Recent results from Daya Bay

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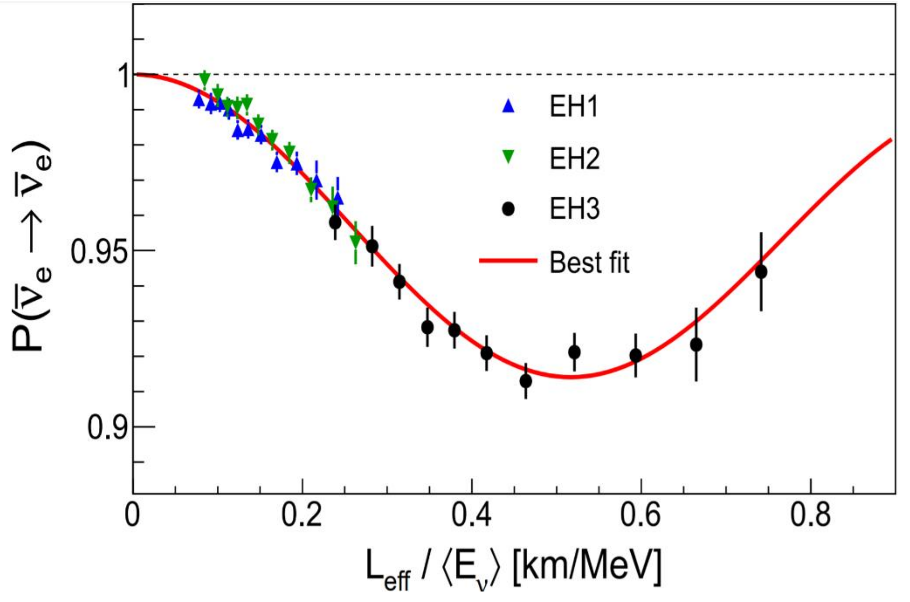
On behalf of the Daya Bay Collaboration

Outline

- Daya Bay
- Latest Results
    - **Oscillation measurement**
    - Sterile neutrino search
    - Flux & spectrum measurement of antineutrino
    - Fuel evolution analysis
- Summary



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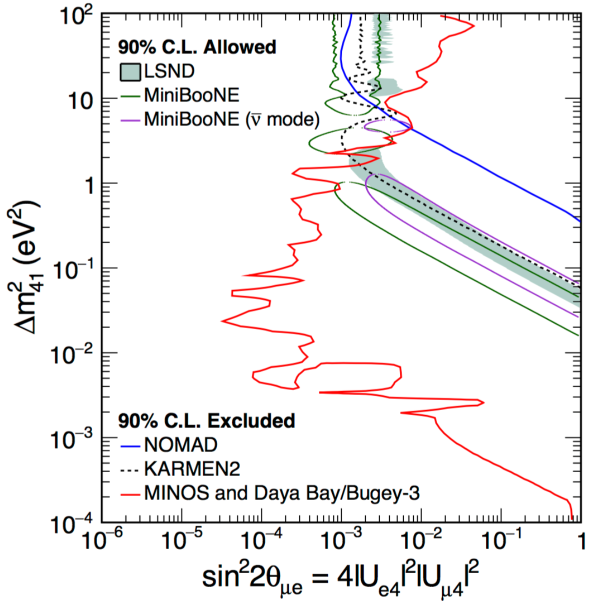

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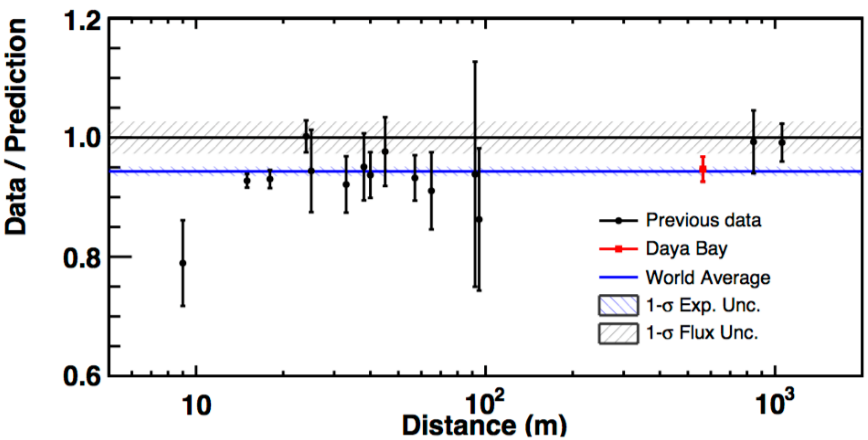

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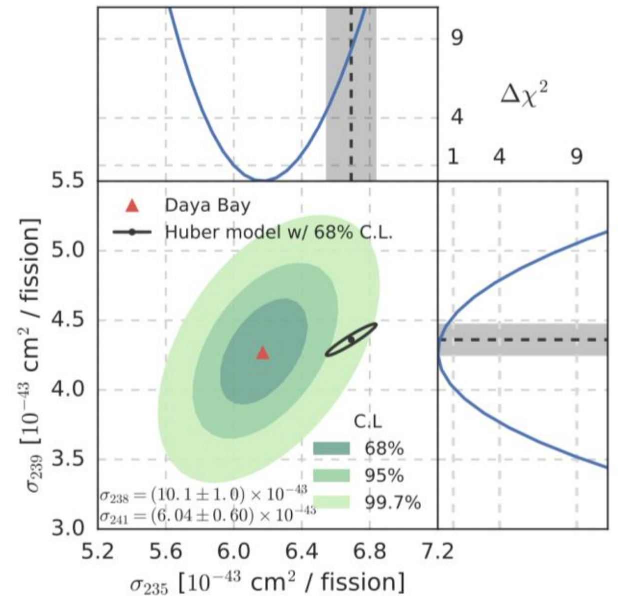


The Daya Bay Collaboration

Asia (23)

Beijing Normal Univ., CGNPG, CIAE, Congqing Univ., Dongguan Univ. Tech., ECUST, IHEP, Nanjing Univ., Nankai Univ., NCEPU, NUDT, Shandong Univ., Shanghai Jiao Tong Univ., Shenzhen Univ., Tsinghua Univ., USTC, Xian Jiaotong Univ., Zhongshan Univ.,

Chinese Univ. of Hong Kong, Univ. of Hong Kong,

National Chiao Tung Univ., National Taiwan Univ., National United Univ.

Europe (2)

Charles University, 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, UCLA, Univ. of Cincinnati, Univ. of Houston,

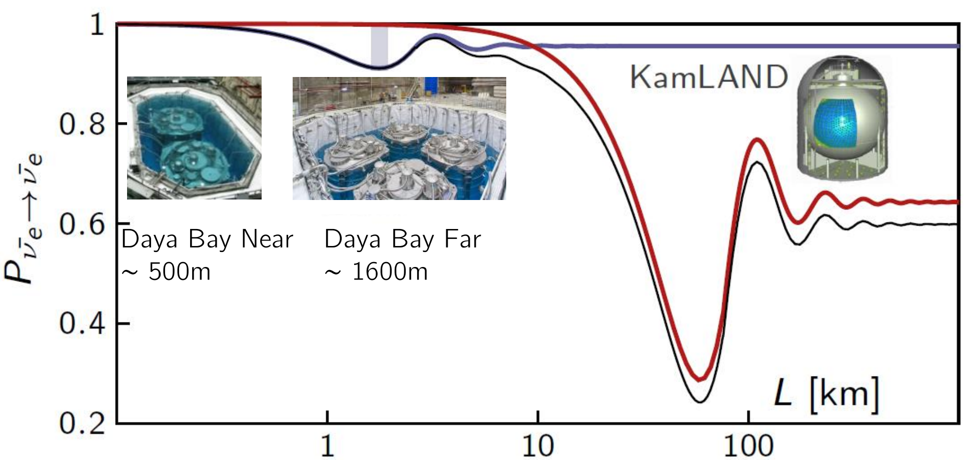
UIUC, Univ. of Wisconsin, Virginia Tech, William & Mary, Yale

South America (1)

Catholic University of Chile

Reactor Neutrino Oscillation

$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \sin^2 2\theta_{13} \sin^2 \left(\Delta m^2_{ee} \frac{L}{4E} \right) - \sin^2 2\theta_{12} \cos^4 \theta_{13} \sin^2 \left(\Delta m^2_{21} \frac{L}{4E} \right)$$



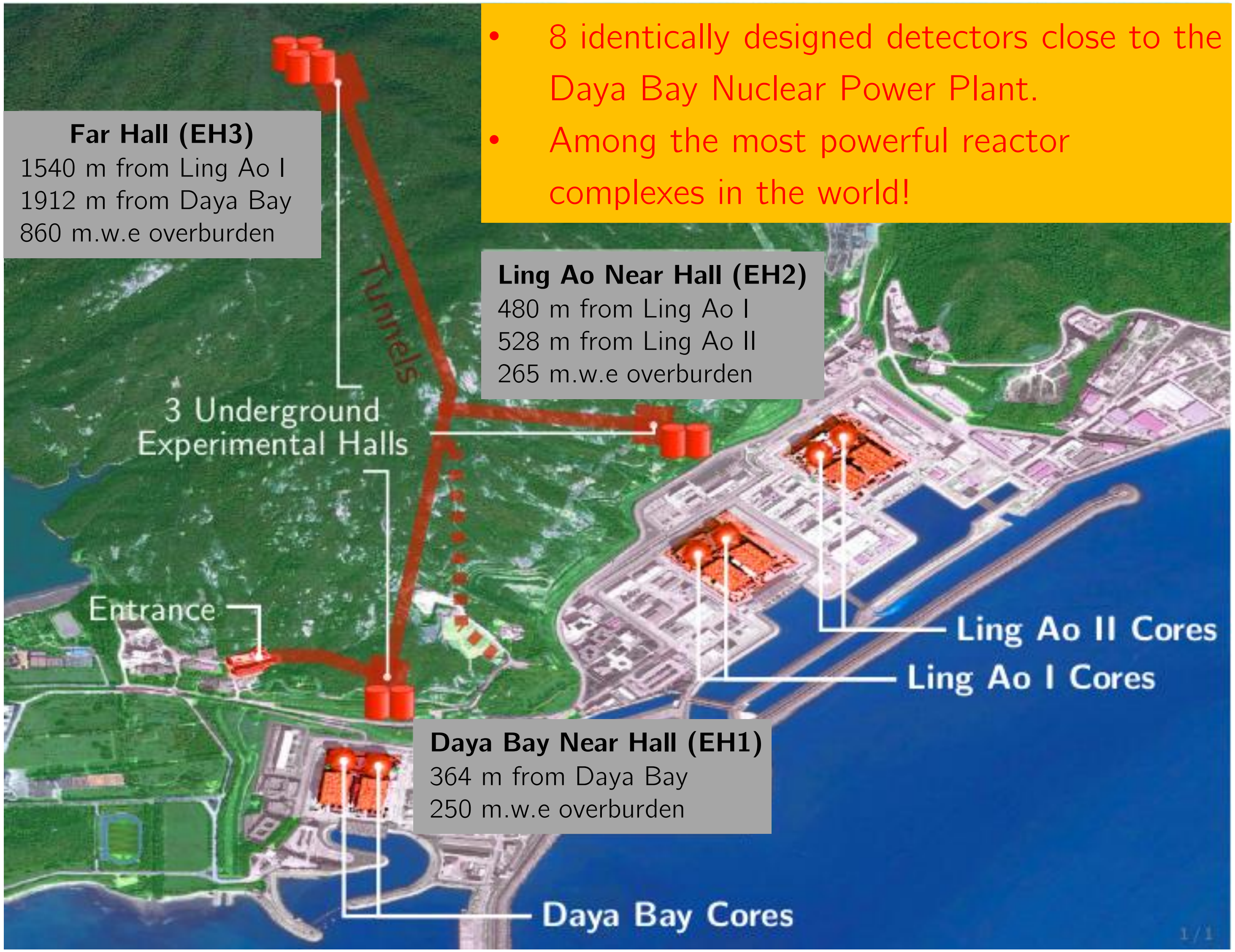
Relative measurement with 8 functionally identical detectors

- Absolute reactor flux single largest uncertainty in previous measurements

Cancels in near/far ratio: $\frac{N_f}{N_n} = \left(\frac{N_{p,f}}{N_{p,n}} \right) \left(\frac{L_n}{L_f} \right)^2 \left(\frac{\epsilon_f}{\epsilon_n} \right) \left(\frac{P_{sur}(E, L_f)}{P_{sur}(E, L_n)} \right)$

Experimental Setup

- 8 identically designed detectors close to the Daya Bay Nuclear Power Plant.
- Among the most powerful reactor complexes in the world!



Antineutrino Detection

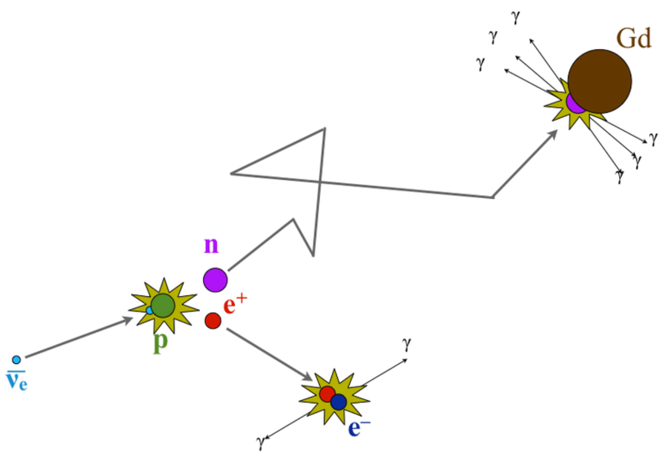
- **Inverse β-decay:** coincidence of two consecutive signals

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

~30μs (0.1% Gd)

$\rightarrow + \mathrm{p} \rightarrow \mathrm{D} + \gamma$ (2.2 MeV) (delayed signal)

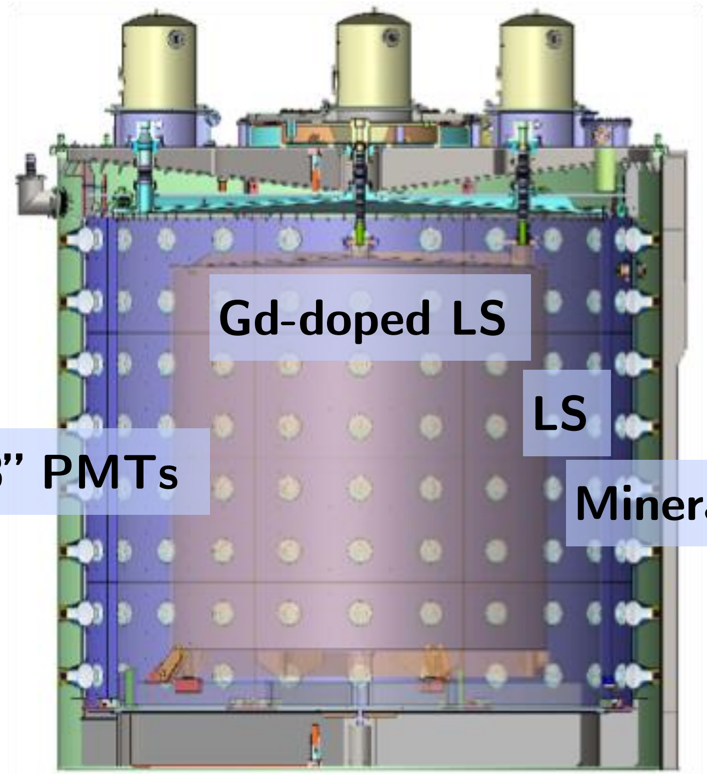
$\rightarrow + \mathrm{Gd} \rightarrow \mathrm{Gd}^* \rightarrow \mathrm{Gd} + \gamma$'s (8 MeV) (delayed signal)



- Powerful background rejection
- Positron preserves most information about antineutrino energy

Antineutrino Detectors

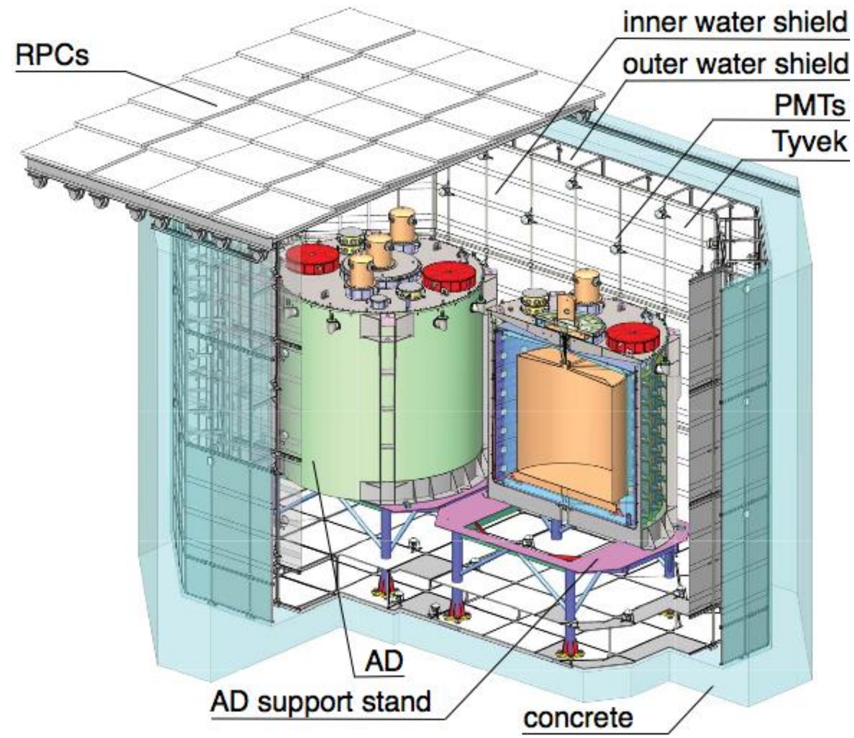
- Antineutrino detectors (ADs): “three-zone” cylindrical modules immersed in water pools



Energy resolution

$\sigma_E/\mathrm{E} = 7.5\%/\sqrt{E}$ [MeV]

NIM A 811, 133 (2016)

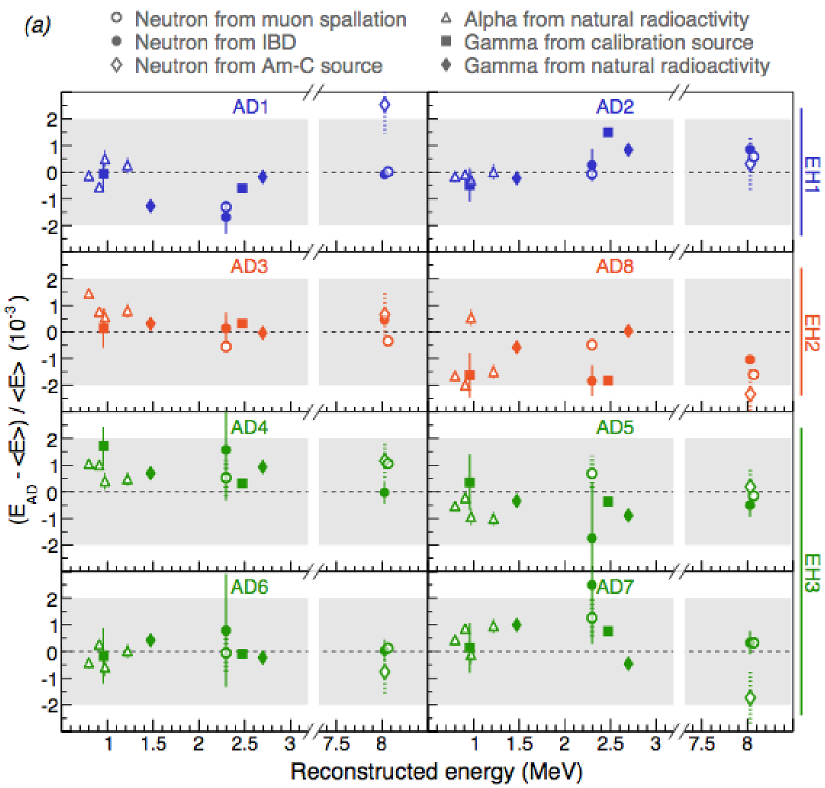


Double purpose: shield the ADs and veto cosmic-rays

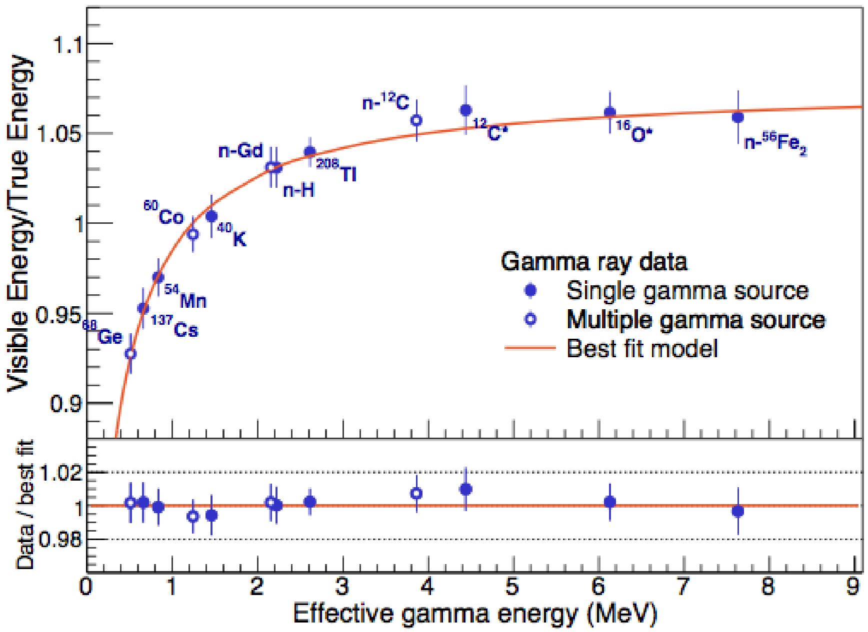
NIM A 773, 8 (2015)

Energy Reconstruction

- A variety of natural and artificial sources to perform the relative calibration of the detectors and to construct an energy model



relative energy scale uncertainty < 0.2%

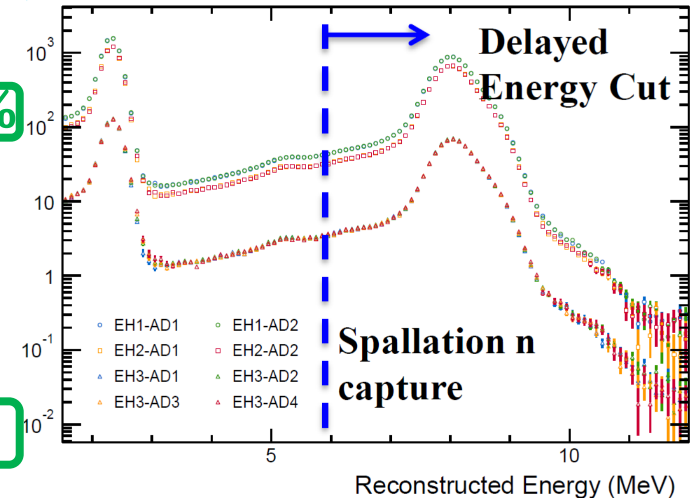


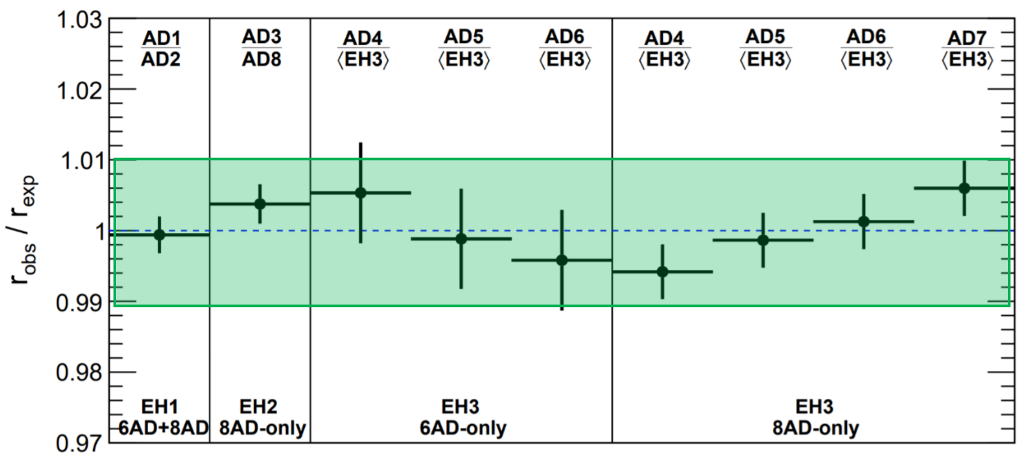
absolute neutrino energy scale uncertainty ~1%

Improvement of Systematics

Detector Efficiency

	Efficiency	Correlated	Uncorrelated	Previous
Target protons	-	0.92%	0.03%	
Flasher cut	99.98%	0.01%	0.01%	
Delayed energy cut	92.7%	0.97%	0.08%	0.12%
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%	0.2%



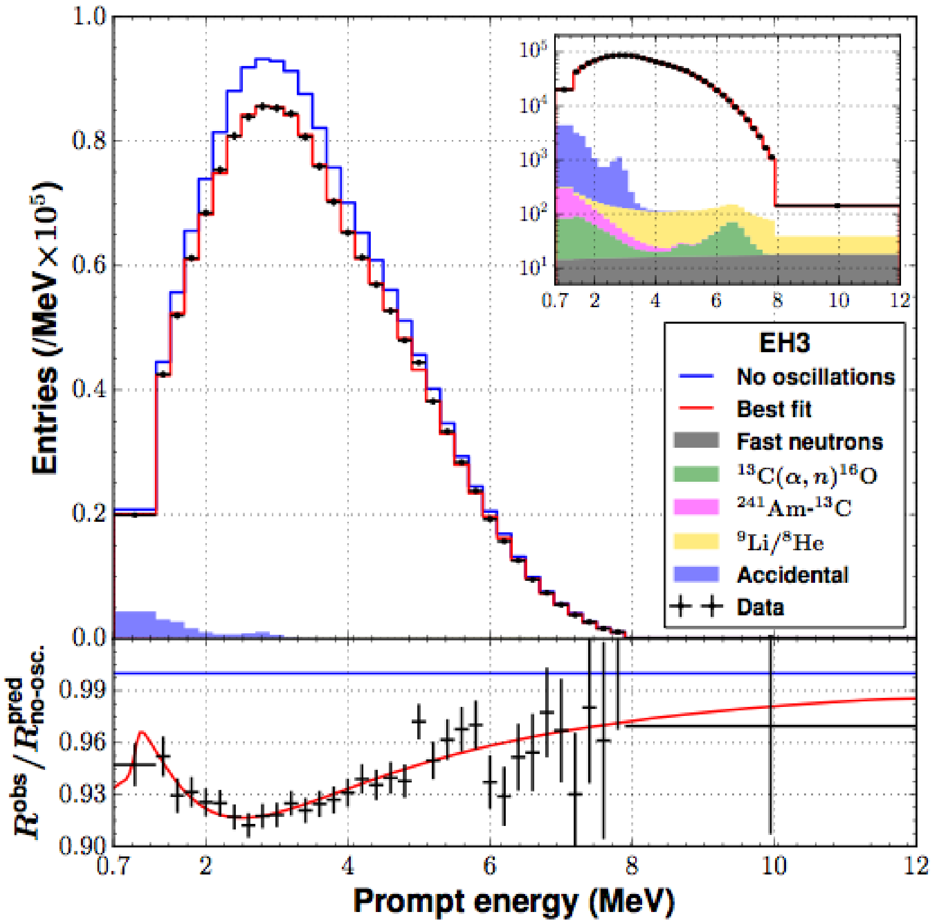


Multiple detectors in the same experimental hall enable the cross-check of the uncorrelated uncertainty

Oscillation Measurement

nGd Oscillation Analysis Dataset

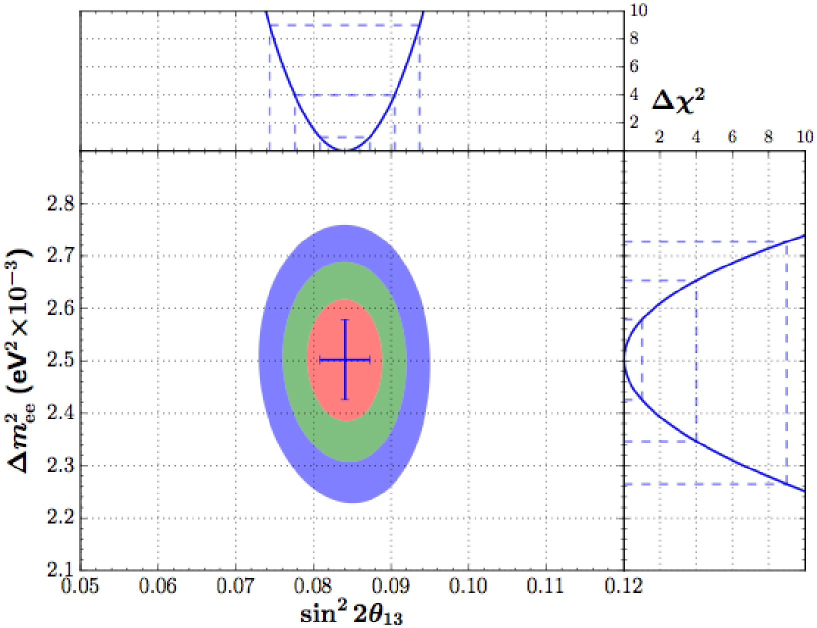
- Oscillation result based on neutron capture on gadolinium (nGd)
- 1230 days of data
- More than **2.5 million antineutrino interactions** (300k in the far hall)
- Significant improvements in
  - background reduction (B/S<2%)
  - energy calibration

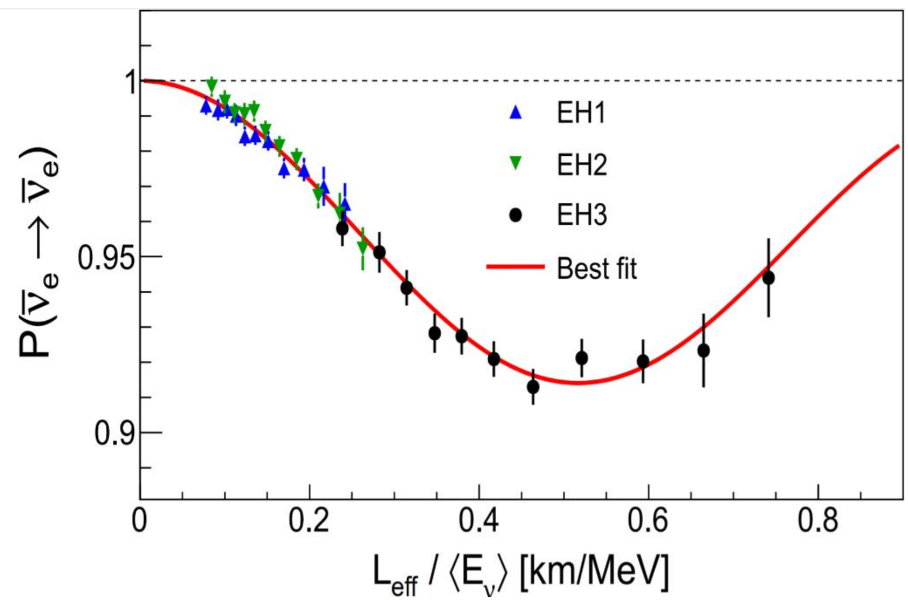


Phys. Rev. D 95, 072006 (2017)

nGd Oscillation Analysis Results

$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \sin^2 2\theta_{13} \sin^2\left(\Delta m^2_{ee} \frac{L}{4E}\right) - \sin^2 2\theta_{12} \cos^4\theta_{13} \sin^2\left(\Delta m^2_{21} \frac{L}{4E}\right)$$



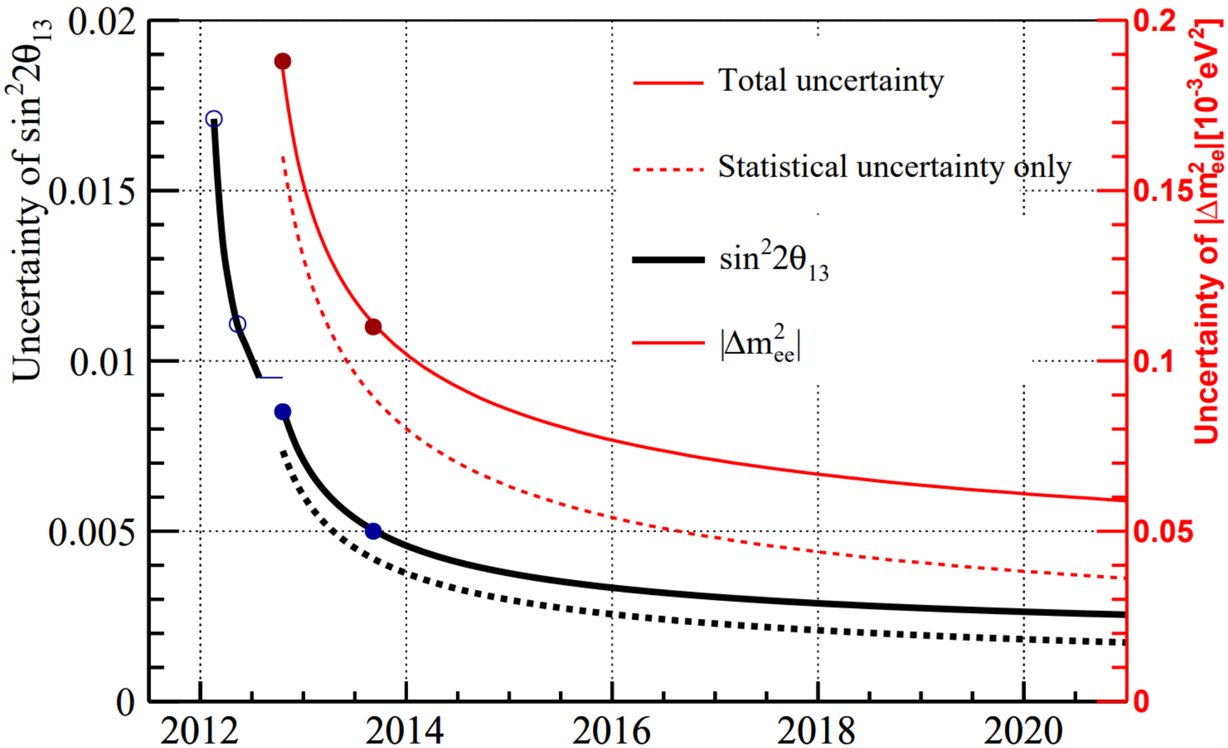


$\sin^2 2\theta_{13}$ = 0.0841 ±0.0027(stat.) ±0.0019(sys.)
$|\Delta m^2_{ee}|$ = [2.50 ±0.06(stat.) ±0.06(sys.)] ×$10^{-3}$$eV^2$
χ^2/NDF = 234.7/263

still statistics dominated!

Precision on Oscillation Parameter

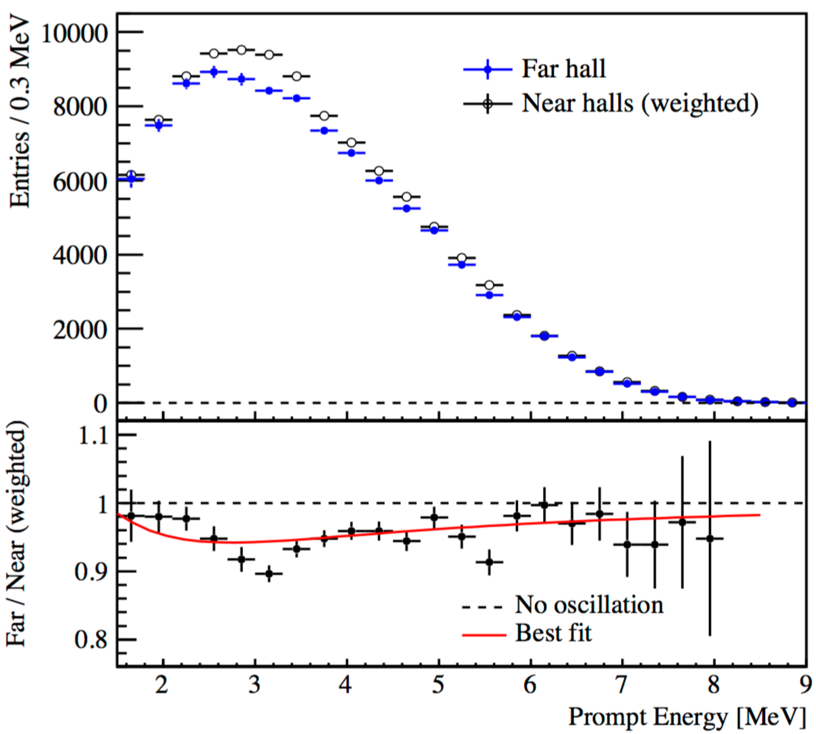
- Plan to run till 2020: uncertainties of $\sin^2 2\theta_{13}$ and $|\Delta m^2_{ee}|$ below 3%

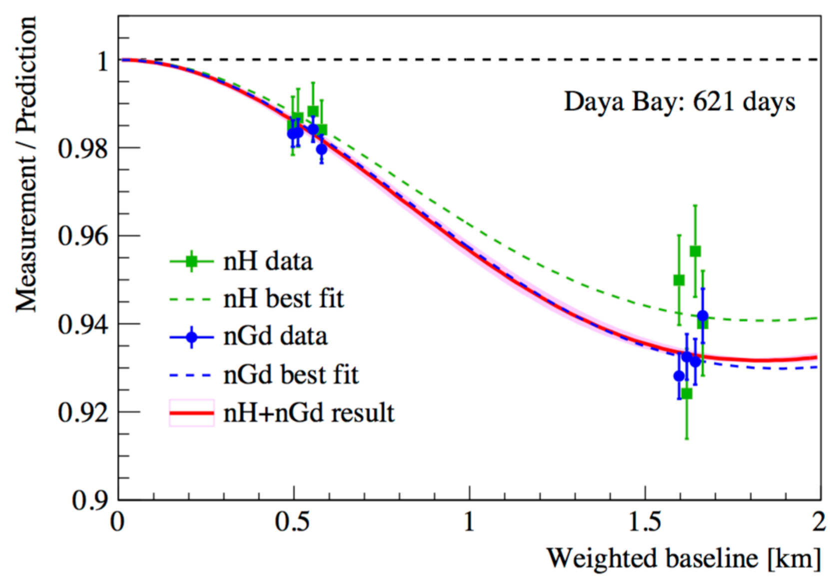


Phys. Rev. D 93, 072011 (2016)

nH Oscillation Analysis Results

- An **independent** measurement is achieved with IBD events where the neutron captures on hydrogen
  - Independent with nGd analysis in detector related systematics
  - Common in reactor related systematics
  - One of the challenges is the large accidental background (>50 times larger than for nGd analysis)





$\sin^2 2\theta_{13} = 0.071 \pm 0.11$, $\chi^2/NDF = 6.3/6$

Global Comparison

Most precise measurement

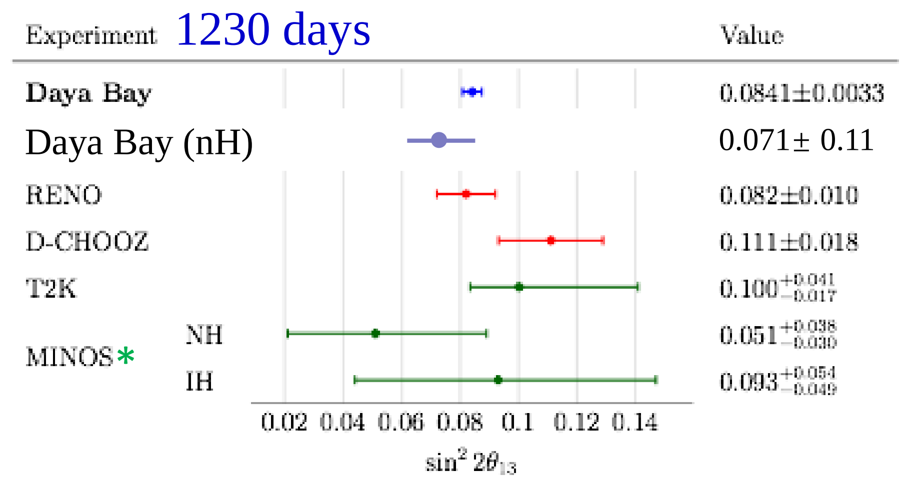
- $\sin^2 2\theta_{13}$ uncertainty: 3.9%
- Δm^2_{32} uncertainty: 3.4%

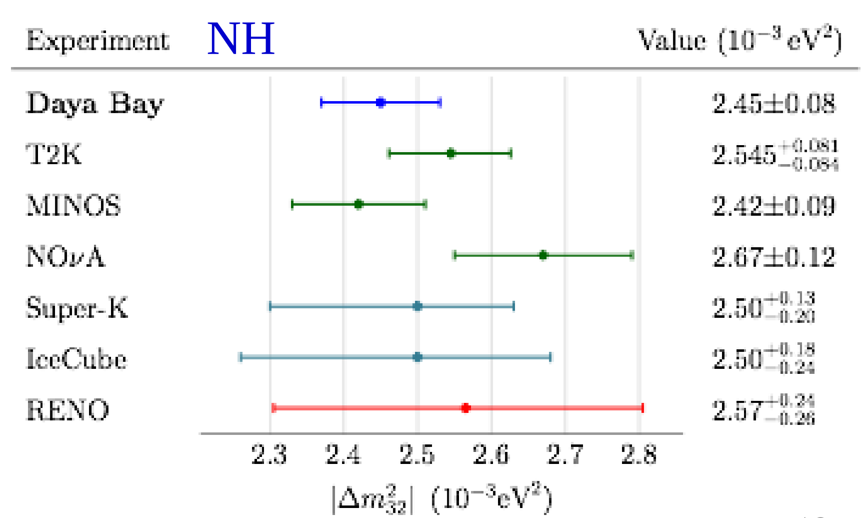
Consistent results with reactor and accelerator experiments

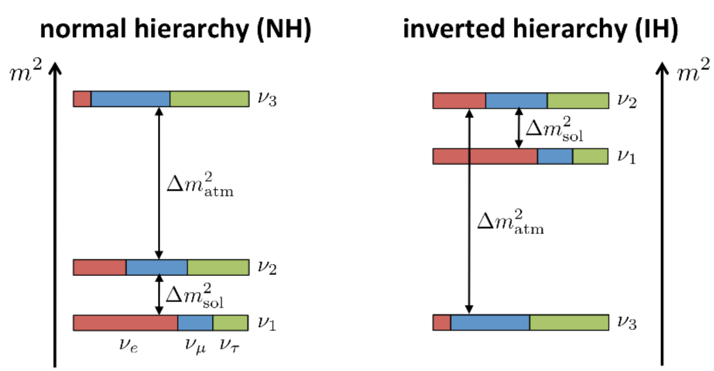
$|\Delta m^2_{ee}| = |\Delta m^2_{32}| \pm 0.05 \times 10^{-3}\ \mathrm{eV}^2$

NH: $\Delta m^2_{32} = [2.45 \pm 0.08] \times 10^{-3}\ \mathrm{eV}^2$

IH: $\Delta m^2_{32} = [-2.56 \pm 0.08] \times 10^{-3}\ \mathrm{eV}^2$







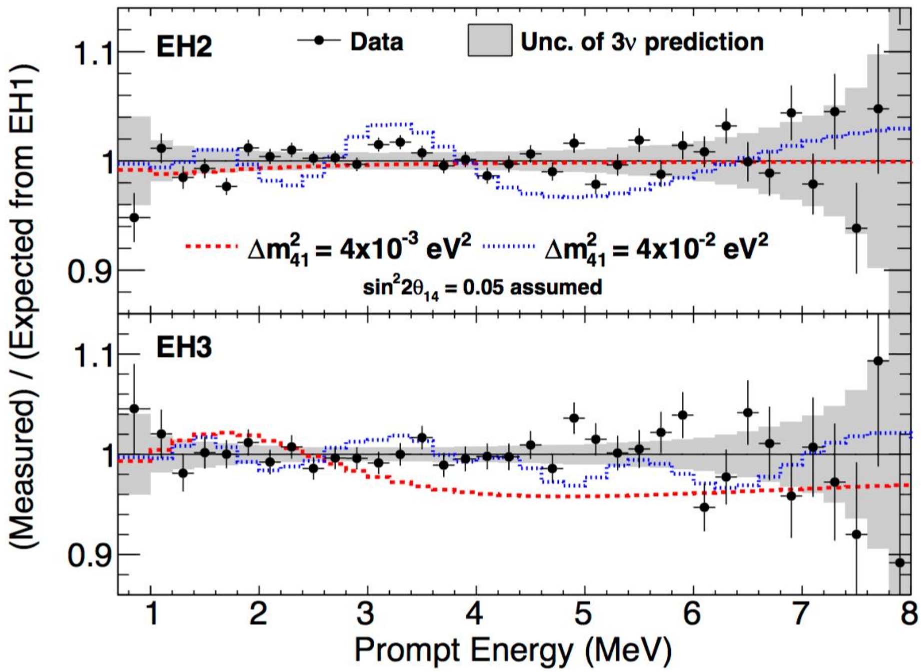
*: combined fit results for $2\sin^2\theta_{23}\sin^2 2\theta_{13}$

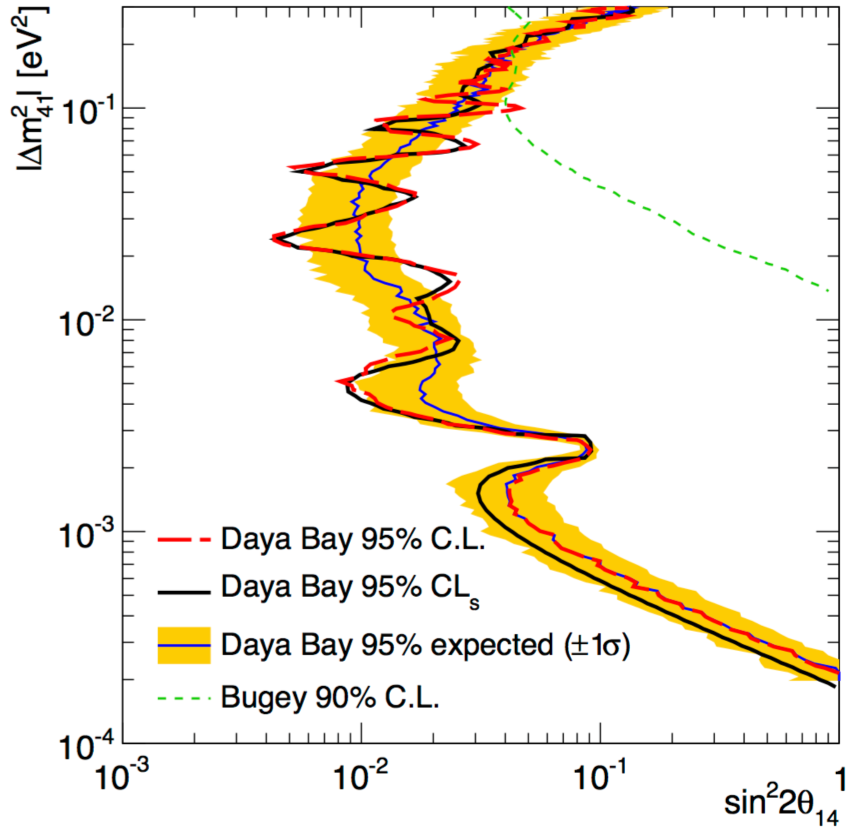
Sterile Neutrino Search

Phys. Rev. Lett. 117 (2016) no.15, 151802

Search for Light Sterile Neutrino

- A relative comparison of the energy spectra at the three sites allows to search for sterile neutrino mixing





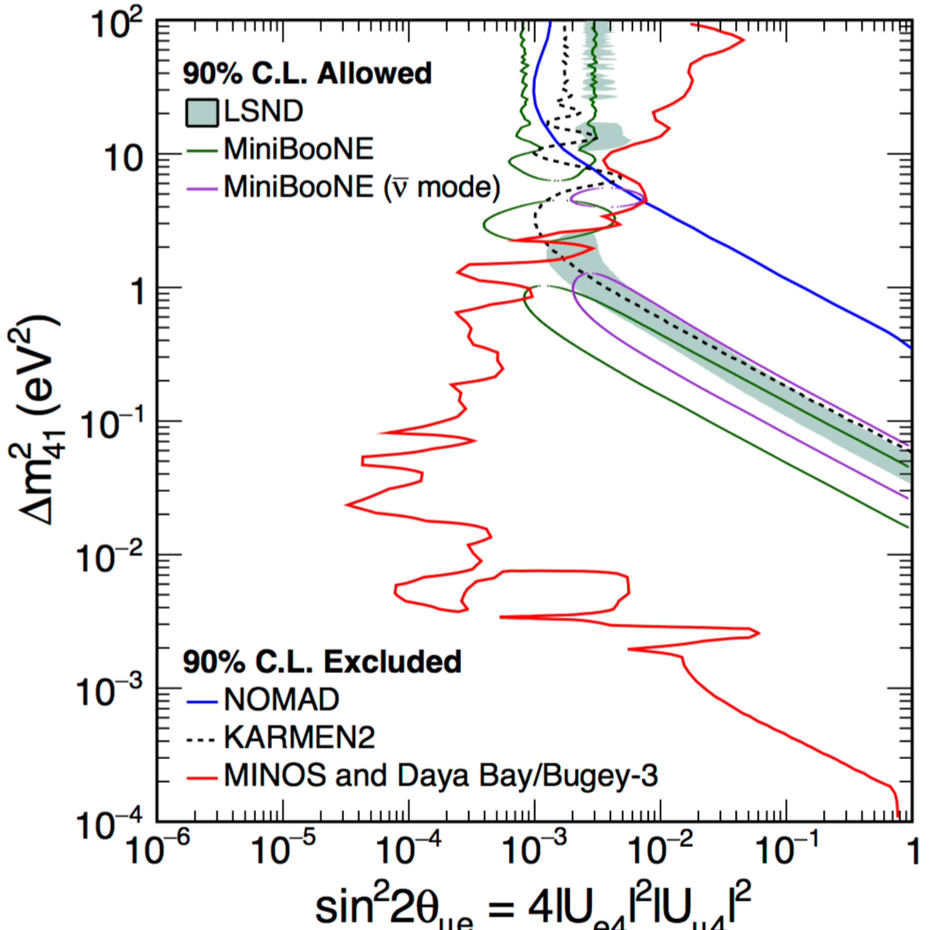
Signal would primarily appear as an additional spectral distortion with a frequency different from standard 3ν oscillations

The most stringent limits on $\sin^2 2\theta_{14}$ in the $2\times10^{-4}\,\mathrm{eV}^2 < \Delta m^2_{41} < 0.2\,\mathrm{eV}^2$ region

Phys. Rev. Lett. 117 (2016) no.15, 151801
Addendum: Phys. Rev. Lett. 117 (2016) no.20, 209901

Constraining Appearance Results

- MINOS & Daya Bay have released a combined result that also includes the Bugey-3 $\bar{\nu}_e$ disappearance data
- Exclude parameter space allowed by MiniBooNE & LSND for $\mathbf{\Delta m^2_{41}} < 0.8\ \mathrm{eV}^2$



constrained with $\bar{\nu}_e$ disapperance

constrained with ν_μ disappearance

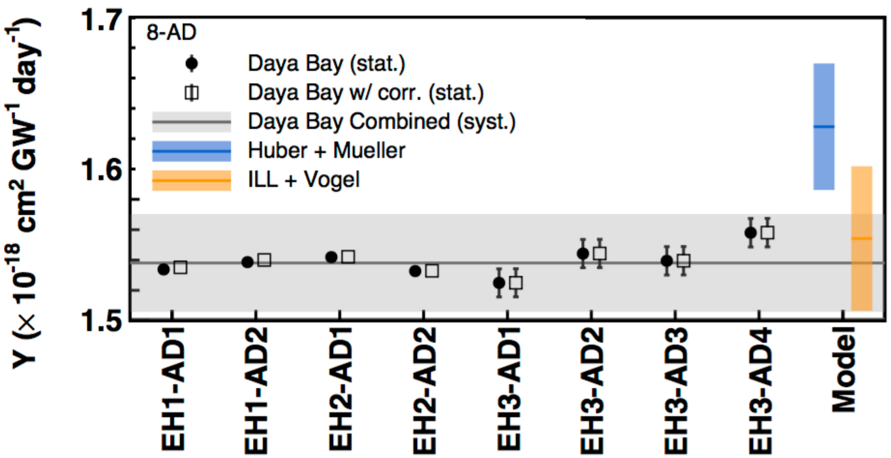
Antineutrino Flux & Spectrum

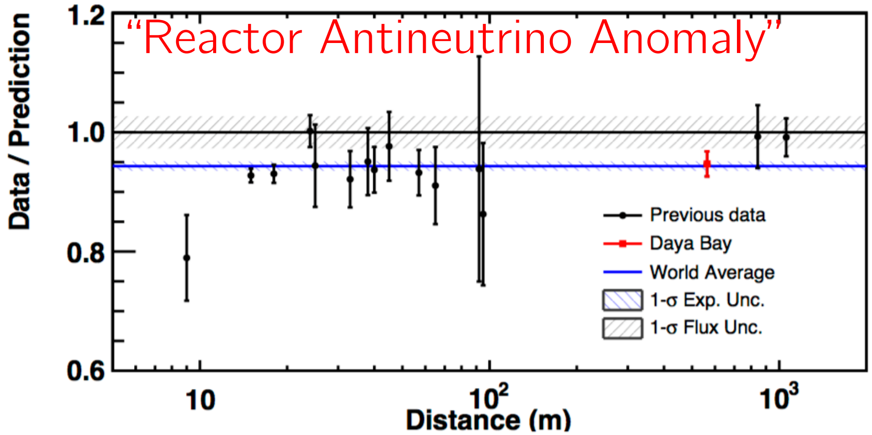
Chin. Phys. C 41(1) (2017)

621 days of data

Reactor Antineutrino Flux

- Measurement of IBD yield in the eight detectors is consistent with other experiments measurement





IBD Yield	
Y (cm^2/GW/day)	$(1.55 \pm 0.03) \times 10^{-18}$
σ_f (cm^2/fission)	$(5.92 \pm 0.12) \times 10^{-43}$
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

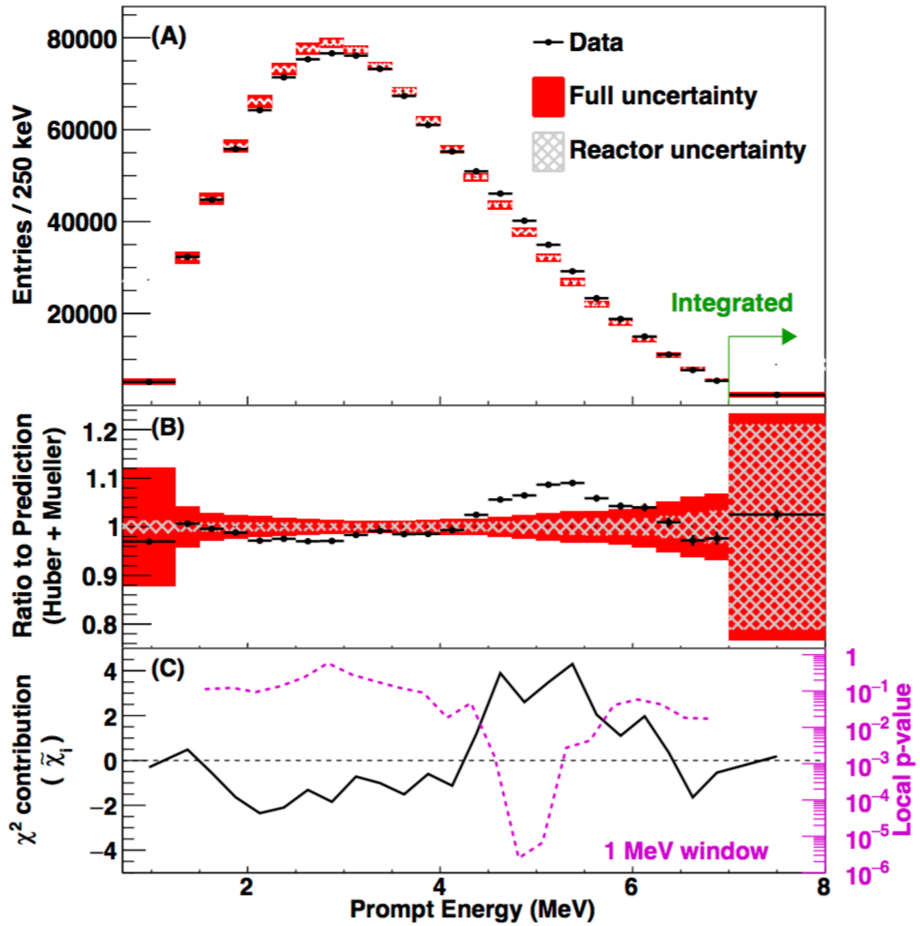
$R_{global} = 0.942 \pm 0.009(exp) \pm 0.023(model)$

$R_{global+DYB} = 0.943 \pm 0.008(exp) \pm 0.023(model)$

Discrepancy with Huber+Mueller (HM) model could be due to underestimated uncertainties in the prediction, and/or the existence of a sterile neutrino.

Reactor Antineutrino Spectrum

- **High-statistics measurement** of the spectral shape of reactor antineutrinos
- Global discrepancy with the Huber+Mueller prediction at 2.9σ (4.4σ in the 4-6 MeV region)
- Excess events have all the IBD characteristics and are
  - correlated with reactor power
  - time independent
- Excess does not appear in ^{12}B spectra (disfavoring detector effects), and cannot be reproduced by a single β-decay branch or mono-energetic line



Chin. Phys. C 41(1) (2017)

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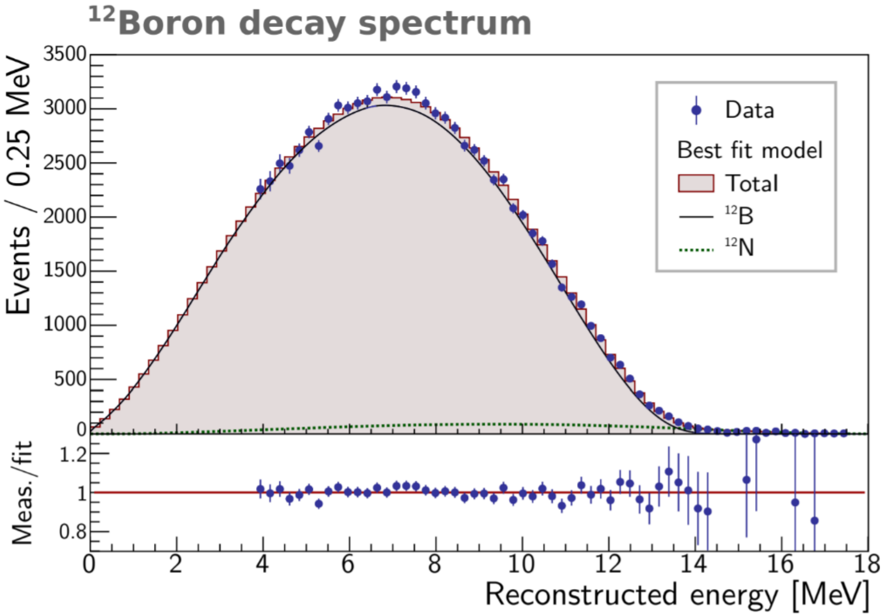
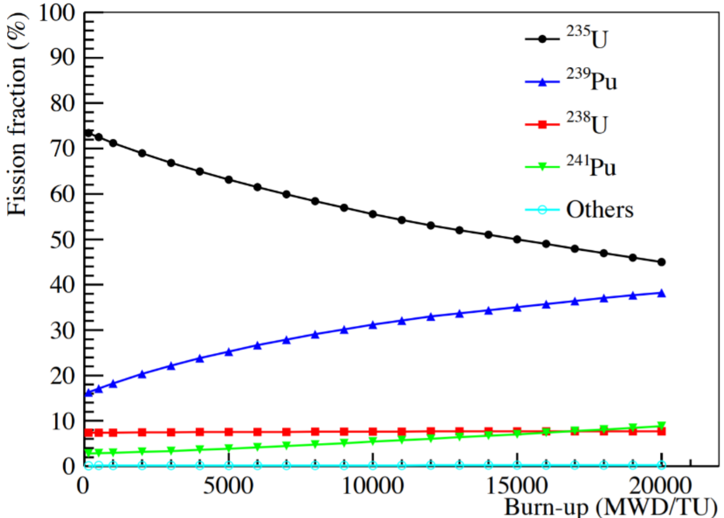
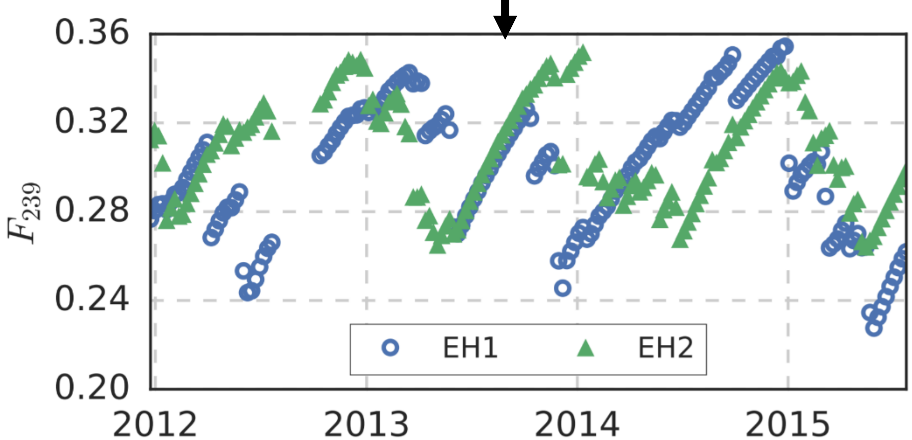


Fuel Evolution Analysis

Fission Fraction in Daya Bay



weight; then repeat x6



- Fission fraction changes in a burn-up cycle for
  - **^{235}U, ^{239}Pu**, ^{238}U, ^{241}Pu
- **Effective fission fraction**: Weight each reactor's fission fraction by distance, power and oscillation

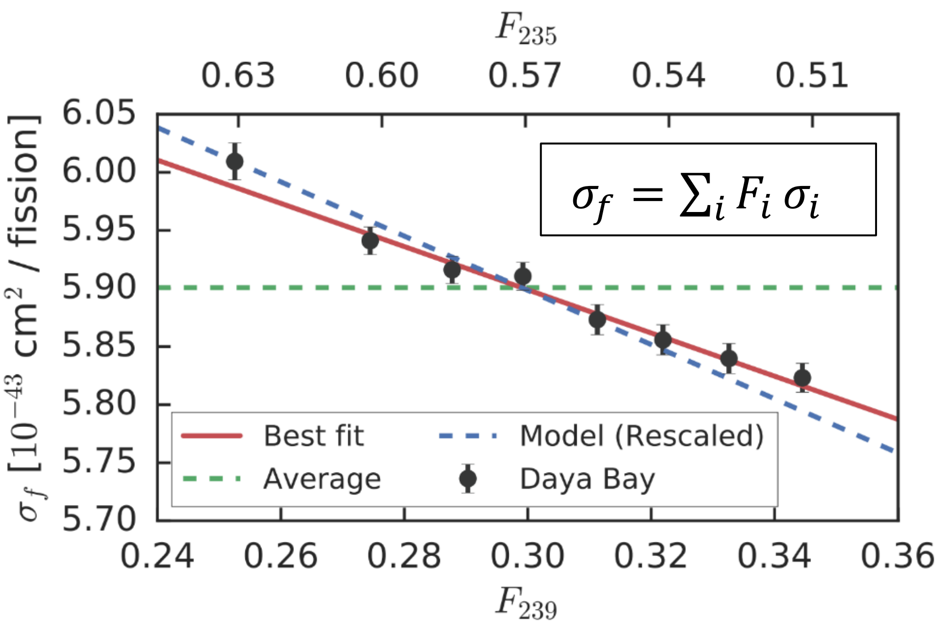
$$F_i(t) = \sum_{r=1}^{6} \frac{W_{\mathrm{th},r}(t)\bar{p}_r f_{i,r}(t)}{L_r^2 \overline{E}_r(t)} \Bigg/ \sum_{r=1}^{6} \frac{W_{\mathrm{th},r}(t)\bar{p}_r}{L_r^2 \overline{E}_r(t)}$$

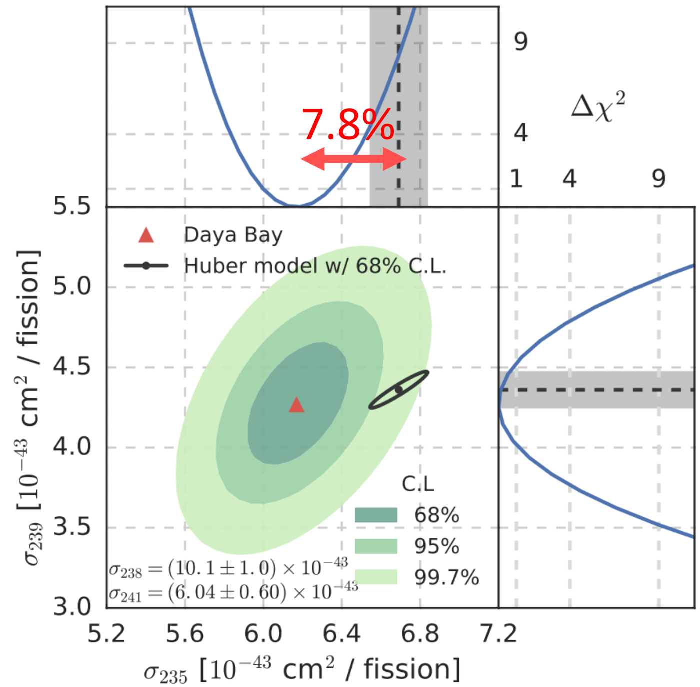
- Can Daya Bay detectors measure the variation in antineutrino flux for different fission fraction?

Phys. Rev. Lett. **118**, 251801

Antineutrino Flux Evolution

- **Flux evolution**: IBD yield per fission changes with fission fraction of ^{239}Pu, as well as ^{235}U





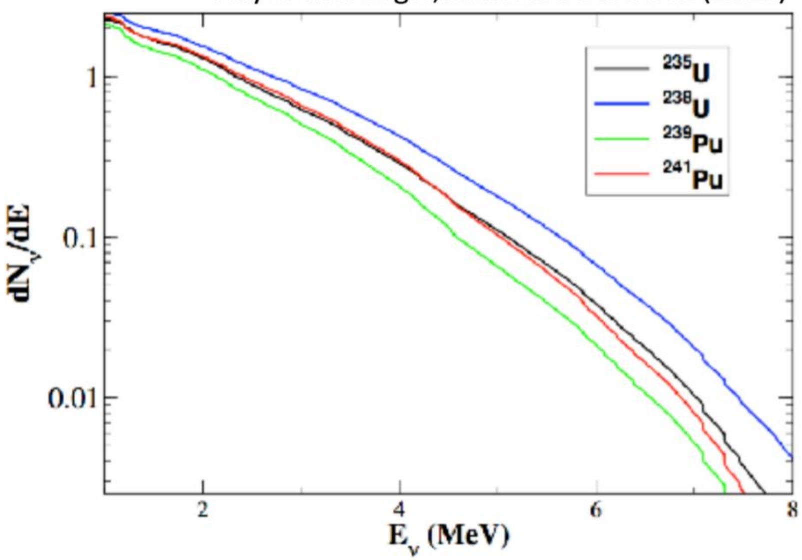
Flux evolution shows some tension with the Huber+Mueller model

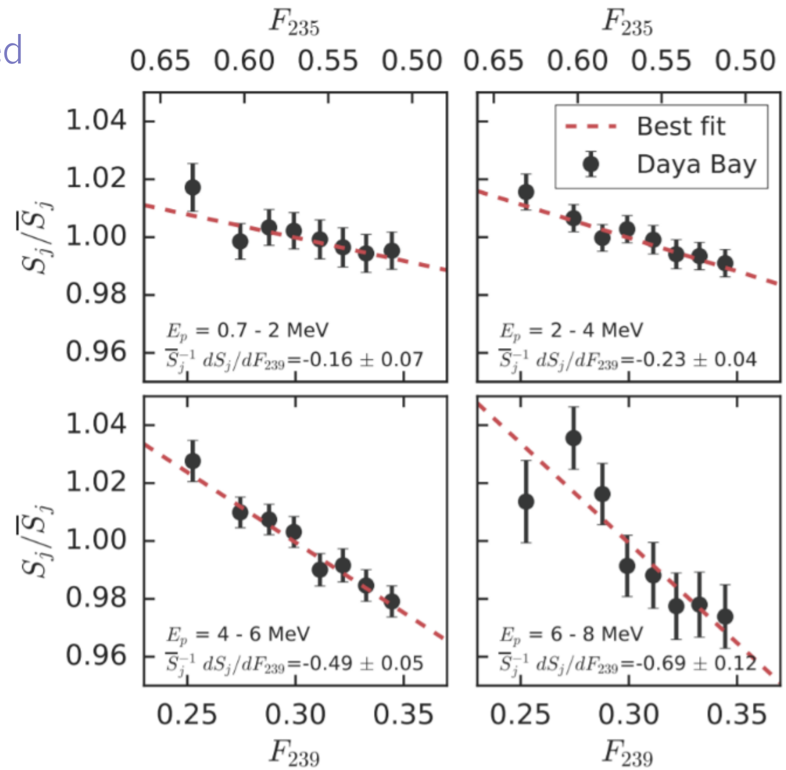
- Data imply a 7.8% overestimation of IBD yield from ^{235}U in Huber model
- ^{235}U could be the primary contributor to the "reactor antineutrino anomaly"

Evolution in Energy Spectrum

- The energy spectrum difference between ^{235}U and ^{239}Pu is also observed in the evolution.
  - First time this is unambiguously measured
  - Most models do predict this, however.

Hayes and Vogel, Ann. Rev. Part. Sci. (2016)

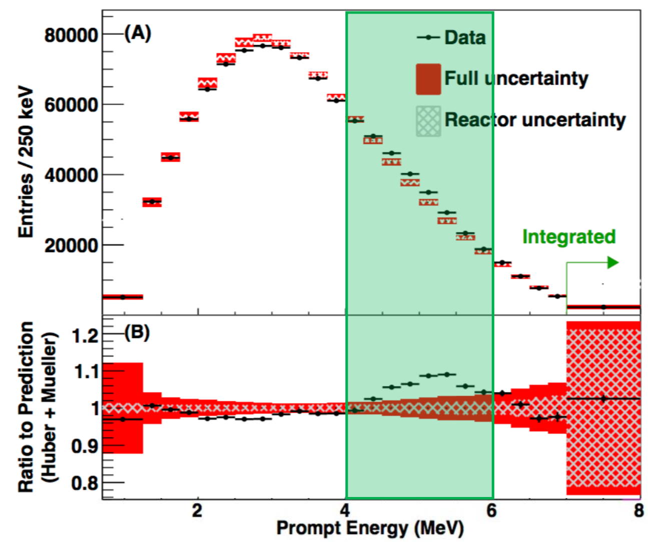


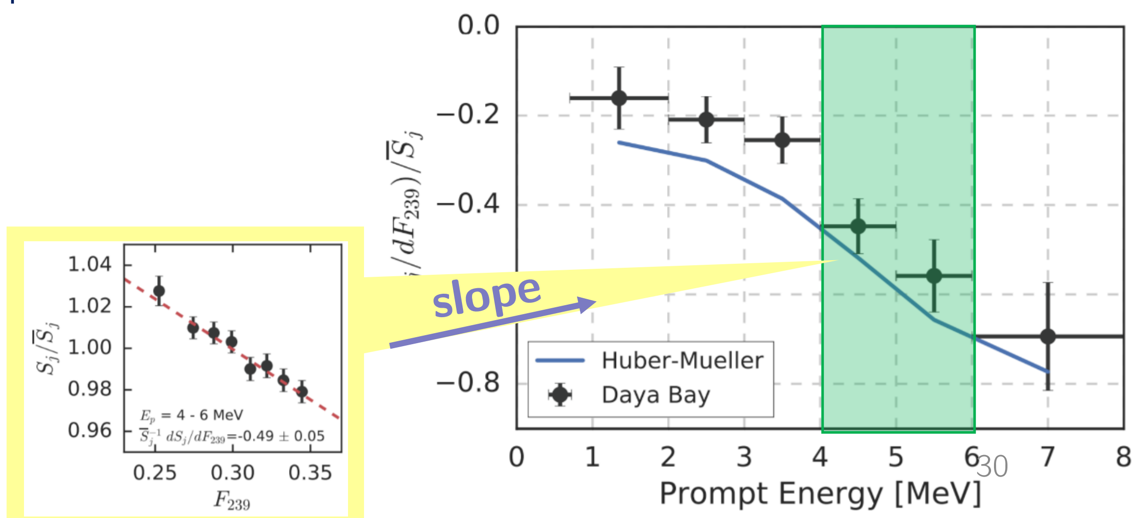


The slopes for flux evolution are different in different energy slides

Spectrum Evolution: Data-Model Comparison

- 4-6 MeV region: no strange behavior visible compared with HM models
  - No major indication that 'bump' comes from a particular isotopes
  - Highly-enriched U reactors is helpful to probe the ^{235}U over-prediction and the isotope origin of the 'bump'

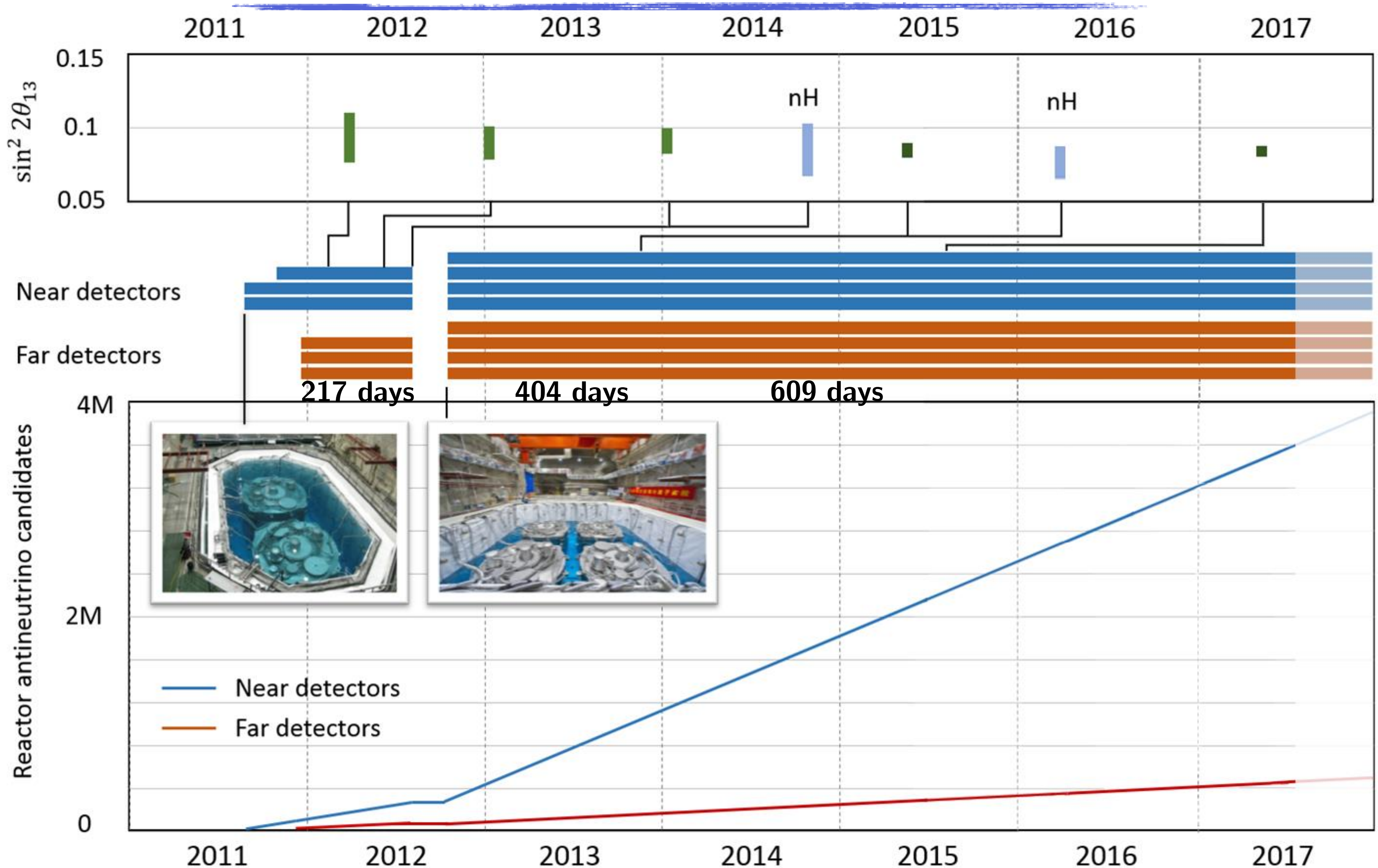




Summary

- Daya Bay **1230** days of data, **>2.5M** IBD candidates
  - Most precise measurement of $\sin^2 2\theta_{13}$: 3.9%
  - Most precise measurement of $|\Delta m^2_{ee}|$: 3.4%
  - Confirmed with independent nH rate measurement (621 days)
- Set new limit to light sterile neutrinos
- Reactor antineutrino flux and spectrum
  - **Flux**: consistent with precious short baseline experiments, but not with theoretical prediction (Huber+Mueller)
  - **Spectrum**: 4.4σ deviation from prediction in [4,6] MeV of positron energy
  - **Evolution observed**: indicates that Huber model has a 7.8% overestimation in the IBD yield for antineutrinos from ^{235}U
- Will continue till 2020.

Data Collection



Daya Bay Timeline

	Physics analysis published date	Detector status
2011	AD 1/2 comparison	2 EH1 ADs start data taking in Aug. 2+1+3 ADs start data taking in Dec.
2012	March, First 5σ θ_{13}, rate only, 55d	Calibration campaign in Jun. 2+2+4 ADs start data taking in Oct.
2013	Improved θ_{13} (9σ), rate only, 139d	
2014	Spectral analysis (θ_{13} and Δm^2), 217d nH rate analysis, 217d Sterile neutrino, 217d	
2015	Full 8AD oscillation analysis, 621d	AD1 Flash-ADC upgrade in Dec.
2016	Reactor flux & spectrum, 217d Improved nH, 621d Improved sterile nu, 621d Combined sterile with MINOS, 621d	
2017	Long reactor paper, 621d Long osc. Paper, 1230d Fuel evolution, 1230d	Calibration campaign in Jan. AD1 taken out for LS study in Jan.