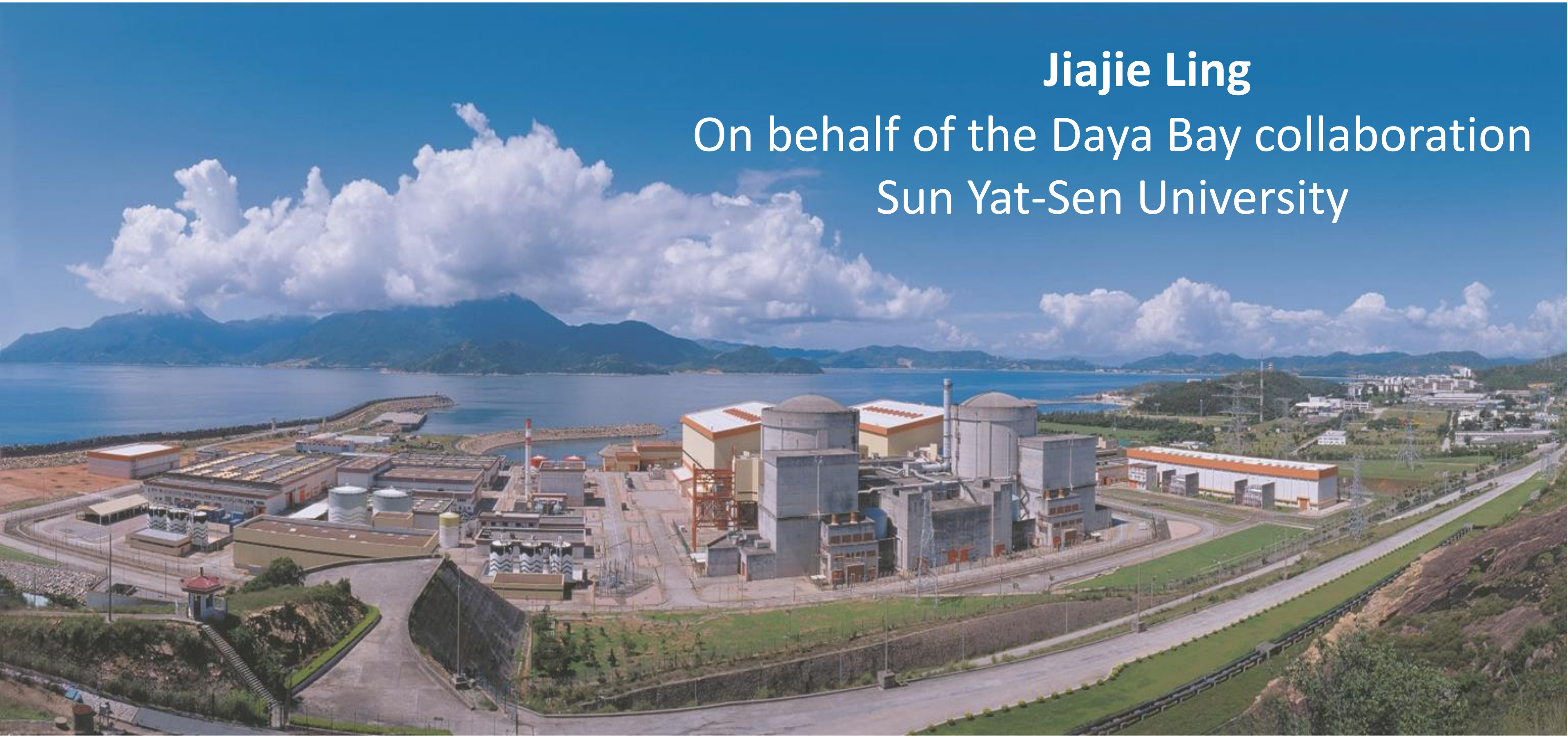
Recent Results from Daya Bay

Jiajie Ling
On behalf of the Daya Bay collaboration
Sun Yat-Sen University



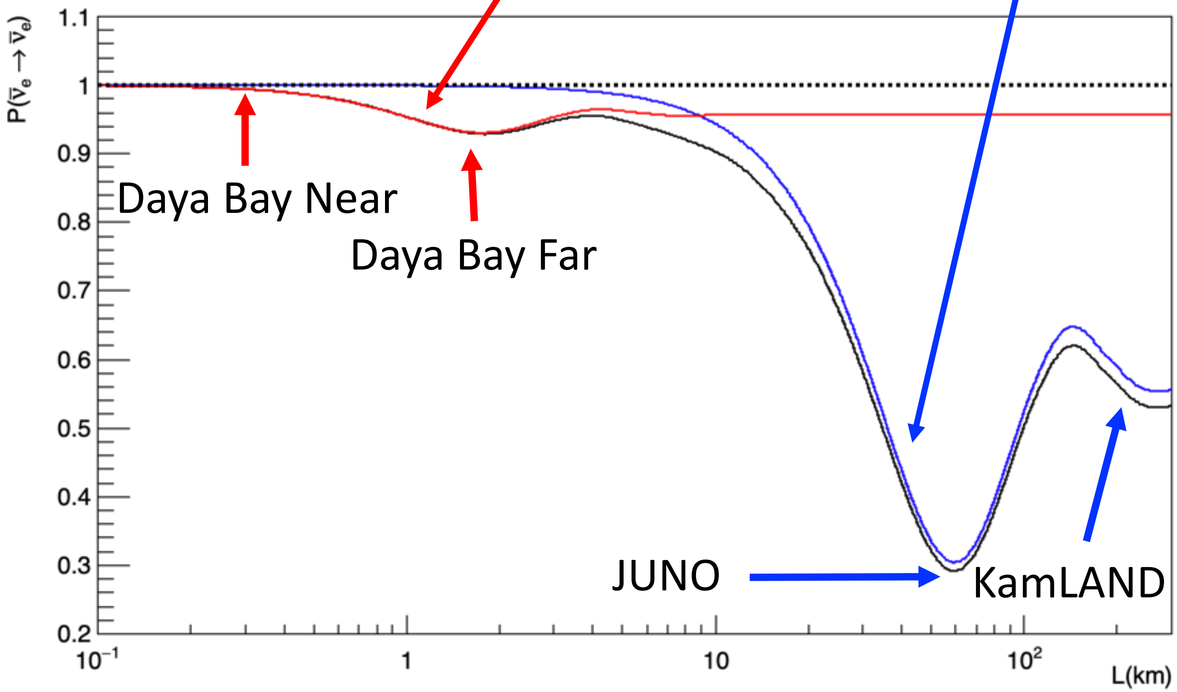
XXIX Neutrino Conference
Fermilab June 22 – July 2, 2020

Reactor Antineutrino Oscillation

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$

$$\approx 1 - \sin^2 2\theta_{13}\sin^2\Delta_{ee} - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$

$$\Delta_{ij} = \Delta m^2_{ij}\frac{L}{4E}$$



Immune to CP violation and matter effects

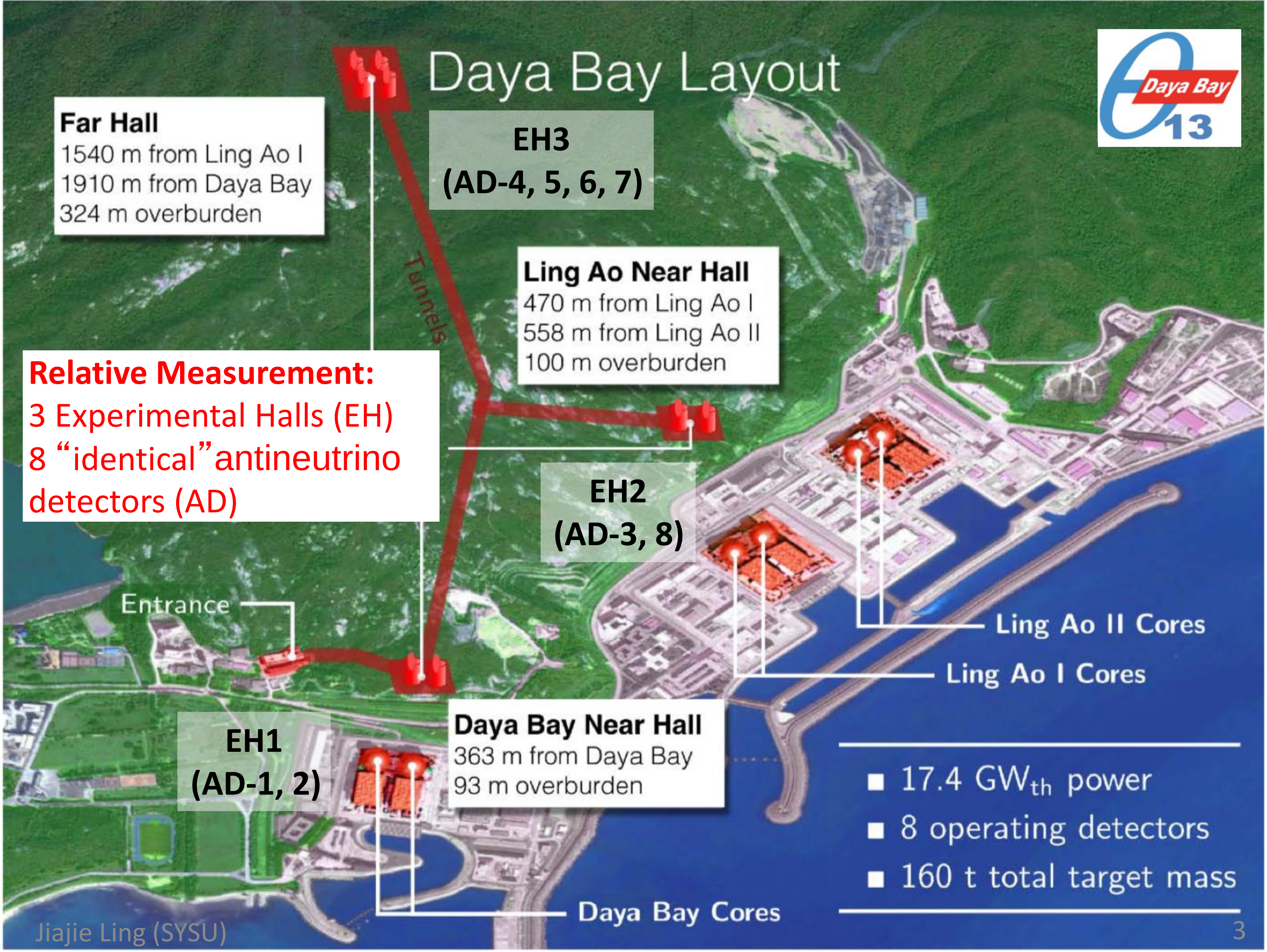
Key for a precise measurement:

- ✓ **Baseline Optimization**

$$L(\mathrm{m}) \sim \frac{\pi \cdot E\ (\mathrm{MeV})}{2.54 \cdot \Delta m^2(\mathrm{eV}^2)}$$

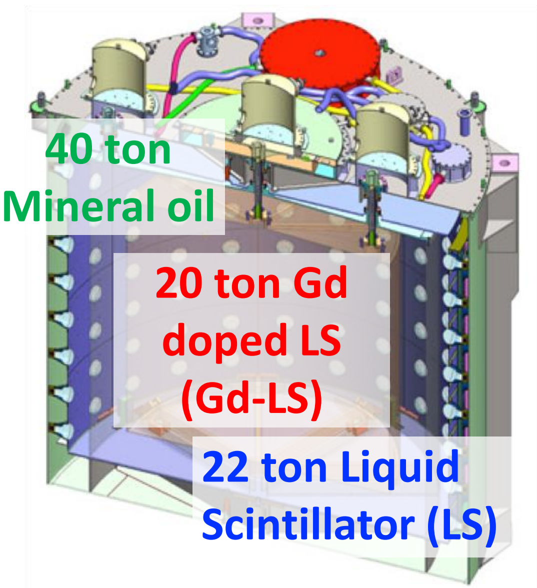
- ✓ **Large statistics**
  - Large $\bar{\nu}_e$ flux
  - Massive target mass
- ✓ **Background control**
  - Large overburden
  - Detector shielding
- ✓ **Systematics control**
  - Relative Far/Near measurement

Daya Bay Layout



Antineutrino Detector (AD) System

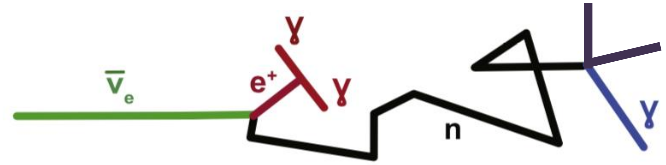
*NIM A**773** 8 (2015)*
*NIM A**811** 133 (2016)*



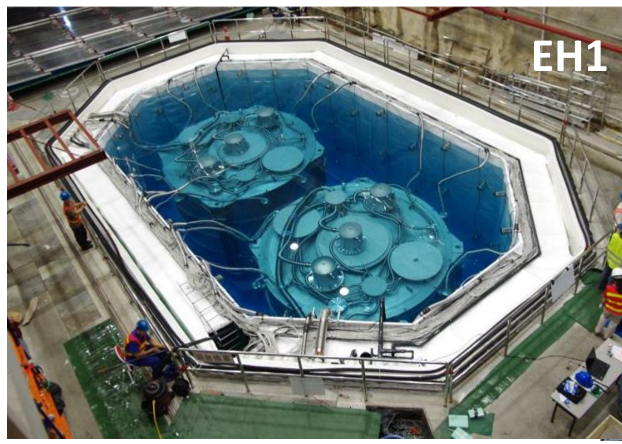
Inverse Beta Decay (IBD)

Coincidence signals

- Prompt: $E_p \approx E_\nu - 0.8$ MeV
- Delayed: nH (2.2 MeV) or nGd (~8 MeV)



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



6-AD (2-1-3)
Dec/2011 – Jul/2012

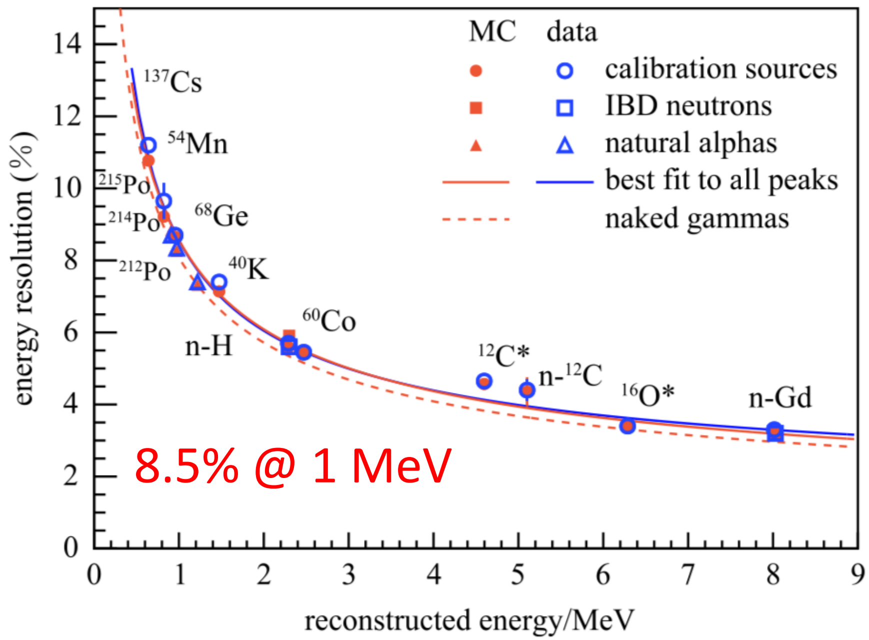
8-AD (2-2-4)
Oct/2012 – Dec/2016

7-AD (1-2-4)
Jan/2017 – Dec/2020

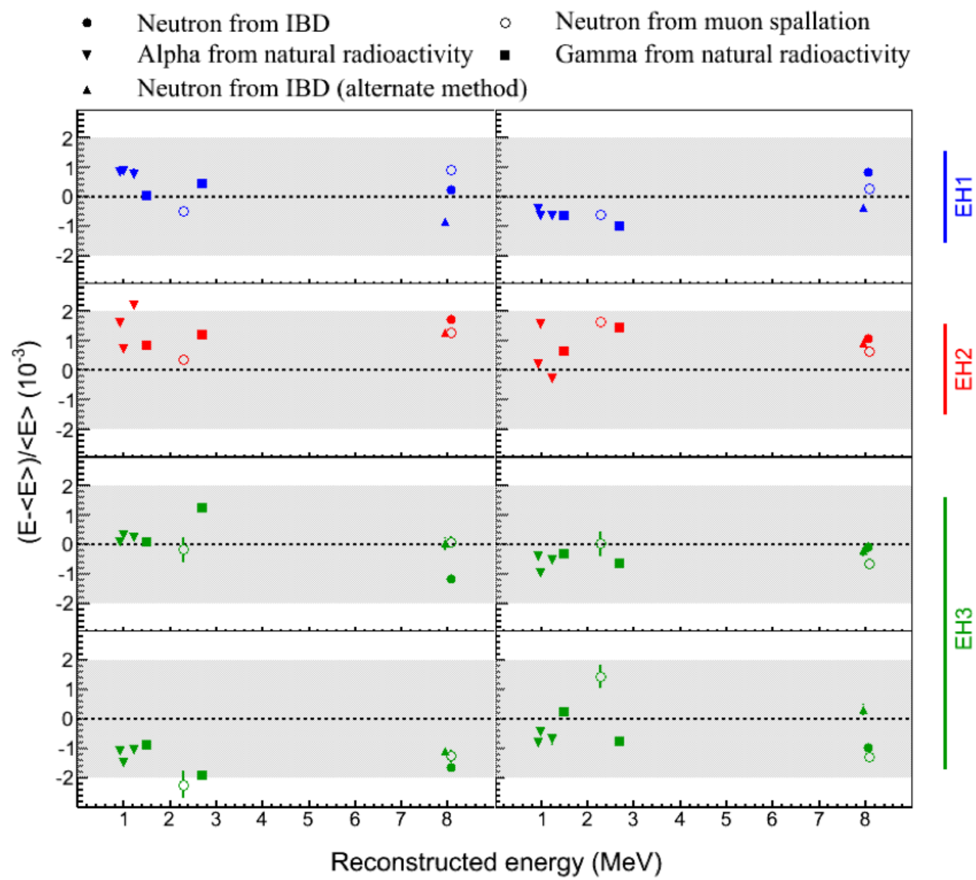
- AD7-8 installation
- Special calibration
- AD1 FADC installation
- AD1 GdLS→ LS
- End of operation

Detector Energy Response

- Rolling gain calibration using dark noise
- Weekly calibration
  - ^{68}Ge, $^{241}Am^{13}C$, ^{60}Co
  - LED diffuser ball
- Special calibration campaigns
  - ^{137}Cs, ^{54}Mn, $^{241}Am^{9}Be$, $^{239}Pu^{13}C$
- Spallation neutrons and ^{12}B
- Natural radioactivity

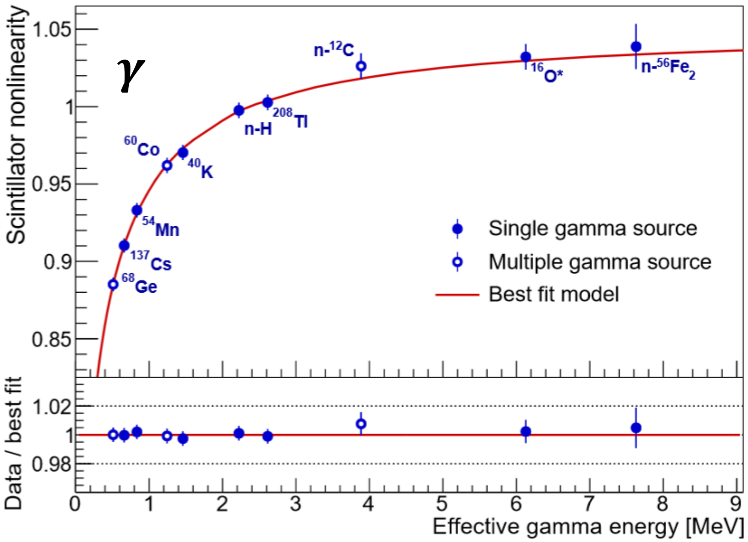


NIM A750 19 (2014)   *NIM A797 260 (2015)*

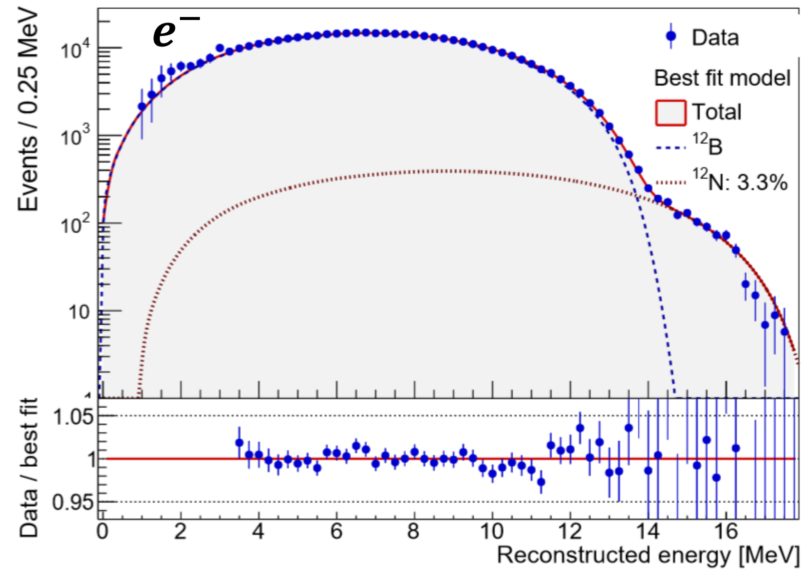


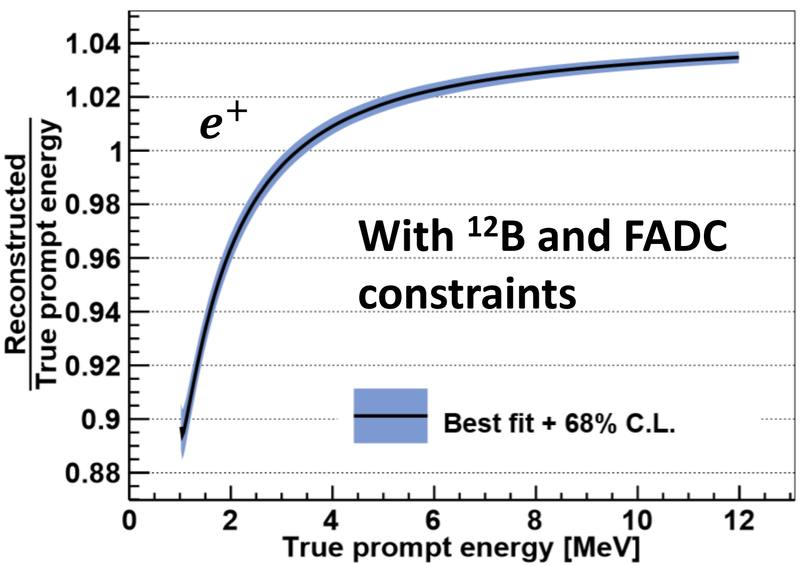
Relative detector energy scale $\lesssim 0.2\%$

Energy Nonlinearity Calibration



*NIM A **940** 230 (2019)*





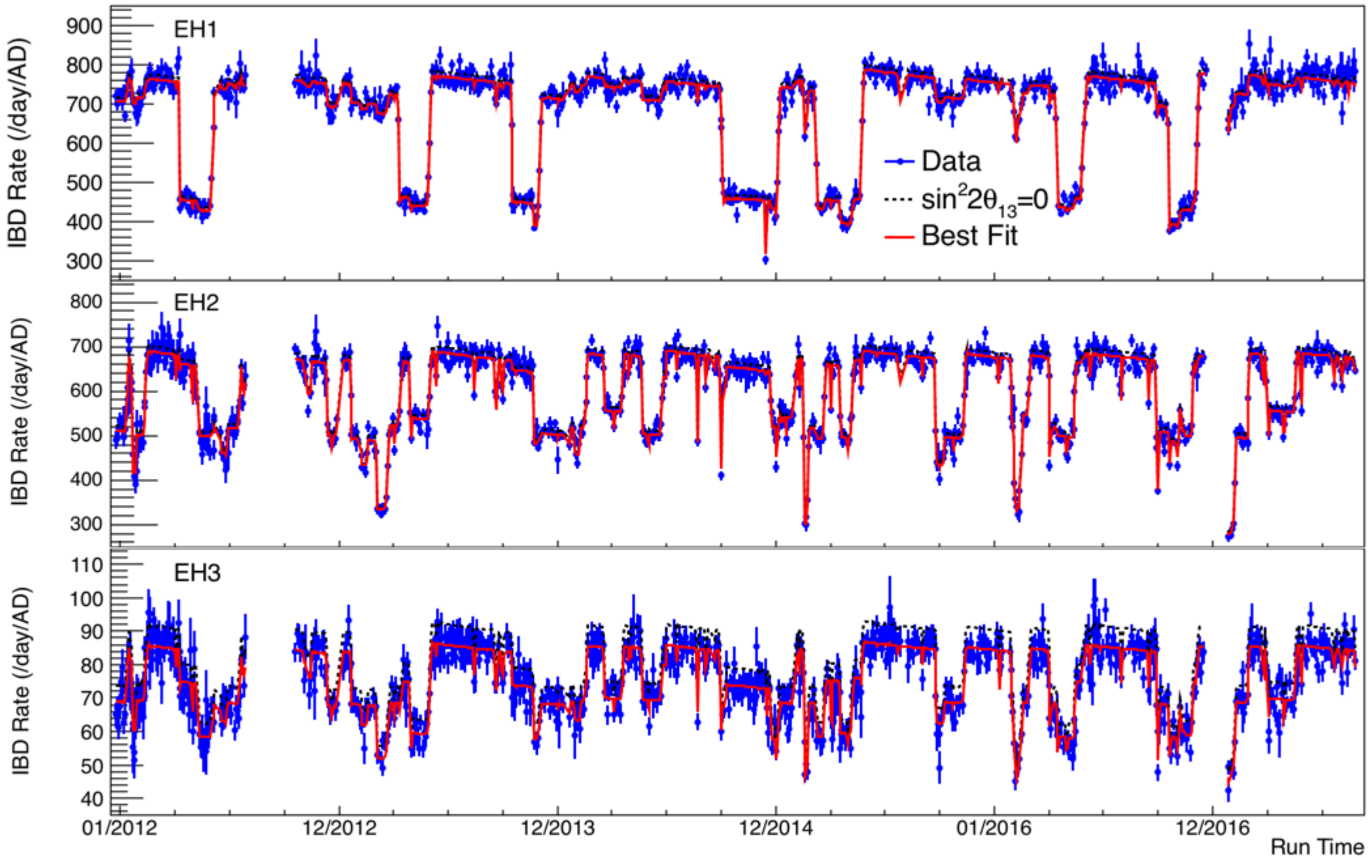
- Two major sources of energy nonlinearity:
  - Scintillator response (Birks + Cherenkov)
  - Readout electronics (FADC correction)
- Energy model for positron is derived from measured gamma and electron responses using simulation.

~0.5% absolute energy uncertainty

4 Million IBD Candidates

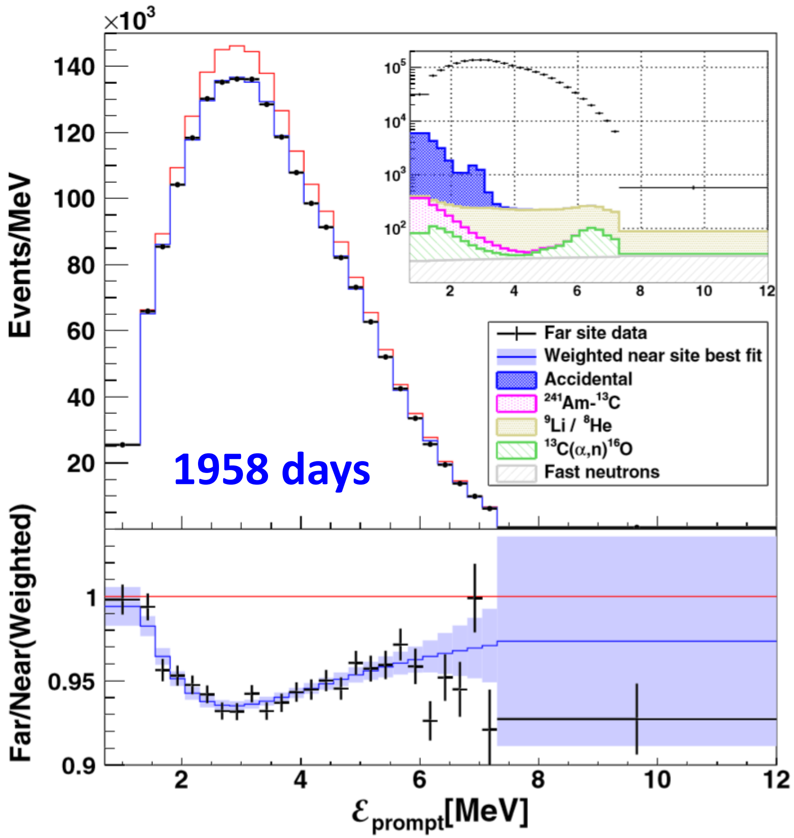
2011/12/24 – 2017/08/30 (1958 days)

Site	EH1 (Near)	EH2 (Near)	EH3 (Far)
# of IBDs	1,794,417	1,673,907	495,421



IBD rates follow the relative reactor flux expectation

Oscillation Results from nGd



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

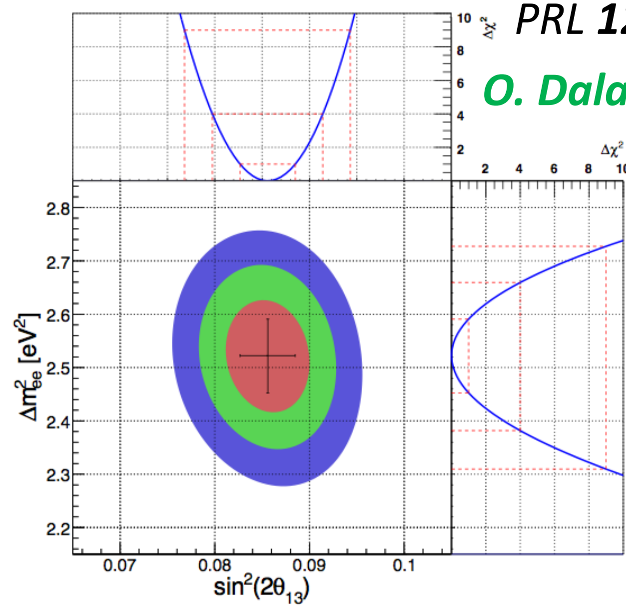
$$|\Delta m^2_{ee}| = (2.52 \pm 0.07) \times 10^{-3}\ \text{eV}^2$$

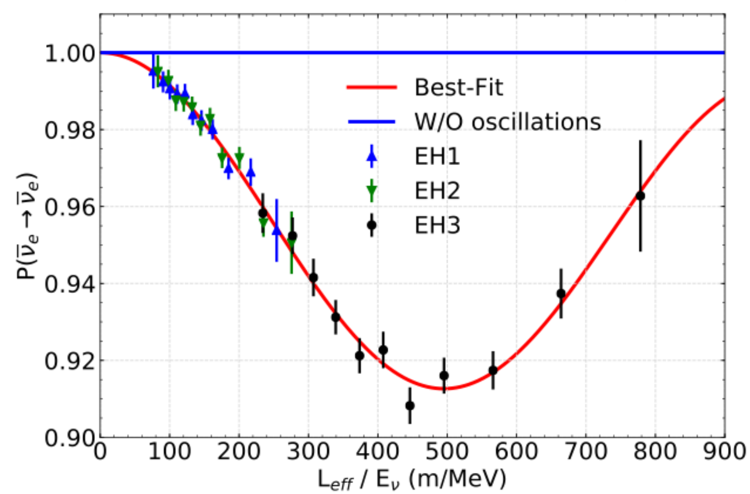
$$\Delta m^2_{32} = (2.47 \pm 0.07) \times 10^{-3}\ \text{eV}^2\ \text{(NO)}$$

$$\Delta m^2_{32} = (-2.58 \pm 0.07) \times 10^{-3}\ \text{eV}^2\ \text{(IO)}$$

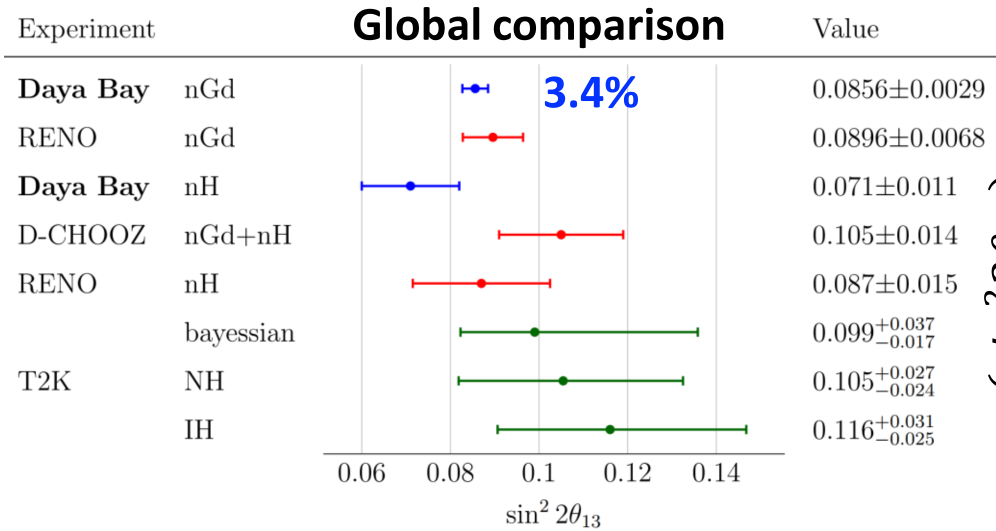
*PRL **121** 241805 (2018)*

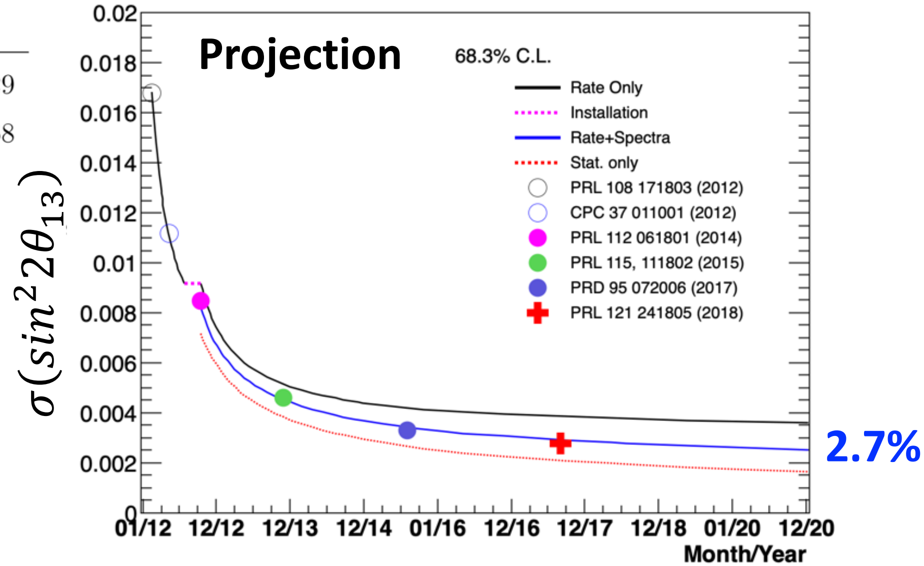
O. Dalager's Poster #531

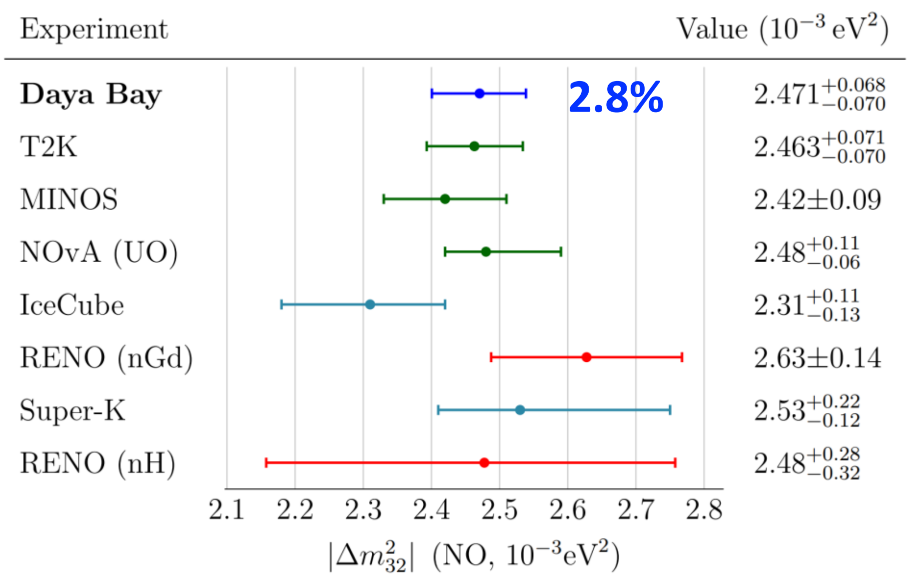


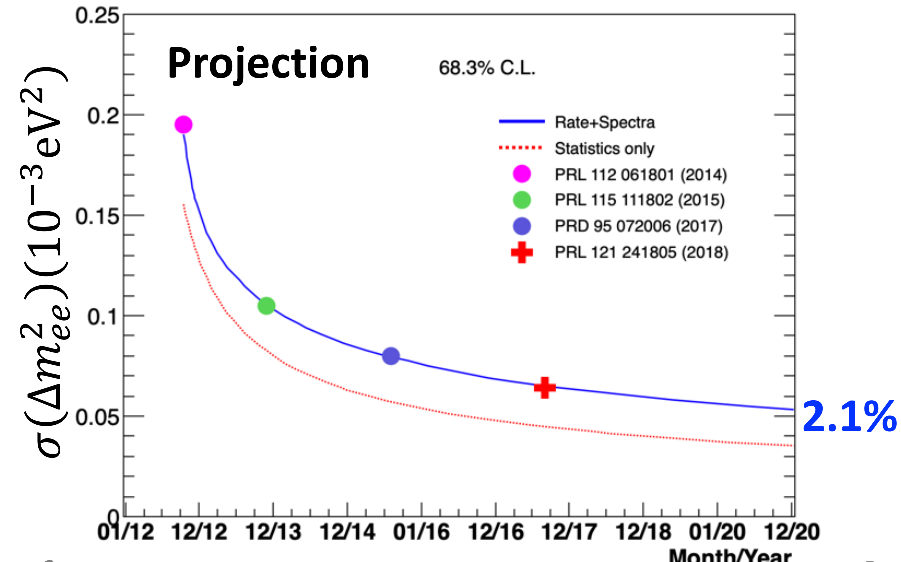


Precision Measurements on $\sin^2 2\theta_{13}$ and $|\Delta m^2_{ee}|$



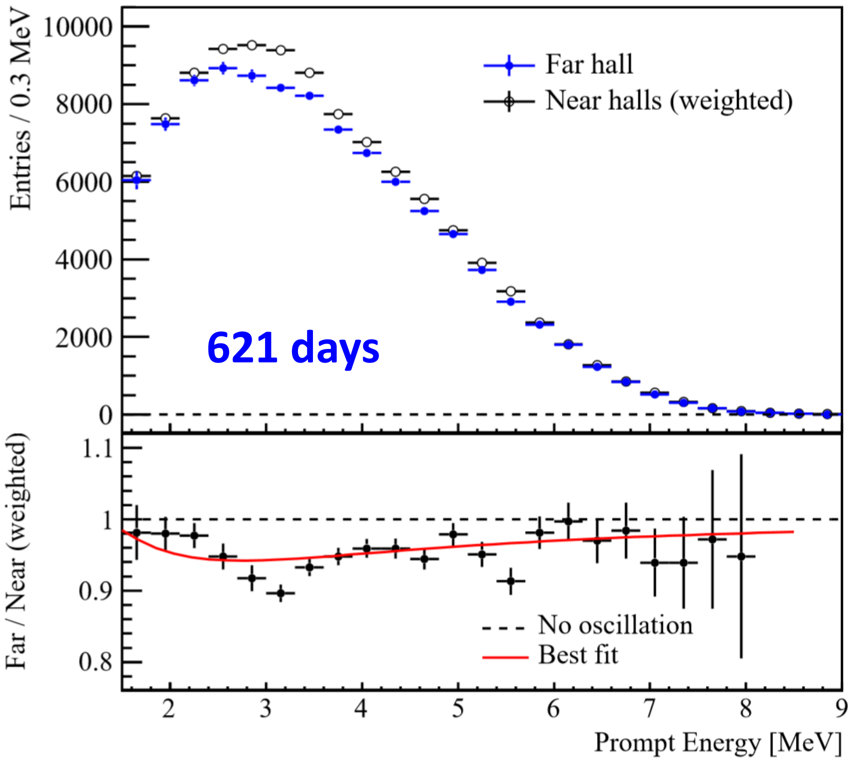




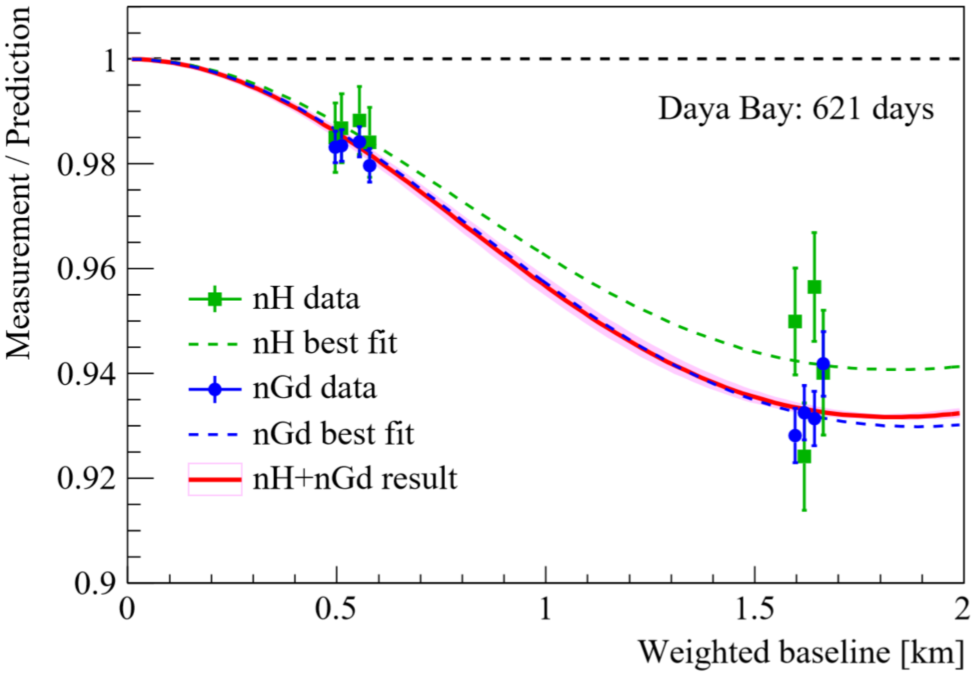


$\sin^2 2\theta_{13}$ from nH-Capture

*PRD **93** 072011 (2016)*



J. Li's Poster #131



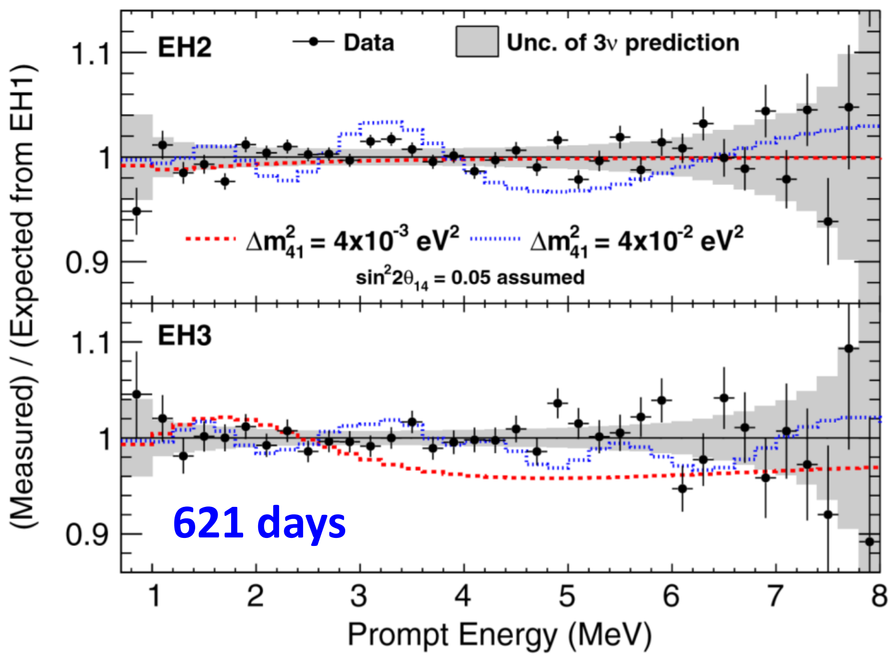
- Independent $\sin^2 2\theta_{13}$ measurement
- Challenging: 12% (54%) accidental background at near (far) hall

Rate Only analysis: $\sin^2 2\theta_{13} = 0.071 \pm 0.011$

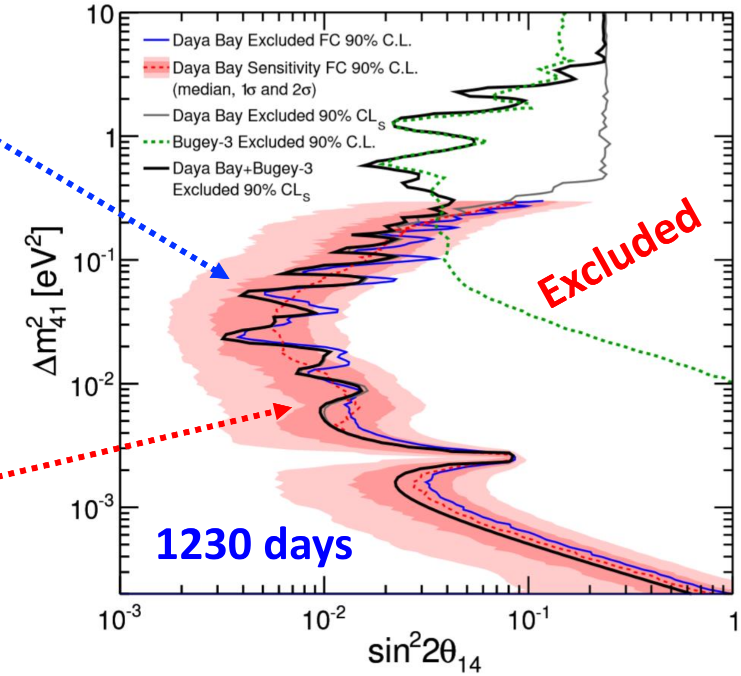
Improved nH analysis result is coming soon

Sterile Neutrino Search

PRL ***117*** *151802 (2016)*



arXiv:2002.00301, accepted by PRL



$$P(\bar{\nu}_e \to \bar{\nu}_e) \cong 1 - cos^4\theta_{14} sin^2 2\theta_{13} sin^2\left(\frac{\Delta m^2_{31} L}{4E_\nu}\right) - sin^2 2\theta_{14} sin^2\left(\frac{\Delta m^2_{41} L}{4E_\nu}\right)$$

- Search for an additional oscillation frequency besides Δm^2_{31} and Δm^2_{32}
- Data is consistent with 3-ν model; No light sterile neutrino signal observed
- Consistent results from Feldman-Cousins and CLs methods

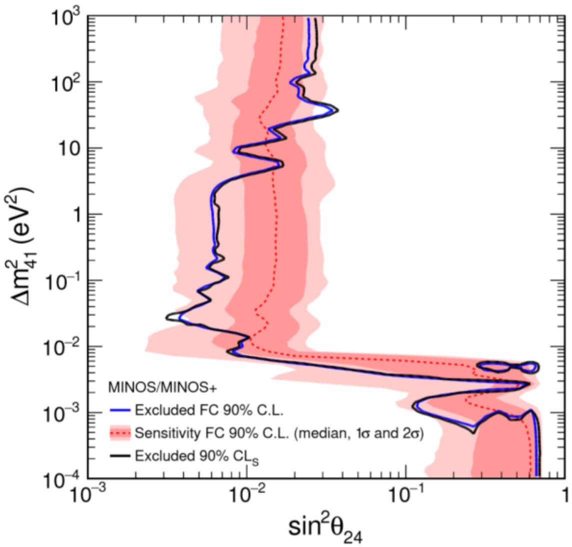
The most stringent upper limit for light sterile neutrinos ($\Delta m^2 < 0.2$ eV^2)

Joint Sterile Neutrino Searches

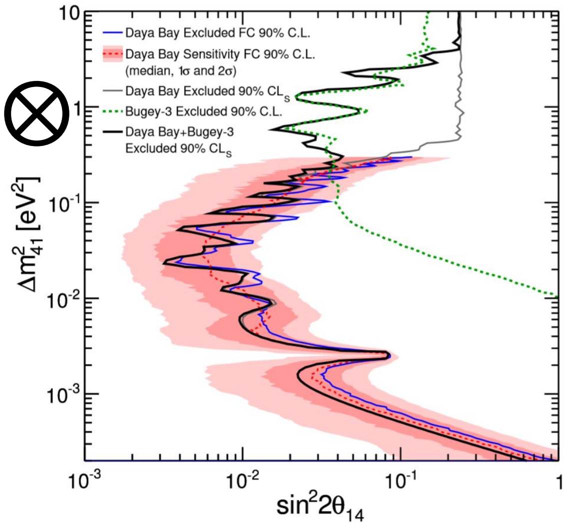
*PRL **122** 091803 (2019)*

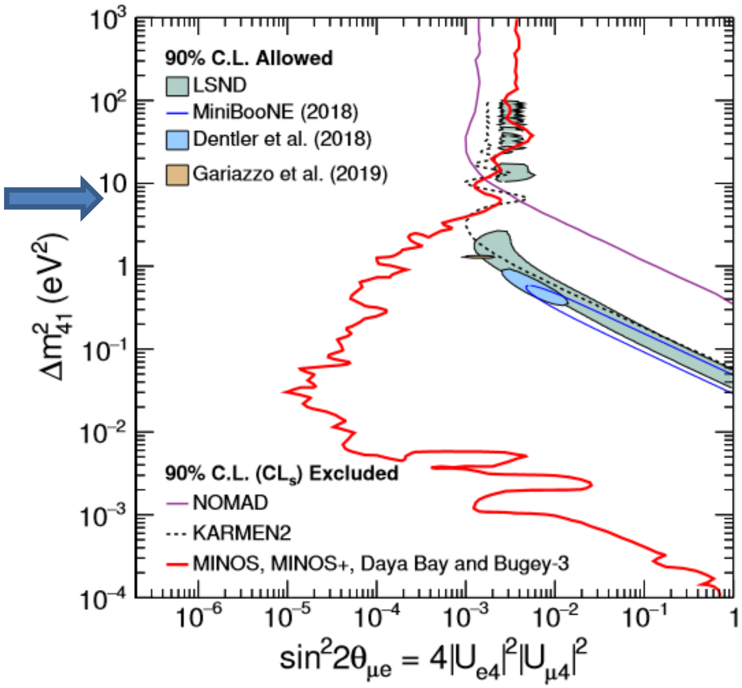
arXiv:2002.00301, accepted by PRL

MINOS/MINOS+



Daya Bay + Bugey-3



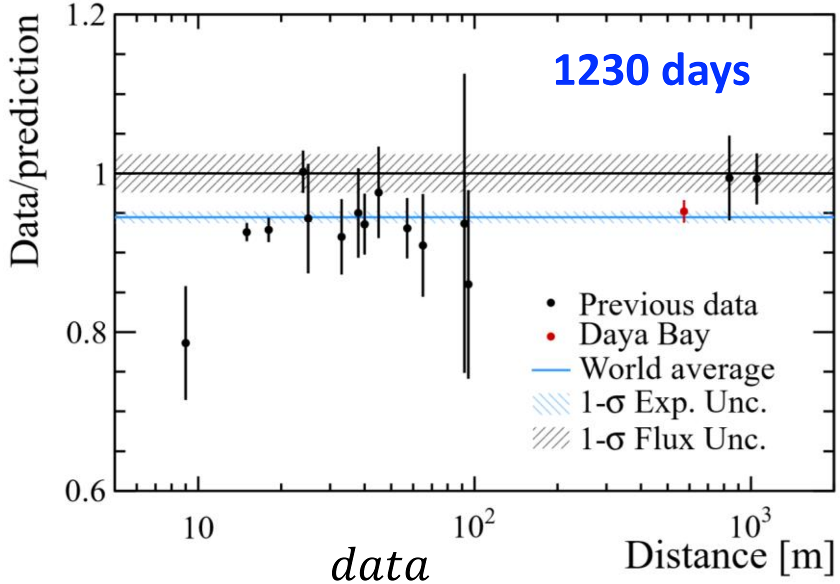


$|U_{\mu 4}|^2 = \sin^2\theta_{24}\cos^2\theta_{14}$ $\qquad$ $|U_{e4}|^2 = \sin^2\theta_{14}$

- The combined results can exclude the LSND and MiniBooNE signal region at $\Delta m^2_{41} < 5$ eV^2 at 90% C.L.
- More details in T. Carroll's talk for MINOS/MINOS+ on July 2nd

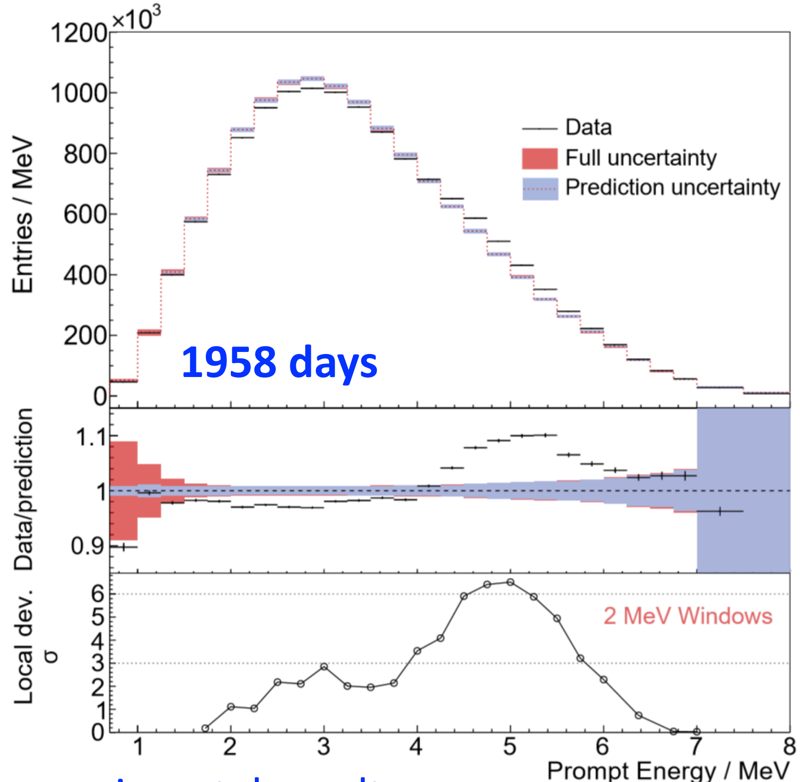
Reactor $\bar{\nu}_e$ Flux and Spectrum

*PRD **100** 052004 (2019)*



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

R. Mandujano's Poster #426

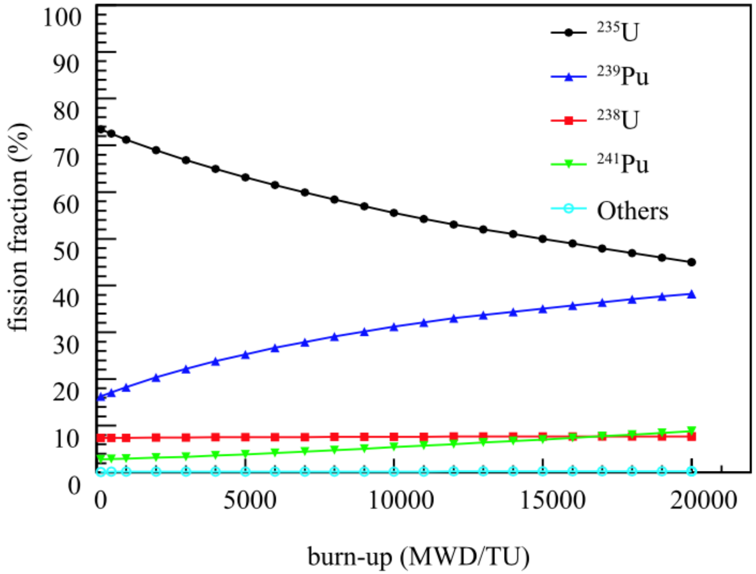


$$R = \frac{data}{Model\ (Huber + Mueller)}$$

$$= 0.952 \pm 0.014(exp) \pm 0.023(model)$$

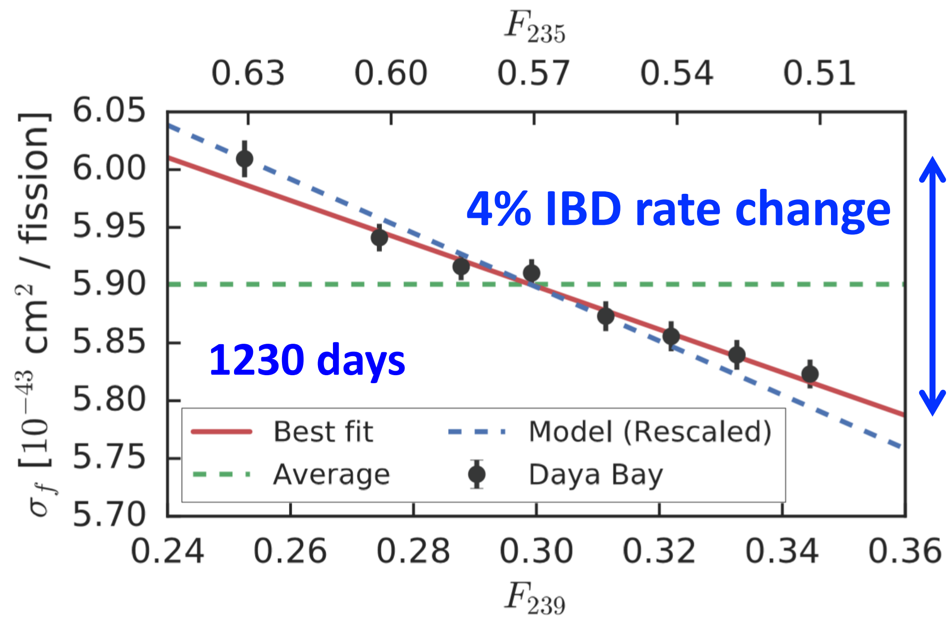
- Daya Bay result is consistent with the previous experimental results
- Data/prediction spectrum shows a total >5σ deviation, especially significant deviation at 4-6 MeV region of the prompt energy (>6σ)
- No effect on far/near relative measurement for θ_{13} and Δm^2_{ee}

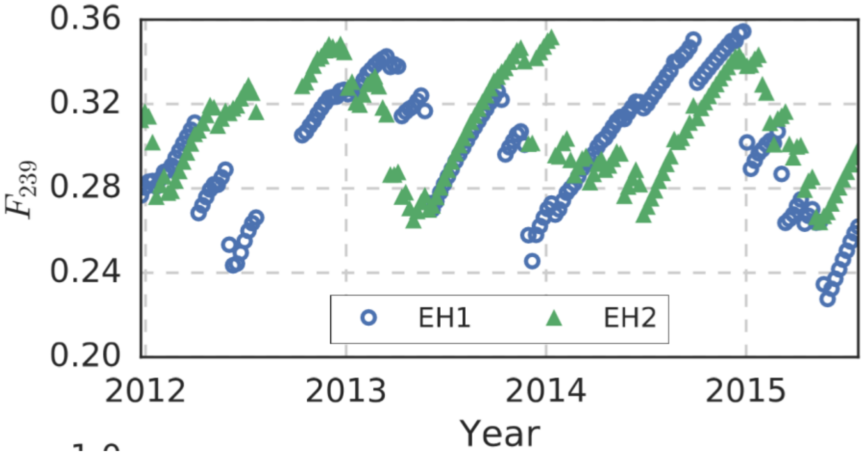
Reactor Isotope Fuel Evolution



*PRL **118** 251801 (2017)*

J. Hu's Poster #149

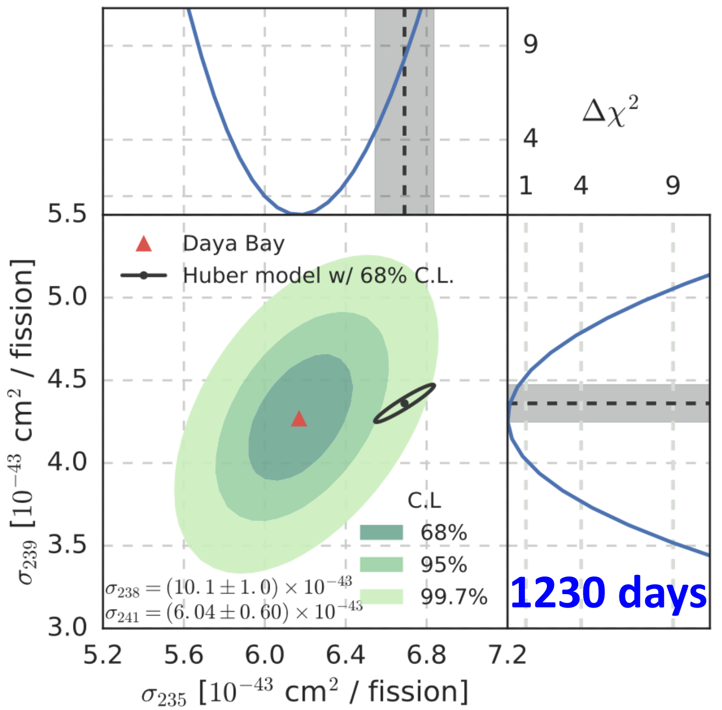




- Clear fuel-dependent evolution
- Evolution slope deviates from Huber + Mueller (H-M) model: disfavors sterile neutrino only (equal deficit) hypothesis at 2.6σ

Isotope Yields and Spectra Measurements from Fuel Evolution Study

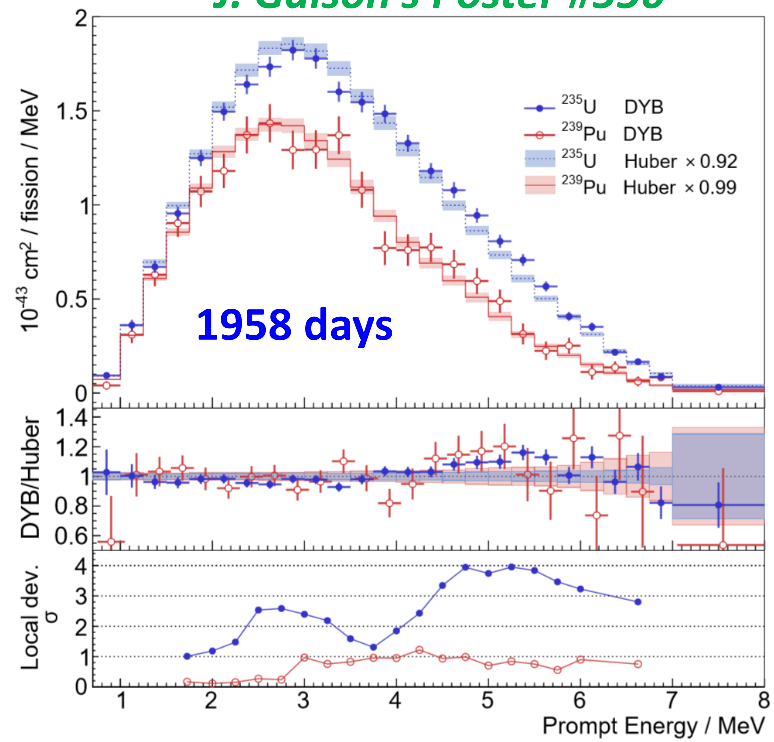
PRL ***118*** *251801 (2017)*



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

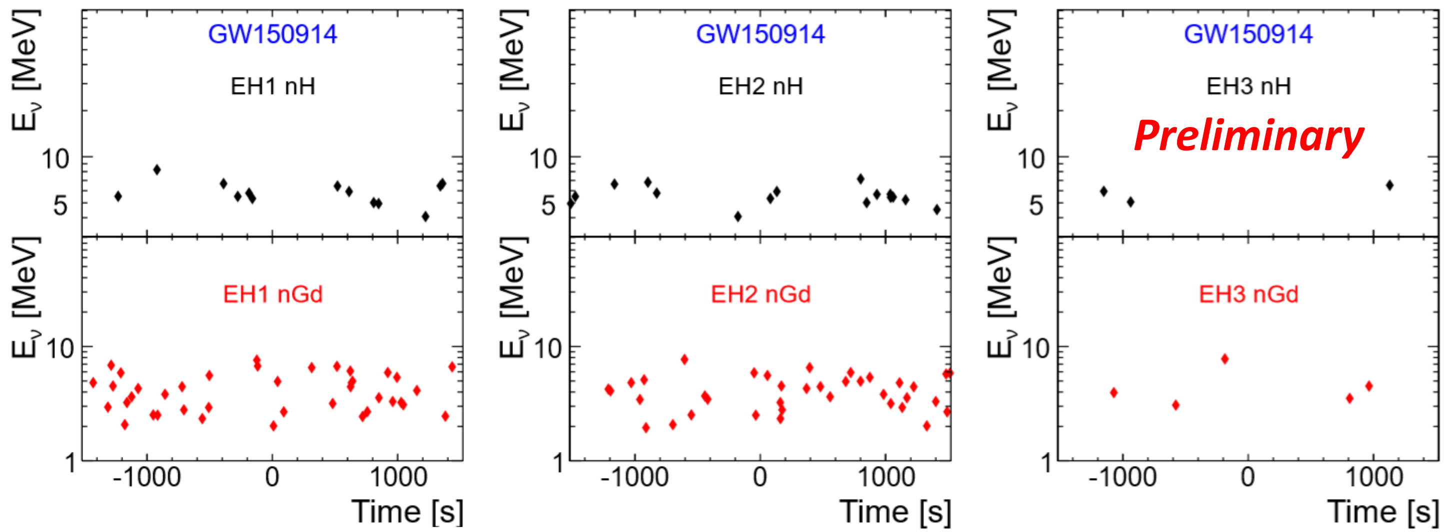
J. Hu's poser #149

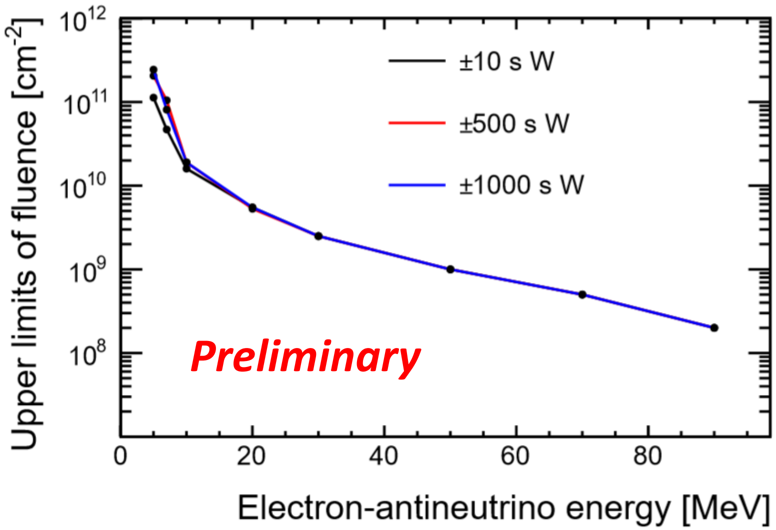
J. Gaison's Poster #556



- Daya Bay data prefer ^{235}U to be mainly responsible for the Reactor $\bar{\nu}_e$ Anomaly
- First measurement of ^{235}U and ^{239}Pu spectra from a commercial reactor
- Consistent with bump structure at 4-6 MeV
- Local spectra deviation from prediction: ^{235}U (4σ) and ^{239}Pu (1.2σ)
- Plan a joint fit with PROSPECT and STEREO to have a better measurement of ^{235}U

$\bar{\nu}_e$ Search associated with Gravitational Wave (GW) Events





- Search GW associated $\bar{\upsilon}_e$ with joint fit of IBDs with both nGd and nH capture at different energy regions
- No significant IBD event excess within $\pm$10/500/1000 s time window of GW event

Summary

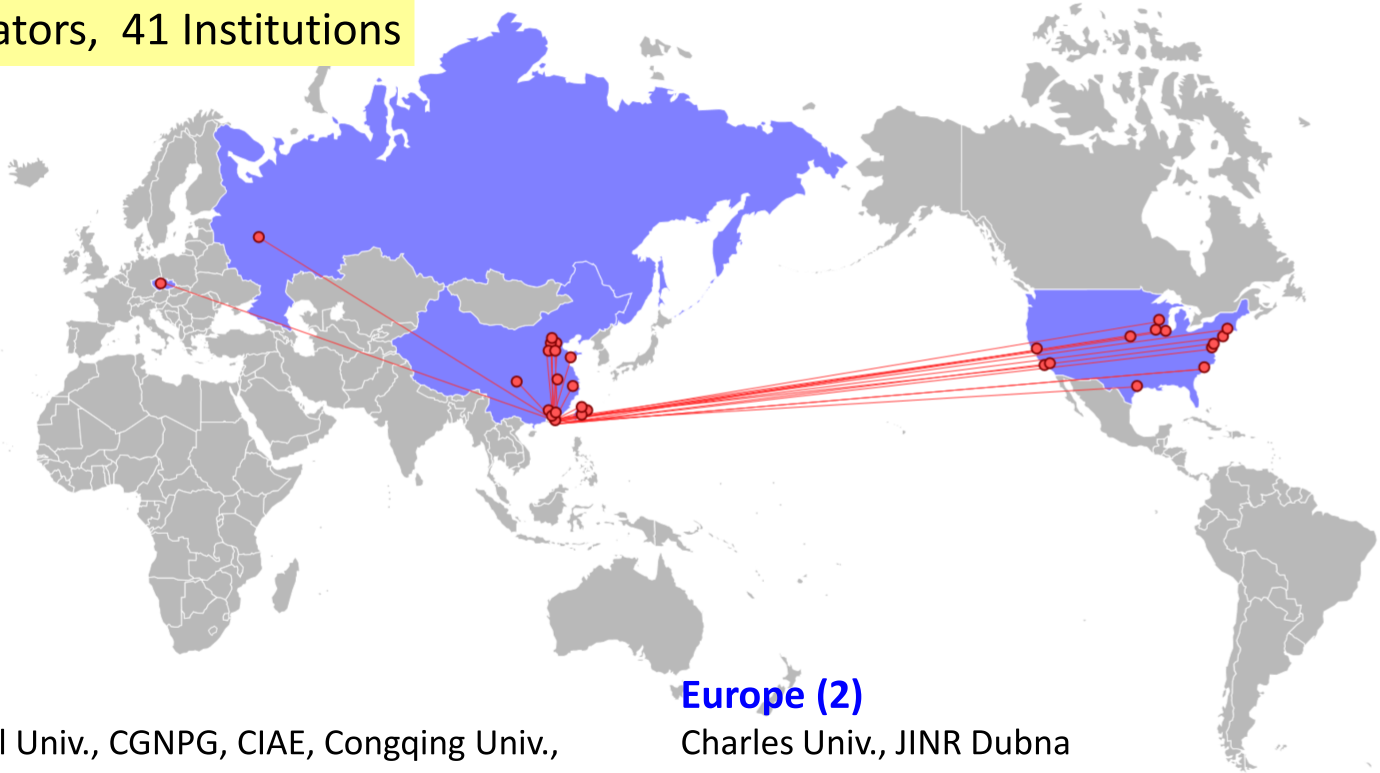
- Daya Bay has made the most precise measurements on $\sin^2 2\theta_{13}$ and $|\Delta m^2_{ee}|$ with ~3% precision
  - Expected final precision of 2.7% on $\sin^2 2\theta_{13}$ is likely to be the standard for decades to come
- Set the most stringent upper limit for light sterile neutrino signal with $\Delta m^2_{41} < 0.2\ \mathrm{eV}^2$
  - A joint fit with MINOS/MINOS+ is able to exclude most of LSND/MiniBooNE signal region
- Reactor fuel evolution is observed
  - Disfavor sterile neutrino as the main explanation of Reactor Antineutrino Anomaly with fuel evolution study
  - First measurement of ^{235}U and ^{239}Pu spectra from commercial reactor
- Daya Bay is taking data through the pandemic and will keep running until the end of 2020
- Final Daya Bay results expected by Neutrino 2022

Poster Advertisement

- **Olivia Dalager**
  - Poster **#531**: Daya Bay's Latest Oscillation Results Using Neutron Capture on Gadolinium
- **Jeremy Gaison**
  - Poster **#556**: Towards a Joint Constraint of the ^{235}U Reactor Antineutrino Spectrum by Combining the Daya Bay, PROSPECT, and STEREO Measurements
- **Jianrun Hu**
  - Poster **#149**: Latest Results of the Reactor Fuel Evolution Study at Daya Bay
- **Jinjing Li**
  - Poster **#131**: Measurement of $\sin^2 2\theta_{13}$ via neutron capture on hydrogen at Daya Bay
- **Roberto Mandujano**
  - Poster **#426**: Reactor Antineutrino Spectrum and Flux Measurement at Daya Bay

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

The Daya Bay Collaboration