Latest Results From Daya Bay

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On Behalf of the Daya Bay Collaboration

Neutrino Colloquium Prague v19
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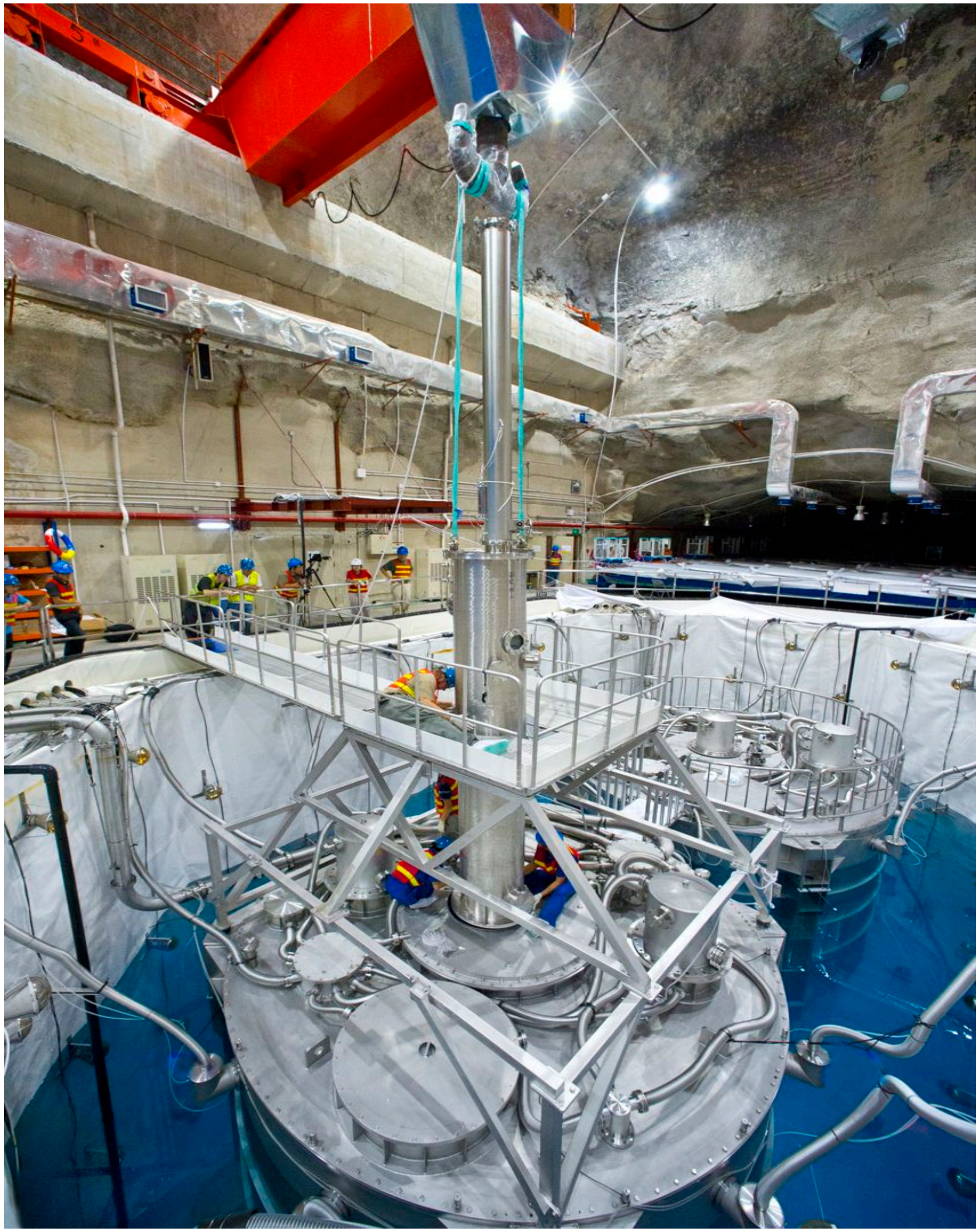
Outline



- Introduction
  - Motivation
  - The Daya Bay experiment
- Latest results:
  - $\sin^2 2\theta_{13}$ and Δm^2 with nGd sample
  - Search for sterile-active neutrino mixing
  - Absolute measurement of reactor antineutrino flux and spectrum
- Summary

Motivation

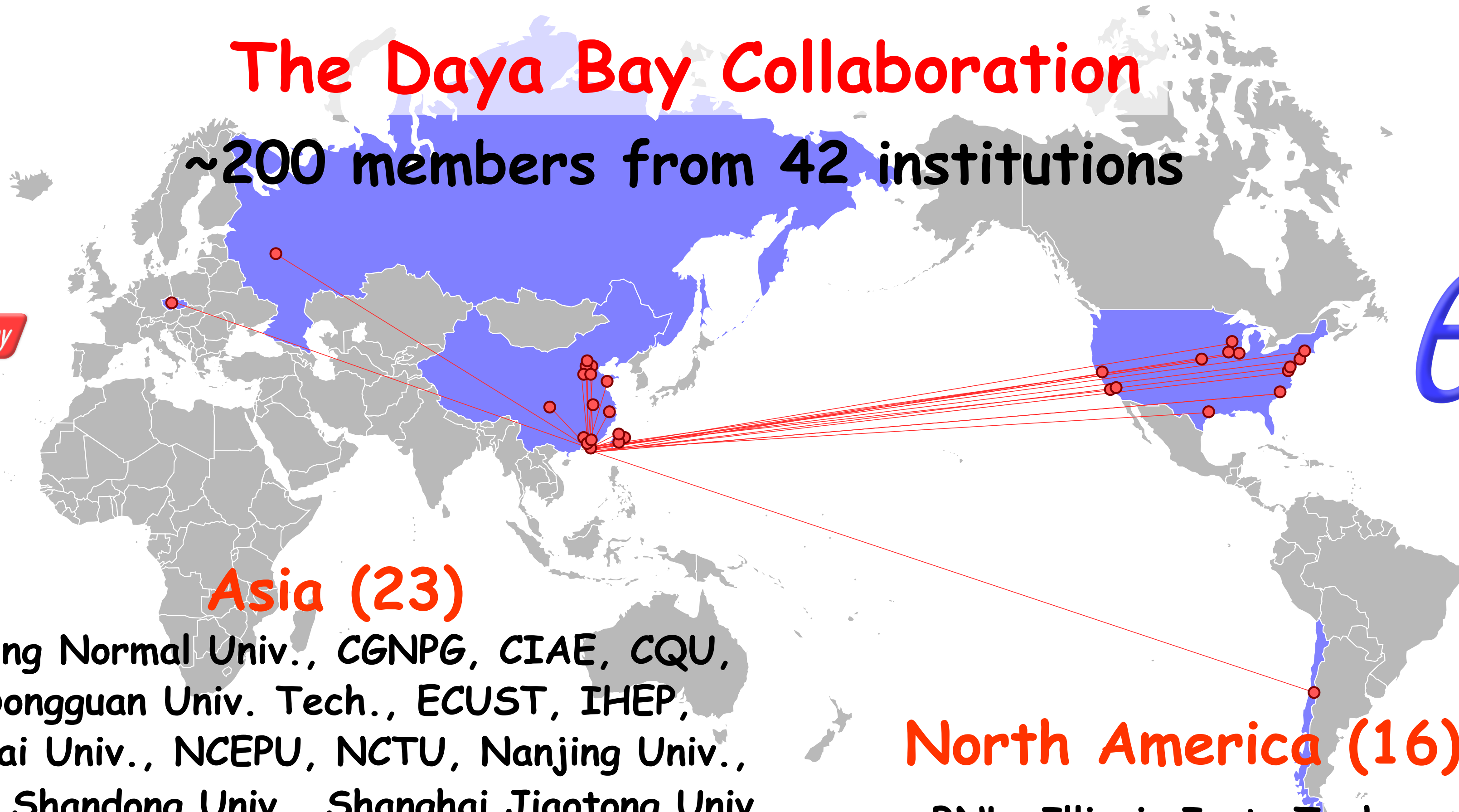
Size of CP violation dictated by: $J = c_{12}s_{12}c_{23}s_{23}c^2_{13}s_{13}\sin\delta$

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

Need to know θ_{13} in order to determine δ

The Daya Bay Collaboration

~200 members from 42 institutions



Asia (23)

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

Europe (2)

JINR, Dubna, Russia
Charles University, Czech Republic

North America (16)

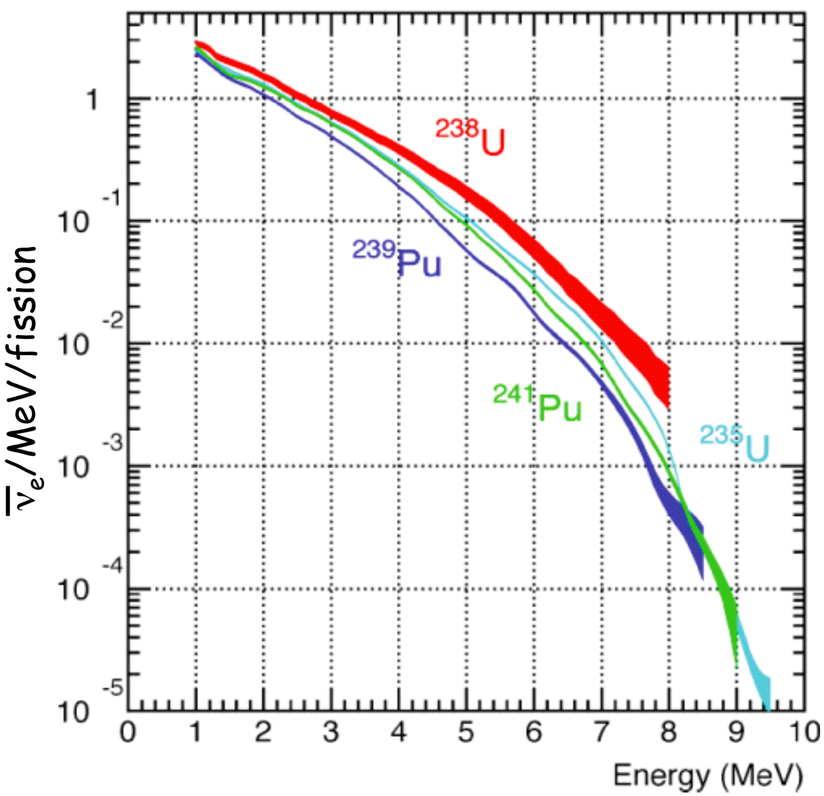
BNL, Illinois Inst. Tech., Iowa State Univ., LBNL, Princeton, RPI, Siena, Temple, UC-Berkeley, UC-Irvine, Univ. of Cincinnati, Univ. of Wisconsin-Madison, Univ. of Illinois-Urbana-Champaign, Virginia Tech., William & Mary, Yale

South America (1)

Cath. Univ. of Chile

Reactor $\overline{\nu}_e$

- A pure, intense source of low-energy $\overline{\nu}_e$:
  - release ~200 MeV/fission
  - 1 GW_{th} generates $2 \times 10^{20}\ \overline{\nu}_e$ per sec



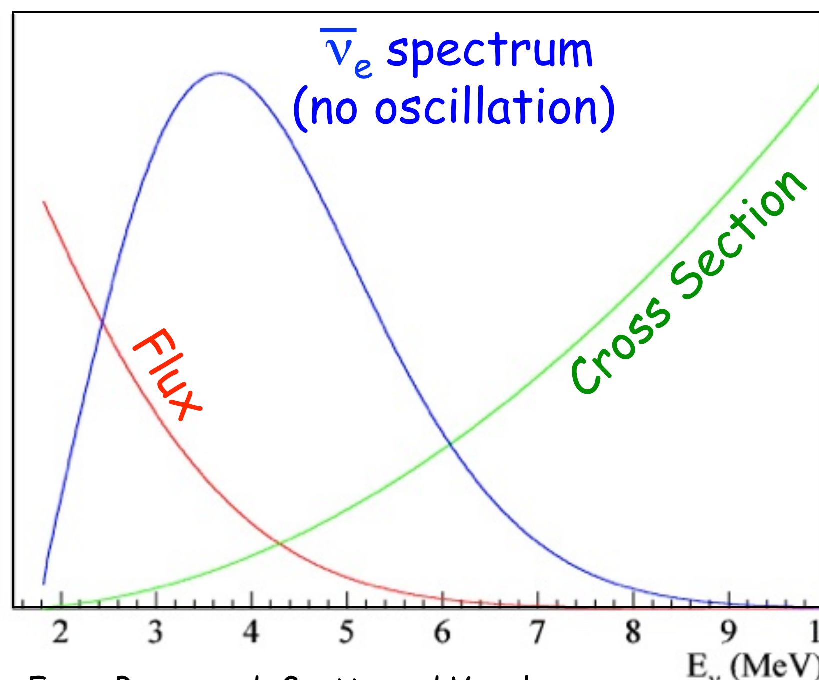
- Inverse β-decay reaction (IBD) in liquid scintillator:

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

n captured on H or Gd

- Energy of $\overline{\nu}_e$:

$$E_\nu \approx T_{e+} + 1.8\ \text{MeV}$$

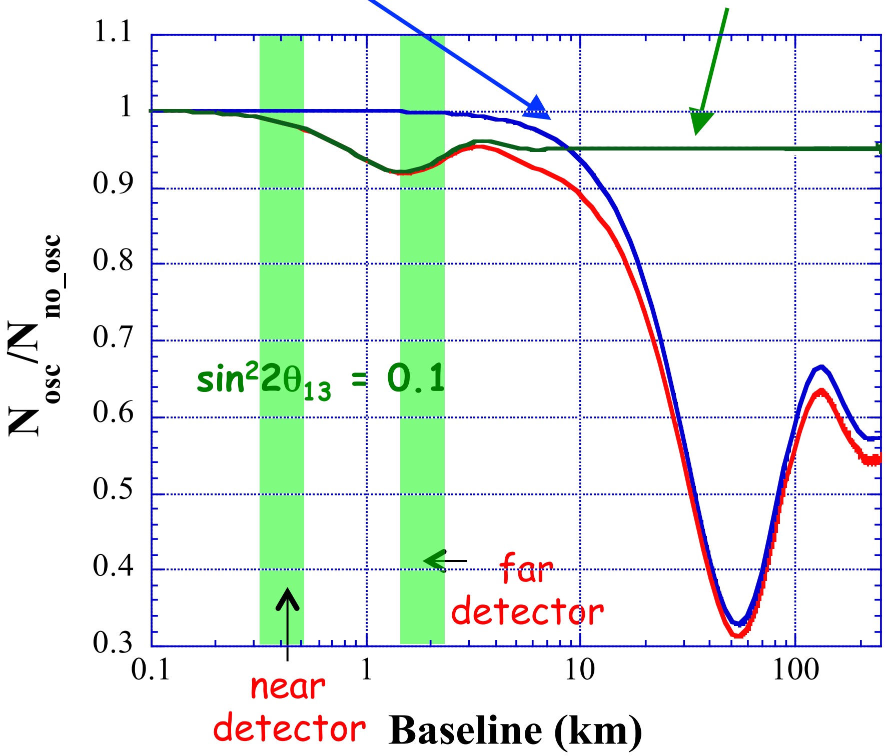


From Bemporad, Gratta and Vogel

Determining θ_{13} With Reactor $\bar{\nu}_e$

- Look for disappearance of electron antineutrinos from reactors:

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



- Perform relative measurement, for a given E :

$$\frac{R_{Far}}{R_{Near}} = \left(\frac{N_{Far}}{N_{Near}}\right)\left(\frac{\varepsilon_{Far}}{\varepsilon_{Near}}\right)\left(\frac{L_{Near}}{L_{Far}}\right)^2\left(\frac{P_{Far}}{P_{Near}}\right)$$

$\bar{\nu}_e$ rate	number of protons	detection efficiency	$1/r^2$	yield $\sin^2 2\theta_{13}$

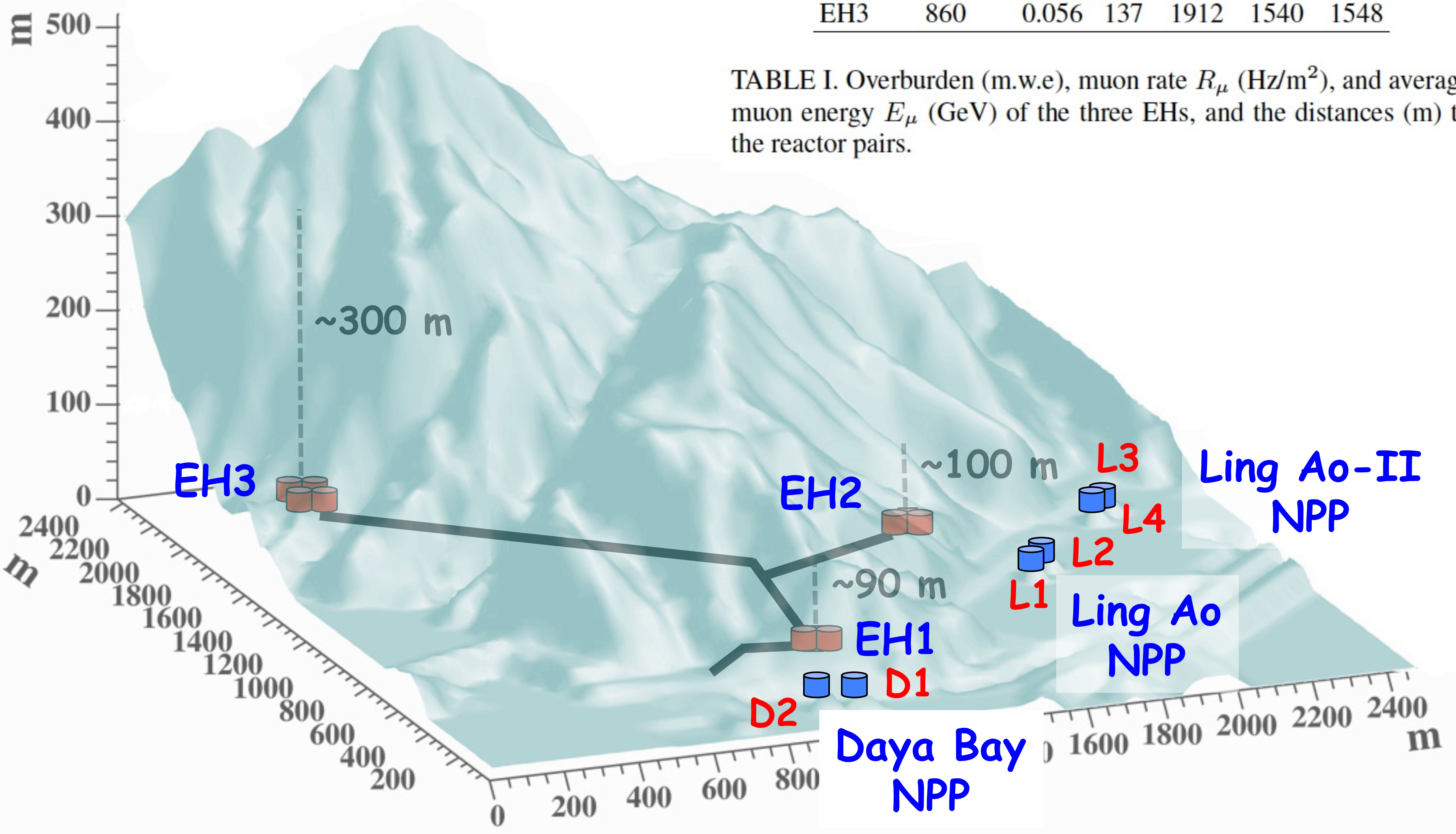
Correlated errors are cancelled & enable precise measurement.

Layout of The Experiment

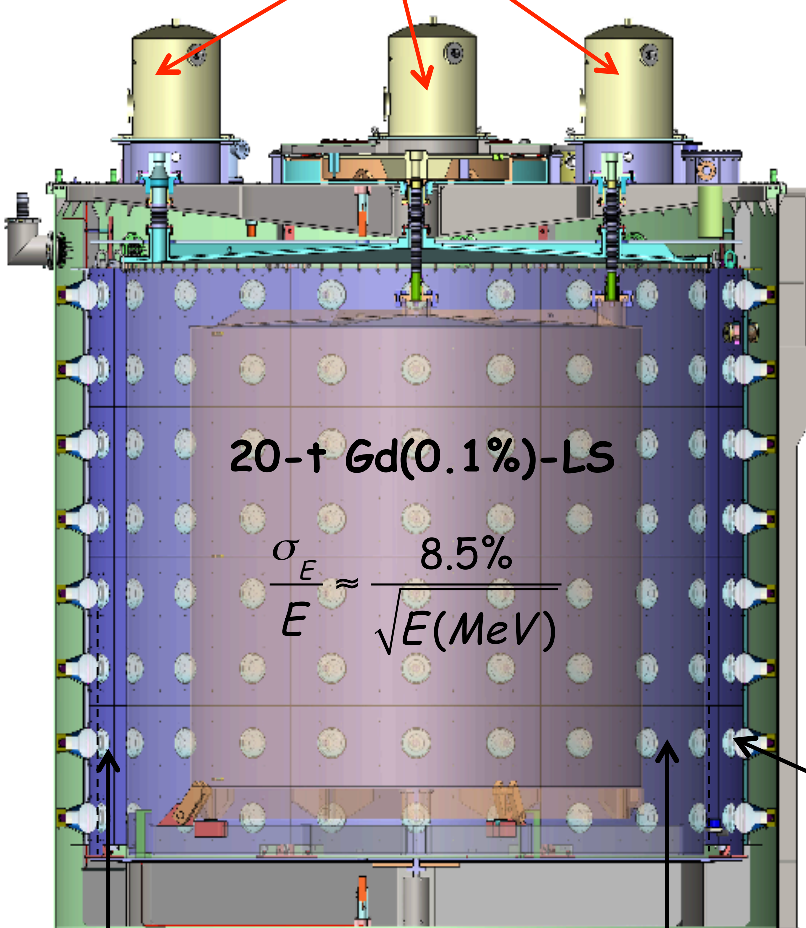
- Maximum power = 6 x 2.9 GW_{th}

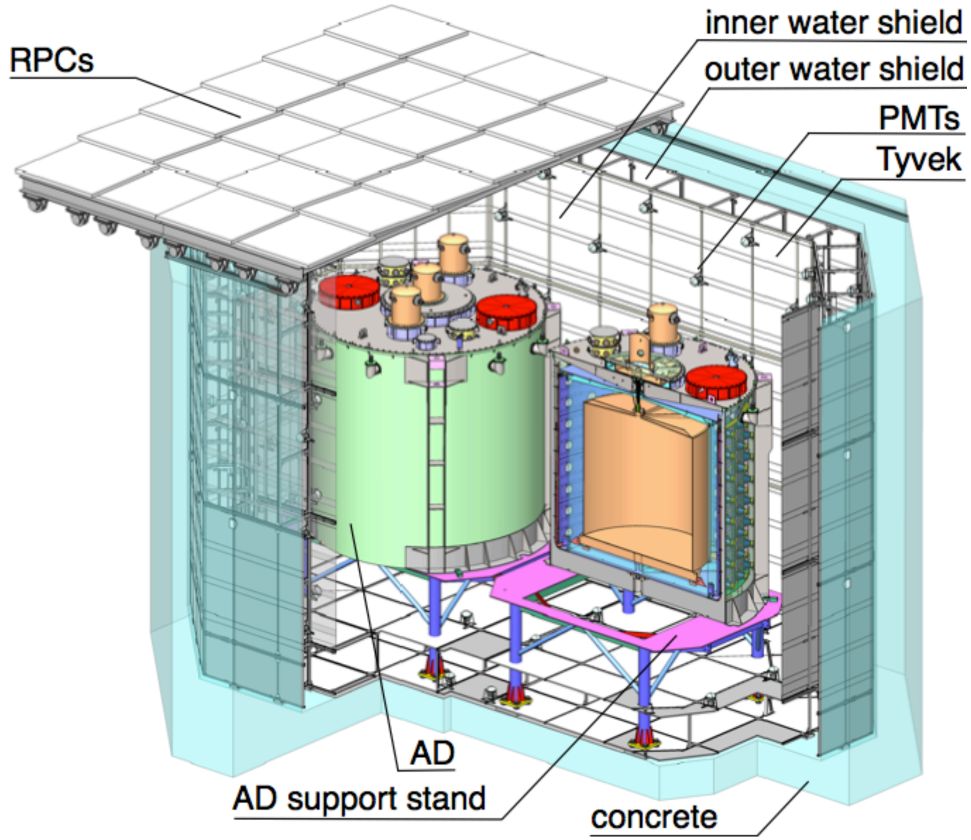
	Overburden	R_μ	E_μ	D1,2	L1,2	L3,4
EH1	250	1.27	57	364	857	1307
EH2	265	0.95	58	1348	480	528
EH3	860	0.056	137	1912	1540	1548

TABLE I. Overburden (m.w.e), muon rate R_μ (Hz/m^2), and average muon energy E_μ (GeV) of the three EHs, and the distances (m) to the reactor pairs.



Daya Bay Detectors





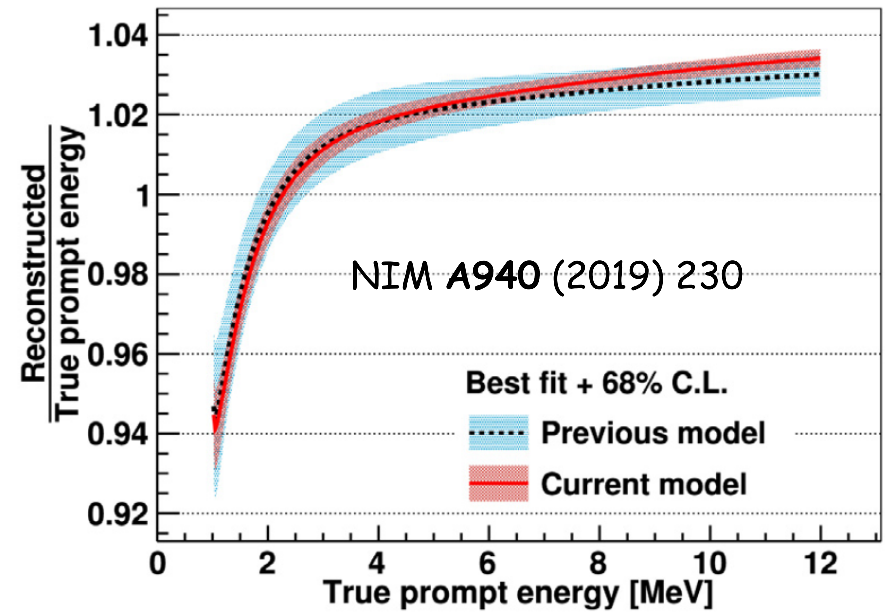
> 2.5-m water:
- attenuates gamma rays & neutrons
- Double muon tag: RPCs and Cherenkov counters

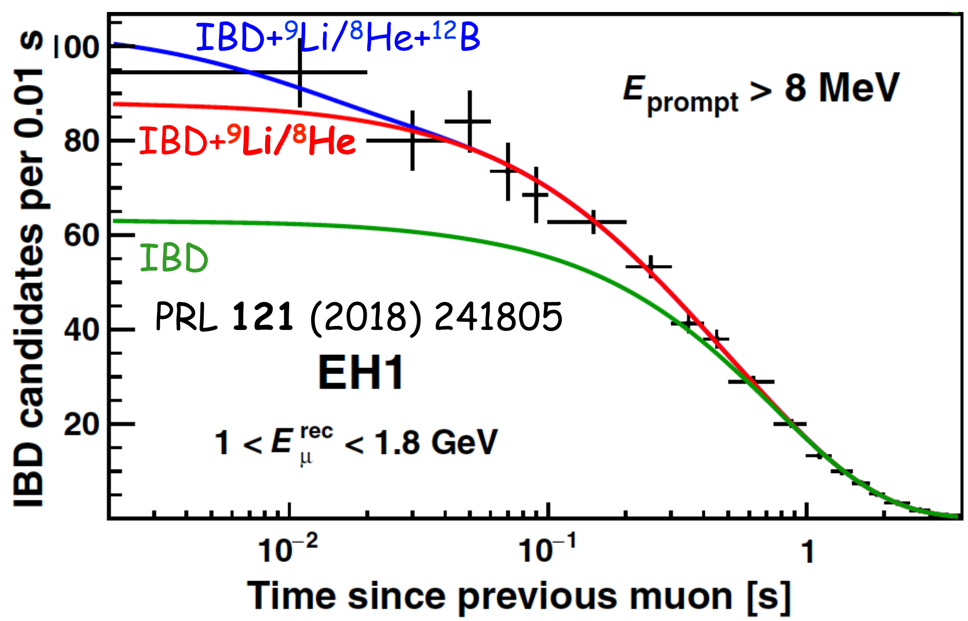
Operation of Daya Bay

Date	Operation
24 December 2011	Data taking with 6 ADs EH1: 2 ADs EH2: 1 AD EH3: 3 ADs
28 July – 19 October 2012	Special calibration runs Installation of last 2 ADs
19 October 2012	Data taking with 8 ADs
20 Dec 2016 – 26 Jan 2017	Special calibration runs EH1 AD1 used for LS studies
26 January 2017	Data taking with 7 ADs EH1: 1 ADs EH2: 2 AD EH3: 4 ADs

Recent Improvements To Analyses

- Reduced uncertainty in absolute energy scale
  - dedicated calibration using ^{60}Co, and n-sources with different encapsulating materials
  - deployed FADC readout in one AD
  - Uncertainty changed from 1% to 0.5%
- Smaller uncertainty in $^{9}Li/^{8}He$ background
  - Cut hard on prompt energy to enhance $^{9}Li/^{8}He$ events in the time-since-last-muon distribution
  - decreased from 43% to 27%
- Reduced uncertainty in spent fuel from 100% to 30%
  - detailed study of spent-fuel history provided by power plant





Prompt-energy Spectrum in 2018

1958 days of data

- 3.5 millions inverse beta decay candidates (IBDs) were detected in the near halls, and 0.5 million IBDs in the far hall.
- B/S ≤ 2% in all halls

	EH1	EH2	EH3
Accidental/IBD	1.3%	1.0%	1.3%
^{9}Li-^{8}He/IBD	0.4%	0.3%	0.3%
Fast n/IBD	0.1%	0.1%	0.07%
Am-C/IBD	0.03%	0.02%	0.07%
^{13}C(a,n)^{16}O/IBD	0.01%	0.01%	0.04%

Background contributes <0.15% to the uncertainty in the IBD rate

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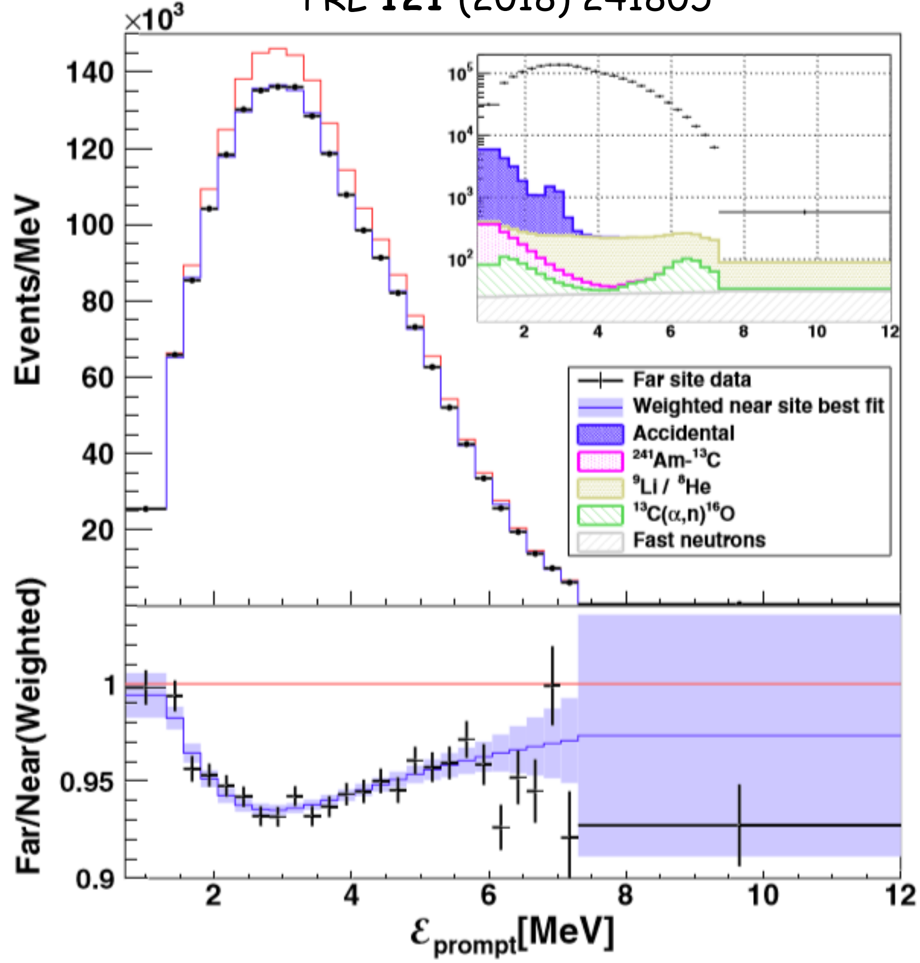

Most Precise $\sin^2 2\theta_{13}$ & Δm^2_{ee}

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

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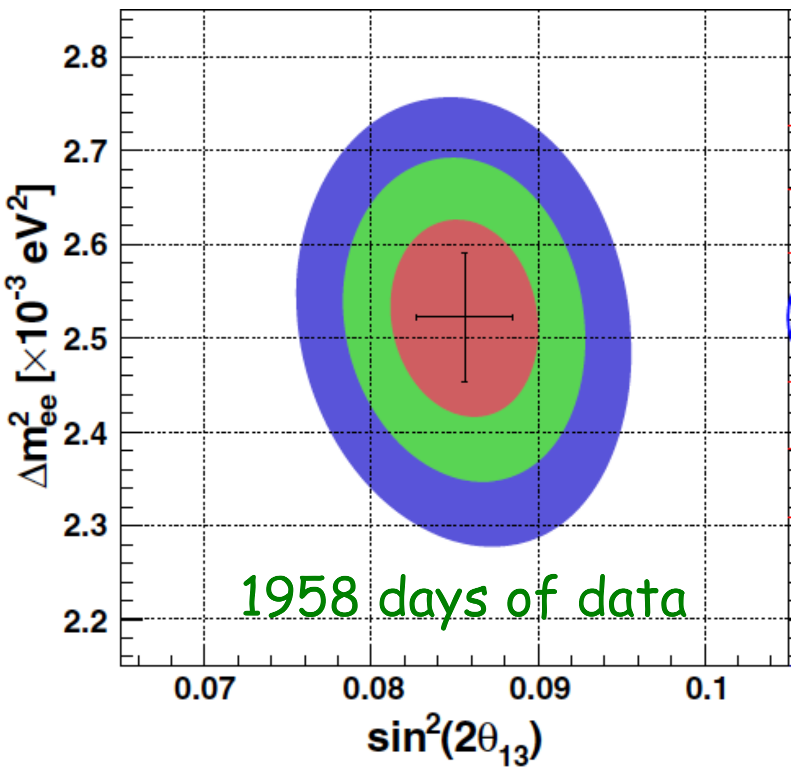
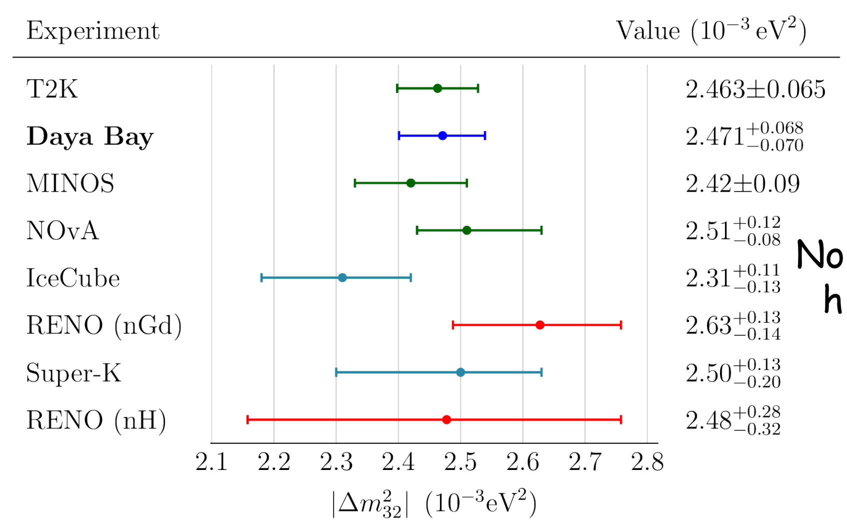


$$\sin^2\left(\frac{\Delta m^2_{ee} L}{4E}\right) \leftrightarrow \cos^2\theta_{12}\sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) + \sin^2\theta_{12}\sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$

$\Delta m^2_{32} = +(2.471^{+0.068}_{-0.070}) \times 10^{-3}$ eV^2 (NH)

$\Delta m^2_{32} = -(2.575^{+0.068}_{-0.070}) \times 10^{-3}$ eV^2 (IH)



Δm^2_{32}
Normal mass hierarchy

$\sin^2 2\theta_{13} = 0.0856 \pm 0.0029$

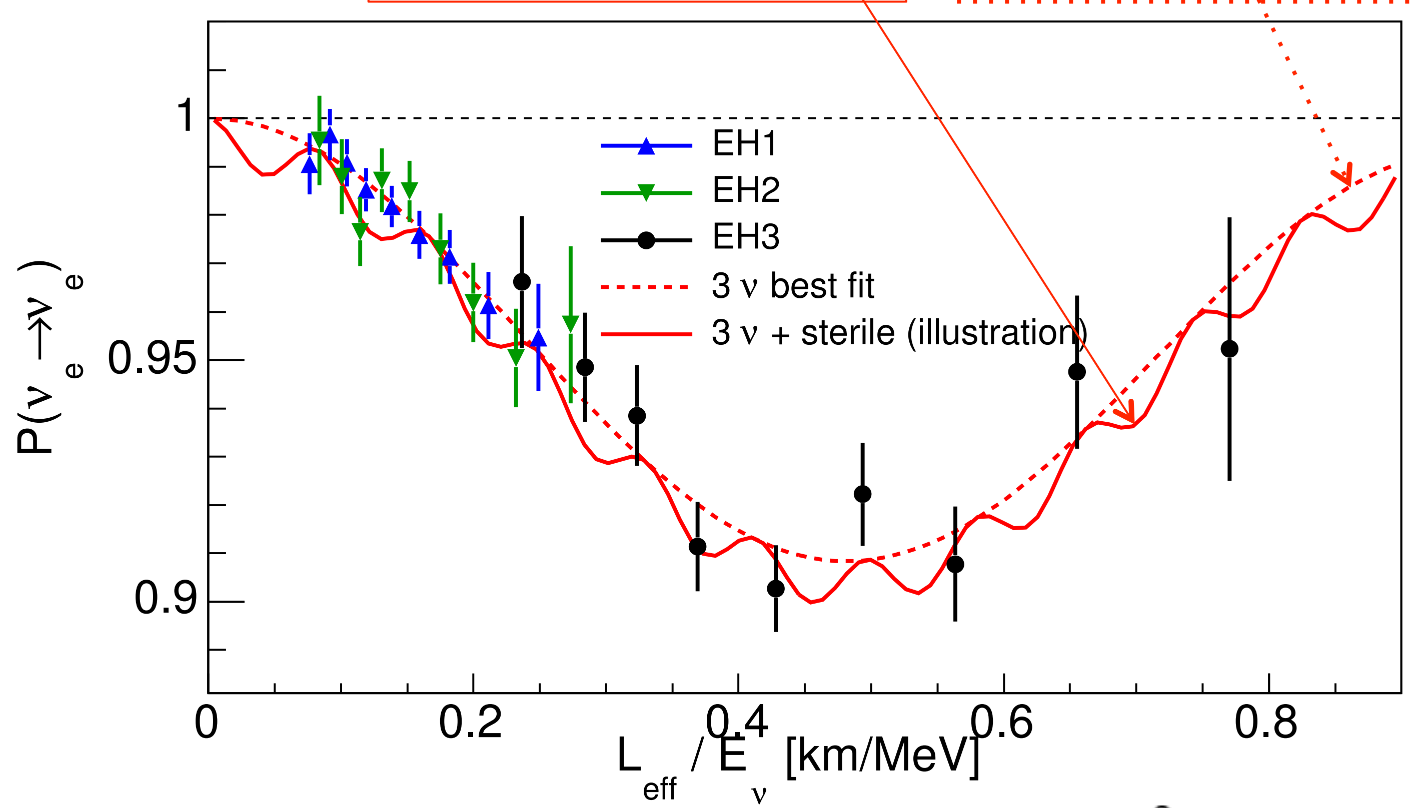
$\Delta m^2_{ee} = (2.522^{+0.068}_{-0.070}) \times 10^{-3}$ eV^2

$|\Delta m^2_{32}|$'s obtained with ν_e & ν_μ agree, supporting 3-flavor paradigm

Sterile-active Neutrino Oscillation

- Assume mixing of 3 flavours of active neutrinos with 1 sterile neutrino.
- Survival probability of reactor antineutrino is modified:

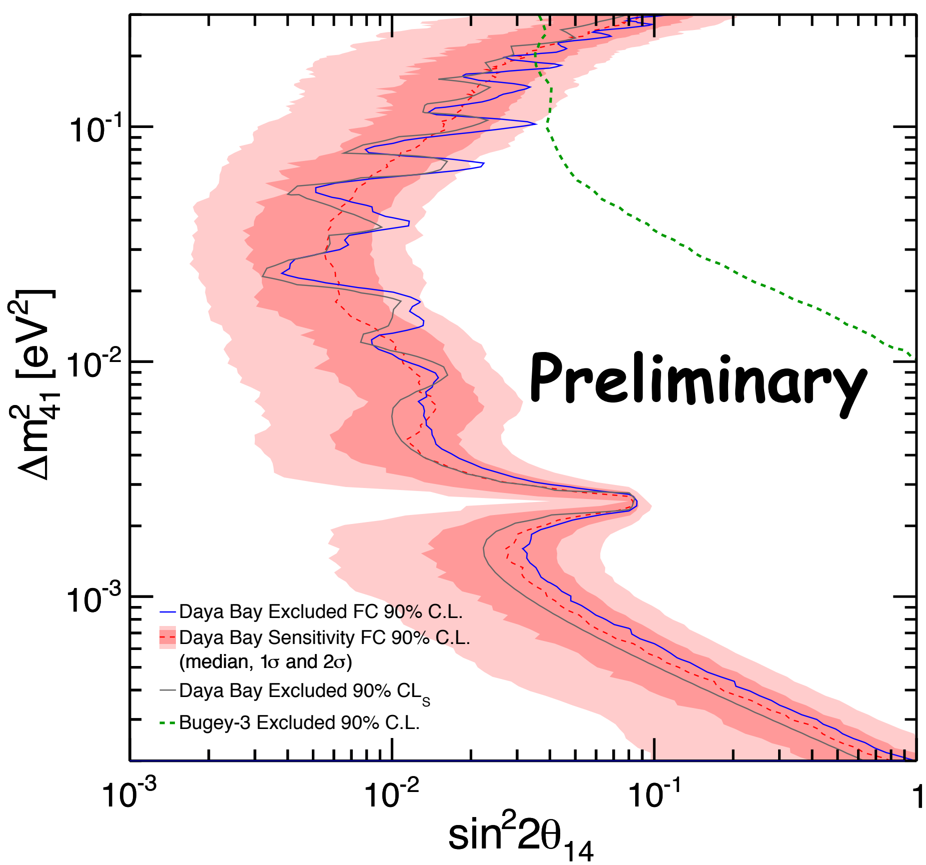
$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \cong 1 - \sin^2 2\theta_{14} \sin^2\left(\frac{\Delta m^2_{41} L}{4E_\nu}\right) - \cos^4\theta_{14} \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{ee} L}{4E_\nu}\right)$$



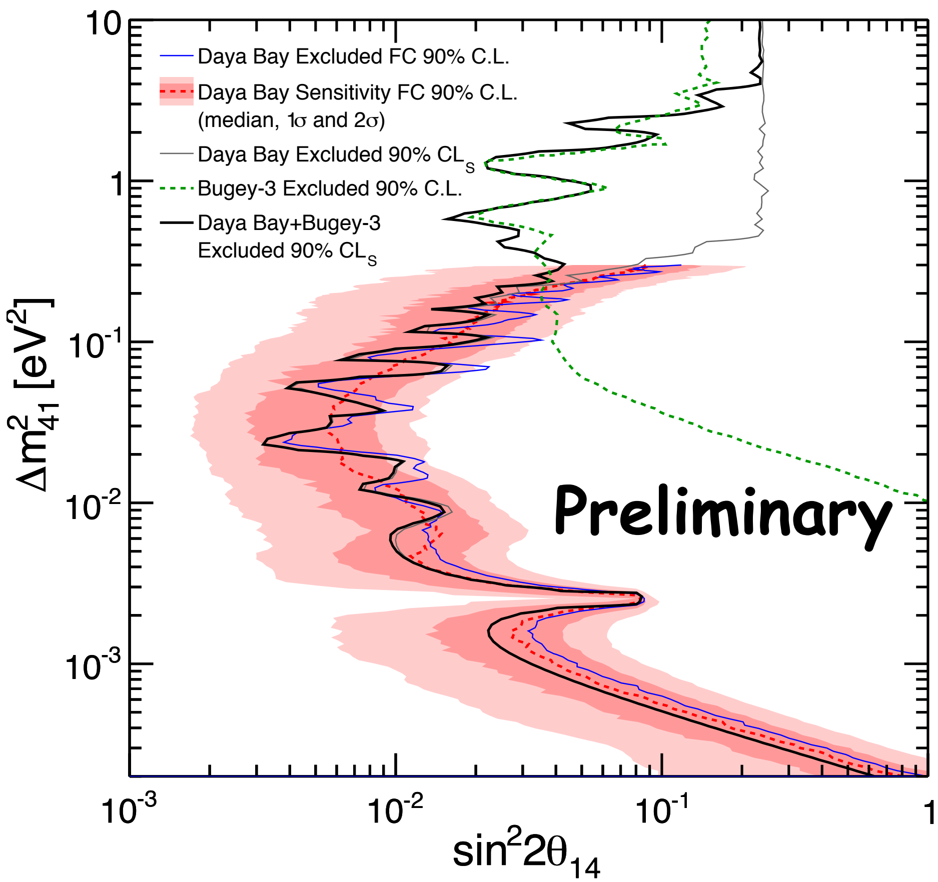
Limit on A Light Sterile Neutrino

- Doubled the data sample by ~2 from the 2016 search

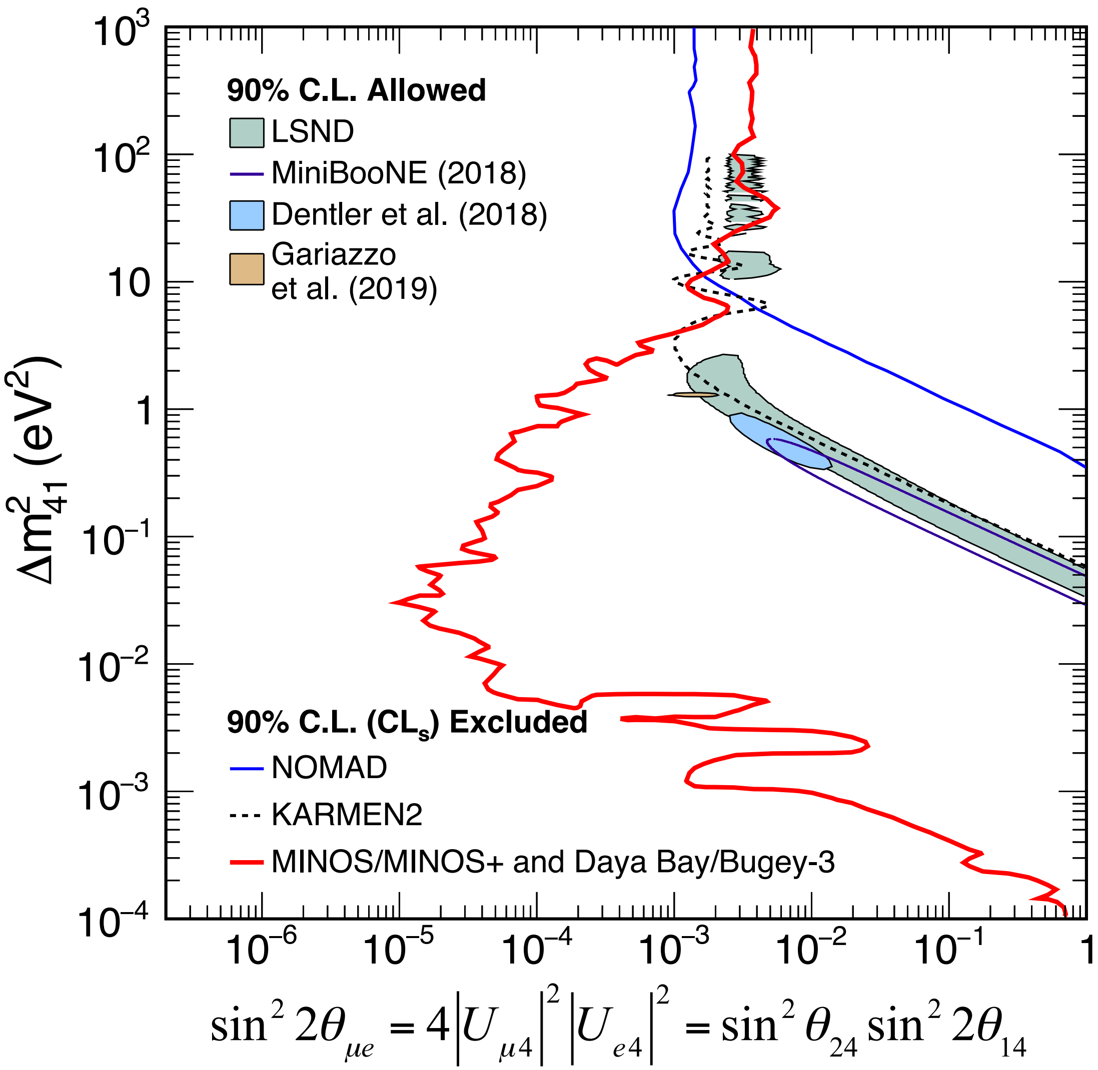
Daya Bay Only
1230 days of data



Daya Bay + Updated Bugey-3



Sterile Neutrinos: MINOS+Daya Bay+Bugey-3



- Excluded all the allowed region of LSND and MiniBooNE for Δm^2_{41} < 10 eV^2 (90% C.L.) and the best fits of Dentler et al. and Gariazzo et al.

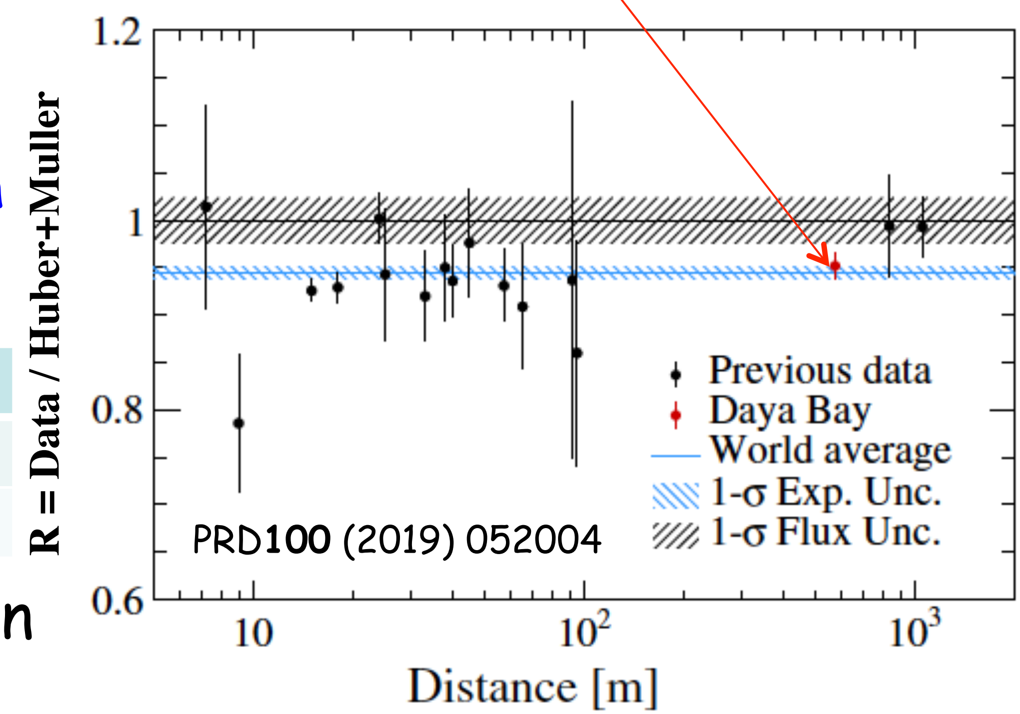
Reactor $\bar{\nu}_e$: Absolute Flux

- Improved neutron detection efficiency
  - special calibration run using ^{241}Am-^{13}C and ^{241}Am-^{9}Be neutron sources in all ACUs of one AD
  - refined simulation to match the special calibration data better

	Previous	Now
ε_n	(81.83±1.69)%	(81.48±0.74)%
Total	2.1%	1.5%

- 1.8σ disagreement between Daya Bay and prediction
- Reactor $\bar{\nu}_e$ anomaly due to
  - new physics ?
  - incomplete theoretical understanding ?

Daya Bay (1230 days) :
R = 0.952 ± 0.014 ± 0.023



Daya Bay agrees with the average of the previous measurements:
R = 0.942 ± 0.009 (exp) ± 0.025 (model)

Reactor $\overline{\nu}_e$: Energy Spectrum

- Improved measurement of the spectral shape disagrees with the Huber-Mueller prediction
  - between 0.7 MeV and 8 MeV by 5.3σ
  - in the range of 4-6 MeV by 6.3σ
- Excess events in 4-6 MeV are correlated with reactor power.
- The spectral anomaly is not consistent with sterile-active neutrino mixing.

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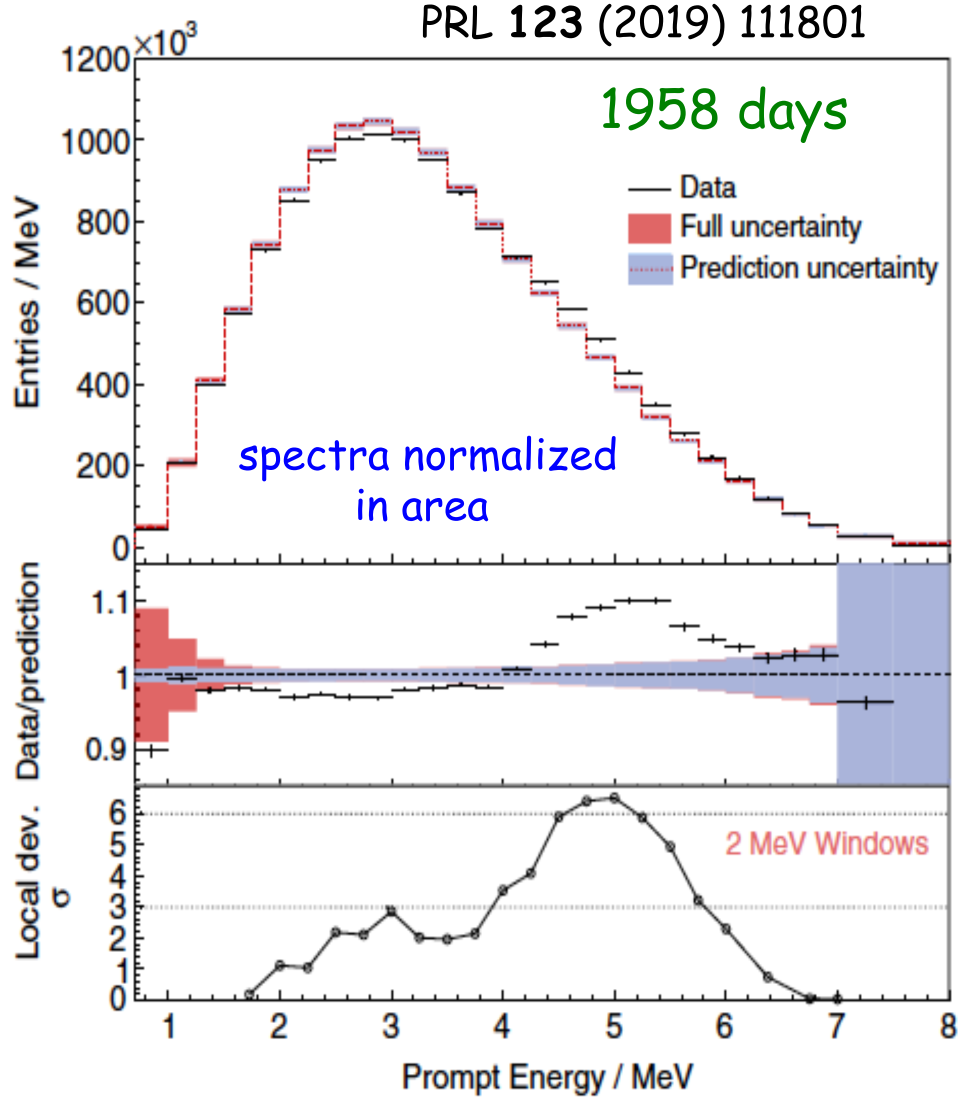
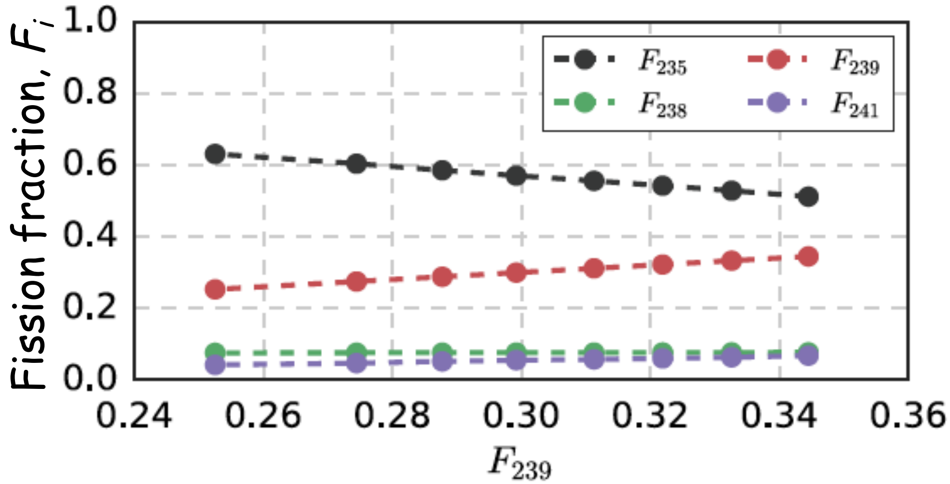
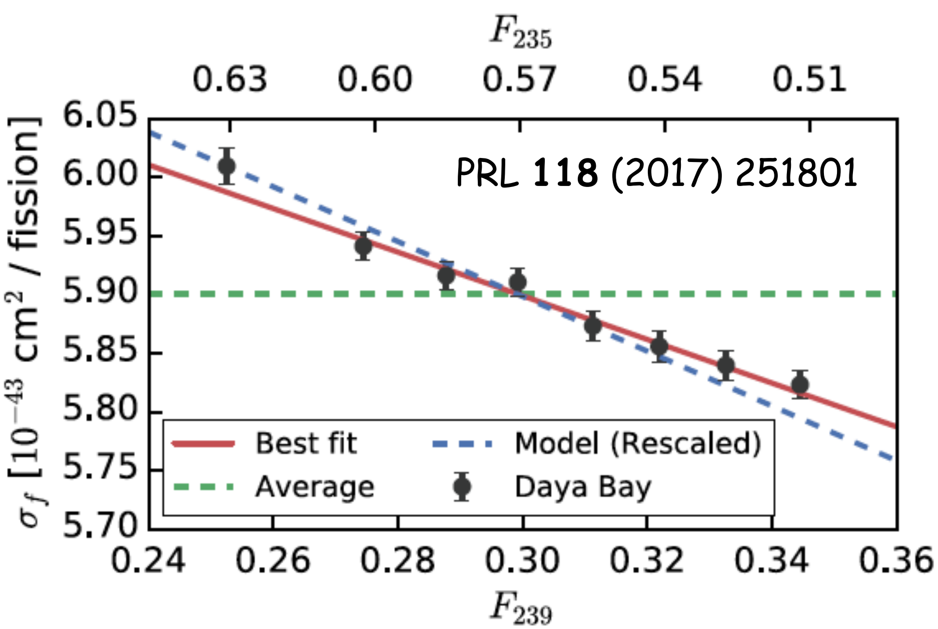


Flux Evolution with Fuel Composition

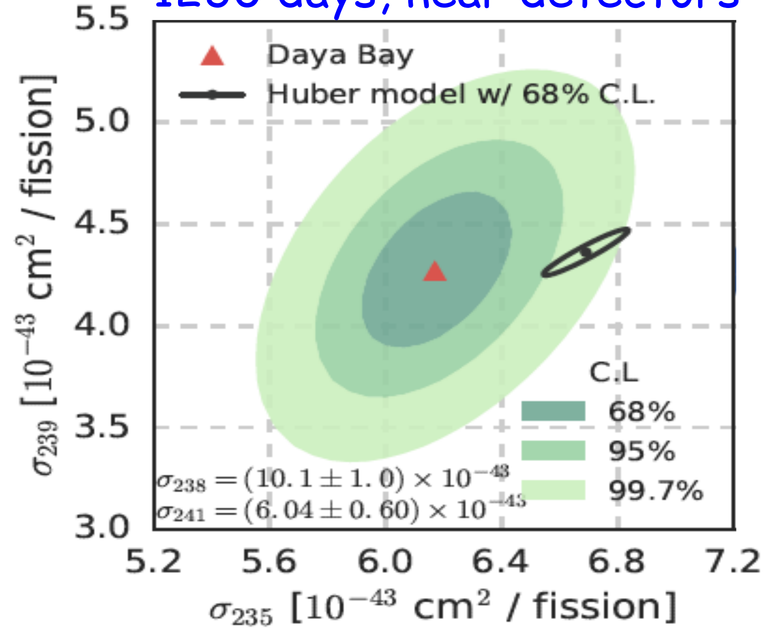
- Reactor $\overline{\nu}_e$ primarily come from ^{235}U, ^{239}Pu, ^{238}U, and ^{241}Pu.



- 7.8% overestimation of predicted $\overline{\nu}_e$ flux from ^{235}U
- ^{235}U could be the key source of the reactor $\overline{\nu}_e$ anomaly.



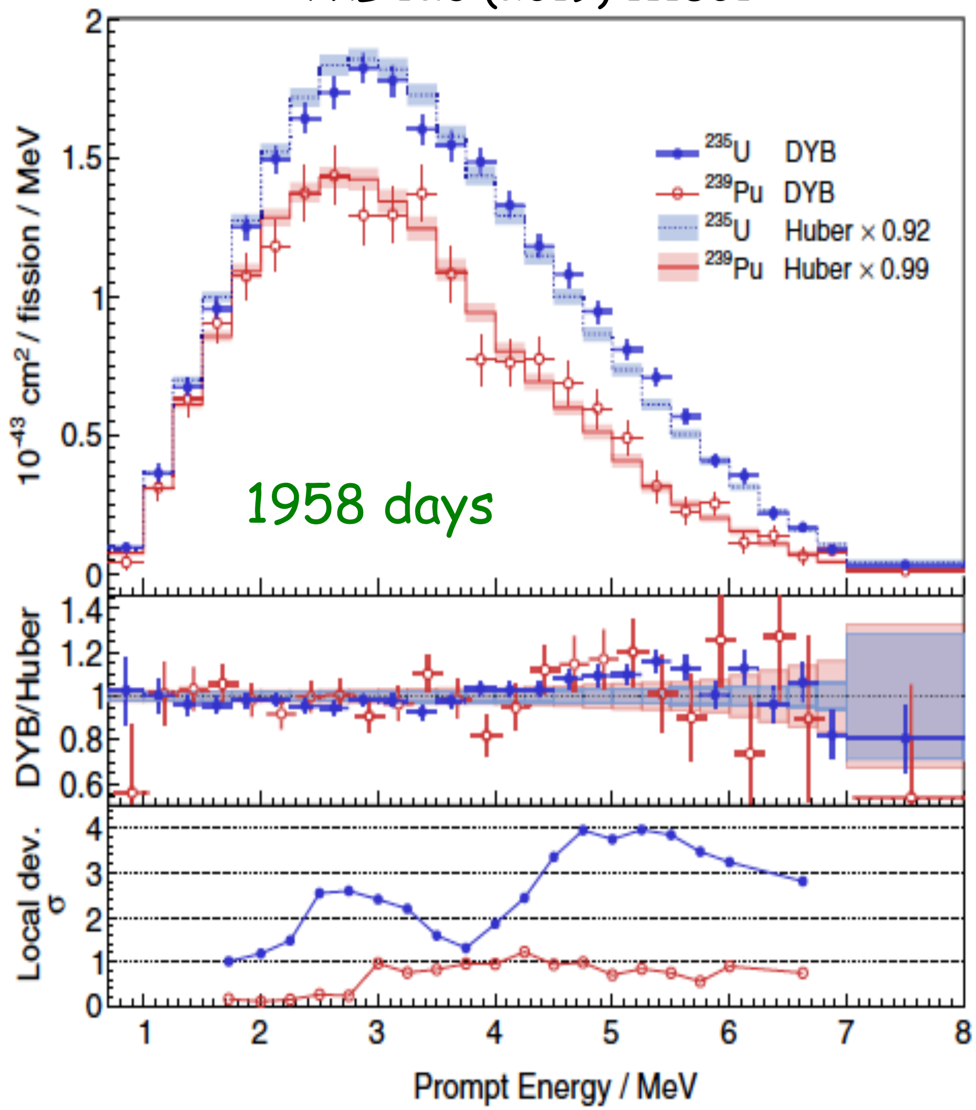
1230 days, near detectors



$\overline{\nu}_e$ Spectra of ^{235}U and ^{239}Pu

- Extract the individual spectra of $\overline{\nu}_e$'s from ^{235}U and ^{239}Pu together from the temporal evolution of the measured prompt spectrum as a function of the ^{239}Pu fission fraction.
- Excess events relative to Huber-Muller predictions are seen in 4-6 MeV region
  - 4σ significance for ^{235}U
  - $\sim 1\sigma$ only for ^{239}Pu
- First measurements of such spectra for LEU reactors.

PRL **123** (2019) 111801



Summary

- Daya Bay
  - has acquired the largest sample of reactor antineutrinos
  - provides the most precise measurement of
    - $\sin^2 2\theta_{13} = 0.0856 \pm 0.0029$
      $\Delta m^2_{ee} = (2.522^{+0.068}_{-0.070}) \times 10^{-3}\ eV^2$
    - absolute reactor antineutrino rates and spectra
  - does not find any evidence of sterile-active neutrino mixing

- Daya Bay will stop data taking by December of 2020
  - Precision in $\sin^2 2\theta_{13} \approx 0.0025$
    - Remains the most precise in the foreseeable future
  - Precision in $\Delta m^2_{ee} \approx 0.06 \times 10^{-3}\ eV^2$

Thank You