



Recent Results from the Daya Bay Experiment

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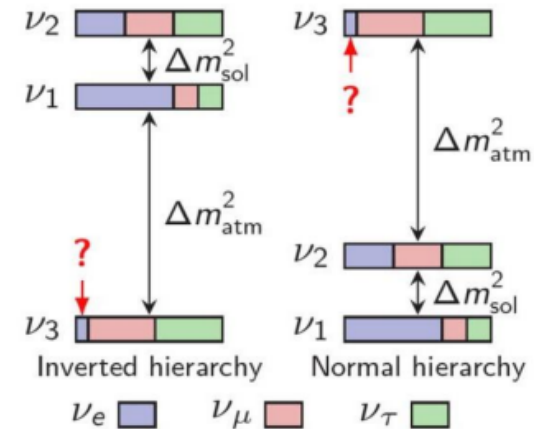
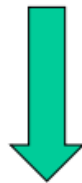
On behalf of the Daya Bay collaboration

Colloquium Towards CP violation in neutrino Physics, Prague 2017

Neutrino oscillation

flavor eigenstate $\xleftrightarrow{\text{neutrino mixing}}$ mass eigenstate

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



NH: $|\Delta m_{31}^2| = |\Delta m_{32}^2| + |\Delta m_{21}^2|, |\Delta m_{31}^2| > |\Delta m_{32}^2|$

IH: $|\Delta m_{31}^2| = |\Delta m_{32}^2| - |\Delta m_{21}^2|, |\Delta m_{31}^2| < |\Delta m_{32}^2|$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_{23} & \sin \theta_{23} \\ 0 & -\sin \theta_{23} & \cos \theta_{23} \end{pmatrix} \begin{pmatrix} \cos \theta_{13} & 0 & \sin \theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin \theta_{13} e^{i\delta} & 0 & \cos \theta_{13} \end{pmatrix} \begin{pmatrix} \cos \theta_{12} & \sin \theta_{12} & 0 \\ -\sin \theta_{12} & \cos \theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$\theta_{23} \sim 45^\circ$
Atmospheric
Accelerator

θ_{13} : The smallest and the last one to be determined
Reactor
Accelerator

$\theta_{12} \sim 34^\circ$
Solar
Reactor

Reactor: a powerful $\bar{\nu}_e$ source

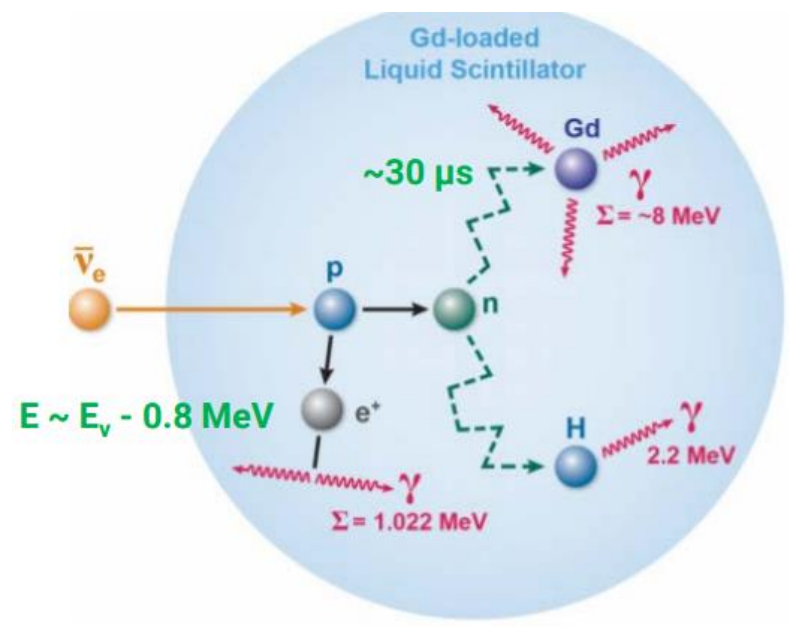
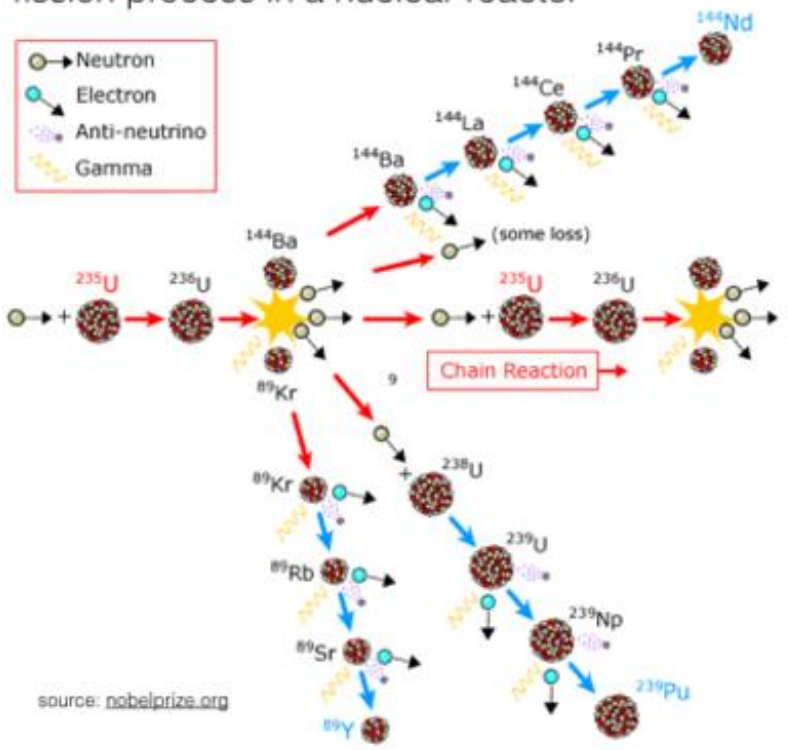
- Pure and powerful $\bar{\nu}_e$ source

- Averaged 6 $\bar{\nu}_e$ per fission
- $6 * 10^{20} \bar{\nu}_e / \text{sec} / 3 \text{GW}_{\text{th}}$

- Major detection method

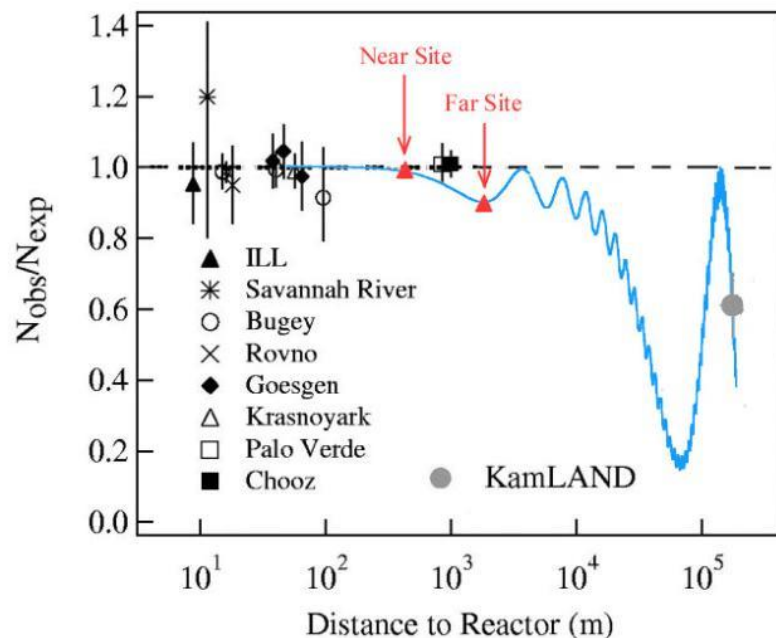
- Inverse Beta Decay: $\bar{\nu}_e + p \rightarrow e^+ + n$
- Distinctive coincidence signature

fission process in a nuclear reactor



How to measure θ_{13}

- Look for **reactor $\bar{\nu}_e$ disappearance** at short baselines (~ 1 to 2 km)
- **Clean in physics**
 - Only related to θ_{13} .
 - No relation with δ_{CP} and matter effect compared to accelerator experiments
- **Relative measurement**
 - Compare $\bar{\nu}_e$ flux and spectrum at near and far locations
 - Cancel most of the detector and reactor related systematics



$$P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} \approx 1 - \sin^2 2\theta_{13} \sin^2 \left(\frac{\Delta m_{31}^2 L}{4E} \right) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \left(\frac{\Delta m_{21}^2 L}{4E} \right)$$

The collaboration

203 collaborators from 42 institutions:

Europe (2)

JINR, Dubna, Russia
Charles University, Czech Republic

North America (16)

BNL, Iowa State Univ., Illinois Inst. Tech., LBNL, Princeton, RPI, Siena, UC-Berkeley, UCLA, Univ. of Cincinnati, Univ. of Houston, Univ. of Wisconsin-Madison, Univ. of Illinois-Urbana-Champaign, Virginia Tech., William & Mary, Yale

Asia (23)

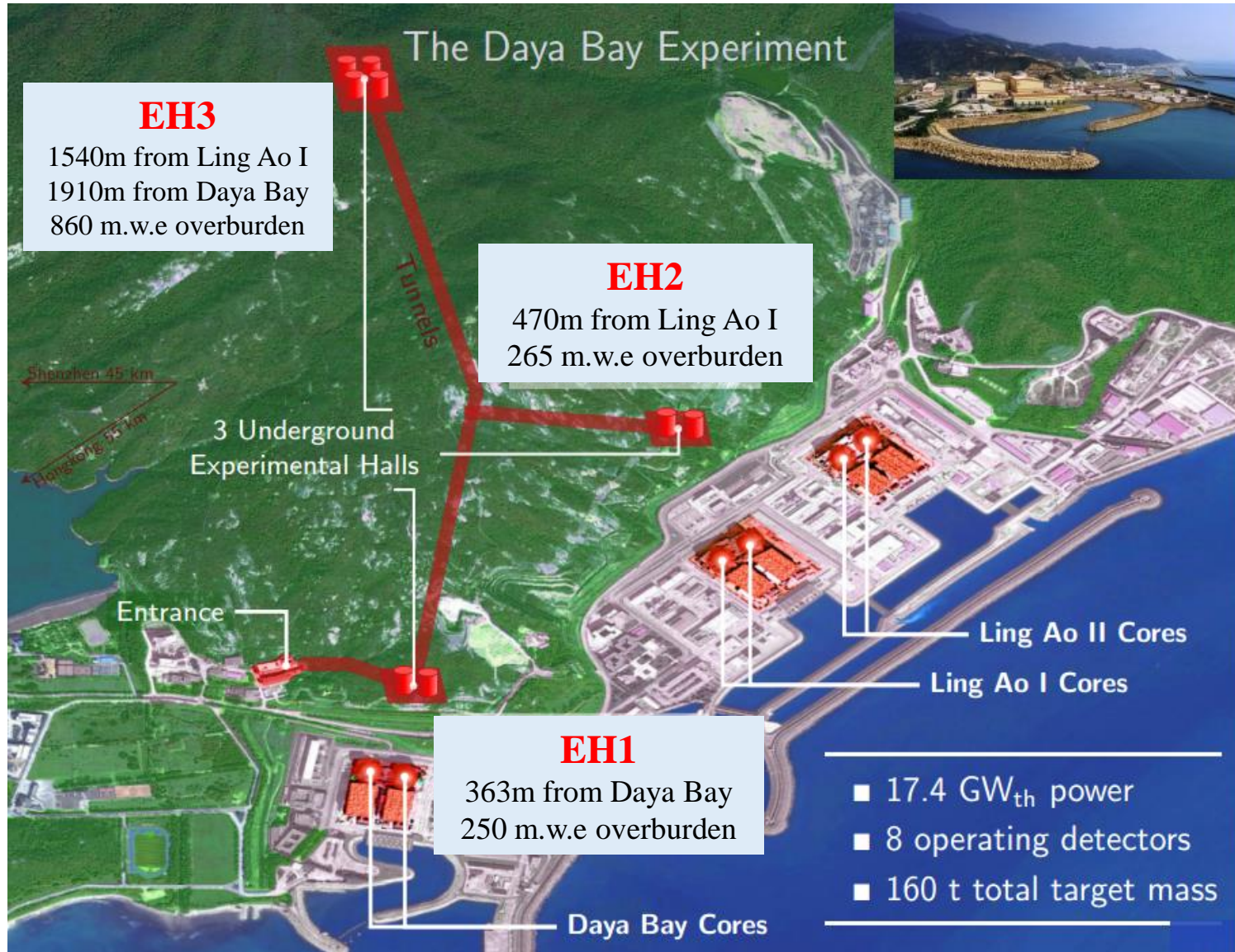
Beijing Normal Univ., CGNPG, CIAE, Dongguan Univ. Tech., IHEP, Nanjing Univ., Nankai Univ., NCEPU, Shandong Univ., Shanghai Jiaotong Univ., Shenzhen Univ., Tsinghua Univ., USTC, Zhongshan Univ., Xi'an Jiaotong Univ., NUDT, ECUST, Congqing Univ., Univ. of Hong Kong, Chinese Univ. of Hong Kong, National Taiwan Univ., National Chiao Tung Univ., National United Univ.

South America (1)

Catholic Univ., Chile



Experimental site

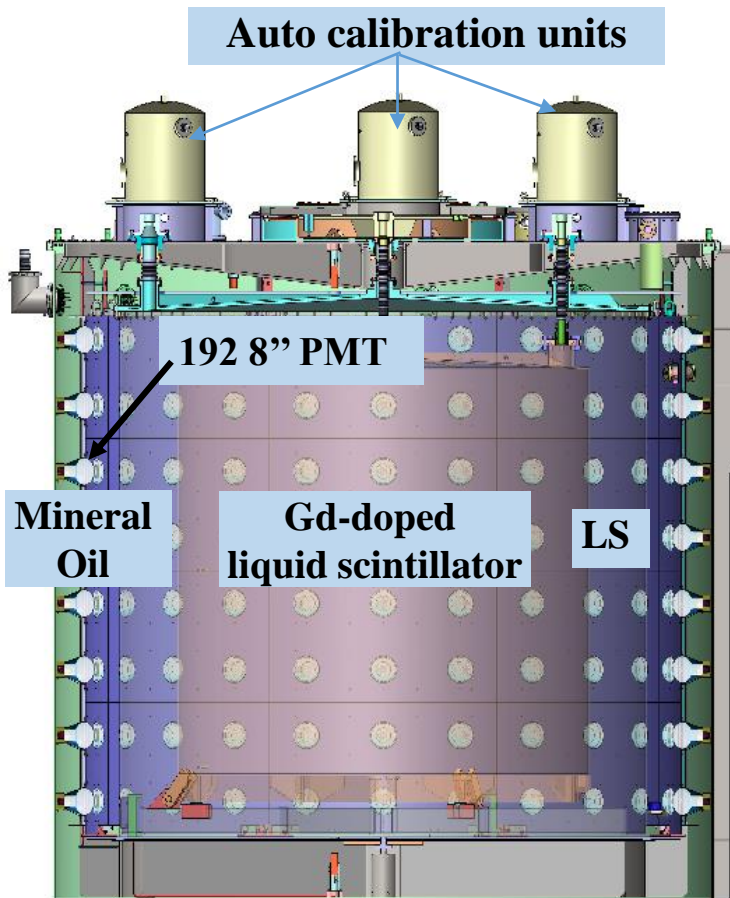


Detector

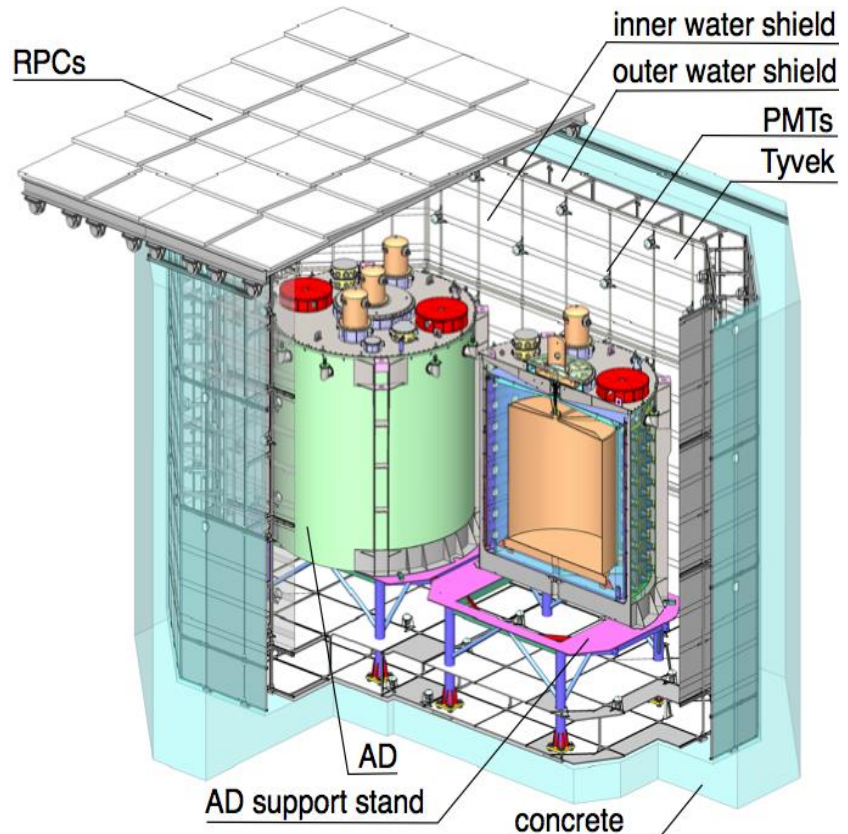
- Study the near/far ratio and spectrum distortion

Eight functionally identical detectors

$$\frac{N_{\text{Far}}}{N_{\text{Near}}} = \left(\frac{N_{\text{target,Far}}}{N_{\text{target,Near}}} \right) \left(\frac{L_{\text{Near}}}{L_{\text{Far}}} \right)^2 \left(\frac{\epsilon_{\text{Far}}}{\epsilon_{\text{Near}}} \right) \left[\frac{P_{\text{survival}}(E, L_{\text{Far}})}{P_{\text{survival}}(E, L_{\text{Near}})} \right]$$



Nucl. Instrum. Meth. A 811, 133 (2016)



Nucl. Instrum. Meth. A 773, 8 (2015)

Far Hall



Energy reconstruction

- **PMT gain calibration**

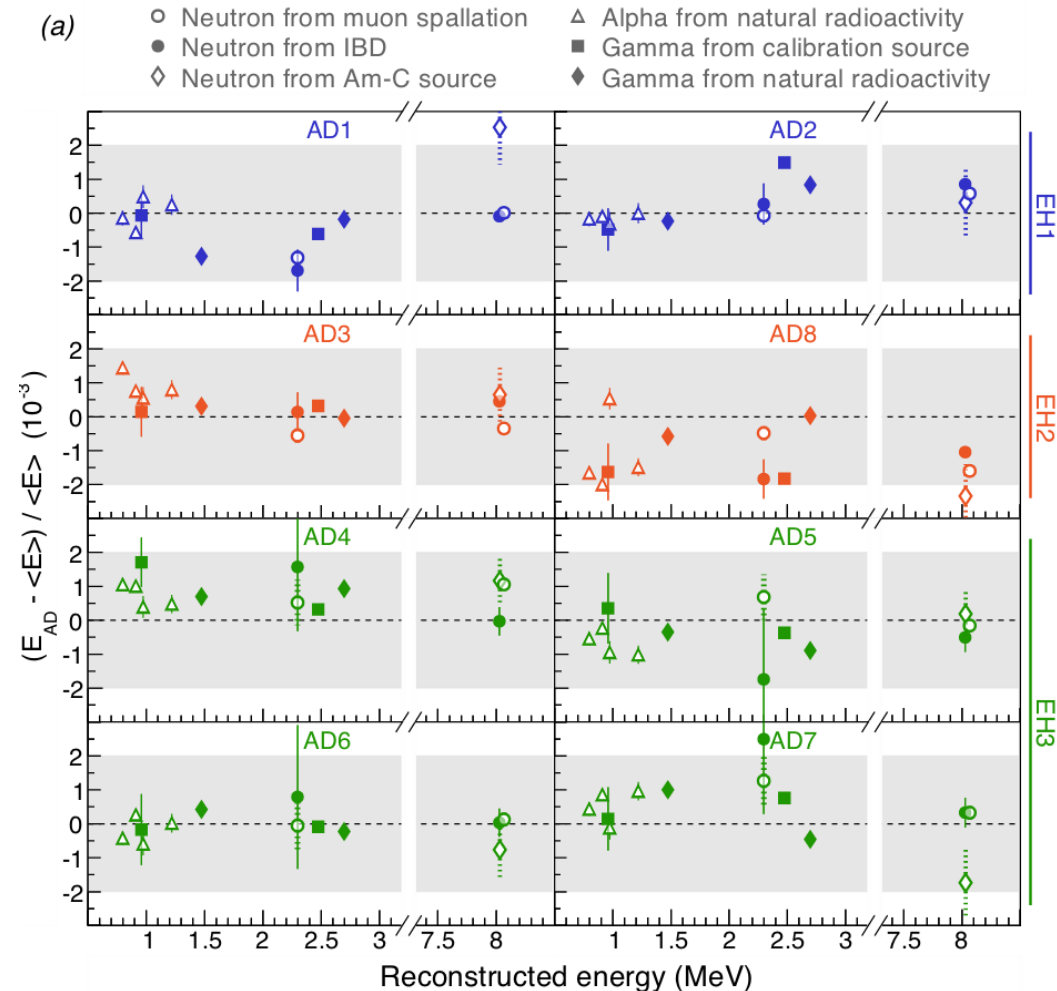
- Single p.e. from PMT dark noise
- Weekly deployment of LED

- **Energy reconstruction**

- Calibration sources
- Spallation neutrons

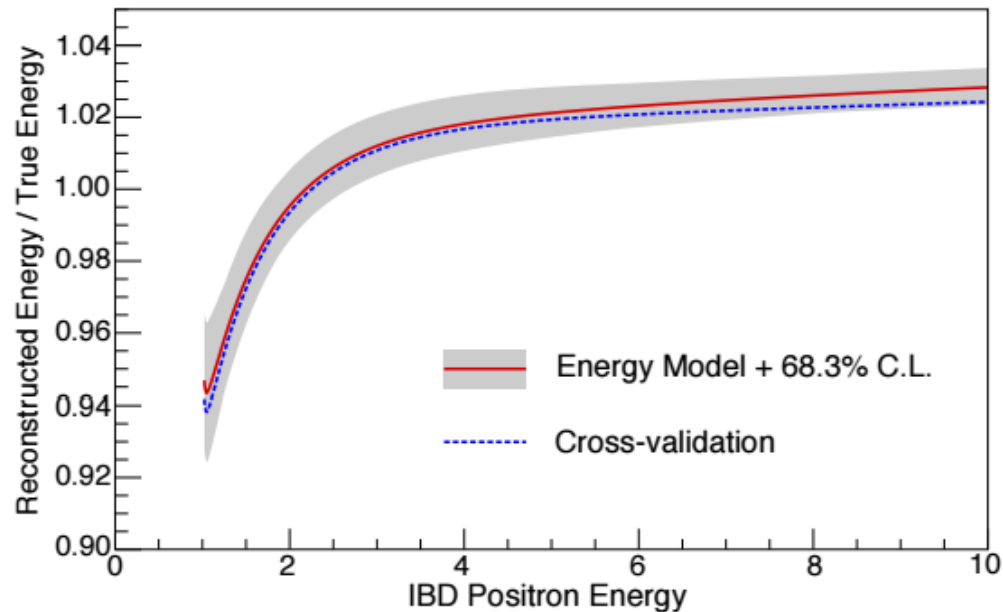
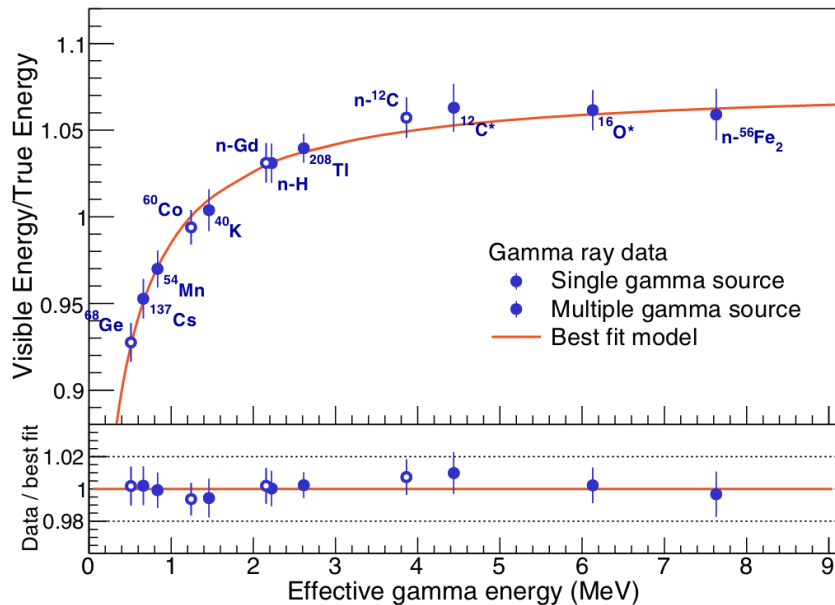
- **Relative energy scale**

- ^{68}Ge , ^{60}Co , ^{241}Am - ^{13}C
- Spallation neutrons
- Natural radioactivity



The relative energy scale uncertainty is less than 0.2%.

Energy model



- **Energy model:**

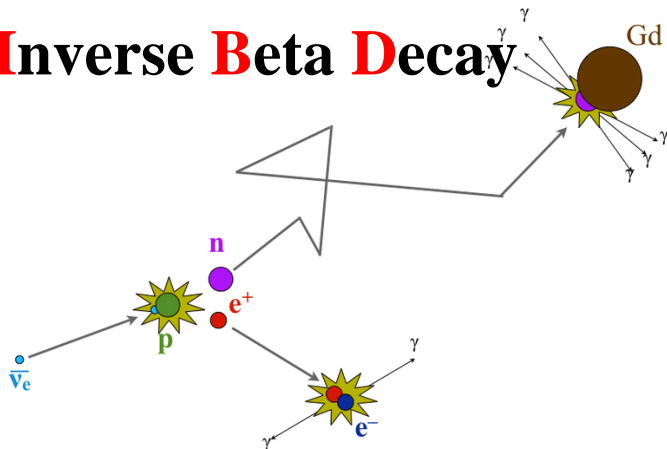
- The relationship between true energy and its reconstructed energy
- Built based on various γ peaks and continuous ^{12}B β spectrum

- **Validated with**

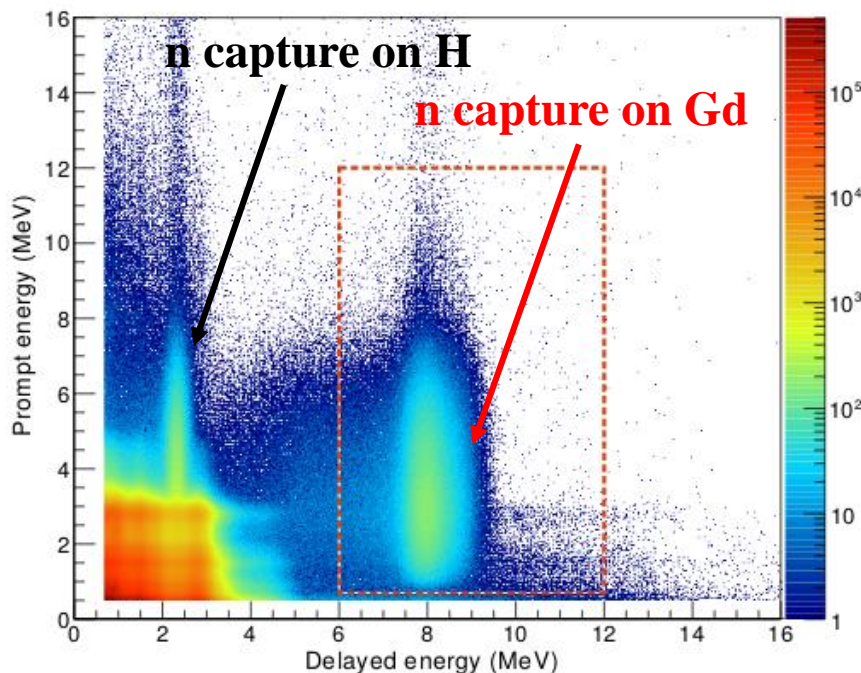
- Michel electron; $\beta+\gamma$ continuous spectra from $^{212/214}\text{Bi}$ and ^{208}Tl
- Bench tests of Compton scattering electrons in LS

$\bar{\nu}_e$ selection

Inverse Beta Decay



- Reject PMT flashers
- Muon veto
- Prompt and delayed energy cuts
- Neutron capture time cut
- Multiplicity cut

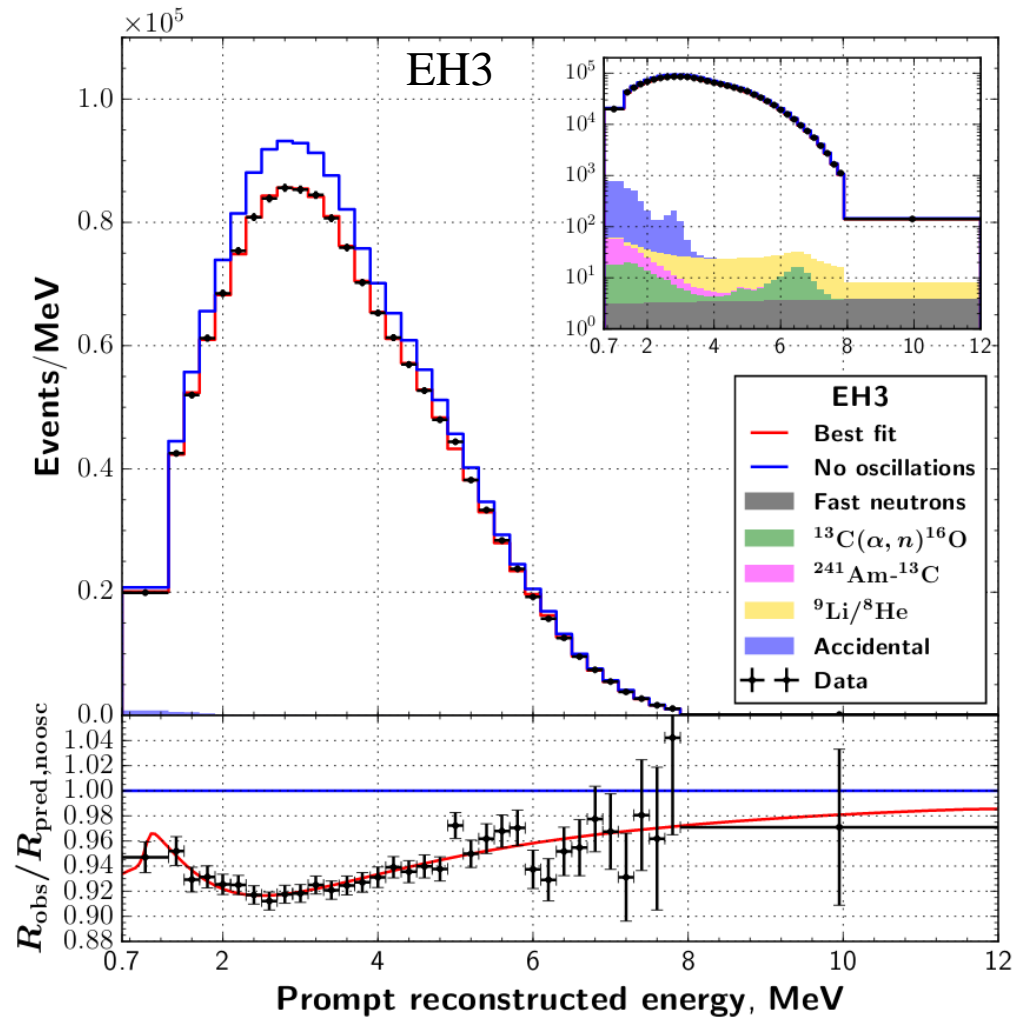


Detection efficiencies

	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%
Previous	80.6%	2.1%	0.2%

Backgrounds

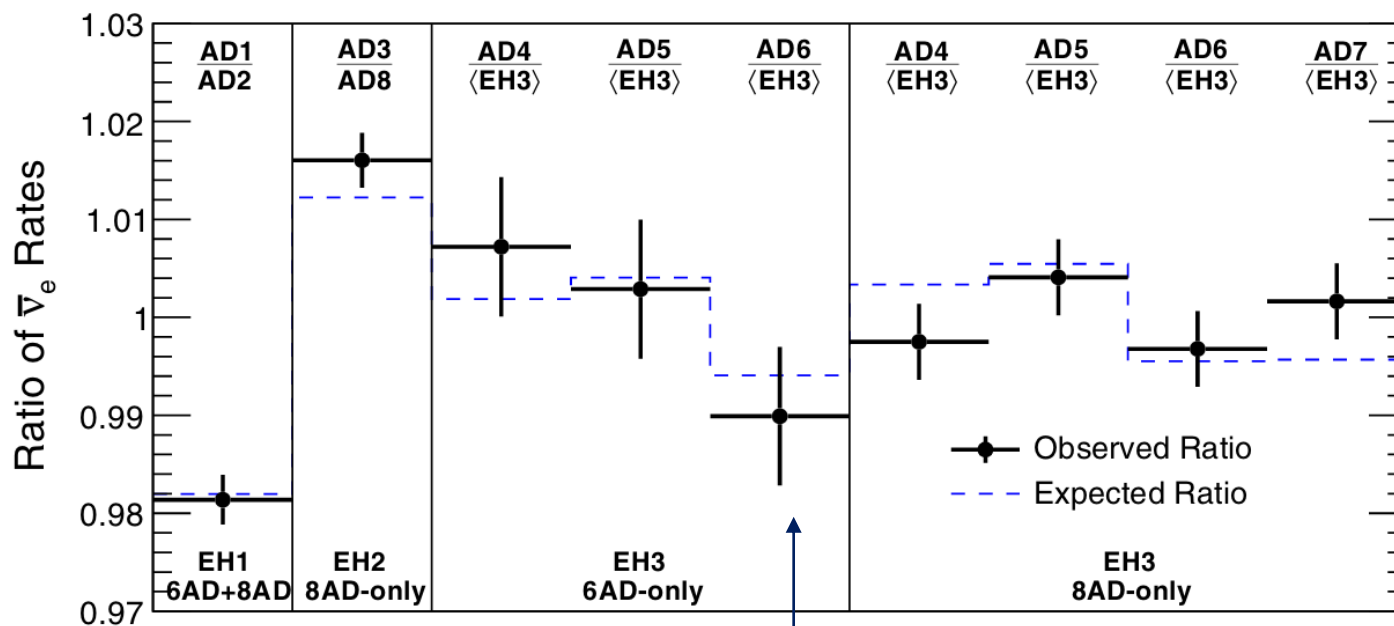
- **Accidentals:**
 - Uncertainty less than 0.02%
- **Fast neutron**
 - Uncertainty less than 0.05%
- **${}^9\text{Li}/{}^8\text{He}$**
 - Uncertainty 0.1%~0.15%
- **From the ${}^{241}\text{Am}-{}^{13}\text{C}$ source**
 - Uncertainty 0.05%~0.1%
- **${}^{13}\text{C}(\alpha,n){}^{16}\text{O}$**
 - Uncertainty less than 0.05%



Sites	B/S ratio	Background uncertainty
Daya Bay	1.8%	0.2%
Ling Ao	1.5%	0.15%
Far	2.0%	0.2%

Side by side comparison

- **Multiple detectors in the same hall**
 - **Allow examination of the 0.13% uncorrelated uncertainty**
 - The observed ratios of IBD rates are consistent with expectations



Uncertainty dominated by statistics and the 0.13% uncorrelated error. Most of the background uncertainty has been cancelled.

Two types of measurements

Over **2.5M (300K)** IBD candidates in total (the far site)!

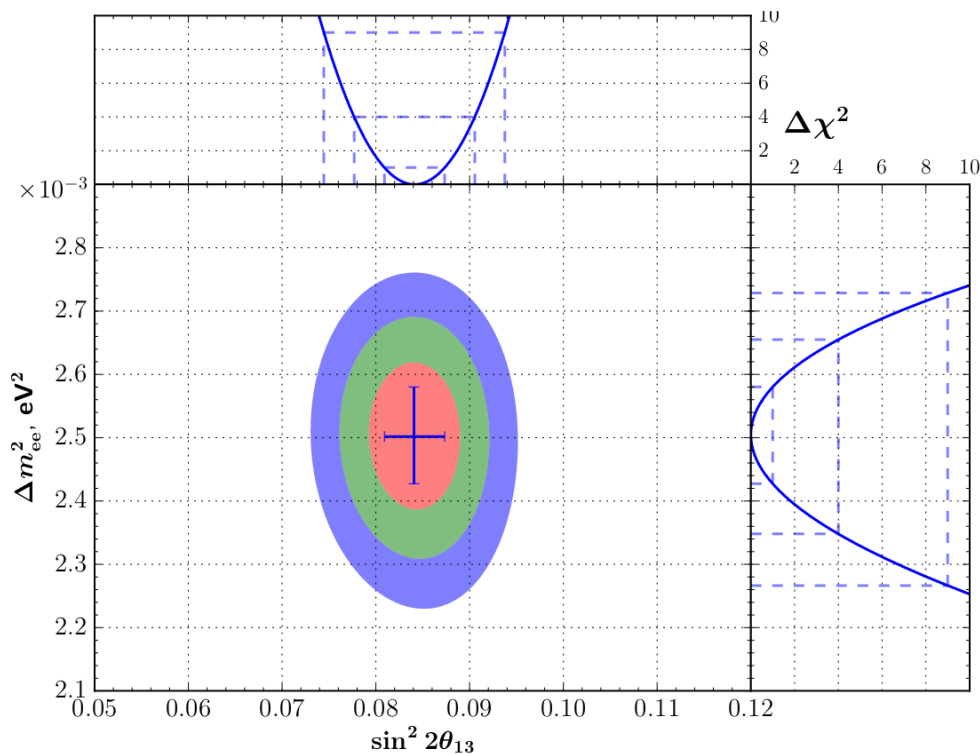
- **Relative measurement**

- Standard ν oscillation, sterile ν search, etc.
- **Compare the rate and spectrum between near and far detectors**
- Cancellation of detector and reactor systematics

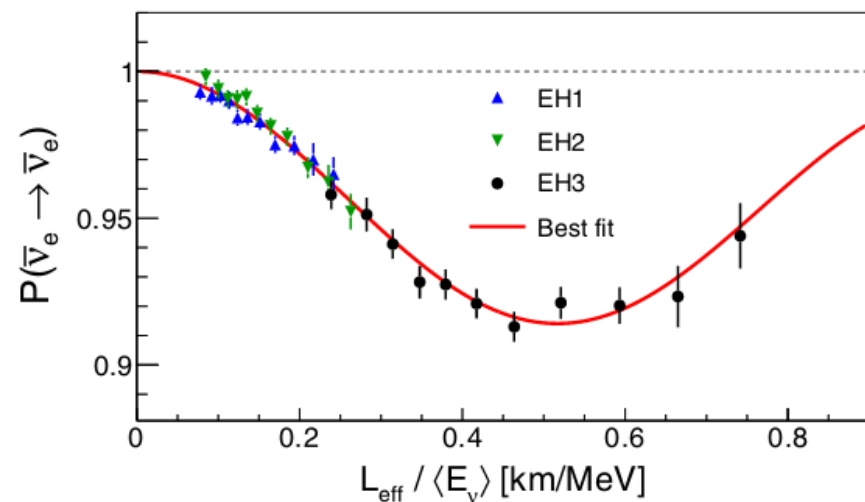
- **Absolute measurement**

- Reactor ν flux and spectrum, fuel evolution
- Compare the measurement to model predictions
- Understanding the reactor and detector systematic uncertainties

Oscillation results

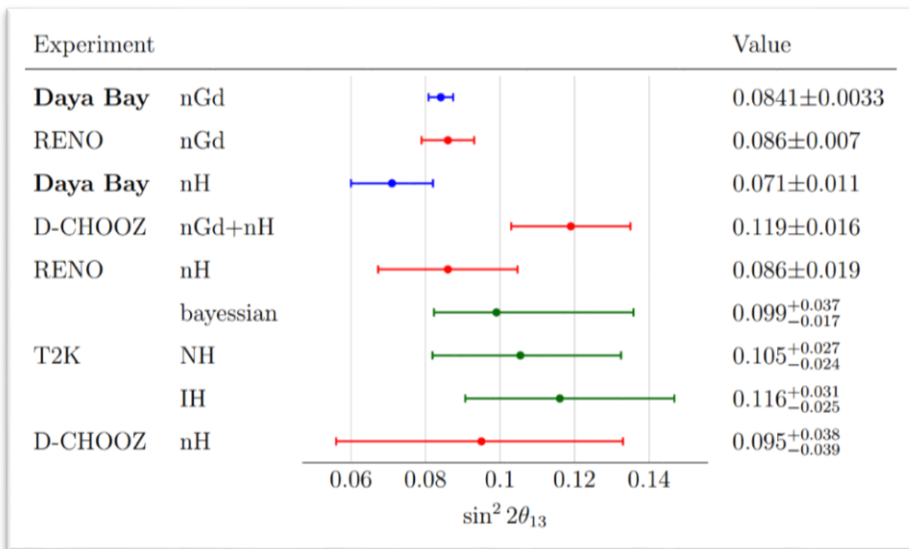


$$P = 1 - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \frac{1.267 \Delta m_{21}^2 L}{E} - \sin^2 2\theta_{13} \sin^2 \frac{1.267 \Delta m_{ee}^2 L}{E}.$$



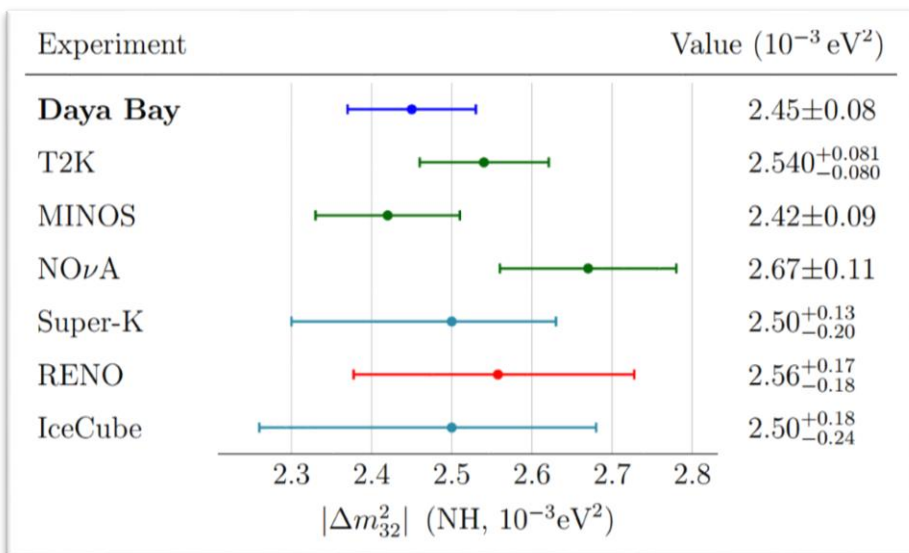
$$\begin{aligned} \sin^2 2\theta_{13} &= [8.41 \pm 0.27(\text{stat.}) \pm 0.19(\text{syst.})] \times 10^{-2} \\ |\Delta m_{ee}^2| &= [2.50 \pm 0.06(\text{stat.}) \pm 0.06(\text{syst.})] \times 10^{-3} \text{ eV}^2 \\ \chi^2/\text{NDF} &= 234.7/263 \end{aligned}$$

Latest results



- θ_{13} : reactor experiments give the most precise measurement

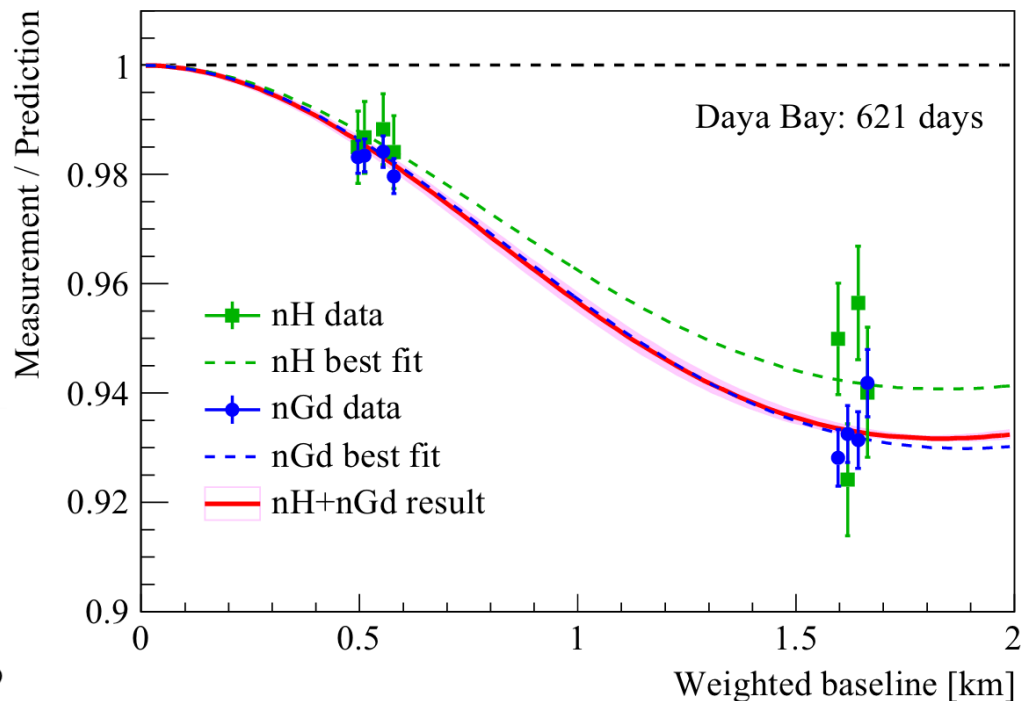
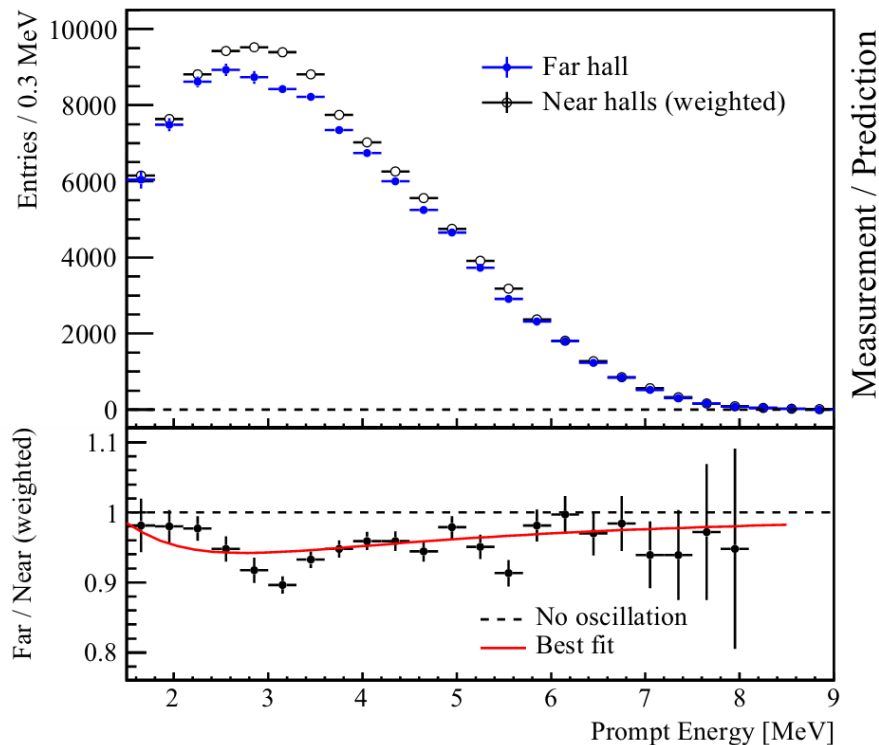
- Key input to the δ_{CP} determination in current generation accelerator experiments



- Δm_{32}^2 : consistent results between

- MeV scale reactor experiments
- GeV scale accelerator and atmospheric ones
- Beauty of nature

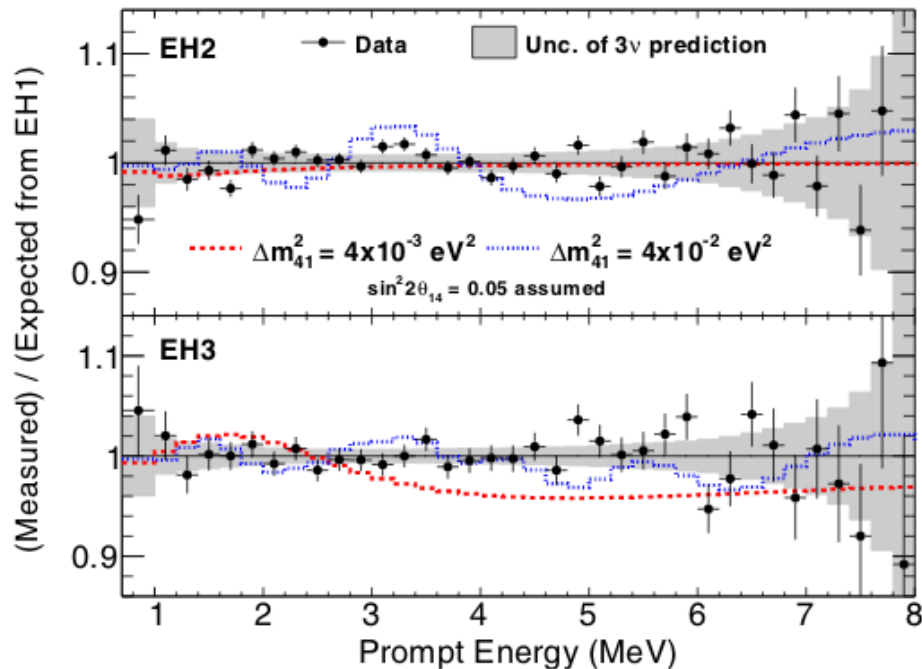
$\sin^2 2\theta_{13}$ through n-H



- **Rate analysis: $\sin^2 2\theta_{13} = 0.071 \pm 0.011$ $\chi^2/\text{NDF} = 6.3/6$**
- Consistent results with those of the n-Gd analysis
- Spectrum distortion consistent with the oscillation hypothesis

Light sterile ν search

- Results from LSND and MiniBooNE suggest the existence of a eV scale sterile neutrino
- Daya Bay could set stringent limit to sub-eV region by relative comparison between experimental halls

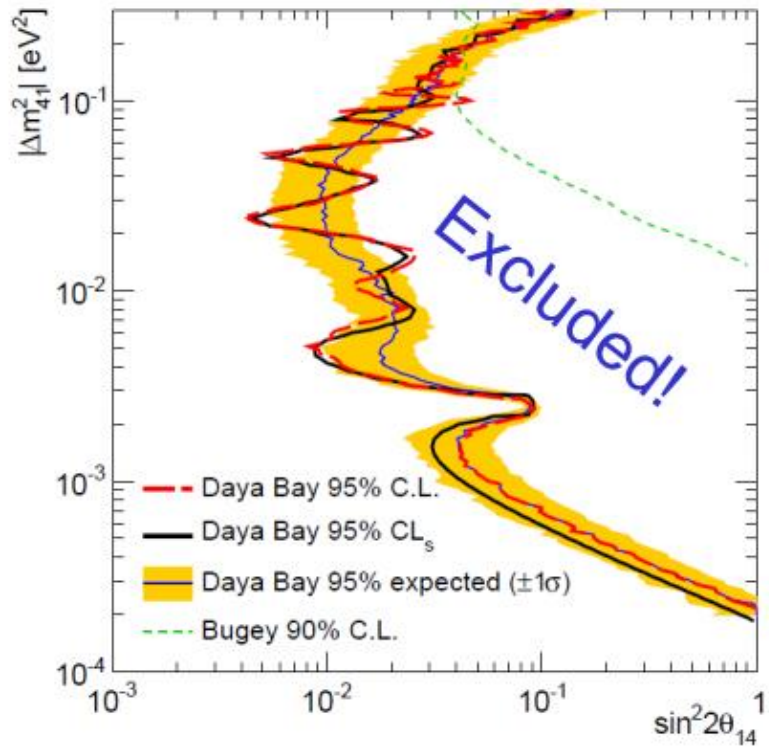


$$\begin{aligned}
 P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} &\approx 1 - 4(1 - |U_{e4}|^2)|U_{e4}|^2 \sin^2 \Delta_{41} \\
 &\quad - 4(1 - |U_{e3}|^2 - |U_{e4}|^2)|U_{e3}|^2 \sin^2 \Delta_{31} \\
 &\approx 1 - \sin^2 2\theta_{14} \sin^2 \Delta_{41} - \sin^2 2\theta_{13} \sin^2 \Delta_{31}.
 \end{aligned}$$

Light sterile ν search

- Sterile neutrino(3+1)**

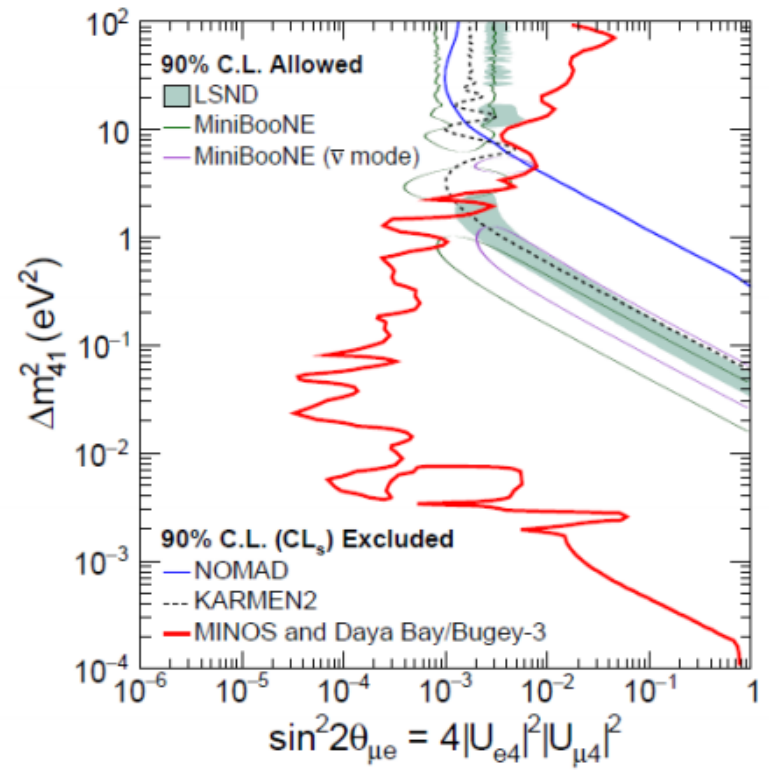
Phys. Rev. Lett. 117 ,151802(2016)



- No hint for light sterile neutrino observed
- Most stringent limit for $|\Delta m_{41}^2| < 0.2 \text{ eV}^2$

DayaBay + MINOS + Bugey-3

Phys. Rev. Lett. 117, 151801 (2016)



- Exclude parameter space allowed by LSND and MiniBooNE for $\Delta m_{41}^2 < 0.8 \text{ eV}^2$

Two types of measurements

- **Relative measurement**

- Standard ν oscillation, sterile ν search, etc.
- Comparison of rate and spectrum between near and far detectors
- Cancellation of detector and reactor systematics

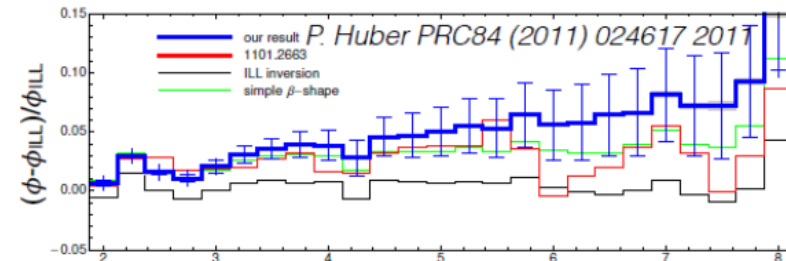
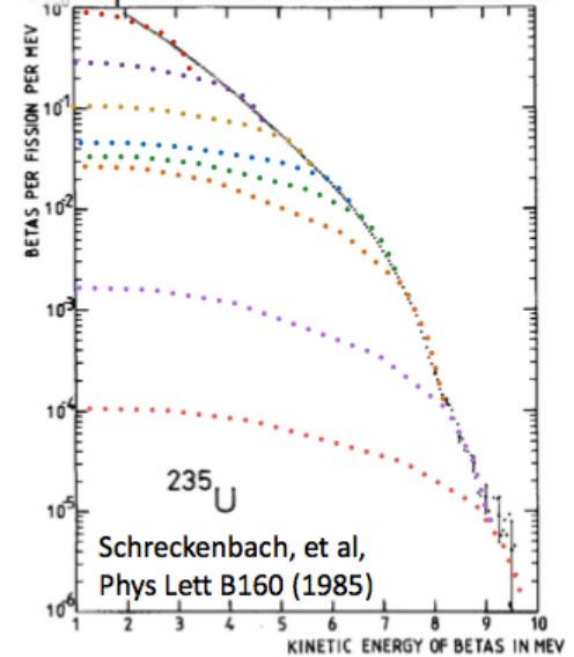
- **Absolute measurement**

- Reactor ν flux and spectrum, fuel evolution
- **Compare the measurement to model predictions**
- Understanding the reactor and detector systematic uncertainties

Reactor neutrino predictions

- **Summation method: 10% uncertainty**
 - Sum over the fission products' $\bar{\nu}_e$ spectra from the nuclear database
- **^{235}U , ^{239}Pu , ^{241}Pu : conversion method, $\sim 2.7\%$ uncertainty**
 - Convert ILL's measured beta spectra to $\bar{\nu}_e$ ones with virtual beta-decay branches
 - **ILL + Vogel model since 1980s**
 - Predicted flux was consistent with Bugey-3 and other short baseline experiments
 - **Huber + Mueller Model**
 - In 2011, two conversion re-analyses increased the predicted flux by $\sim 5\%$
 - **Reactor Antineutrino Anomaly**

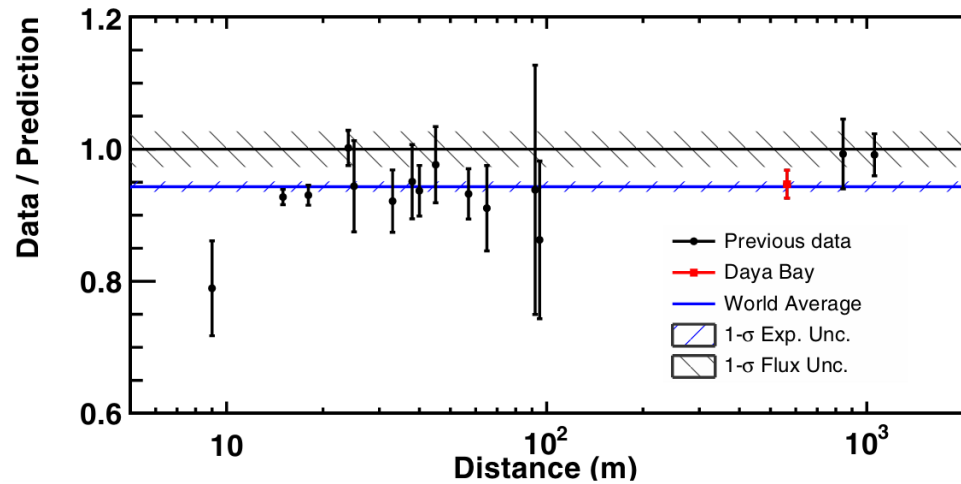
Example: Fit virtual beta branches



Absolute reactor $\bar{\nu}_e$ flux

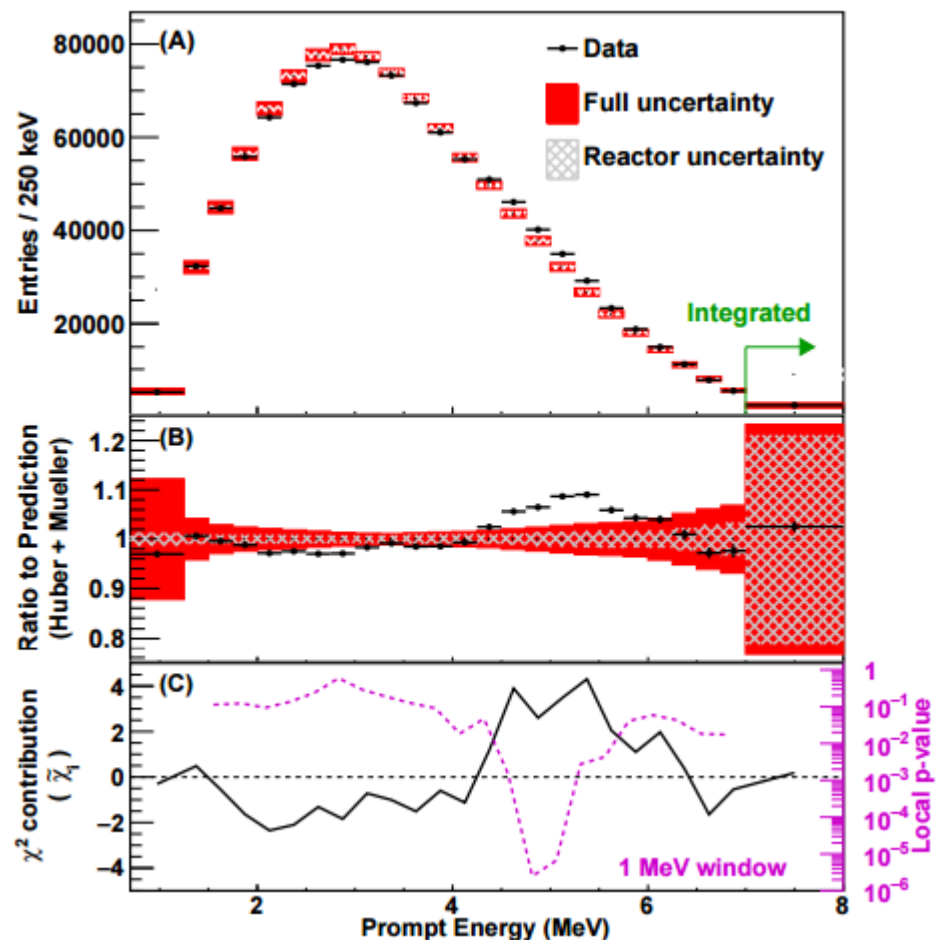
- **Daya Bay's blind analysis of reactor neutrino flux agrees with previous experiments**
- **Discrepancies to the Huber+Mueller model indicate:**
 - Over estimated flux and/or underestimated flux uncertainty
 - Or the existence of a sterile neutrino

IBD Yield	
Y (cm ² /GW/day)	$(1.53 \pm 0.03) \times 10^{-18}$
σ_f (cm ² /fission)	$(5.91 \pm 0.12) \times 10^{-43}$
Data / Prediction	
R (Huber+Mueller)	0.946 ± 0.020 (exp.)
R (ILL+Vogel)	0.992 ± 0.021 (exp.)
²³⁵ U : ²³⁸ U : ²³⁹ Pu : ²⁴¹ Pu	0.561 : 0.076 : 0.307 : 0.056

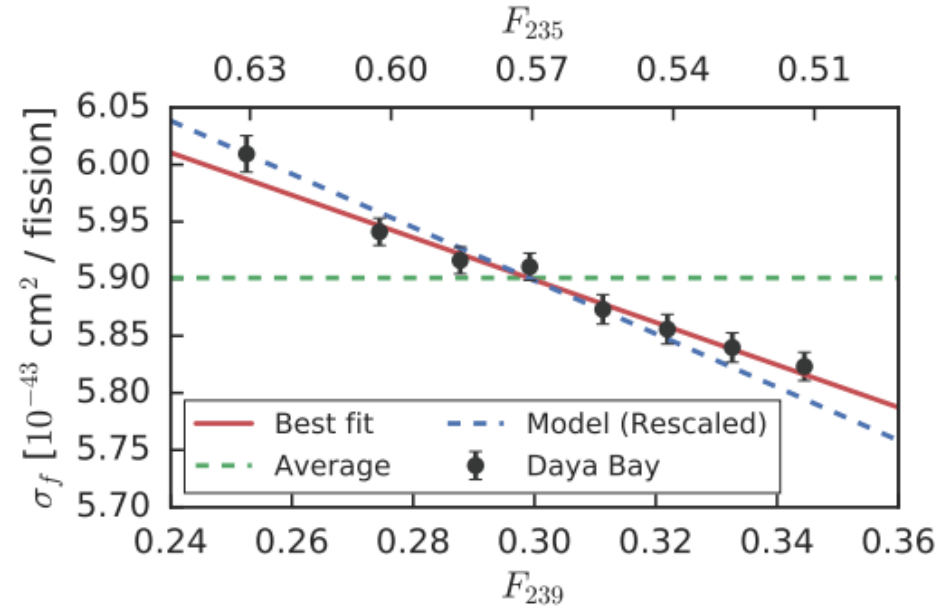
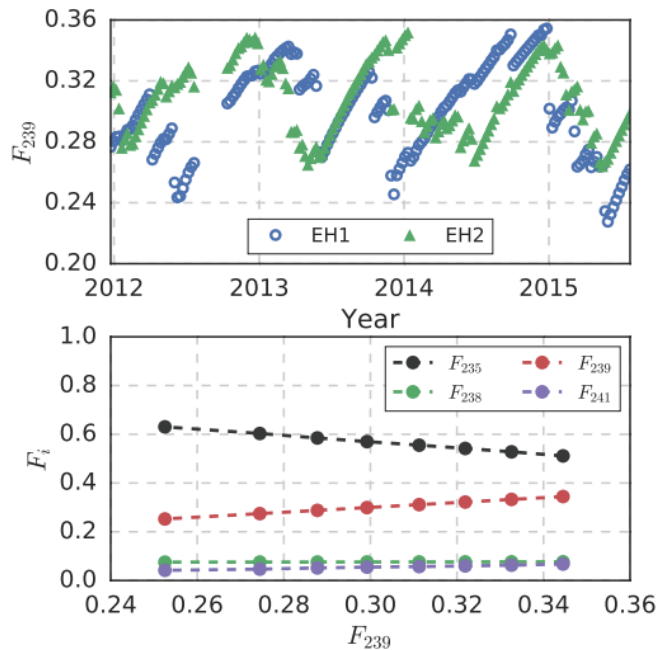


Absolute $\bar{\nu}_e$ spectrum

- **Compare the prompt energy spectrum to the Huber+Mueller model**
 - 2.9σ discrepancy at the full energy range
 - 4.4σ local significance at 4 to 6 MeV
- **Excess events have all characteristics of IBD**
 - Correlated to reactor power
 - Could not be explained by detector response



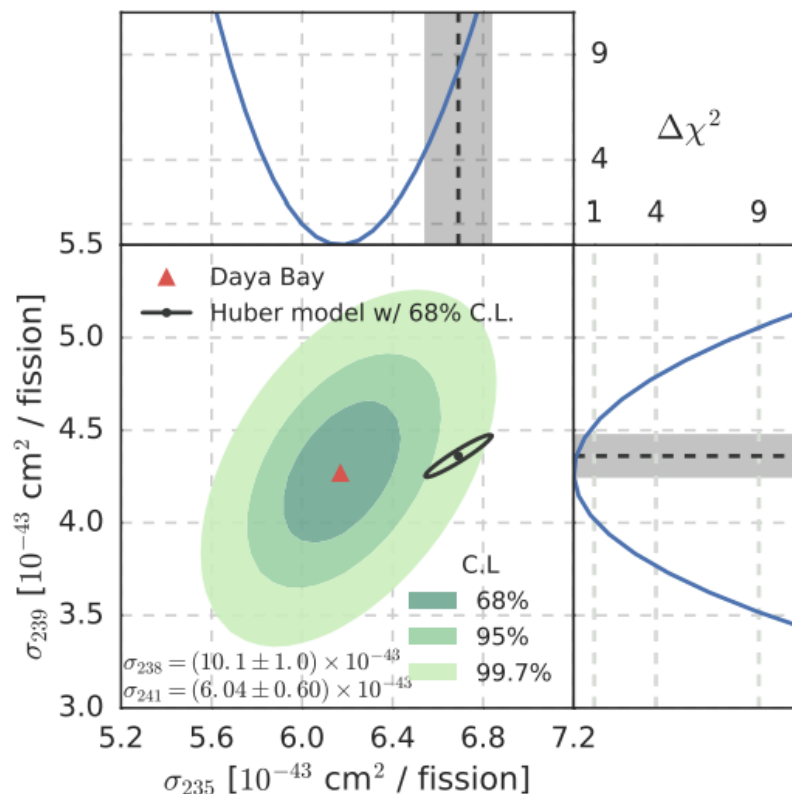
Fuel evolution analysis



- With the nuclear fuel burning, the fission fraction of ^{235}U is decreasing while ^{239}Pu is increasing
- Clear linear evolution between the neutrino yield and the ^{239}Pu fission fraction
 - However, the slopes of data and model prediction disagree

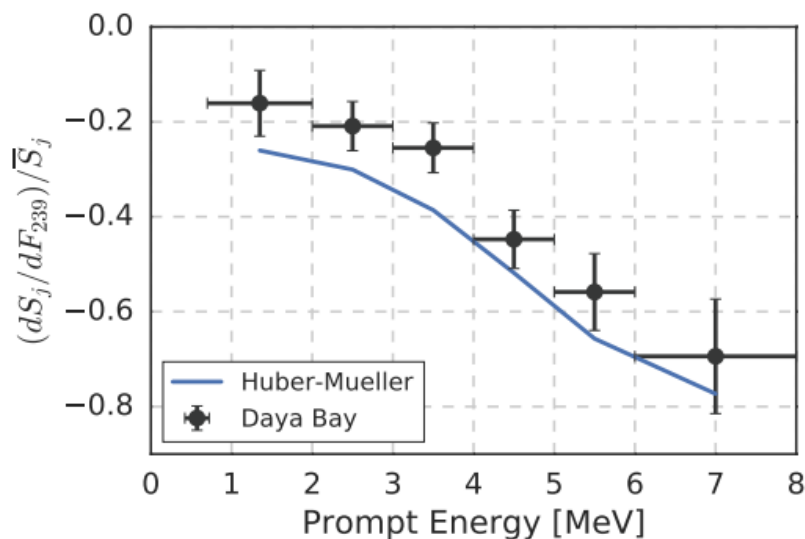
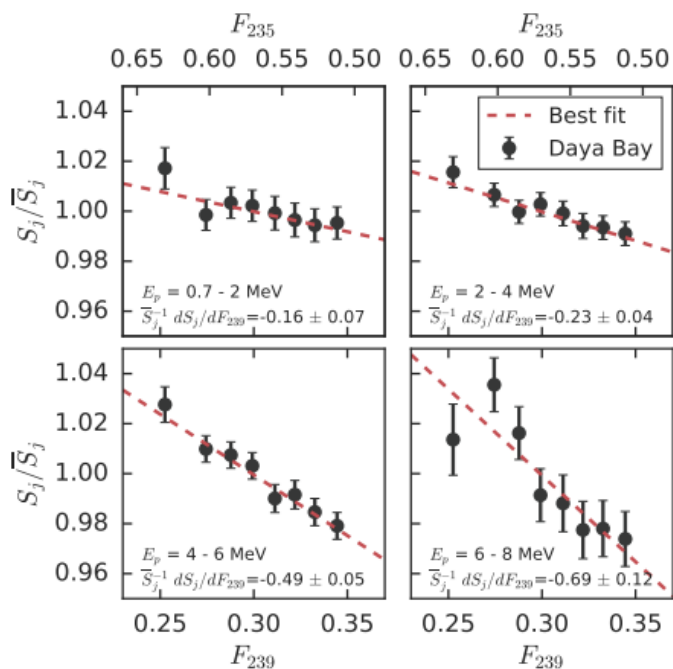
^{235}U and ^{239}Pu yield

- **Combined fit to the major fission isotopes ^{235}U and ^{239}Pu**
 - Assume yields of the minor fission isotopes ^{238}U and ^{241}Pu from model with an enlarged uncertainty 10%
- **Results suggest ^{235}U being the main contributor to the Reactor Antineutrino Anomaly (RAA)**
 - ^{235}U is 7.8% lower than H-M model (2.7% meas. uncertainty)
 - ^{239}Pu is consistent with H-M model (6% meas. uncertainty)
- **Sterile neutrino as the sole cause of RAA is disfavored by 2.8σ**



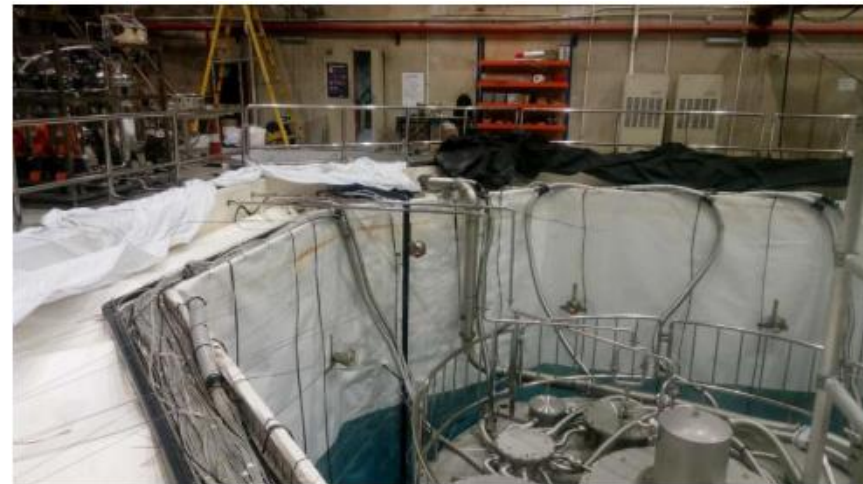
Spectrum evolution

- **The evolution slopes are different at different energy ranges**
 - Neutrino spectrum do change with ^{239}Pu fission fraction, in agreement with most models' predictions
 - No strange behavior at 4 to 6 MeV region
 - **Larger statistics** and **better detection efficiency estimates** would improve the fuel evolution results



Recent progresses

- **To further reduce the systematics**
 - **A Flash ADC readout system was installed in Dec. 2015**
 - **Special calibration campaigns in Dec. 2016**
- **Technical studies:**
 - **GdLS replacement with JUNO LS in AD1 in Feb. 2017**
 - Light yield, natural radio-purity studies for JUNO LS
 - Build a validated LS optical model



Summary



- **Daya Bay gives the most precise measurements to $\sin^2 2\theta_{13}$ and $|\Delta m_{ee}^2|$.**
 - Together with the updated measurement to reactor neutrino flux and spectrum, new limit on the light sterile neutrino
- **A reactor fuel evolution analysis is performed.**
 - Suggesting the Reactor Antineutrino Anomaly is mainly contributed by the overestimated ^{235}U flux in H-M model
- **Plan to run till 2020: uncertainties of $\sin^2 2\theta_{13}$ and $|\Delta m_{ee}^2|$ below 3%.**

