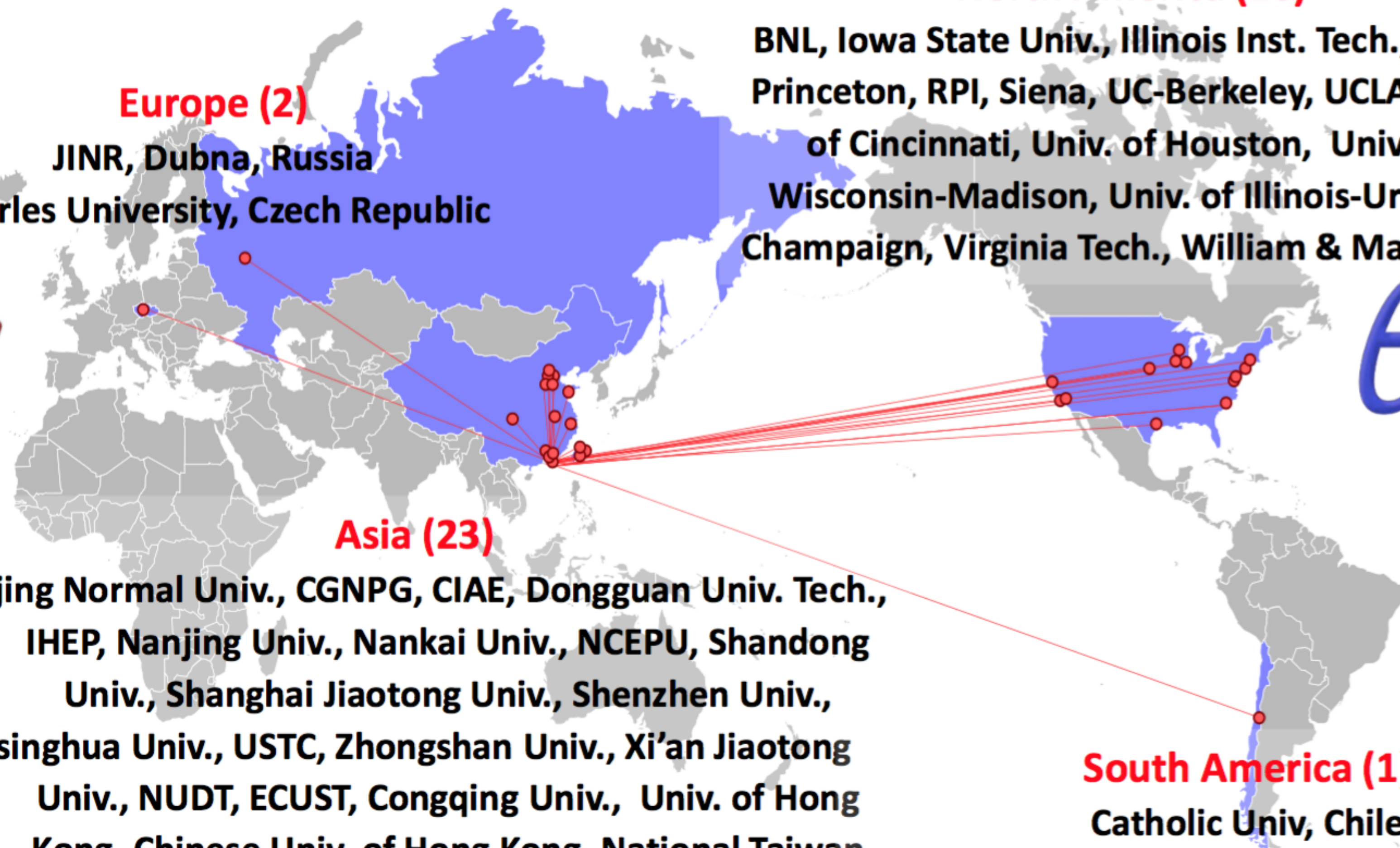
Latest results from neutrino oscillation experiment Daya Bay

Vít Vorobel, Charles University, Prague
on behalf of Daya Bay Collaboration

Daya Bay 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.

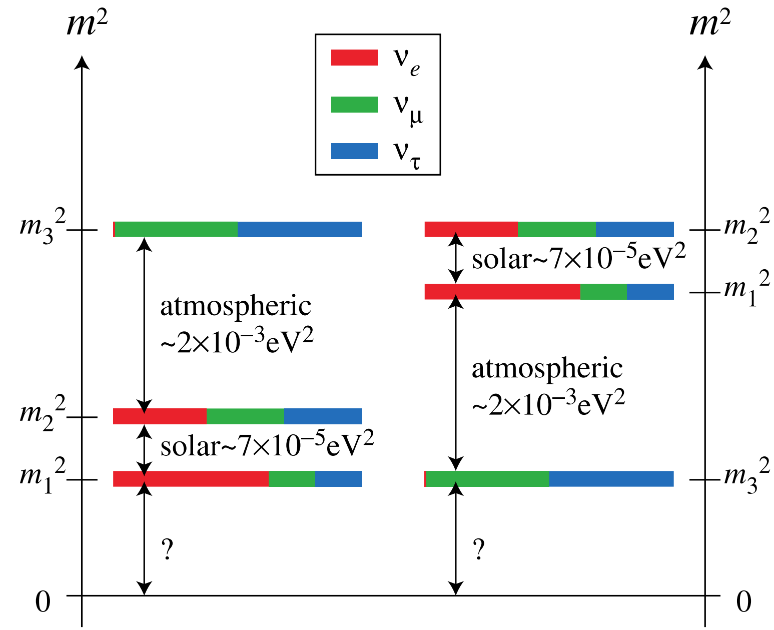
South America (1)

Catholic Univ, Chile

Neutrino mixing

$\Delta m^2_{21} \approx 7.6 \times 10^{-5}\ eV^2$

$|\Delta m^2_{32}| \approx |\Delta m^2_{31}| \approx 2.4 \times 10^{-3}\ eV^2$



Pontecorvo-Maki-Nakagawa-Sakata Matrix

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}$$

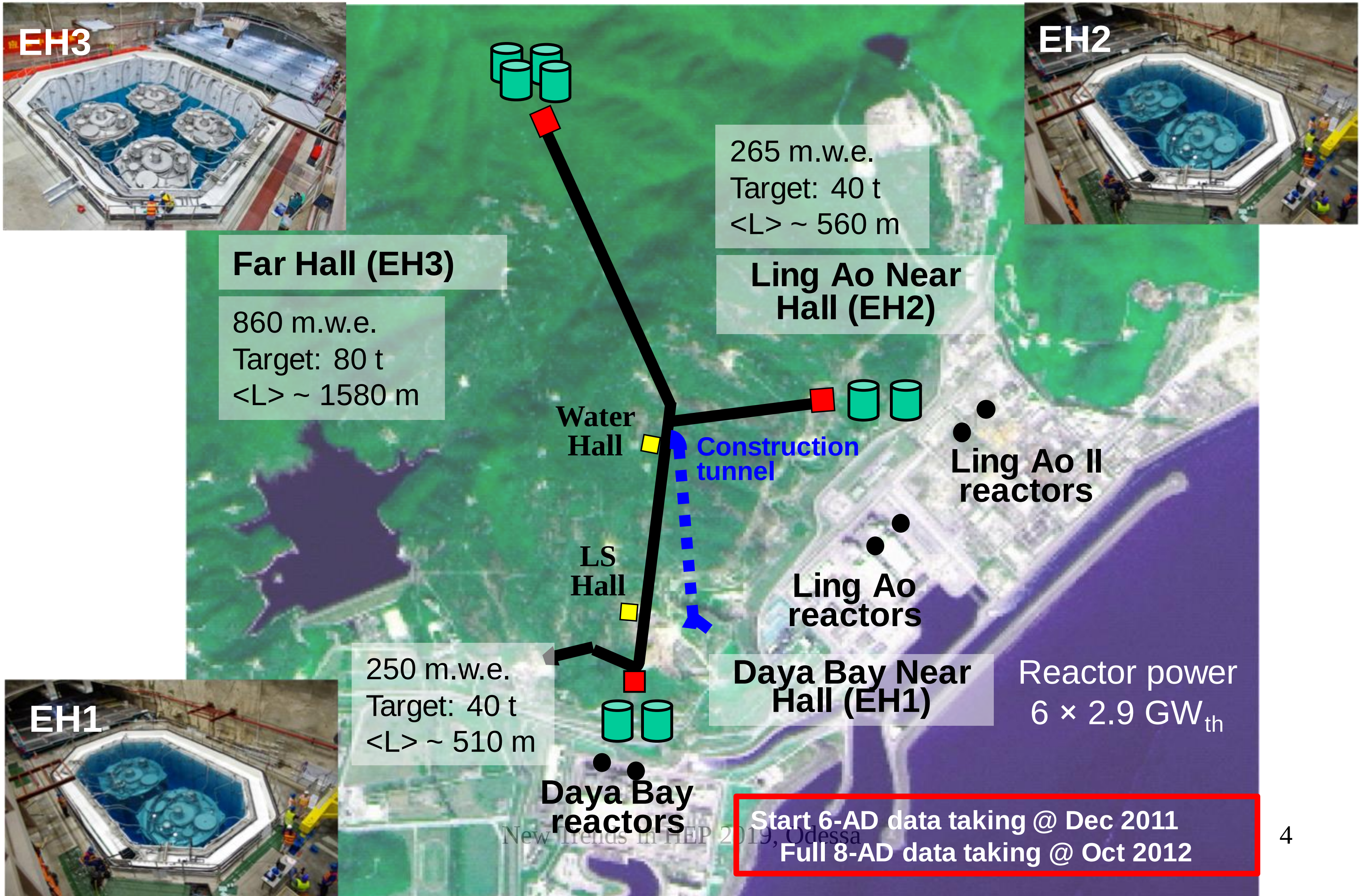
Atmospheric — $\theta_{23} \approx 45°$

Reactor — $\theta_{13} \approx 9°$

Solar — $\theta_{12} \approx 34°$

Majorana **$0\nu\beta\beta$**

Daya Bay experimental setup

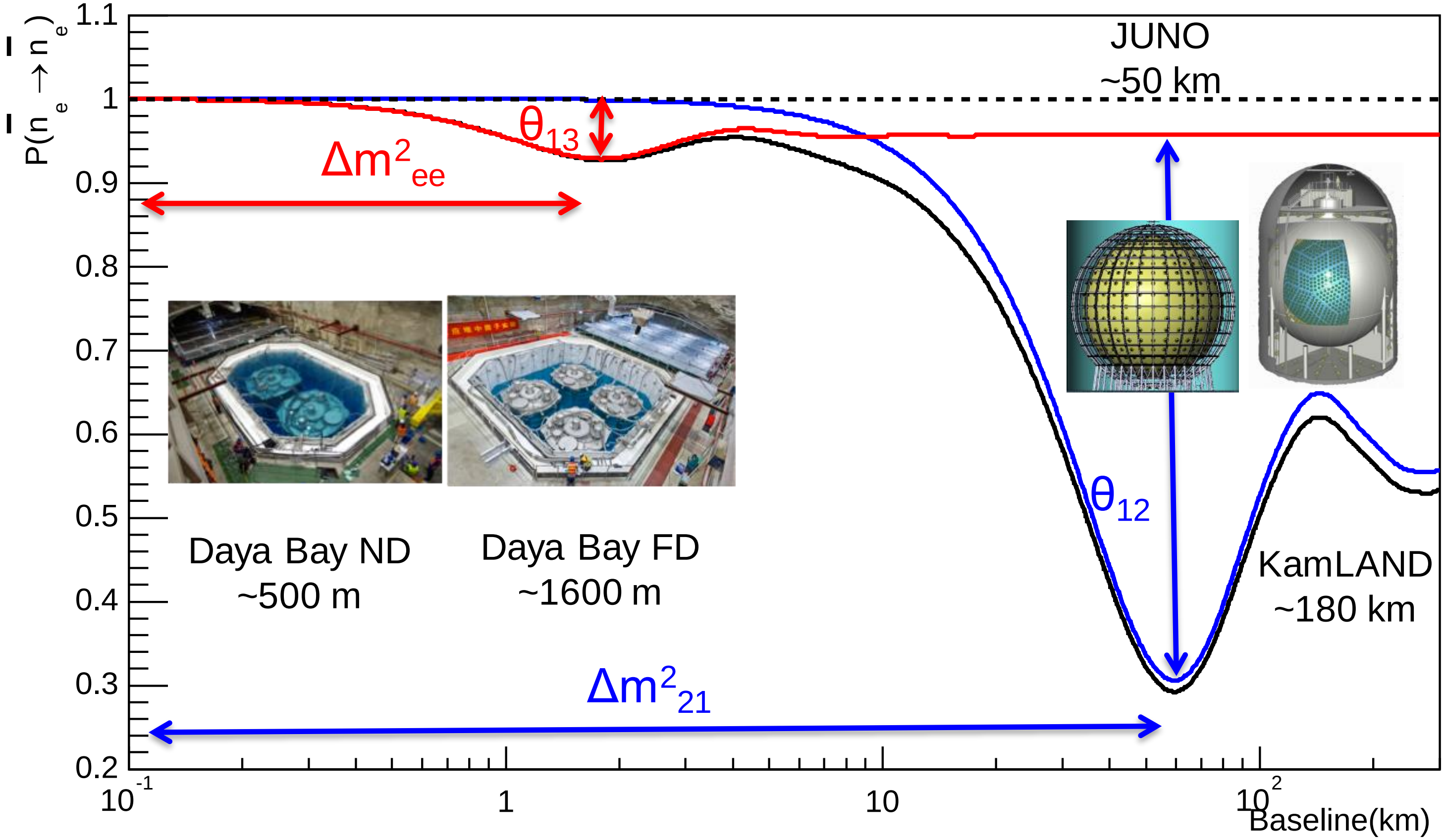


Reactor anti-neutrino oscillation

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

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

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



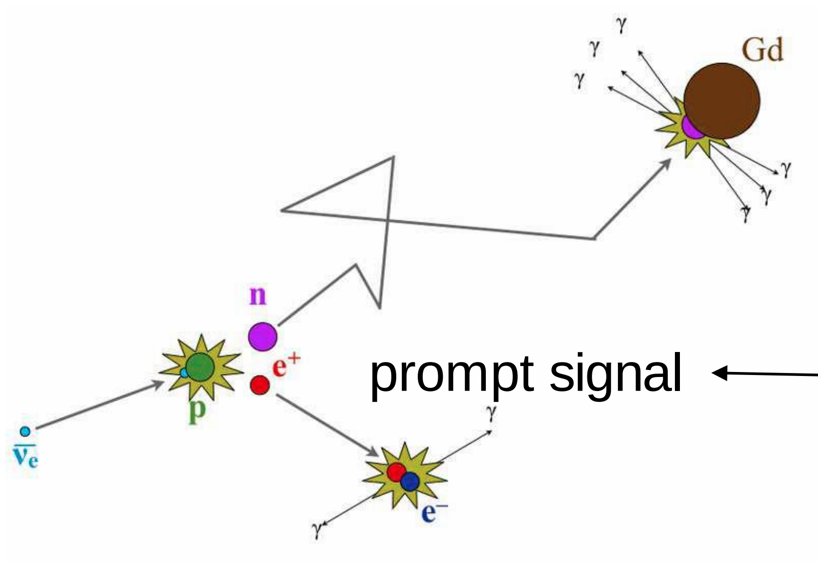
Detection of $\overline{\nu}_e$

Inverse beta-decay (IBD) in Gd-doped liquid scintillator:

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

$\rightarrow$ + p $\rightarrow$ D + γ(2.2 MeV) (t~180 μs) 0.3 b

$\rightarrow$ + Gd $\rightarrow$ Gd* $\rightarrow$ Gd + γ's(8 MeV) (t~30 μs) 50,000 b



delayed signal

prompt signal

Coincidence

$E_{\bar{\nu}} \approx T_{e+} + T_n + (m_n - m_p) + m_{e+} \approx T_{e+} + 1.8$ MeV (threshold)

$E_{prompt} = T_{e+} + 2m_e$ (annihilation gammas)

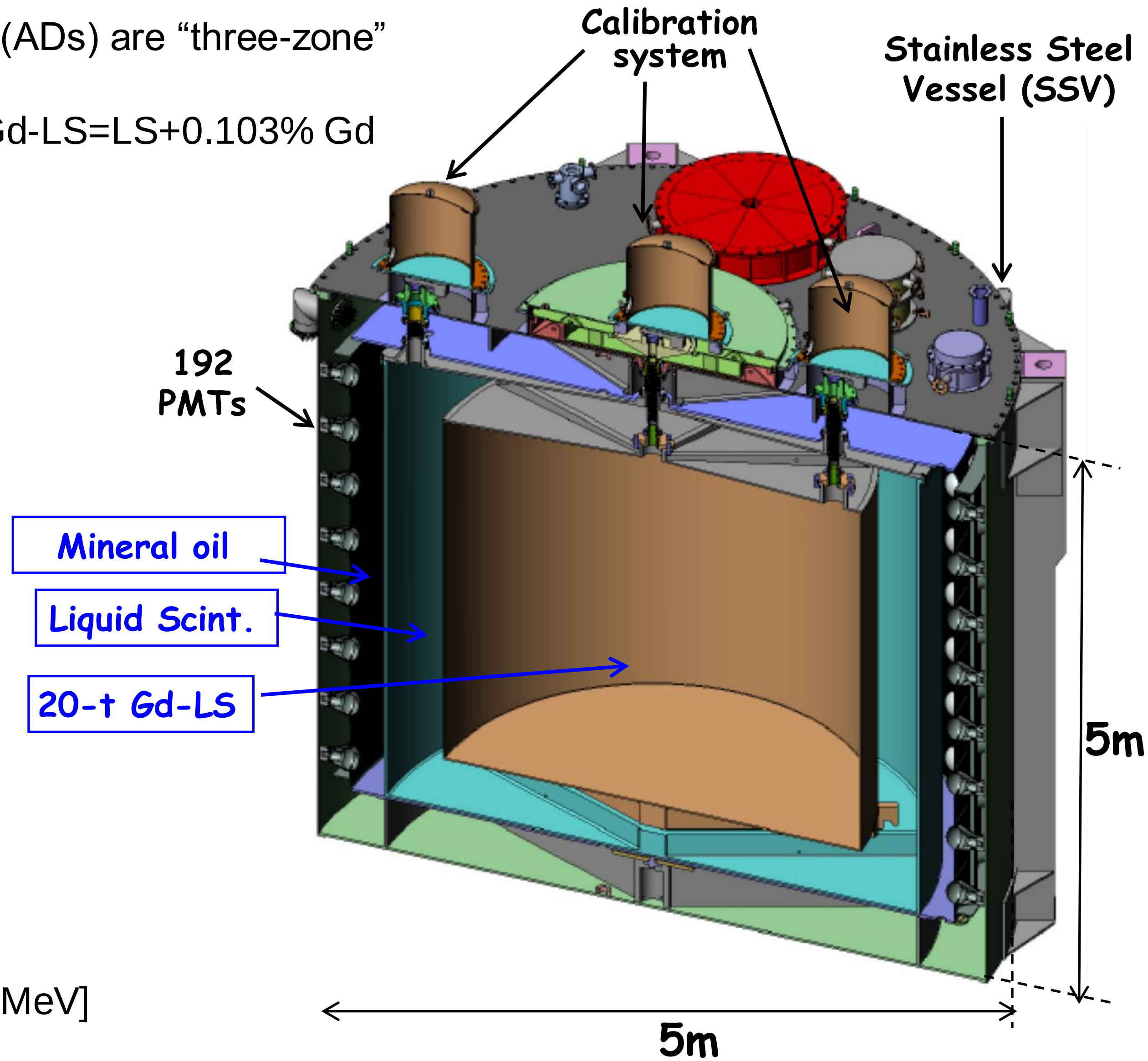
$E_{\bar{\nu}} \approx E_{prompt} + 0.8$ MeV

Anti-neutrino detectors

- The Daya Bay anti-neutrino detectors (ADs) are "three-zone" cylindrical modules
- LS=LAB+PPO(3 g/l)+MSB(15 mg/l), Gd-LS=LS+0.103% Gd
  - Zones are separated by acrylic vessels:

Zone	Mass	Liquid	Purpose
Inner acrylic vessel	20 t	Gd-doped liquid scintillator	**Anti-neutrino target**
Outer acrylic vessel	20 t	Liquid scintillator	Gamma catcher (from target zone)
Stainless steel vessel	40 t	Mineral Oil	Radiation shielding

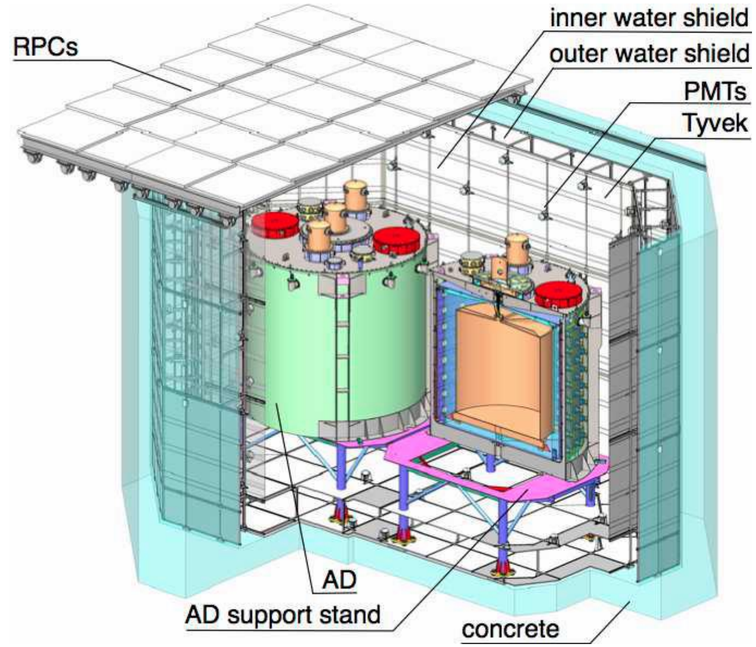
  - Top and bottom reflectors are used to increase light yield
  - Energy resolution: $s_E/E = 8.5\ \% / \sqrt{E[\mathrm{MeV}]}$



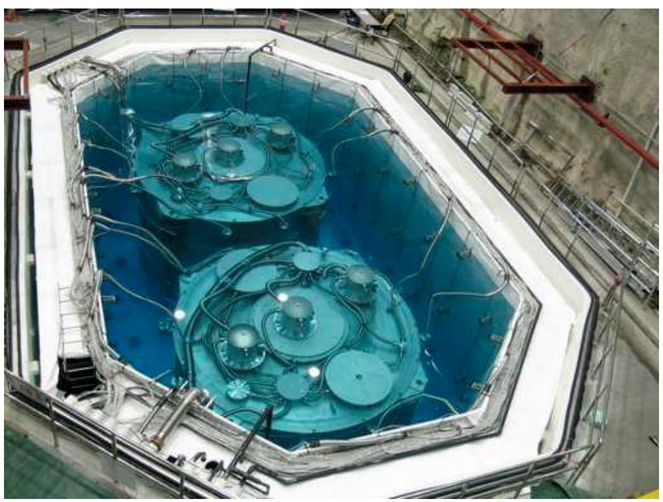
NIM A 811, 133 (2016)

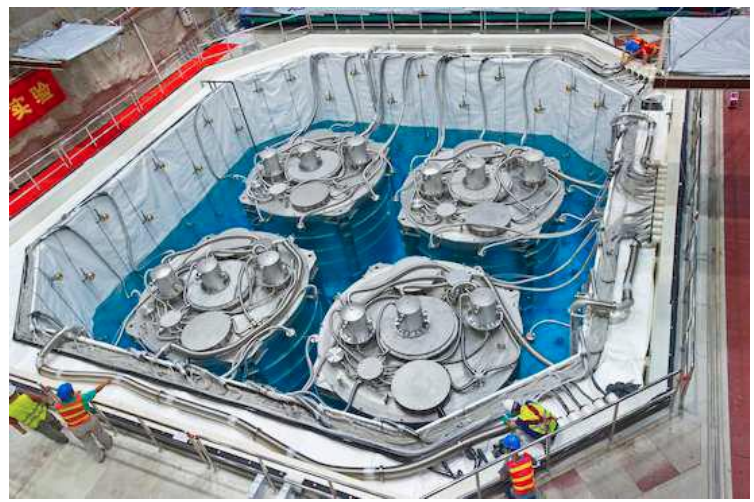
Muon tagging system

- Outer layer of water Čerenkov detector (on sides and bottom) is 1 m thick, inner layer >1.5 m.
Water extends 2.5 m above ADs
    - 288 8” PMTs in each near hall
    - 384 8” PMTs in Far Hall



- 4-layer RPC modules above pool
    - 54 modules in each near hall
    - 81 modules in Far Hall





NIM A 773, 8 (2015)

Detector calibration

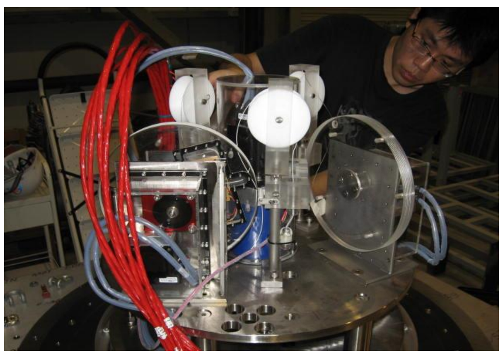
❖ Calibration is key to the reduction of the detector-related systematic errors:

➢ Three sources + LED in each calibration unit, on a turn-table:

- ^{68}Ge (1.02MeV)
- ^{60}Co (2.5MeV)
- ^{241}Am-^{13}C (8MeV)

→ **Energy calibration (linearity, detector response… etc)**

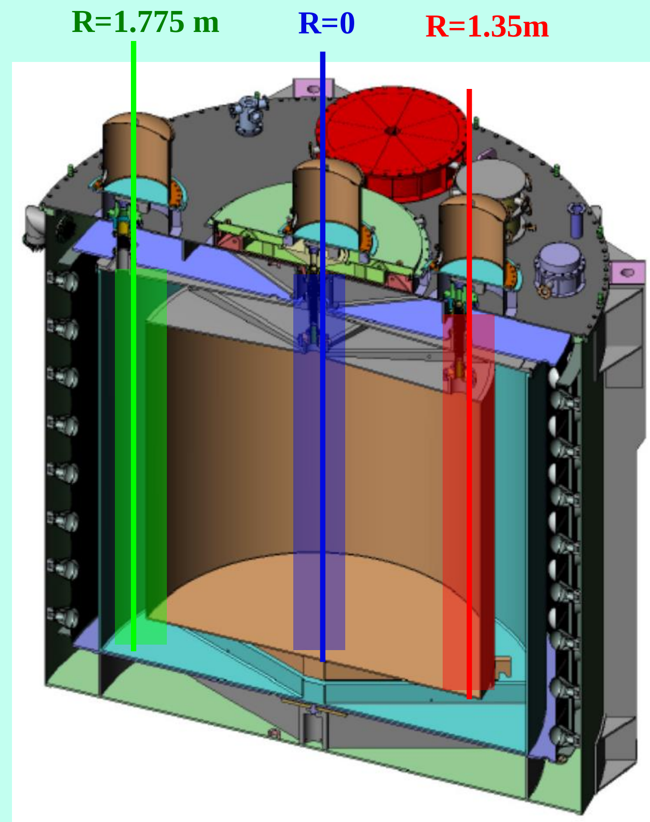
- LED → **Timing, gain and relative QE**



➢ Can also use spallation neutrons (uniformity, stability, calibration, … etc).

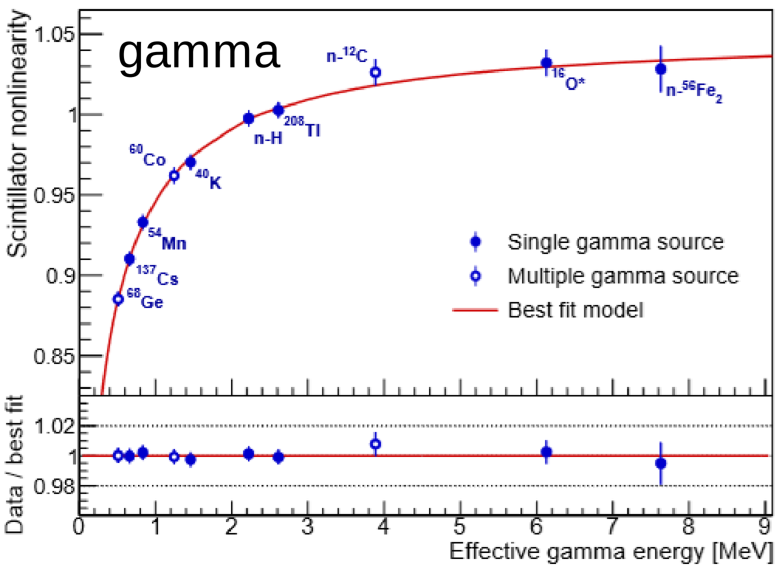
➢ Special calibration run in 2012, 2017 and new FADC readout in 2015 (EH1-AD1) helped in reducing the systematic uncertainties.

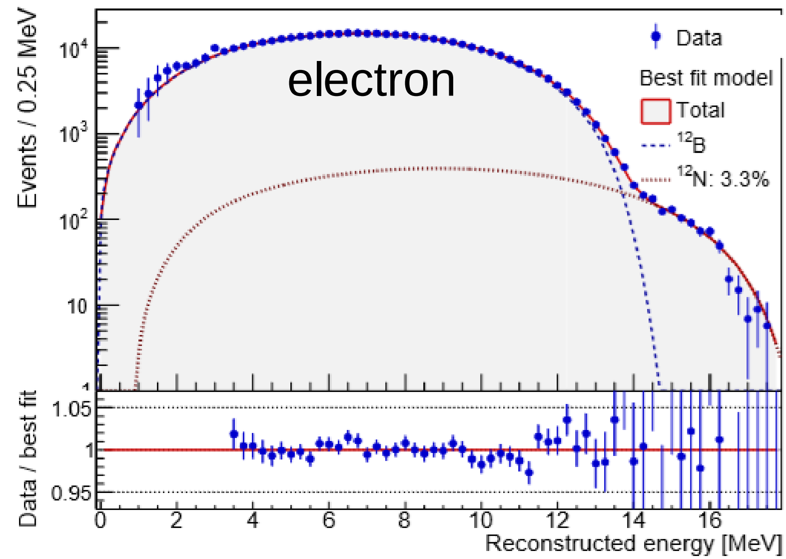
Three calibration units per detector that deploy sources along z-axis

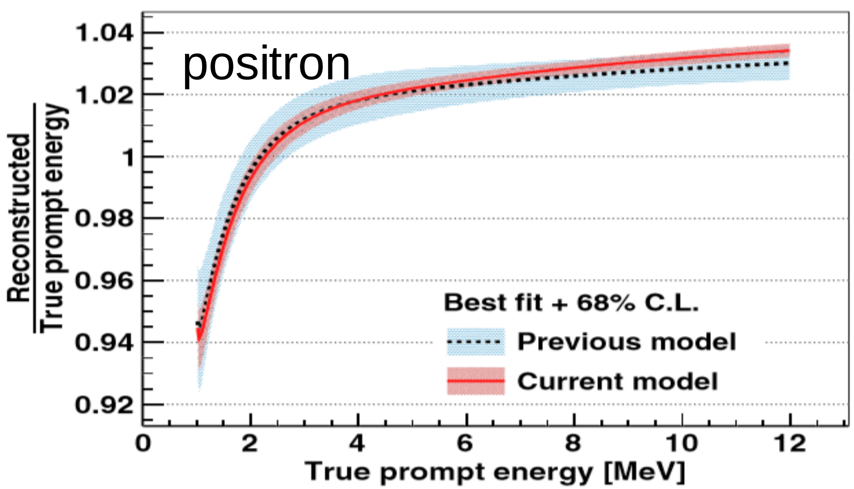


Automated Calibration Units

Energy non-linearity calibration





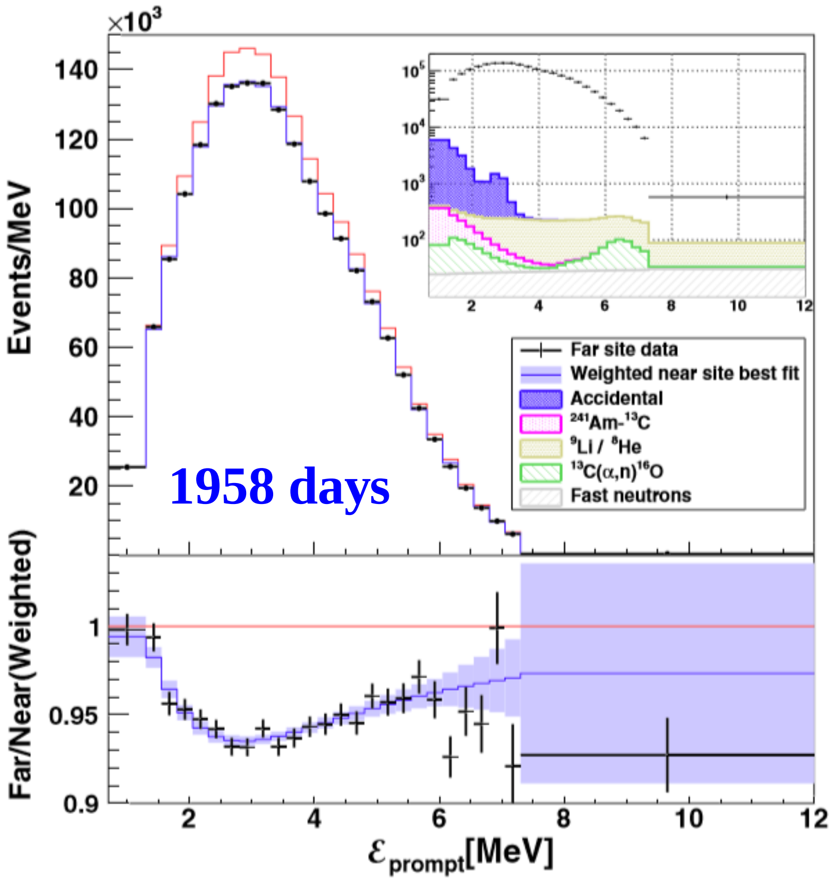


arXiv:1902.08241 (2019)

- Two major sources of non-linearity:
  - Scintillator response
  - Readout electronics
- Energy model for positron is derived from measured gamma and electron responses using simulation.

uncertainty reduced to ~0.5% since 2018
(~1% previously)

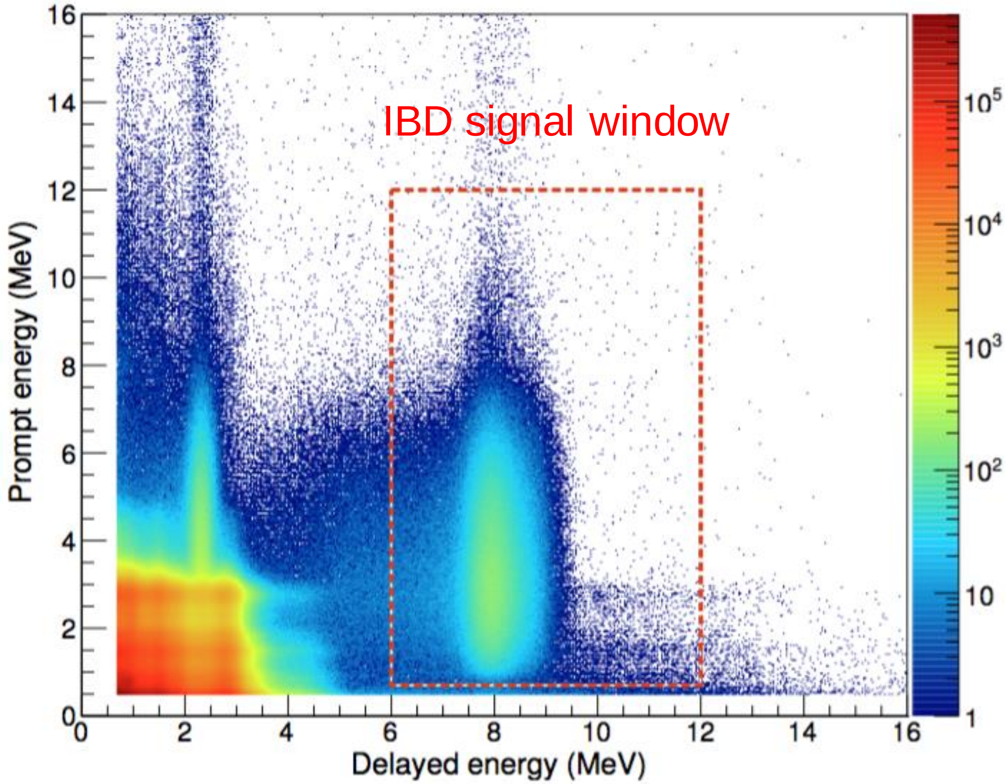
Summary of IBD candidates



- In the presented nGd analysis 3.5 millions inverse beta decays (IBD) have been detected in near halls.
- 0.5 milion IBD have been detected in far hall.
- Daily rate is ~2500 IBD events in near halls and ~300 IBD in far hall.
- ≤ 2% backgrounds.

6-AD: 217 days (Dec/2011 – Jul/2012)
8-AD: 1524 days (Oct/2012 – Dec/2016)
7-AD: 217 days (Jan/2017 – Aug/2017)

Coincidence IBD selection



IBD selection cuts

- Reject Flashers
- Prompt: 0.7 MeV < E_p < 12 MeV
- Delayed: 6.0 MeV < E_d < 12 MeV
- Capture time: 1 μs < Δt < 200 μs
- Muon Veto:
  - Pool Muon: *Reject 0.6 ms*
  - AD Muon (>20 MeV): *Reject 1 ms*
  - AD Shower Muon (>2.5 GeV): *Reject 1 s*
- Multiplicity:
  No other signal > 0.7 MeV in -200 μs to 200 μs of IBD.

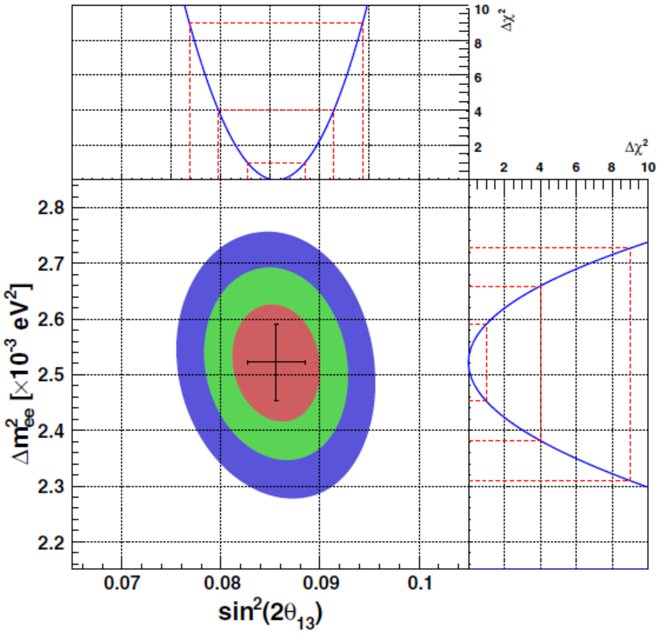
Oscillation analysis result

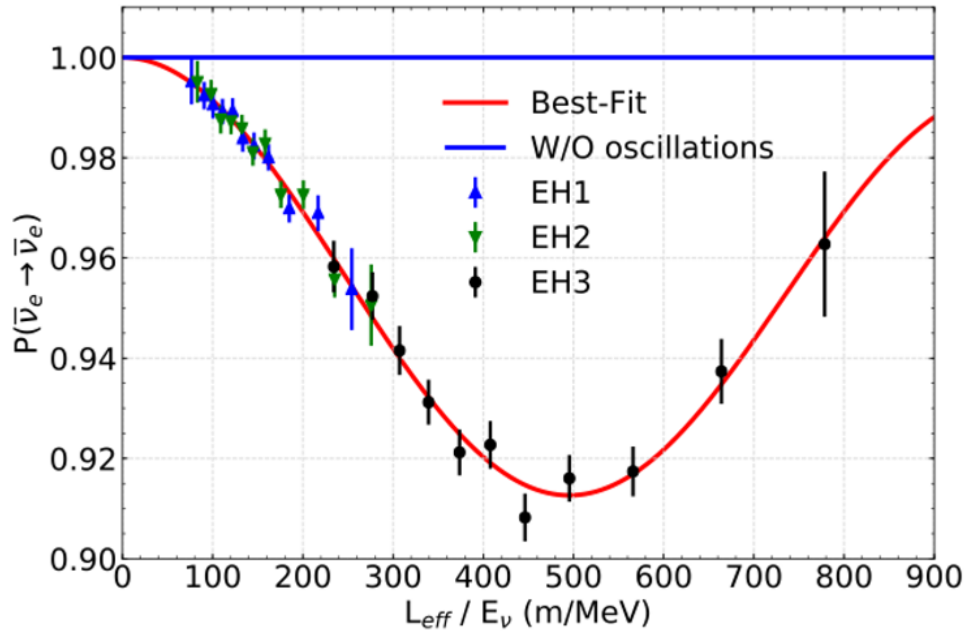
1958 days

Phys. Rev. Lett. 121, 241805 (2018)

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

χ^2/NDF = 148.0/154





$$\sin^2 2\theta_{13} = 0.0856 \pm 0.0029 \qquad \Delta m^2_{ee} = \left[2.522^{+0.068}_{-0.070}\right] \times 10^{-3} eV^2$$

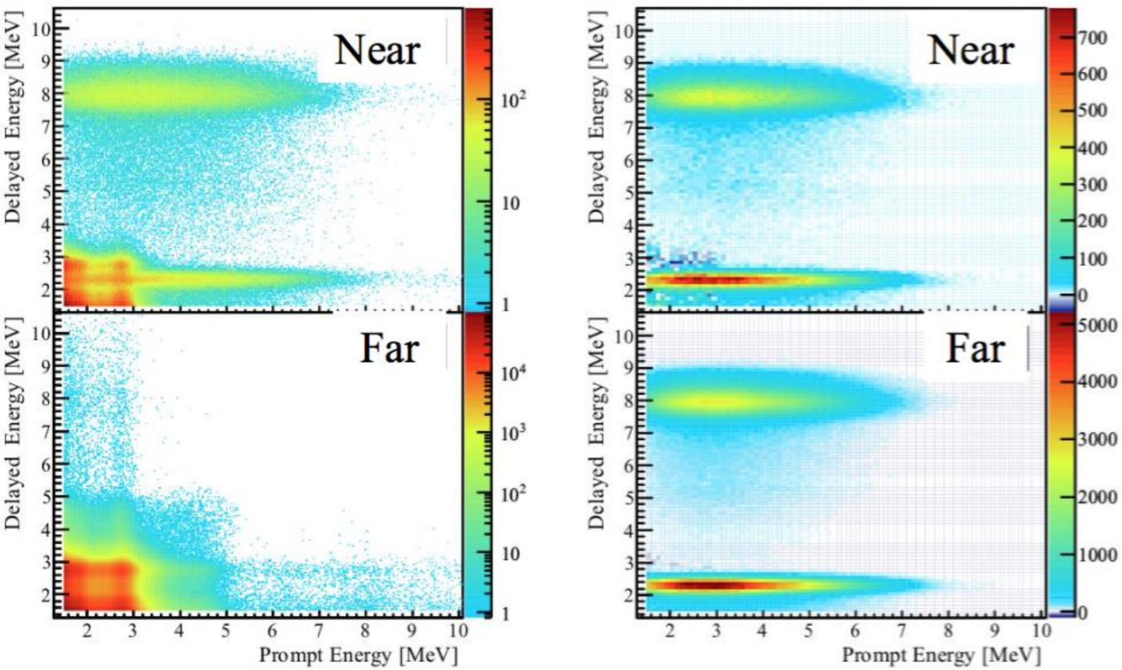
$$\Delta m^2_{32} = +\left[2.471^{+0.068}_{-0.070}\right] \times 10^{-3} eV^2 \qquad \text{(NH)}$$

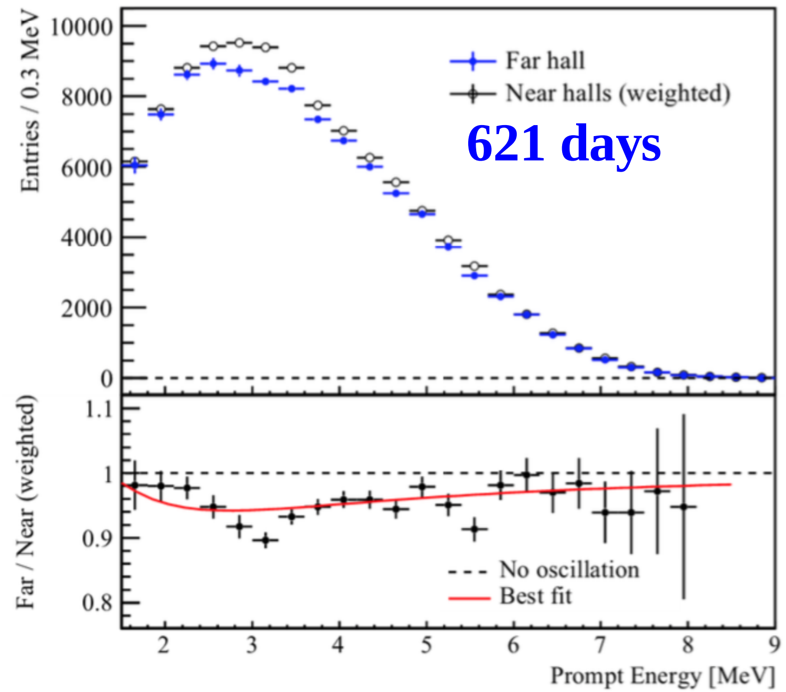
$$\Delta m^2_{32} = -\left[2.575^{+0.068}_{-0.070}\right] \times 10^{-3} eV^2 \qquad \text{(IH)}$$

- Consistent with 3-neutrino oscillation framework
- Multiple analyses yield consistent results

$\sin^2 2\theta_{13}$ from nH analysis

All candidates **After acc. bkg. subtraction**





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

$\sin^2 2\theta_{13} = 0.071 \pm 0.011$

Phys. Rev. D 93, 072011 (2016)

Global comparison

1958 days

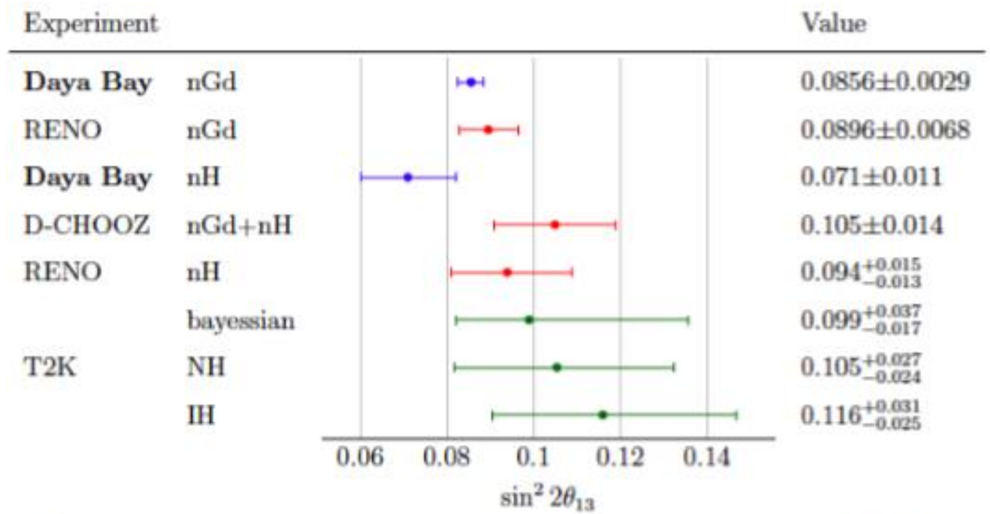
Most precise measurement

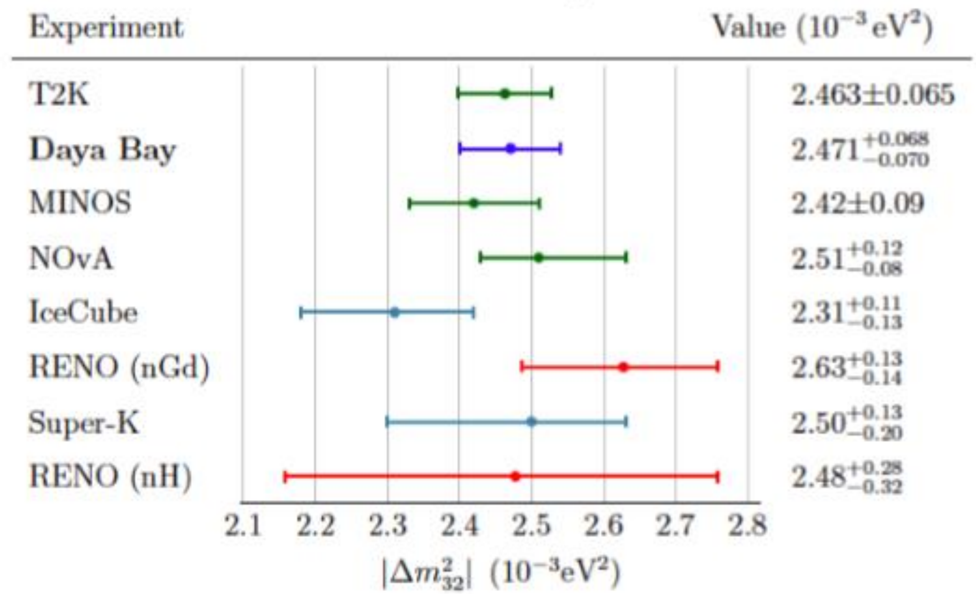
- $\sin^2 2\theta_{13}$ uncertainty: 3.4%
- $|\Delta m^2_{32}|$ uncertainty: 2.8%

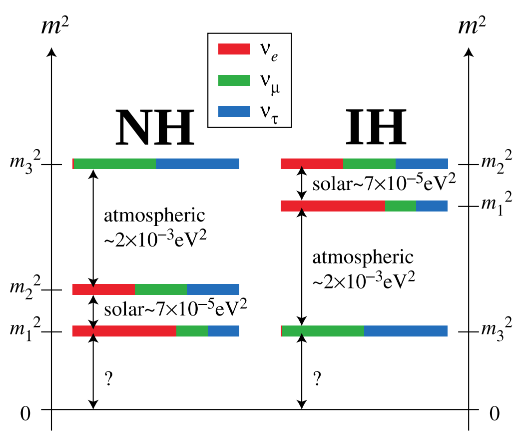
Consistent results with reactor and accelerator experiments.

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

NH: $\Delta m^2_{32} = [2.47 \pm 0.07] \times 10^{-3}$ eV^2
IH: $\Delta m^2_{32} = [-2.58 \pm 0.07] \times 10^{-3}$ eV^2





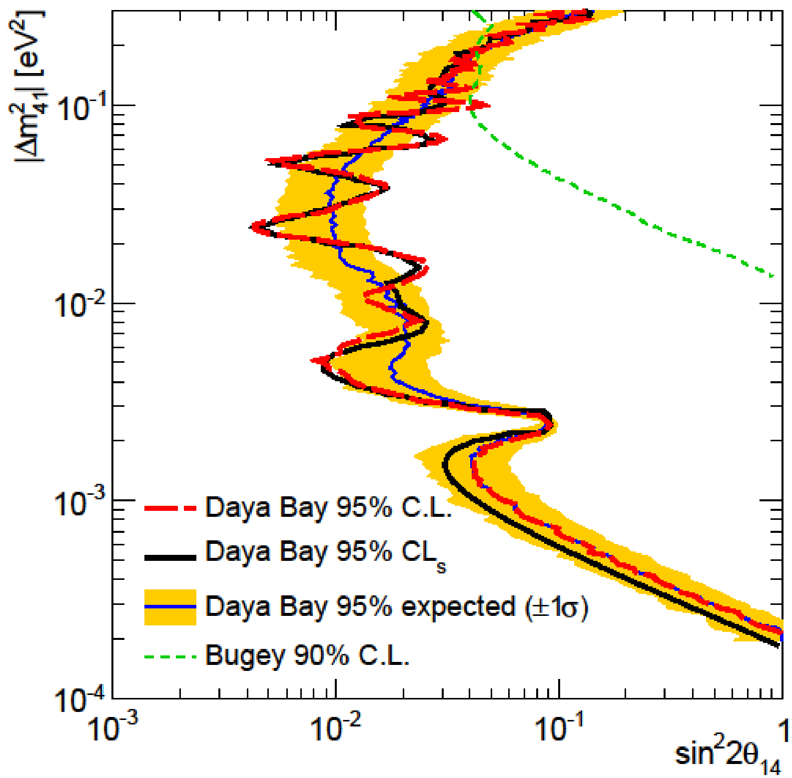


Search for light sterile neutrino

Survival probability formula

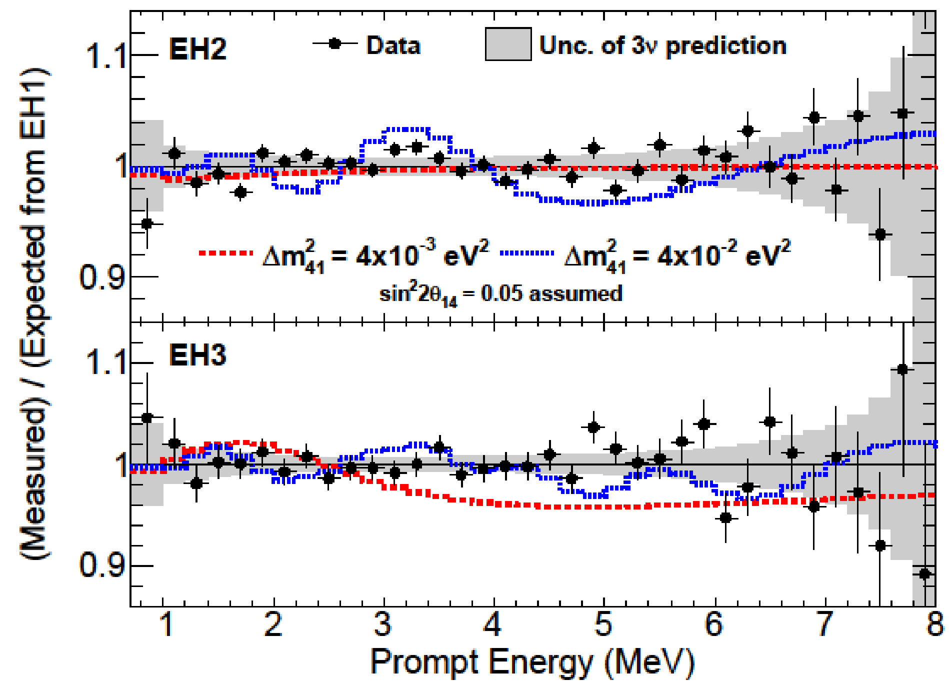
Phys. Rev. Lett. 117 (2016) no.15, 151802

$$P_{ee} \approx 1 - \cos^4\theta_{14}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{ee}L}{4E}\right) - \sin^2 2\theta_{14}\sin^2\left(\frac{\Delta m^2_{41}L}{4E}\right)$$

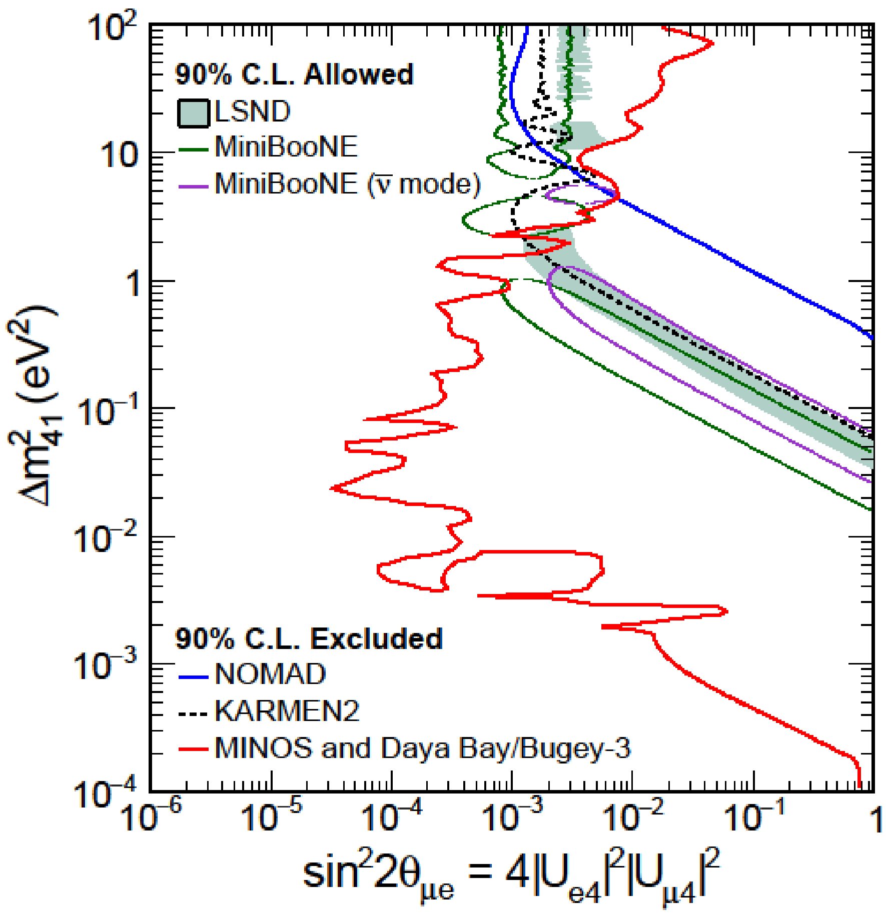


Results

- No hint of light sterile neutrino observed
- Most stringent limit for $\Delta m^2_{41} < 0.2$ eV^2



Daya Bay + MINOS + Bugey-3 sterile neutrino search



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

- Combined $\bar{\nu}_e$ disappearance of DayaBay and Bugey-3 with $\bar{\nu}_\mu$ disappearance of MINOS
- Excluded parameter space allowed by MiniBooNE & LSND for $\Delta m^2_{41} < 0.8$ eV^2

Reactor anti-neutrino flux

$\sigma_f = (5.91 \pm 0.12) \times 10^{-43}$ cm^2/fission

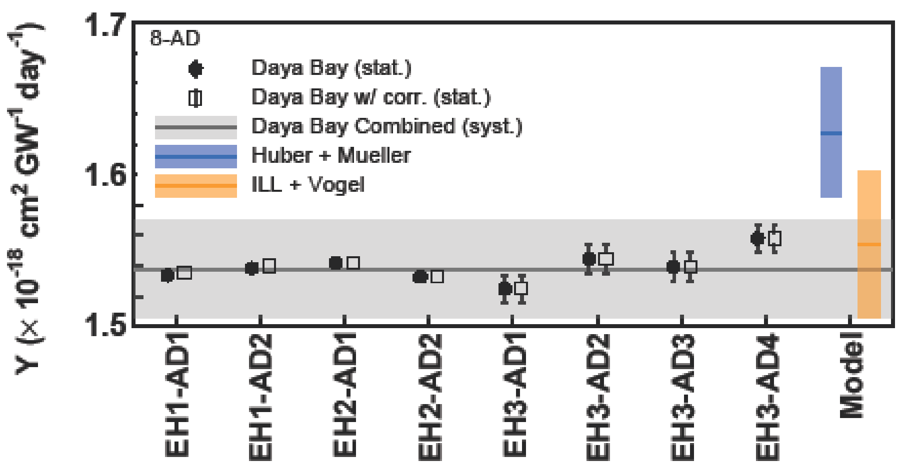
arXiv:1808.10836 (2018)

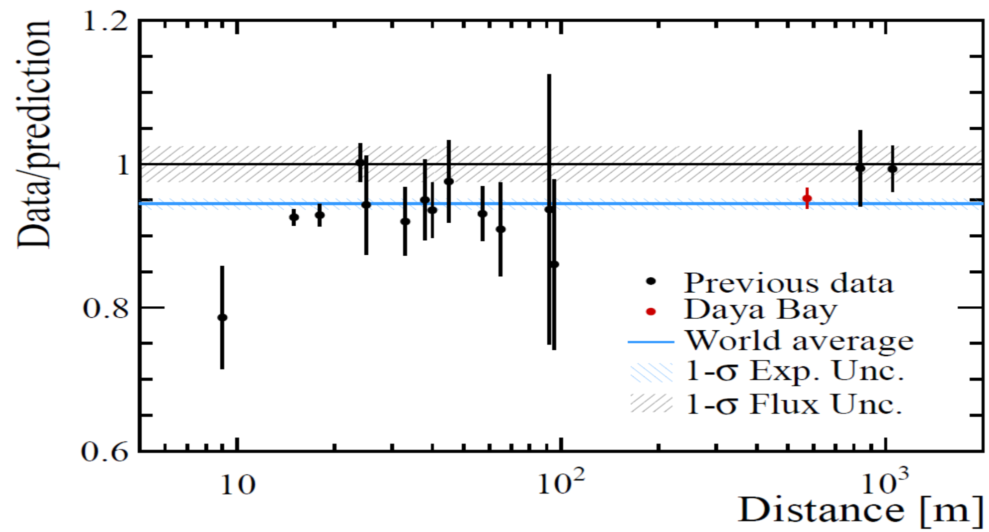
1230 days of data

Data / Prediction:

- Huber+Mueller: 0.952±0.014±0.023 (exp., theor.)
- ILL+Vogel: 1.001±0.015±0.027 (exp., theor.)

Measurement of IBD yield in the eight detectors is consistent with that from other short baseline reactor experiments:

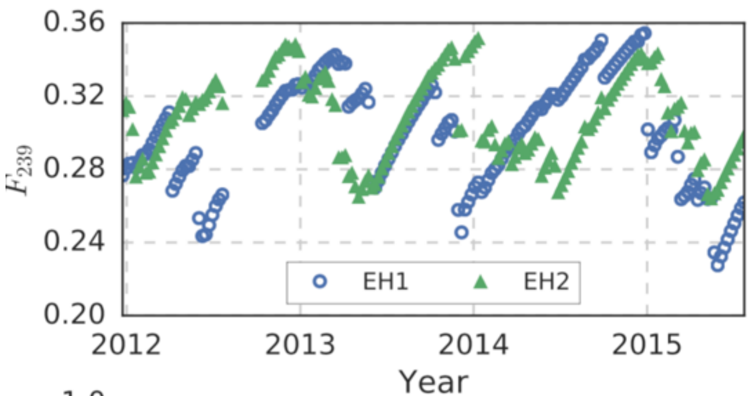




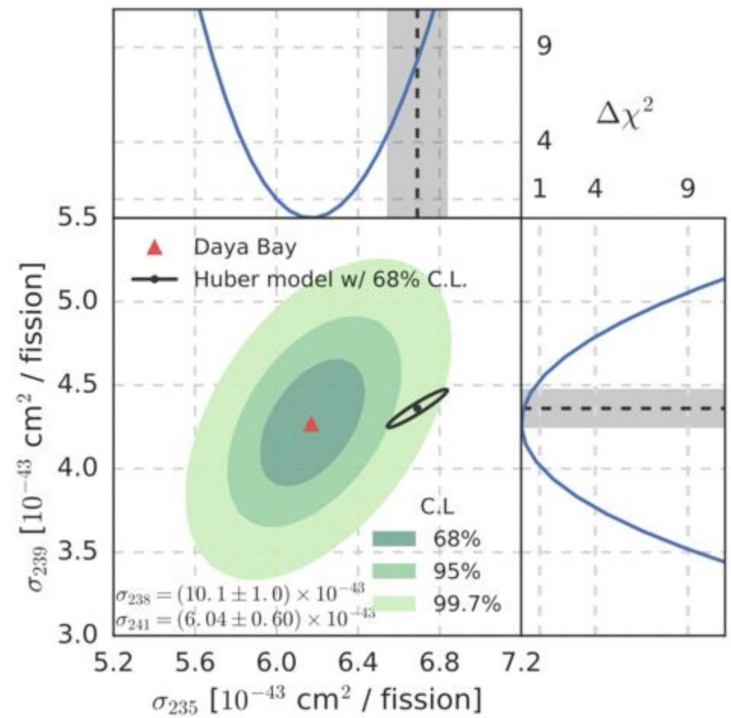
Anti-neutrino flux evolution

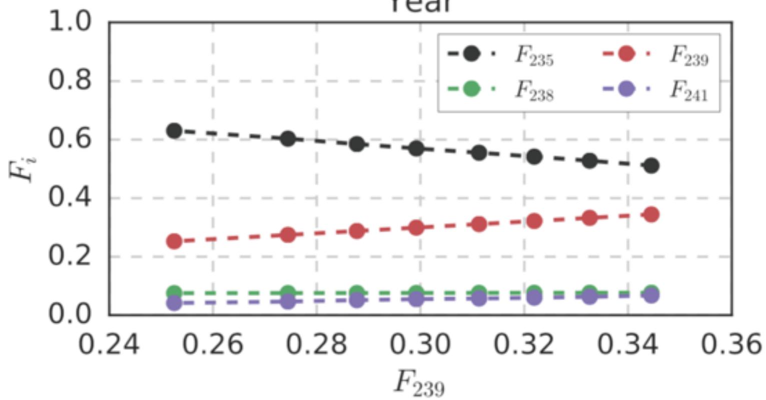
Analysis of dependence of IBD yield/fission σ_i for each fission isotope (i = ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu) on effective fission fraction F_{239} instead of time integration.

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



$$\sigma_f = \sum_i F_i \sigma_i$$





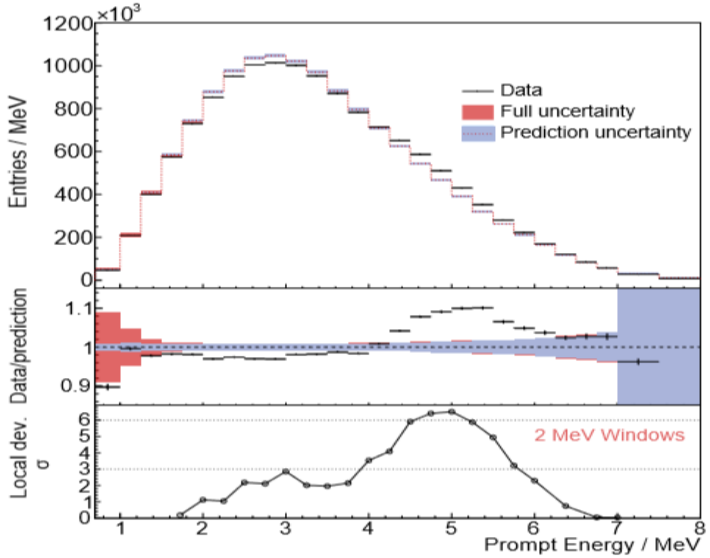
3.1 σ discrepancy in the anti-neutrino flux variation with respect to the reactor fuel composition model prediction.

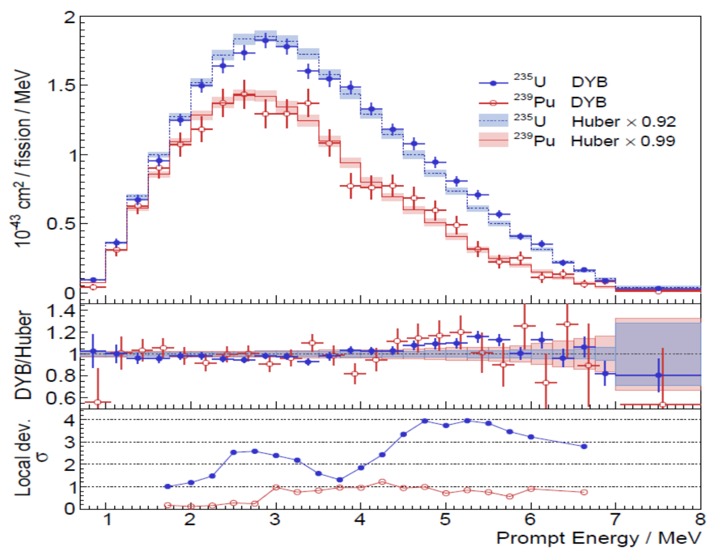
Such discrepancy suggests a 7.8% overestimation of predicted anti-neutrino flux from ^{235}U, and indicates that ^{235}U could be the primary contributor to the reactor anti-neutrino anomaly.

PRL 118, 251801 (2017)

1230 days, near detectors

Anti-neutrino spectrum decomposition





1958 days of data

arXiv:1904.07812 (2019)

- High-statistics measurement of the spectral shape of reactor anti-neutrinos:
  - Global discrepancy with the Huber+Mueller prediction at 5.3σ (6.3σ in the 4-6 MeV region)
  - Excess events have all the IBD characteristics and are correlated with reactor power, relative size does not change in time
  - Excess does not appear in ^{12}B spectra (disfavoring detector effects)
  - Individual spectra of two dominant contributors ^{235}U and ^{239}Pu extracted using evolution of the prompt spectrum as a function of the isotope fission fractions.
  - Excess 7% (9%) in 4-6MeV observed for ^{235}U (^{239}Pu)

Summary

Daya Bay Experiment provided

- Most precise measurement of $\sin^2 2\theta_{13}$ and $|\Delta m^2_{ee}|$ —1958 days of data.
- Independent measurement of $\sin^2 2\theta_{13}$ using neutron capture on hydrogen — 621 days.
- Most stringent limit for neutrino mixing to light sterile neutrino for new mass square splitting $|\Delta m^2_{41}| < 0.2\ \mathrm{eV}^2$ — 621 days.
- Reactor anti-neutrino flux consistent with other experiments but inconsistent with predictions – 1230 days.
- Reactor anti-neutrino spectrum inconsistent with predictions.
- Evolution of both flux and spectrum observed. Flux evolution measurement indicates that ^{235}U could be the primary contributor to the reactor anti-neutrino anomaly – 1230 days, near detectors.
- Individual spectra of two dominant contributors ^{235}U and ^{239}Pu extracted using evolution of the prompt spectrum as a function of the isotope fission fractions.

Other investigations: physics beyond SM, cosmic μ physics, decoherence effect

Daya Bay is expected to continue running until 2020.