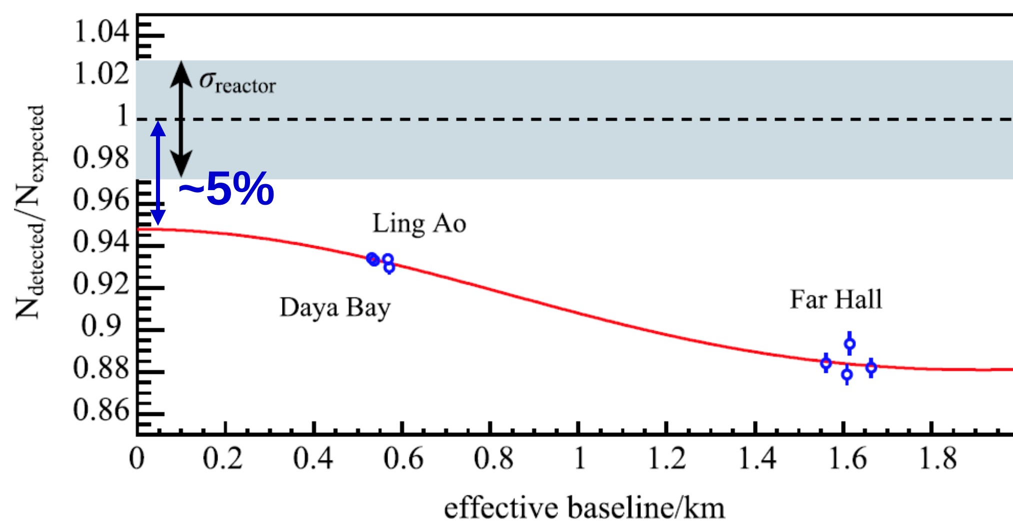
Data/Prediction (ILL+Vogel)
0.992 ± 0.021

Data/Prediction (Huber+Mueller)
0.946 ± 0.020: ~5% deficit

Flux-weighted average fission fractions

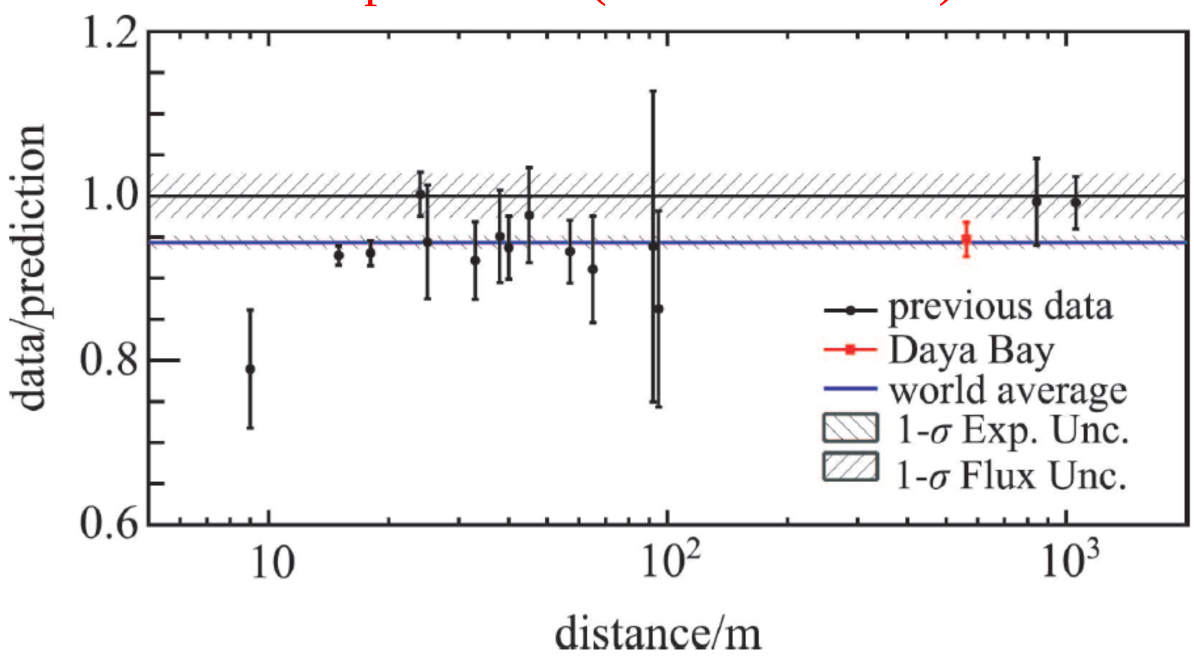
^{235}U	^{238}U	^{239}Pu	^{241}Pu
0.561	0.076	0.307	0.056





Comparison with past experiments

Experiments/(Huber+Mueller)



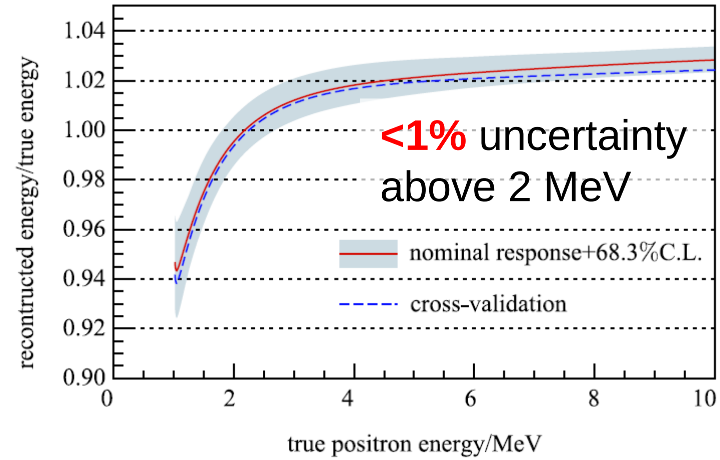
R_{global}= 0.942 ±0.009

R_{DYB}= 0.946 ±0.020

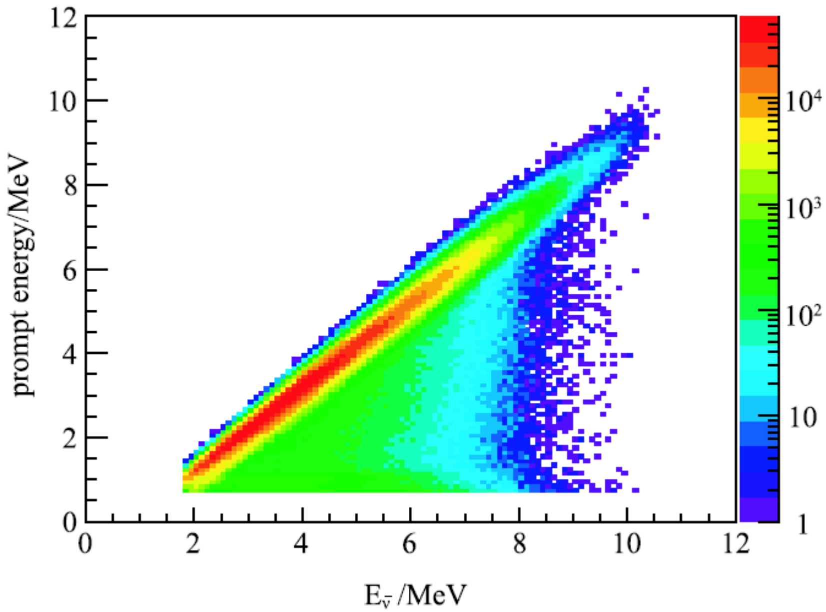
- Daya Bay's flux is consistent with previous short baseline experiments: ~5% deficit, known as "*Reactor Antineutrino Anomaly*".
- Either uncertainty of the reactor model is underestimated, or an additional oscillation with eV-mass-scale sterile neutrinos.

Detector response

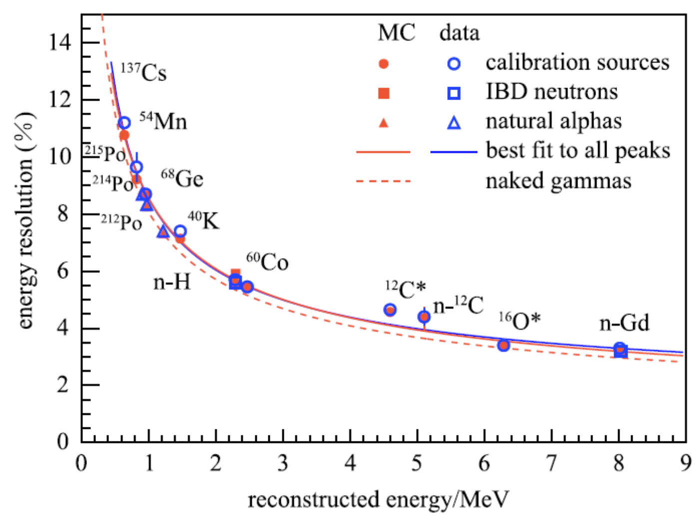
- Method 1: Geant4 based MC simulation tuned with data
- Method 2: analytical calculation with input from data
- Additional uncertainty below 1.25 MeV from method 1&2 difference



Energy nonlinearity



Detector response matrix



Energy resolution

Prompt spectrum measurement

- χ^2 definition

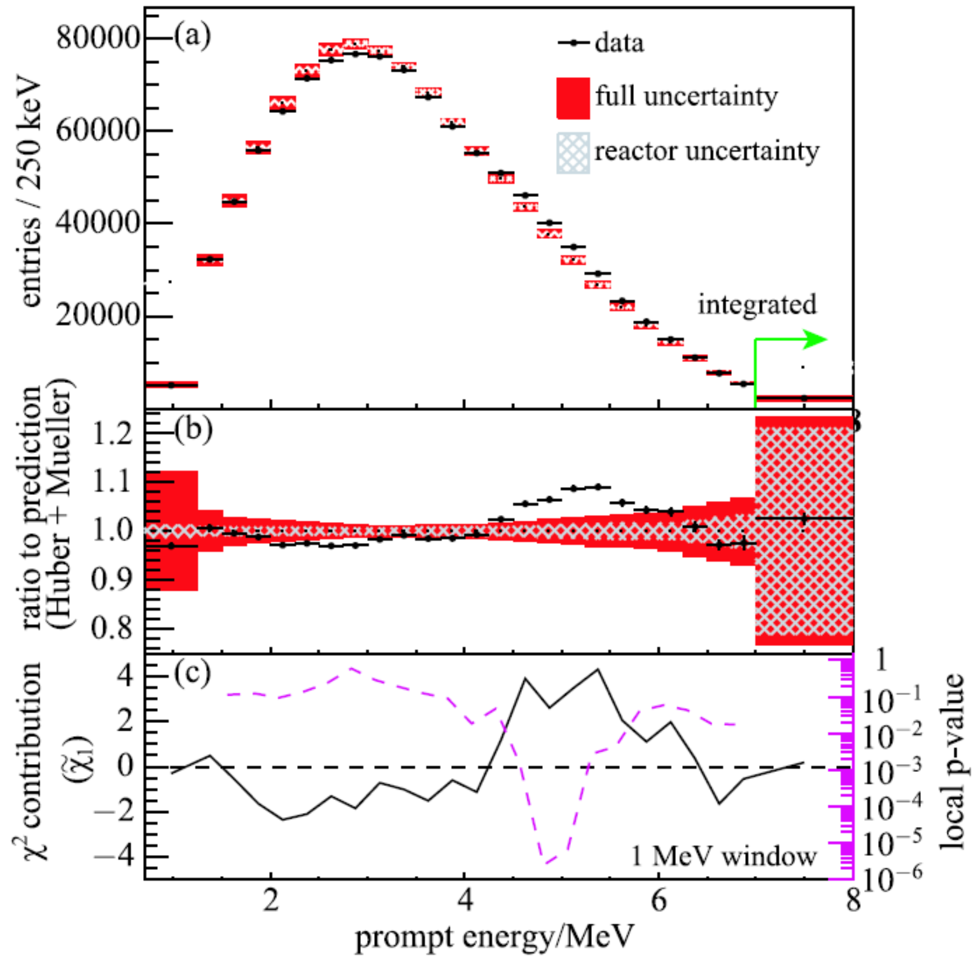
$$\chi^2 = \sum_{i,j} (N_i^{\text{obs}} - N_i^{\text{pred}})(V^{-1})_{ij}(N_j^{\text{obs}} - N_j^{\text{pred}})$$

- Covariance matrix

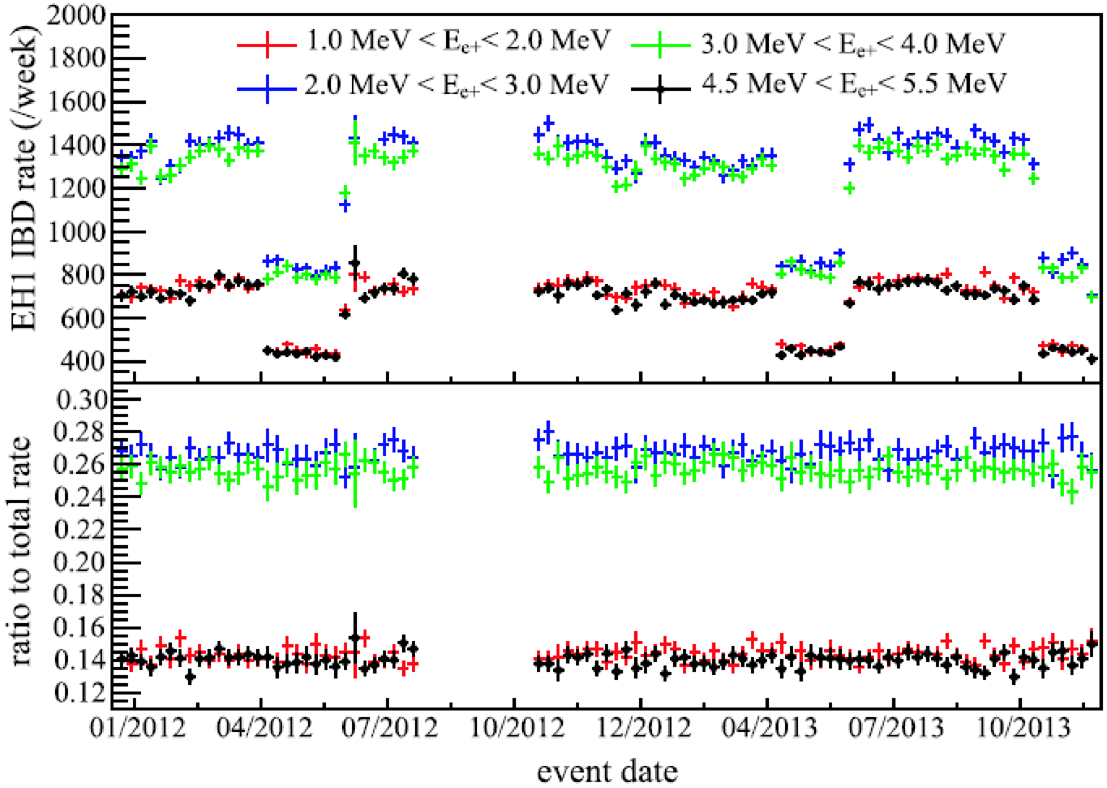
$$V = V^{\text{stat}} + V^{\text{sys}}$$

$$V_{ij}^{\text{sys}} = \frac{1}{N^{\text{expts}}} \sum^{N^{\text{expts}}} (N_i^{\text{ran}} - N_i^{\text{nom}})(N_j^{\text{ran}} - N_j^{\text{nom}})$$

- A clear "bump" in 4-6 MeV when compared to Huber+Mueller model, local significance 4.4σ
- Comparison to ILL+Vogel model gives similar "bump"



Source of the bump

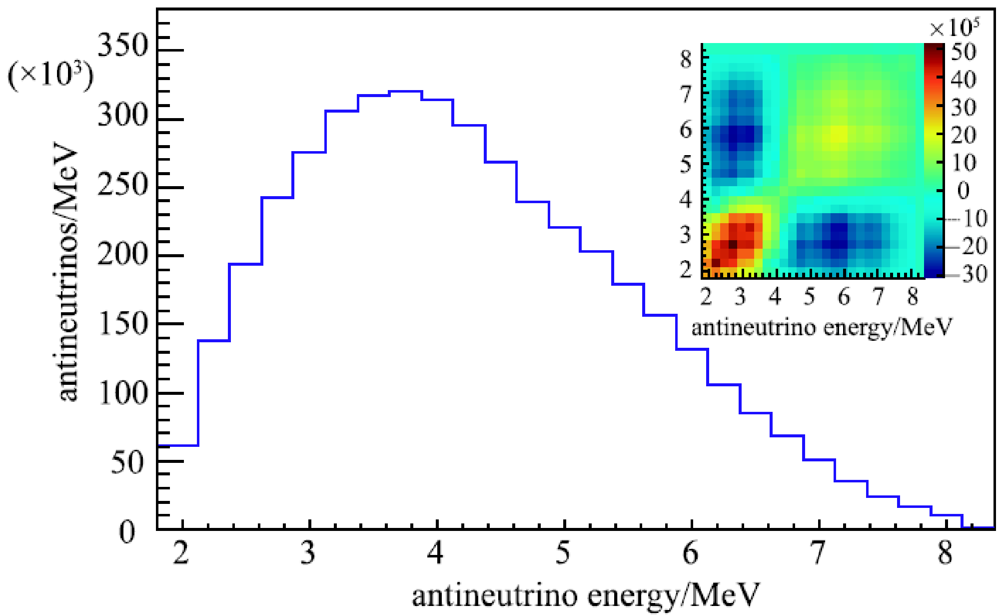


Event rates in and out of the bump are highly correlated.

- Evidence that the 4-6 MeV excess comes from reactors
  - NOT from background or energy nonlinearity
  - Clear correlation with reactor thermal power
- Underestimation of reactor prediction uncertainty?

Generic reactor antineutrino spectrum

- Unfolding to neutrino energy: SVD regularization method and Bayesian iterative method give consistent results
- Correction of oscillations
- Normalization of baselines and nuclear fission

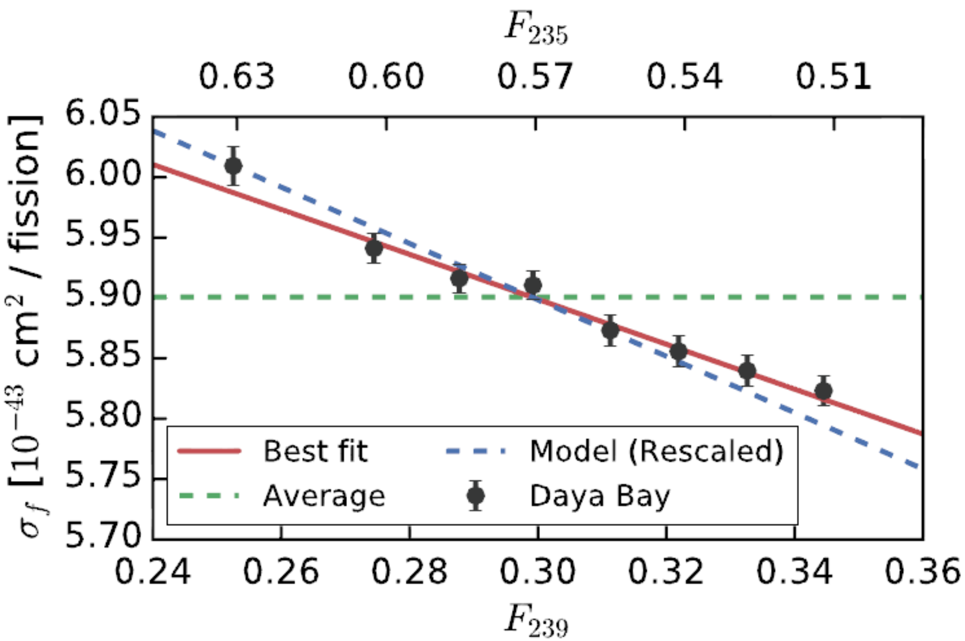


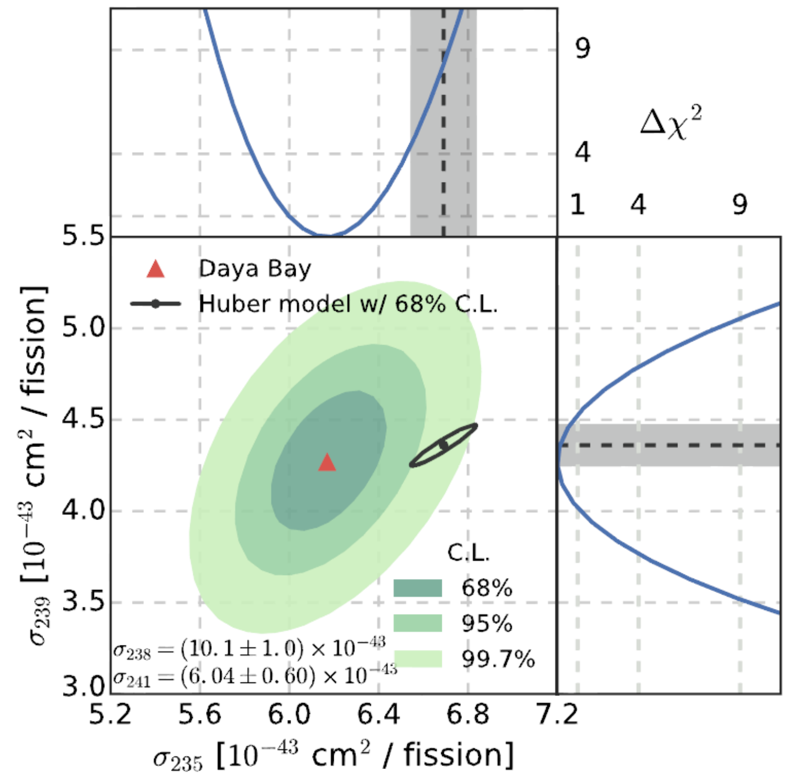
Unfolded antineutrino spectrum

A model-independent spectrum for other reactor experiments, with small correction to different fission fractions.

Reactor fuel evolution

- Study of the neutrino flux and shape changing with reactor fuel evolution by Daya Bay
- ^{235}U appears to be the main contributor to the reactor anomaly
- Equal deficit hypothesis suggested by the sterile neutrino as the sole cause of reactor anomaly is disfavored by 2.8σ





Summary

- Reactor neutrinos played an important role in the history, leading to the first discovery of the neutrino, the first confirmation of solar neutrino oscillation, and the first observation of θ_{13}
- Daya Bay has measured the absolute neutrino flux, spectrum, and the fuel revolution
  - **σ_f = (5.91±0.12)×10^{-43} cm^2/fission,** consistent with previous experiments, ~5% deficit compared to Huber+Mueller model
  - A “bump” in 4-6 MeV of prompt energy was found when compared to reactor models, with local significance 4.4σ
  - Reactor fuel evolution study suggests ^{235}U as the main contributor to the reactor anomaly, and disfavors sterile neutrino as the sole cause by 2.8σ
- Future plan
  - Reduce absolute efficiency uncertainty to improve flux measurement
  - Reduce energy response uncertainty to improve spectrum measurement
  - Improve fuel revolution study and try isotopes decomposition