Updated Results from the Daya Bay Experiment

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(On behalf of the Daya Bay Collaboration)

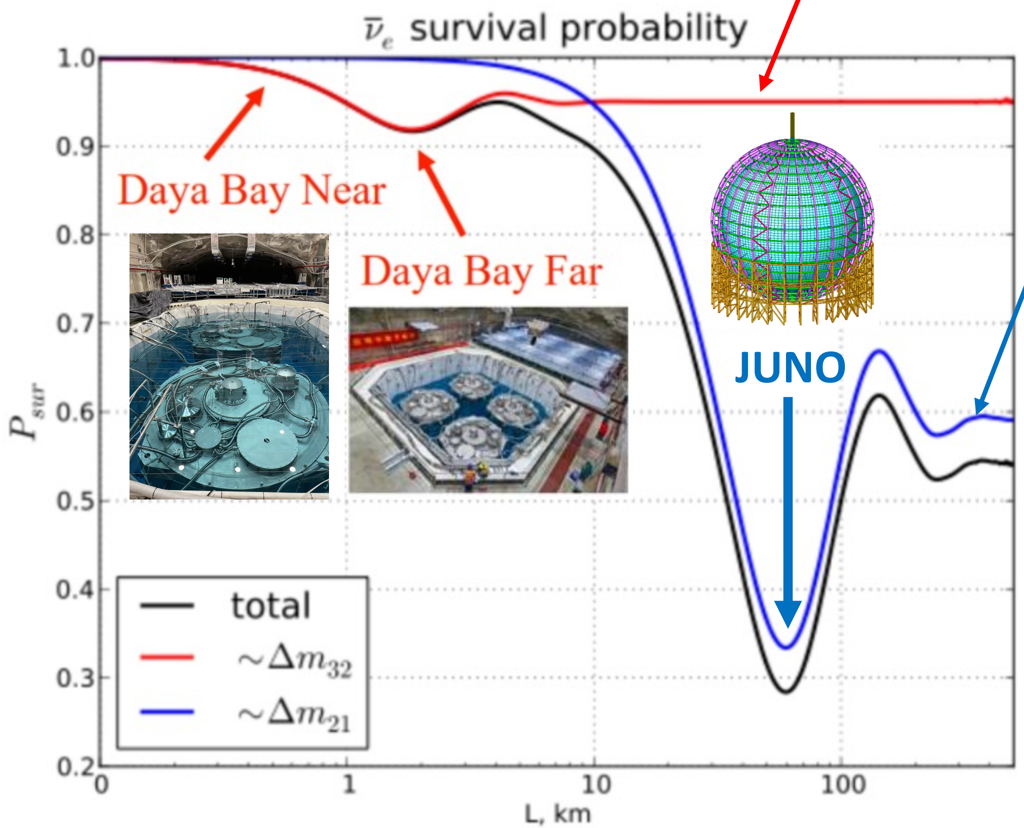
NNN23, Procida, 11 Oct 2023

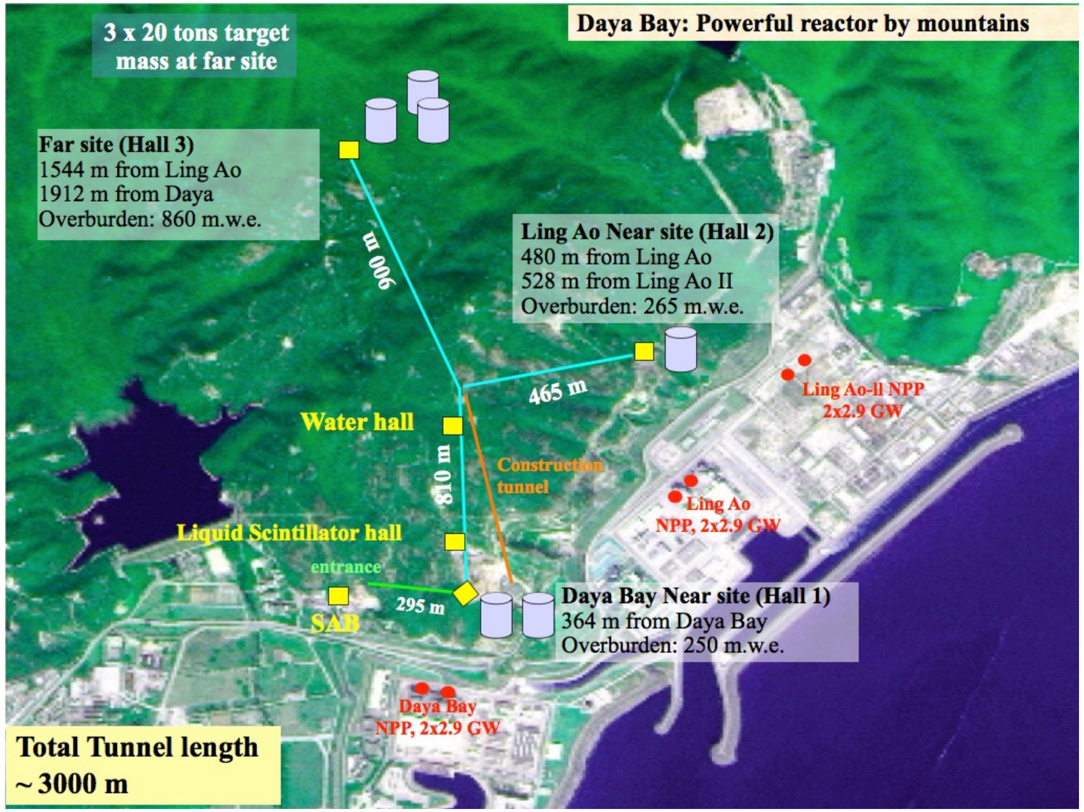
Measure θ_{13} with reactor $\bar{\nu}_e$

- Survival Probability

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

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





- Reduce systematic uncertainties by performing relative measurements with Far/Near ratio

Antineutrino Detectors (ADs)

- Detect inverse β-decay reaction (IBD)

prompt, delayed

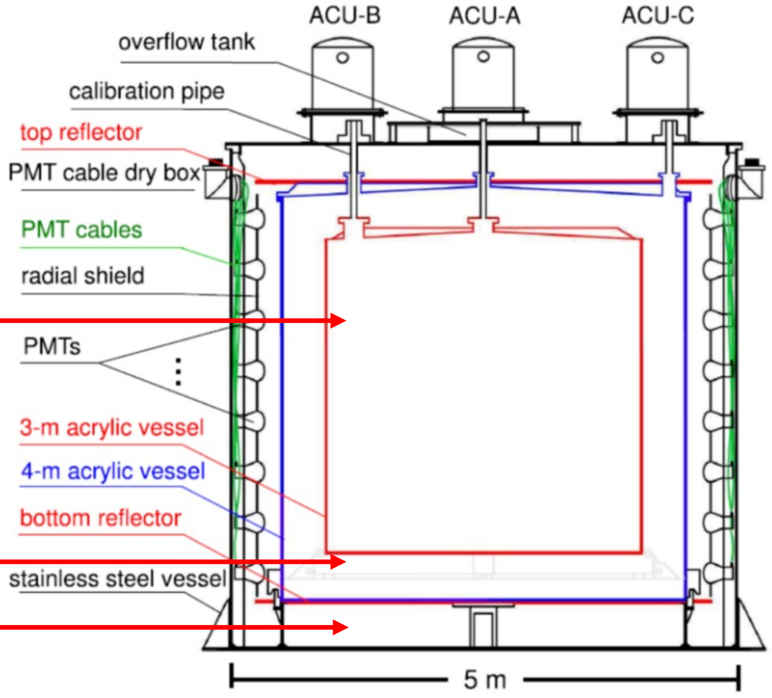
$$\overline{\nu}_e + p \rightarrow e^+ + n$$

↳ ~180 μs: $+ p \rightarrow d + \gamma$ (2.2 MeV)

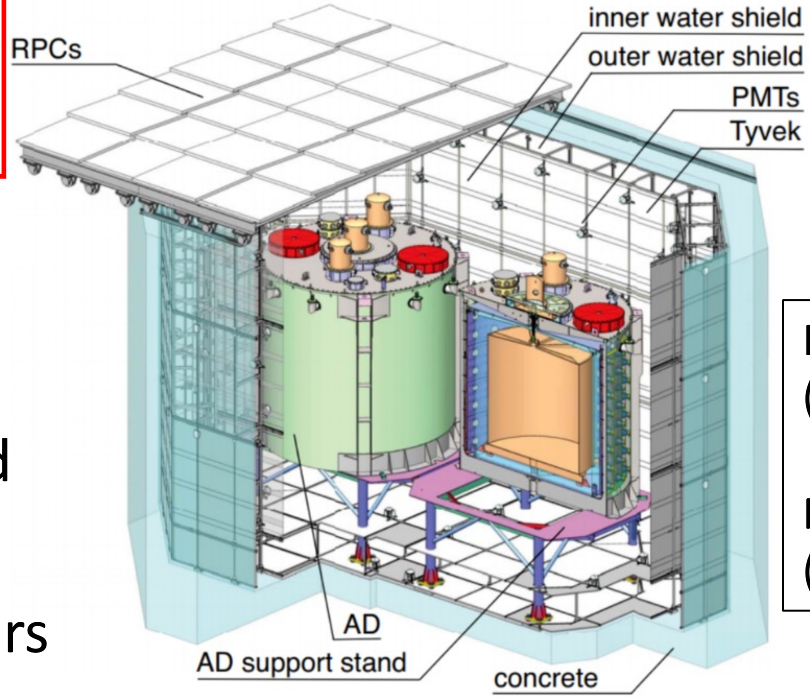
↳ $+ Gd \rightarrow Gd^*$ (~30 μs for 0.1% Gd)

↳ $Gd + \gamma$'s (~8 MeV)

- 20-t 0.1% Gd-loaded liquid scintillator as target
- 21-t LS as gamma catcher
- 40-t mineral oil as shielding
- 192 photomultiplier tubes (PMTs)



- Water pools as shielding against cosmic muons and neutrons
- Provide two optically decoupled Cherenkov counters

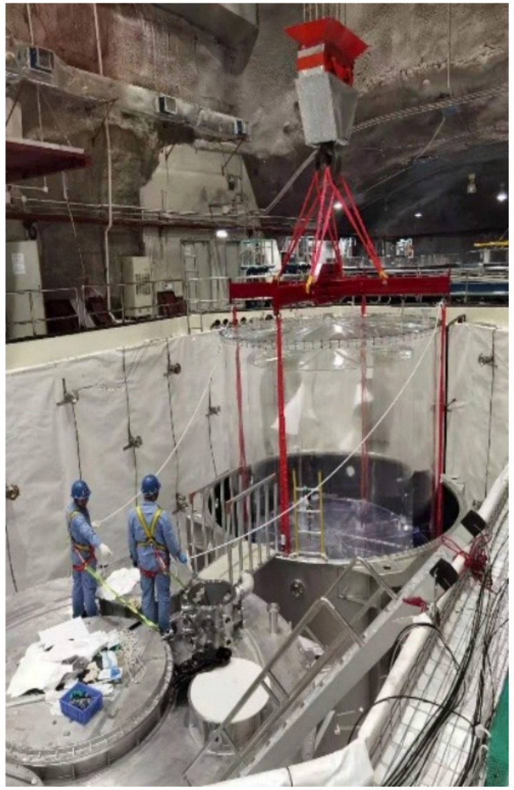
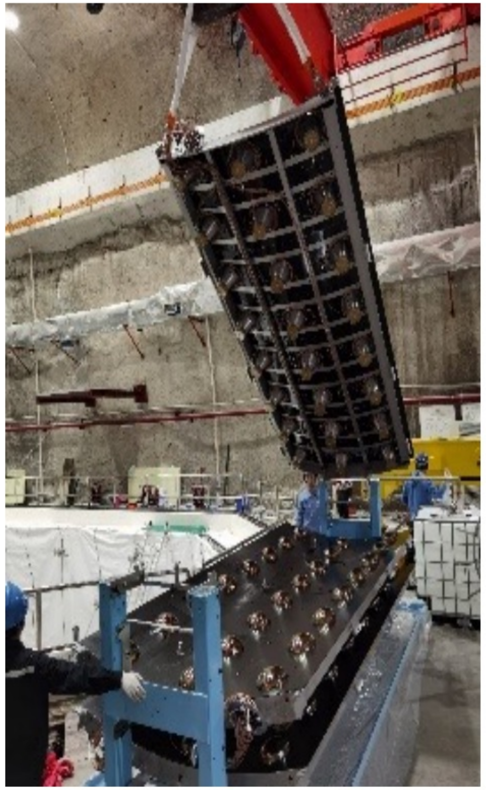


NIM A773 (2015) 8;

NIM A811 (2016) 133

Brief History of Onsite Operation

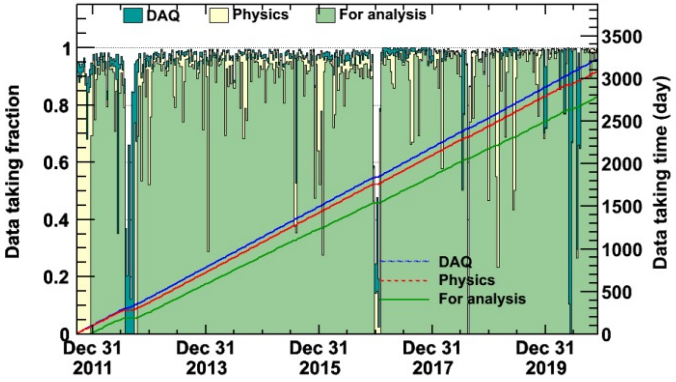
- Detector commissioning on 15 Aug 2011
- Collection on physics data began on 24 Dec 2011
- Collection on physics data ended on 12 Dec 2020
- Decommissioning: 12 Dec 2020 – 31 Aug 2021

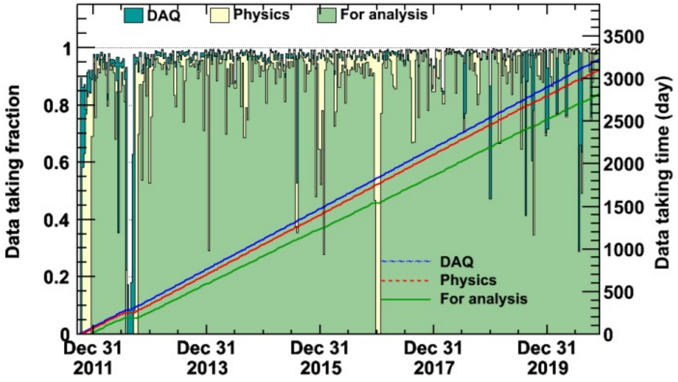

Data Collection

- Operational statistics:

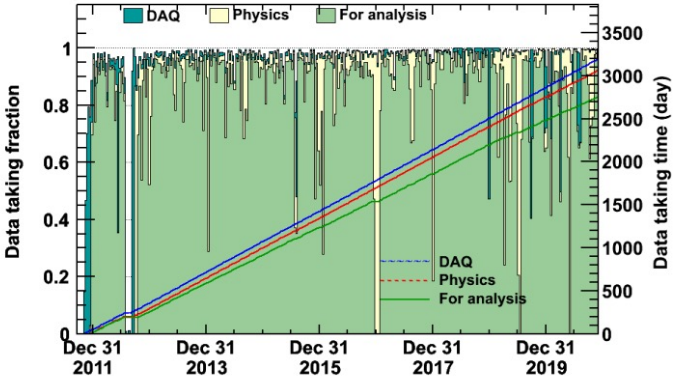
EH1



EH2



EH3



- Three physics runs:

Configuration	EH1	EH2	EH3	Start date – End date	Duration (days)
6-AD	2	1	3	24 Dec 2011 – 28 Jul 2012	217
8-AD	2	2	4	19 Oct 2012 – 20 Dec 2016	1524
7-AD	1	2	4	26 Jan 2017 – 12 Dec 2020	1417
Total					3158

- Data available for analyses: ~ 2700 days

Oscillation Parameters: Improvements

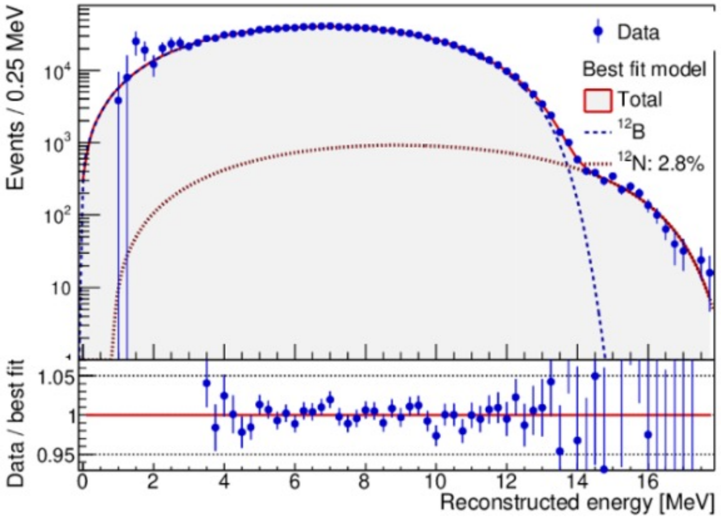
- Statistics of nGd data

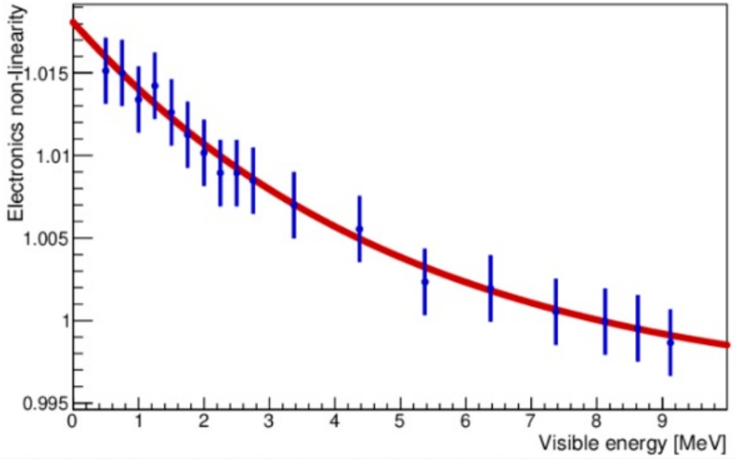
Year	Calendar days	EH1	EH2	EH3	Total IBD's
2018 (PRL 121, 241805)	1958	1,794,417	1,673,907	495,421	3,963,745
2023 (PRL 130, 161802)	3158	2,236,810	2,544,894	764,414	5,546,118

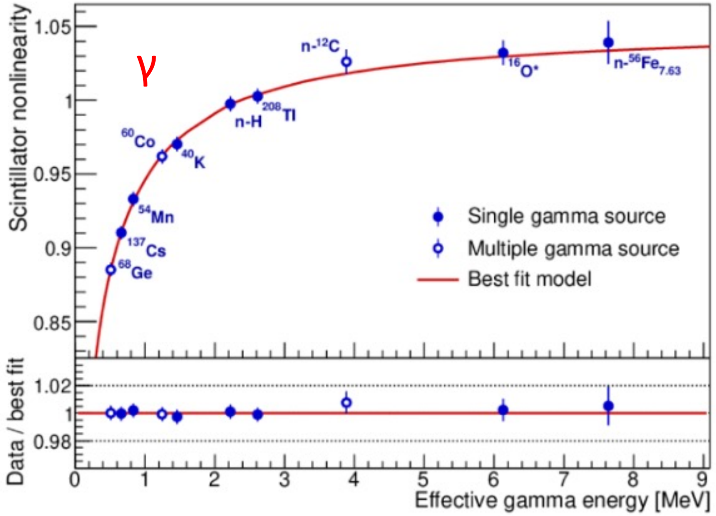
- Analysis:
  - **Energy Calibration**
    - Electronics non-linearity calibrated at the channel-by-channel level
    - Improvement on non-uniformity correction
  - **New correlated background after 2017**
    - Remove additional very rare PMT flashers
    - Suppress and identify untagged muon events
  - **Correlated background**
    - New approach to determine the $^{9}Li/^{8}He$ background

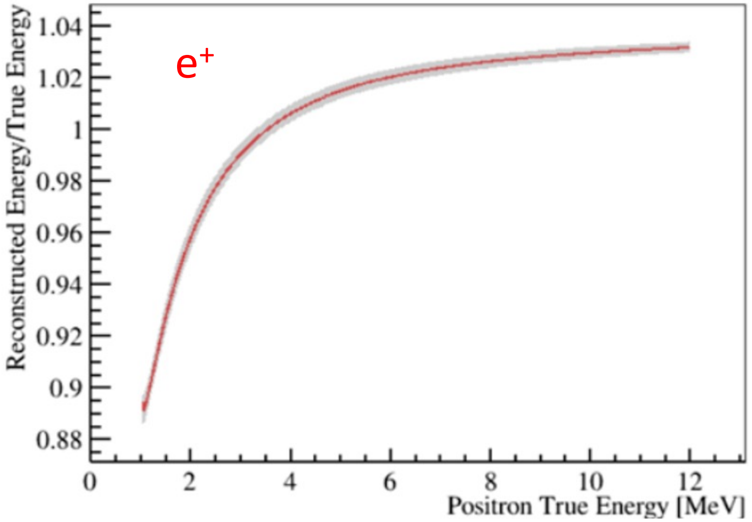
Non-linear Energy Response

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



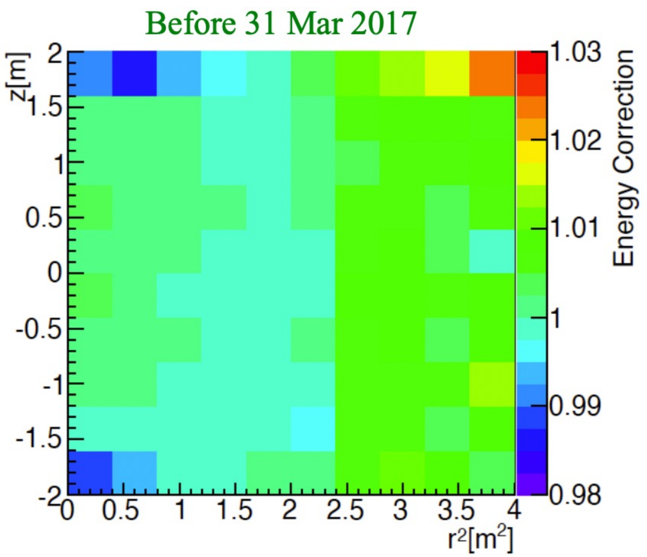




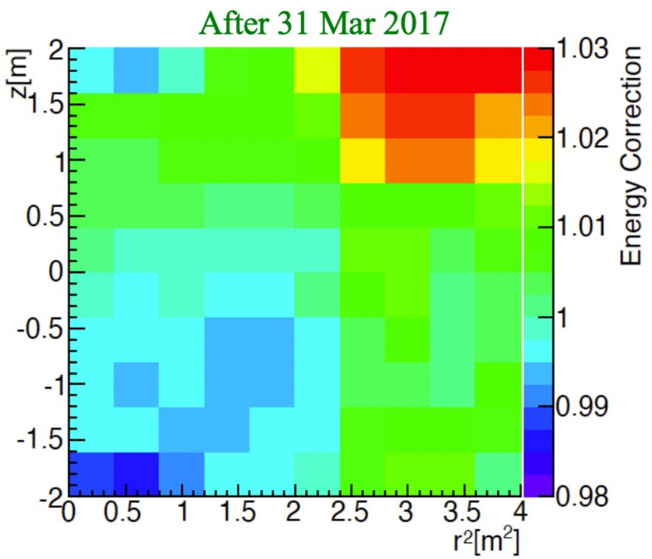


Improved Non-uniformity of Energy Scale

- 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



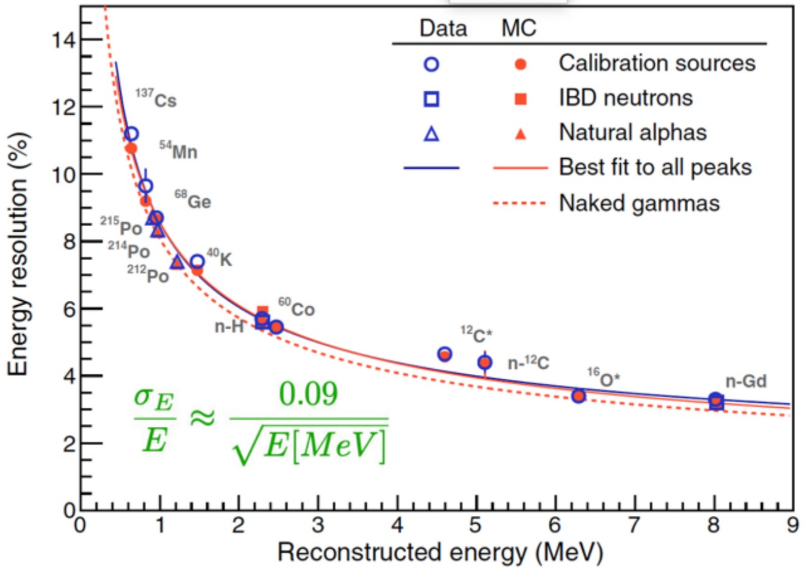
Example:
EH2 AD2

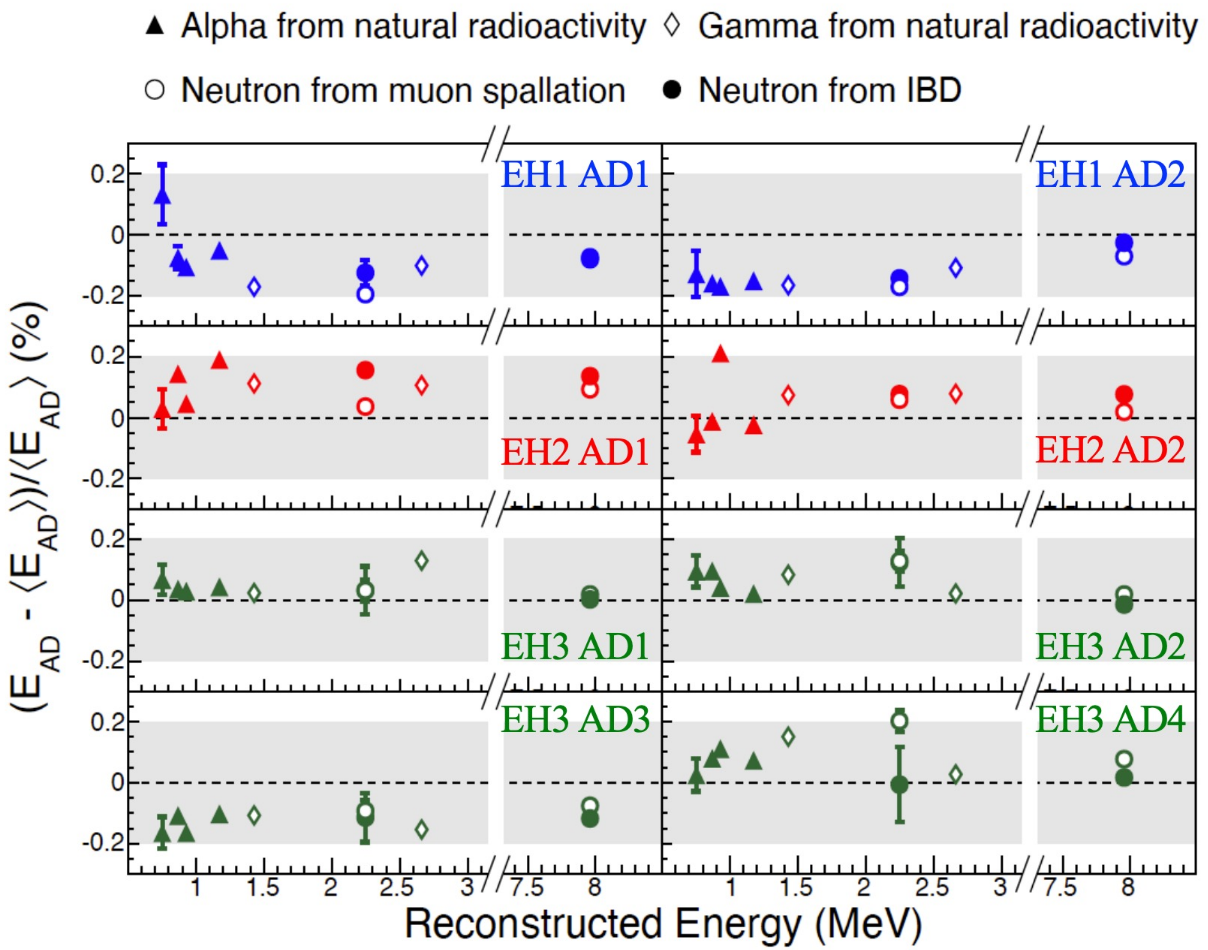


- The largest additional correction is about 3%

Energy Scale

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

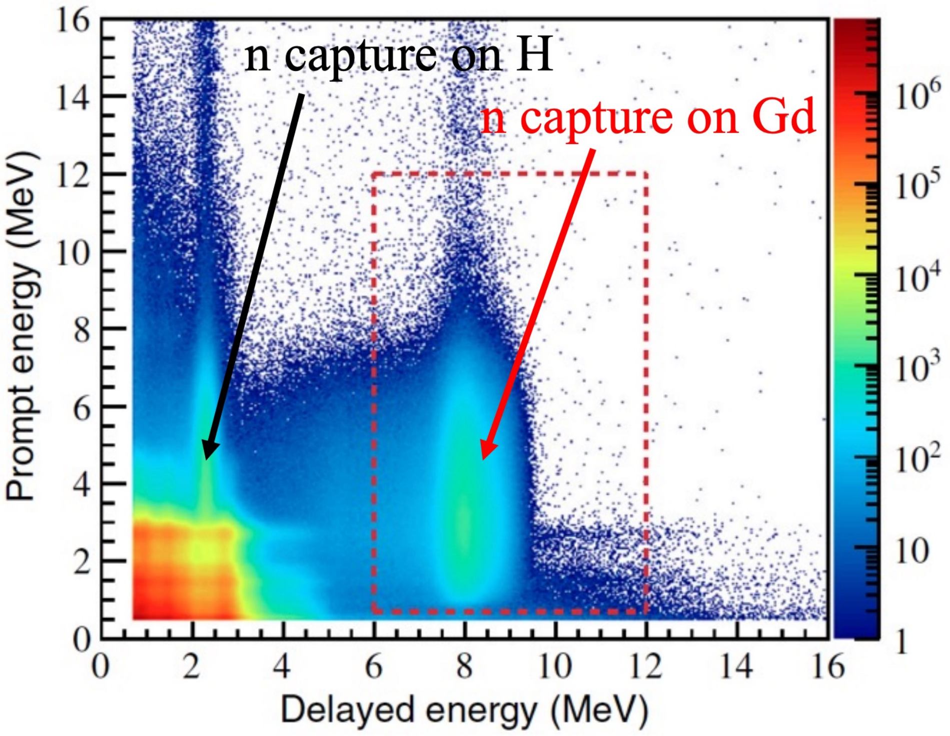




Relative uncertainty in energy scale ~0.2%

Selection of IBD Candidates

- Remove flashing PMT evengs
- 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%

PRD95 (2017) 072006

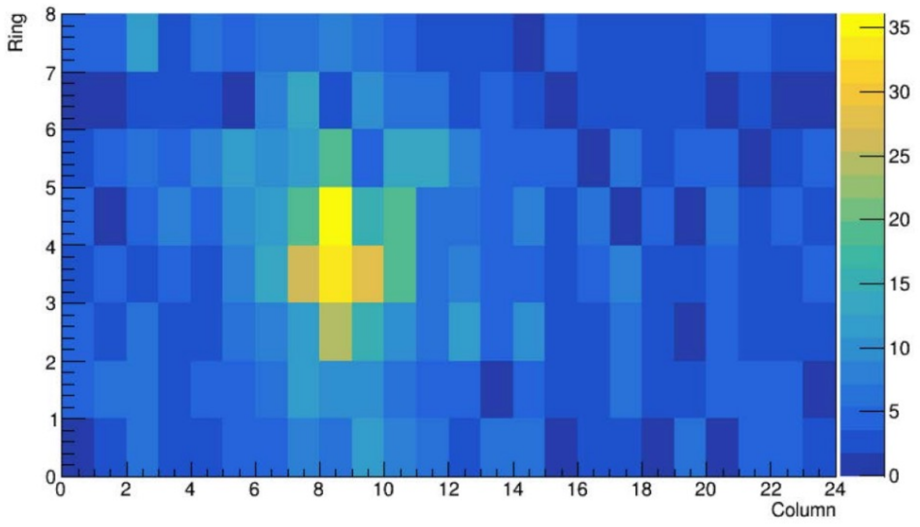
Background

- Uncorrelated
  - Accidental
- Correlated
  - 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
  - $^{13}C(\alpha,n)^{16}O$
    - A from decay of natural radioactive isotope in the liquid scintillator
  - Residual PMT flasher
  - Muon-x

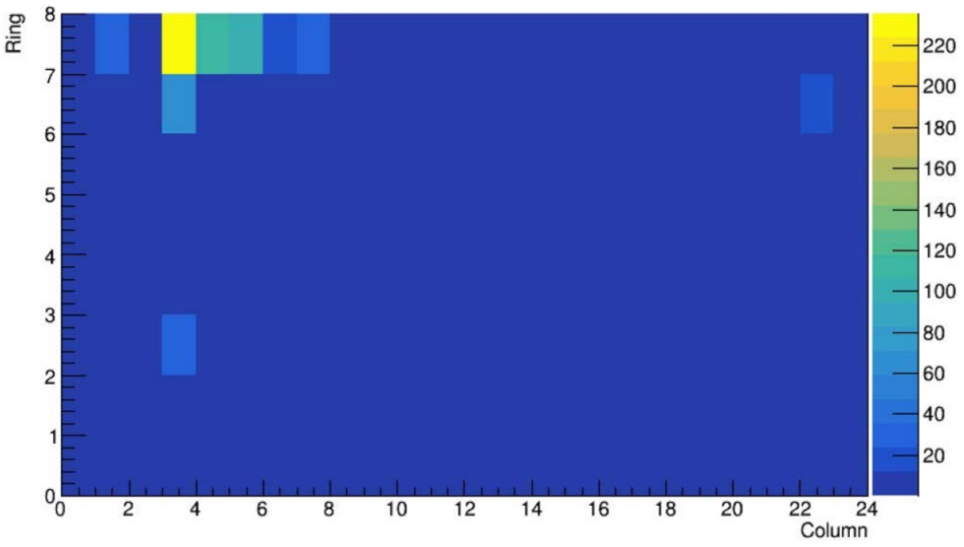
} new background

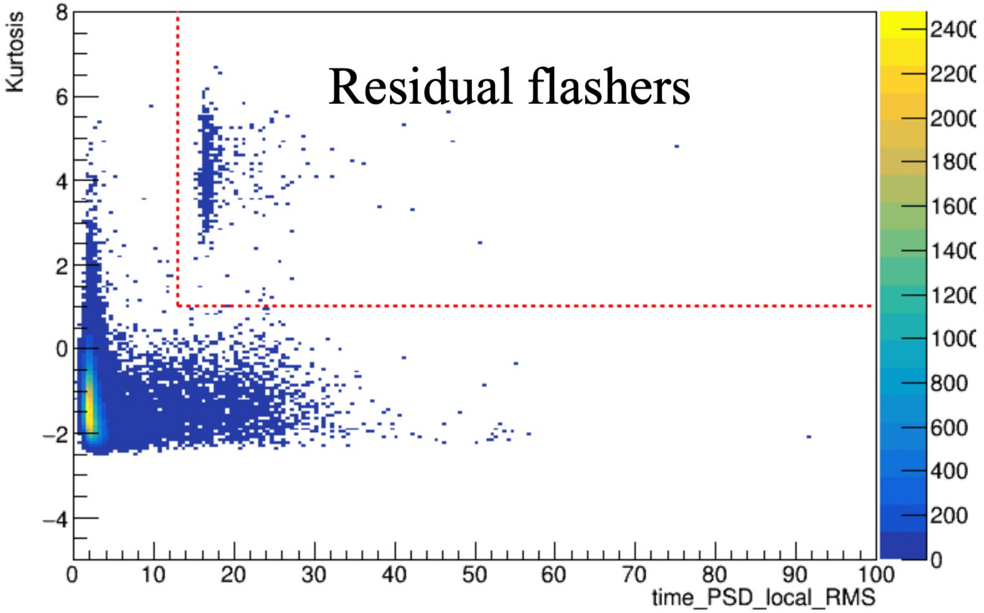
Residual PMT flashers

A typical singles event



A residual flasher event

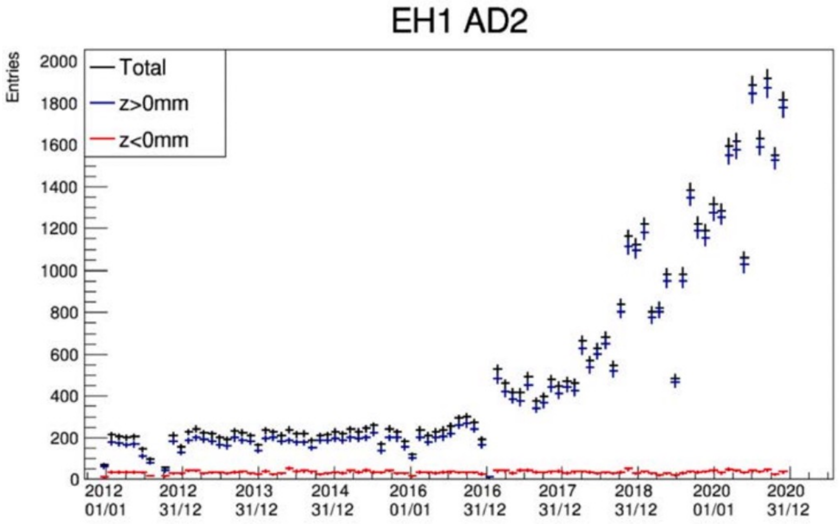


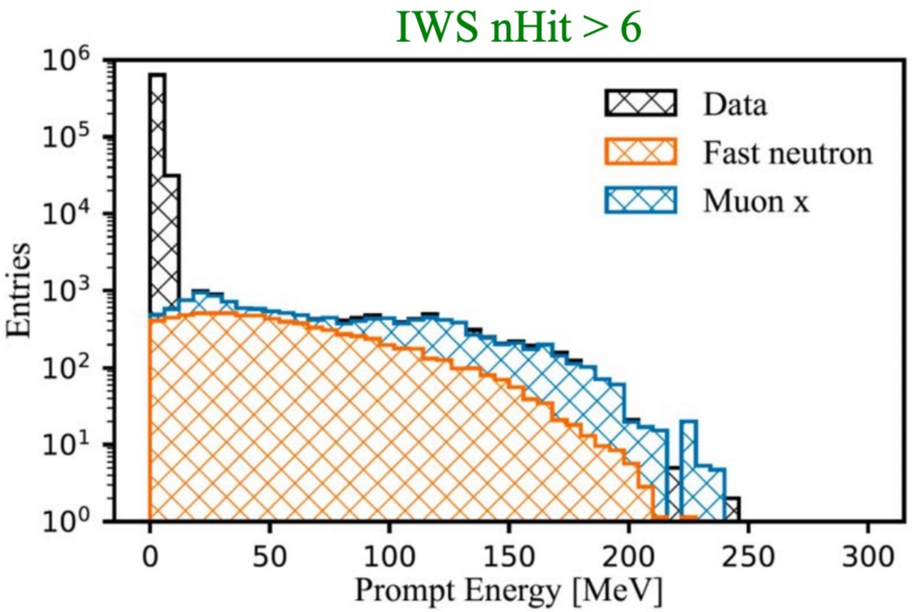


- Located near the top of some ADs
- Removed by cutting on Kurtosis and time_PSD_local_RMS
- After rejecting residual flashers
  - ➢ Negligible contamination in IBD sample
  - ➢ Retain 99.997% of the IBD candidates

Muon-x Background

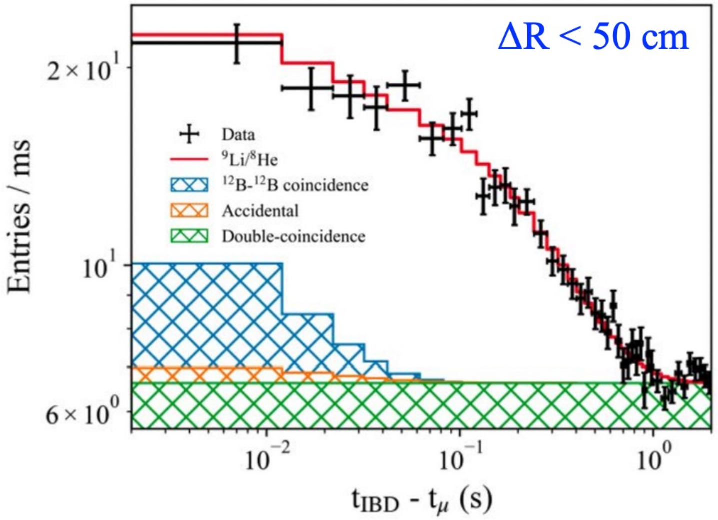
- Gradual failure of PMTs in the inner water shield (IWS) since Jan 2017
  - Reduction in muon detection efficiency
  - Muon decays and additional spallation (muon x) in the top hald of some ADs
- Lower the hit multiplicity of PMTs (nHit) in IWS from 12 to 6 to tag muons
  - Reject ~80% of muon decays
  - Extend cut on E_{prompt} from 12 MeV to 250 MeV to determine the rate and spectrum for fast neutron and muon x

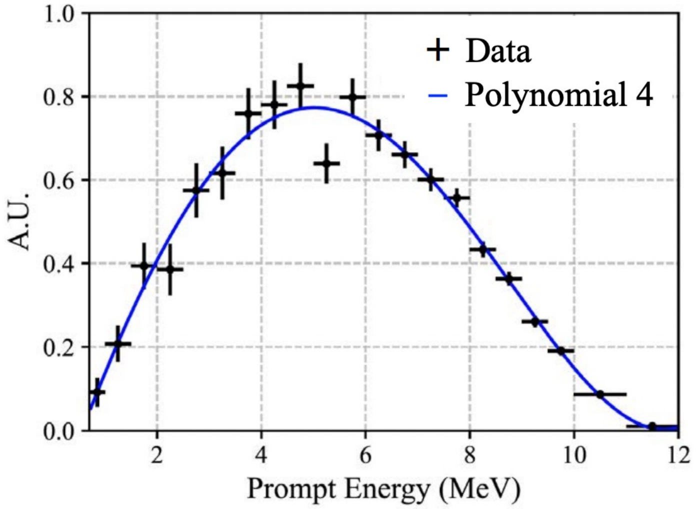




$^9Li/^8He$ Background

- β-n decay
  - τ_{Li} = 257.2 ms τ_{He} = 171.7 ms
- Perform a multi-dimensional fit
  - Time interval after the preceding muon (t_{IBD} - t_{μ})
  - 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

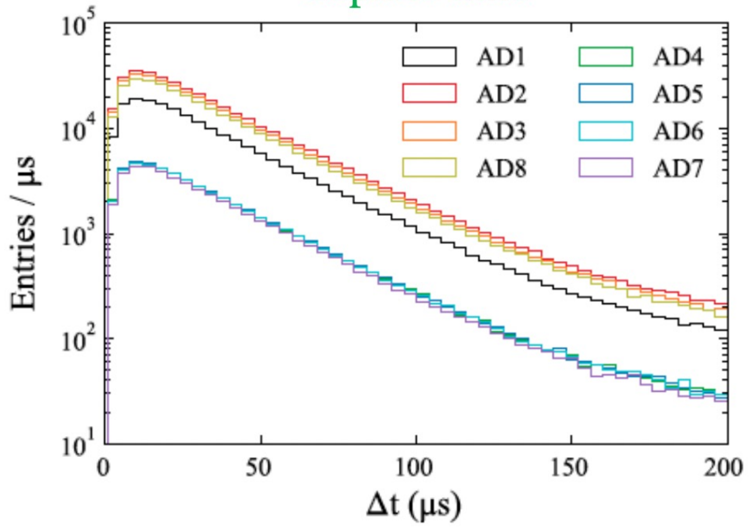


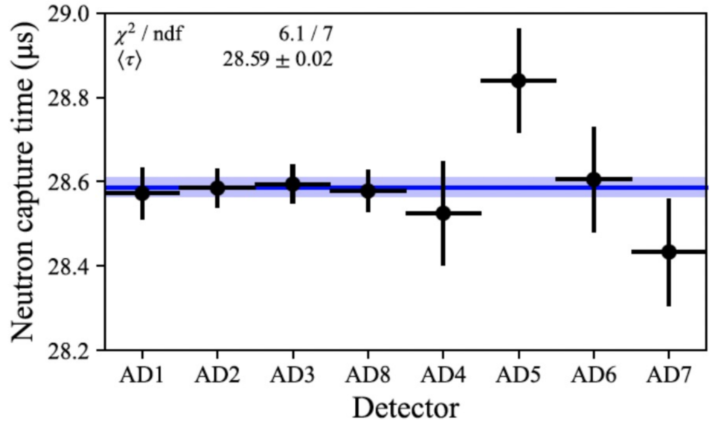


AD Performances

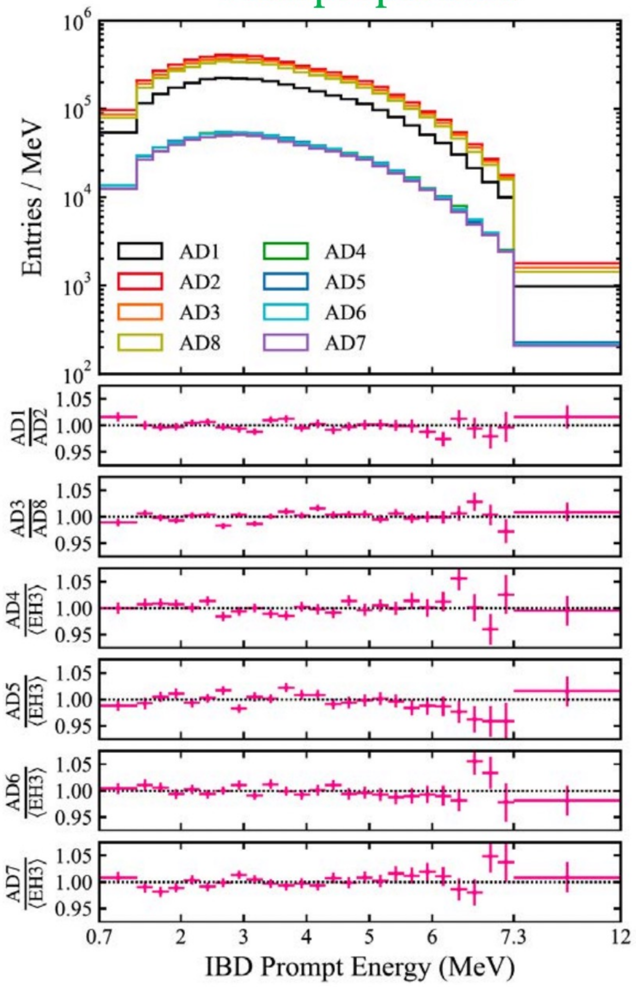
- IBD candidates including background (<3%)

Capture time





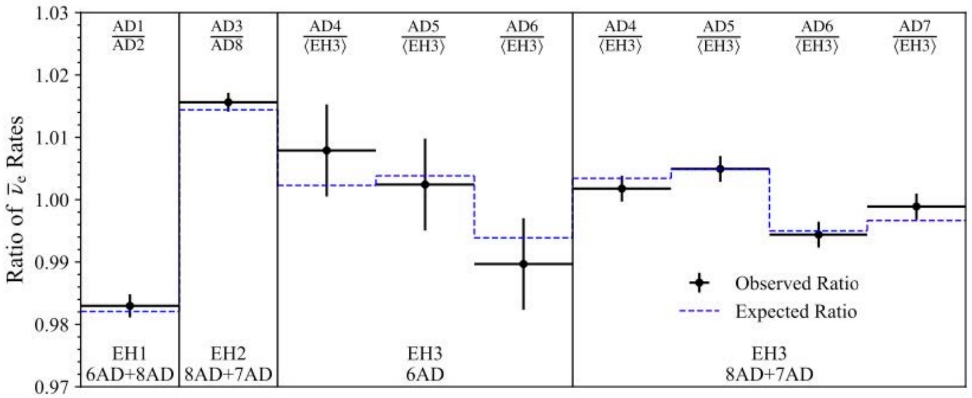
Prompt spectrum



➢ Antineutrino detectors in the same hall have similar performances

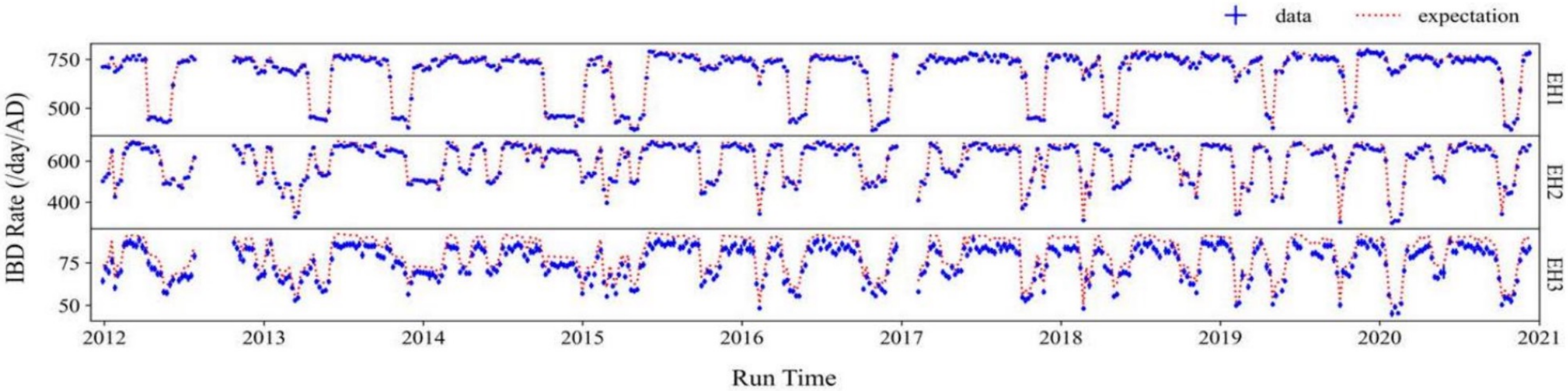
IBD Rate (background subtracted)

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

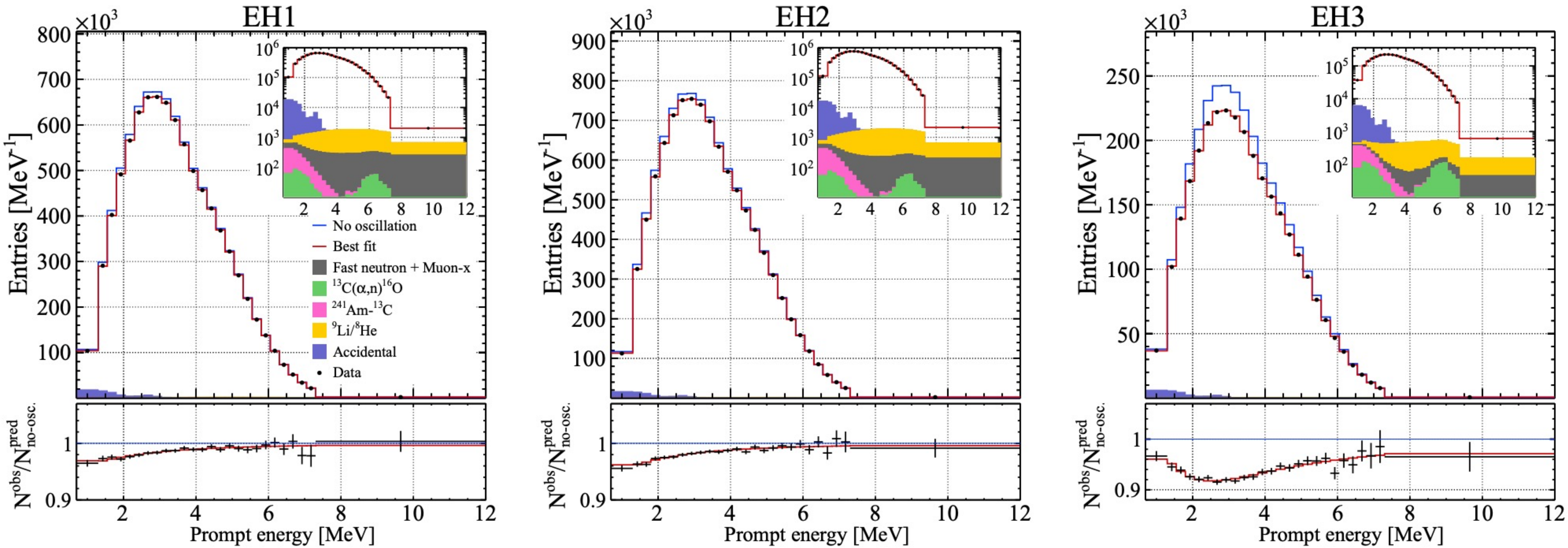


Errors include relative detection efficiency of 0.13%

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

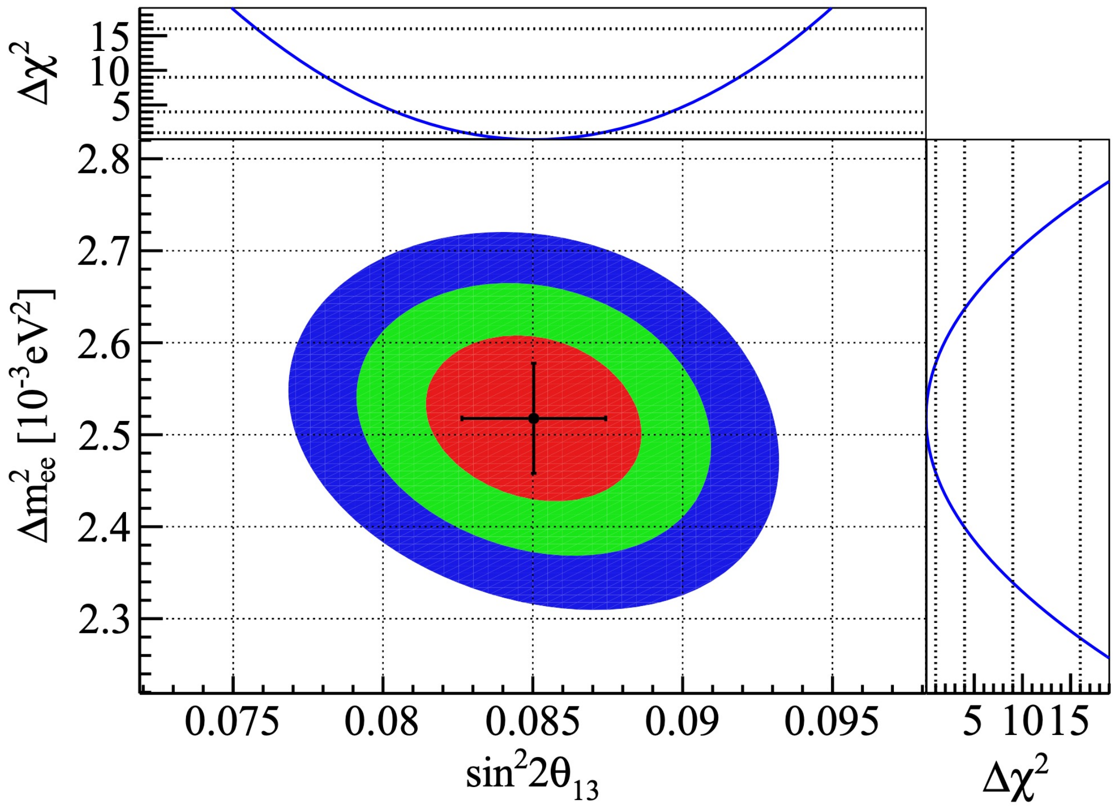


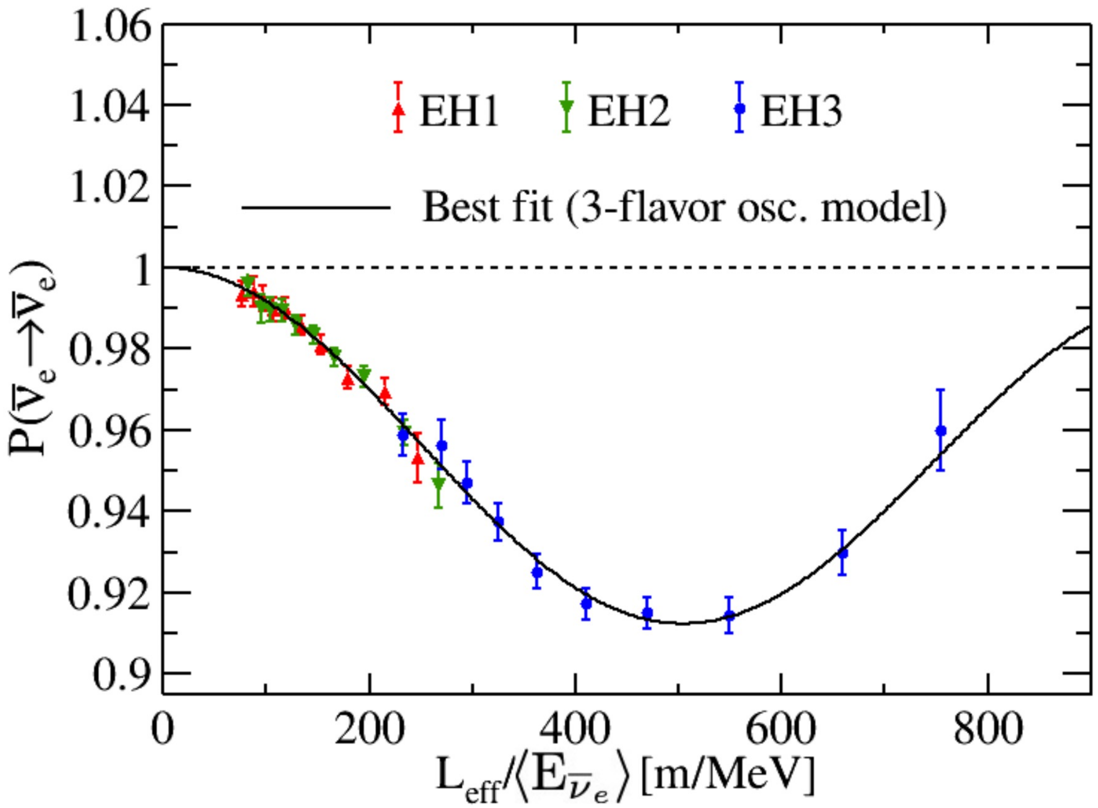
Prompt-energy Spectra



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

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





Best-fit results: χ^2/ndf = 559/518

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

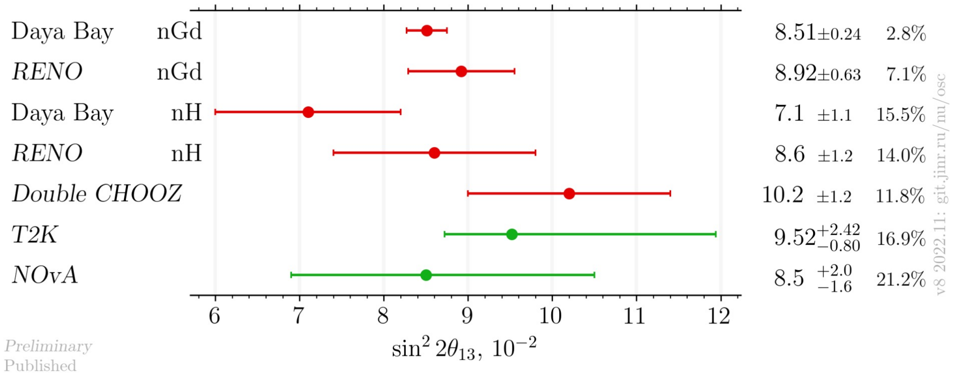
Normal hierarchy: Δm^2_{32} = + $(2.466^{+0.060}_{-0.060})$ x 10^{-3} eV^2 (2.4% precision)

Inverted hierarchy: Δm^2_{32} = - $(2.571^{+0.060}_{-0.060})$ x 10^{-3} eV^2 (2.3% precision)

Present Global Landscape

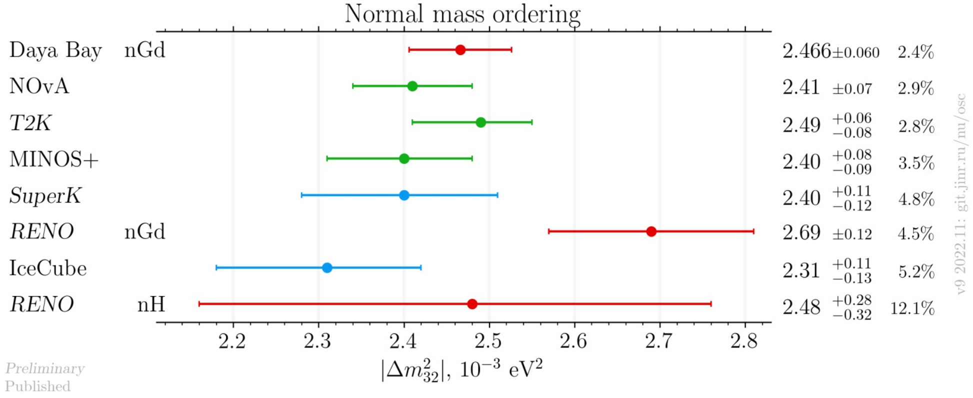
- Compare Daya Bay's current results with published results

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



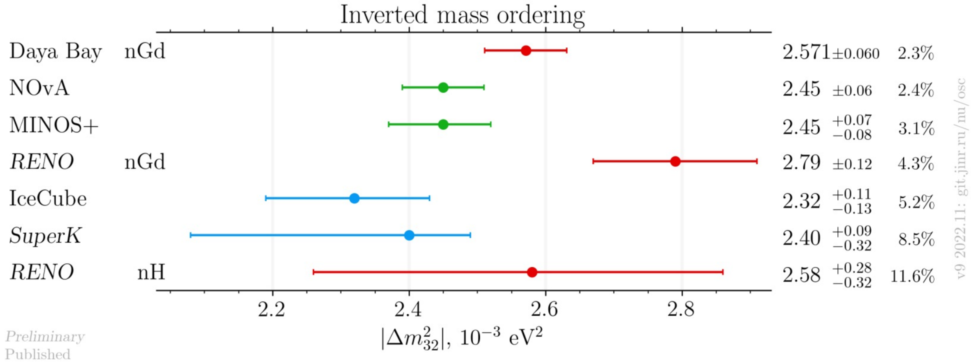
Will likely be the best measurement in the foreseeable future

Δm^2_{32} (NO)



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

Δm^2_{32} (IO)

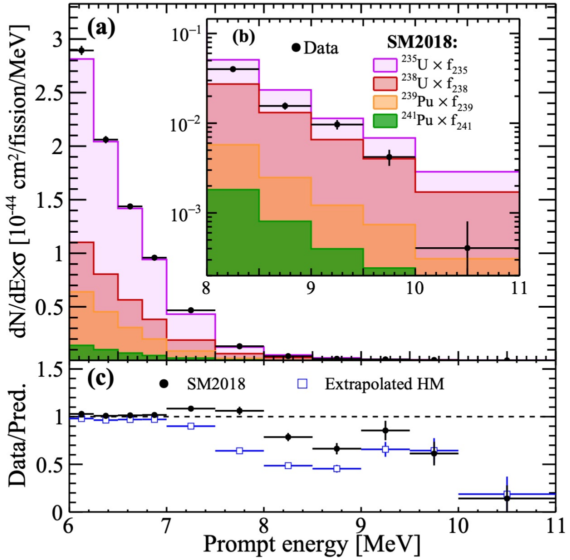


First Evidence of Reactor $\bar{\nu}_e$ with E > 10 MeV

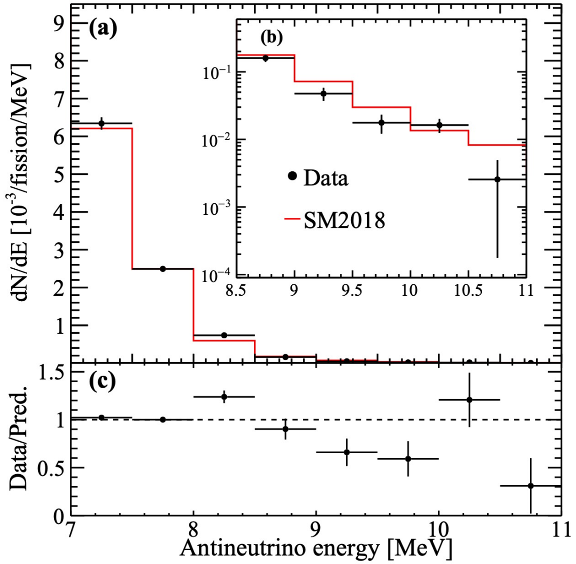
- Can come from high-Q β-decay of short-lived isotopes, e.g. ^{88,90}Br, ^{94,96,98}Rb
- Use the 1958-day dataset to extract IBD and background event together from an event-by-event multi-dimensional fit
  - ~2500 IBD events with $8 < E_{prompt} < 12$ MeV

PRL 129 (2022) 041801

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



After unfolding



- 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 ruled out at 6.2σ

Summary

Daya Bay:

- ❑ Finished data taking on 12 Dec 2020
- ❑ Acquired world's 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 reported in the future, for example:
  - Updated results on oscillations parameters with nH samples

Thank you!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HKUST Jockey Club
Institute for Advanced Study

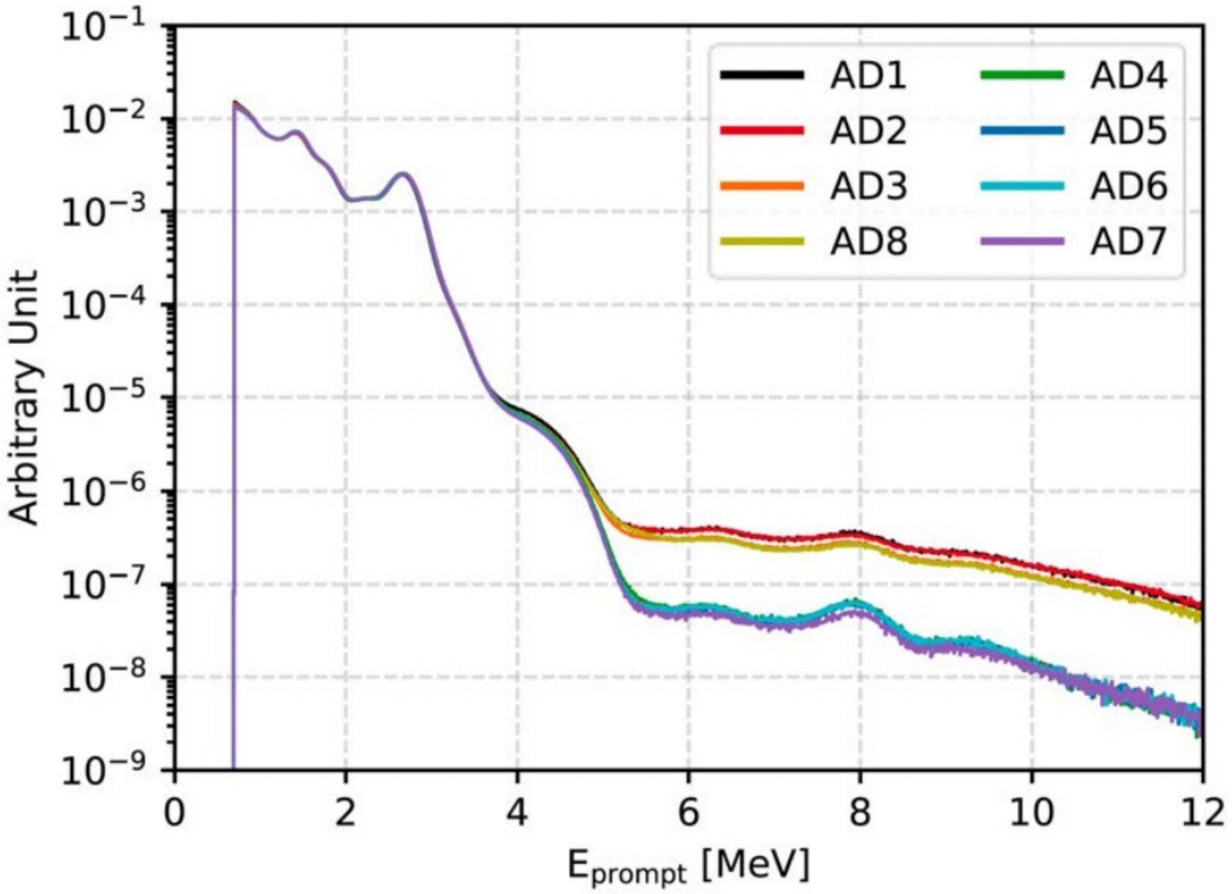
Backup Slides

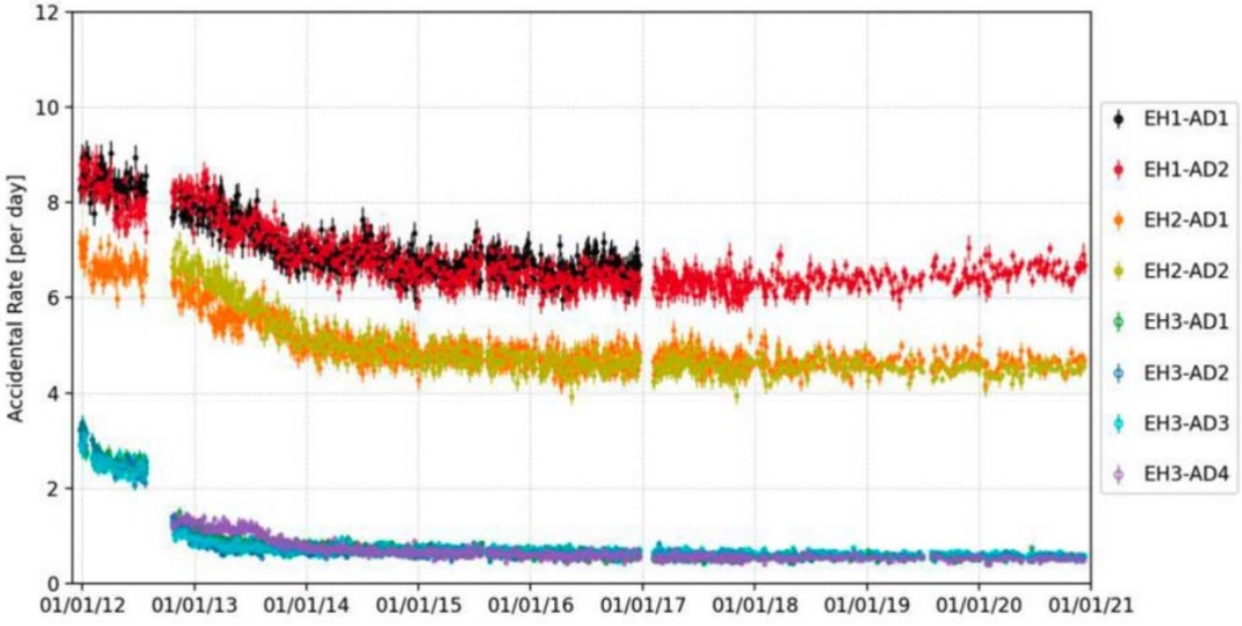
Summary Table

PRL 130 (2023) 161802

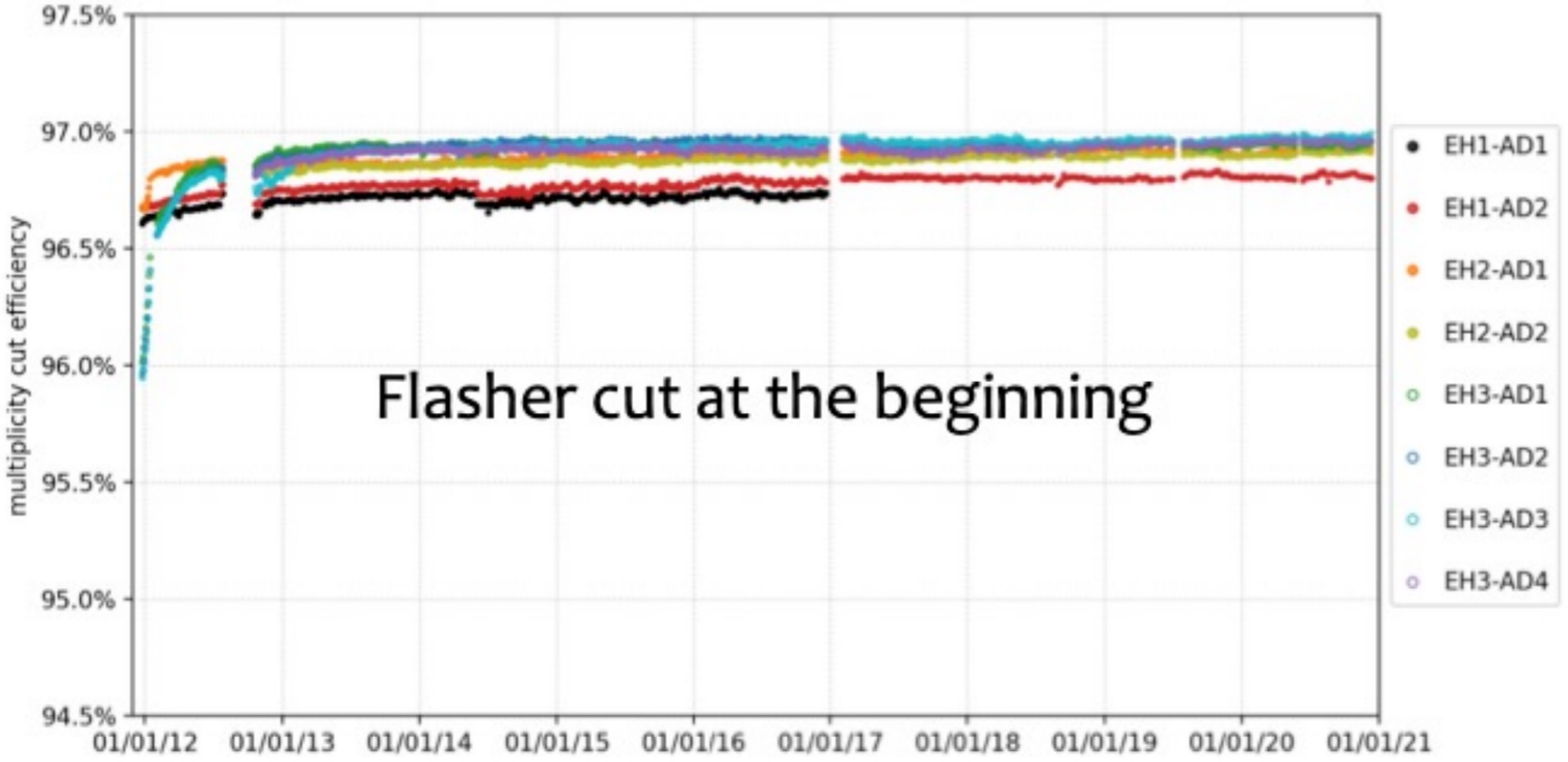
	EH1		EH2		EH3			
	AD1	AD2	AD3	AD8	AD4	AD5	AD6	AD7
$\overline{\nu}_e$ candidates	794335	1442475	1328301	1216593	194949	195369	193334	180762
DAQ live time [days]	1535.111	2686.110	2689.880	2502.816	2689.156	2689.156	2689.156	2501.531
$\varepsilon_\mu \times \varepsilon_m$	0.7743	0.7716	0.8127	0.8105	0.9513	0.9514	0.9512	0.9513
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 n + 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 [AD^{-1} day^{-1}]	2.92 ± 0.78		2.45 ± 0.57		0.26 ± 0.04			
^{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
$\overline{\nu}_e$ rate [day^{-1}]	657.16 ± 1.10	685.13 ± 1.00	599.47 ± 0.78	591.71 ± 0.79	75.02 ± 0.18	75.21 ± 0.18	74.41 ± 0.18	74.93 ± 0.18

Accidentals





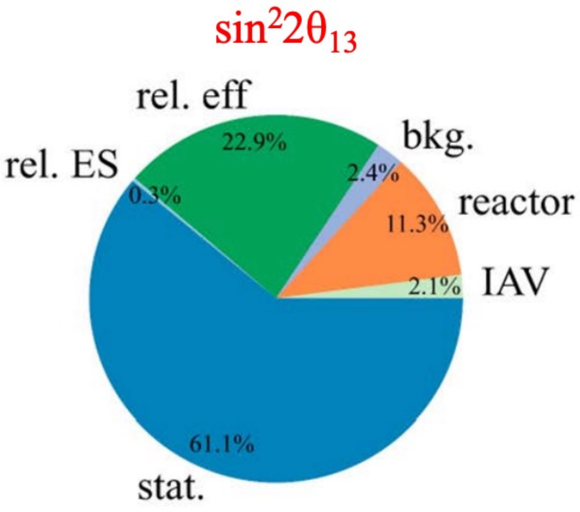
Efficiency of Multiplicity Cut

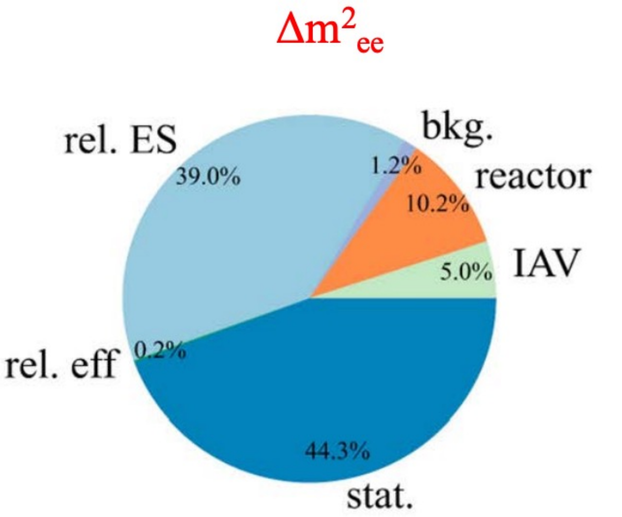


Error Budget

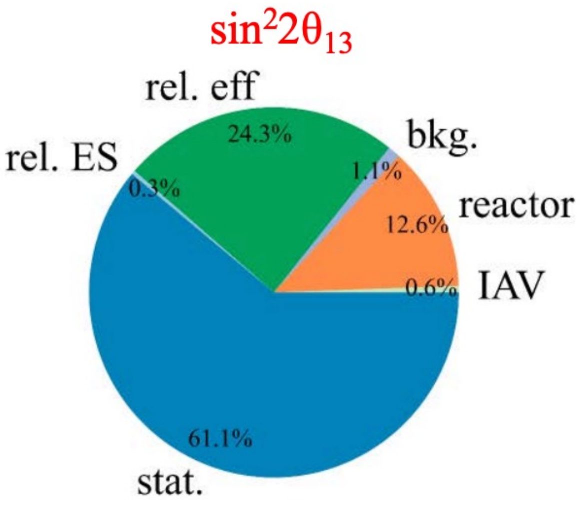
- Based on Asimov sample:

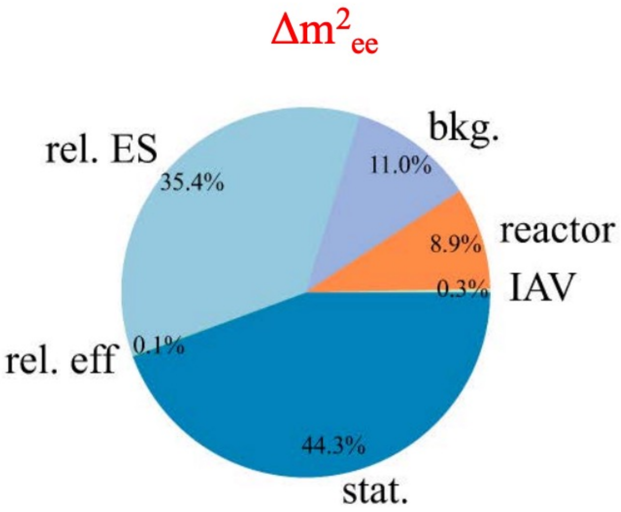
- Add-on method:





- Subtraction method:





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

- an event-by-event multi-dimensional fit

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$$F(\boldsymbol{r}; \boldsymbol{\Delta t}, z, w) = \sum_p r_p f_p(\boldsymbol{\Delta t}) h_p(z) k_p(w) \qquad \chi^2(\boldsymbol{r}) = -2\sum[\log F(\boldsymbol{r}; \boldsymbol{\Delta t}, z, w)] + g(\boldsymbol{\epsilon})$$

- p: event types (IBD, cosmogenic isotopes, fast neutron)
- r_p: ratio of number of type-p events over the total event number in each E_{prompt} bin
- h(z): distribution of vertical vertex coordinates z of prompt signal
- f(**Δt**): distribution of time difference **Δt** between IBD candidate and preceding muons
- k(w): distribution of the weighted reactor power w when event occurred
- g(**ε**): constraints on nuisance parameters describing the above distributions