Latest Results From Daya Bay With Full Dataset

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On behalf of the Daya Bay Collaboration

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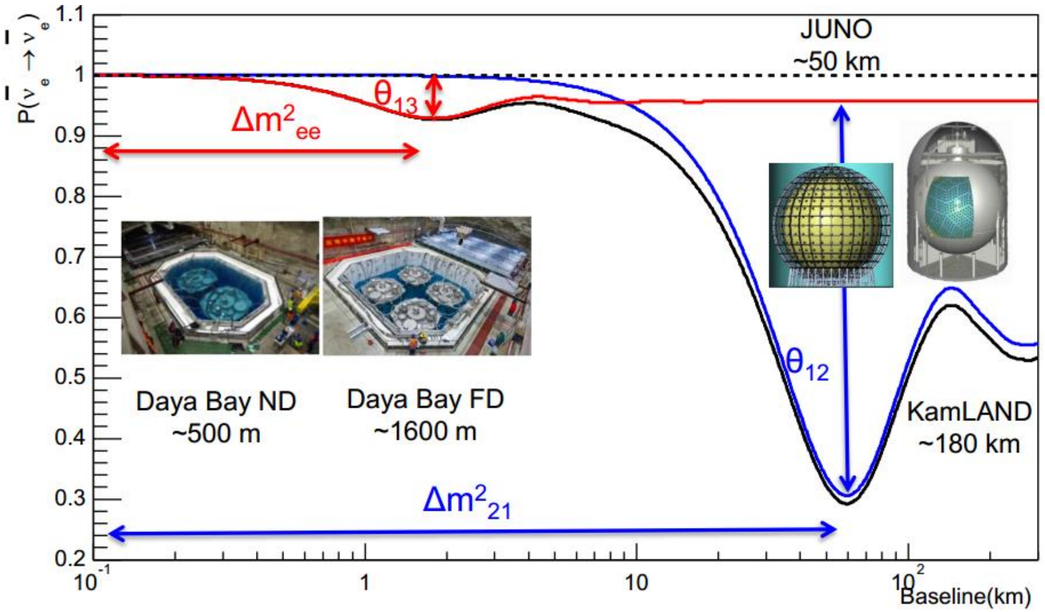
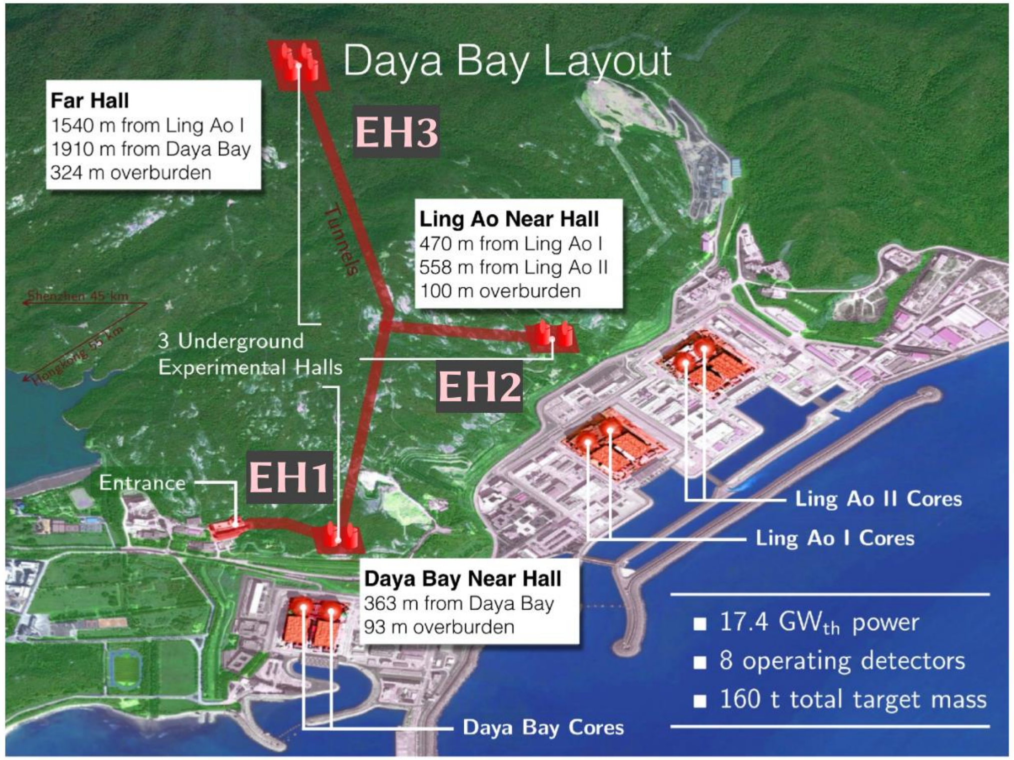
■Measuring θ_{13} with Reactor $\bar{\nu}_e$ at Daya Bay

- Survival probability:

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

$$\approx 1 - \boxed{\sin^2 2\theta_{13}\sin^2\Delta_{ee}} - \boxed{\cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}} \qquad \Delta_{ij} = \Delta m^2_{ij}\frac{L}{4E}$$

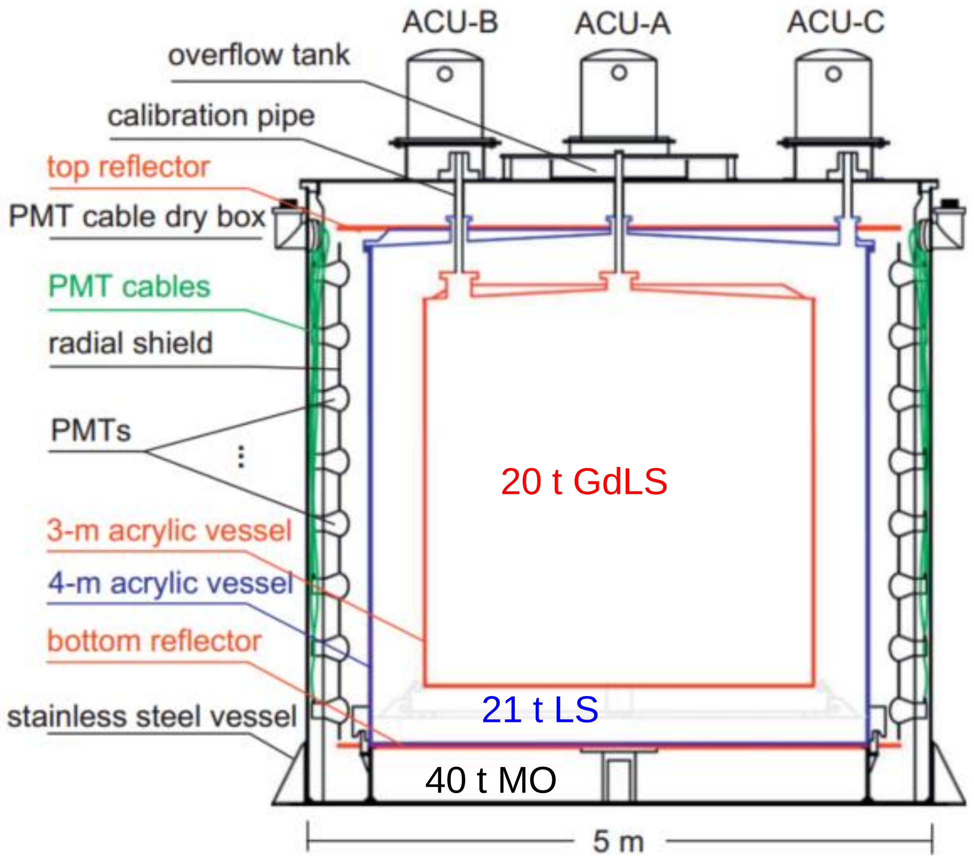




➢ Reduce systematic issues by performing relative measurement with Far/Near ratio

■Antineutrino Detectors (ADs)

NIM A773 (2015) 8; NIM A811 (2016) 133



- 20 tons of 0.1% Gd-loaded liquid scintillator (GdLS) as target
- 21 tons of liquid scintillator (LS) as gamma catcher
- 40 tons of mineral oil (MO) as shielding

prompt | delayed

$$\overline{\nu}_e + p \rightarrow \underbrace{e^+}_{\text{prompt}} + \underbrace{n}_{\text{delayed}}$$

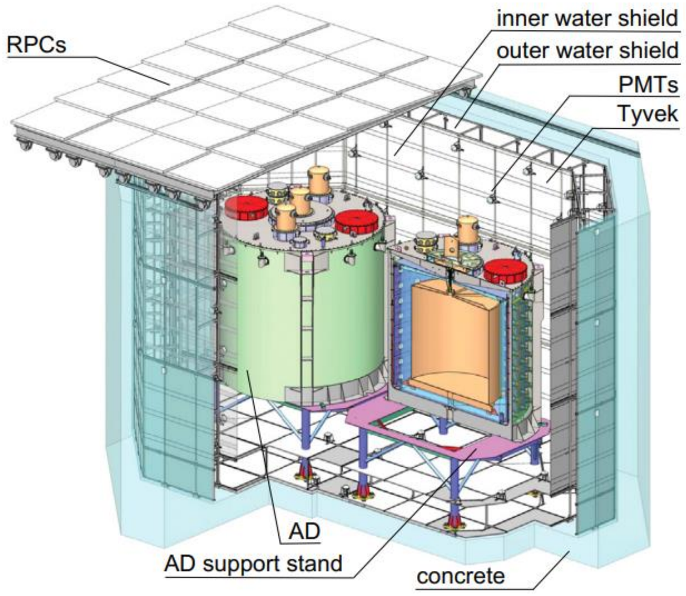
$$\xrightarrow{\sim 180\ \mu s} + p \rightarrow d + \gamma \text{ (2.2 MeV)}$$

$$\rightarrow + Gd \rightarrow Gd^*$$

~30 μs for 0.1% Gd

$$\hookrightarrow Gd + \gamma\text{'s } (\sim 8 \text{ MeV})$$

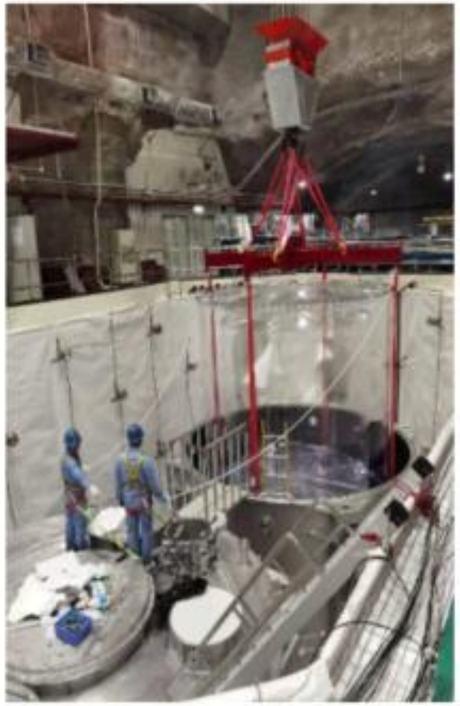
- Detect inverse β-decay reaction (IBD)



- Water pools provide shielding against cosmic-ray muons, secondary neutrons
- Providing a muon veto system via detection of Cherenkov light

Brief History of Onsite Operation

- Detector commissioning on 15 August 2011
- Collection of physics data began on 24 Dec 2011
- Collection of physics data ended on 12 Dec 2020
- Decommissioning: 12 Dec 2020 – 31 Aug 2021



■Oscillation Parameters: Improvements

- Statistics of nGd data:

Year	Calendar days	EH1	EH2	EH3	Total IBD’s
2018 (PRL **121**, 241805)	1958	1,794,417	1,673,907	495,421	3,963,745
2023	3158	2,236,810	2,544,894	764,414	5,546,118

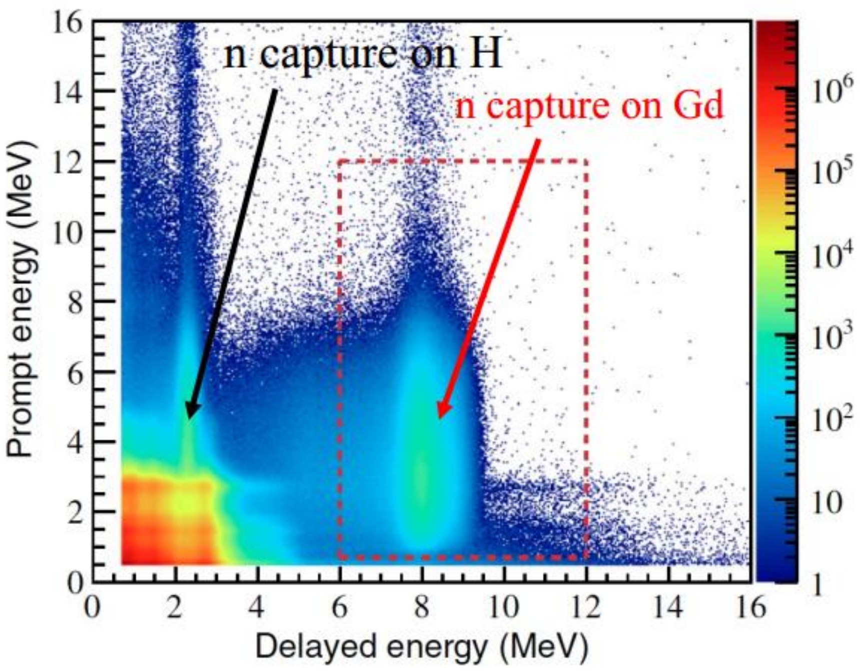
- Analysis:
  - **Energy calibration**

    See more details in backup

    - Electronics non-linearity calibrated at the channel-by-channel level
    - Improved non-uniformity correction
  - **New correlated background after 2017**
    - Remove additional very rare PMT flashers
    - Suppress and identify untagged muon events
  - **Correlated background**
    - New approach for determining the ^{9}Li/^{8}He background

■Selection of IBD Candidates

- Remove flashing PMT events
- Veto muon events
- Require 0.7 MeV < E_{prompt} < 12 MeV, 6 MeV < $E_{delayed}$ < 12 MeV
- Neutron capture time: 1 μs < Δt < 200 μs
- Multiplicity cut: select time-isolated energy pairs



Detection efficiencies

	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%

See PRD 95, 072006 (2017)

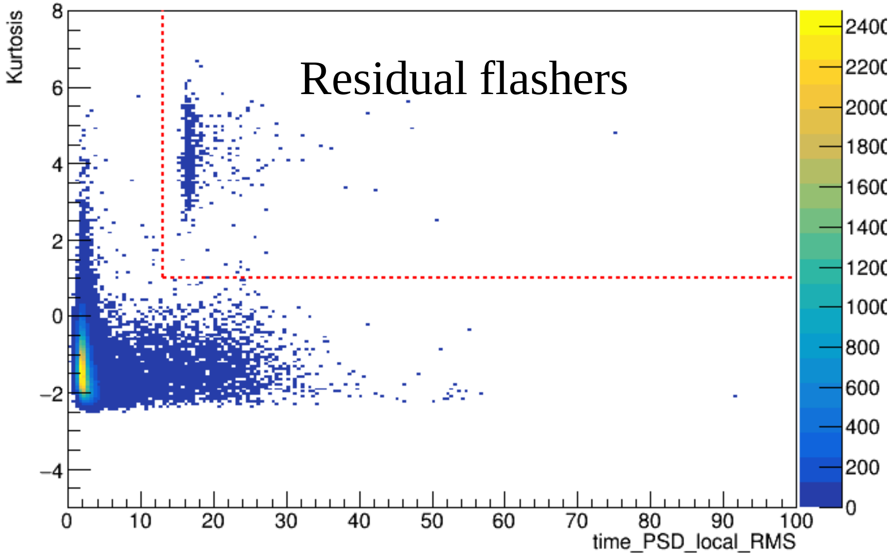
Overview of Background

- Uncorrelated background
  - Accidental: uncorrelated pairs
- Correlated background
  - Fast neutron
    - produced outside of the AD but enters the active volume of the AD
  - $^{9}Li/^{8}He$
    - spallation product produced by cosmic-ray muons inside the AD
  - ^{241}Am-^{13}C
    - neutron calibration source resides inside the ACU
  - $^{13}C(\alpha,n)^{16}O$
    - α from decay of natural radioactive isotope in the liquid scintillator
  - Residual PMT flasher
  - Muon-x

new background

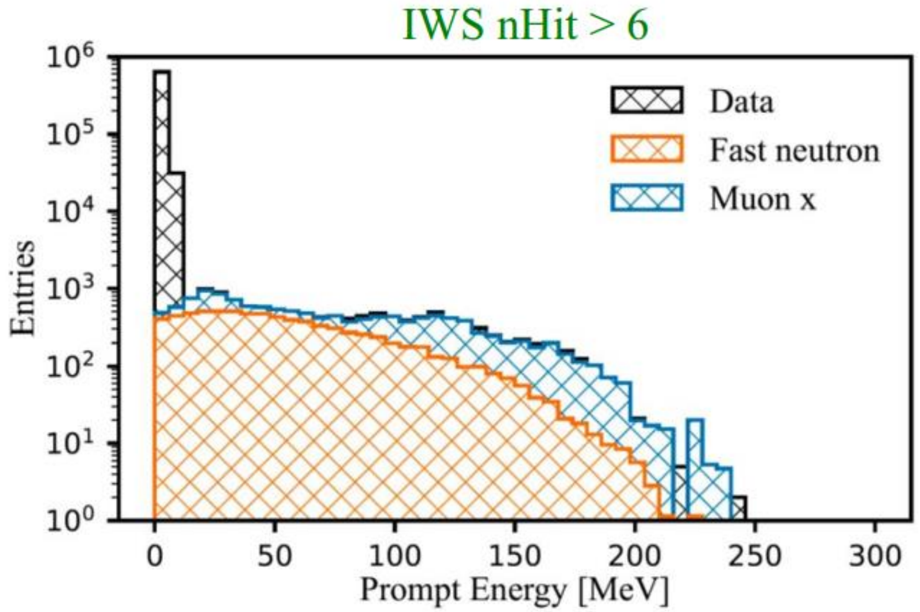
■Analysis of New Background

Residual PMT flashers



- Located near the top of some ADs
- Removed by cutting on Kurtosis and time_PSD_local_RMS
- After rejecting residual flashers,
  - ➢ Negligible contamination in the IBD sample
  - ➢ Retain 99.997% of the IBD candidates

Muon-x background

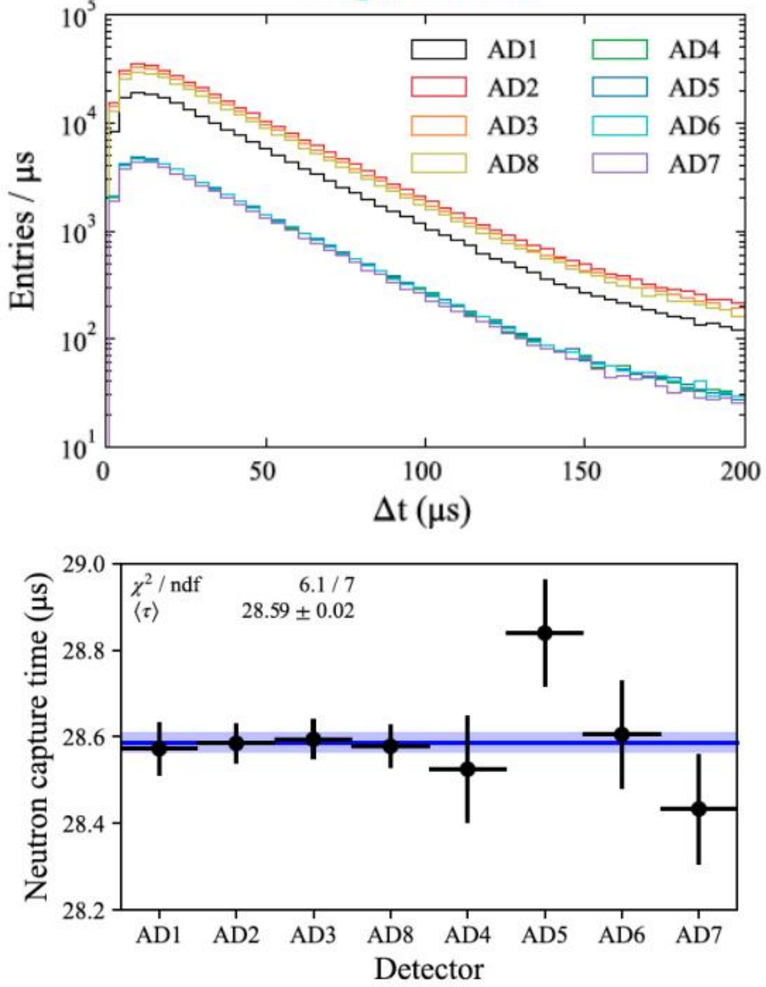


- Gradual failure of PMTs in the water pool since January 2017
  - ➢ Reduction in muon detection efficiency
  - ➢ Muon decays and additional spallation
- Lower the hit multiplicity of PMTs in IWS to tag muons
- Extend cut on E_{prompt} to determine the rate and spectrum for fast neutron and muon-x

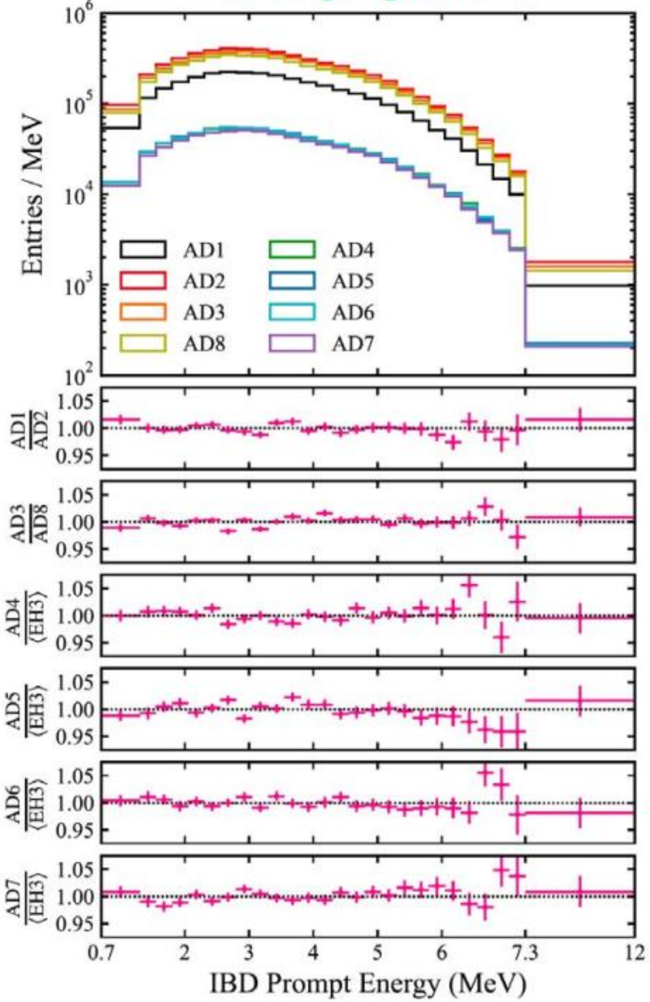
■Performance of Antineutrino Detectors

- IBD candidates including background (< 3%)

Capture time



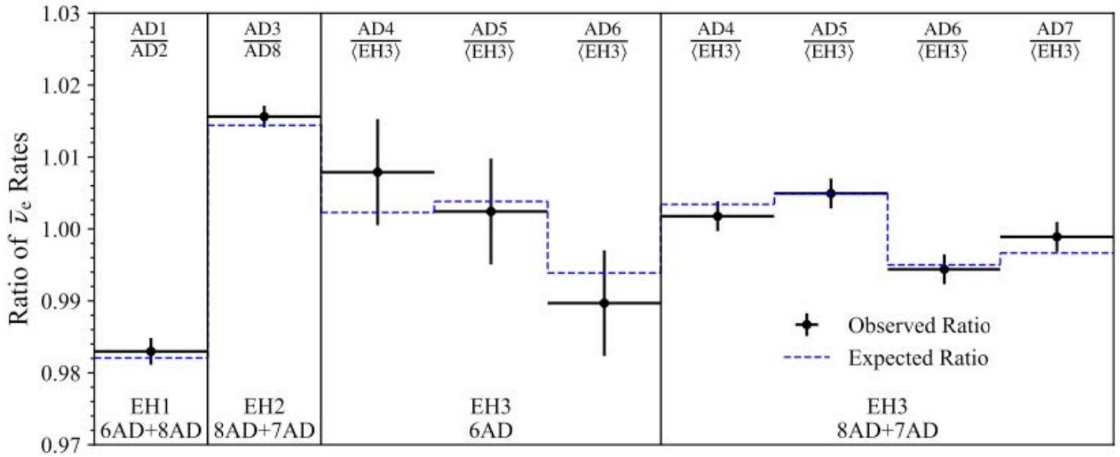
Prompt spectrum



- Antineutrino detectors in the same hall have similar performance

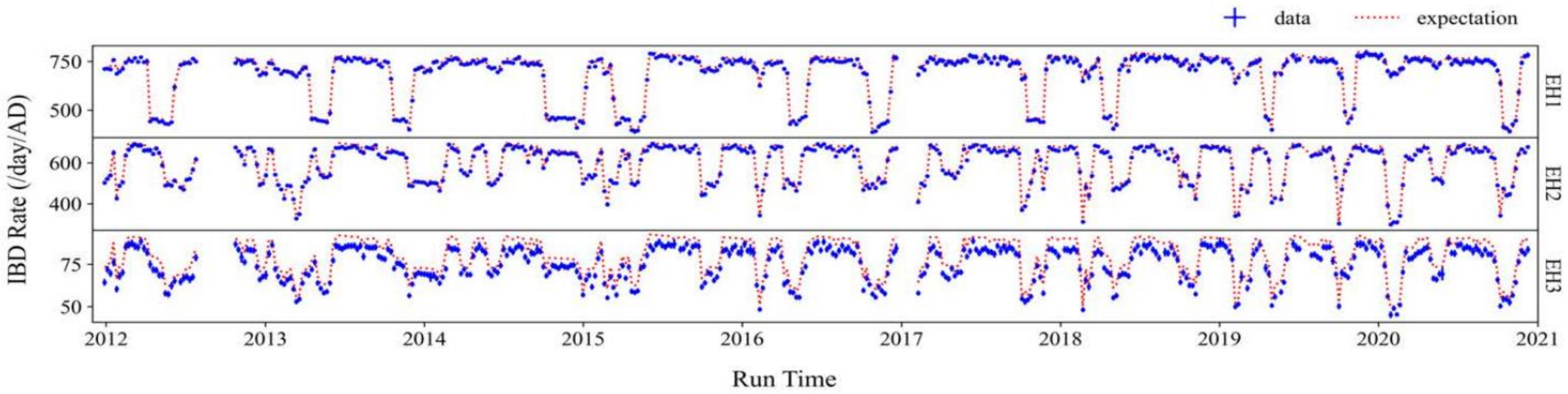
■IBD Rate (background subtracted)

- Side-by-side comparison: measurements consistent with predictions

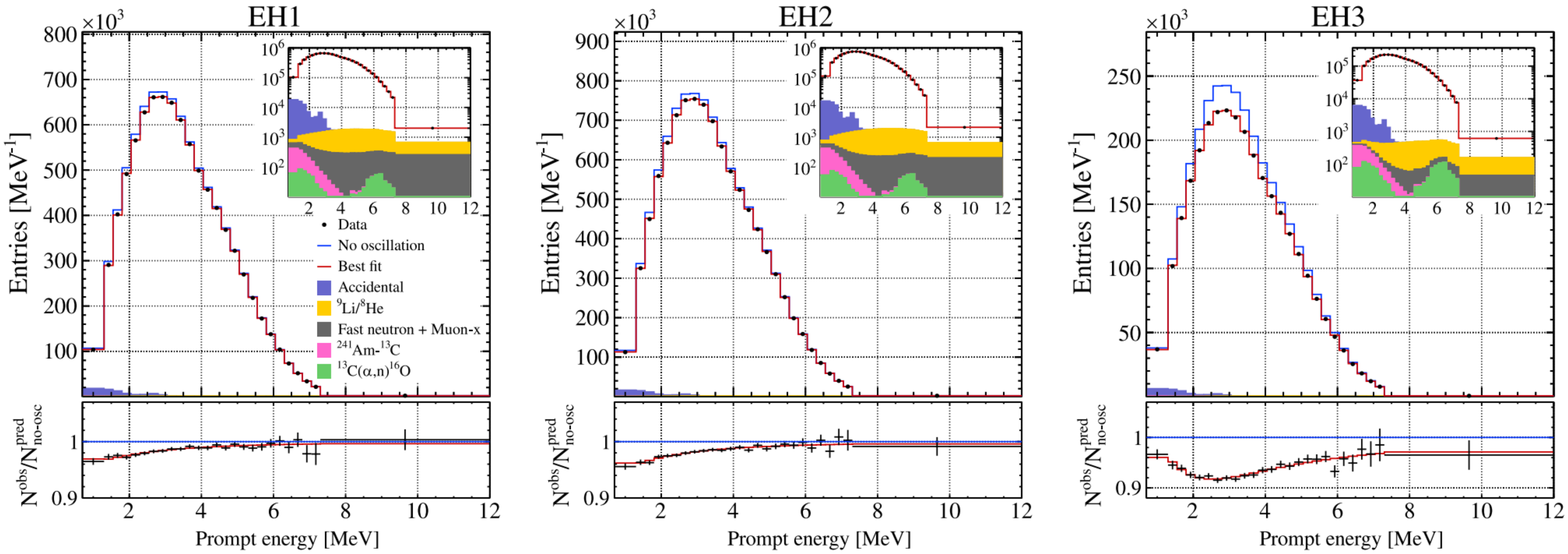


Errors include relative detection efficiency of 0.13%

- Correlation with operation of reactors
  - ➢ Expectation based on weekly reactor operational information
  - ➢ Measurements track expectations



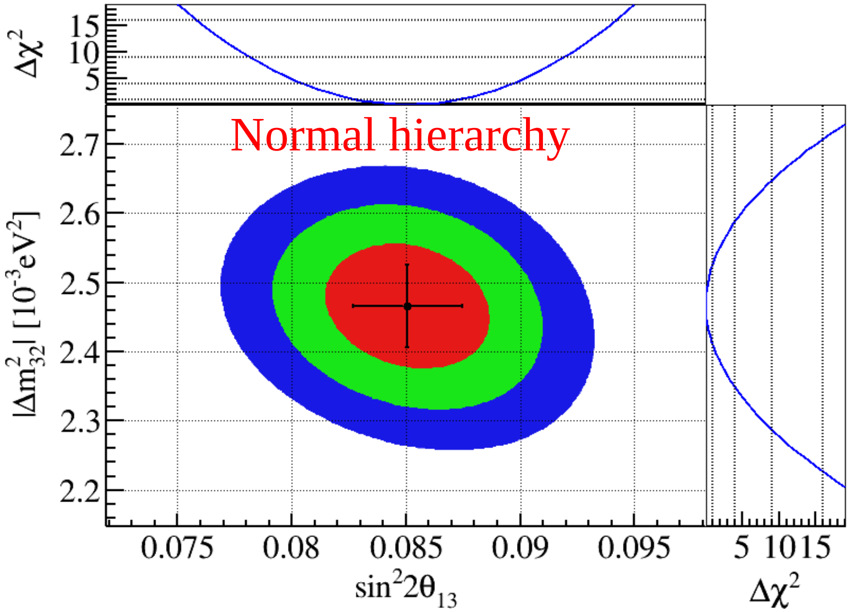
■Prompt-energy Spectra

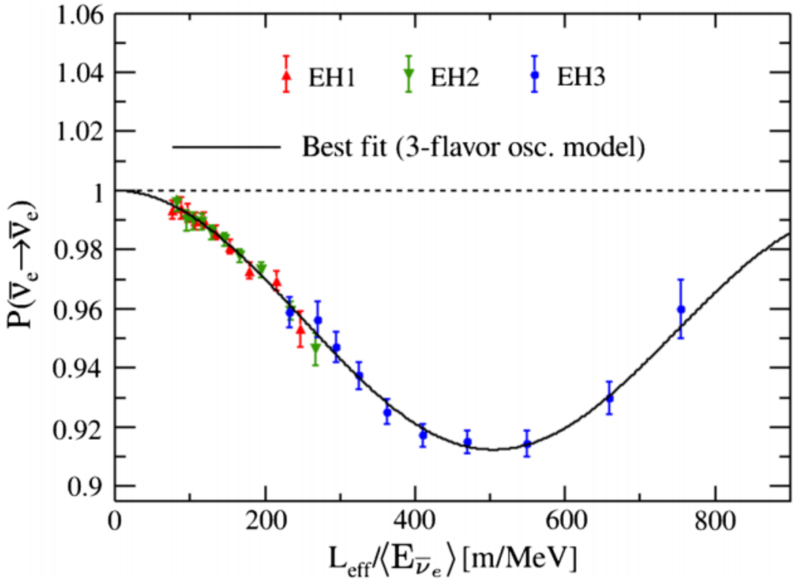


- The best-fit prompt energy distribution is in excellent agreement with the observed spectra in each experimental hall.

■Improved $\sin^2 2\theta_{13}$ and Δm^2_{32}

Phys. Rev. Lett. 130, 161802 (2023)





Best-fit results:

χ^2/ndf = 559/518

$$\sin^2 2\theta_{13} = 0.0851^{+0.0024}_{-0.0024}$$ (2.8% precision)

Normal hierarchy: $$\Delta m^2_{32} = +(2.466^{+0.060}_{-0.060}) \times 10^{-3}\mathrm{eV}^2$$ (2.4% precision)

Inverted hierarchy: $$\Delta m^2_{32} = -(2.571^{+0.060}_{-0.060}) \times 10^{-3}\mathrm{eV}^2$$ (2.3% precision)

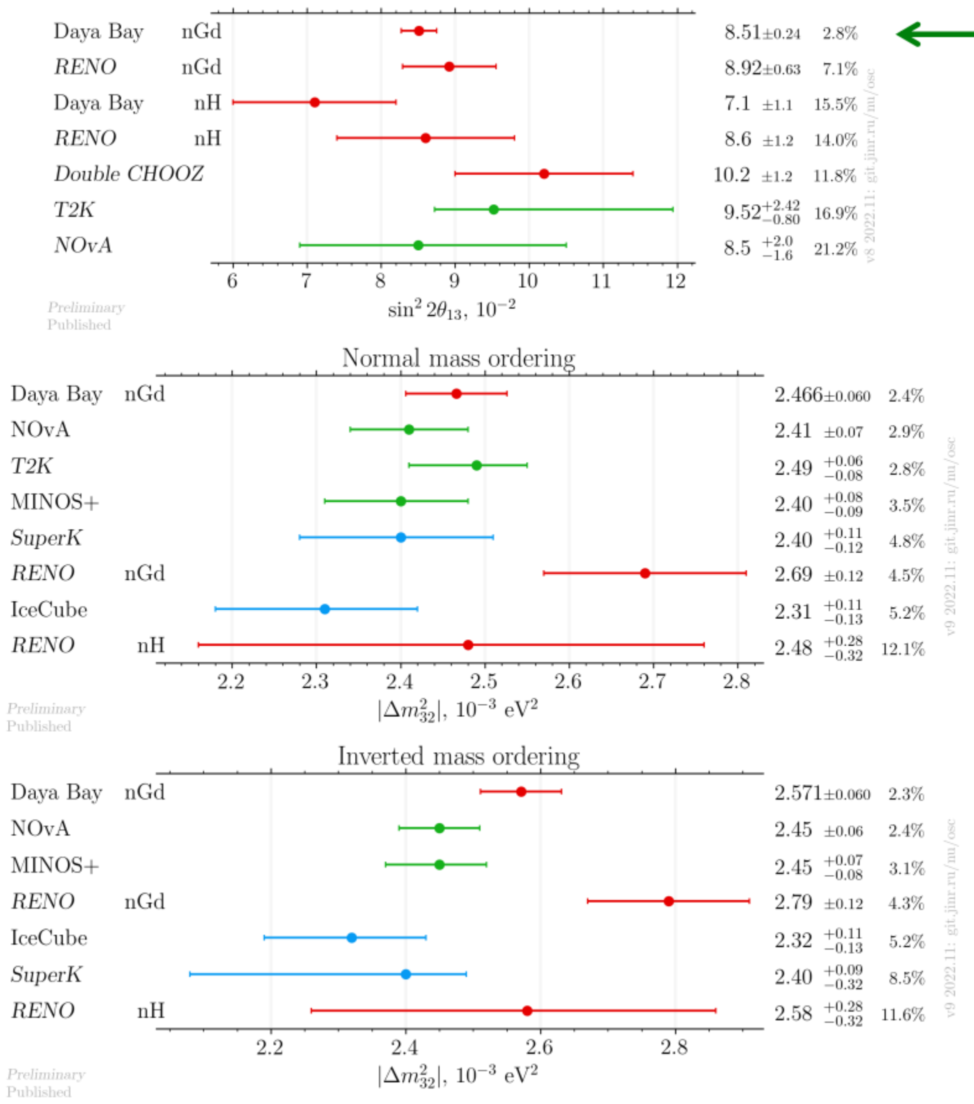
■Present Global Landscape

- Compare Daya Bay’s current results with published results

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

Δm^2_{32} (NO)

Δm^2_{32} (IO)

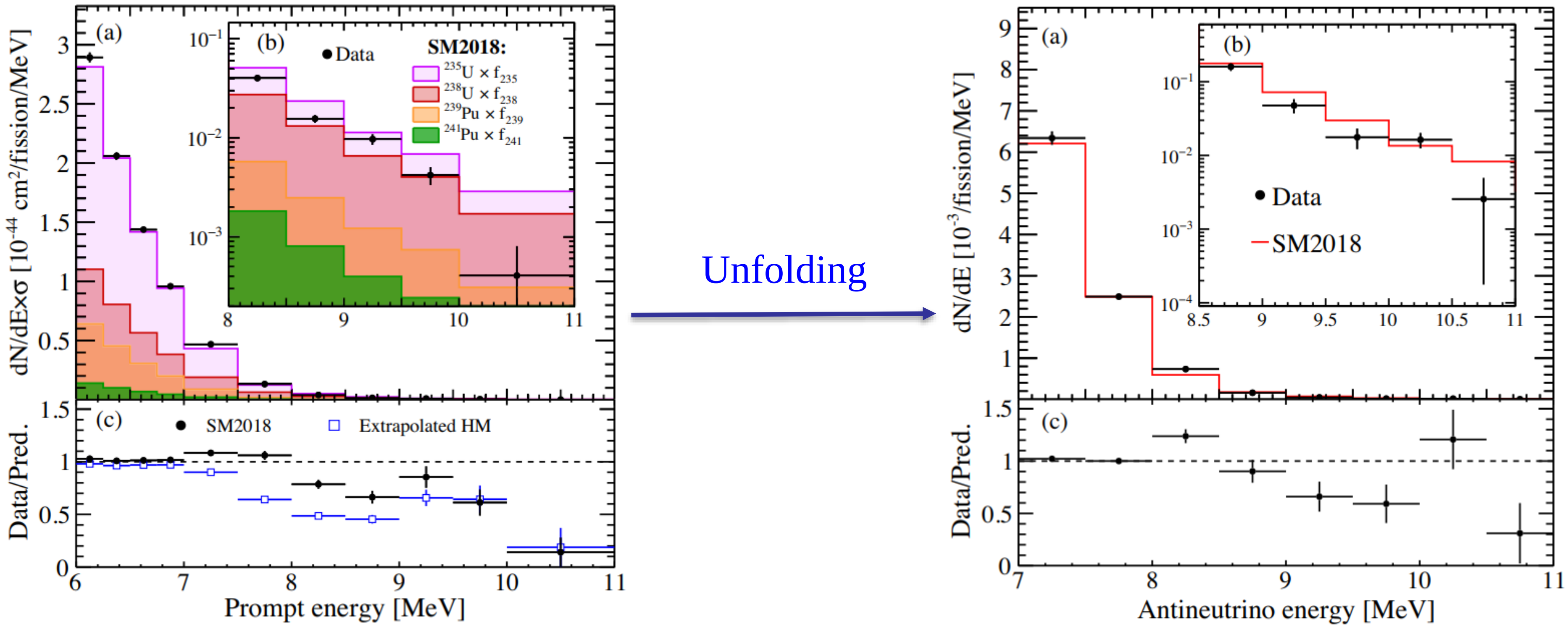


Currently the best measurement for a foreseeable future

Consistent results from ν_e and ν_μ measurements strongly support 3-flavor framework

■First Evidence of Reactor $\overline{\nu}_e$ with E > 10 MeV

Phys. Rev. Lett. 129, 041801 (2022)

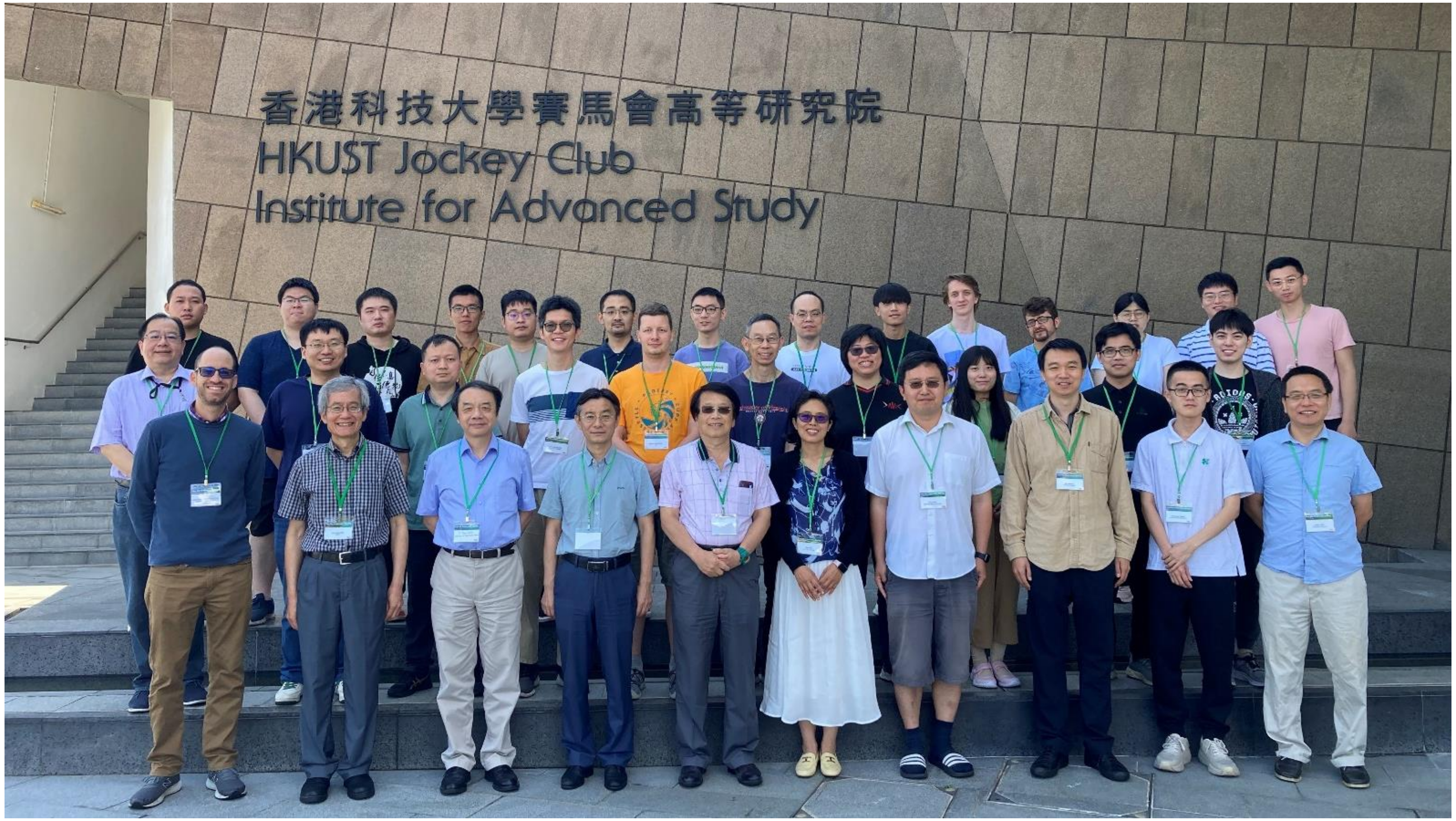


- Discover reactor antineutrinos above 10 MeV with 6.2σ significance for the first time
- Compared with data, a deficit of 29% in 8-11 MeV with SM2018, and larger disagreement above 7 MeV for extrapolated HM
- Can come from high-Q β-decay of short-lived isotopes, e.g. ^{88,90}Br, ^{94,96,98}Rb

Summary

- **Acquired the largest sample of reactor antineutrinos to date**
- **Obtains the world's most precise determination of $\sin^2 2\theta_{13}$**
- **Provides one of the best measurements of $|\Delta m^2_{32}|$**
- **Yields leading results on other topics not covered here such as**
  - Search for a light sterile neutrino
  - Measurement of absolute flux and spectrum of reactor $\bar{\nu}_e$
  - Evolution of absolute reactor $\bar{\nu}_e$ flux and spectrum
- **Will have more results to be presented in the future, for example:**
  - Updated results on oscillation parameters with nH samples

The Daya Bay Collaboration



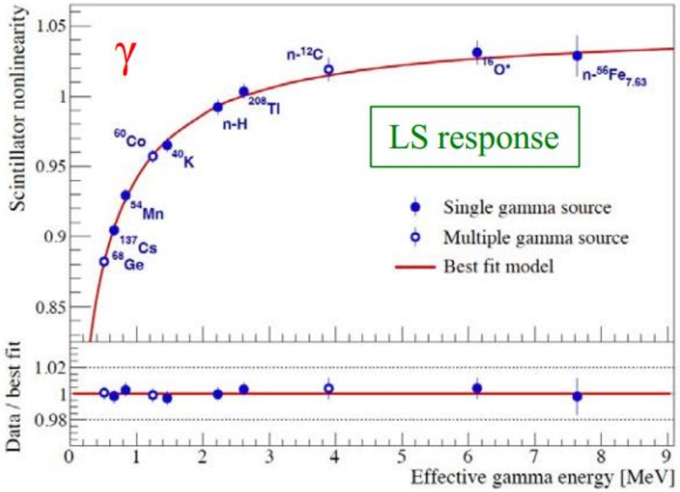
Thank you!

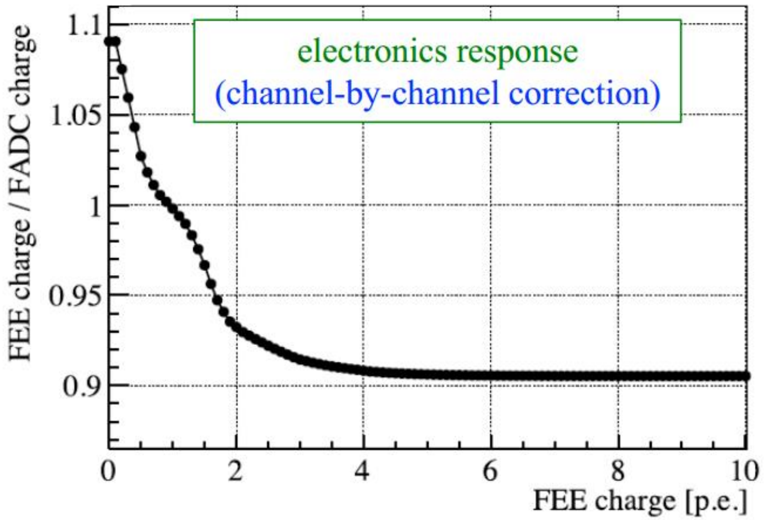
■Backup

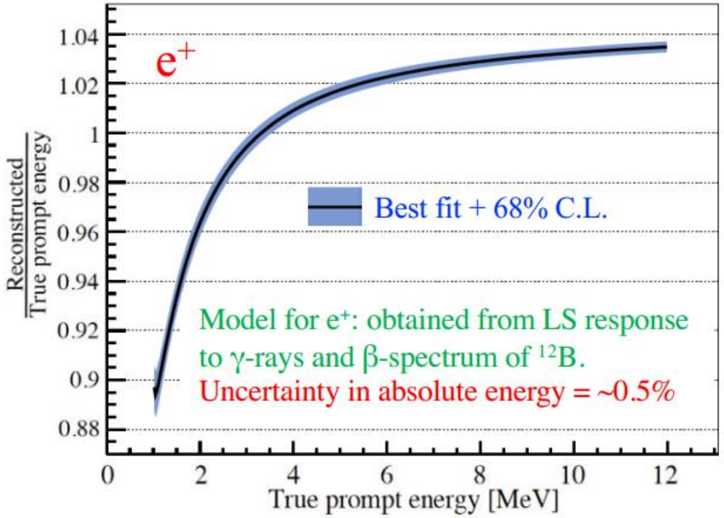
■Non-linear Energy Response

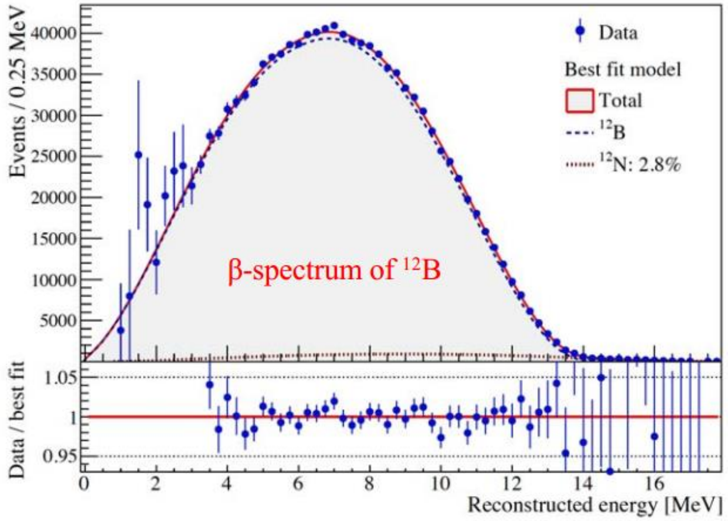
- Due to nature of liquid scintillator (LS) and charge measurement of electronics

NIM A**940** (2019) 230



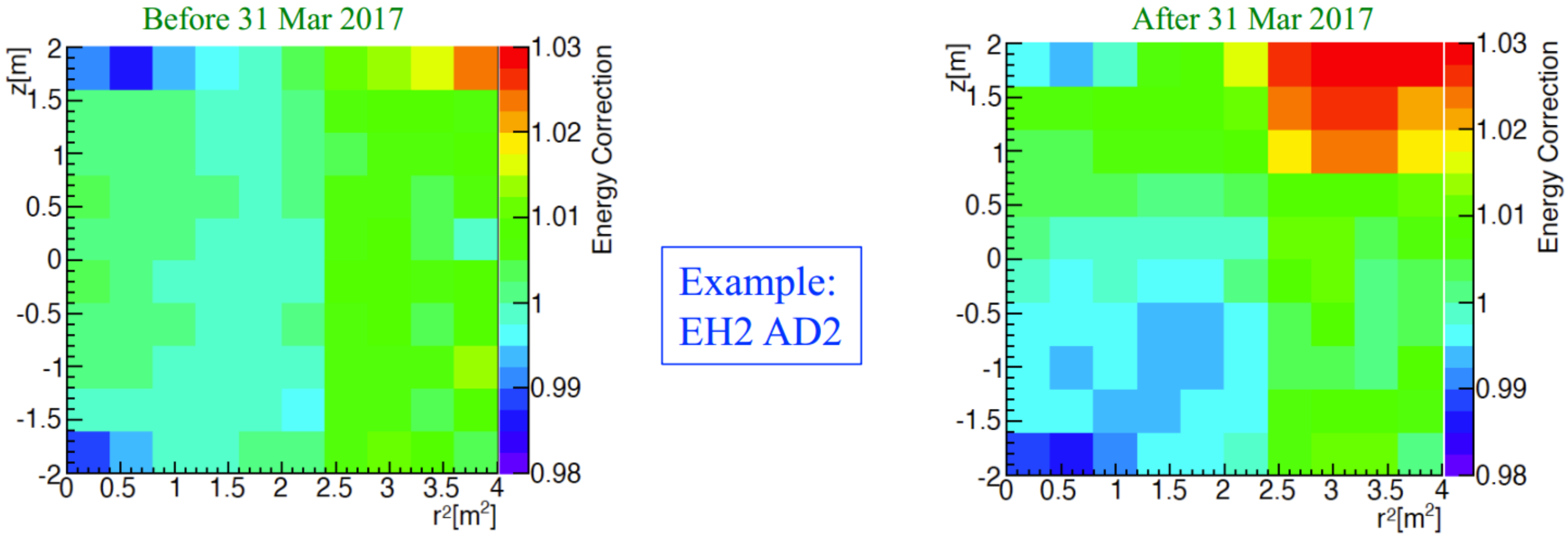






Improved Nonuniformity of Energy Scale

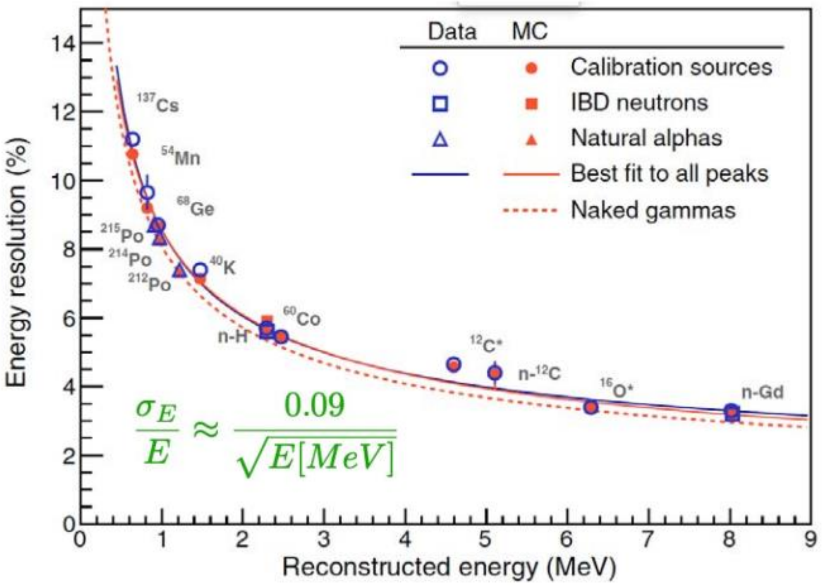
- Additional non-uniformity on top of already-corrected geometric nonuniformity
  - Residual effect of the Earth magnetic field
  - Dead PMTs or high-voltage supply channels
- Corrections
  - Use γ's from spallation-neutron capture on Gd and α's from natural radioactive isotopes
  - Time dependent, referencing to the γ's from spallation-neutron capture

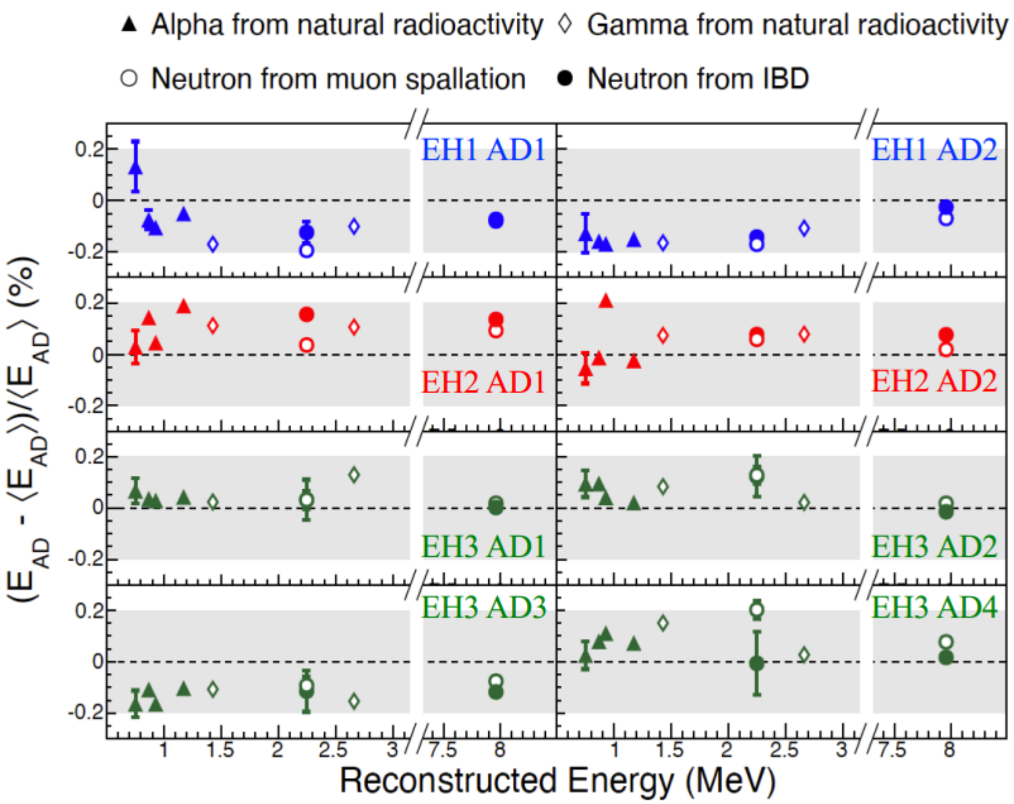


- The largest additional correction is about 3%

■Energy Scale

- Gain of photomultiplier tubes
  - Single-photoelectron dark noise
  - Weekly LED monitoring
- Energy calibration
  - Weekly ^{68}Ge, ^{60}Co, ^{241}Am-^{13}C
  - Spallation neutrons
  - Natural radioactivity

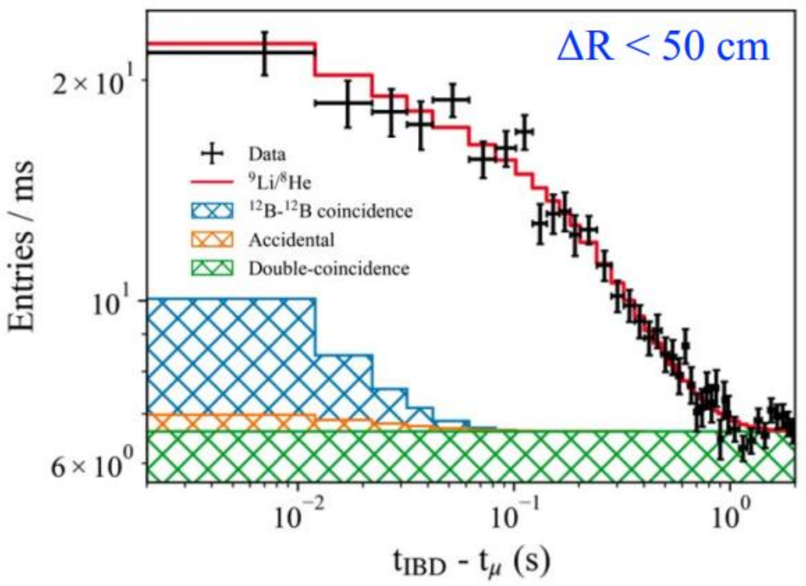


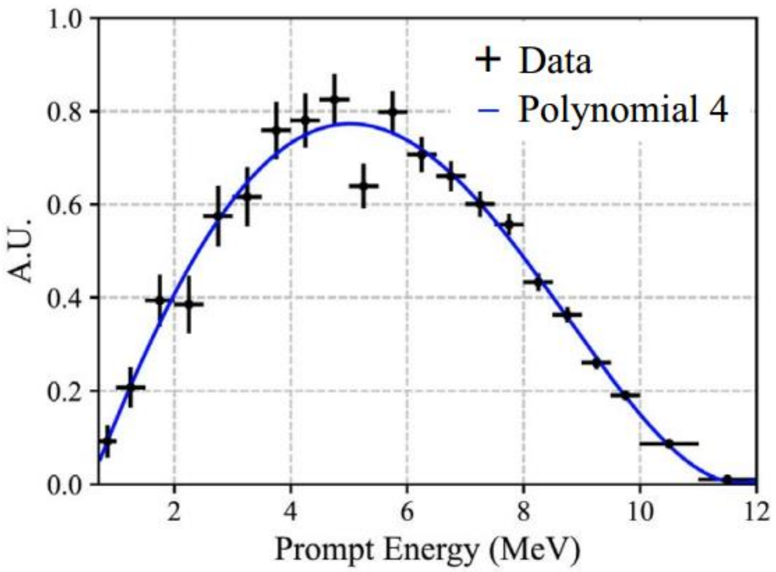


Relative uncertainty in energy scale: ~0.2%

■$^9Li/^8He$ Background

- $^9Li/^8He$
  - β-n decay
  - τ_{Li} = 257.2 ms, τ_{He} = 171.7 ms
- Perform a multi-dimensional fit using
  - Time interval after the preceding muon ($t_{IBD} - t_\mu$)
  - Prompt energy (E_{prompt})
  - Distance between the prompt and delayed signals (ΔR)
  - Low-energy (E_{vis} < 2 GeV) and high-energy (E_{vis} > 2 GeV) muon samples from all three halls simultaneously





■Summary Table

	EH1		EH2		EH3			
	AD1	AD2	AD3	AD8	AD4	AD5	AD6	AD7
$\bar{\nu}_e$ candidates	794335	1442475	1328301	1216593	194949	195369	193334	180762
DAQ live time [days]	1535.111	2686.11	2689.88	2502.816	2689.156	2689.156	2689.156	2501.531
ϵ_μ	0.8006	0.7973	0.8387	0.8366	0.9815	0.9815	0.9814	0.9814
$\bar{\epsilon}_m$	0.9671	0.9678	0.969	0.9688	0.9693	0.9693	0.9692	0.9693
Accidentals [day^{-1}]	7.11 ± 0.01	6.76 ± 0.01	5.00 ± 0.00	4.85 ± 0.01	0.80 ± 0.00	0.77 ± 0.00	0.79 ± 0.00	0.66 ± 0.00
Fast neutron & muon-x [day^{-1}]	0.83 ± 0.17	0.96 ± 0.19	0.56 ± 0.11	0.56 ± 0.11	0.05 ± 0.01	0.05 ± 0.01	0.05 ± 0.01	0.05 ± 0.01
^{9}Li, ^{8}He [$\text{AD}^{-1}\ \text{day}^{-1}$]	2.97 ± 0.53		2.09 ± 0.36		0.25 ± 0.03			
^{241}Am-^{13}C [day^{-1}]	0.16 ± 0.07	0.13 ± 0.06	0.12 ± 0.05	0.11 ± 0.05	0.04 ± 0.02	0.04 ± 0.02	0.04 ± 0.02	0.03 ± 0.01
^{13}C(α, n)^{16}O [day^{-1}]	0.08 ± 0.04	0.06 ± 0.03	0.04 ± 0.02	0.06 ± 0.03	0.04 ± 0.02	0.04 ± 0.02	0.03 ± 0.02	0.04 ± 0.02
$\bar{\nu}_e$ rate, $R_{\bar{\nu}_e}$ [day^{-1}]	657.11 ± 0.94	685.09 ± 0.81	599.83 ± 0.65	592.07 ± 0.67	75.03 ± 0.18	75.22 ± 0.18	74.42 ± 0.18	74.94 ± 0.18