Latest Results From Daya Bay

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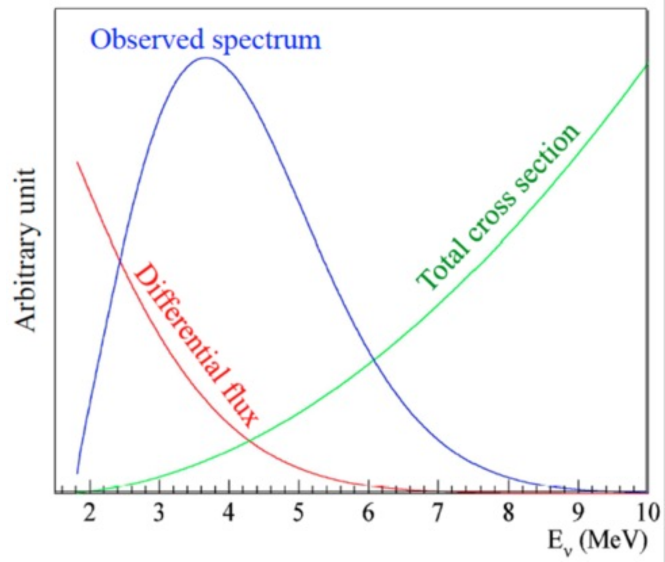
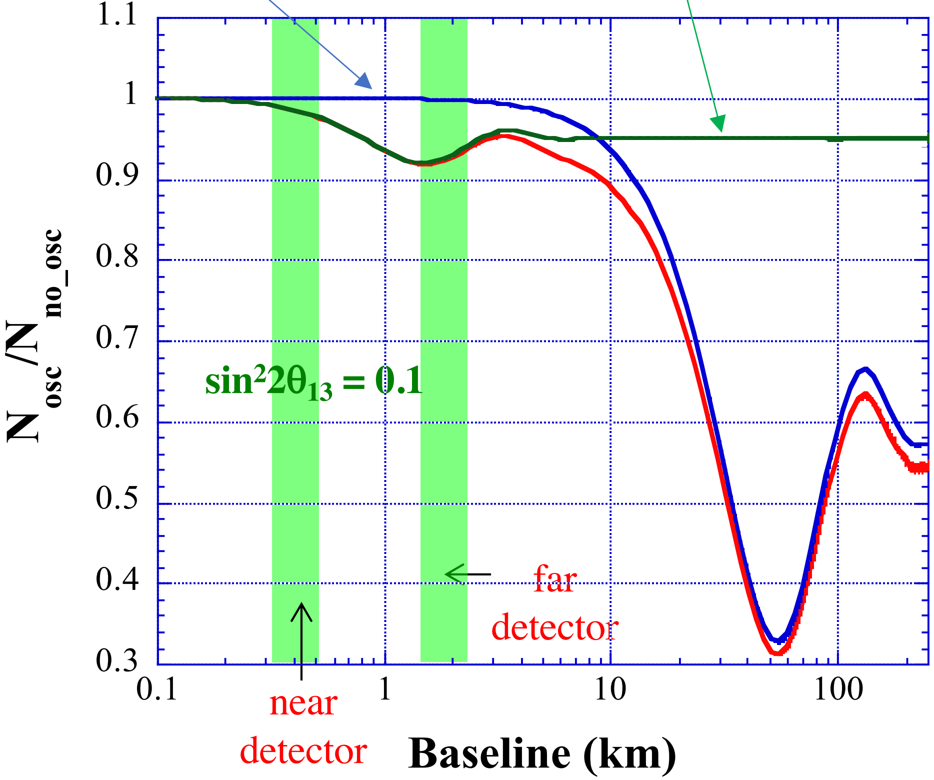
Neutrino 2022, Seoul (remote), 1 June 2022

Measuring θ_{13} with Reactor $\bar{\nu}_e$

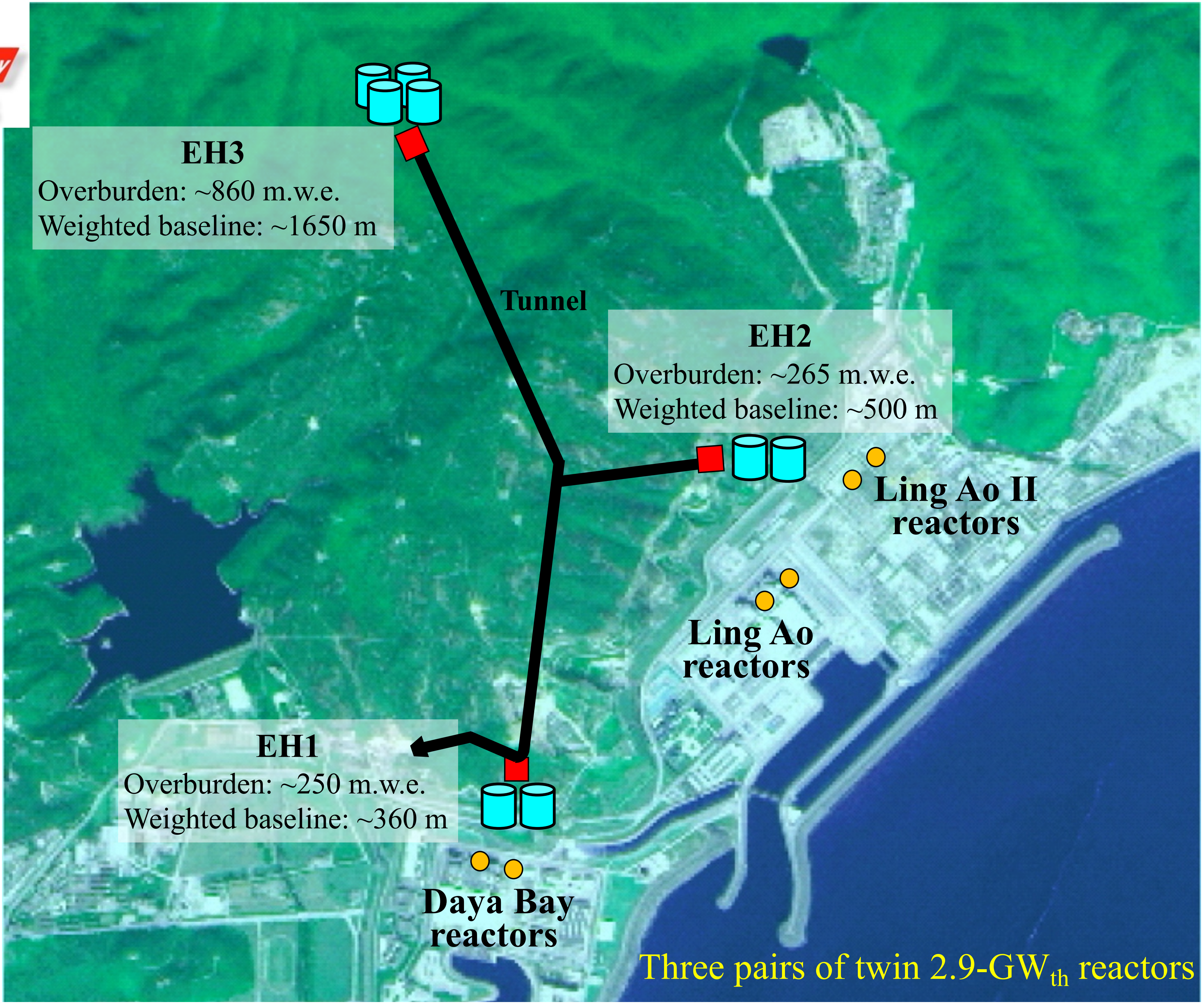
- Survival probability:

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \boxed{\sin^2 2\theta_{13}\left[\cos^2\theta_{12}\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right) + \sin^2\theta_{12}\sin^2\left(\frac{\Delta m^2_{32}L}{4E}\right)\right]}$$
$$- \boxed{\cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\left(\frac{\Delta m^2_{21}L}{4E}\right)}$$





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



EH3

Overburden: ~860 m.w.e.

Weighted baseline: ~1650 m

Tunnel

EH2

Overburden: ~265 m.w.e.

Weighted baseline: ~500 m

Ling Ao II reactors

Ling Ao reactors

EH1

Overburden: ~250 m.w.e.

Weighted baseline: ~360 m

Daya Bay reactors

Three pairs of twin 2.9-GW_{th} reactors

Detectors

- Detect inverse β-decay reaction (IBD):

prompt delayed

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

~180 μs

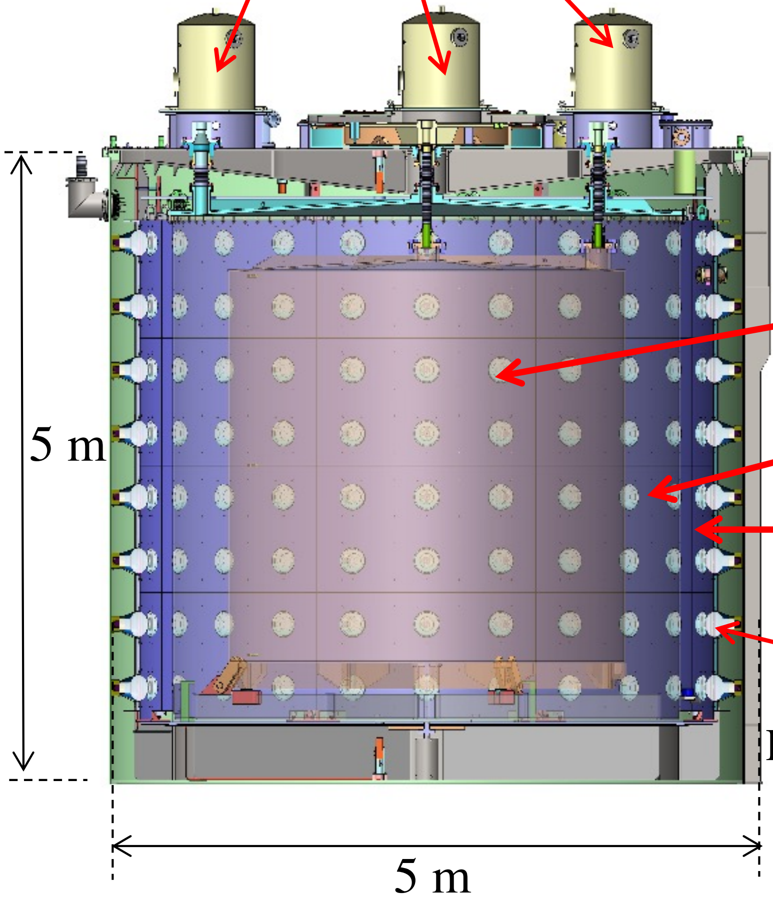
$$\to + p \to d + \gamma \text{ (2.2 MeV)}$$

$$\to + Gd \to Gd^*$$

~30 μs
for 0.1% Gd

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

Automated Calibration units
(LED, ^{68}Ge, AmC-Co)



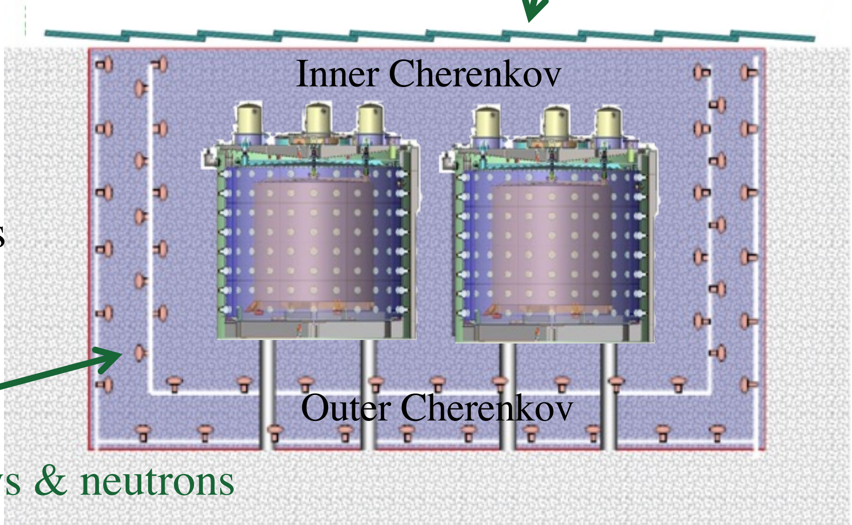
20-t 0.1% Gd-loaded liquid scintillator (target)

22-t LS (gamma catcher)
(LS = LAB + 3 g/l PPO + 15 mg/l Bis-MSB)

40-t mineral oil shield

192 Photomultiplier tubes (PMTs)

Four layers of RPC's to tag muons



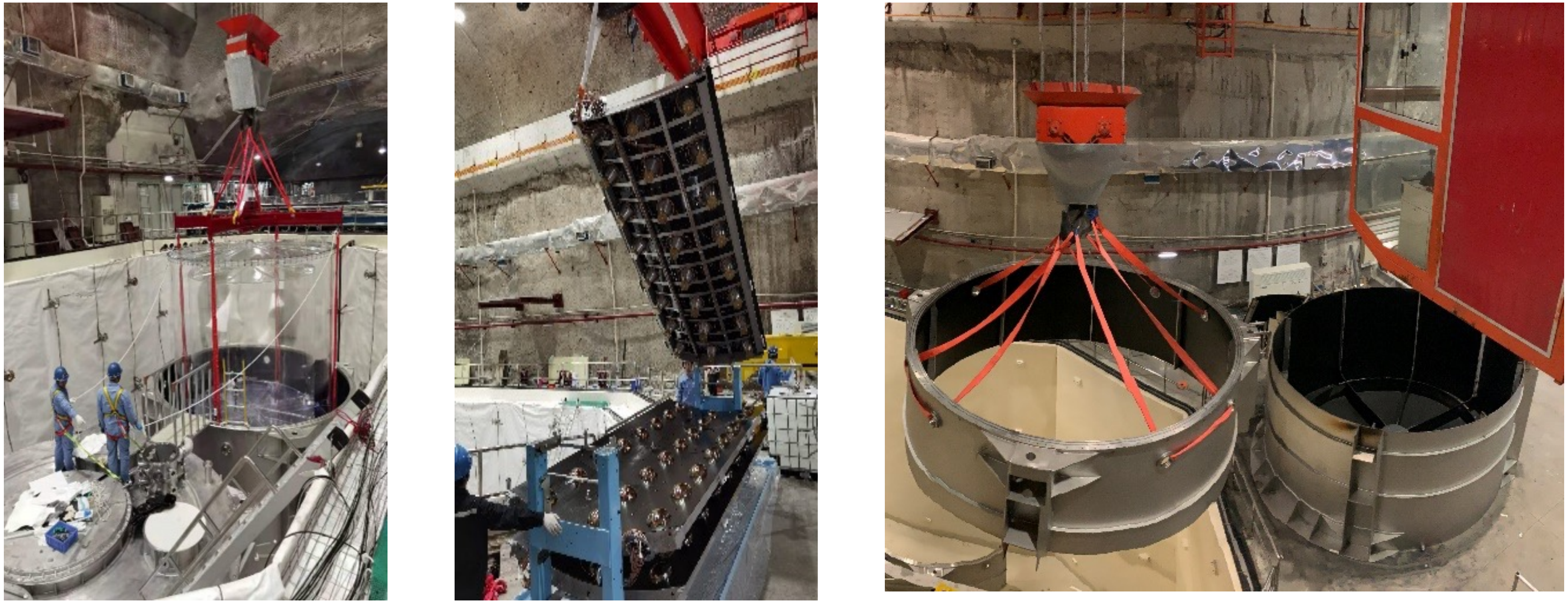
2.5-m water:

- Attenuates gamma rays & neutrons
- Forms two optically decoupled Cherenkov counters

NIM A**773** (2015) 8
NIM A**811** (2016) 133

Brief History of Onsite Operation

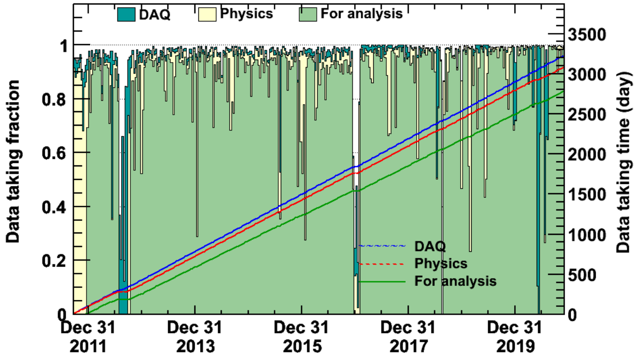
- Detector commissioning on 15 August 2011
- Collection of physics data began on 24 Dec 2011
- Collection of physics data ended on 12 Dec 2020
- Decommissioning: 12 Dec 2020 – 31 Aug 2021



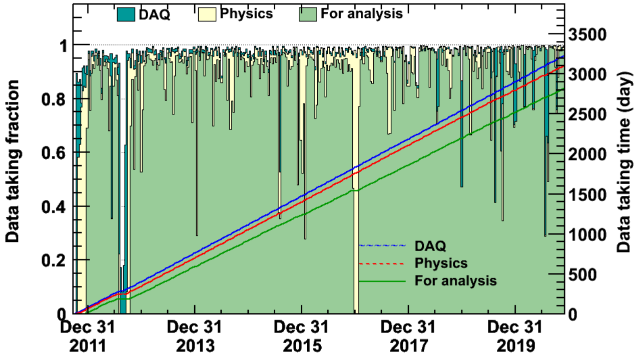
Data Acquisition

- Operational statistics:

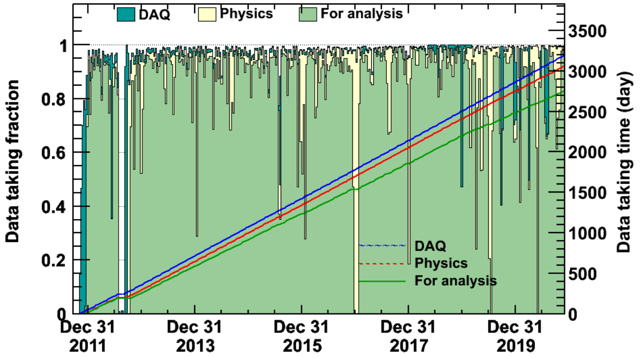
EH1



EH2



EH3



- Three physics runs:

Configuration	**EH1**	**EH2**	**EH3**	**Start date – End date**	**Duration (Days)**
6-AD	2	1	3	24 Dec 2011 – 28 July 2012	217
8-AD	2	2	4	19 Oct 2012 – 26 Dec 2016	1524
7-AD	1	2	4	26 Jan 2017 – 12 Dec 2020	1417
Total					**3158**

- Data available for analyses: ~2700 days

Latest Results

1. Precision measurement of $\sin^2 2\theta_{13}$ and Δm^2_{32} using the full neutron-capture-on-gadolinium (nGd) data set (Poster 350)
2. Joint spectral determination of reactor antineutrinos from ^{235}U and ^{239}Pu fission of Daya Bay and PROSPECT (Poster 307)
3. First measurement of high-energy reactor antineutrinos with energy between 8 MeV and 11 MeV (Poster 212)

- Some other recent results from Daya Bay in the poster session:
  - Determination of $\sin^2 2\theta_{13}$ using neutron-capture-on-hydrogen (nH) data sample (Poster 435)
  - Evolution of reactor fuel (Poster 566)
  - Search for $\overline{\nu}_e$s associated with gravitational-wave events (Poster 569)
  - Seasonal Modulation of the Muon Flux Correlated with Atmospheric Temperature (Poster 589)

Oscillation Parameters: Improvements

- Statistics of nGd data:

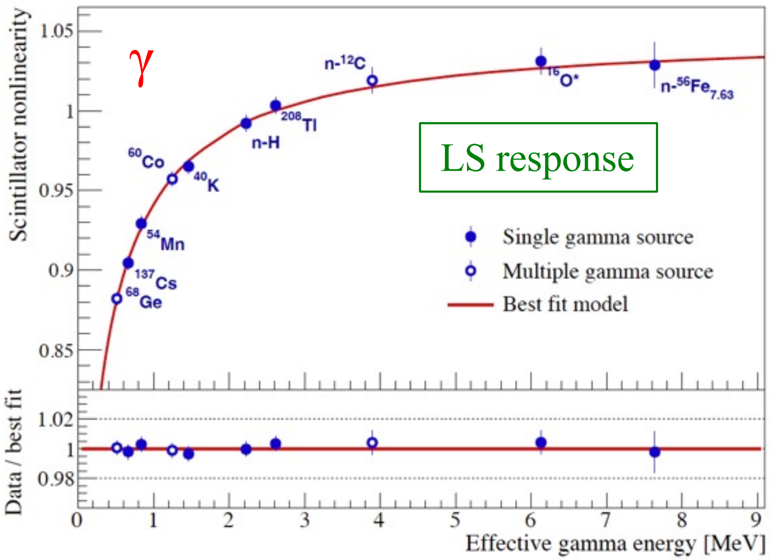
Year	Calendar days	EH1	EH2	EH3	Total IBD's
2018 (PRL **121**, 241805)	1958	1,794,417	1,673,907	495,421	3,963,745
2022	3158	2,236,810	2,544,894	764,414	5,546,118

- Analysis:
  - Energy calibration
    - 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

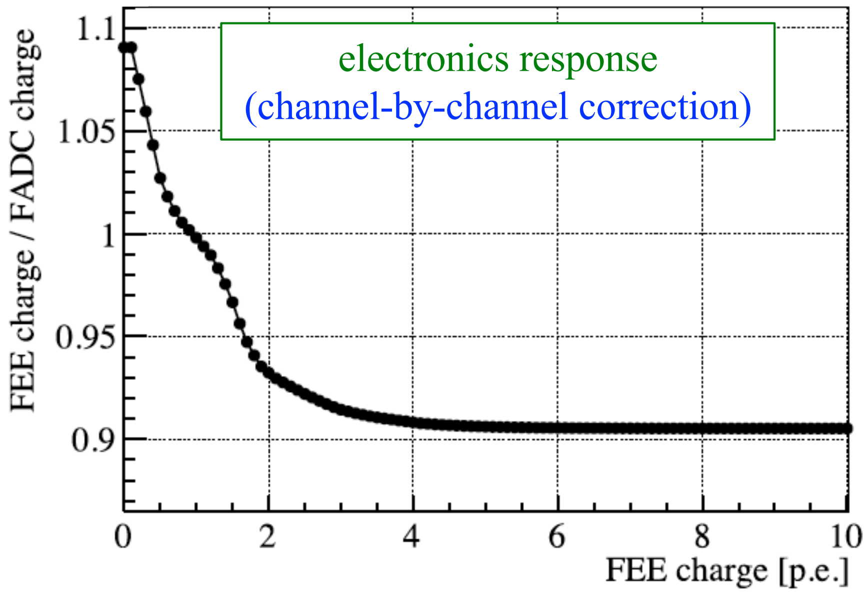
Non-linear Energy Response

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

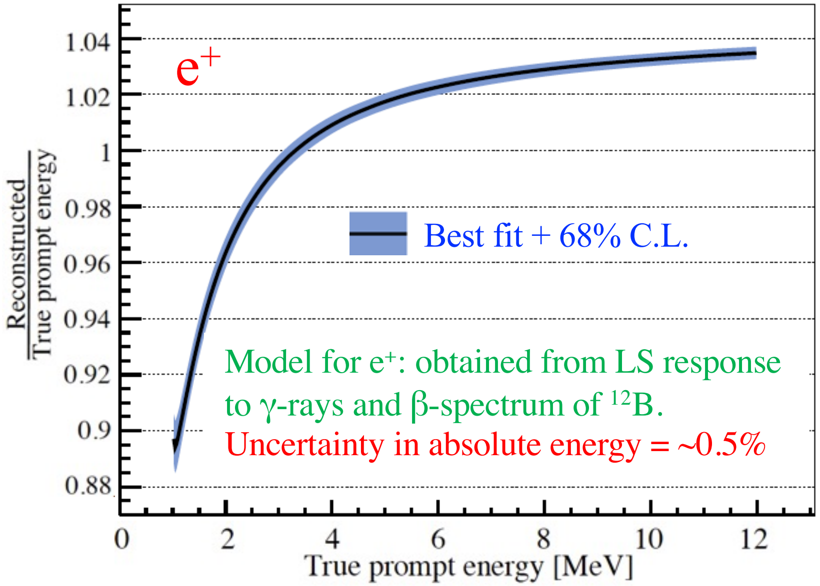
NIM A**940** (2019) 230



LS response

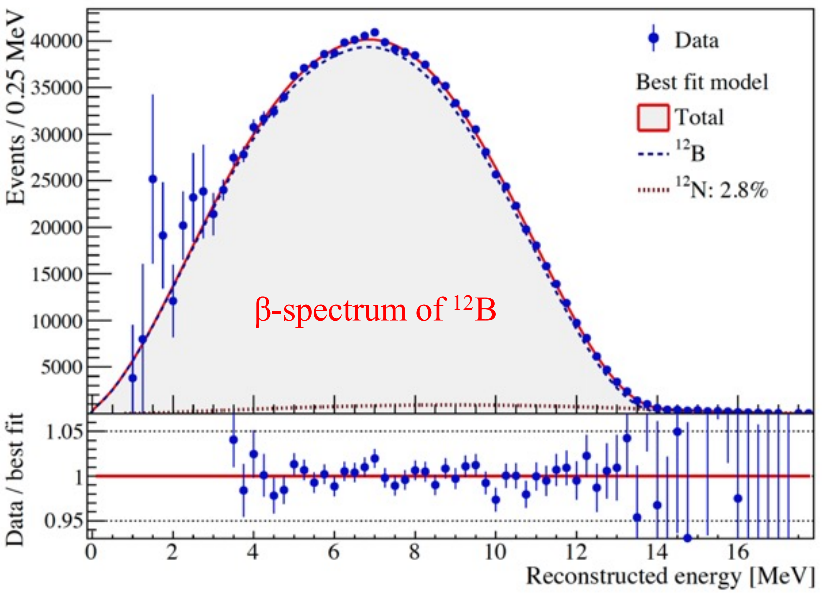


electronics response
(channel-by-channel correction)



Model for e$^+$: obtained from LS response to γ-rays and β-spectrum of ^{12}B.

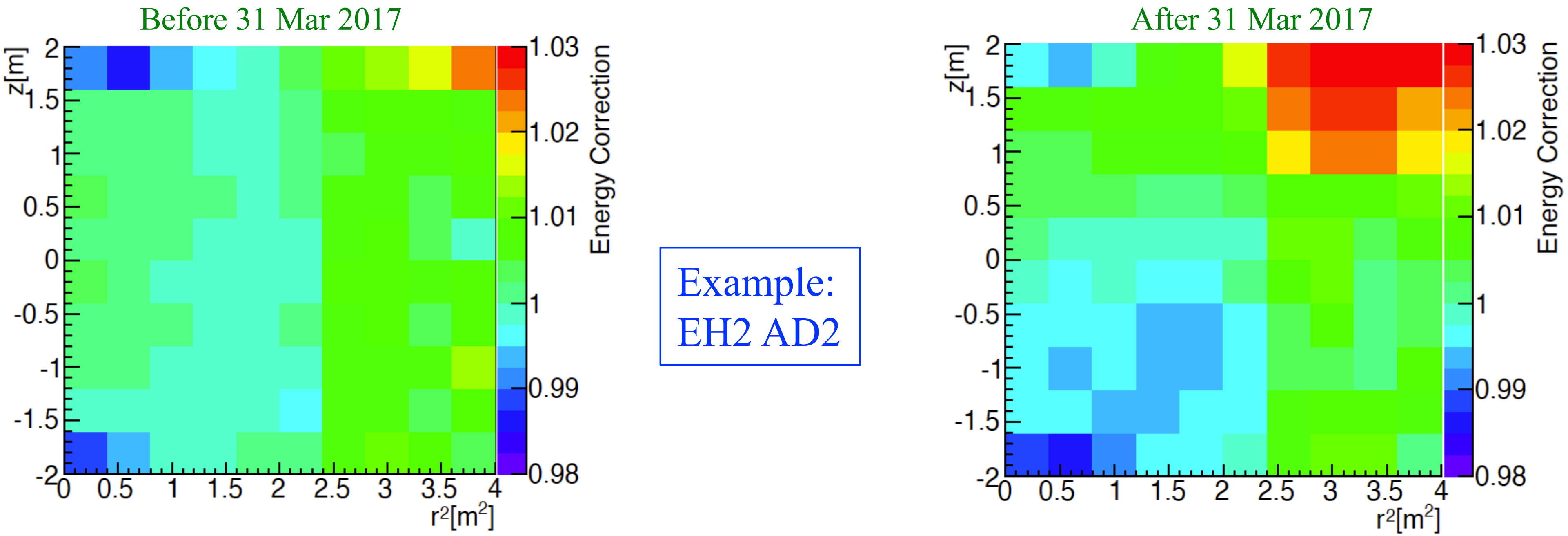
Uncertainty in absolute energy = ~0.5%



β-spectrum of ^{12}B

Improved Non-uniformity of Energy Scale

- Additional non-uniformity on top of already-corrected geometric non-uniformity
  - 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

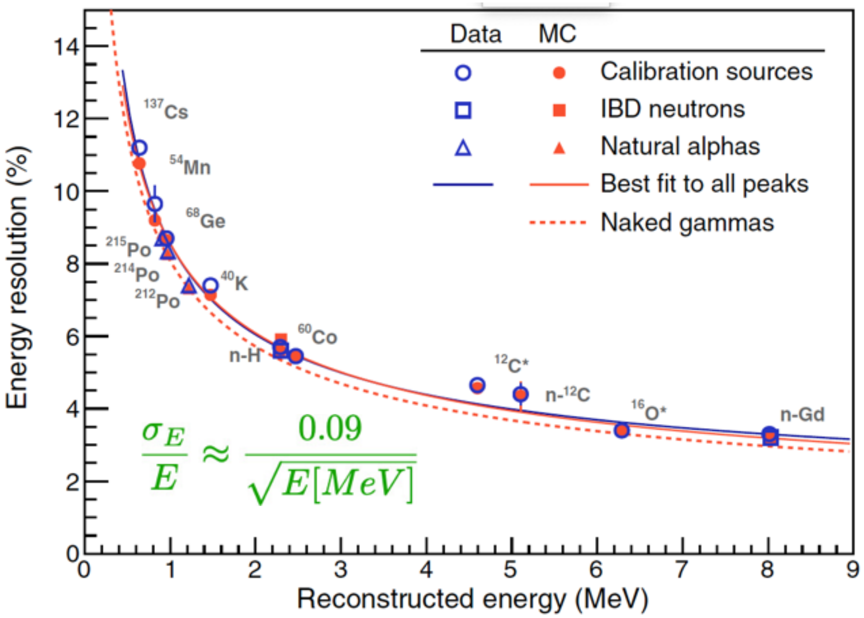


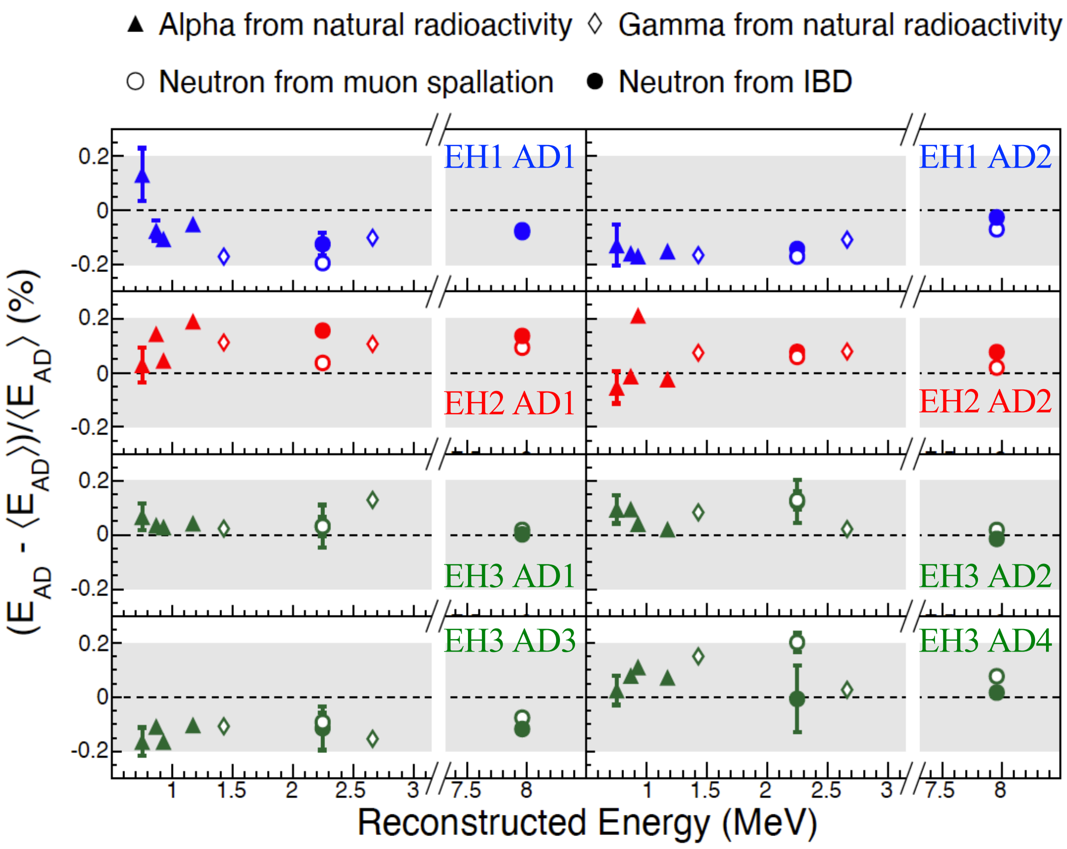
Example:
EH2 AD2

- 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%

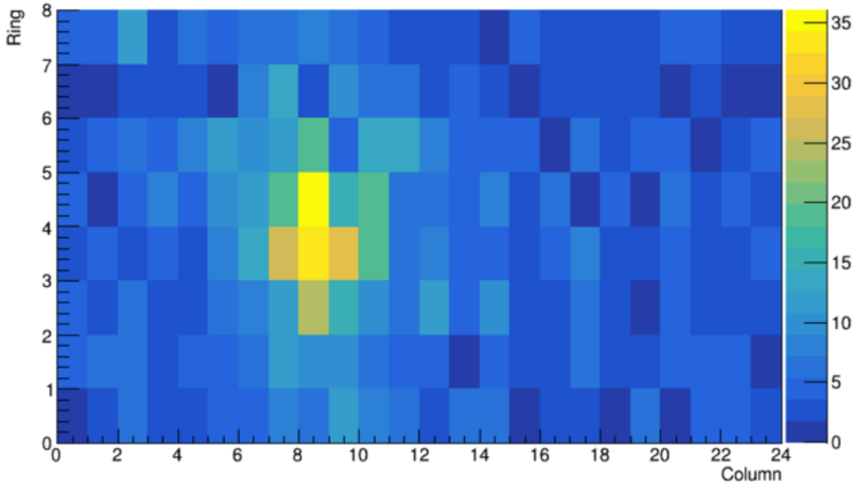
Background

- Uncorrelated background
  - Accidental
- 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

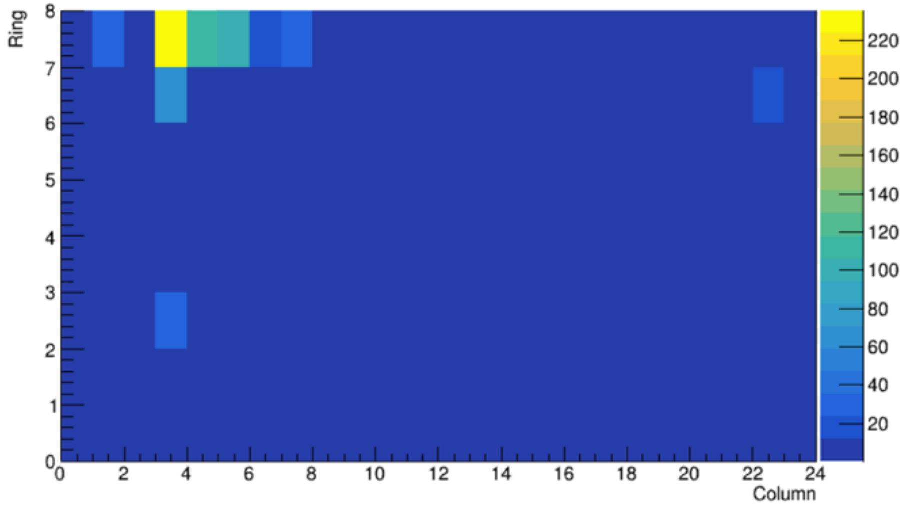
} new background

Residual PMT Flashers

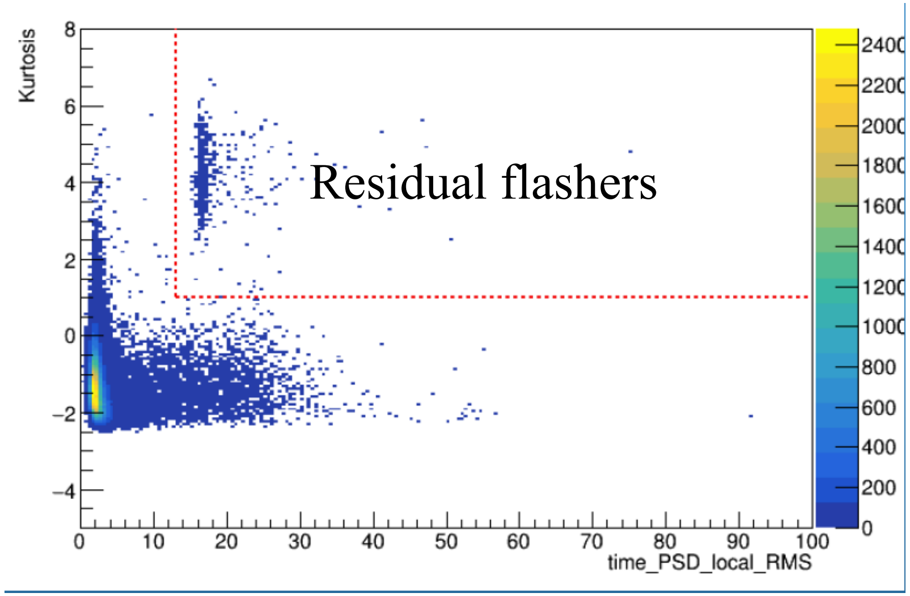
A typical singles event



A residual flasher event

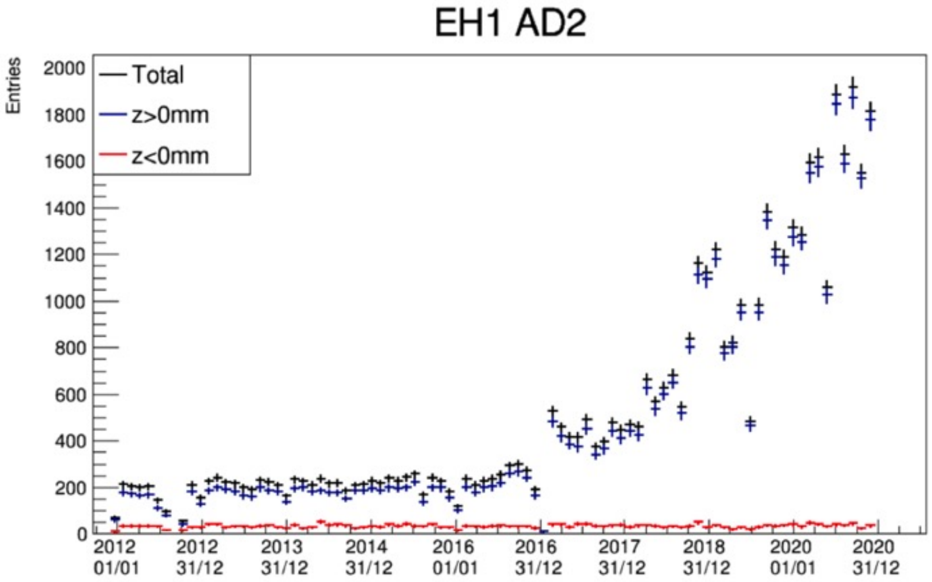


- Located near the top of some ADs
- Removed by cutting on Kurtosis and time_PSD_local_RMS
- After rejecting residual flashers,
  - Contamination in the IBD sample is negligible
  - Retain 99.997% of the IBD candidates

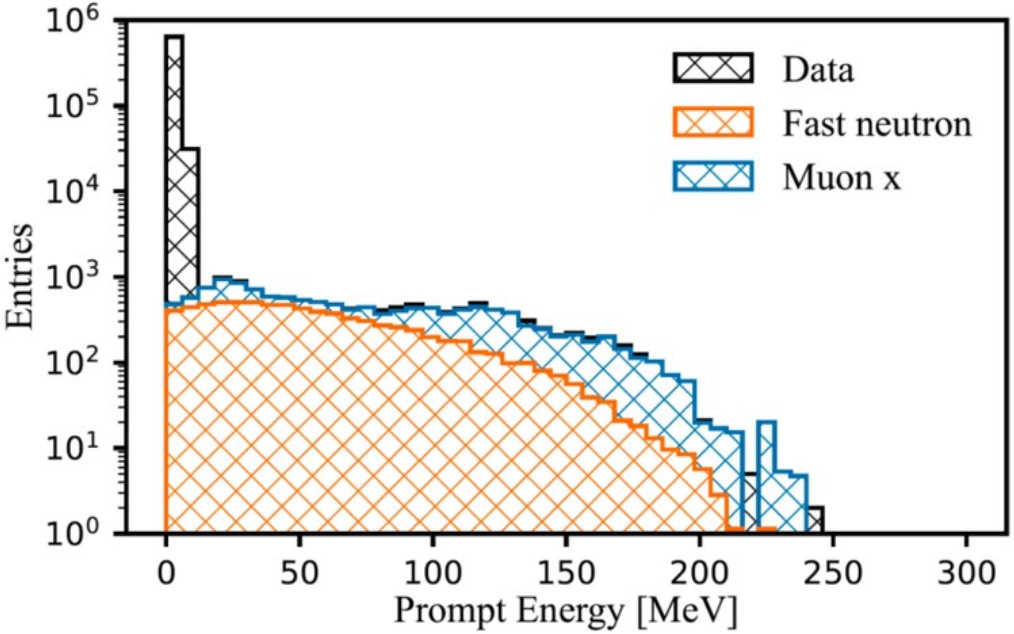


Muon-x Background

- Gradual failure of PMTs or high-voltage channels in the inner water Cherenkov counter (IWS) in the water pool since January 2017
  - Reduction in muon detection efficiency
  - Muon decays and additional spallation (muon x) in the top half of some ADs
- Lower the hit multiplicity of PMTs (nHit) in IWS from 12 to 6 to tag muons
  - Reject about 80% of muon decays
  - Extend cut on E_{prompt} from 12 MeV to 250 MeV to determine the rate and spectrum for fast neutron and muon x

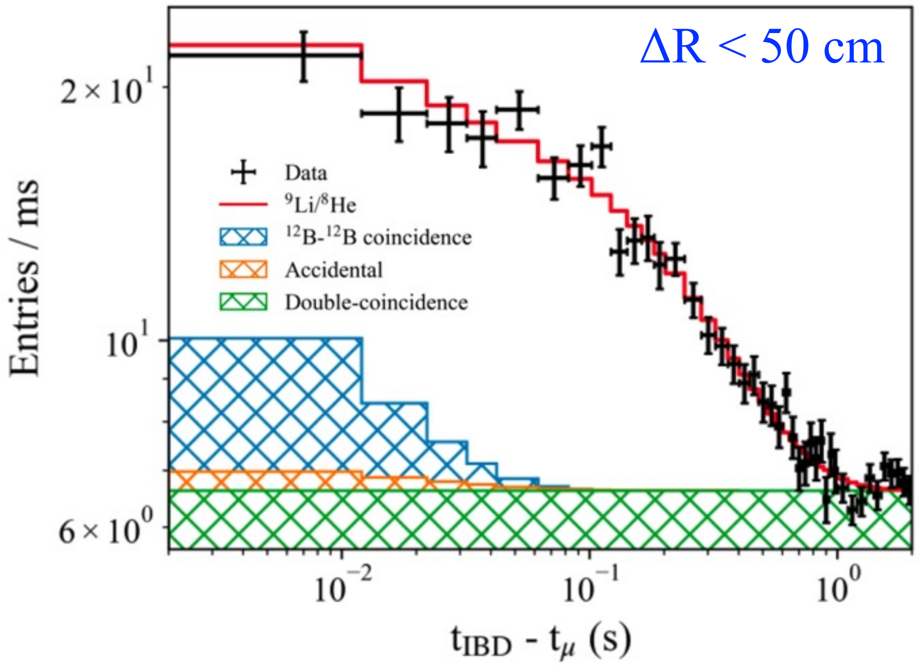


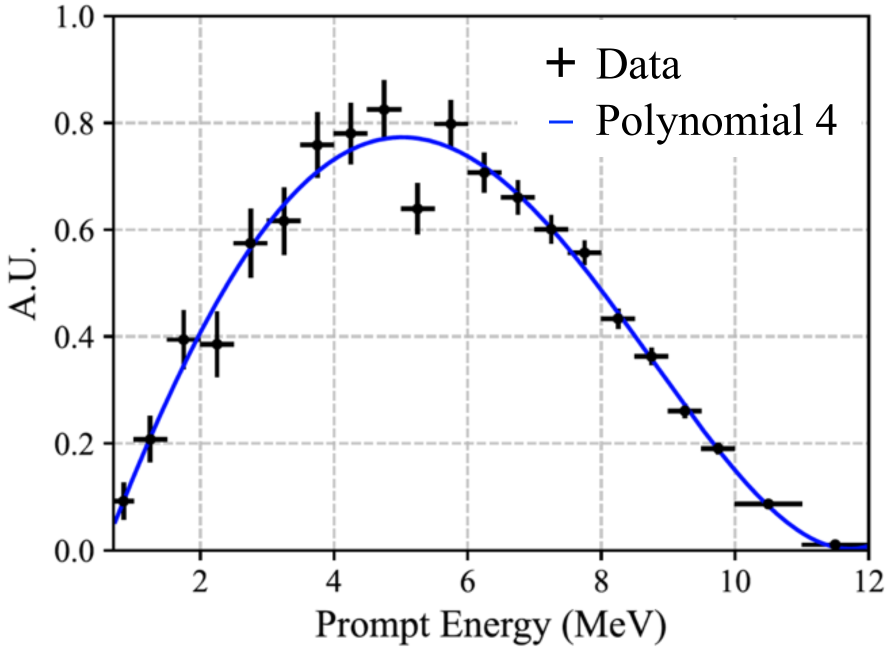
IWS nHit > 6



^{9}Li/^{8}He Background

- ^{9}Li/^{8}He
  - β-n decay
  - $\tau_{Li} = 257.2$ ms $\tau_{He} = 171.7$ 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

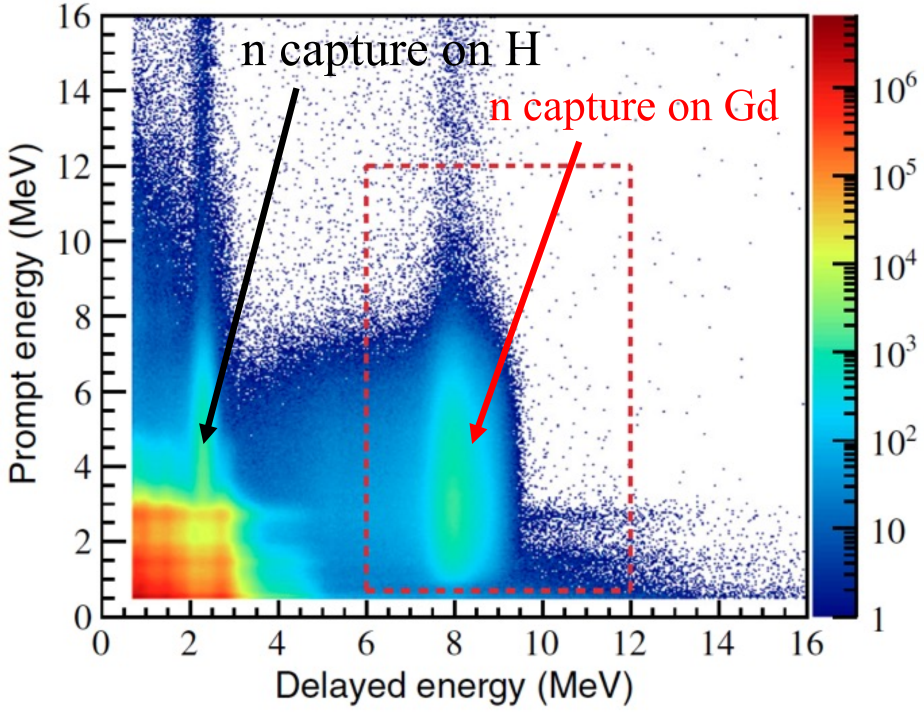




Selection of $\overline{\nu}_e$ Candidates

PRD**95** (2017) 072006

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



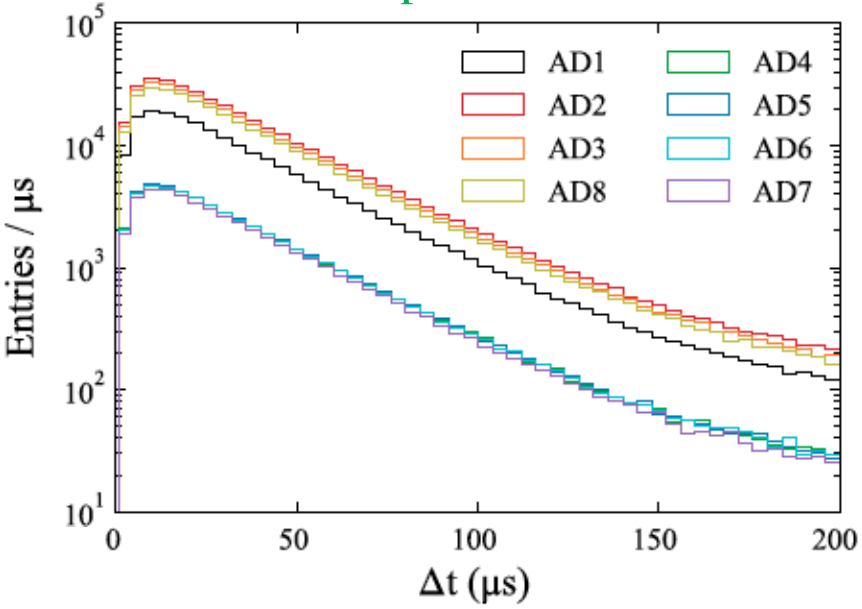
Detection efficiencies

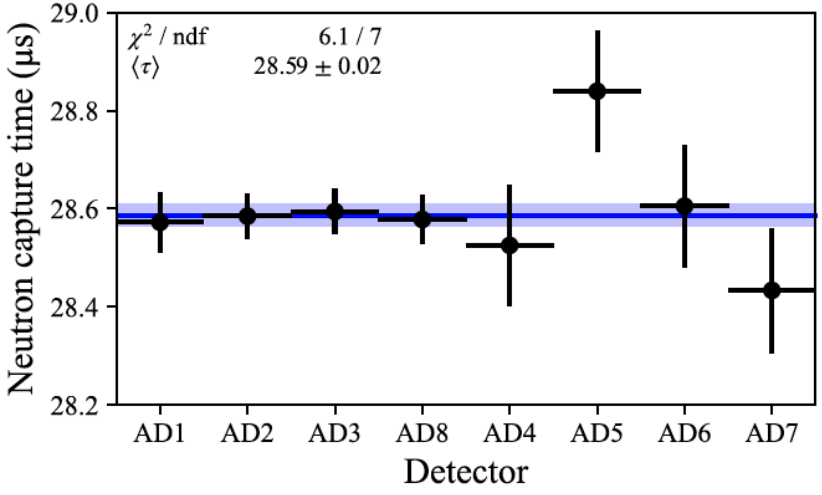
	Efficiency	Correlated	Uncorrelated
Target protons	-	0.92%	0.03%
Flasher cut	99.98%	0.01%	0.01%
Delayed energy cut	92.7%	0.97%	0.08%
Prompt energy cut	99.8%	0.10%	0.01%
Multiplicity cut		0.02%	0.01%
Capture time cut	98.7%	0.12%	0.01%
Gd capture fraction	84.2%	0.95%	0.10%
Spill-in	104.9%	1.00%	0.02%
Livetime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

Performance of Antineutrino Detectors

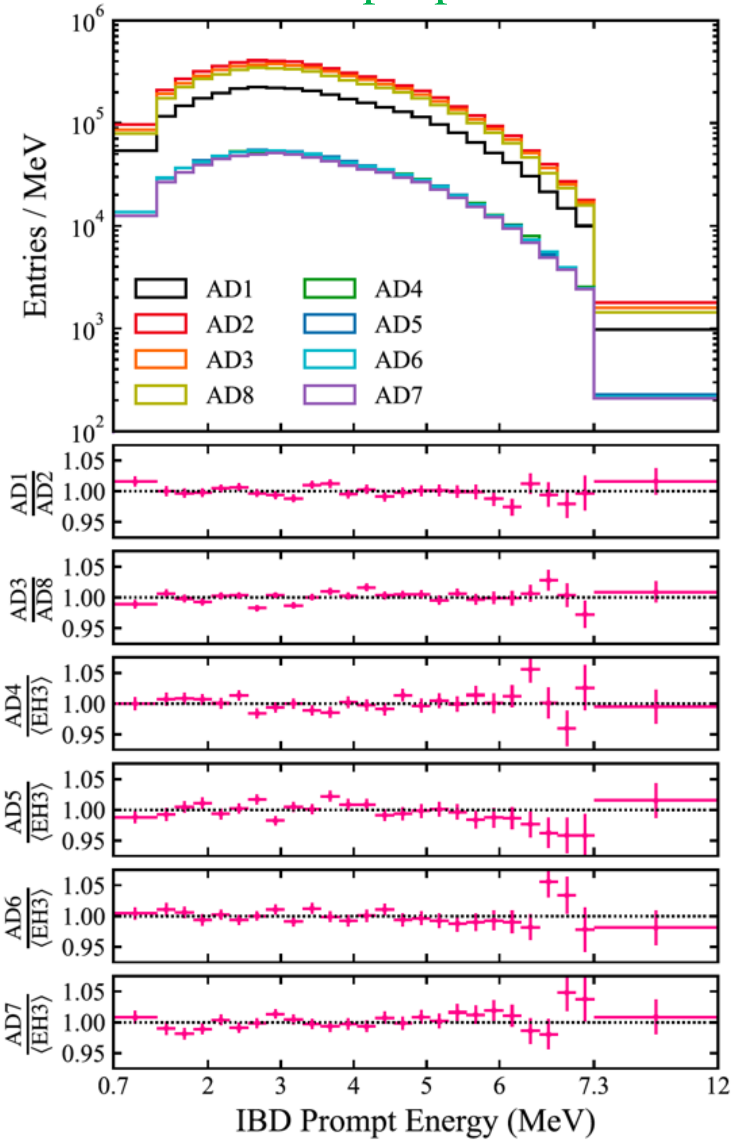
IBD candidates including background (< 3%)

Capture time





Prompt spectrum

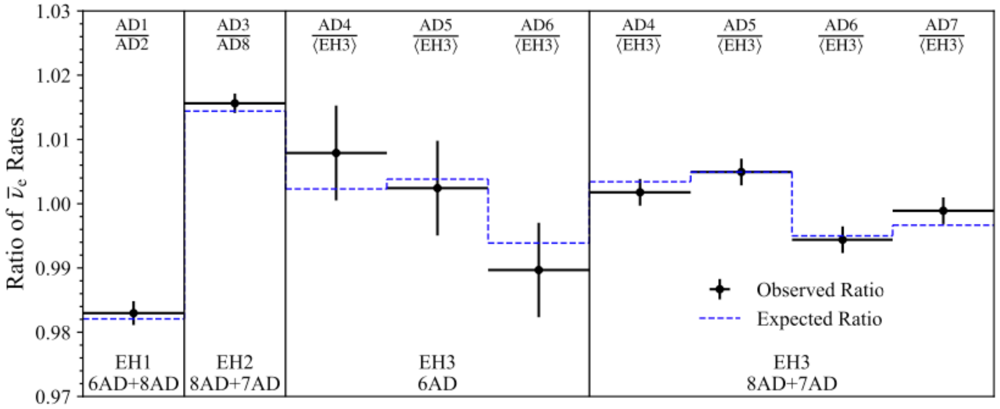


Antineutrino detectors in the same hall have similar performance

IBD Rate

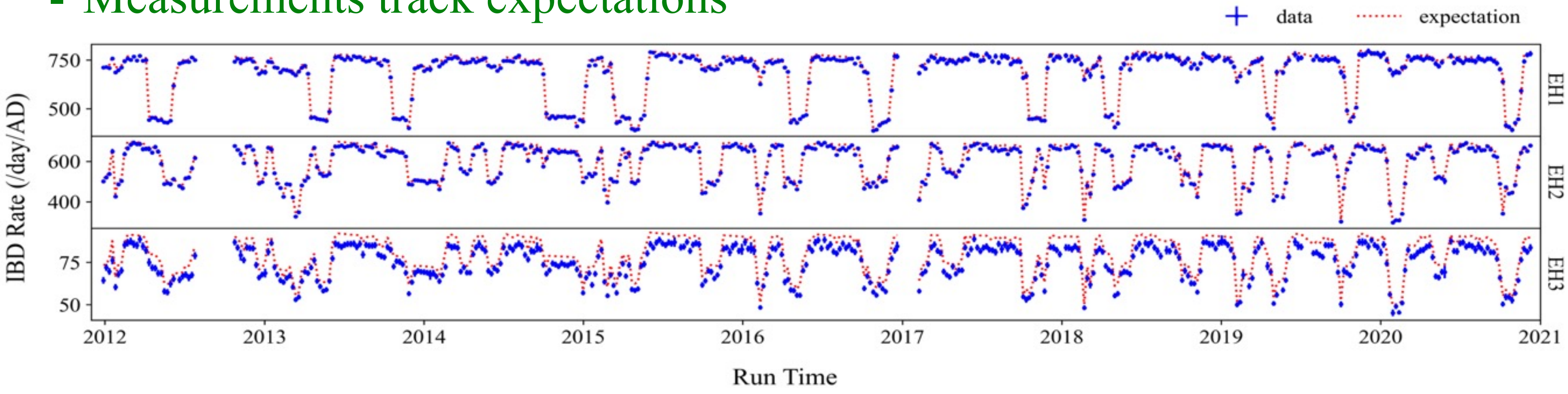
Background-subtracted

- Side-by-side comparison
  - Measurements consistent with predictions

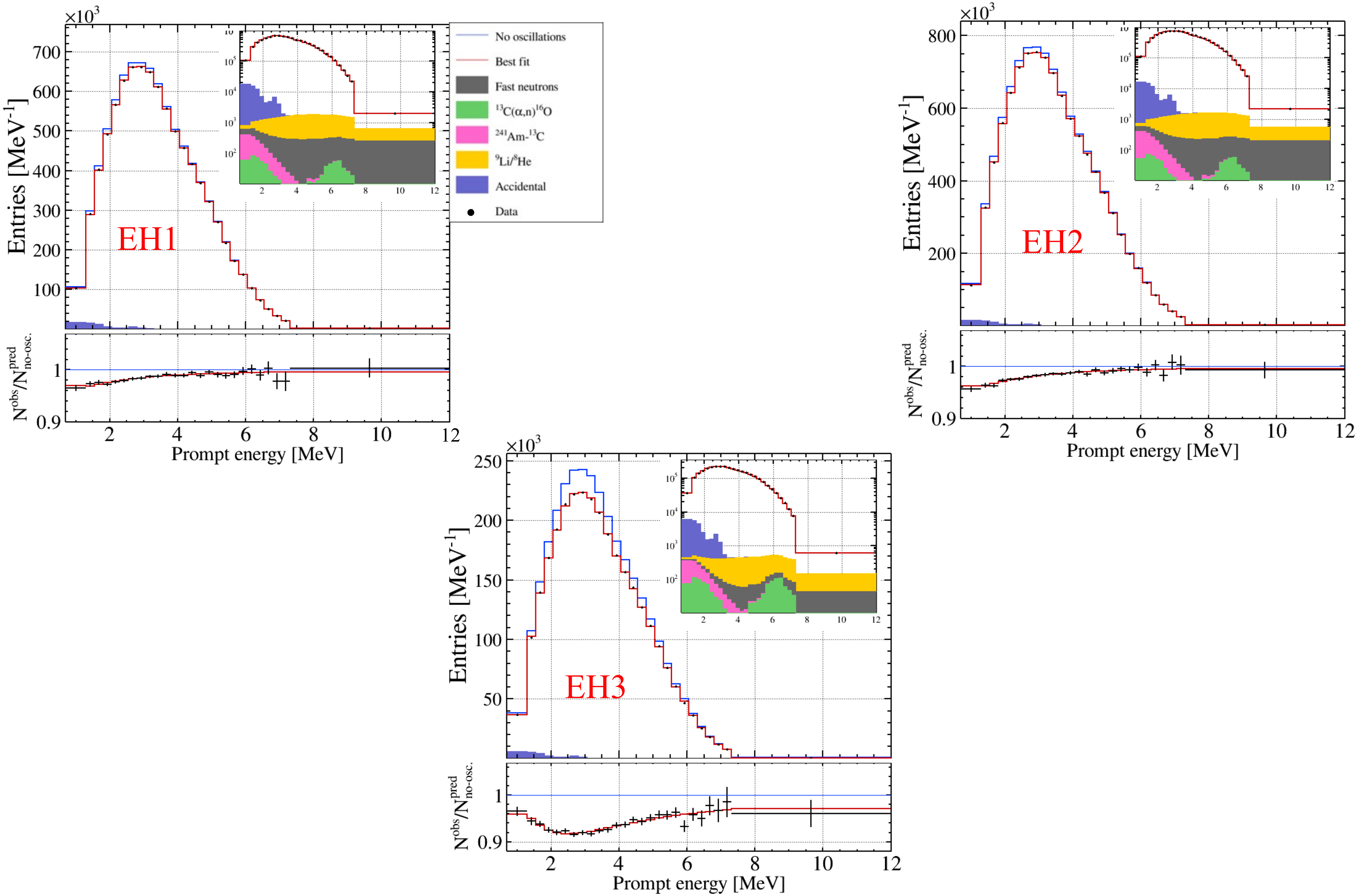


Errors include relative detection efficiency of 0.13%

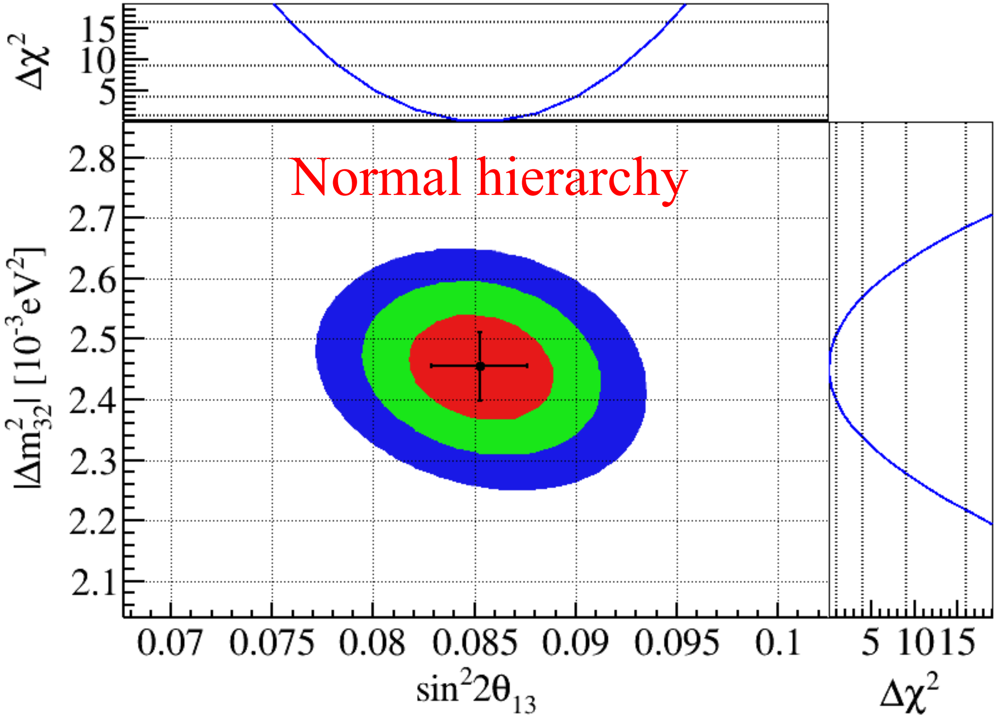
- Correlation with operation of reactors
  - Expectation based on weekly reactor operational information
  - Measurements track expectations

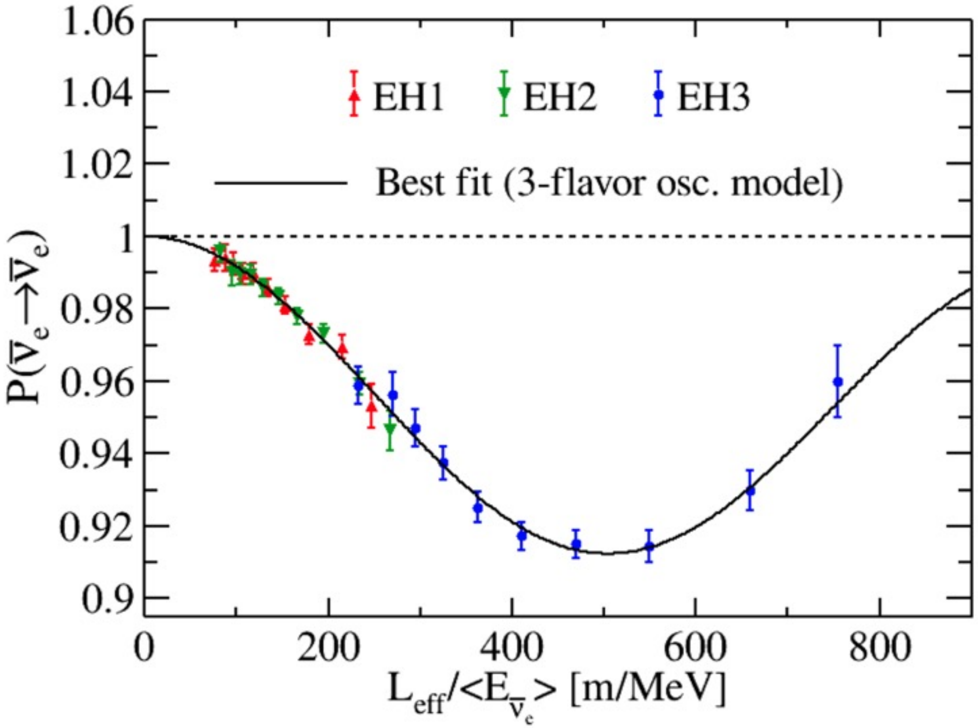


Prompt-energy Spectra



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





Best-fit results: $\chi^2/\mathrm{ndf} = 559/518$

$$\sin^2 2\theta_{13} = 0.0853^{+0.0024}_{-0.0024}$$ (2.8% precision)

Normal hierarchy: $\Delta m^2_{32} = +\left(2.454^{+0.057}_{-0.057}\right) \times 10^{-3}\ \mathrm{eV}^2$

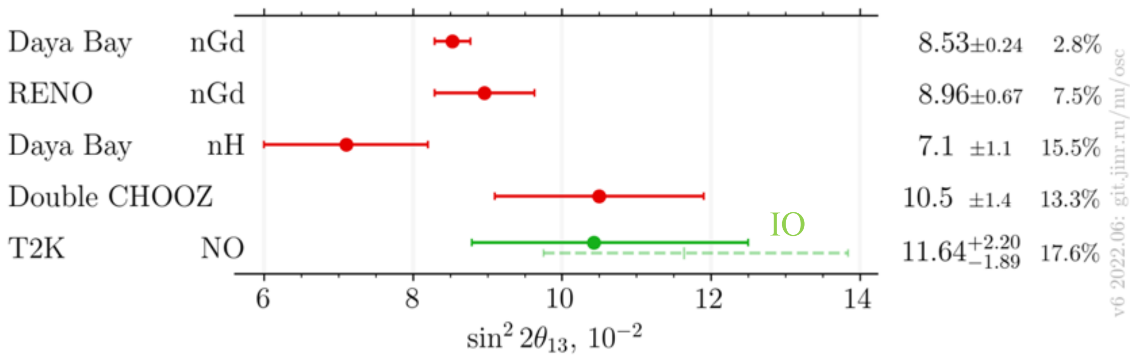
Inverted hierarchy: $\Delta m^2_{32} = -\left(2.559^{+0.057}_{-0.057}\right) \times 10^{-3}\ \mathrm{eV}^2$

(2.3% precision)

Present Global Landscape

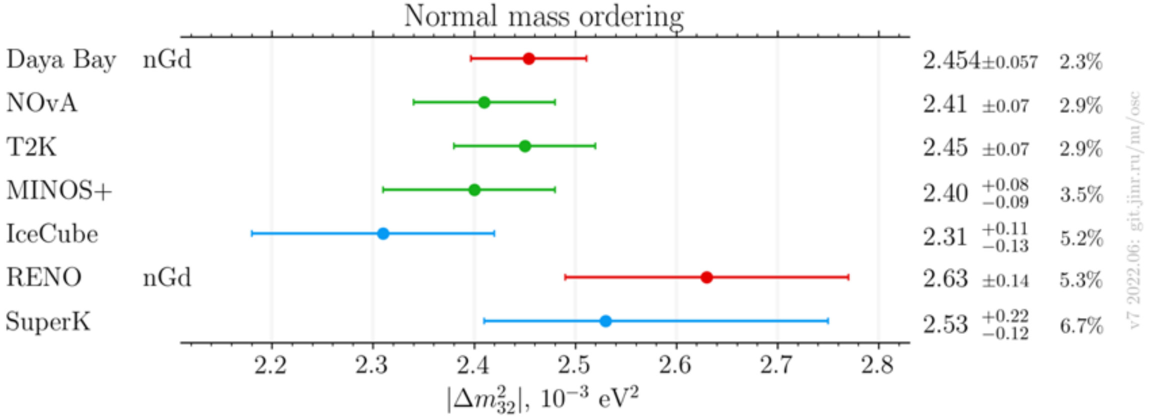
Compare Daya Bay's current results with published results

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

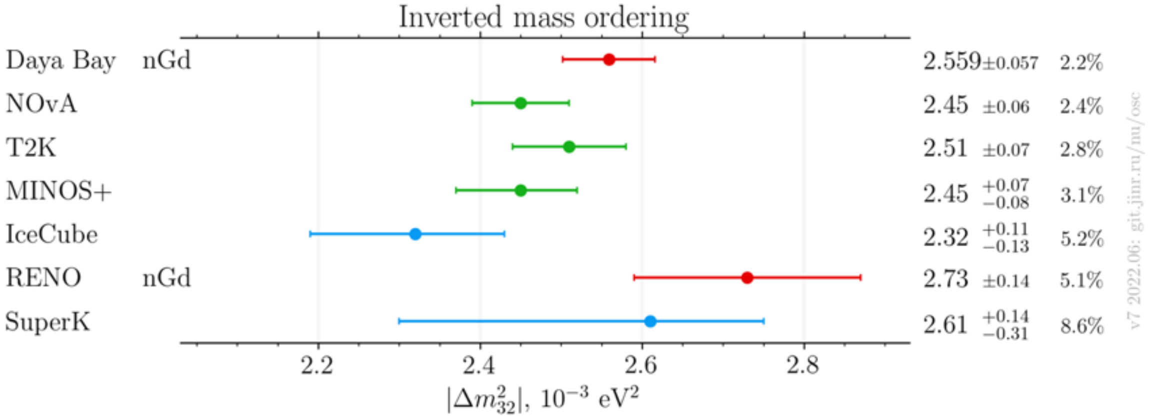


Will likely be the best measurement in the foreseeable future

Δm^2_{32} (NO)

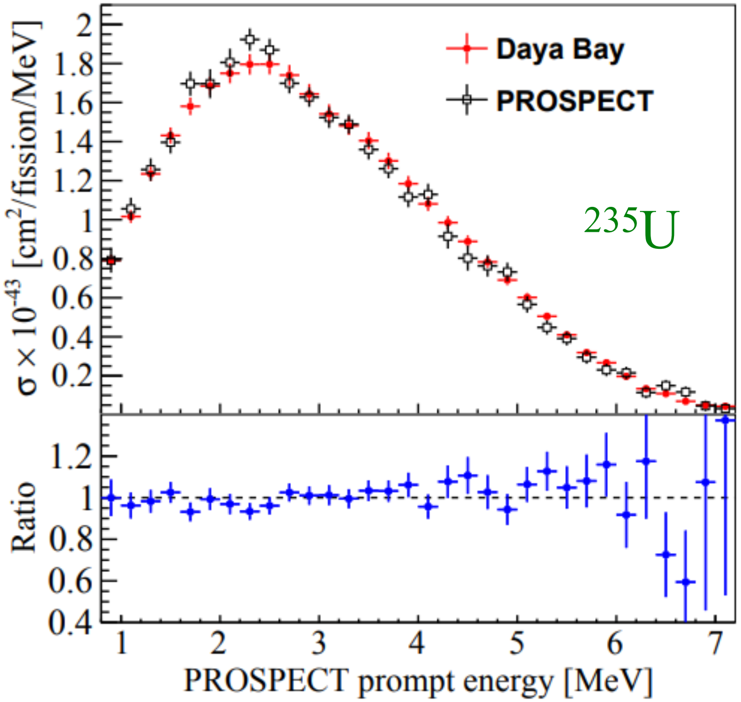


Δm^2_{32} (IO)

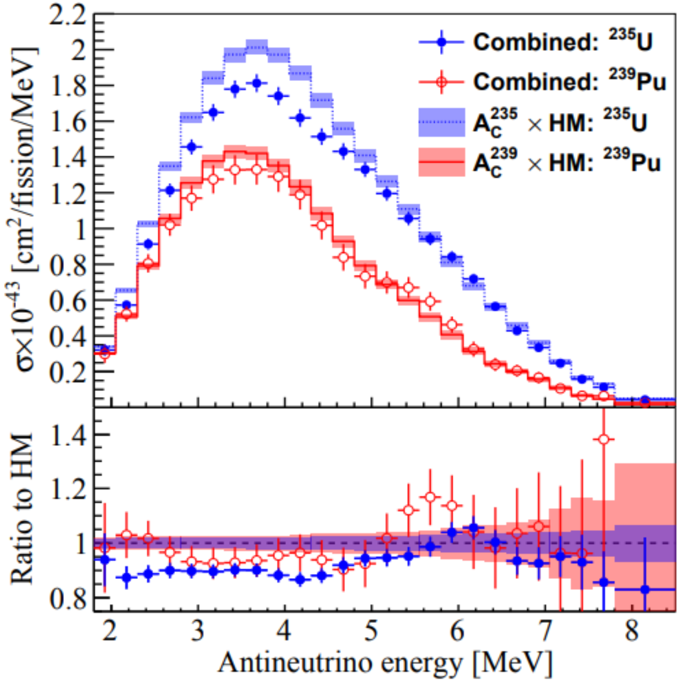


$\bar{\nu}_e$ Spectra from ^{235}U & ^{239}Pu Fission

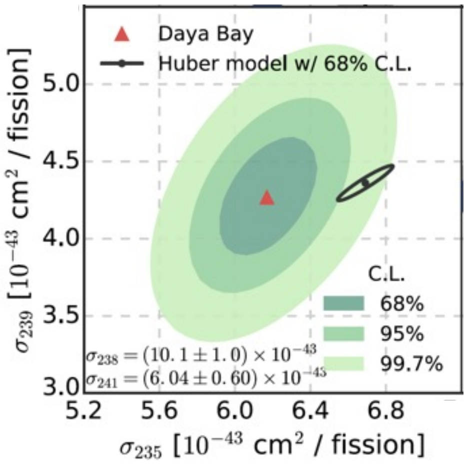
Joint effort between Daya Bay and PROSPECT (Poster 307)



PRL **128** (2022) 081801



PRL **118** (2017) 251801



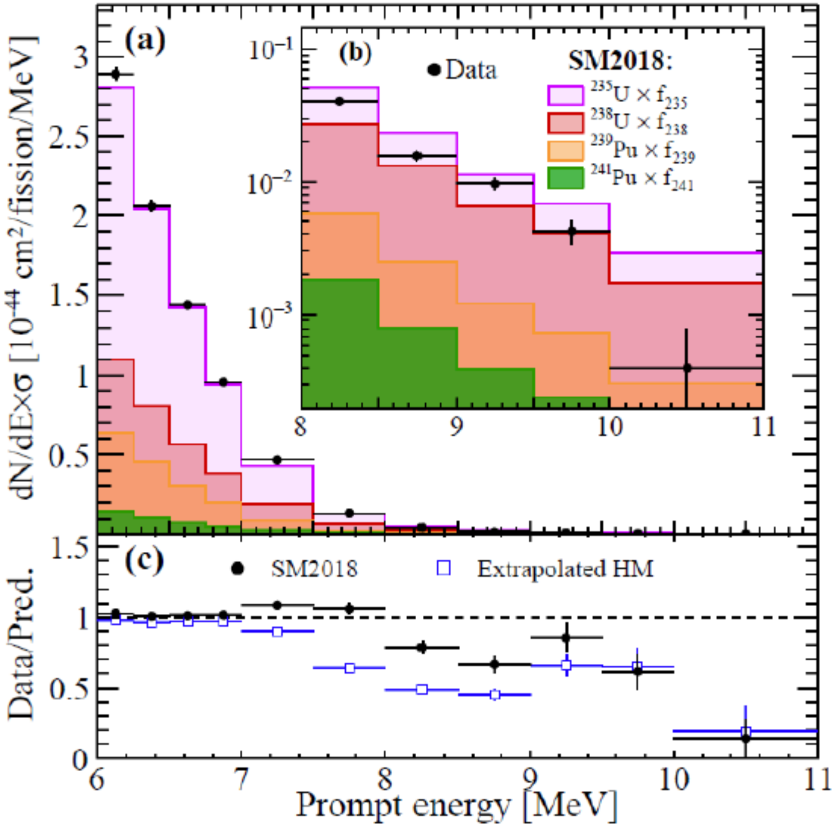
absolute $\bar{\nu}_e$ flux

- Measured spectra of Daya Bay (LEU) and PROSPECT (HEU) agree well.
- PROSPECT's prompt-energy spectrum as constraint in Daya Bay's fit
  - Improve spectral shape of ^{235}U to 3%
  - No obvious improvement to the spectrum of ^{239}Pu
  - Reduce degeneracy in spectra of ^{235}U and ^{239}Pu by ~20%

- Both Daya Bay's measured absolute flux and spectrum of $\bar{\nu}_e$ from
  - ^{239}Pu fission: in reasonable agreement with Huber-Mueller model (HM)
  - ^{235}U fission: disfavor HM significantly

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

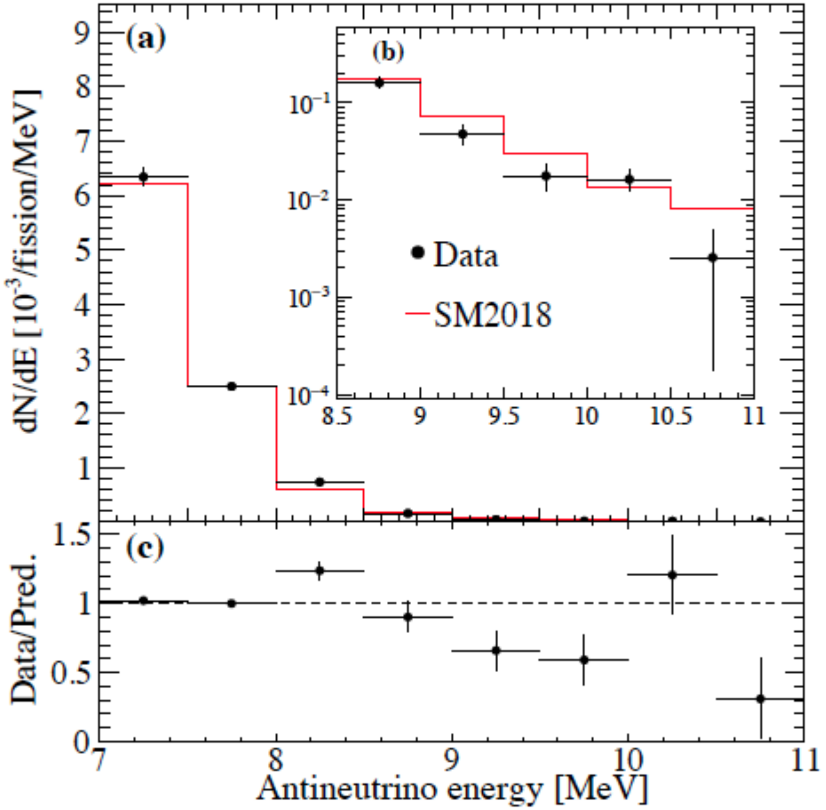
- Can come from high-Q β-decay of short-lived isotopes, e.g. ^{88,90}Br, ^{94,96,98}Rb
- Use the 1958-day data set to extract IBD and background events together from a fit,
  - obtain 2500 IBD events with $8 < E_{prompt} < 12$ MeV



$f_{235} = 0.564$
$f_{238} = 0.076$
$f_{239} = 0.304$
$f_{241} = 0.056$

After unfolding

arXiv: 2203.0668 [hep-ex]
Poster 212



- Updated Summation Model (SM2018):
  - 3% more for 6-8 MeV, 29% less for 8-11 MeV
- Extrapolated HM:
  - Larger disagreement above 7 MeV

- Hypothesis of no reactor $\bar{\nu}_e$ with $E_\nu > 10$ MeV is ruled out at 6.2σ

Summary

- Daya Bay
  - Has 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 $\overline{\nu}_e$
    - Evolution of absolute reactor $\overline{\nu}_e$ flux and spectrum
  - Will have more results to be presented in the future, for example,
    - Updated results on oscillation parameters with nH samples

- Daya Bay plans to archive data that will be open to the scientific community
  - We request proposals from the community to use this open-access data

The Daya Bay Collaboration

Thank You! 고마워요!