Latest results from Daya Bay

Wenqiang Gu

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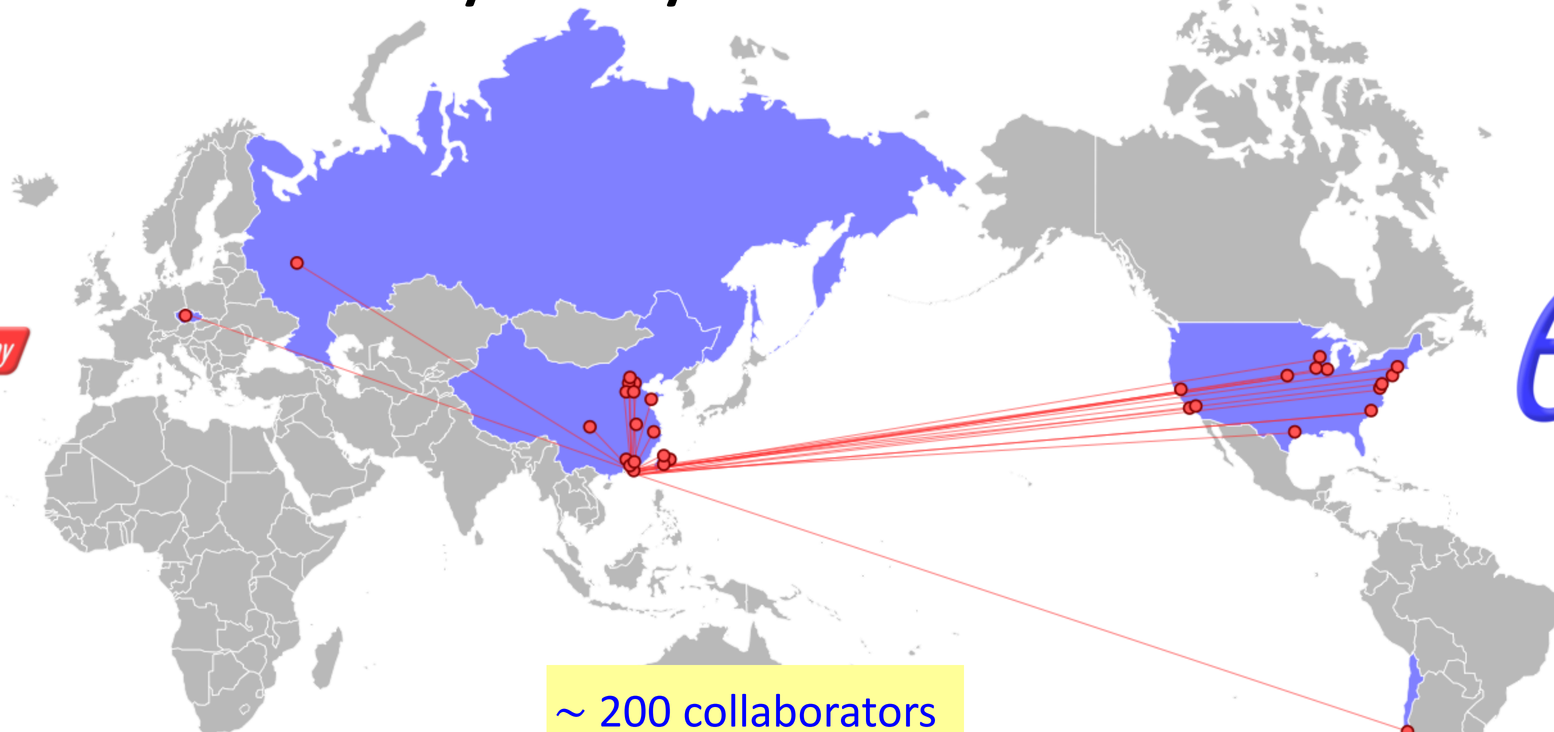
On behalf of the Daya Bay Collaboration

Outline

- The Daya Bay Experiment
- New oscillation measurement
  - ~ 4 million $\bar{\nu}_e$'s
- Improved measurement of reactor $\bar{\nu}_e$ flux
  - Neutron calibration campaign
- Search for a time-varying electron $\bar{\nu}_e$ signal
- Summary

The Daya Bay Collaboration



Asia (23)

Beijing Normal Univ., CGNPG, CIAE, Chongqing 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.

Europe (2)

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

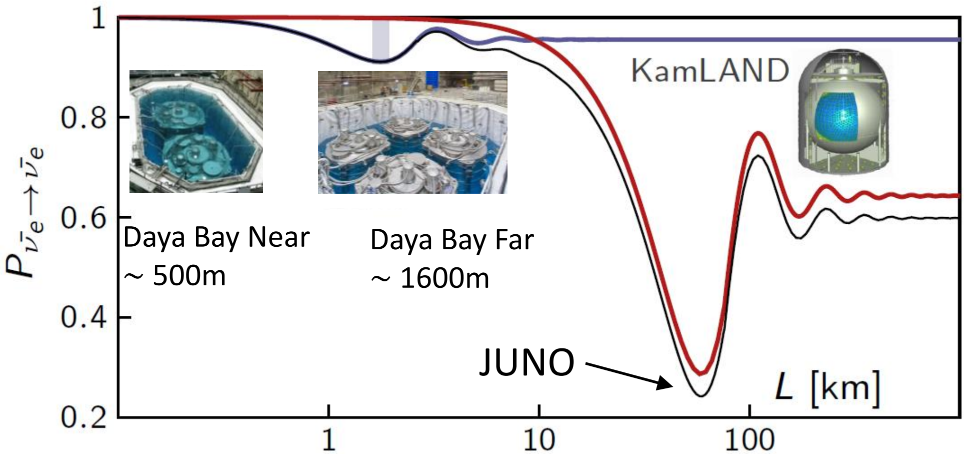
South America (1)

Catholic University of Chile

Reactor Neutrino Oscillation

$$P_{\overline{\nu}_e \to \overline{\nu}_e} \approx 1 - \sin^2 2\theta_{13} \sin^2 \Delta m^2_{ee} \frac{L}{4E} - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta m^2_{21} \frac{L}{4E}$$

- Keys to a precise measurement
  - High-statistics
  - Suppressing backgrounds
  - Systematics control

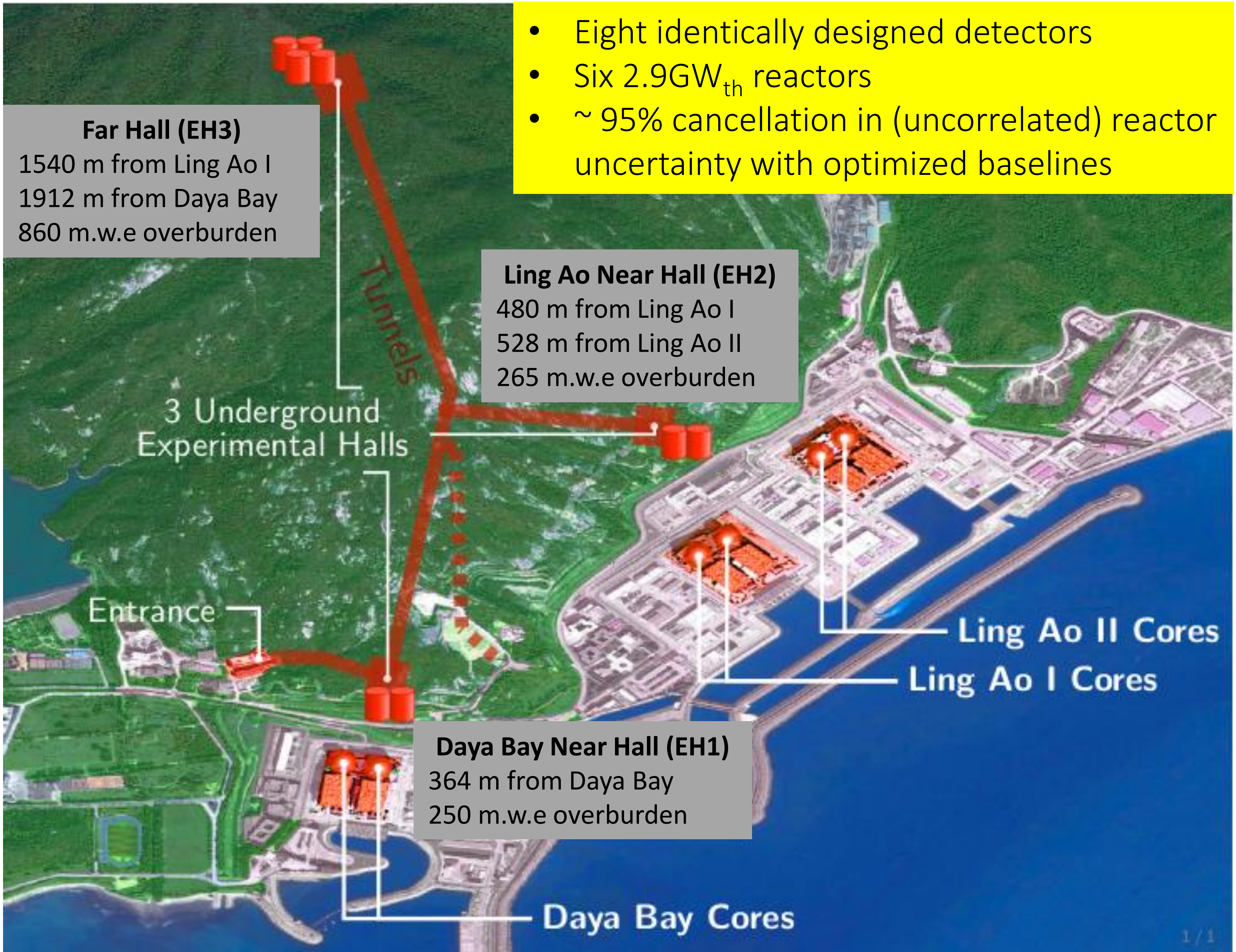


Relative measurement with 8 functionally identical detectors

- Absolute neutrino flux: significant uncertainty in previous experiments (e.g., Chooz)

Daya Bay Experimental Layout

- Eight identically designed detectors
- Six 2.9GW_{th} reactors
- ~ 95% cancellation in (uncorrelated) reactor uncertainty with optimized baselines



Antineutrino Detection

- **Inverse β-decay (IBD)**: coincidence of two consecutive signals

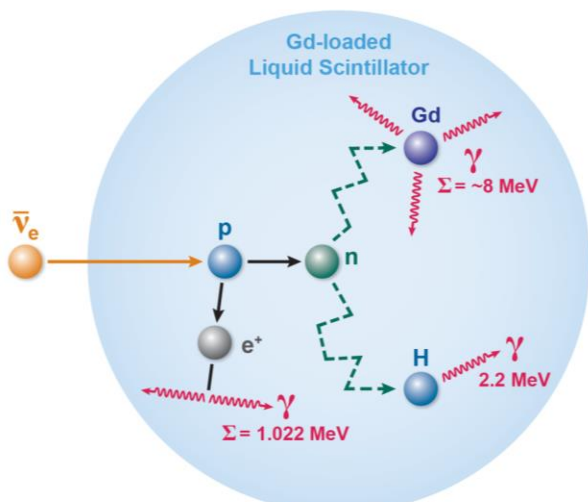
$\bar{\nu}_e$ + p → e^+ + n (prompt signal)

~30μs (0.1% Gd)

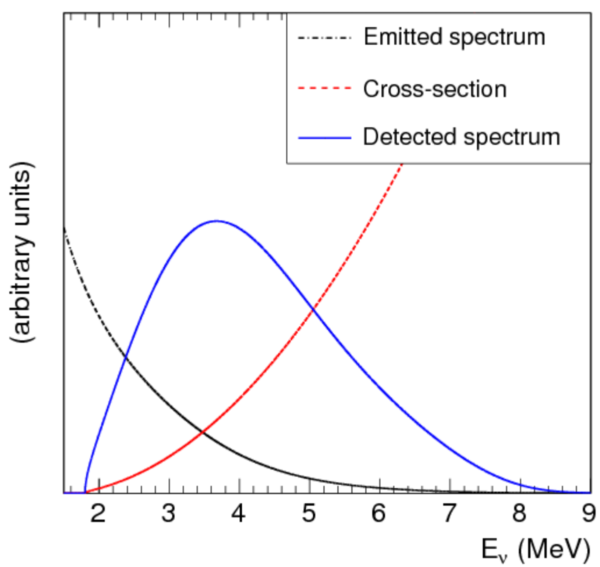
→ + p → D + γ (2.2 MeV) (delayed signal)

→ + Gd → Gd* → Gd + γ's (8 MeV) (delayed signal)

- Powerful background rejection

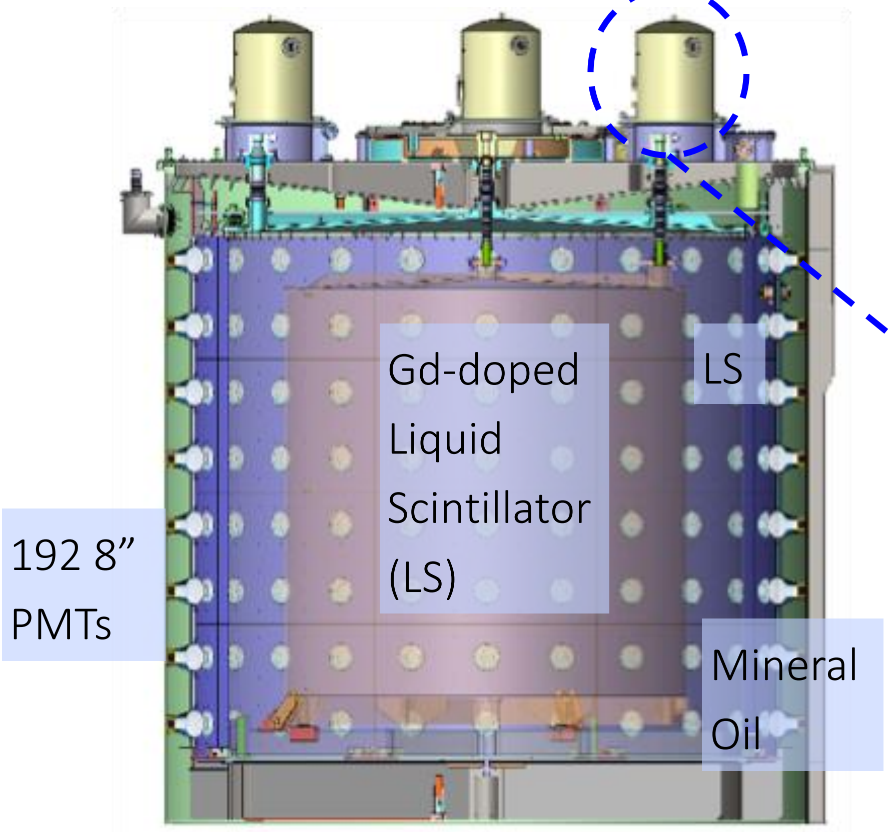


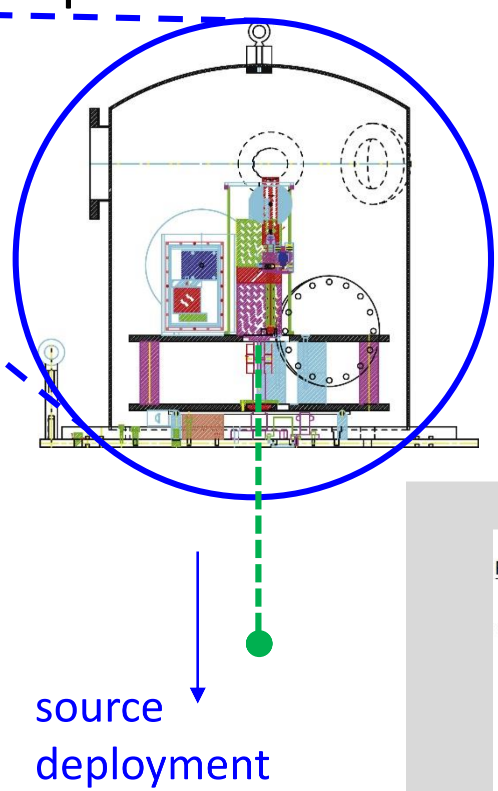
- Positron preserves most information about antineutrino energy



Daya Bay Detectors

- The antineutrino detectors (ADs) are “three-zone” cylindrical modules immersed in water pools





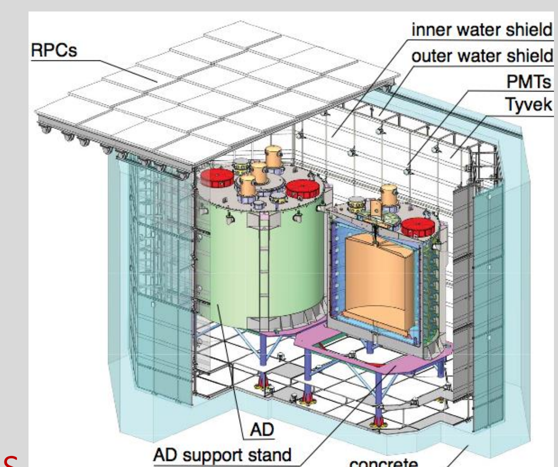
Automated calibration unit (ACU)

NIM A750, 19-37 (2014)

Energy resolution:

$\sigma_E/E \approx 8.5\%/\sqrt{E}$ [MeV]

NIM A 811, 133 (2016)

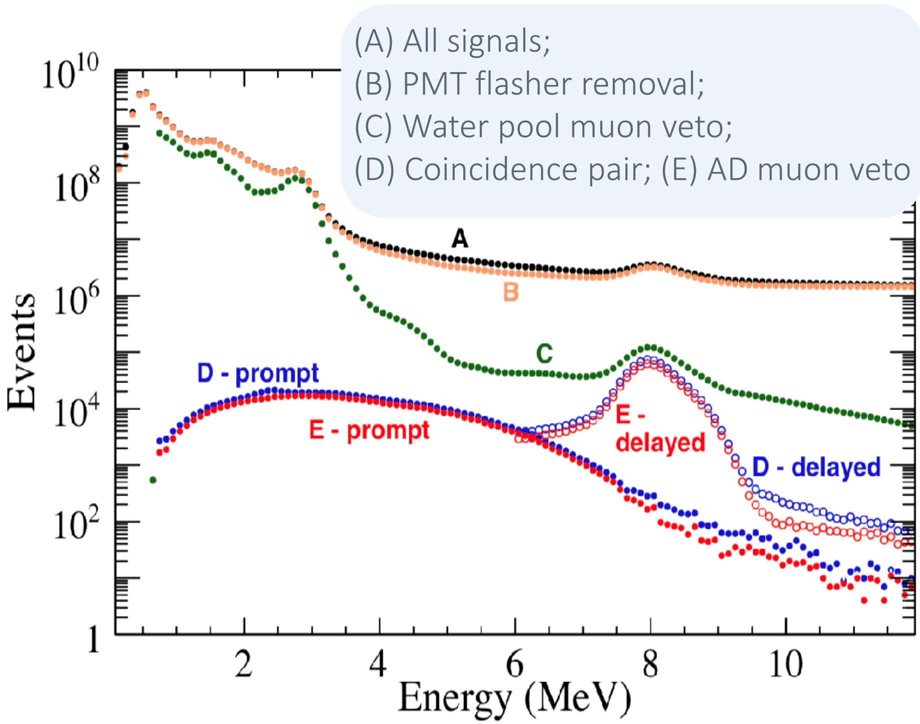


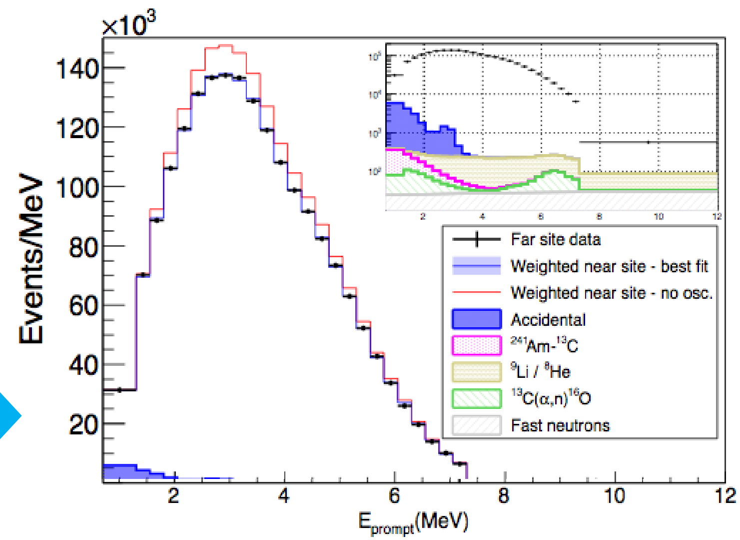
Water pool: shield the ADs and veto cosmic-rays

NIM A 773, 8 (2015)

IBD Selection

- New oscillation result with **1958 days of data**
  - Dec 24, 2011 to Aug 30, 2017





- **< 2% background** in all halls
- Roughly 60% increase in statistics with respect to previous result
- Other important improvements (see next slides)

New Dataset

- Some highlights of the new 1958-day dataset

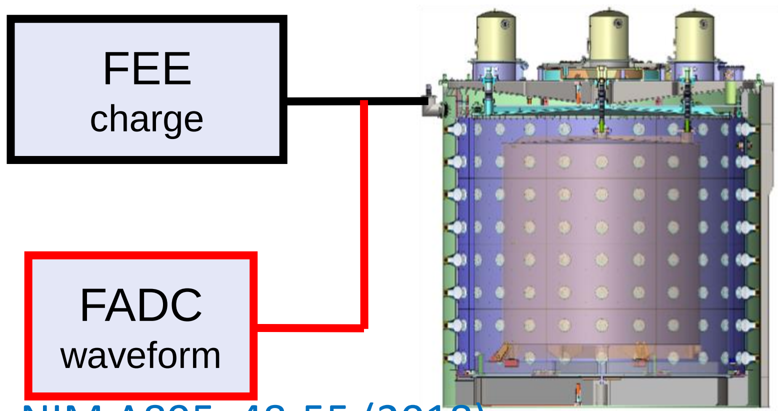
~ 4 million **antineutrino interactions** (0.5 million at far site)

Statistical error in $\bar{\nu}_e$ rates: ~0.11% (near ADs), ~0.29% (far ADs)

Background uncertainty in $\bar{\nu}_e$ rates: ~0.12% (all ADs)

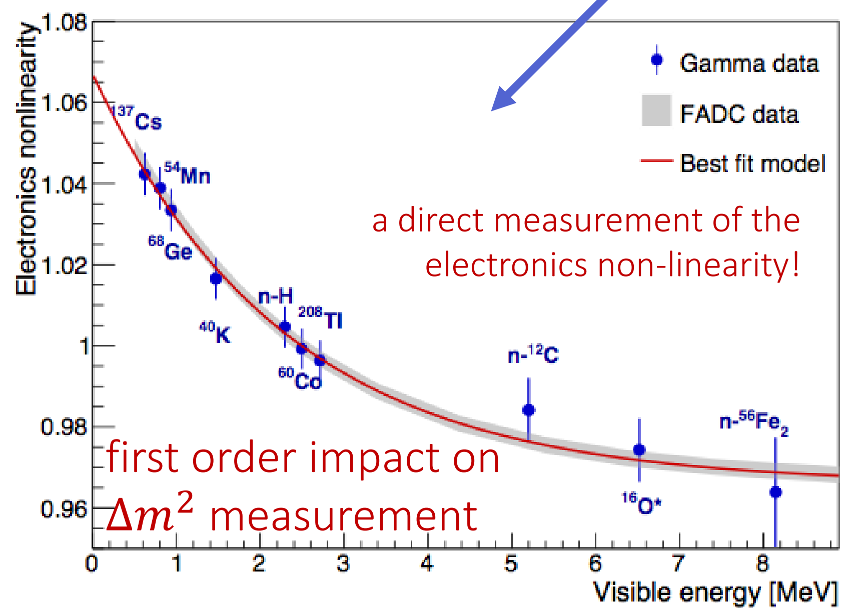
Improved Energy Response Model

- Energy model: reconstructed positron energy to antineutrino energy
- Non-linear energy response:
  - Normal quenching + Cerenkov light in liquid scintillator
  - Response of the electronics
- Carried out two key measurements:
  - End of 2015: installation of a full FADC readout system in EH1-AD1, taking data simultaneously with standard electronics
  - Early 2017: deployment of ^{60}Co calibration sources with different encapsulating materials, to constrain optical shadowing effects



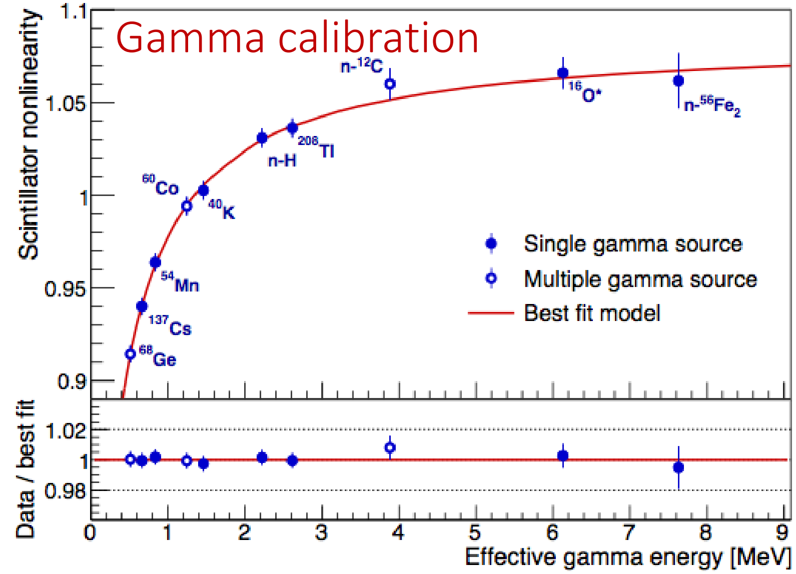
NIM A895, 48-55 (2018)

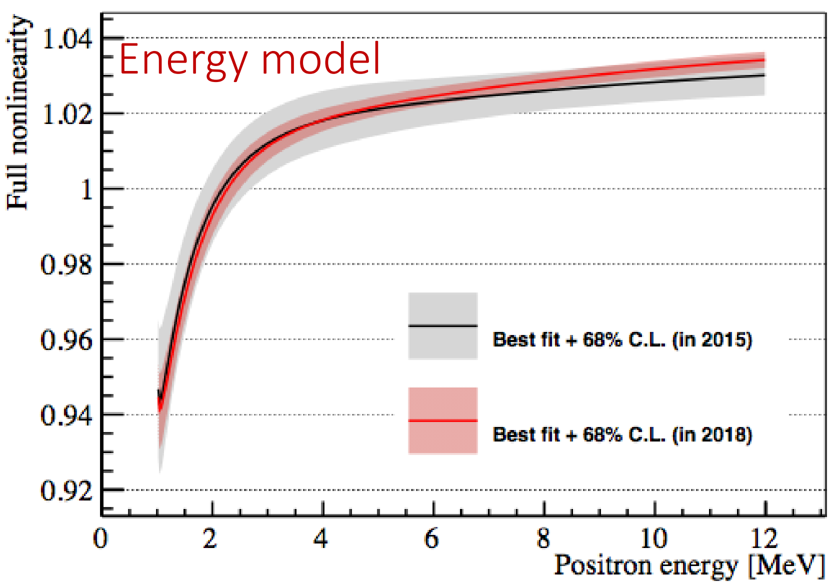
EH1-AD1

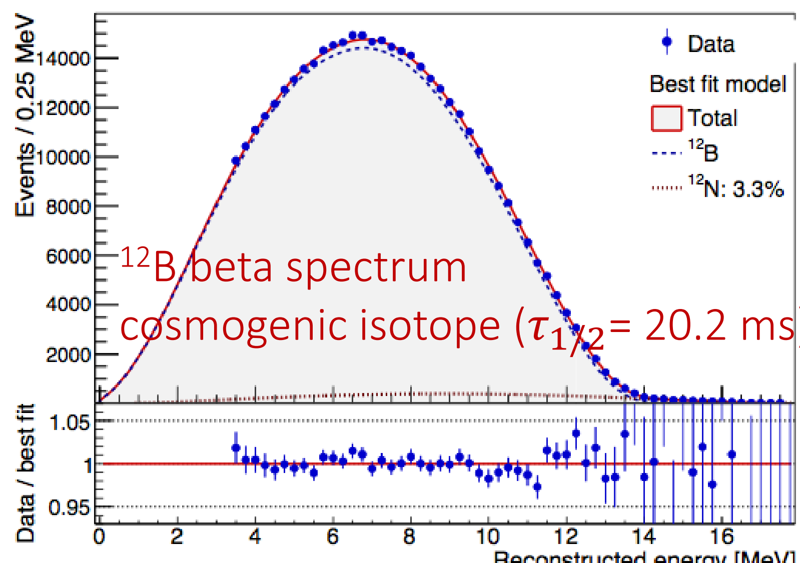


Improved Energy Response Model

- The model is built based on various gamma peaks and the continuous ^{12}B spectrum
  - Validated with low energy β+γ spectra from ^{212}Bi and ^{214}Bi
  - Uncertainty reduced to be **~0.5%** from previous ~1.0%



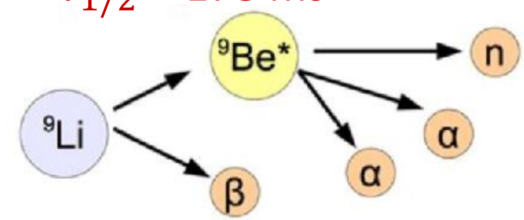




^{12}B beta spectrum
cosmogenic isotope ($\tau_{1/2}$ = 20.2 ms)

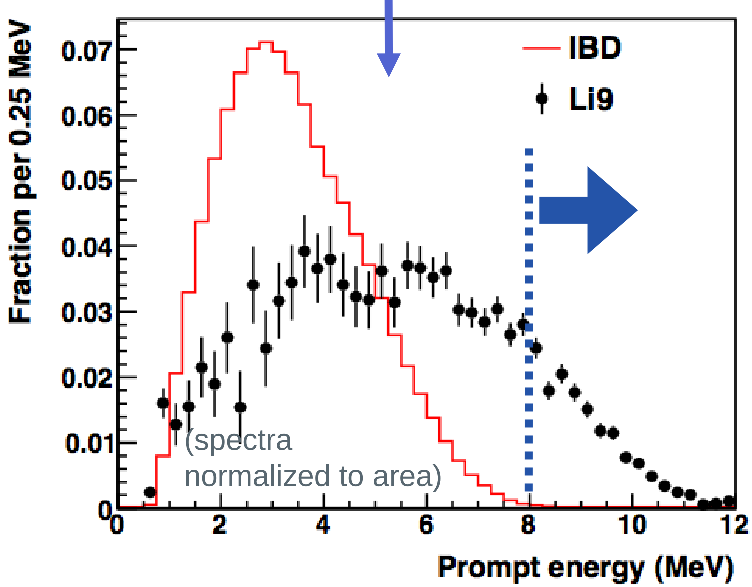
Improved ^{9}Li/^{8}He and SNF Uncertainty

- β-n decays of cosmogenically produced ^{9}Li/^{8}He are indistinguishable from IBD signals of $\bar{\nu}_e$

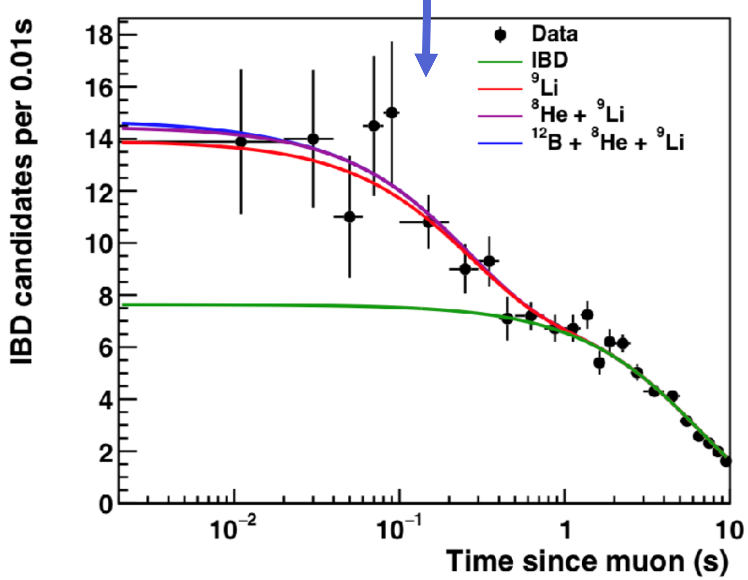


- Now can take advantage of very large statistics:

Apply a large E_{prompt} cut to enhance the ^{9}Li/^{8}He fraction



Fit the time-since-last-muon distribution

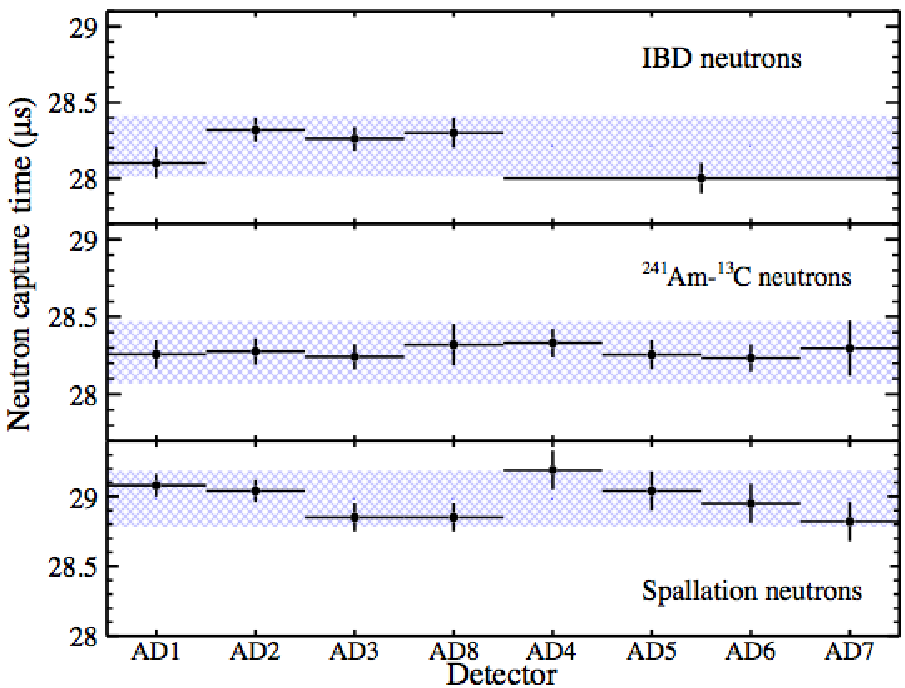


^{9}Li/^{8}He uncertainty in near ADs reduced from 50% to 30%

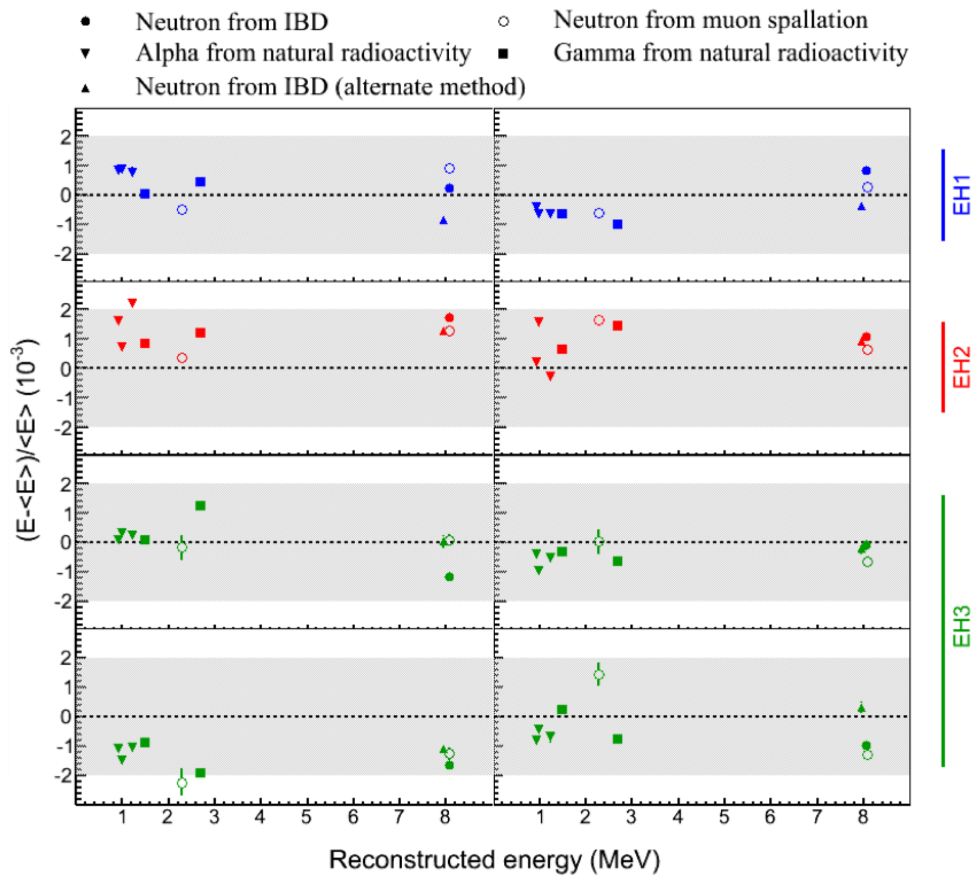
- Also, a review of the spent nuclear fuel (SNF) history with power plant reduced its uncertainty from 100% to 30% (SNF=0.3% of total rate)

Relative Detection Efficiency

- The **relative detection efficiency** uncertainty and the **relative energy scale** uncertainty are the dominant systematics for θ_{13} and $|\Delta m^2_{ee}|$:



Relative Gd capture fraction uncertainty < 0.10%

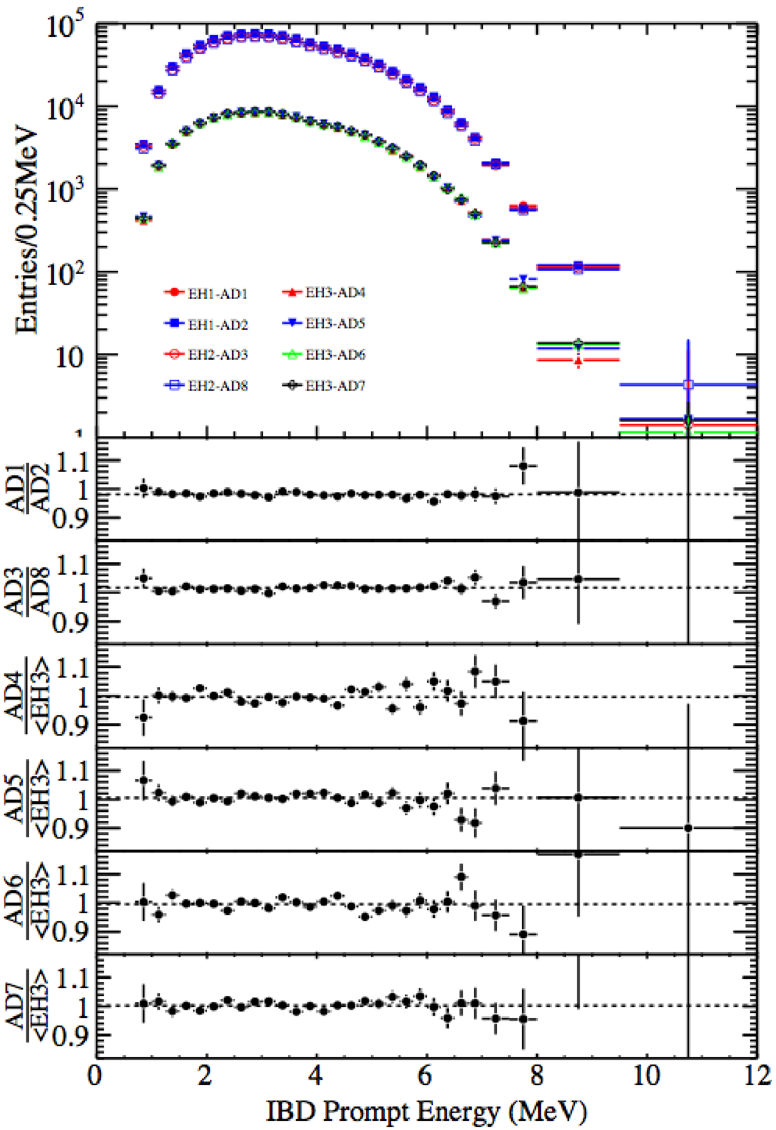


Relative energy scale uncertainty < 0.2%

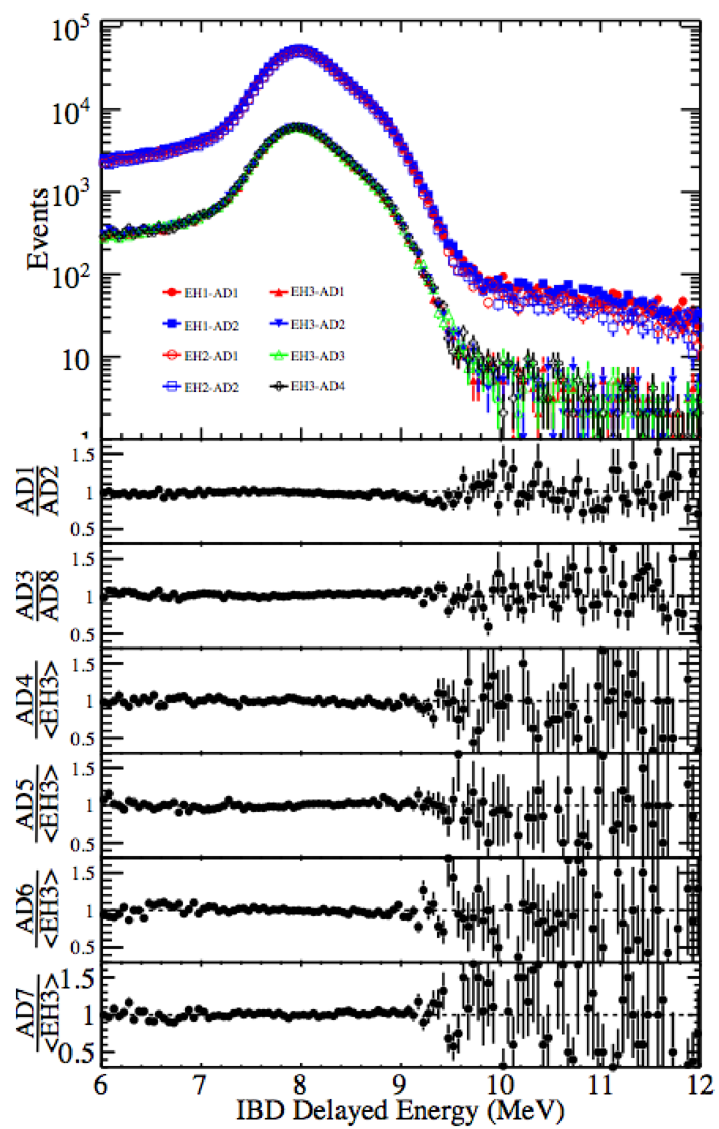
Achieve a relative detection efficiency uncertainty of **0.13%**

Side-by-side Spectral Comparison

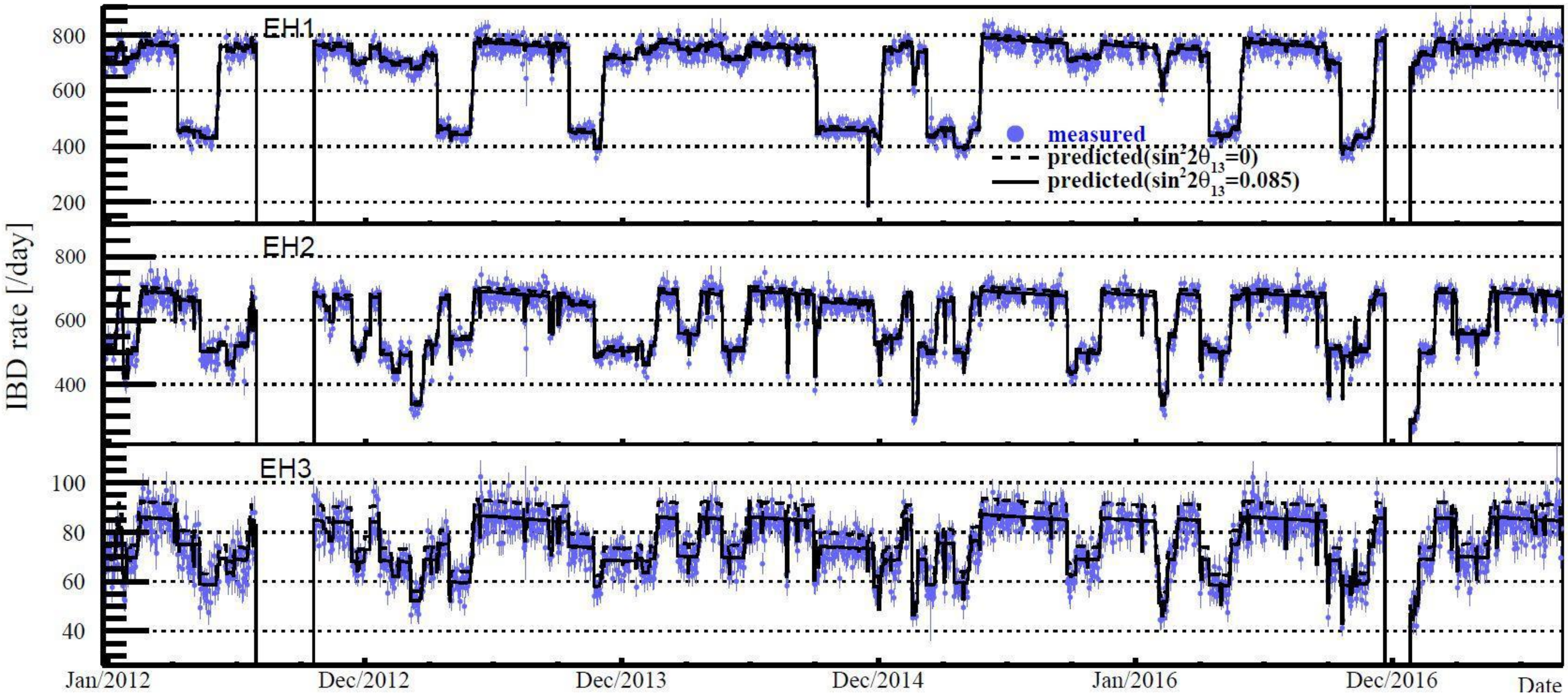
Prompt Spectra



Delayed Spectra



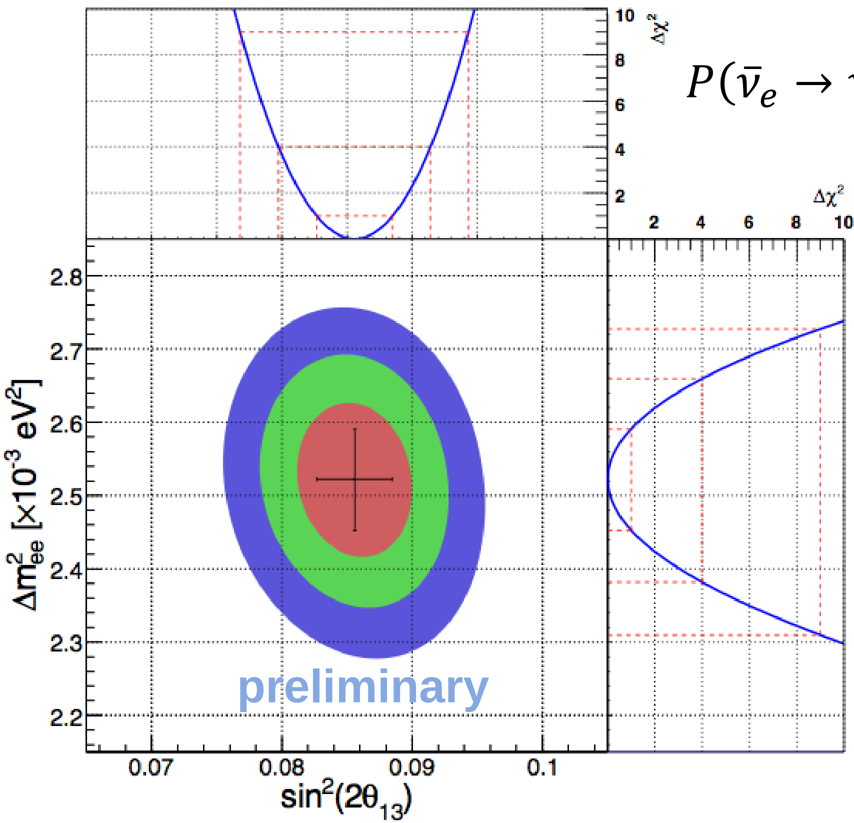
IBD Candidates vs. Real Time

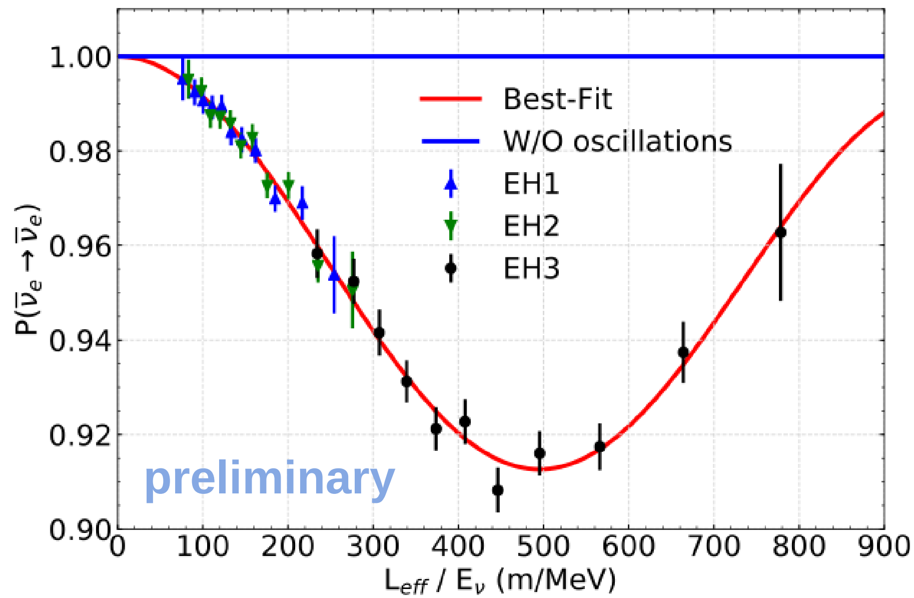


Oscillation Results with 1958 Days

- Measure $\sin^2 2\theta_{13}$ and $|\Delta m^2_{ee}|$ to **3.4%** and **2.8%** respectively

$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{1.267 \Delta m^2_{ee} L}{E} - \text{solar term}$$





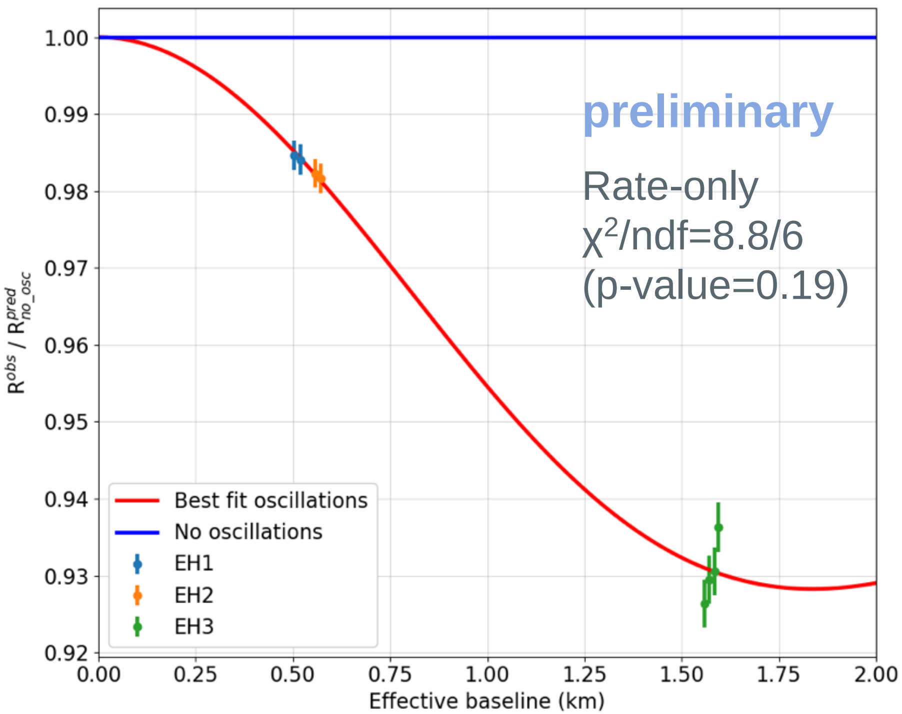
$$\sin^2 2\theta_{13} = 0.0856 \pm 0.0029$$
$$|\Delta m^2_{ee}| = (2.52 \pm 0.07) \times 10^{-3}\ \text{eV}^2$$

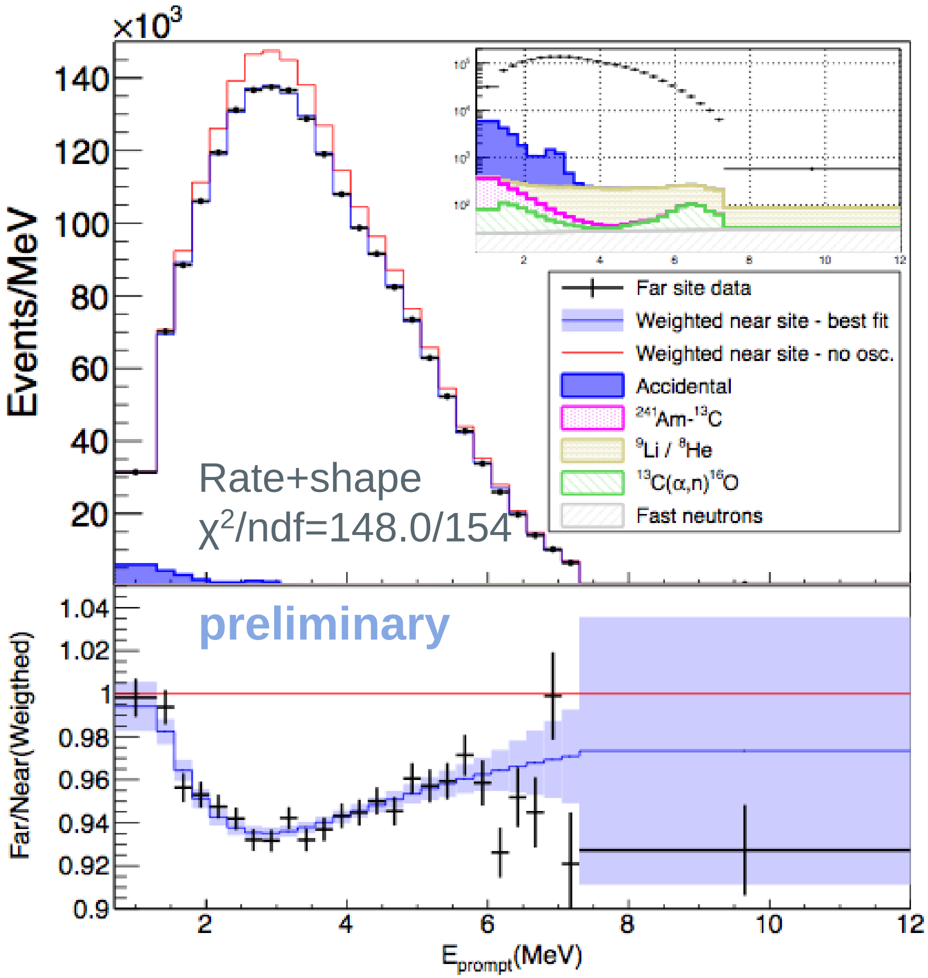
The statistical uncertainty contributes about 60% (50%) of the total θ_{13} (Δm^2_{ee}) uncertainty.

Results are cross-checked by a few independent analyses

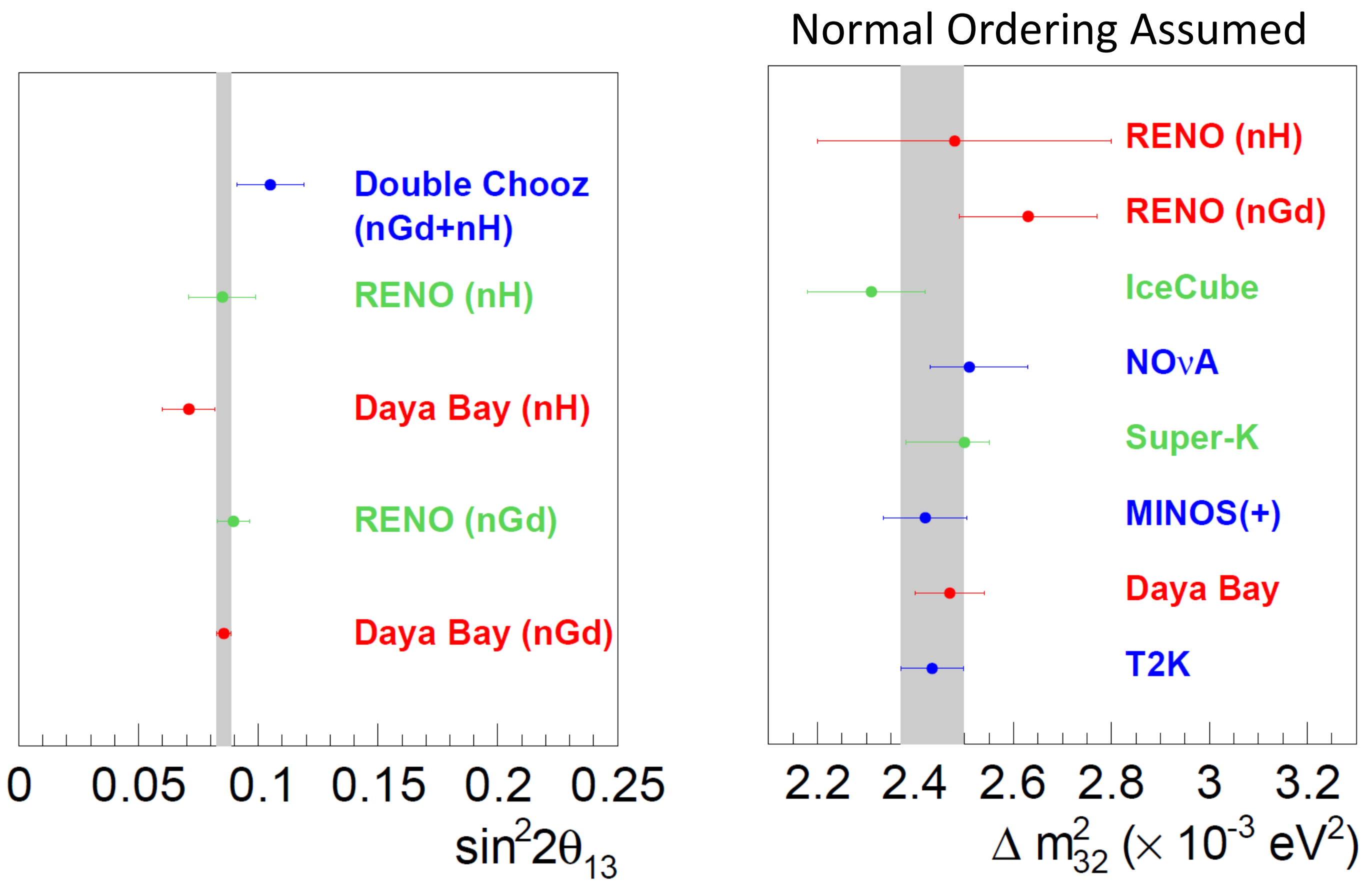
Distortion vs. 3ν Oscillation

- See a clear rate and shape distortion that fits well to the 3-neutrino hypothesis





Global Comparison



- Daya Bay – best precision of θ_{13} in the foreseeable future
- Consistent measurement of Δm^2_{32} between accelerator & reactor experiments

Absolute Antineutrino Flux

- Previous measurement of the absolute reactor $\bar{\nu}_e$ flux compared to the Huber-Mueller expectation

$R_{data/pred} = 0.946 \pm 0.020$ (exp.) ← systematics-dominated from absolute detection efficiency

- New strategy: take new neutron calibration data and use it to constrain the "neutron detection efficiency" ε_n
  - Target: improve the ε_n uncertainty (x2)

previous efficiency values

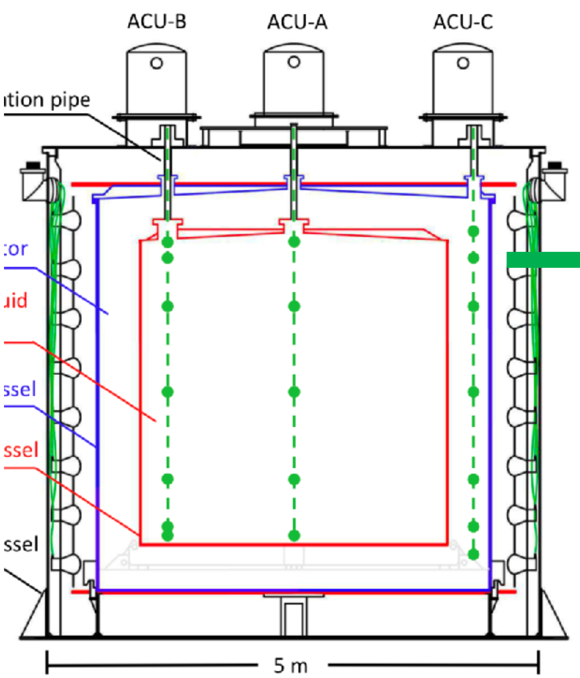
Source	ϵ	$\delta\epsilon/\epsilon$
Target protons	-	**0.92%**
Flasher cut	99.98%	0.01%
Capture time cut	98.70%	0.12%
Prompt energy cut	99.81%	0.10%
Gd capture fraction	84.17%	**0.95%**
nGd detection efficiency	92.7%	**0.97%**
Spill-in correction	104.9%	**1.00%**
Combined	80.6%	1.93%

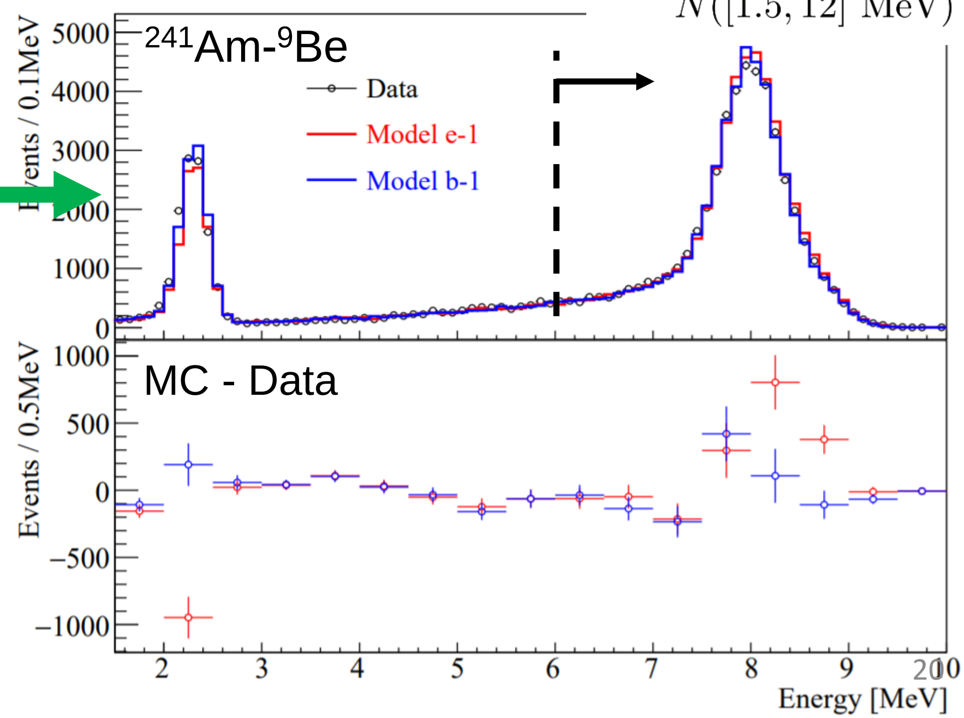
previous
$\varepsilon_n = 81.83 \pm 1.38\%$

Neutron Calibration Campaign

- Extensive neutron calibration campaign in early 2017
- Deployed two neutron sources (^{241}Am-^{13}C and ^{241}Am-^{9}Be) along three vertical calibration axes
- For each calibration point define a proxy for ε_n

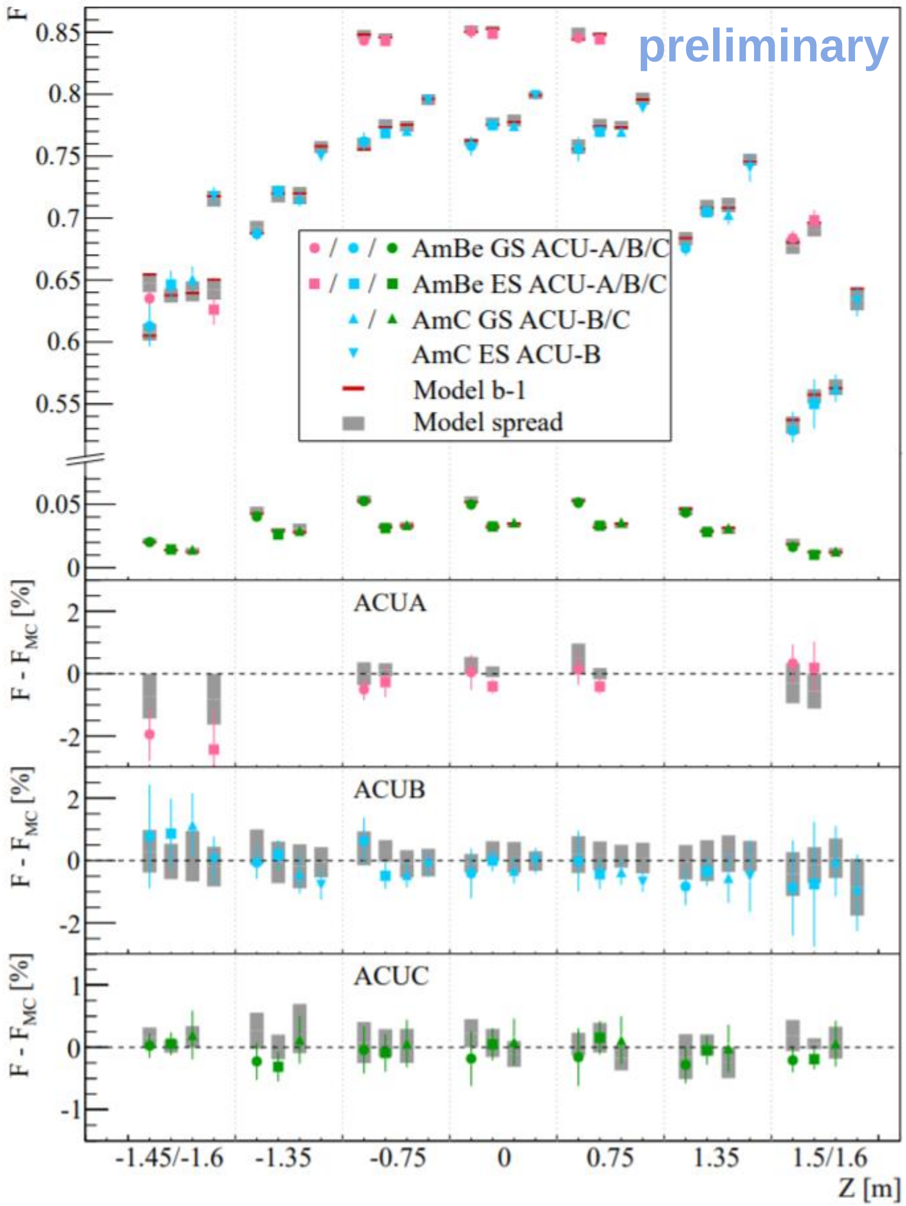
$$F = \frac{N([6, 12]\ \mathrm{MeV})}{N([1.5, 12]\ \mathrm{MeV})}$$





[NIM A750, 19-37 (2014)]
[NIM A797, 260–264 (2015)]

Neutron Calibration Campaign



- 59 calibration points
  - AmC, AmBe in ground state and excited state (n+γ)
  - ACU-A, B, C

$$F = \frac{N([6,12]\ \mathrm{MeV})}{N([1.5,12]\ \mathrm{MeV})}$$

- Vast change from F= 85% to 1%

- Visited 20 different simulation models (5 neutron scattering × 4 Gd capture gamma emission models)
- Best model: sub-1% agreement with data
- Residual differences mostly covered by model span (gray bar)

Improved Absolute Antineutrino Flux

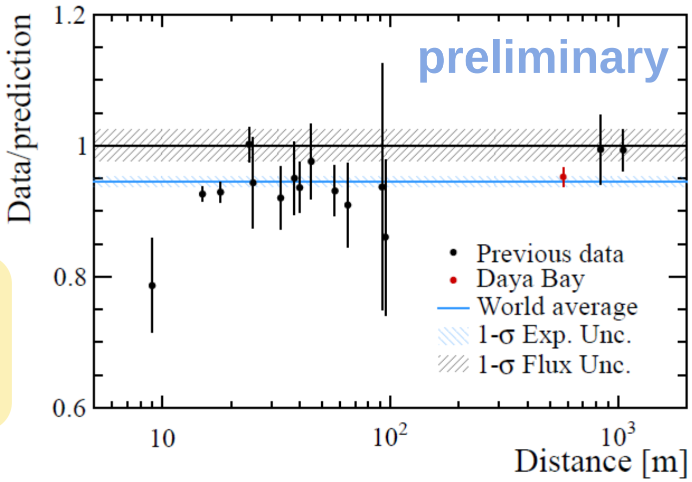
- The ε_n estimated by
  - MC simulation of best-fit model
  - A correction obtained from a linear regression analysis of the remaining data-MC difference
- Uncertainty estimated with spread of models

$$\varepsilon_{\mathrm{n}} = (81.48 \pm 0.60)\%$$

Target achieved: uncertainty improved by a factor of 2

results with 1230 days

$$R_{\mathrm{data/pred}}\ (\text{Huber-Mueller}) = 0.952 \pm 0.014(\text{exp.})$$
$$\sigma_f = (5.91 \pm 0.09) \times 10^{-43}\mathrm{cm}^2/\text{fission}$$



Flux model: Anna Hayes talk at N'18

Search for Time-Varying Antineutrino Signal

- Performed a search for a time-varying $\bar{\nu}_e$ signal over 704 calendar days
  - Motivated by Lorentz and CPT violation [PRD 80, 076007 (2009)]
  - No significant periodic signal for periods ranging from two hours to nearly two years

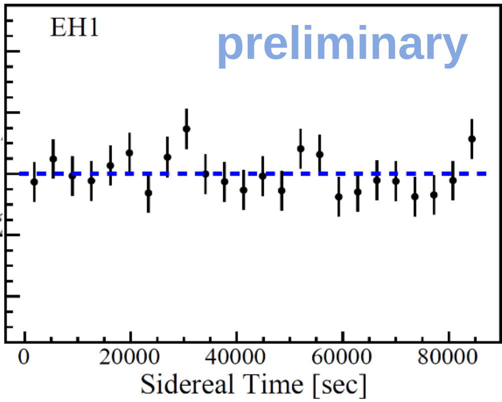
- Unique layout of multiple directions and high-statistics
  - Simultaneous constraint of individual Standard-Model Extension (SME) coefficients

$$P(t) \propto L\left[(\mathcal{C})_{\bar{e}\bar{d}} + (\mathcal{A}_s)_{\bar{e}\bar{d}} \sin\omega_\oplus T_\oplus + (\mathcal{A}_c)_{\bar{e}\bar{d}} \cos\omega_\oplus T_\oplus + \ \ldots\right.$$

$$(\mathcal{A}_s)_{\bar{e}\bar{d}} = \hat{N}^Y (a_R)^X_{\bar{e}\bar{d}} - \hat{N}^X (a_R)^Y_{\bar{e}\bar{d}} + E\{-2\hat{N}^Y (c_R)^{TX}_{\bar{e}\bar{d}} + 2\hat{N}^X (c_R)^{TY}_{\bar{e}\bar{d}} + 2\hat{N}^Y \hat{N}^Z (c_R)^{XZ}_{\bar{e}\bar{d}} - \ldots$$

energy

direction



Outlook

- Daya Bay plans to run until 2020
  - Will achieve < 3% precision in $\sin^2 2\theta_{13}$

- After the special calibration campaign in early 2017, EH1-AD1 has been used only for studying JUNO LS
  - Purification methods, different LS recipes, etc.
  - Studying energy scale and resolution
  - See JUNO talks from Xuefeng Ding and Yuekun Heng

Summary

- Daya Bay has three new results this summer:

new oscillation results with 1958 days

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

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

$$|\Delta m^2_{32}| = (2.47 \pm 0.07) \times 10^{-3}\ \mathrm{eV}^2\ \text{(NH)}$$

Articles in preparation

absolute reactor antineutrino flux (wrt Huber+Mueller) with 1230 days

$$R_{\mathrm{data/pred}} = 0.952 \pm 0.014(\mathrm{exp.})$$

  - Set limits on the Lorentz and CPT violation under SME framework with a time-varying search

- We also have many other recent results in other areas

We encourage you to look at the Daya Bay poster from Shengchao Li

Backup

	Physics analysis published date	Detector status
2011	AD 1/2 comparison	2 EH1 ADs start data taking in Aug. 2+1+3 ADs start data taking in Dec.
2012	March, First 5σ θ_{13}, rate only, 55d	Calibration campaign in Jun. 2+2+4 ADs start data taking in Oct.
2013	Improved θ_{13} (9σ), rate only, 139d	
2014	Spectral analysis (θ_{13} and Δm^2), 217d nH rate analysis, 217d Sterile neutrino, 217d	
2015	Full 8AD oscillation analysis, 621d	AD1 Flash-ADC upgrade in Dec.
2016	Reactor flux & spectrum, 217d Improved nH, 621d Improved sterile nu, 621d Combined sterile with MINOS, 621d	
2017	Long reactor paper, 621d Long osc. paper, 1230d Fuel evolution, 1230d	Calibration campaign in Jan. AD1 taken out for LS study in Jan.
2018	Muon flux variation Cosmogenic neutron production Long osc. Paper, 1958d (in preparation) New reactor flux, 1230d (in preparation) Time-varying antineutrino signal (in preparation)	

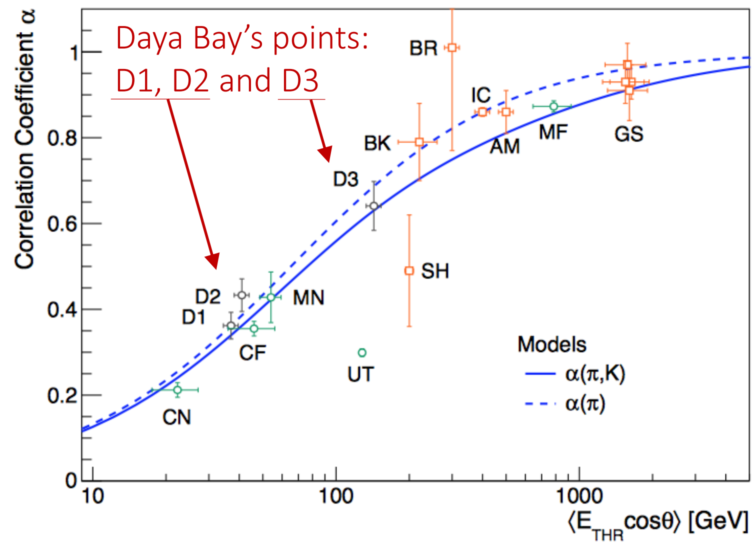
Cosmic-Ray Results from Daya Bay

- Two cosmic-ray results from Daya Bay were released recently

Seasonal Variation of the Underground Cosmic Muon Flux

Observe a clear correlation between atmospheric temperature and variations in muon flux

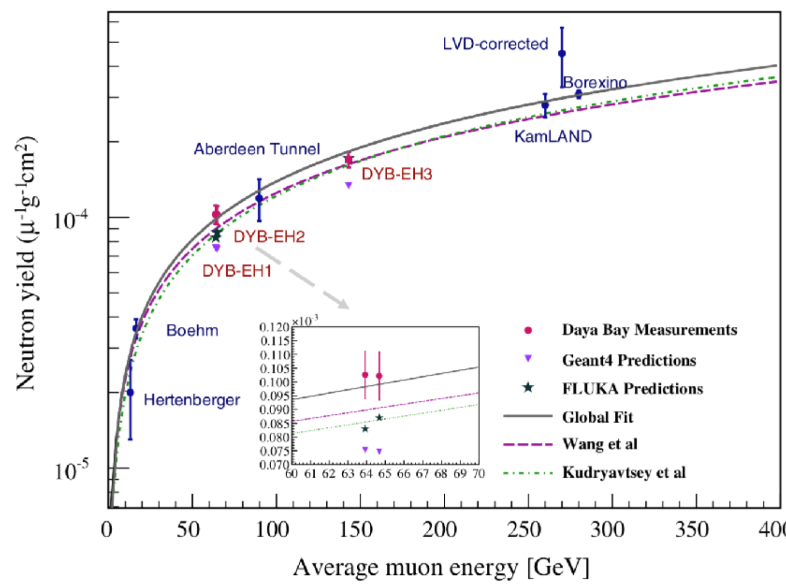
JCAP 01 (2018) 001



Cosmogenic neutron production at Daya Bay

Measurement of neutron yield in LS. Important input for underground experiments.

Phys. Rev. D97, 052009 (2018)

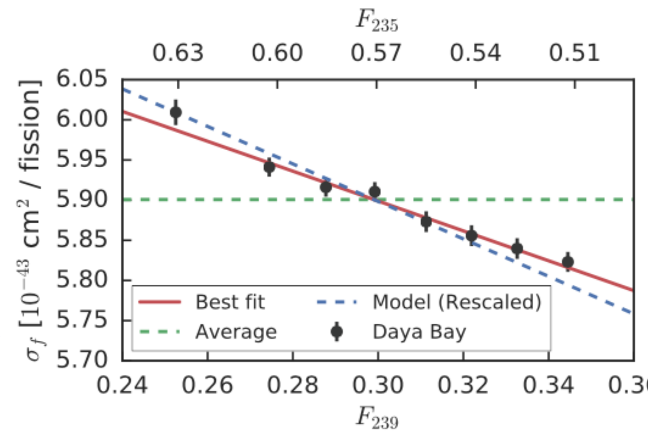


Other Results

- Finally, there are also other older results:

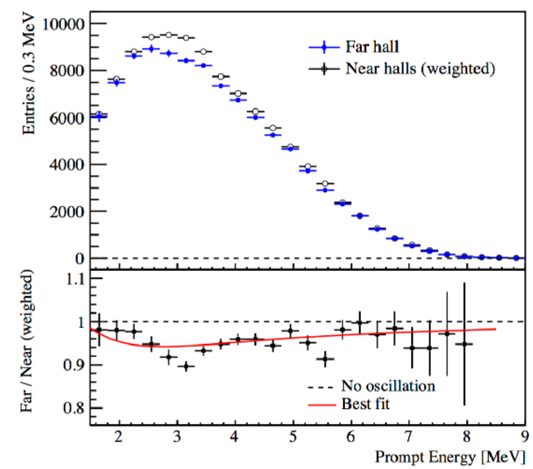
Evolution of the Reactor Antineutrino Flux and Spectrum

Phys. Rev. Lett. 182, 251801 (2017)



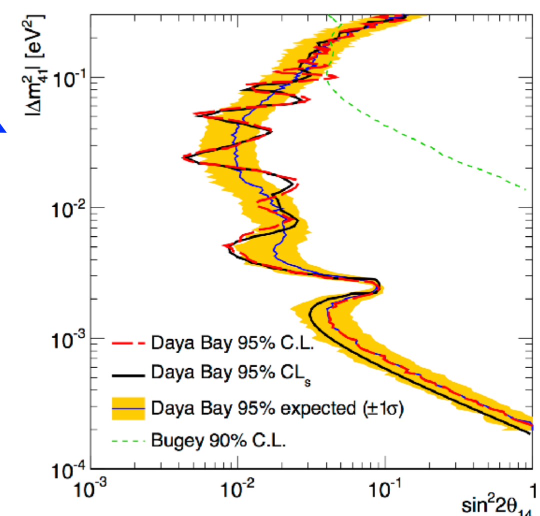
Independent measurement of θ13 via neutron capture on hydrogen

Phys. Rev. D93, 072011 (2016)



Improved search for a sterile neutrino (with Bugey-3 + MINOS)

Phys. Rev. Lett. 117, 151802 (2016)
Phys. Rev. Lett. 117, 151801 (2016)

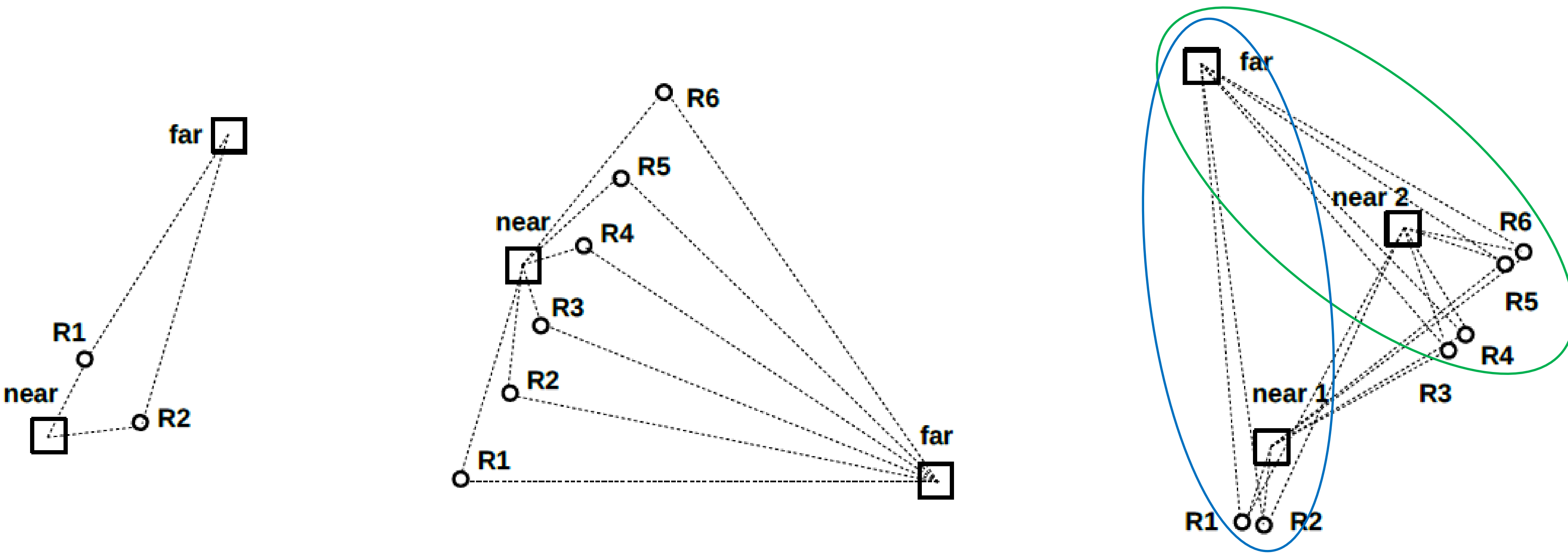


Search for neutrino decoherence

Eur. Phys. J. C77, 606 (2017)

Near/Far Ratio

- 100% cancellation of flux uncertainty with one reactor, one near and one far detector



Double Chooz
~88% suppression of systematic uncertainties

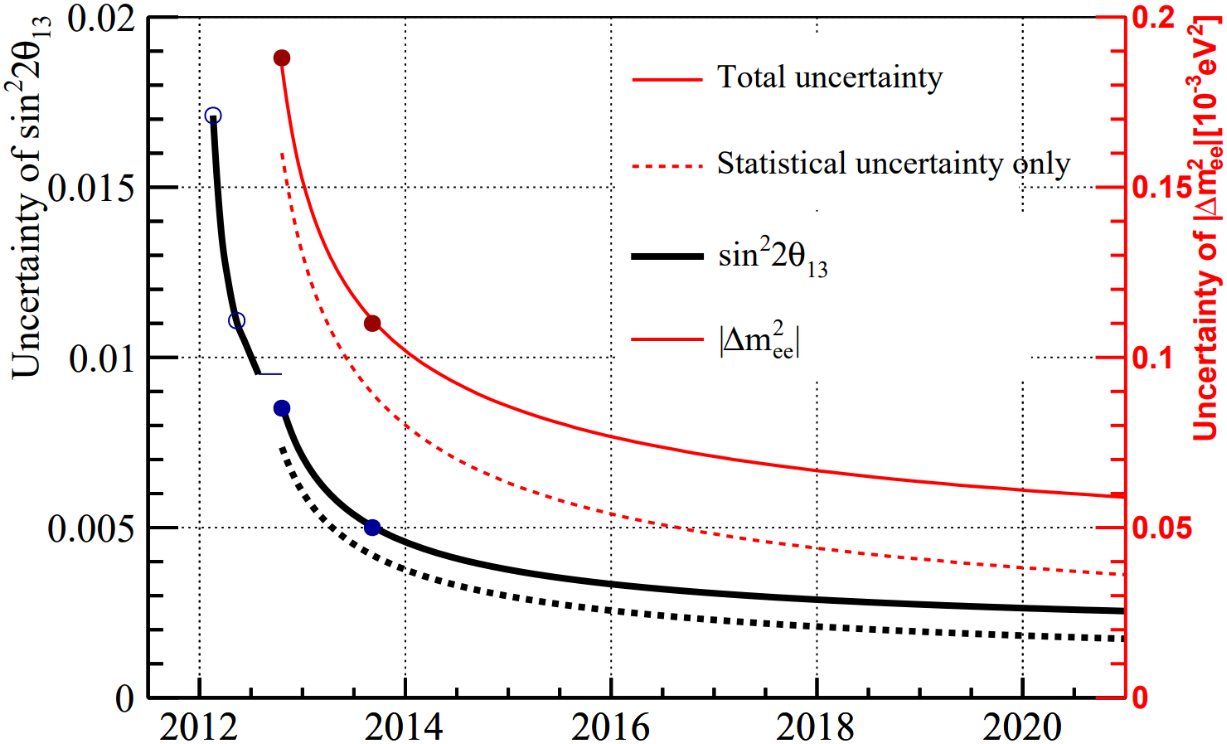
RENO
~77%

Daya Bay
~95%

Statement (~80% suppression) in arXiv:1501.00356 regarding DYB is incorrect

Precision on Oscillation Parameters

- Plan to run till 2020: uncertainties of $\sin^2 2\theta_{13}$ below 3%



Oscillation Results

- Summary of oscillation results with 1958 days:

results with 1958 days →

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

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

$$|\Delta m^2_{32}| = (2.47 \pm 0.07) \times 10^{-3}\ \mathrm{eV}^2 \text{ (NH)}$$

$$|\Delta m^2_{32}| = (-2.57 \pm 0.07) \times 10^{-3}\ \mathrm{eV}^2 \text{ (IH)}$$

Effective Mass Splitting

- Full oscillation probability:

$$P_{\overline{\nu}_e\to\overline{\nu}_e} = 1 - \sin^2 2\theta_{13}\left(\cos^2\theta_{12}\sin^2\frac{\Delta \mathrm{m}_{31}^2 L}{4\mathrm{E}} + \sin^2\theta_{12}\sin^2\frac{\Delta \mathrm{m}_{32}^2 L}{4\mathrm{E}}\right) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\frac{\Delta \mathrm{m}_{21}^2 L}{4\mathrm{E}}$$

- Effective oscillation probability:

$$P_{\overline{\nu}_e\to\overline{\nu}_e} = 1 - \sin^2 2\theta_{13}\sin^2\frac{1.267\Delta m_{\mathrm{ee}}^2 L}{E} - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\frac{\Delta \mathrm{m}_{21}^2 L}{4\mathrm{E}}$$

Advantages: independent of mass hierarchy and solar oscillation parametes

- For Daya Bay's L/E values, the full formula becomes:

$$P_{\overline{\nu}_e\to\overline{\nu}_e} = 1 - 4s_{13}^2c_{13}^2\left[\frac{1-\cos(2\Delta_{32}\pm\phi)}{2}\right] - (\text{solar term})$$
$$= 1 - \sin^2 2\theta_{13}\sin^2(\Delta_{32} \pm \phi/2) - (\text{solar term})$$

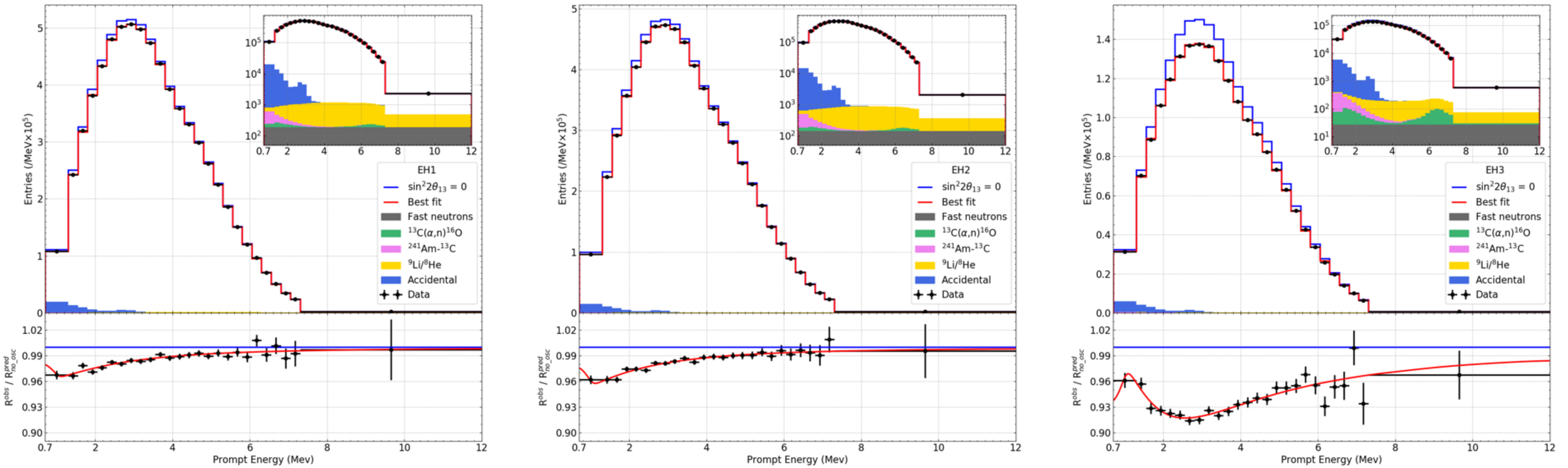
where: $\Delta_x = \Delta m_x^2\frac{L}{4E}$

Comparing this expression with the effective one we conclude:

$$|\Delta m_{\mathrm{ee}}^2| = |\Delta m_{32}^2| \pm \left(\phi\times\frac{4E}{L}\right)/2$$
$$= |\Delta m_{32}^2| \pm (5.17\times 10^{-5})\ \mathrm{eV}^2$$

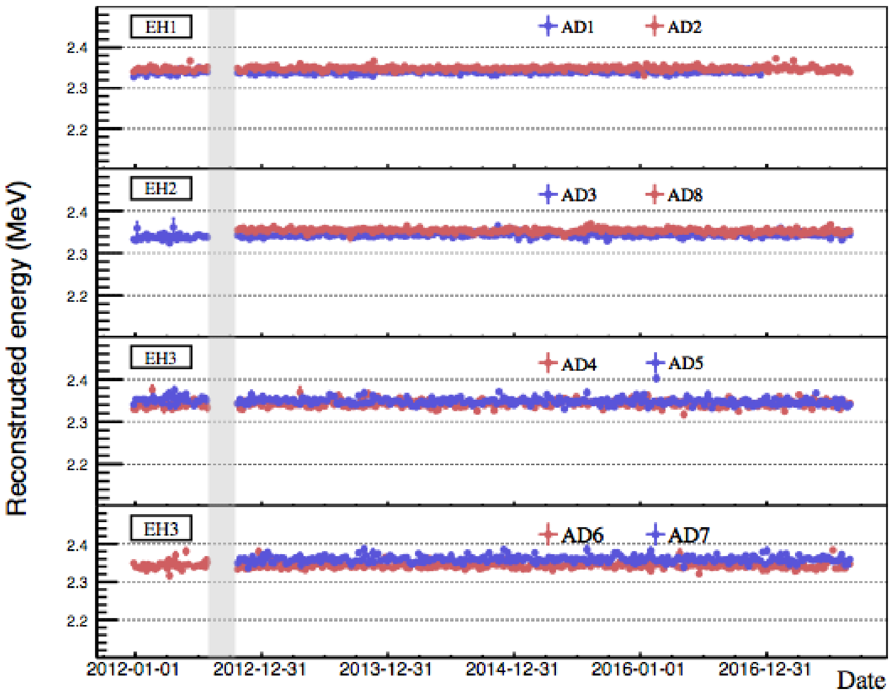
The fit is always done with the full oscillation probability.

Spectra

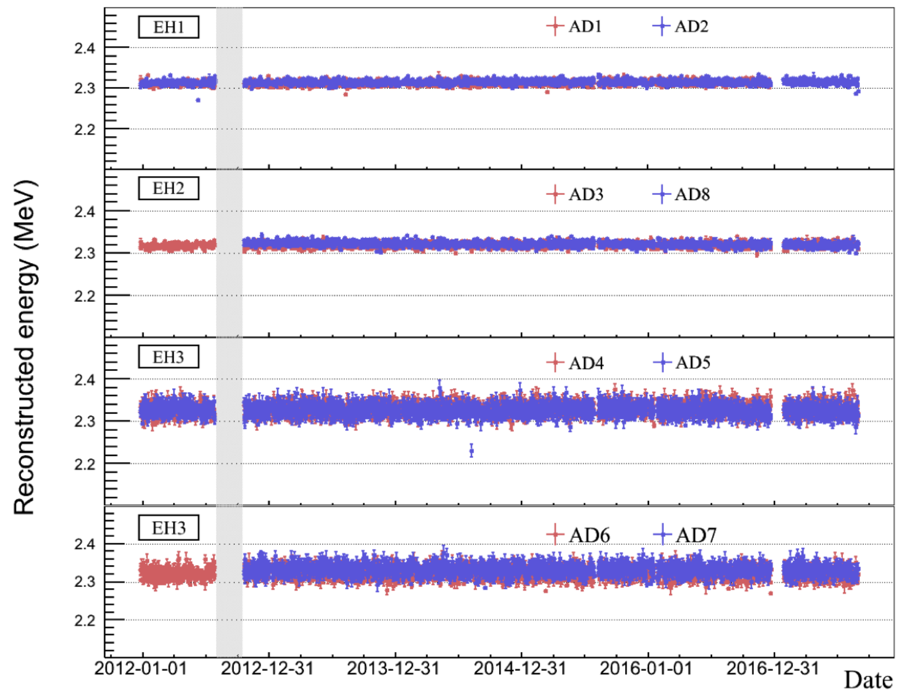

EH1
EH2
EH3
$\sin^2 2\theta_{13} = 0$
Best fit
Fast neutrons
$^{13}C(\alpha,n)^{16}O$
$^{241}Am\text{-}^{13}C$
$^{9}Li/^{8}He$
Accidental
Data
Entries (/MeV×10^5)
$R^{obs} / R^{pred}_{no\_osc}$
Prompt Energy (Mev)

Energy Response Stability

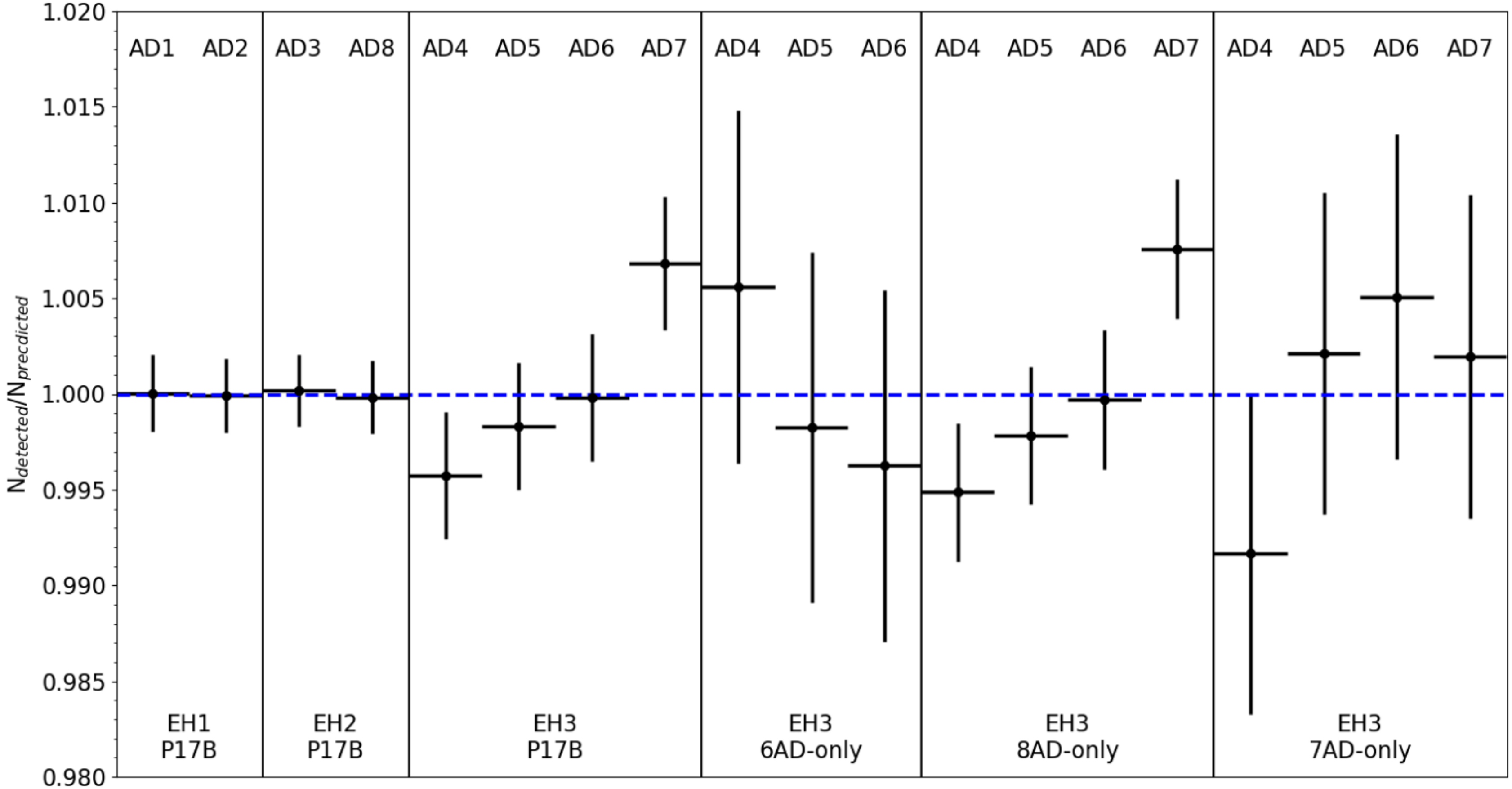
^{60}Co calibration method



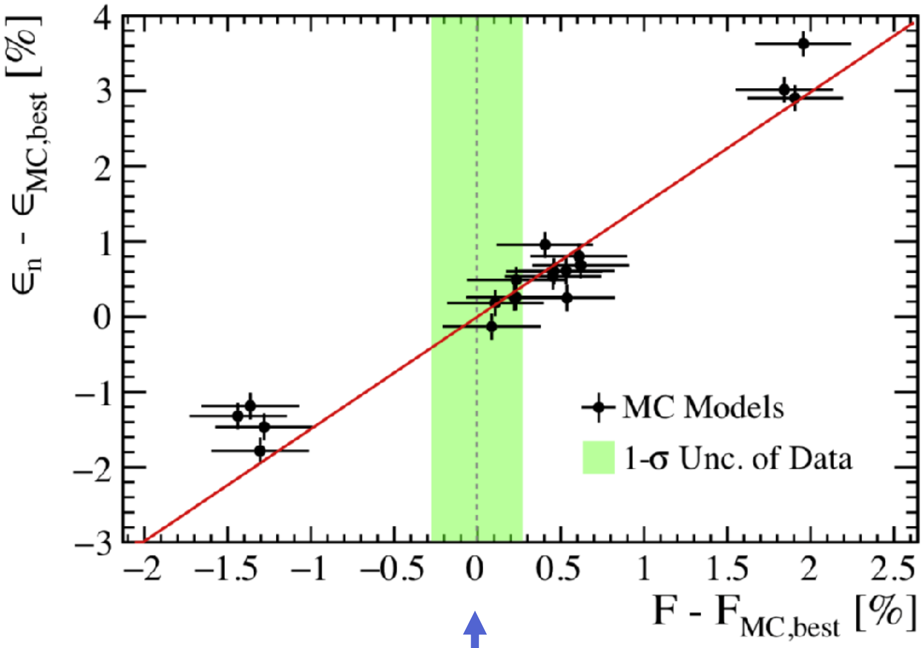
spn-nGd calibration method

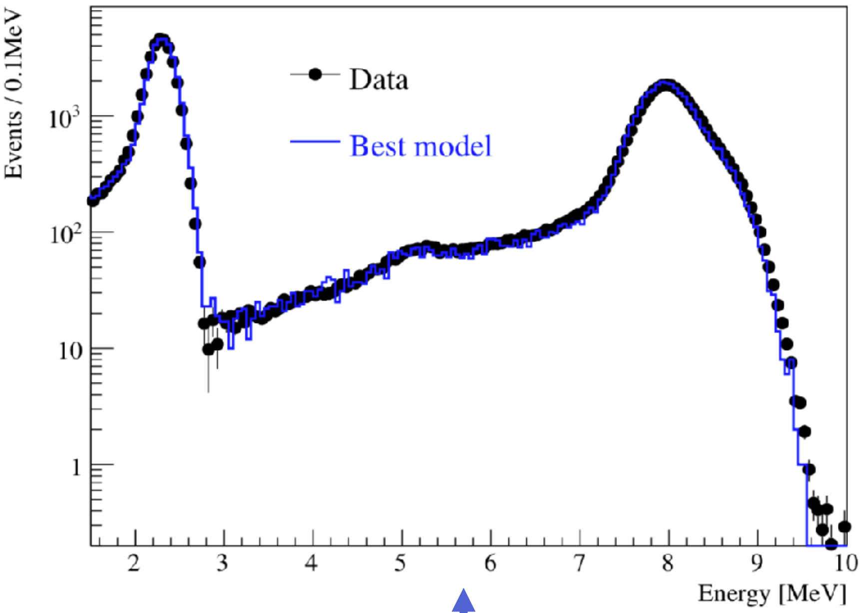


Side-by-side comparison



Absolute Reactor Antineutrino Flux



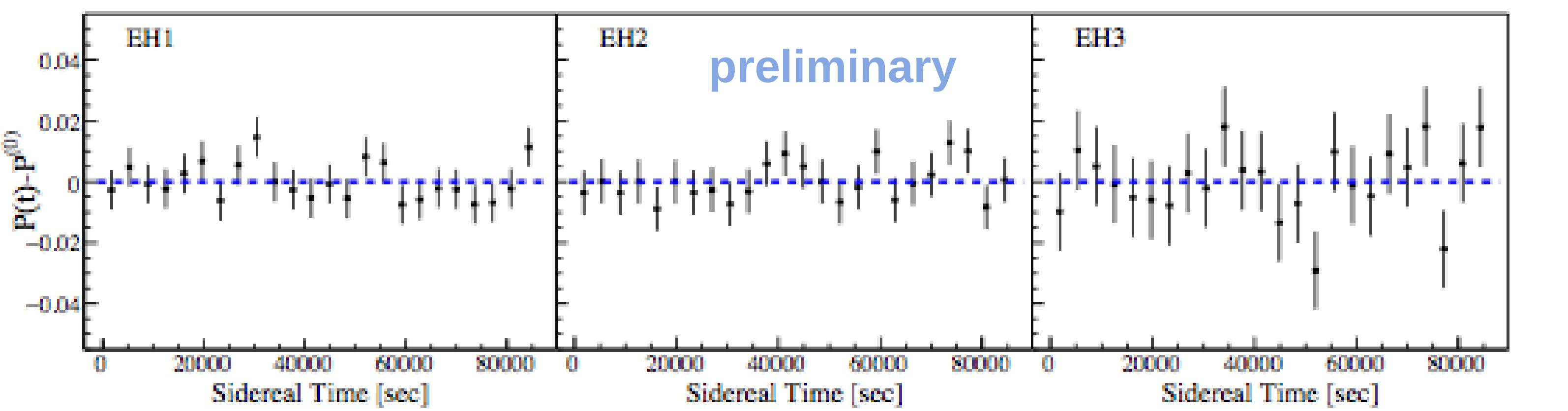


20 models at a single source location point (ACU B, z=0m)

Cross-check: delayed energy spectrum of LS+GdLS IBD events compared to the best model. The ratio F is consistent to within 0.1% between the two

Search for a Sidereal Modulation

- We searched for a sidereal time modulation in the context of the Standard Model Extension (SME):



$$P(t) \propto L\left[(\mathcal{C})_{\bar{c}\bar{d}} + (\mathcal{A}_s)_{\bar{c}\bar{d}} \sin \omega_\oplus T_\oplus + (\mathcal{A}_c)_{\bar{c}\bar{d}} \cos \omega_\oplus T_\oplus + (\mathcal{B}_s)_{\bar{c}\bar{d}} \sin 2\omega_\oplus T_\oplus + (\mathcal{B}_c)_{\bar{c}\bar{d}} \cos 2\omega_\oplus T_\oplus\right]$$

- Relationship between the so-called sidereal amplitudes and the individual SME coefficients is quite complex:

For example: $(\mathcal{A}_s)_{\bar{c}\bar{d}} = \hat{N}^Y (a_R)^X_{\bar{c}\bar{d}} - \hat{N}^X (a_R)^Y_{\bar{c}\bar{d}} + E\{-2\hat{N}^Y (c_R)^{TX}_{\bar{c}\bar{d}} + 2\hat{N}^X (c_R)^{TY}_{\bar{c}\bar{d}} + 2\hat{N}^Y \hat{N}^Z (c_R)^{XZ}_{\bar{c}\bar{d}} - 2\hat{N}^X \hat{N}^Z (c_R)^{YZ}_{\bar{c}\bar{d}}\}$

energy

direction

- Daya Bay's high-statistics and unique configuration with multiple neutrino directions allowed to disentangle the energy and direction dependence in these expressions for the first time