Latest Results from Daya Bay

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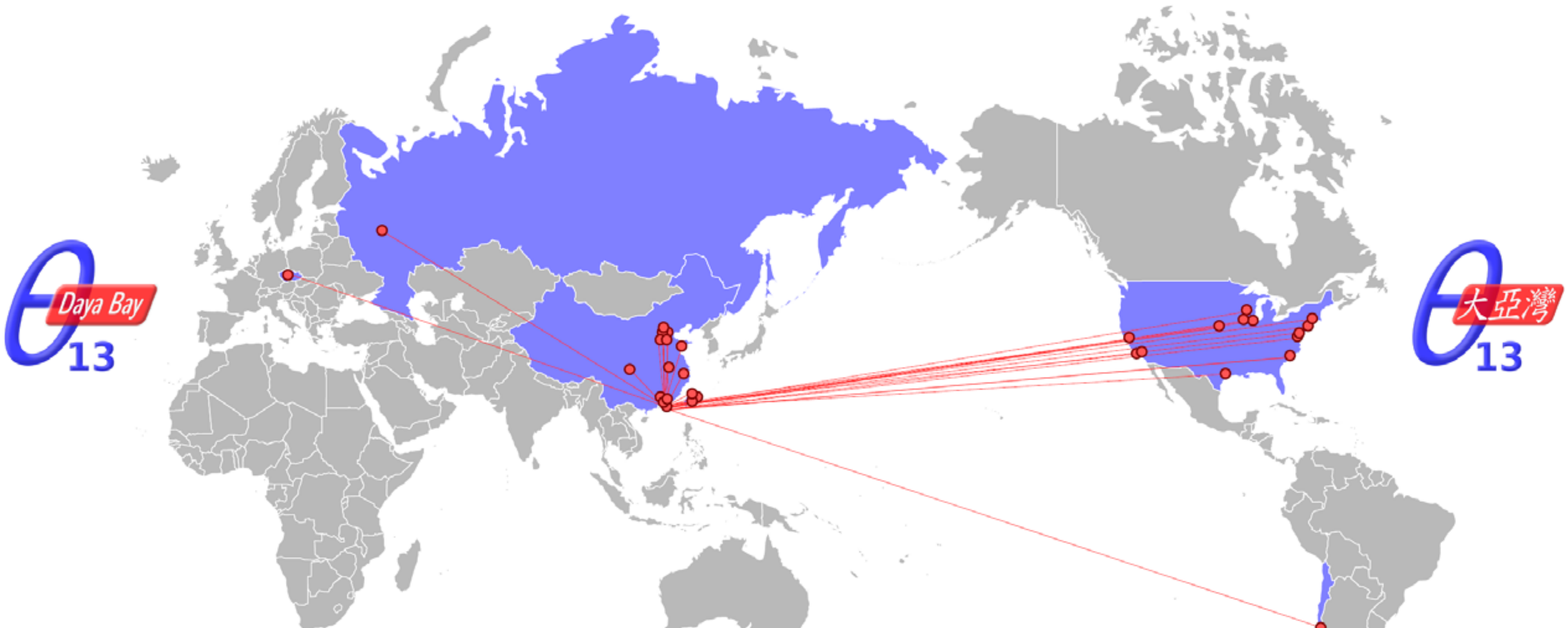
Shandong University
On behalf of the Daya Bay Collaboration

The Daya Bay Collobration



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.

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

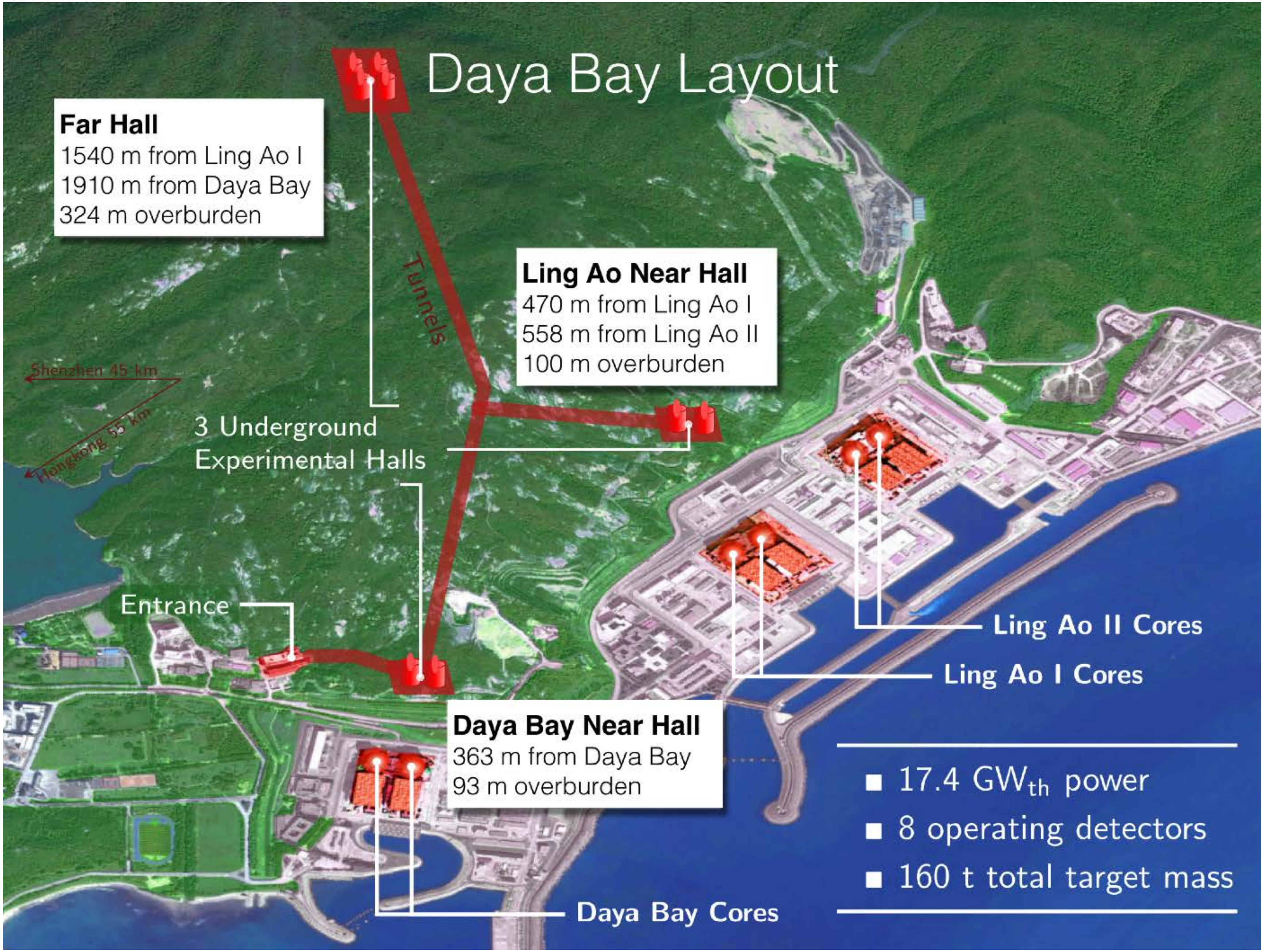
Europe (2)

Charles University, JINR Dubna

~200 Collaborators

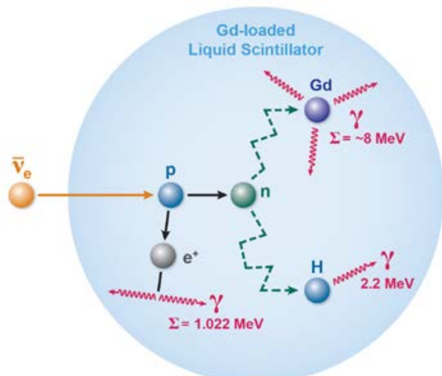
South America (1)

Catholic University of Chile

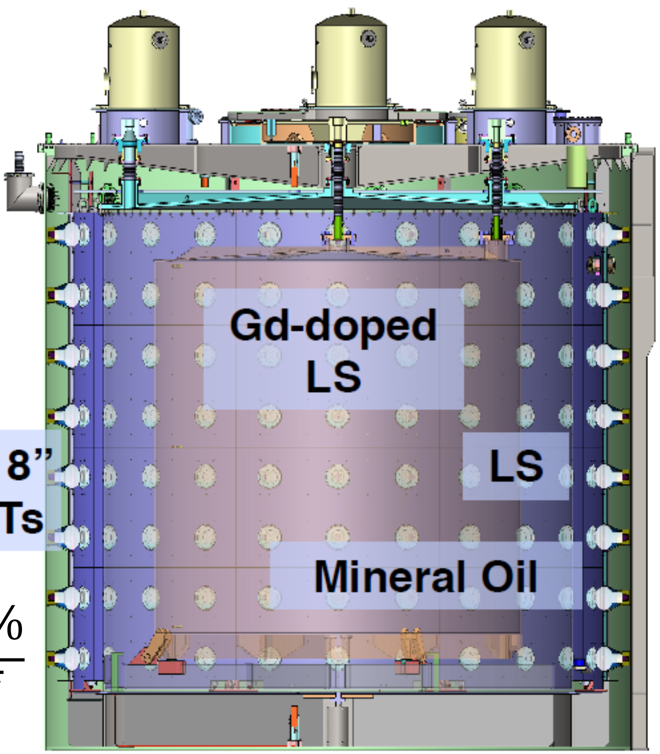


Daya Bay Layout
Far Hall
1540 m from Ling Ao I
1910 m from Daya Bay
324 m overburden
Tunnels
Ling Ao Near Hall
470 m from Ling Ao I
558 m from Ling Ao II
100 m overburden
Shenzhen 45 km
Hongkong 55 km
3 Underground
Experimental Halls
Entrance
Ling Ao II Cores
Ling Ao I Cores
Daya Bay Near Hall
363 m from Daya Bay
93 m overburden
■ 17.4 GW_{th} power
■ 8 operating detectors
■ 160 t total target mass
Daya Bay Cores

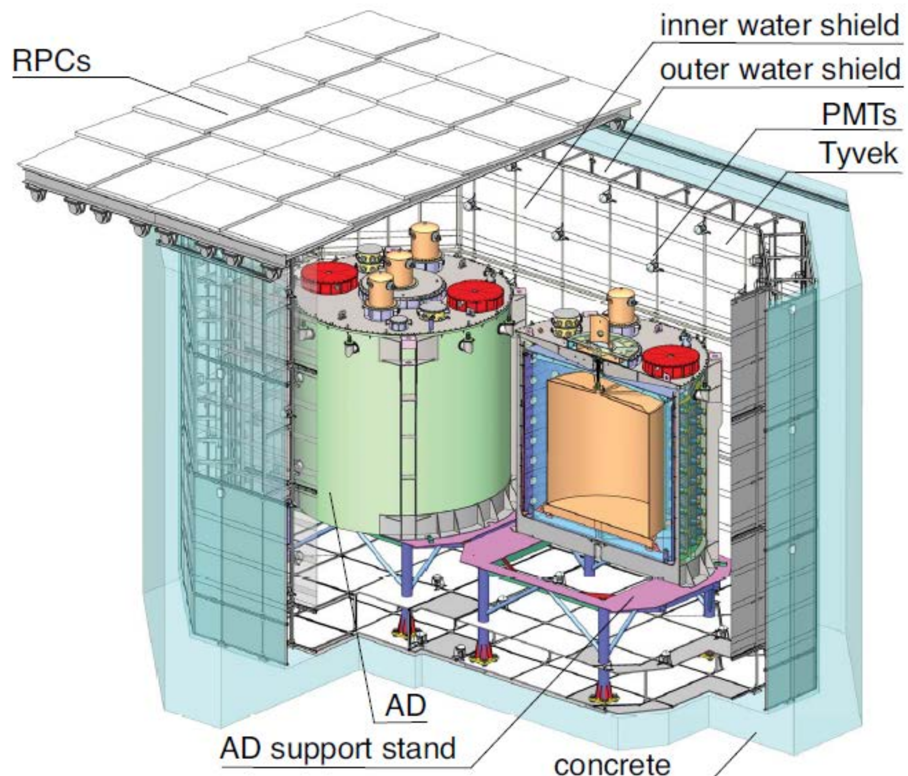
Antineutrino Detectors (AD)



- $\overline{\nu}_e$ are detected via Inverse Beta Decays (IBDs) :
  $\overline{\nu}_e + p \rightarrow e^+ + n$
- 3-zone detector module
- immersed in water pool, providing shielding and muon tagging



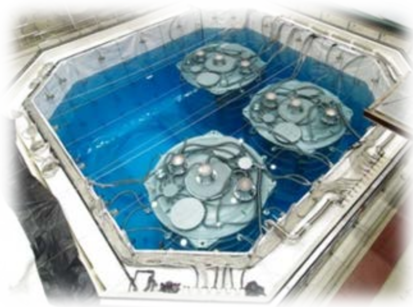
$$\frac{\sigma_E}{E} \approx \frac{8.5\%}{\sqrt{E}}$$



Experiment Installation and Operation History

EH1

EH3



EH3

2011Aug

2011Dec

2012Aug

6-AD Data Taking

2011Dec-2012Jul

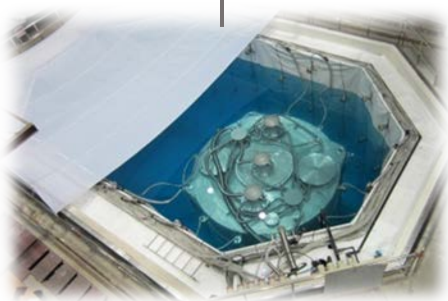
8-AD Data Taking

2012Oct-Now

2011Nov

2012Aug

2016Dec



EH2

EH2

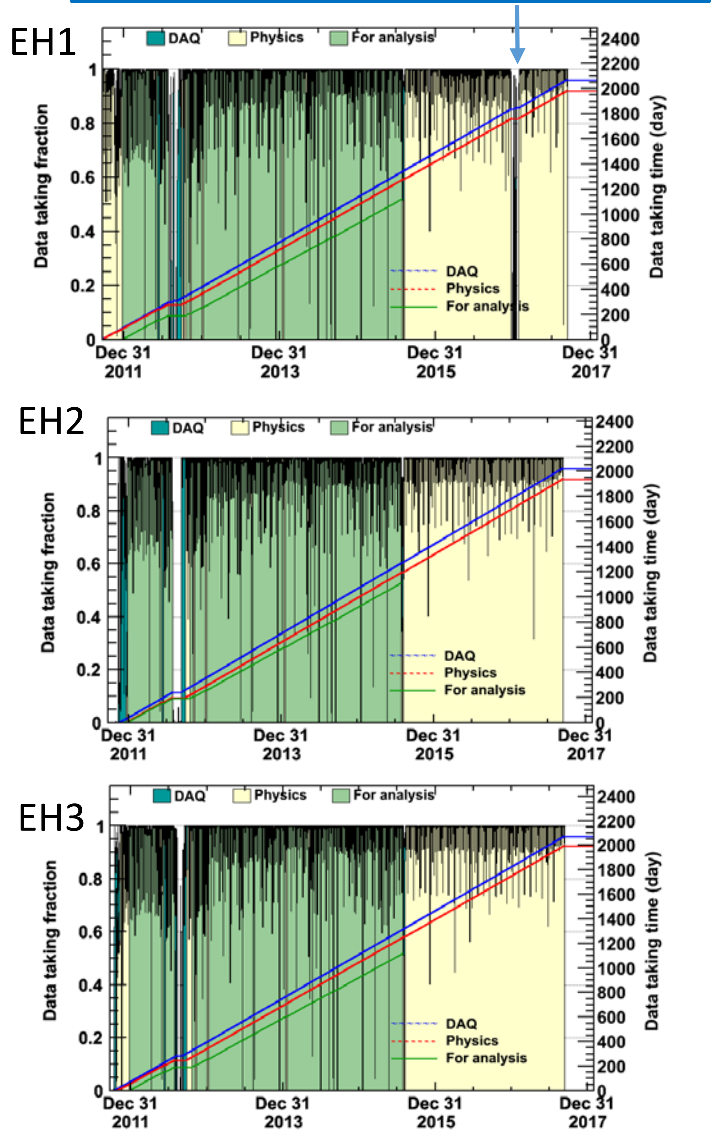
EH1-AD1:
Special Calib
^{40}K calib
LS replacement

Latest Results

$\epsilon(DAQ) \simeq 97\% \epsilon(Physics) \simeq 95\%$

EH1-AD1:
Special Calib/^{40}K Calib/LS replacement

- 3-ν Oscillation Measurements:
  - nGd analysis (1230 days)
  - nH analysis (621 days)
- Search for a sterile neutrino (621 days)
- Reactor antineutrino :
  - Absolute rate & shape measurement(621 days)
  - Evolution of the Rate and shape (1230 days)
- Search for neutrino decoherence
- Search for a seasonal variation of cosmic muon flux (621 days)
- Cosmogenic neutron production measurement (621 days)

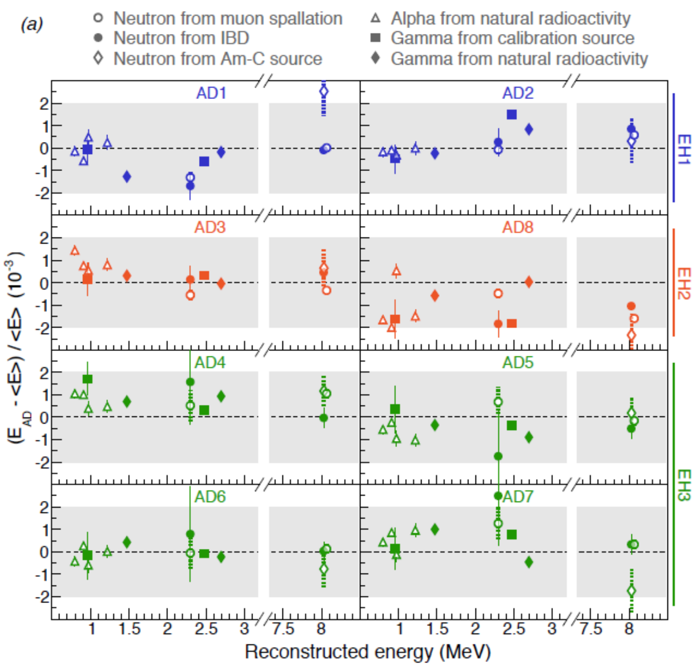


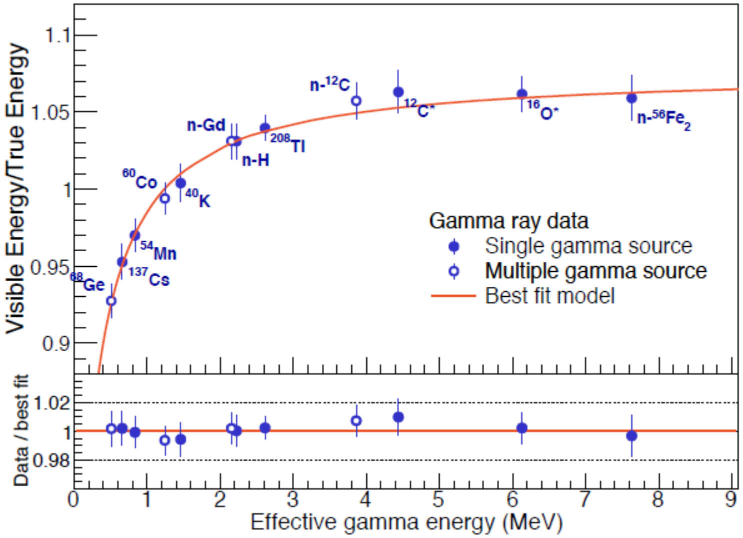
6AD(217days) : 2011Dec-2012Jul

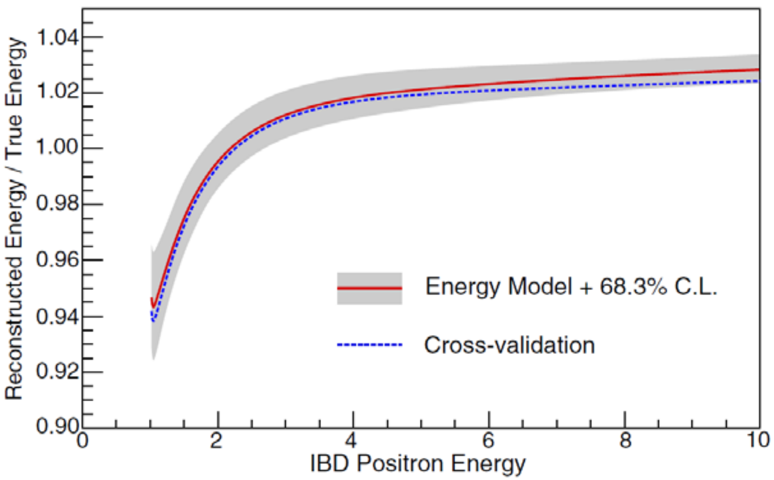
8AD(404days): 2012Oct-2013Nov

8AD(1013 days): 2012Oct-2015Jul

Energy reconstruction





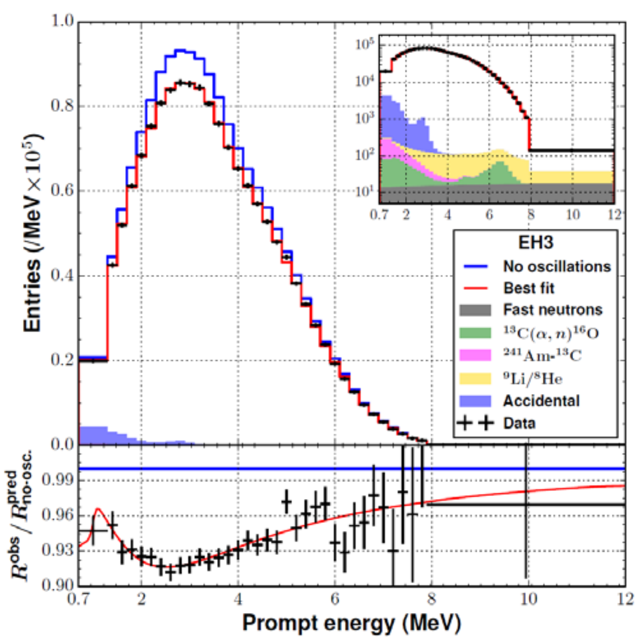


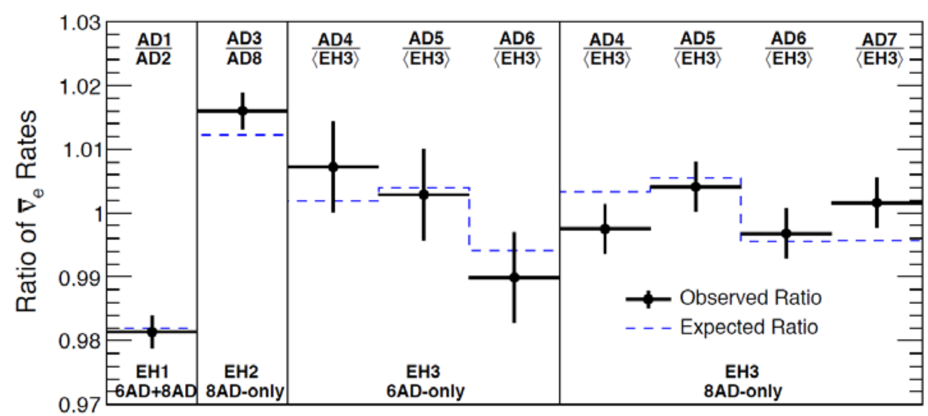
- AD-by-AD differences:
  - various calibration references (deployed/naturally occurring)
  - **Relative Energy scale uncertainty < 0.2%**
- Absolute antineutrino energy
  - Obtained via energy model which maps reconstructed energy to true energy
  - Calibrated with mono-energy gamma sources

Absolute energy scale uncertainty ~1%

Oscillation Analyses –nGd

- More than 2.5 million IBDs (300K in the far hall) with background contamination < 2%
- Major improvement is the relative detection efficiency uncertainty : reduced from 0.2% to 0.13%:

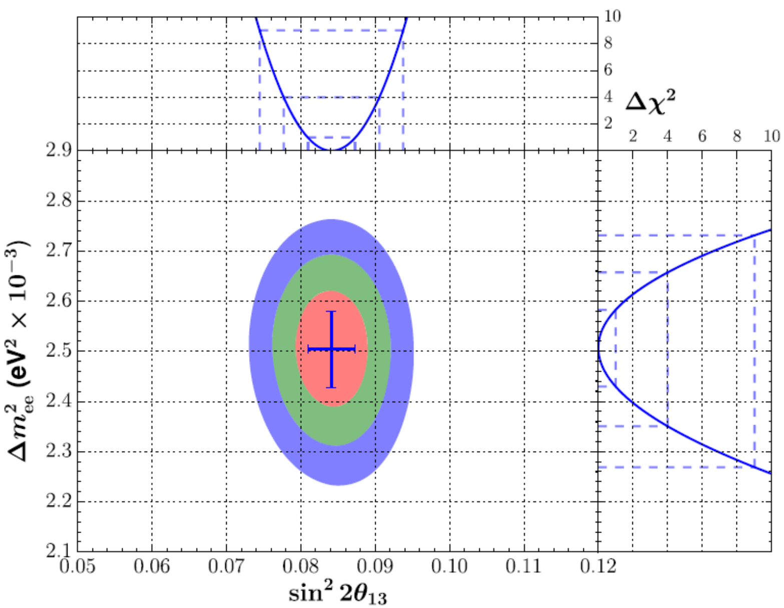




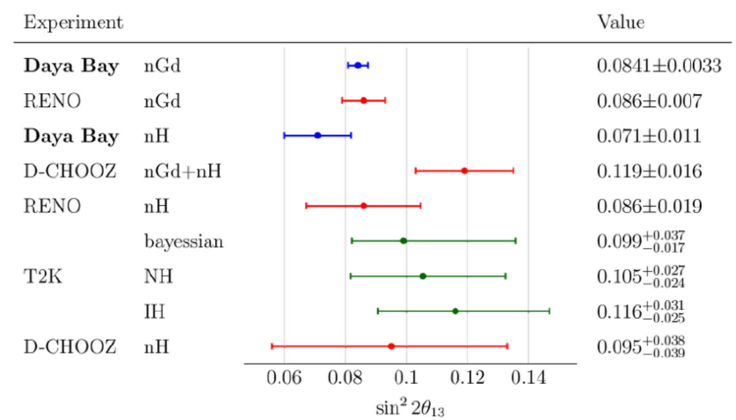
Ratios of IBD rates consistent with expectation

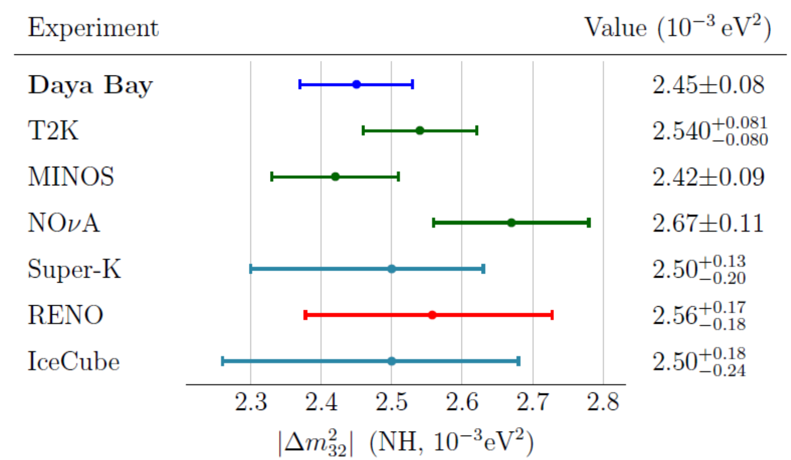
Oscillation Analyses Result- nGd

- $P_{\overline{\nu}_e \to \overline{\nu}_e} \approx 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\frac{1.267\Delta m^2_{21}L}{E} - \sin^2 2\theta_{13}\sin^2\frac{1.267\Delta m^2_{ee}L}{E}$,
  $\Delta m^2_{ee} \approx cos^2\theta_{12}\,|\Delta m^2_{31}| + \sin^2\theta_{12}|\Delta m^2_{32}|$, $|\Delta m^2_{32}| \approx |\Delta m^2_{ee}| \mp 5.2 \times 10^{-5} eV^2$ for NH (-) /IH(+)
- A relative Rate+Shape measurement provides the world's most precise measurement of θ_{13} and Δm^2_{ee}



$$\sin^2 2\theta_{13} = 0.0841 \pm 0.0027(stat.) \pm 0.0019(syst.)$$
$$|\Delta m^2_{ee}| = \left(2.50 \pm 0.06(stat.) \pm 0.06(syst.)\right) \times 10^{-3} eV^2$$
$$\frac{\chi^2}{ndf} = 234.7/263$$

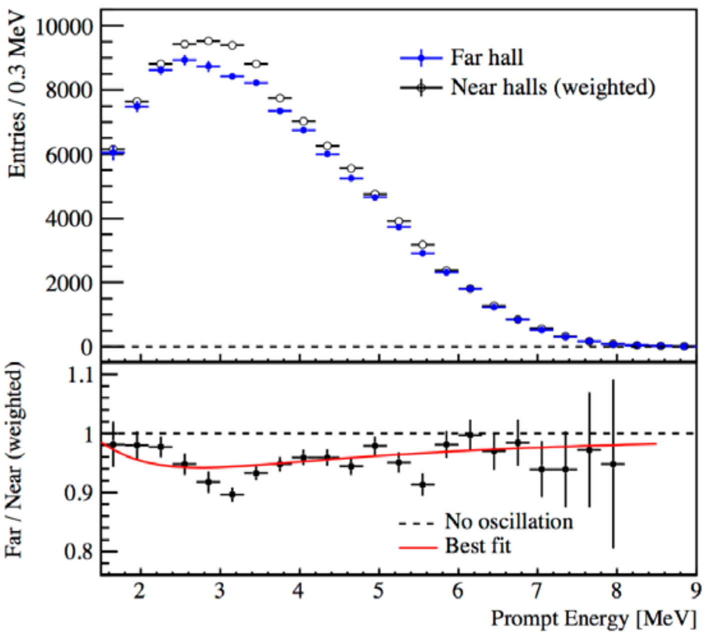


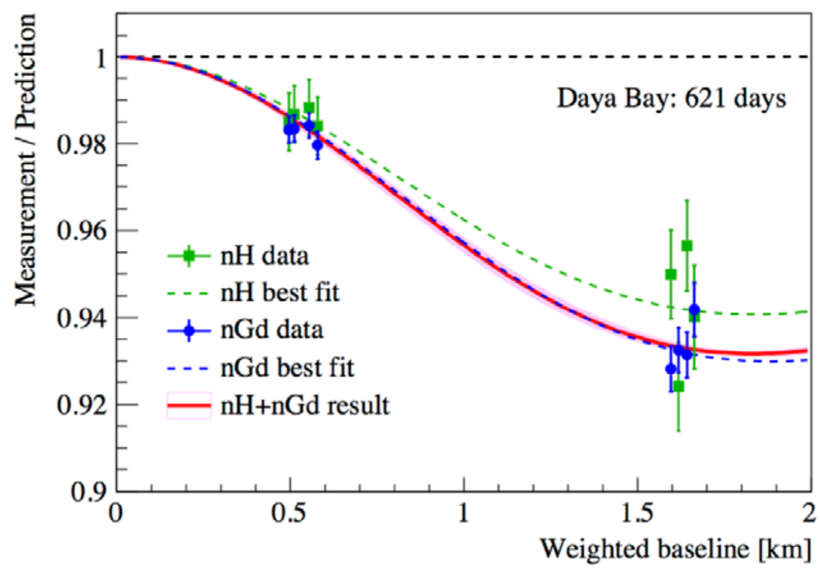


Phys. Rev. D 95, 072006 (2017)

Oscillation Analyses: nH

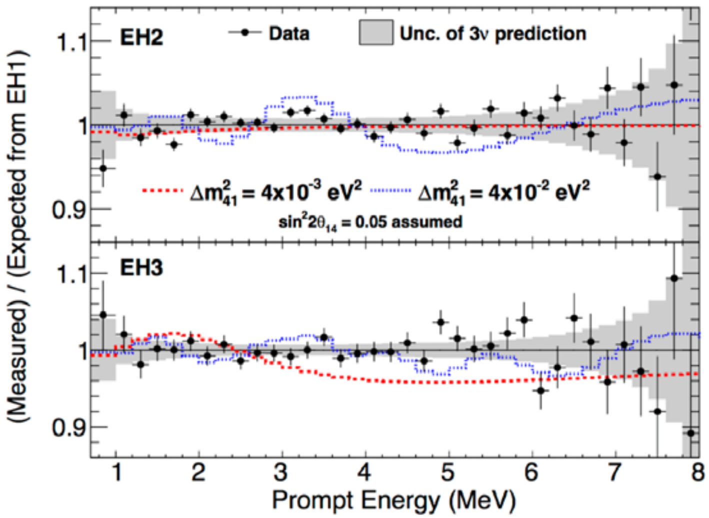
- Independent measurement using relative rate difference between far and near
- Challenging:
  - much higher accidental contamination
  - Control the detection efficiency uncertainties
- nH: $\sin^2 2\theta_{13} = 0.071 \pm 0.011, \frac{\chi^2}{ndf} = 6.3/6$
- Combined nH+nGd: $\sin^2 2\theta_{13} = 0.082 \pm 0.004$



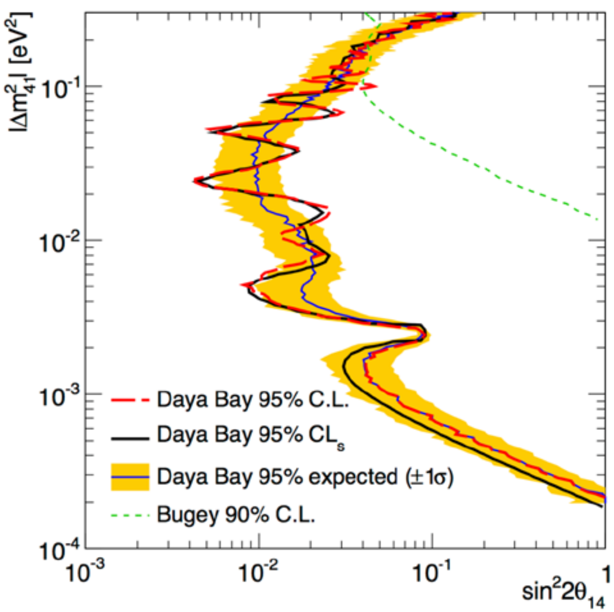


Phys. Rev. D 93, 072011 (2016)

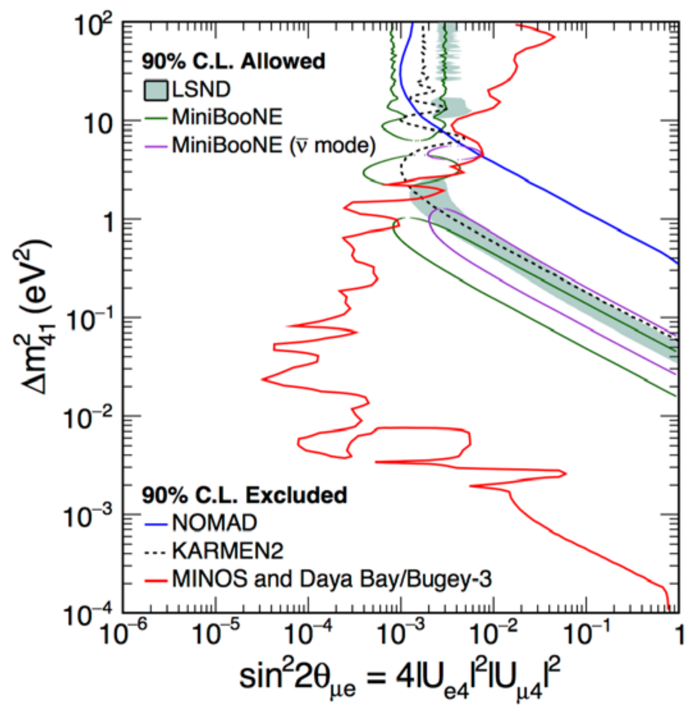
Search for Light Sterile Neutrino Mixing



- Search for sterile mixing by a relative comparison of energy spectrum at the three sites
- Obtain the most stringent limits on $\sin^2 2\theta_{14}$ in the $|\Delta m^2_{41}|$ region from $2 \times 10^{-4} eV^2$ to $0.2\ eV^2$ *PRL 117, 151802 (2016)*
- Including Bugey-3 $\overline{\nu}_e$ disappearance data, Dayabay & MINOS combined analysis exclude parameter space allowed by MiniBoone and LSND for $\Delta m^2_{41} < 0.8\ eV^2$ *PRL 117, 151801 (2016)*

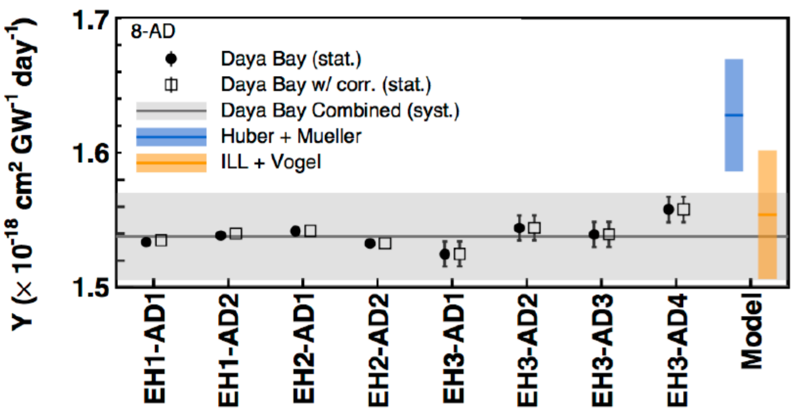


PRL 117, 151802 (2016)

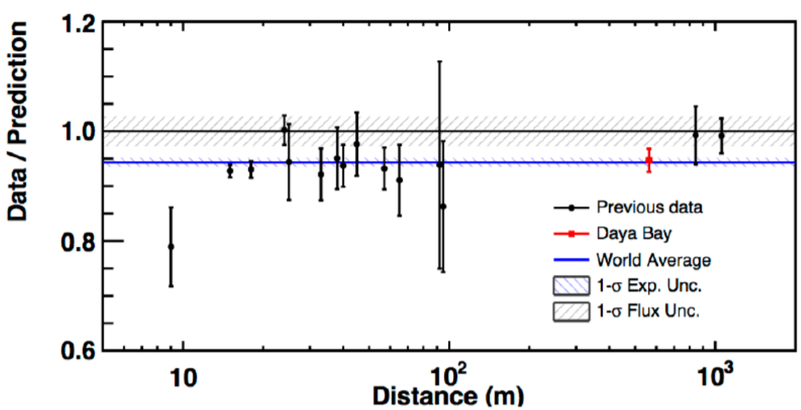


Reactor Antineutrino Flux and Spectrum

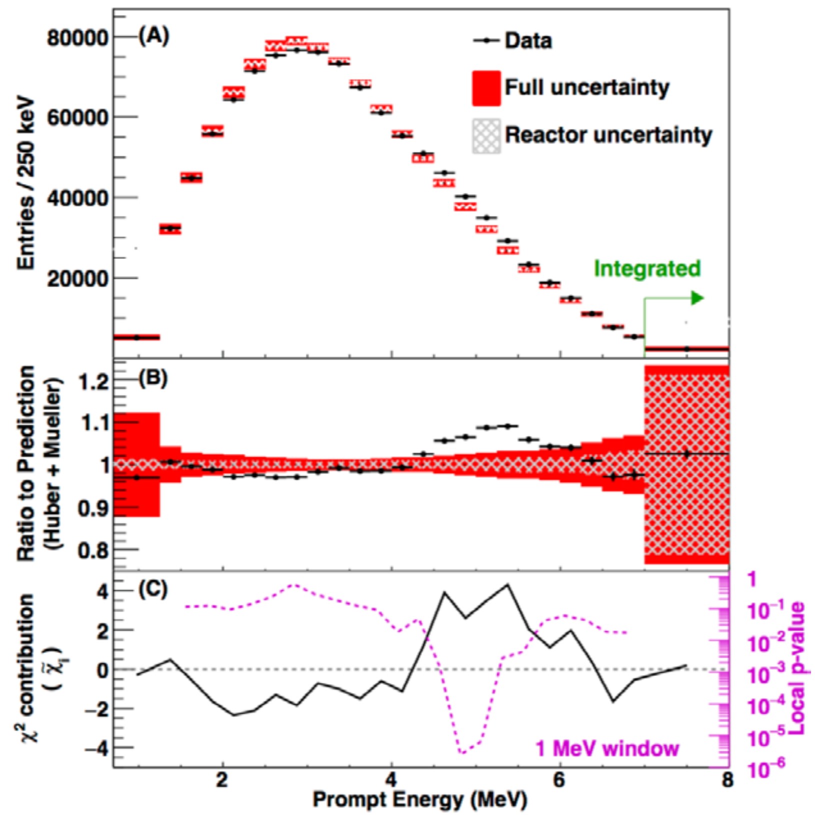
Measurement of IBD yield is consistent with other short baseline reactor experiments



R (Huber+Mueller)	0.946 ± 0.020 (exp.)
R (ILL+Vogel)	0.992 ± 0.021 (exp.)



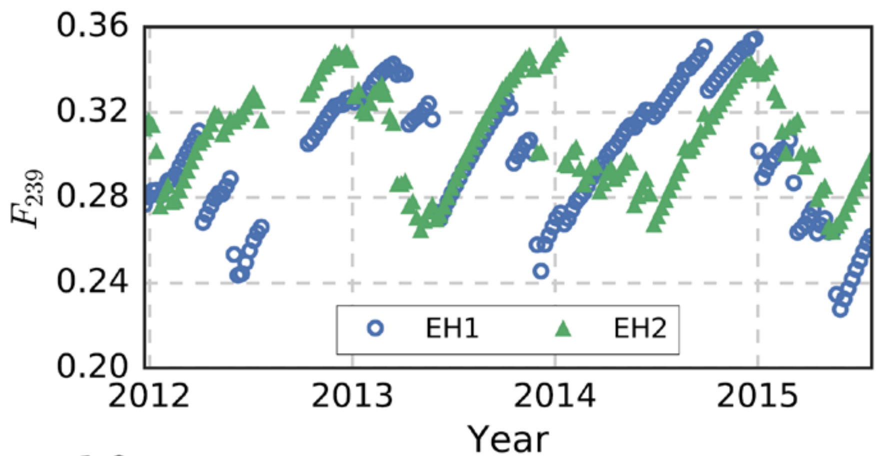
Comparison between the measured spectrum Shape with Huber+Mueller shows a 2.9 σ discrepancy overall(4.4 σ in the 4-6 MeV)

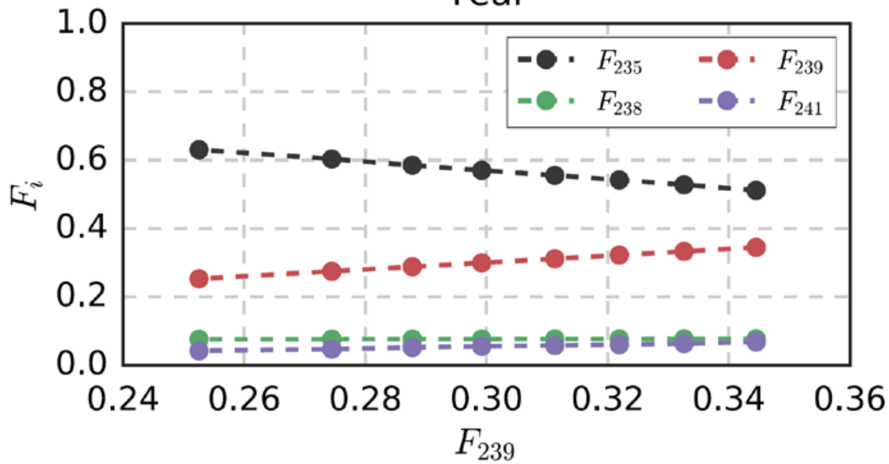


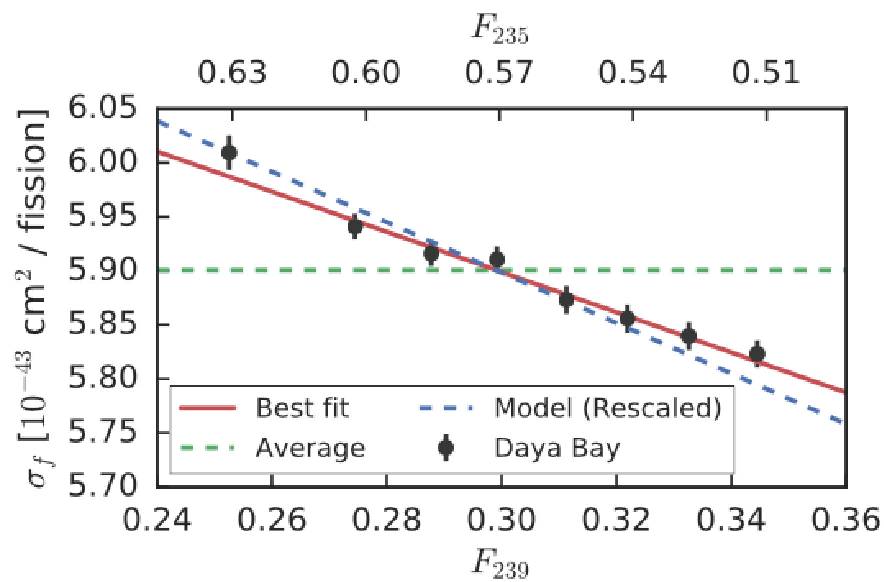
Chin. Phys. C 41, 13002(2017)

Evolution of Reactor $\overline{\nu}_e$ Flux and Spectrum

Fuel evolution are measured in effective fission fraction of F_i





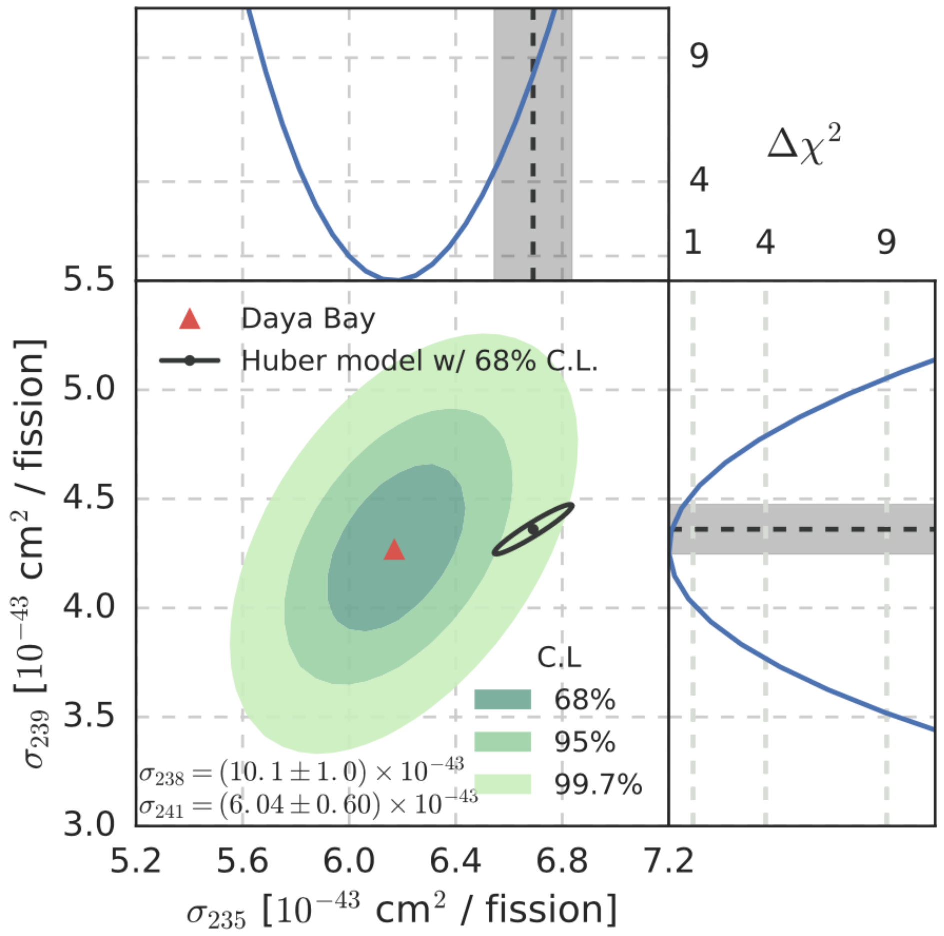


- Clear correlation between $\overline{\nu}_e$ yield and fuel evolution
- **inconsistent with Huber+Muller model at 3 σ, indicating non-equal fractional deficit of the 4 isotopes , that resulting to the overall measured flux deficit compared with theory prediction**

Phys. Rev. Lett. 118, 251801(2017)

Evolution of Reactor $\overline{\nu}_e$ Flux and Spectrum

- Extracted the individual yield for the two dominant isotopes(^{235}U, ^{239}Pu) using constraints from two minor ones (^{238}U,^{241}Pu)
- Identified ^{235}U as the primary source for the reactor anomaly
- Disfavored equal deficit of all isotopes at 2.8 σ
- Evolution of spectrum is in good agreement with Huber-Mueller model and shows no abnormalities at 4-6 MeV

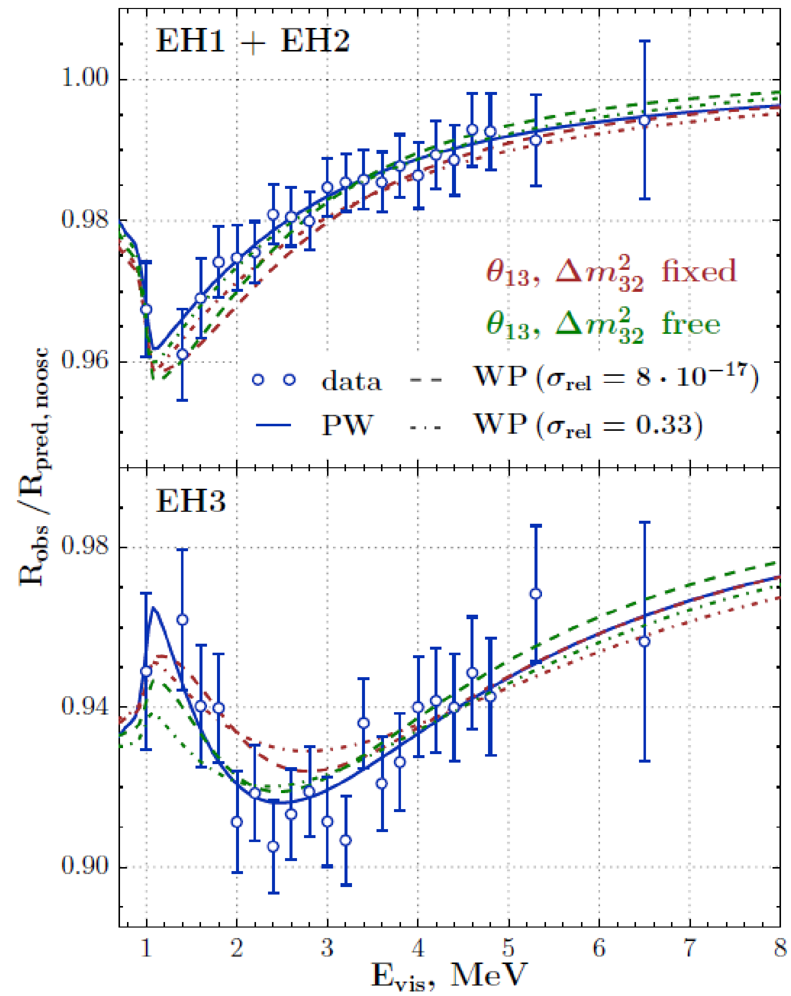


Phys. Rev. Lett. 118, 251801(2017)

Search for Neutrino Decoherence

- Neutrino planewave approximation:
    - Flavor state is the coherence supposition of the mass states
    - Not self-consistant, even though successful in explaining most experimental results
- In the wave package treatment frame work, where neutrino momentum is described by a Gaussian wave-packet, the oscillation probability depends on one additional parameter: relative intrinsic momentum dispersion σ_{rel}
- Provide the first experimental constraints on σ_{rel}

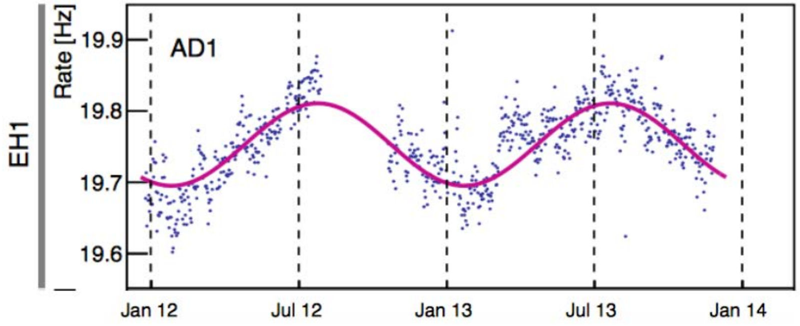
$$10^{-14} \lesssim \sigma_{\rm rel} < 0.23$$

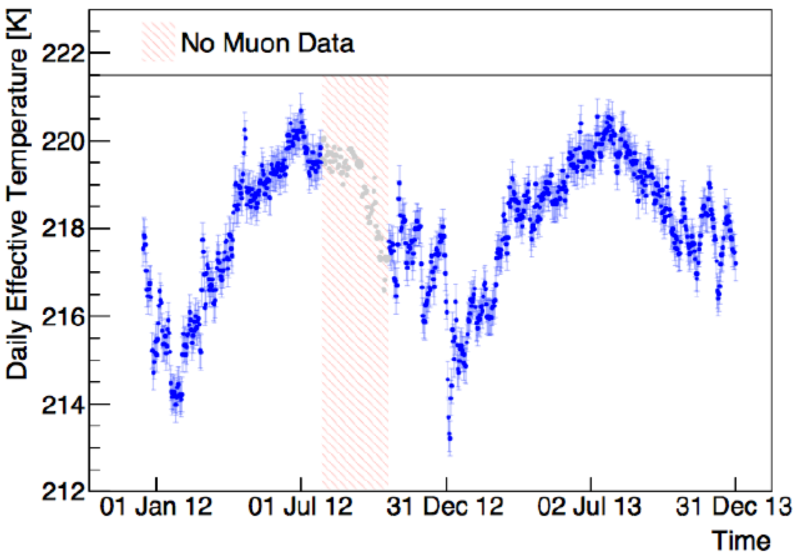


Eur. Phys. C. 77: 606 (2017)

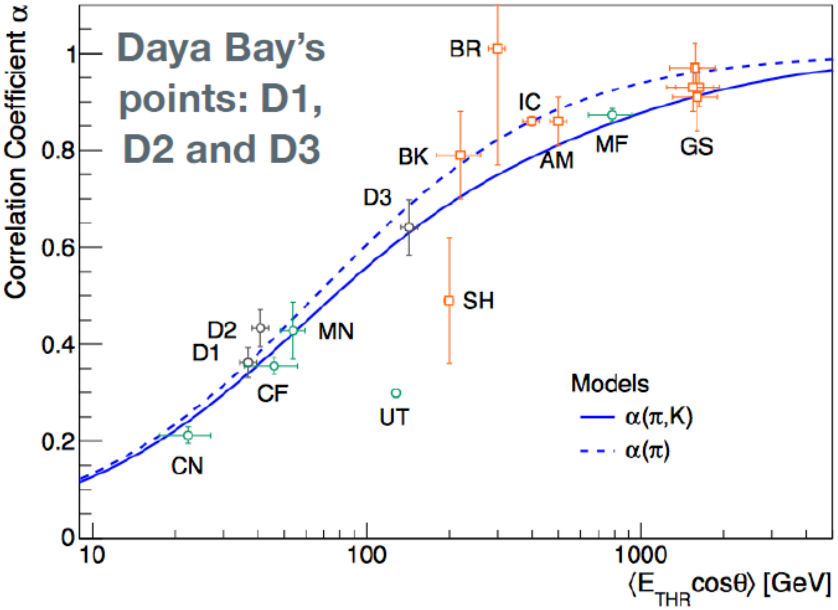
Modulation of Cosmic Muon Flux

- Precise Measurement of the cosmic muon at different overburdens (i.e. average muon energies)
- Observed a clear correlation with the effective atmospheric temperature
    - Less dense atmosphere under higher temperature, lower the mesons' probability of interaction





The measured correlation coefficients is consistent with the model prediction

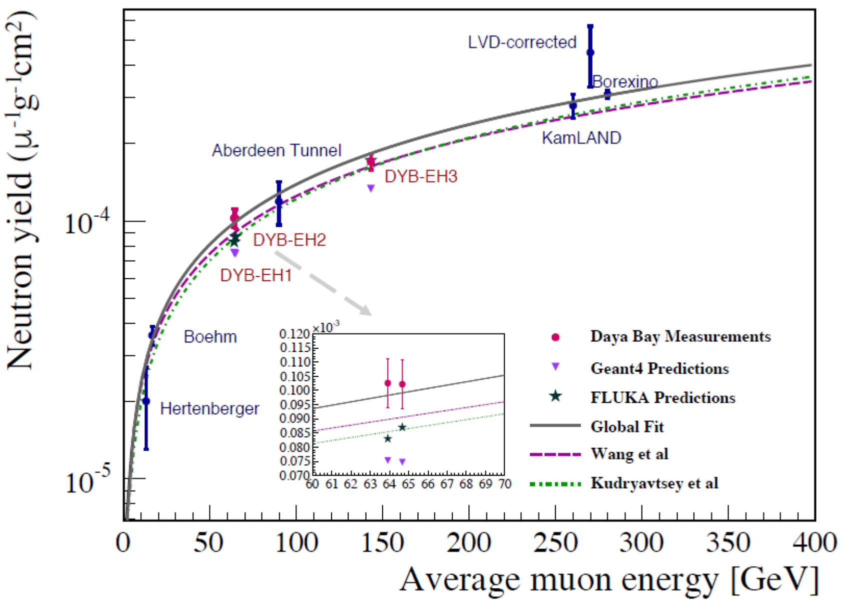


JCAP01(2018)001

Neutron Yield Measurement

- Neutrons produced by cosmic rays are important background in underground experiments
- Measured Neutron yields in the three experimental halls with different overburdens (I.e. different average muon energies)
- Comparison between measurement and MC (Geant4 and Fluka) shows some discrepancies of the MC models

	EH1	EH2	EH3
E^{μ}_{avg} (GeV)	63.9 ±3.8	64.7 ±3.9	143.0 ±8.6
Measured Values ($\times10^{-5}\mu^{-1}$ g^{-1} cm^{2})			
Y_n	10.26 ±0.86	10.22 ±0.87	17.03 ±1.22
MC Predictions ($\times10^{-5}\mu^{-1}$ g^{-1} cm^{2})			
Y_n (GEANT4)	7.53 ±0.01	7.47 ± 0.05	13.35 ± 0.03
Y_n (FLUKA)	8.34 ±0.02	8.70 ±0.03	17.15 ±0.04

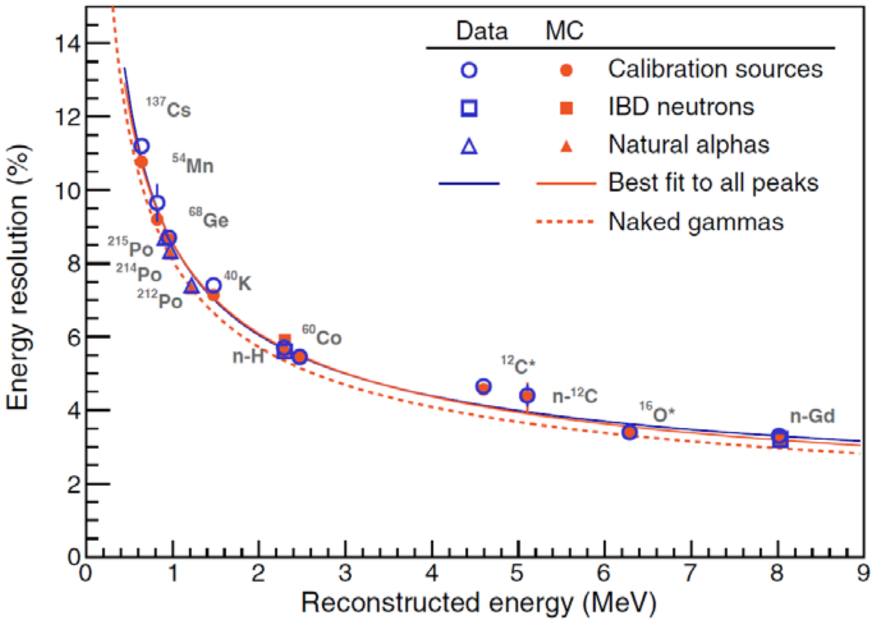


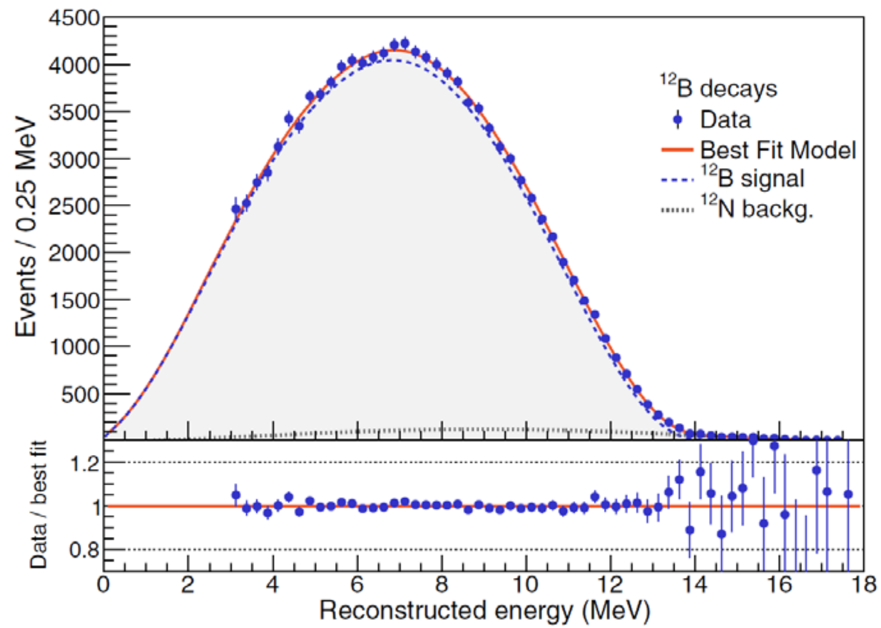
Summary & Outlook

- Updated many results :
  - the most precise measurement of $\sin^2 2\theta_{13}$: 3.9 %
  - the most precise measurement of $|\Delta m^2_{ee}|$: 3.4%
  - Independent nH oscillation analysis, high-statistic absolute reactor antineutrino flux and shape measurement, fuel evolution, searchers for a sterile neutrino…
- Continue to run till 2020
  - Efforts to further reduce the systematics :
    - A FADC readout system in EH1-AD1
    - Special calibration campaign, ^{40}K calibration
  - Goal is to reduce uncertainties in $\sin^2 2\theta_{13}$ and $|\Delta m^2_{ee}|$< 3%
  - Updated results will coming soon, stay tuned!

BACKUP

Energy Model





$$\frac{\sigma_E}{E_{rec}} = \sqrt{a^2 + \frac{b^2}{E} + \frac{c^2}{E^2}},\ a = 0.016, b = 0.081\ MeV^{\frac{1}{2}}, \text{ and c=0.026 MeV}$$

Scintillator quenching is described by Berk's constant and Cherenkov radiation fraction

Electronics nonlinearity is model using two parameters for amplitude and energy dependency.

Parameters were obtained by various calibration data and ^{12}B beta-decay spectrum,validated with the 53MeV endpoint of the Michel electron spectrum of muon decay, the continuous β+γ spectra from natural bismuth and thallium decays.