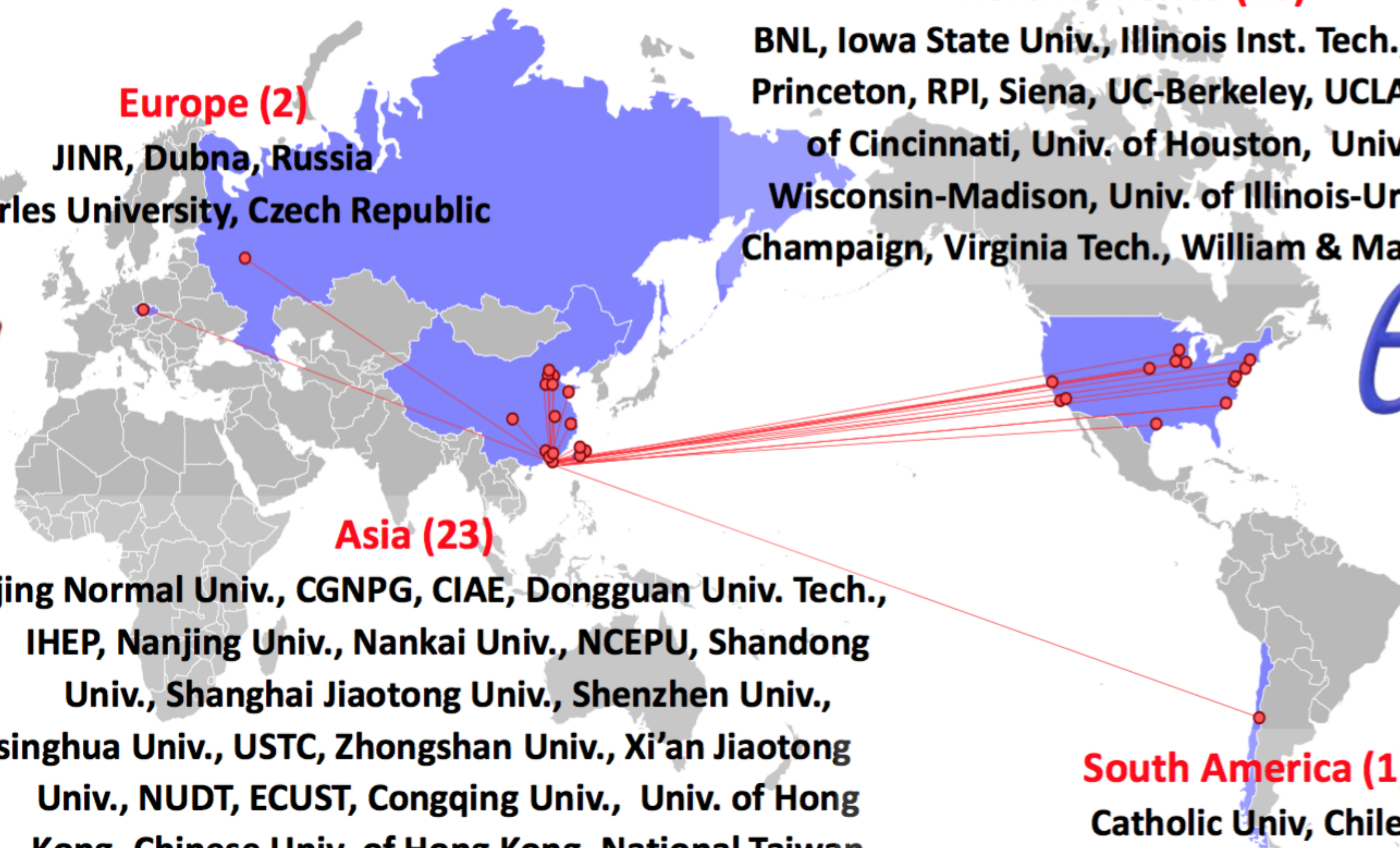
Recent results from Daya Bay

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

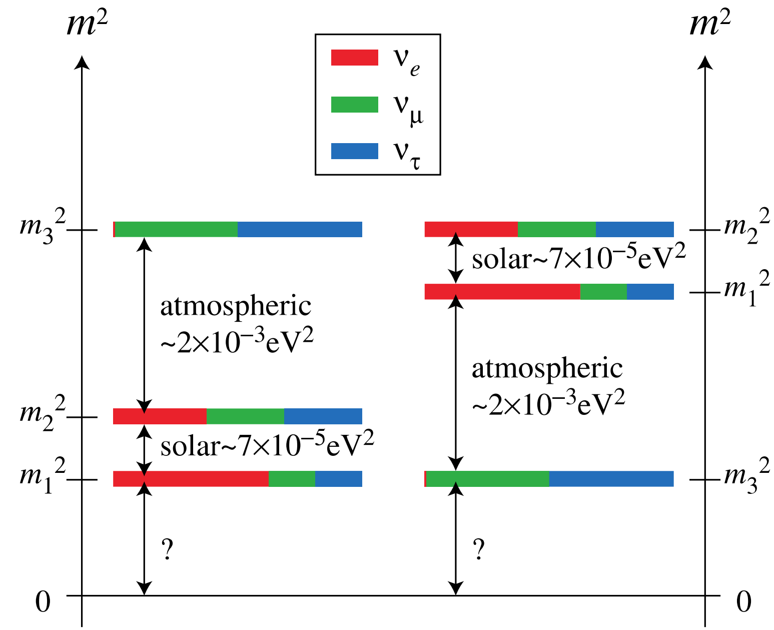
Asia (23)

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



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

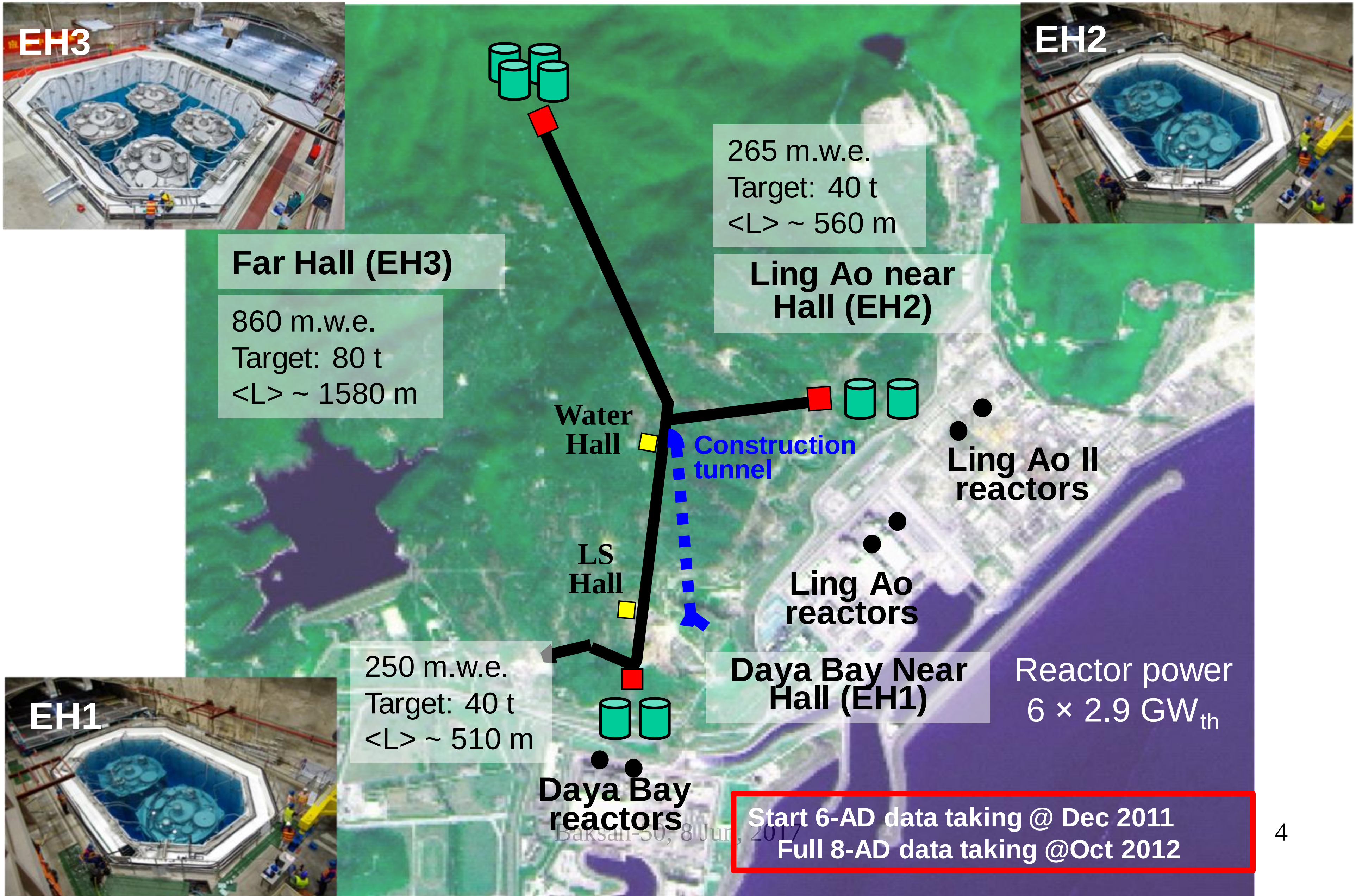
$$|\Delta m^2_{32}| \approx |\Delta m^2_{31}| \approx 2.4 \times 10^{-3}\ \mathrm{eV}^2$$

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	Reactor	Solar	Majorana $0\nu\beta\beta$
$\theta_{23} = 45°$	$\theta_{13} = 9°$	$\theta_{12} \approx 34°$	

Daya Bay experimental setup

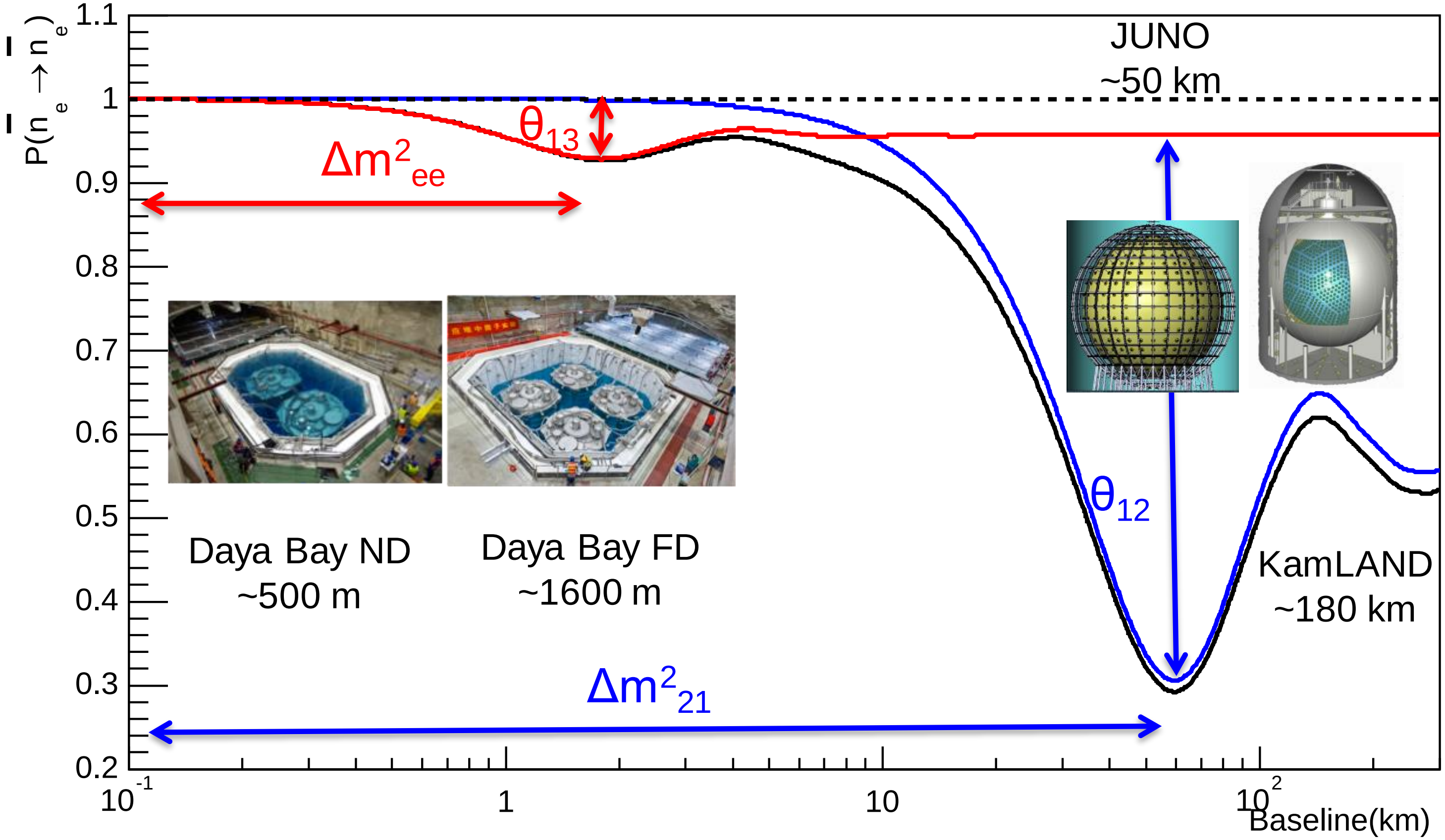


Reactor anti-neutrino oscillation

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

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

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



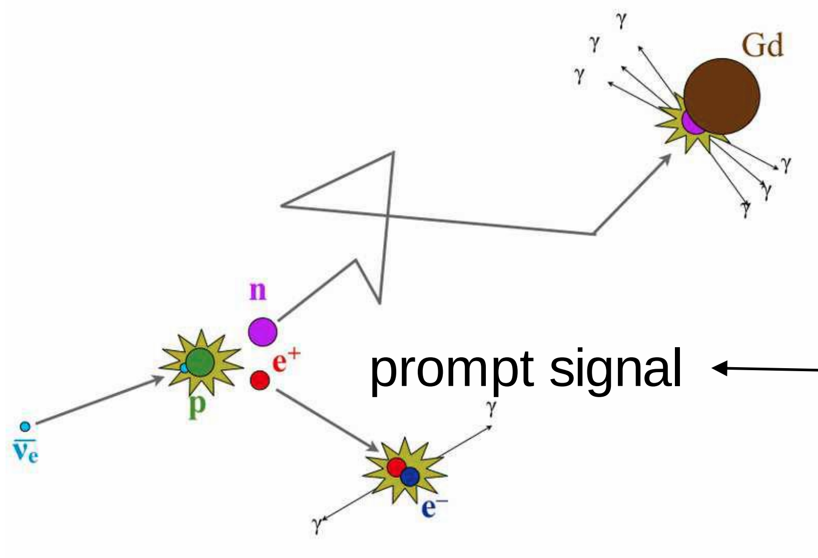
Detection of $\bar{\nu}_e$

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

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

$\rightarrow$ + 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)

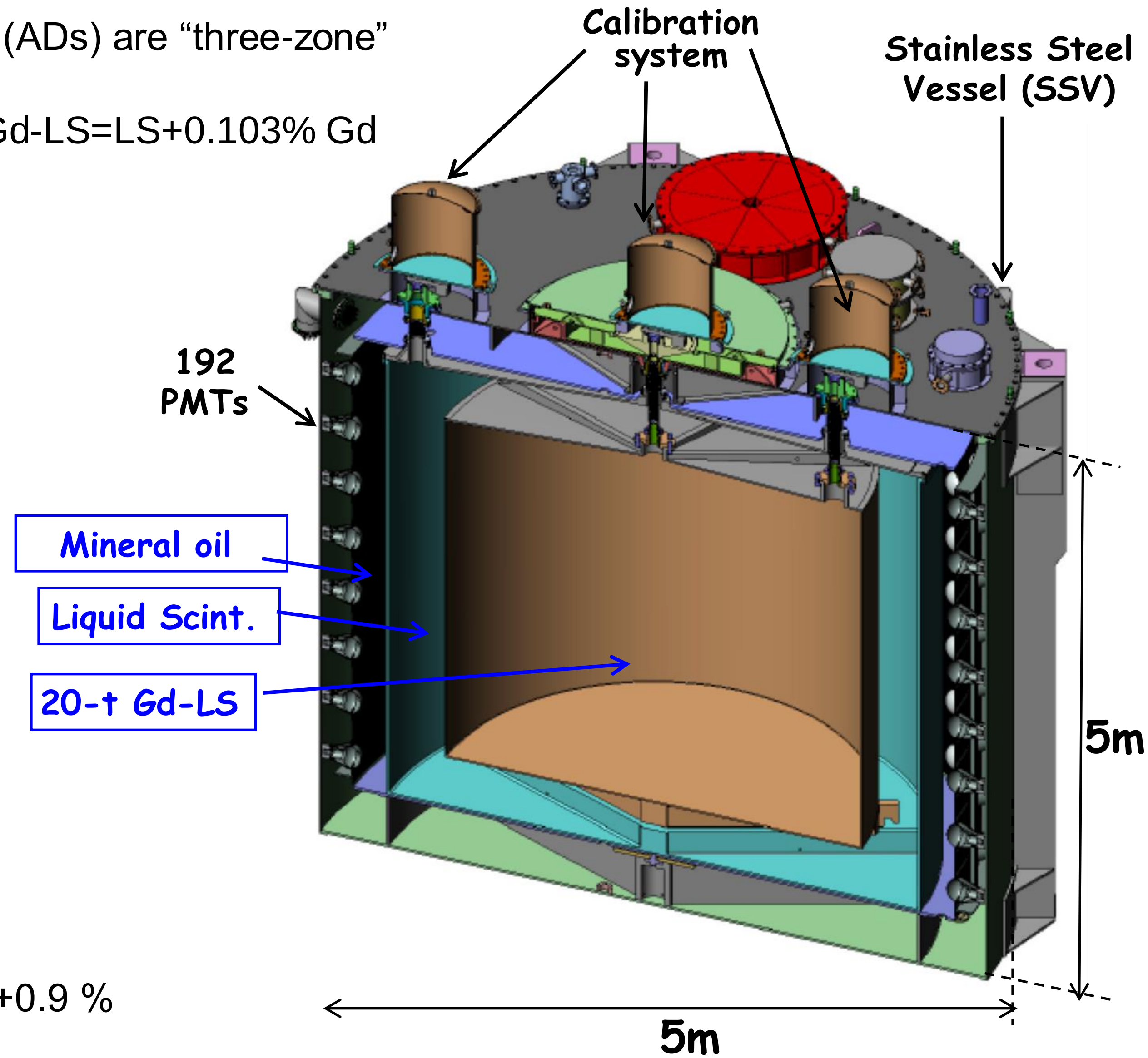
$E_{prompt} = T_{e+} + 2m_e$ (annihilation gammas)

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

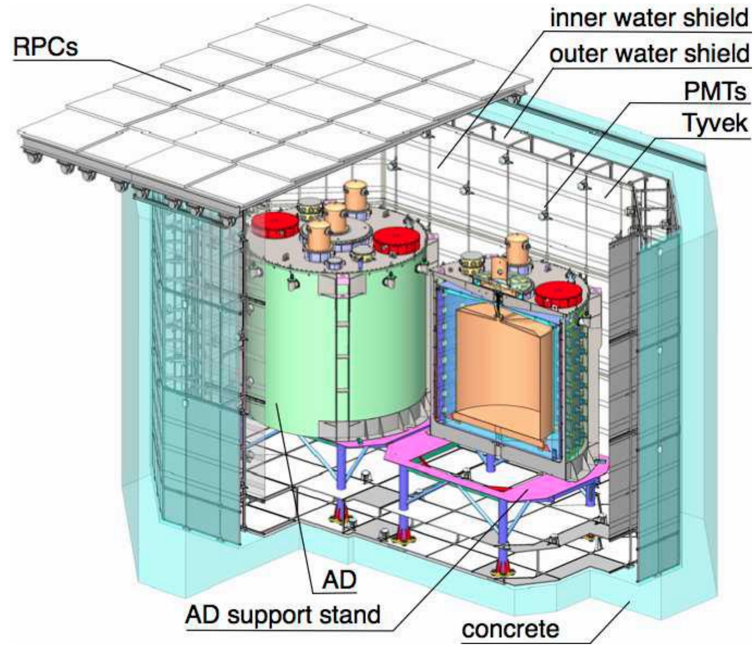


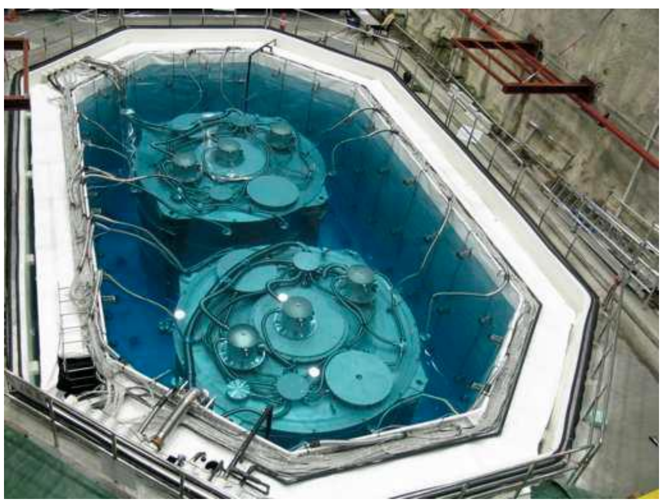
  - Top and bottom reflectors are used to increase light yield
  - Energy resolution: $s_E/E = 7.5\ \% /\sqrt{E}+0.9\ \%$

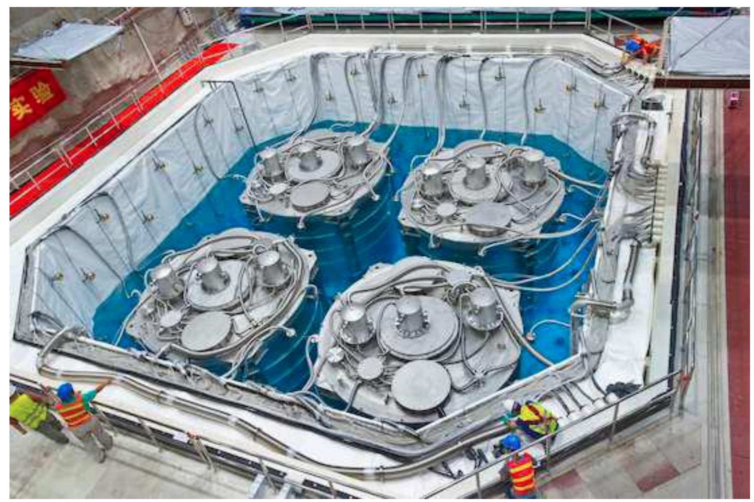
Muon tagging system

- 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





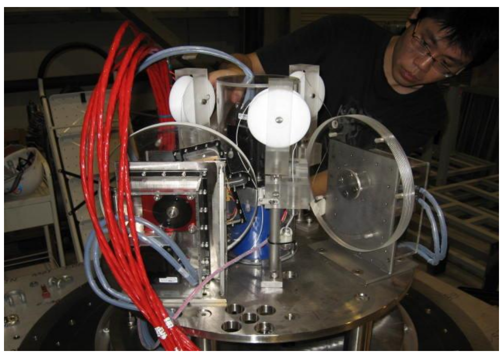


Detector calibration

- 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)
    - LED

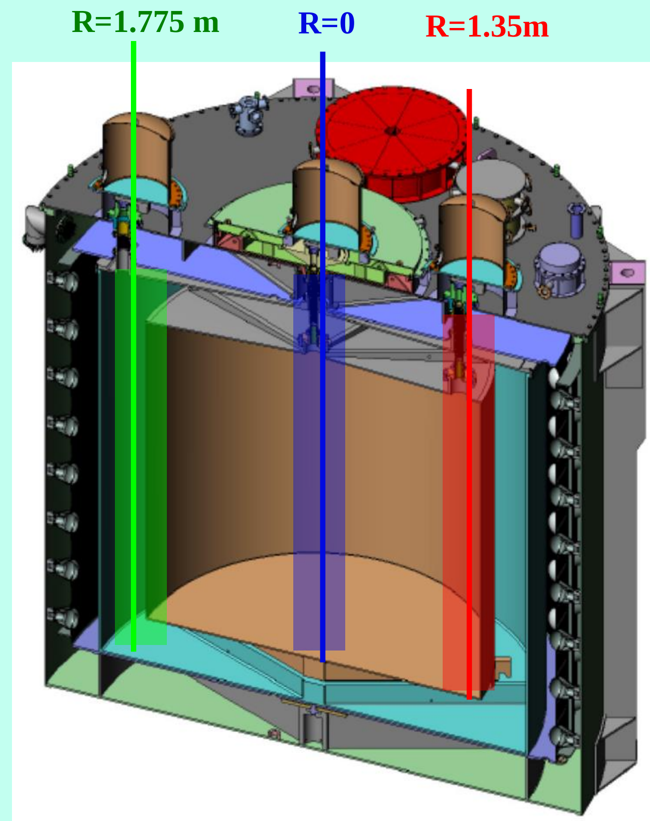
Energy calibration (linearity, detector response… etc) (^{68}Ge, ^{60}Co, ^{241}Am-^{13}C)

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



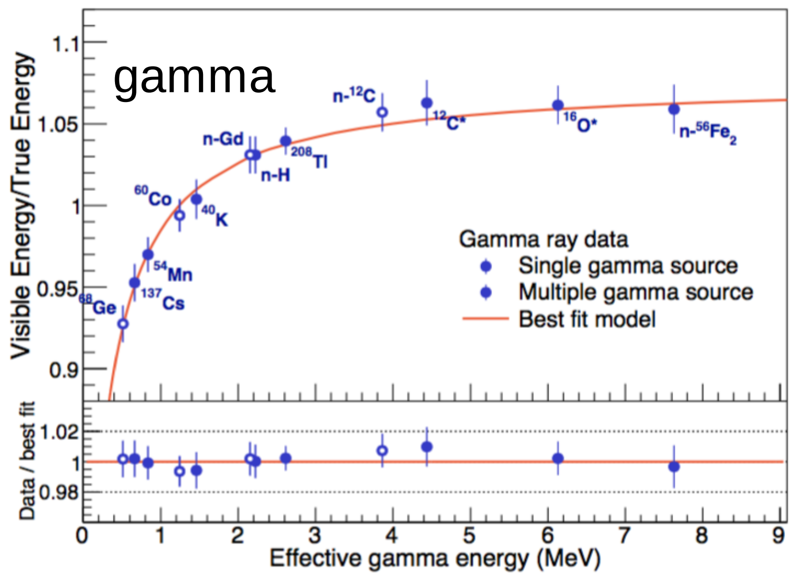
  - Can also use spallation neutrons (uniformity, stability, calibration, … etc).
  - Special calibration run in Summer 2012 helped in reducing the systematic uncertainties.

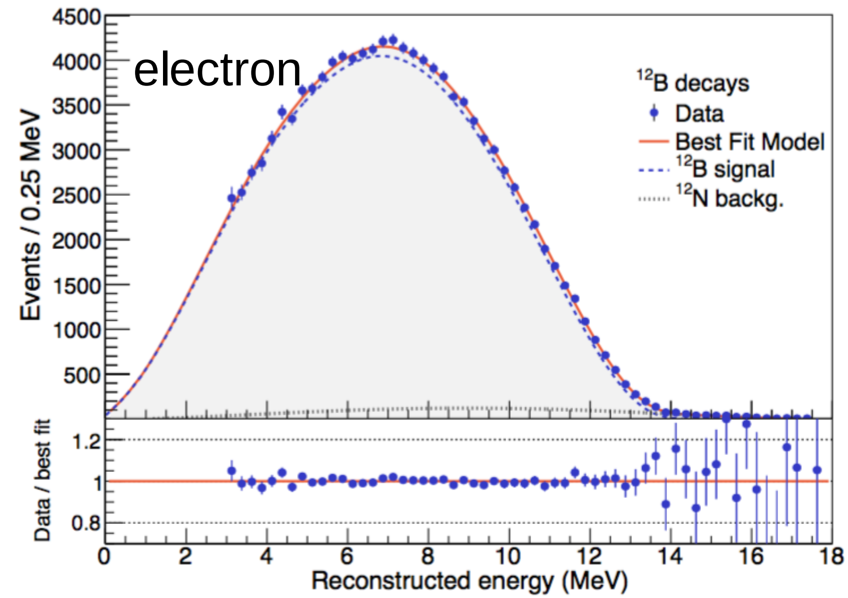
Three calibration units per detector that deploy sources along z-axis

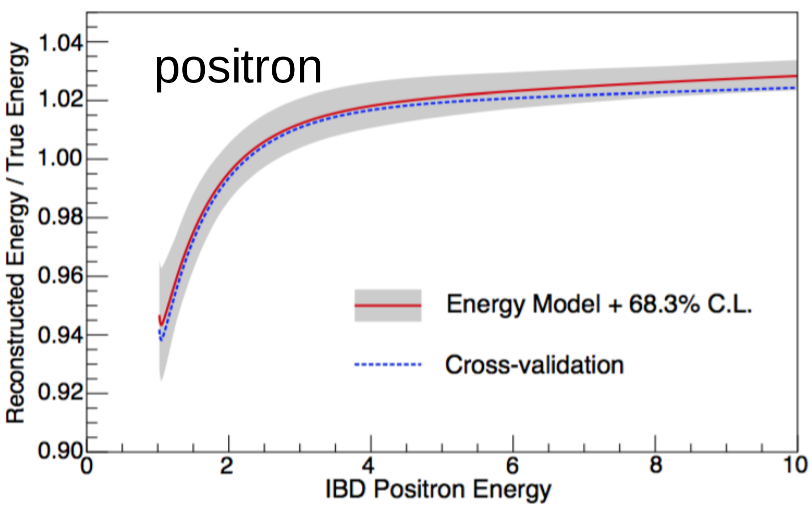


Automated Calibration Units

Energy non-linearity calibration



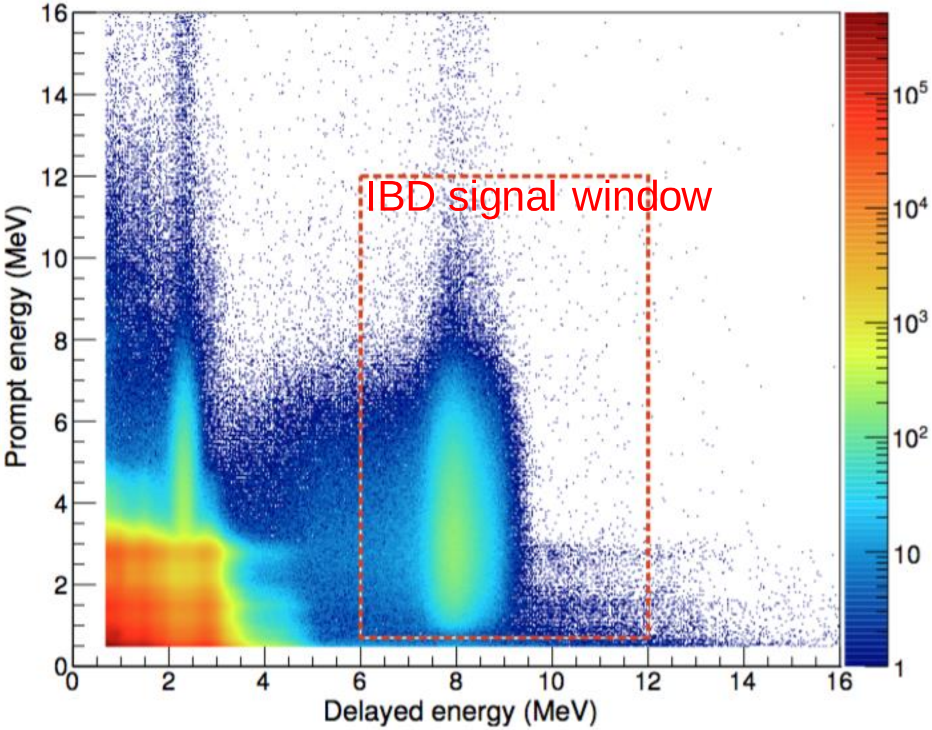




- Two major sources of non-linearity:
  - Scintillator response
  - Readout electronics
- Energy model for positron is derived from measured gamma and electron responses using simulation.

~1% uncertainty (correlated among detectors)

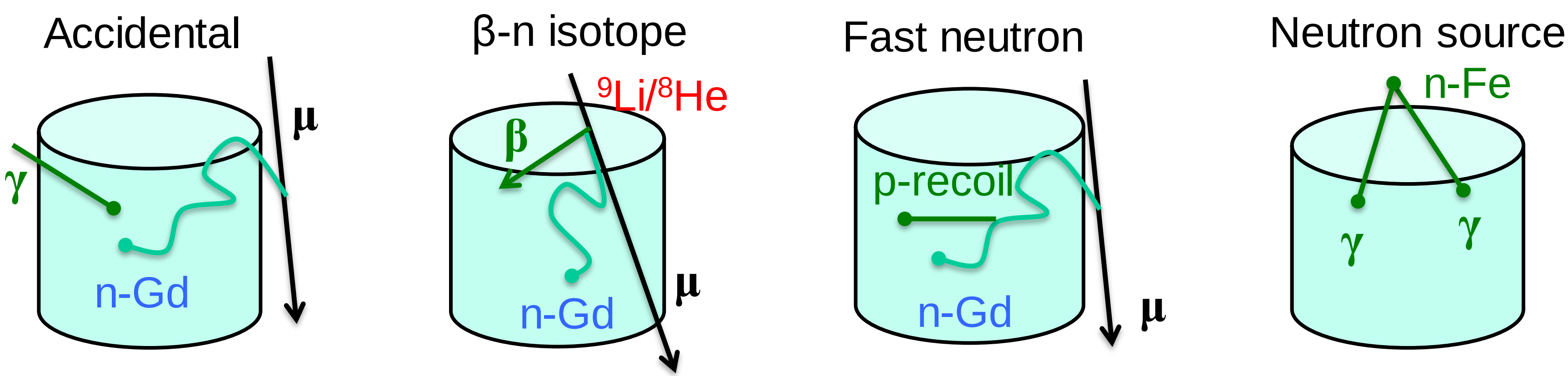
Coincidence IBD selection



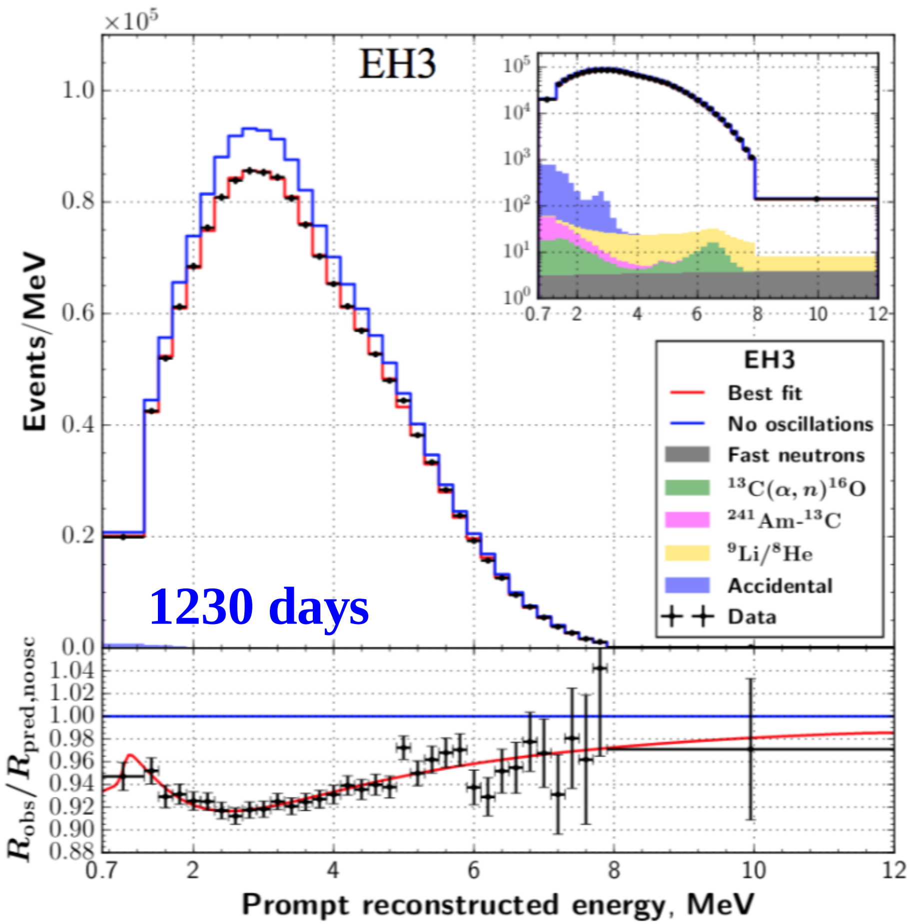
IBD selection cuts

- 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.

Main Backgrounds:



Summary of IBD candidates



6-AD: 217 days (Dec/2011 – Jul/2012)
8-AD: 1013 days (Oct/2012 – Jul/2015)

- **In the presented nGd analysis more than million inverse beta decays have been detected in near halls.**
- **More than 150 thousands IBD have been detected in far hall.**
- **Daily rate is ~2500 IBD events in near halls and ~300 IBD in far hall.**
- **$\leq$ 2% backgrounds.**
- **$^{9}Li/^{8}He$ has the largest uncertainty on B/S ratio: 0.1% ~ 0.15% .**

Summary of systematics

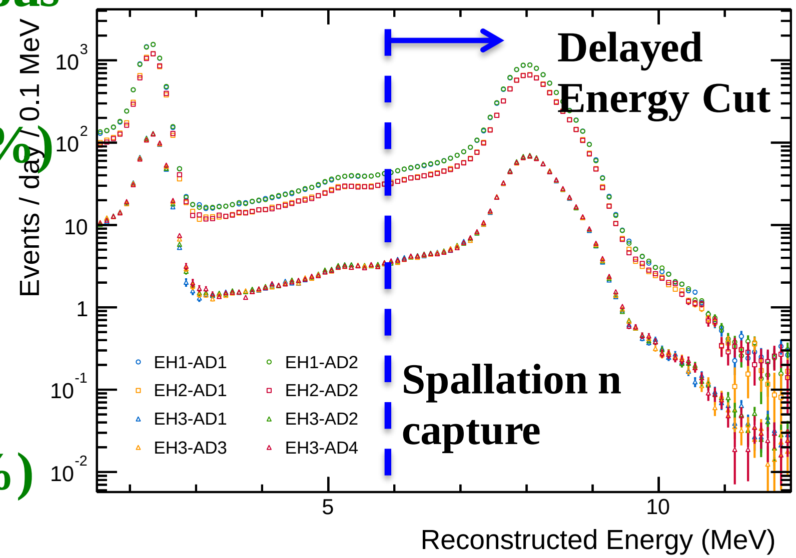
Detector efficiency

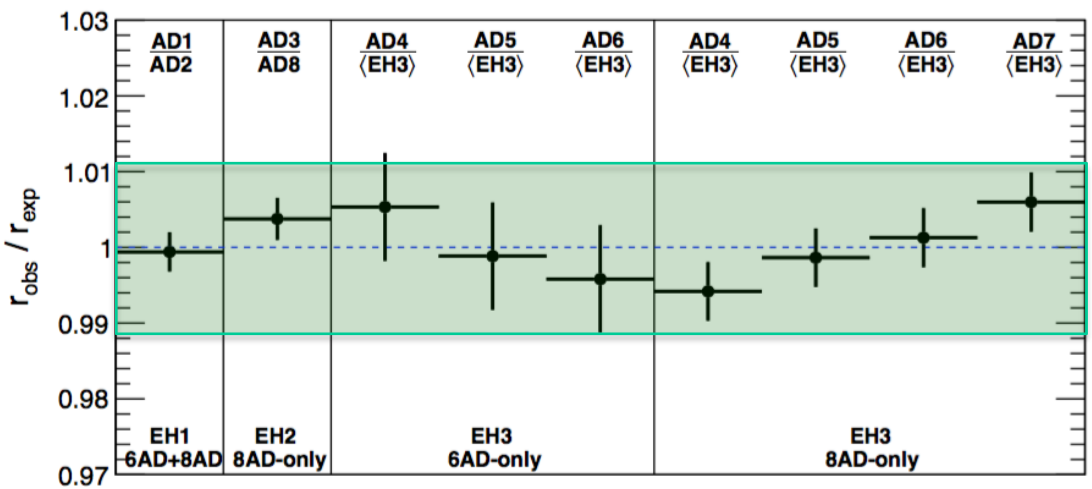
	Efficiency	Correlated	Uncorrelated
Target protons	-	0.92%	0.03%
Flasher cut	99.98%	0.01%	0.01%
Delayed energy cut	92.7%	0.97%	0.08%
Prompt energy cut	99.8%	0.10%	0.01%
Multiplicity cut		0.02%	0.01%
Capture time cut	98.7%	0.12%	0.01%
Gd capture fraction	84.2%	0.95%	0.10%
Spill-in	104.9%	1.00%	0.02%
Livetime	-	0.002%	0.01%
Combined	80.6%	1.93%	0.13%

Previous

(0.12%)

(0.2%)

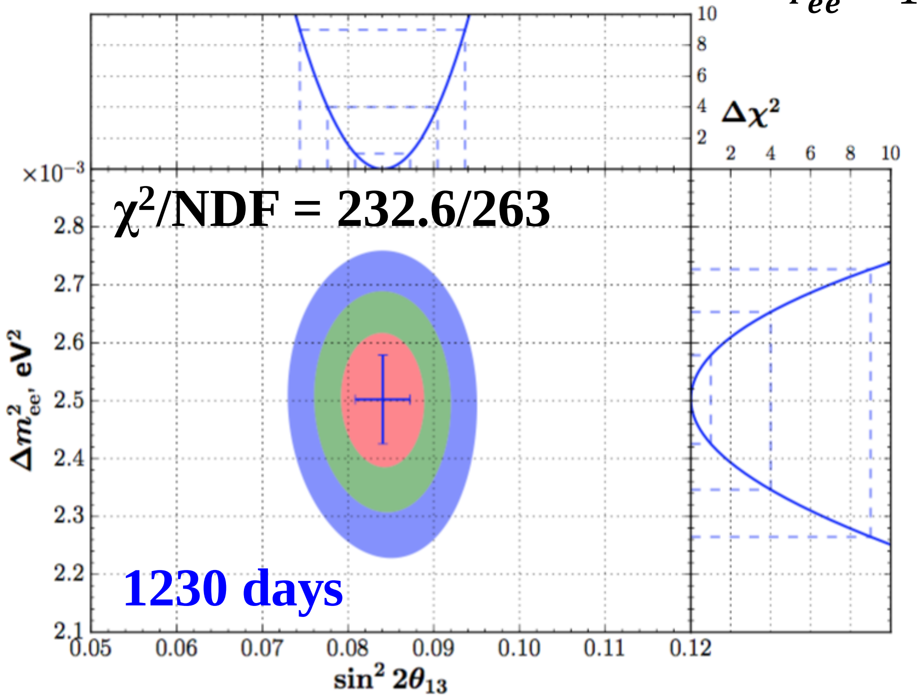


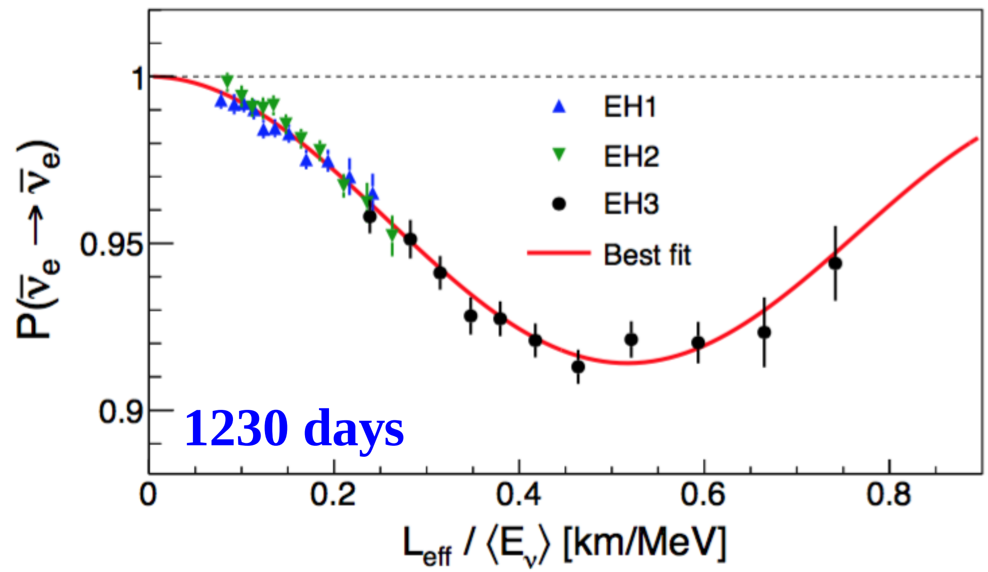


Multiple detectors in the same experimental hall enable cross-check of the uncorrelated uncertainty

Oscillation analysis result

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





$$\sin^2 2\theta_{13} = \mathbf{0.0841 \pm 0.0027}(\boldsymbol{stat.}) \pm \mathbf{0.0019}(\boldsymbol{syst.})$$

$$|\Delta m^2_{ee}| = [\mathbf{2.50 \pm 0.06}(\boldsymbol{stat.}) \pm \mathbf{0.06}(\boldsymbol{syst.})] \times \mathbf{10^{-3}} \boldsymbol{eV^2}$$

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

Phys. Rev. D 95, 072006 (2017)

Global comparison

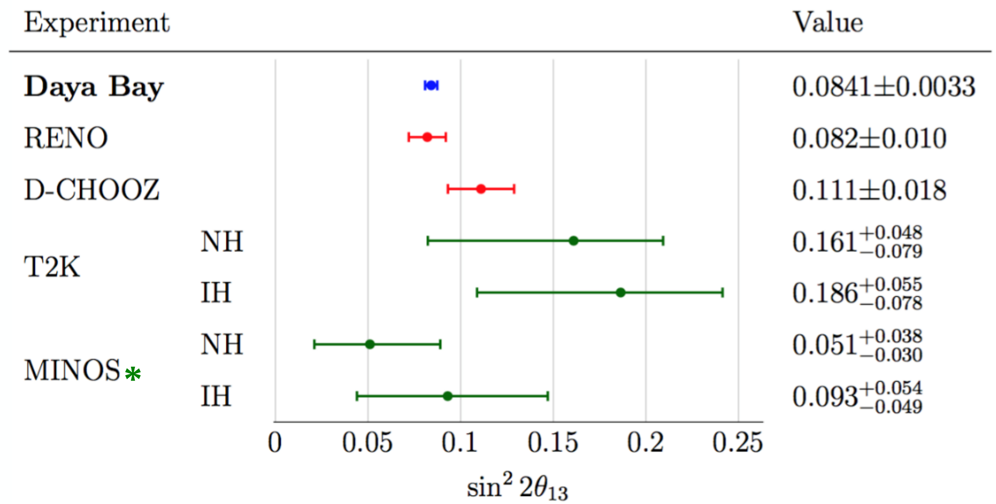
1230 days

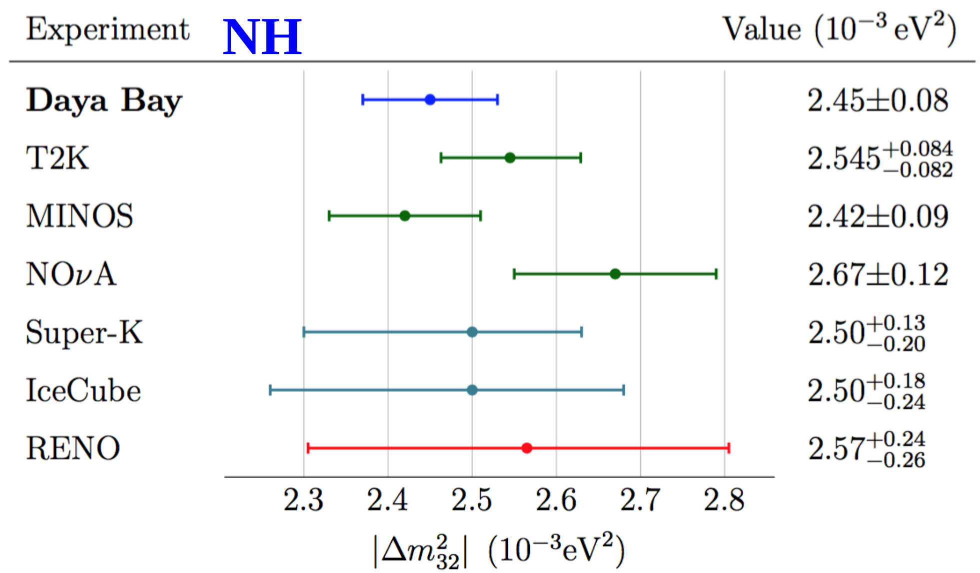
Most precise measurement
- $\sin^2 2\theta_{13}$ uncertainty: 3.9%
- $|\Delta m^2_{32}|$ uncertainty: 3.4%

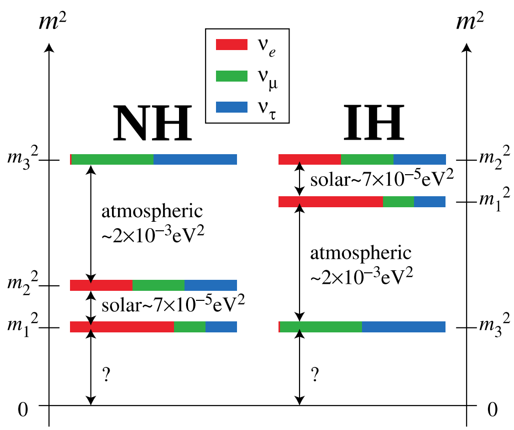
Consistent results with reactor and accelerator experiments.

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

NH: Δm^2_{32} = [2.45 ± 0.08] × 10^{-3} eV^2
IH: Δm^2_{32} = [-2.55 ± 0.08] × 10^{-3} eV^2



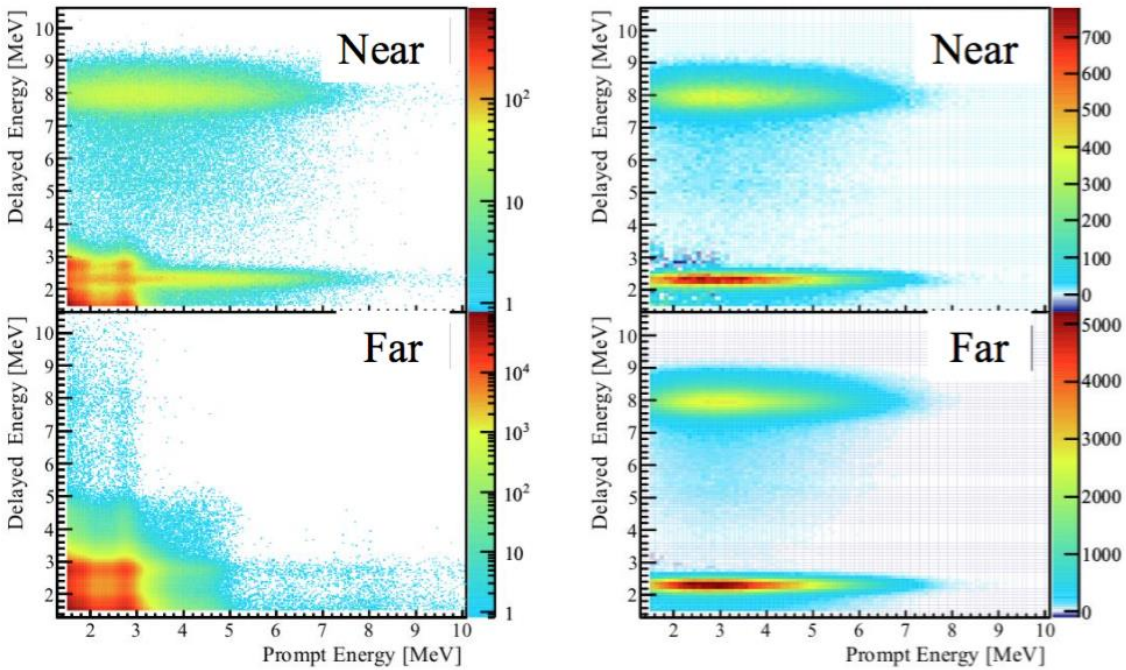


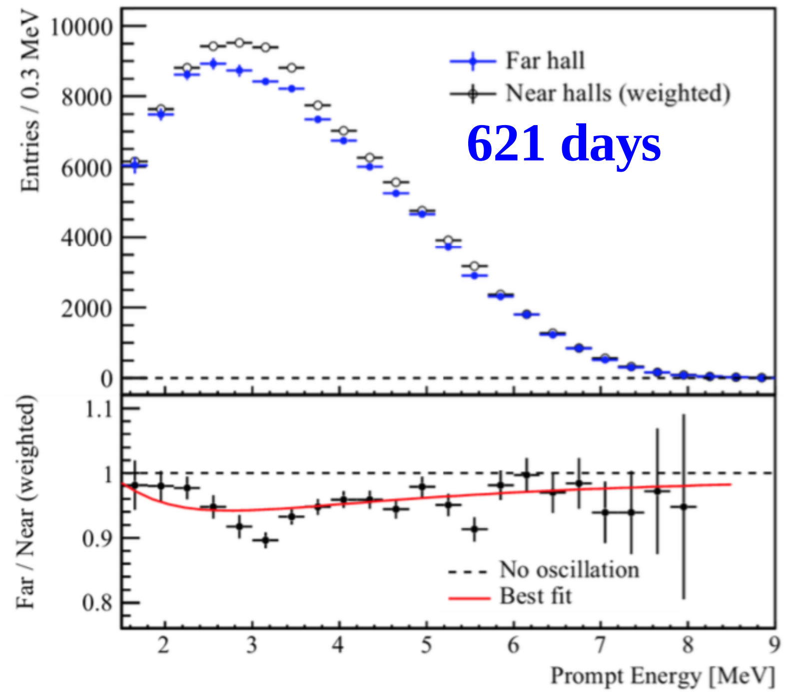


** Combined fit results for $2\sin^2\theta_{23}\sin^2 2\theta_{13}$*

$\sin^2 2\theta_{13}$ 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

Phys. Rev. D 93, 072011 (2016)

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

Reactor anti-neutrino flux

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

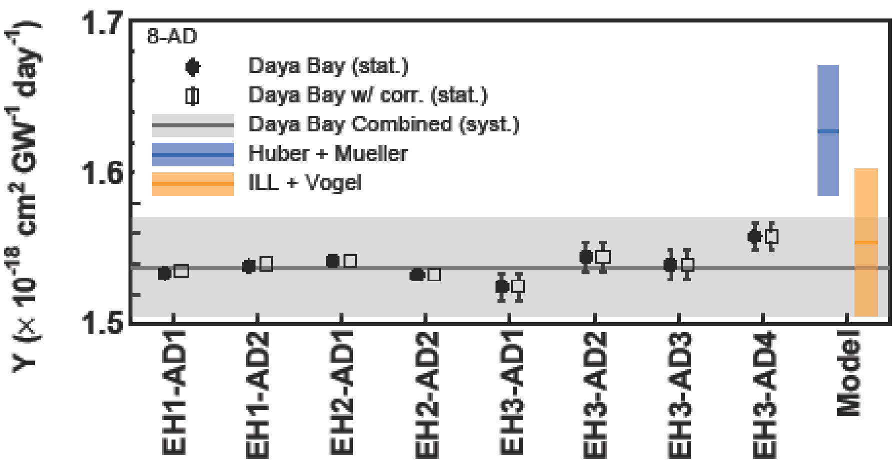
Phys. Rev. Lett. 116 (2016) no.6, 061801

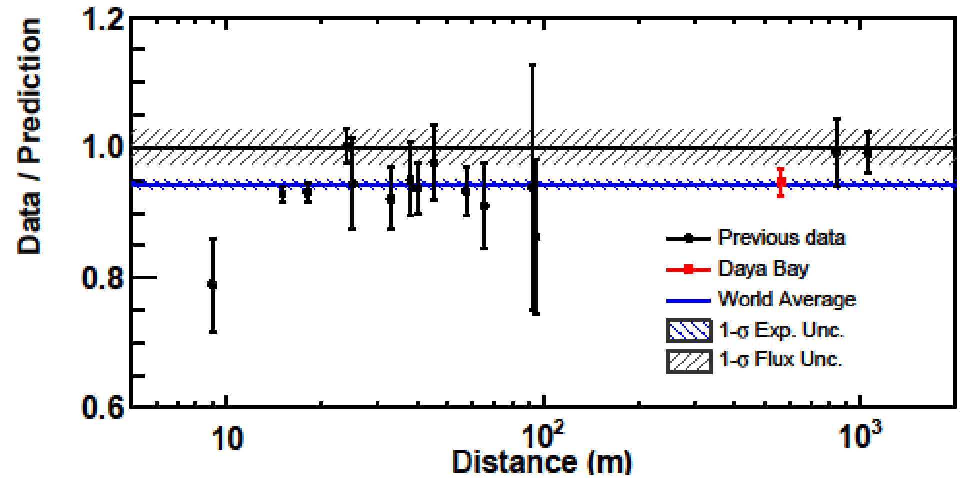
621 days of data

Data / Prediction:

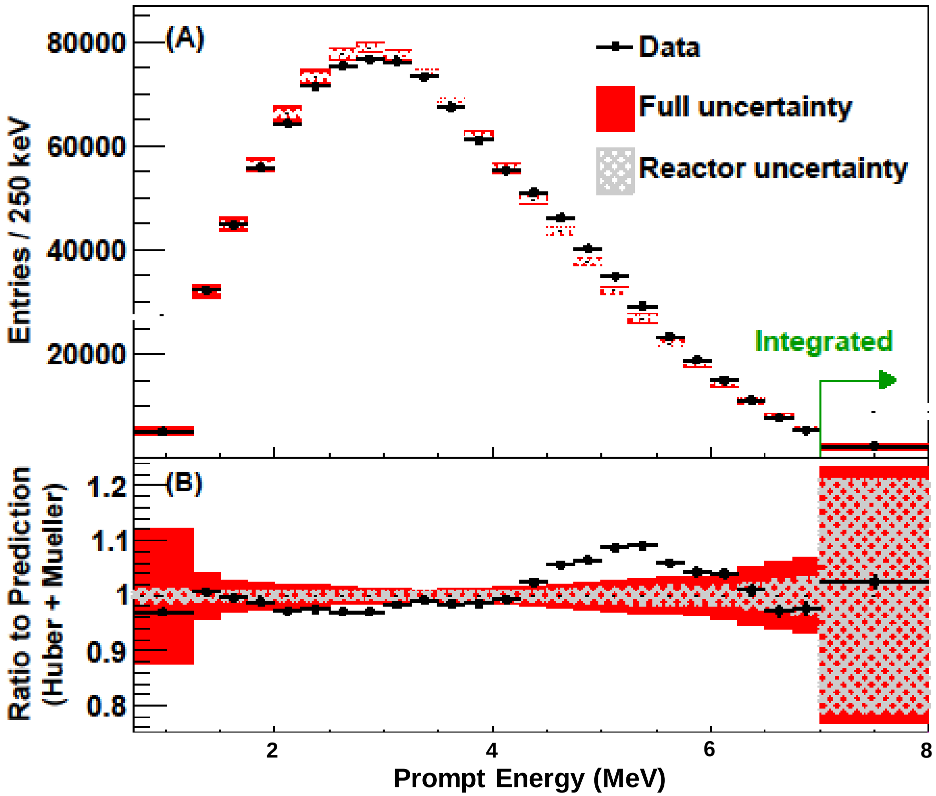
- Huber+Mueller: 0.946±0.020
- ILL+Vogel: 0.992±0.021

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





Reactor anti-neutrino energy spectrum



621 days of data

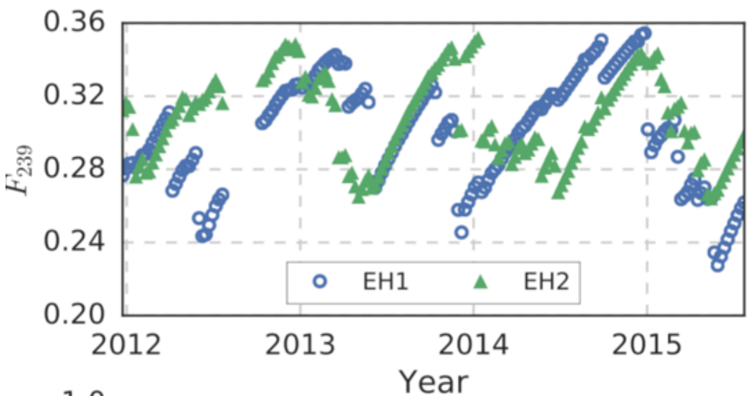
Phys. Rev. Lett. 116 (2016) no.6, 061801

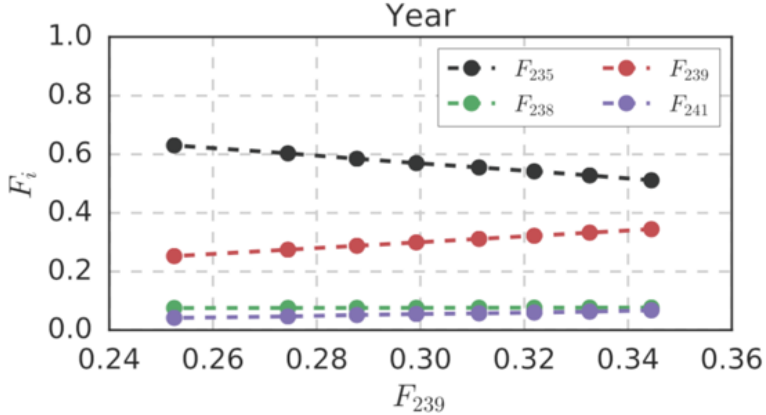
- High-statistics measurement of the spectral shape of reactor antineutrinos:
  - Global discrepancy with the Huber+Mueller prediction at 2.9σ (4.4σ in the 4-6 MeV region)
  - Excess events have all the IBD characteristics and are correlated with reactor power, relative size does not change in time
  - Excess does not appear in ^{12}B spectra (disfavouring detector effects)

Antineutrino flux evolution

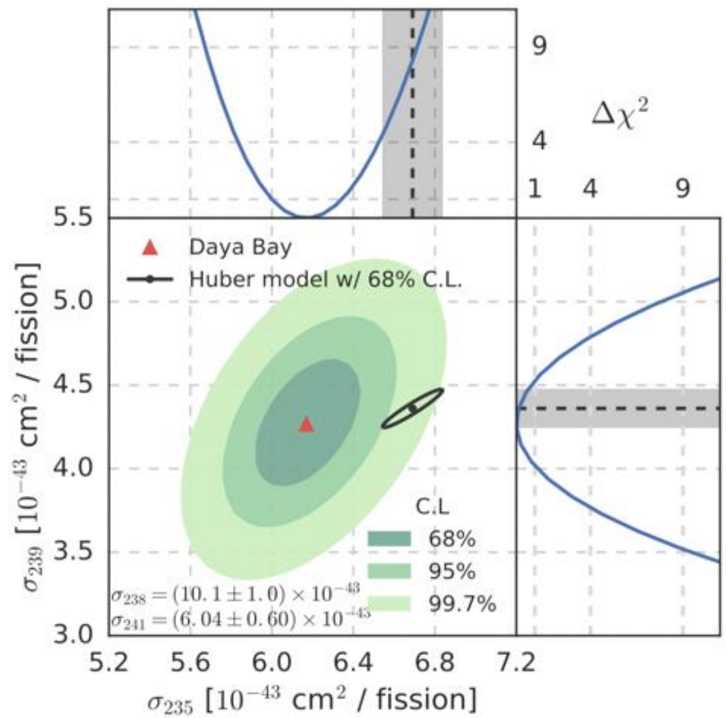
Analysis of dependence of IBD yield/fission σ_i for each fission isotope (i = ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu) on effective fission fraction F_{239} instead of time integration.

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





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



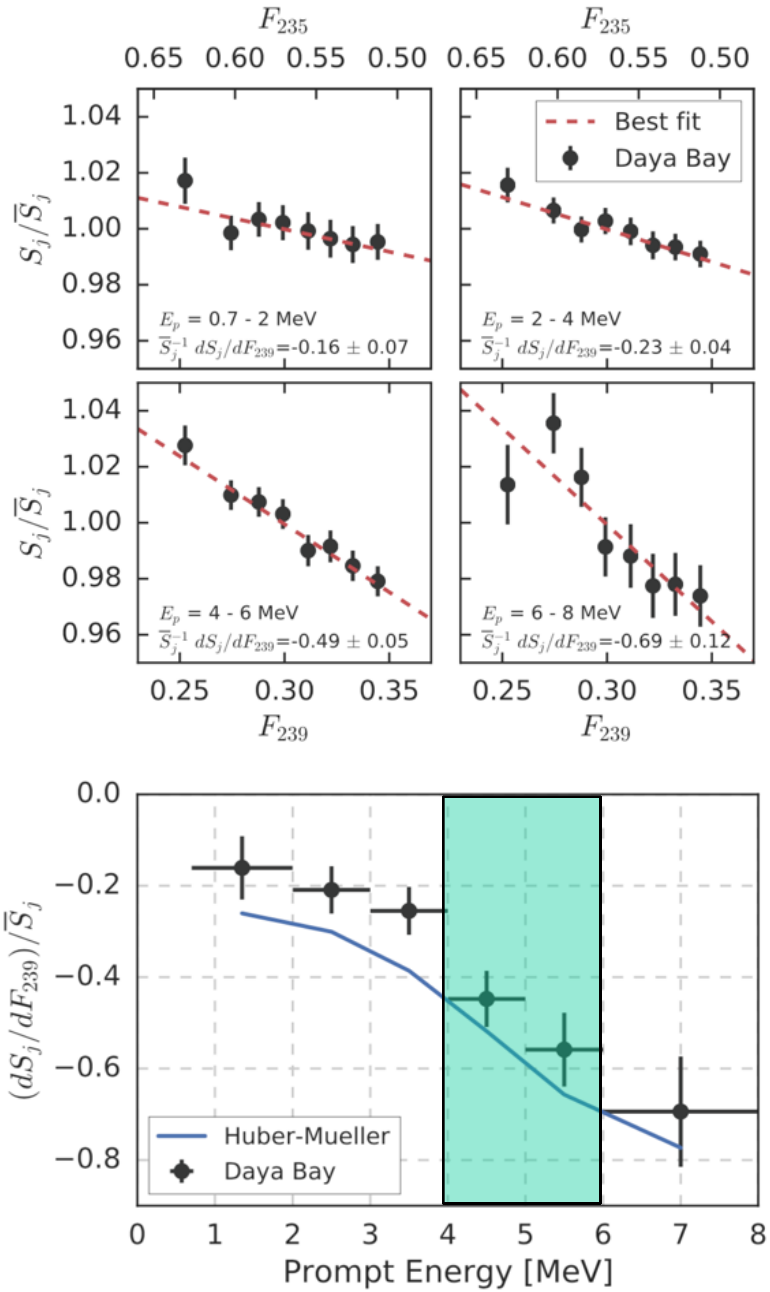
3.1 σ discrepancy in the antineutrino flux variation with respect to the reactor fuel composition model prediction.

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

1230 days, near detectors

arXiv:1704.01082

Antineutrino energy spectrum evolution



Examine IBD yield/fission evolution in separate energy ranges.

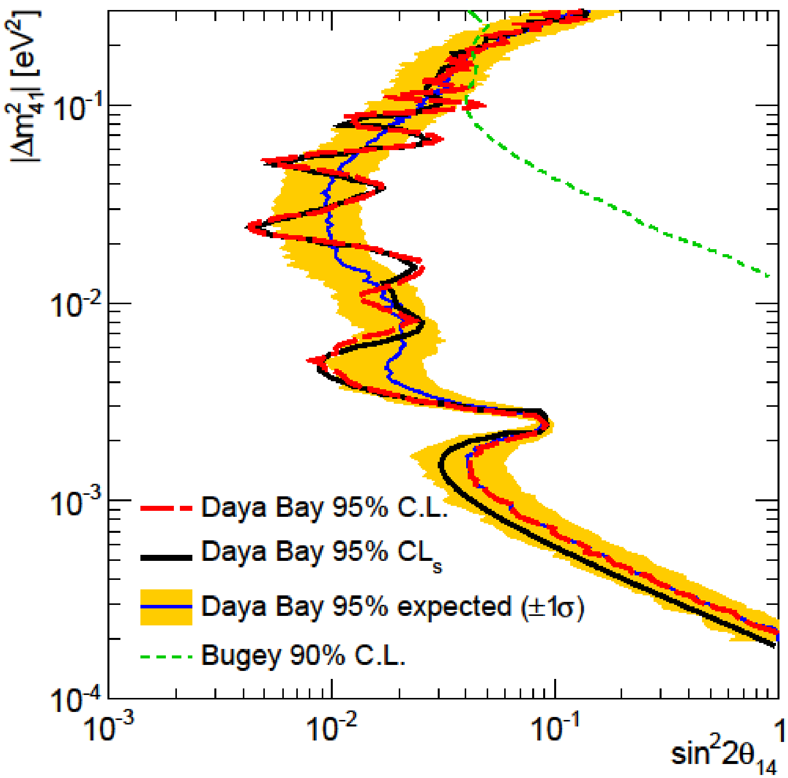
Slope is different for different energy ranges → IBD spectrum is changing with F_{239}. Spectrum evolution is generally consistent with Huber-Mueller model.

Improved Daya Bay uncertainties and future short baseline experiments with highly-enriched U reactors to probe the ^{235}U over-prediction are desired.

Search for light sterile neutrino

Survival probability formula

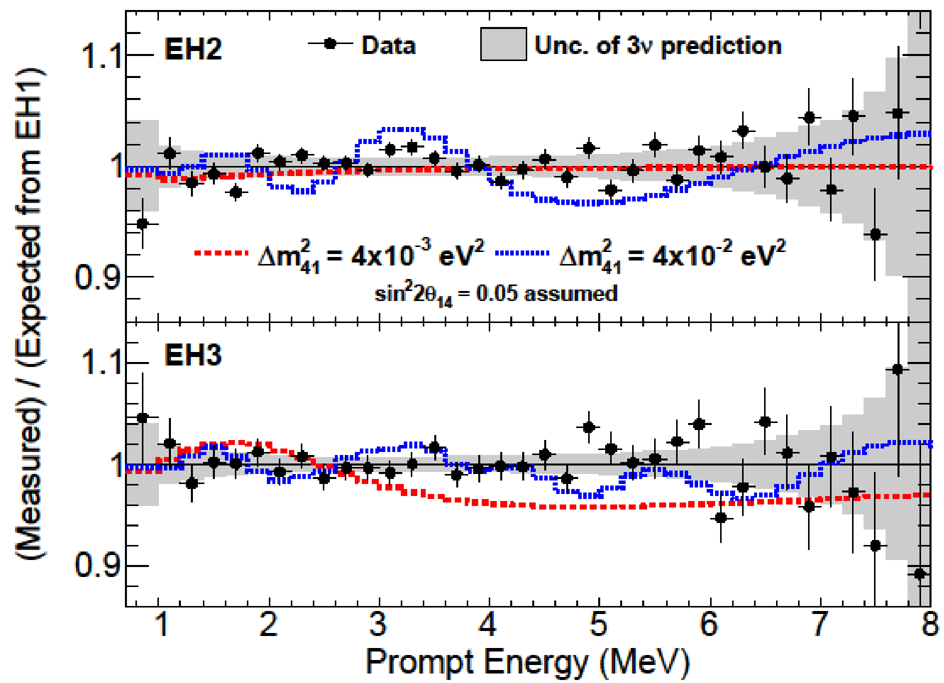
$$P_{ee} \approx 1 - \cos^4\theta_{14}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m_{ee}^2 L}{4E}\right) - \sin^2 2\theta_{14}\sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right)$$



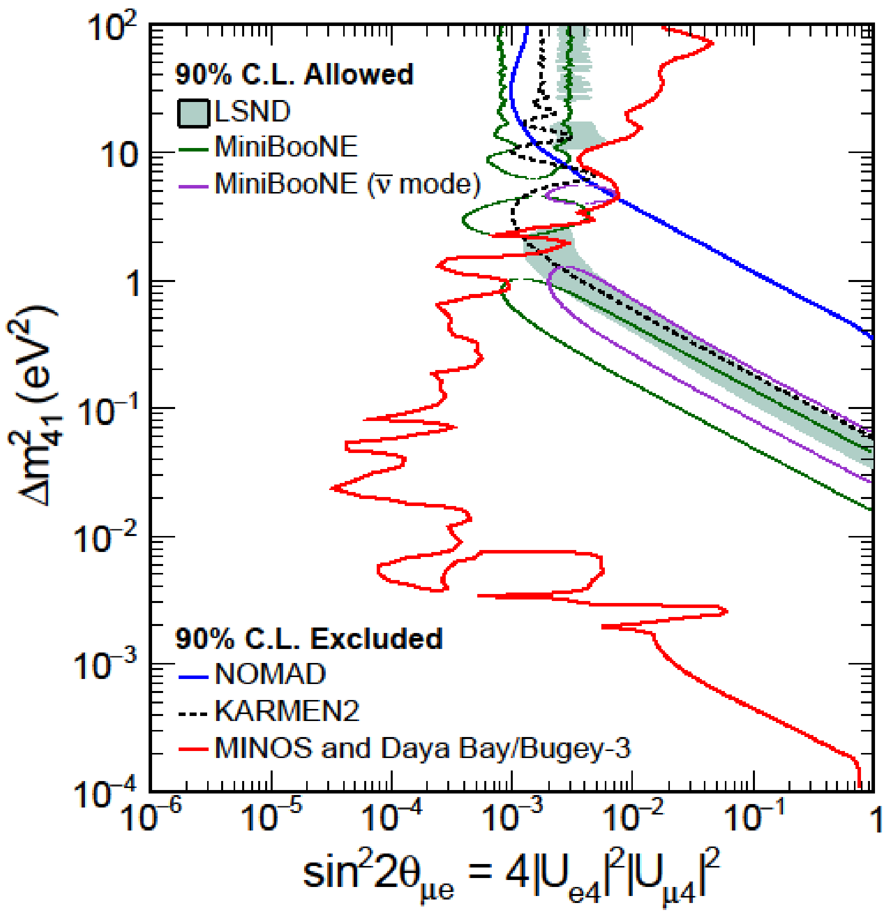
Phys. Rev. Lett. 117 (2016) no.15, 151802

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

Summary

Daya Bay Experiment provided

- Most precise measurement of $\sin^2 2\theta_{13}$ and $|\Delta m^2_{ee}|$ —1230 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 squared
- splitting $|\Delta m^2_{41}| < 0.2$ eV^2 — 621 days.
- Reactor antineutrino flux consistent with other experiments but inconsistent with predictions – 621 days.
- Reactor antineutrino 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 antineutrino anomaly – 1230 days, near detectors.

Further investigations: physics beyond SM, decoherence effect, cosmic μ physics.

Daya Bay is expected to continue running until 2020.