Latest Results From Daya Bay

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On behalf of the Daya Bay Collaboration

High Energy Physics Branch of CPS, 11th August 2022

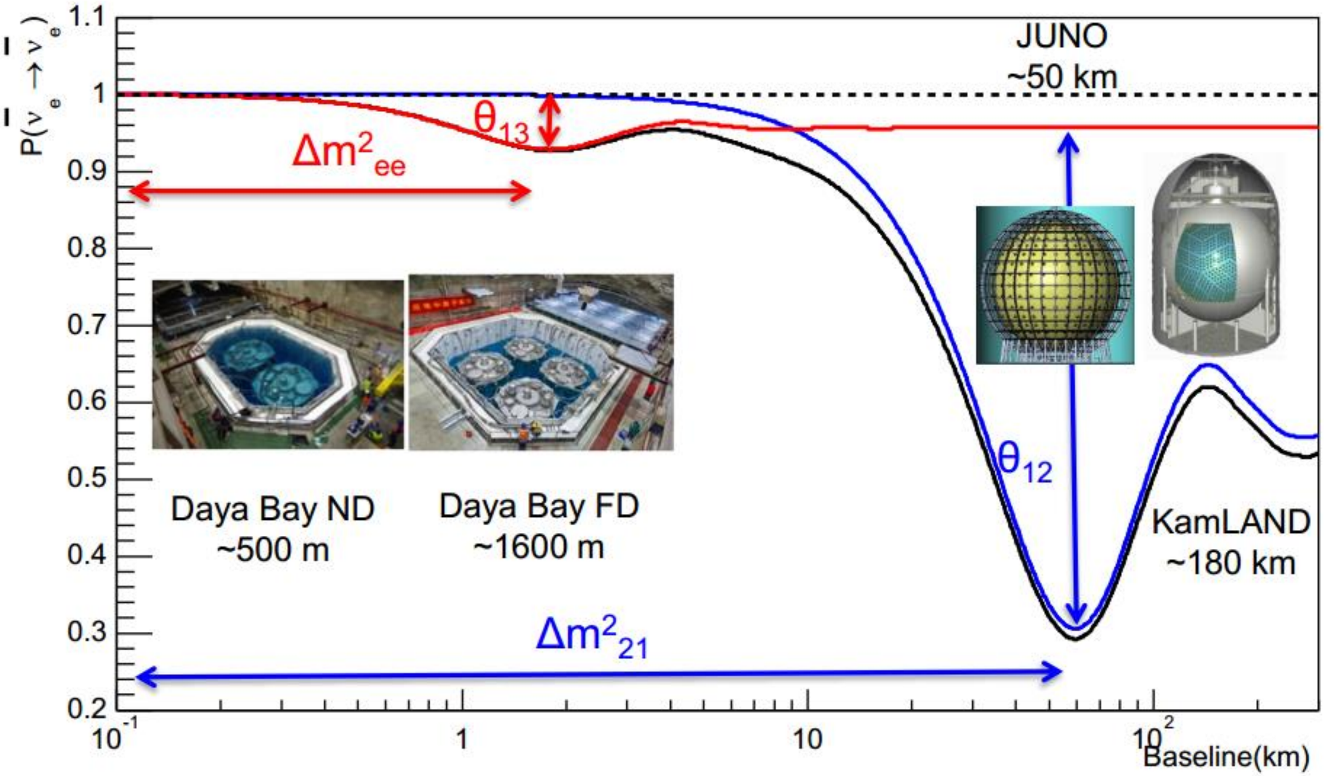
■Reactor anti-neutrino oscillation

- Survival probability:

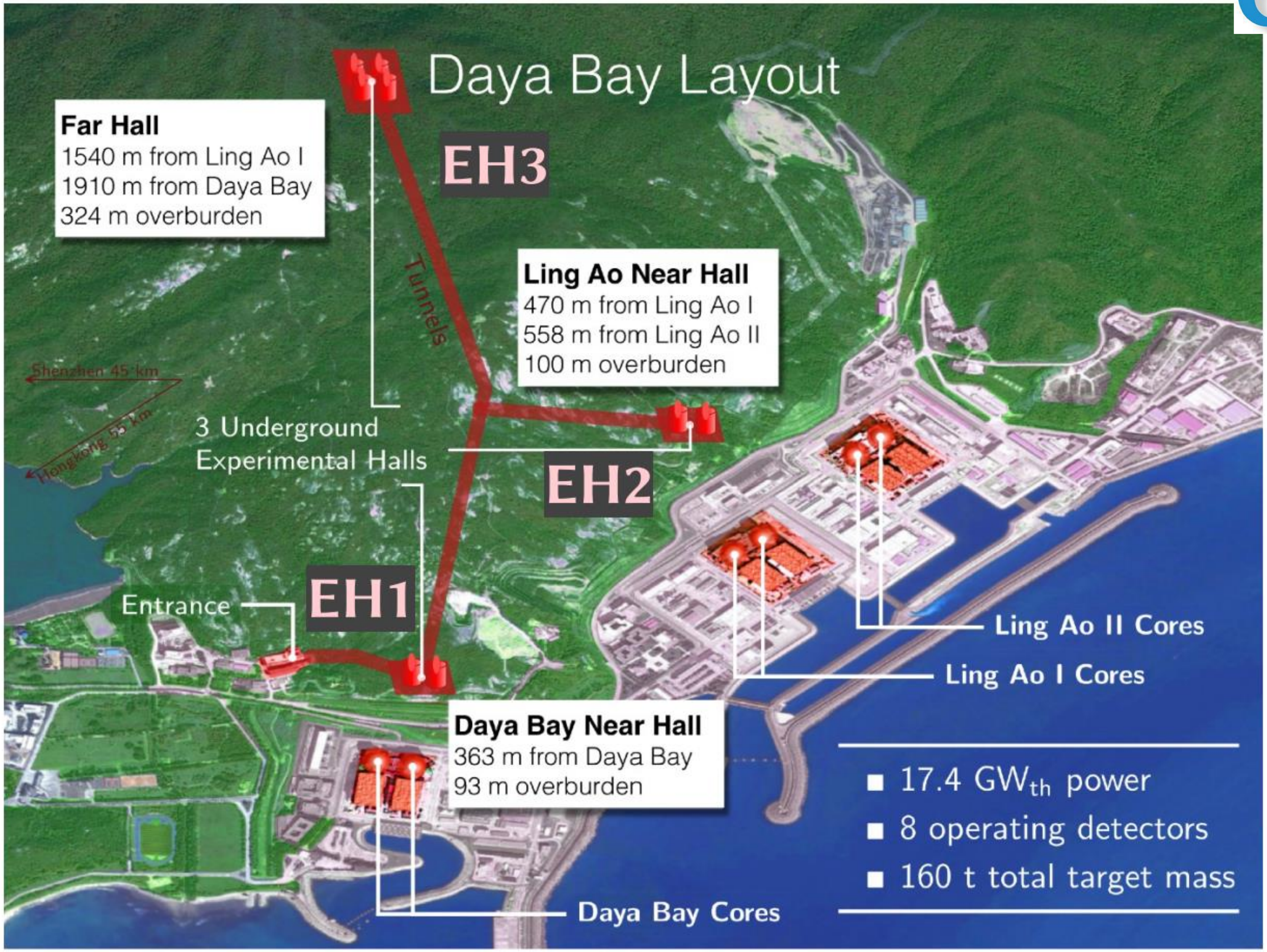
$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{13}\left(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}\right) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$

$$\approx 1 - \sin^2 2\theta_{13}\sin^2\Delta_{ee} - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$

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



■Daya Bay experiment



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

■Antineutrino detectors (ADs)

- Detect inverse β-decay reaction (IBD):

prompt delayed

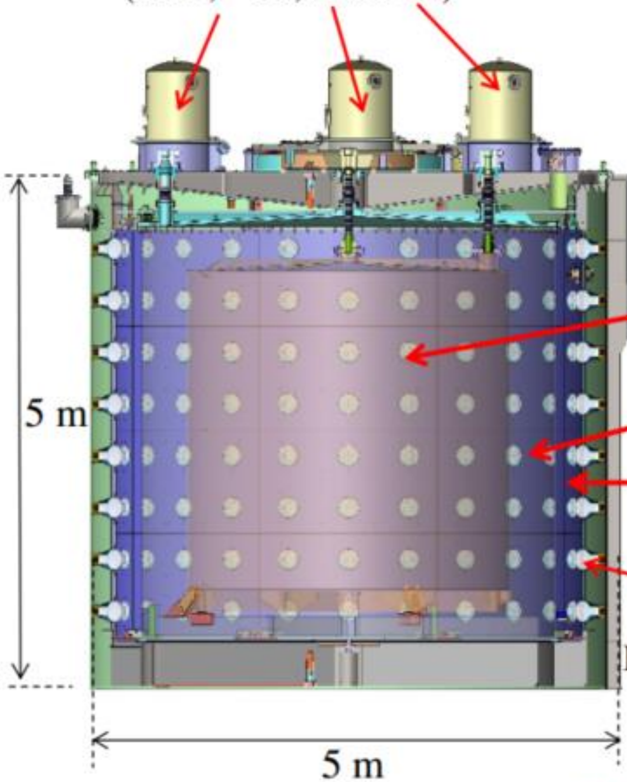
$$\overline{\nu}_e + p \rightarrow e^+ + n$$

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

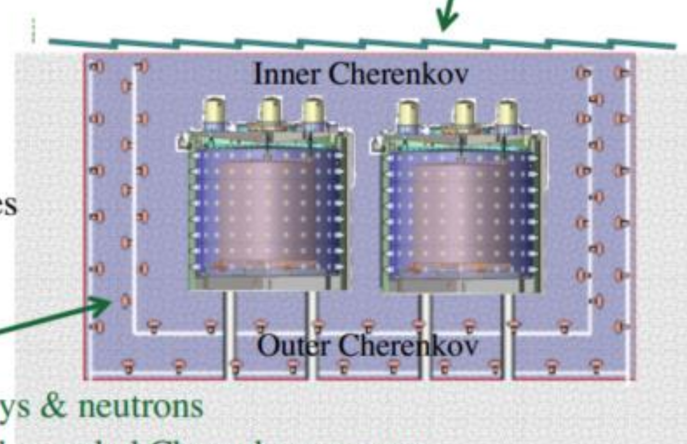
$\rightarrow + Gd \rightarrow Gd^*$

~30 μs for 0.1% Gd

$\rightarrow Gd + \gamma$'s (~8 MeV)



Four layers of RPC's to tag muons



2.5-m water:
- Attenuates gamma rays & neutrons
- Forms two optically decoupled Cherenkov counters

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

■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

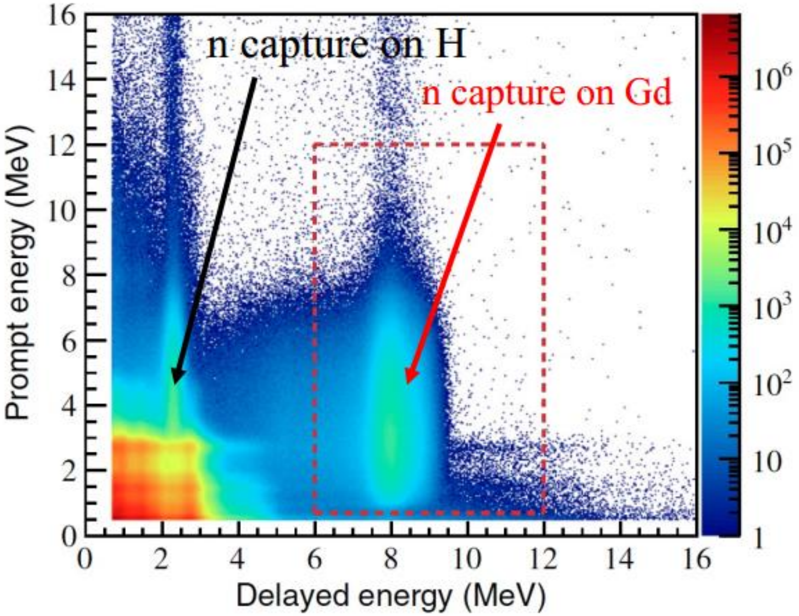
- Analysis:
  - ➢ **Energy calibration**

    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 $\bar{\nu}_e$ 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%

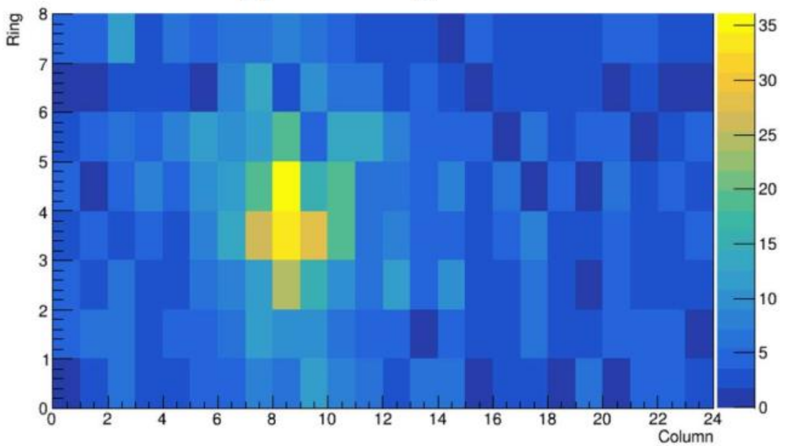
See PRD 95 (2017) 072006

Background

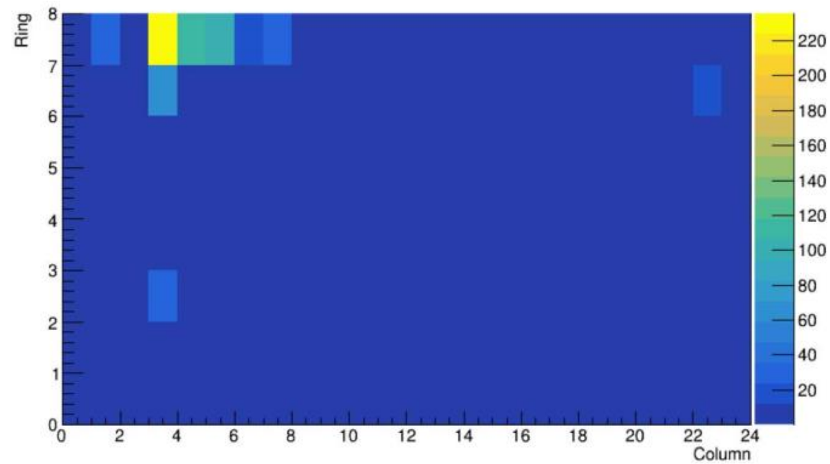
- Uncorrelated background
  - Accidental
- Correlated background
  - Fast neutron
    - produced outside of the AD but enters the active volume of the AD
  - $^{9}Li/^{8}He$
    - spallation product produced by cosmic-ray muons inside the AD
  - ^{241}Am-^{13}C
    - neutron calibration source resides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

■Residual PMT Flashers

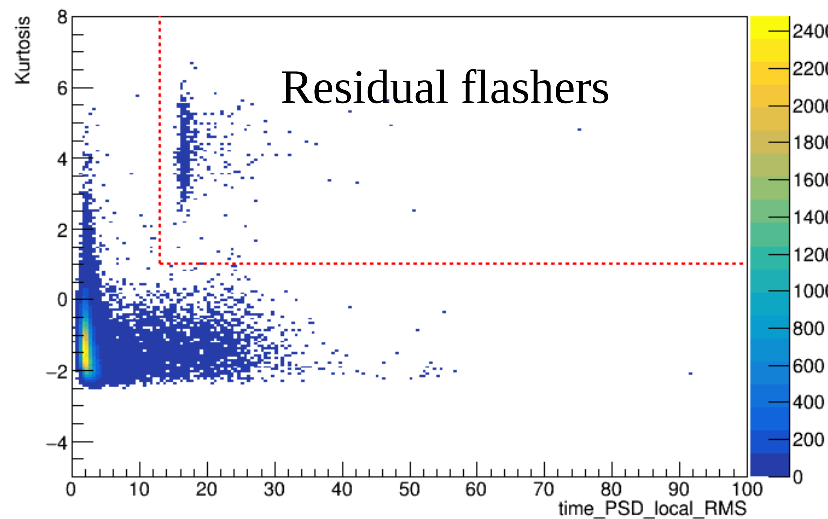
A typical singles event



A residual flasher event

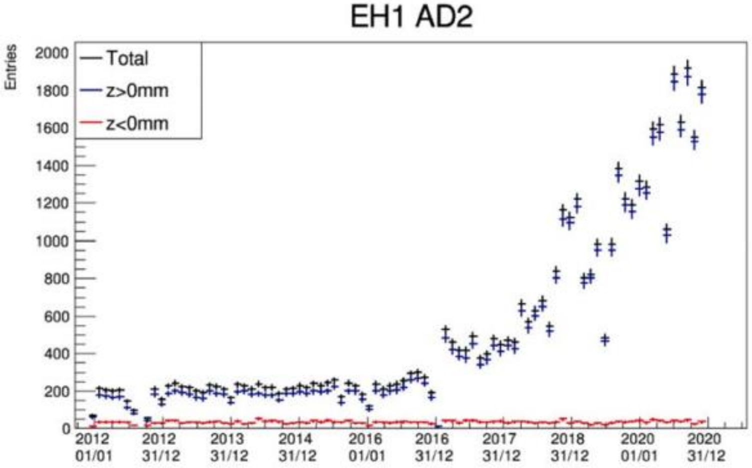


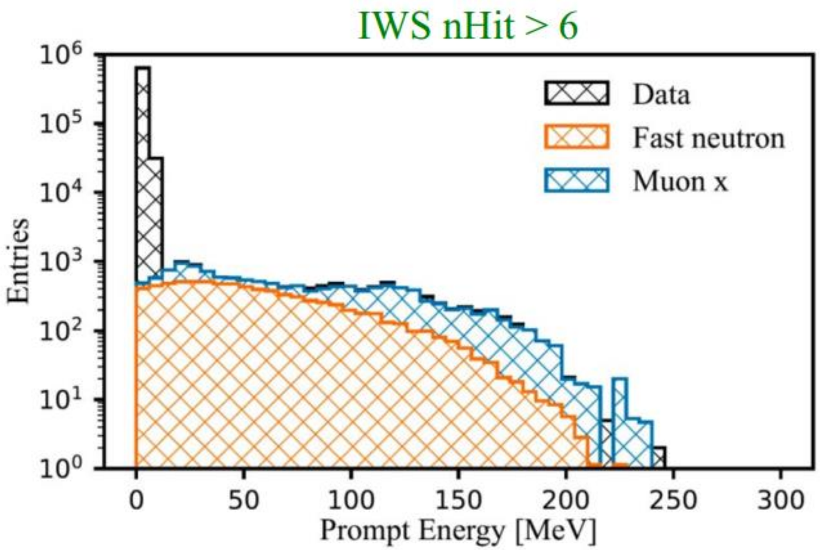
- Located near the top of some ADs
- Removed by cutting on Kurtosis and time_PSD_local_RMS
- After rejecting residual flashers,
  - ➢ Contamination in the IBD sample is negligible
  - ➢ Retain 99.997% of the IBD candidates



■Muon-x Background

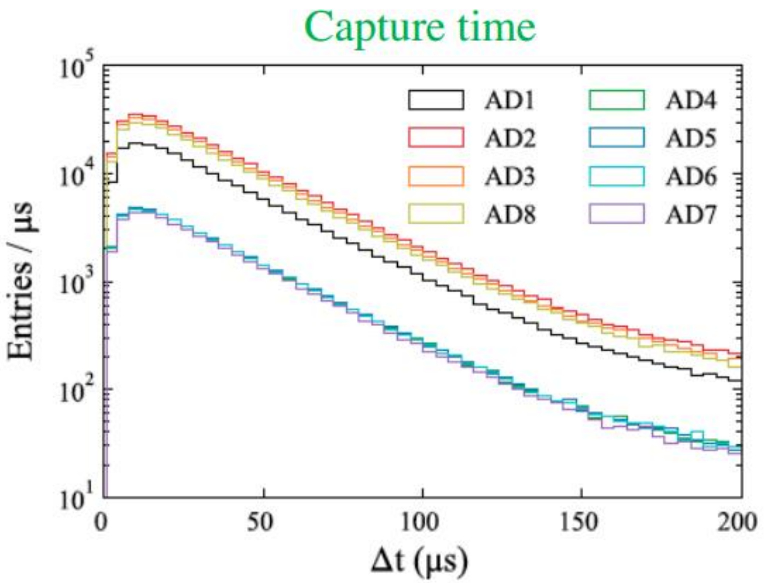
- Gradual failure of PMTs or high-voltage channels in the inner water Cherenkov counter (IWS) in the water pool since January 2017
  - ➢ Reduction in muon detection efficiency
  - ➢ Muon decays and additional spallation (muon-x) in the top half of some ADs
- Lower the hit multiplicity of PMTs (nHit) 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

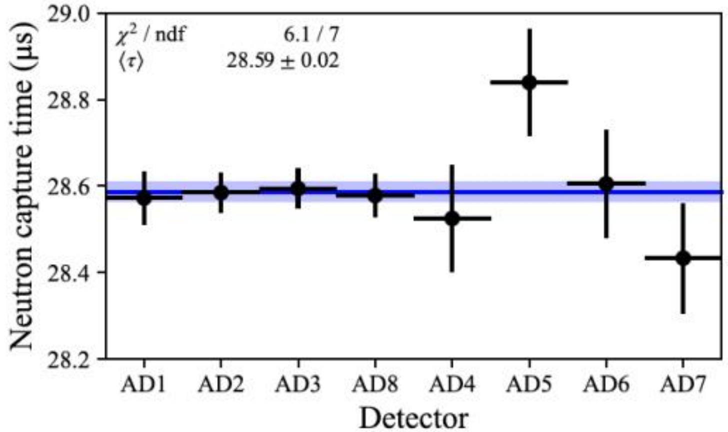


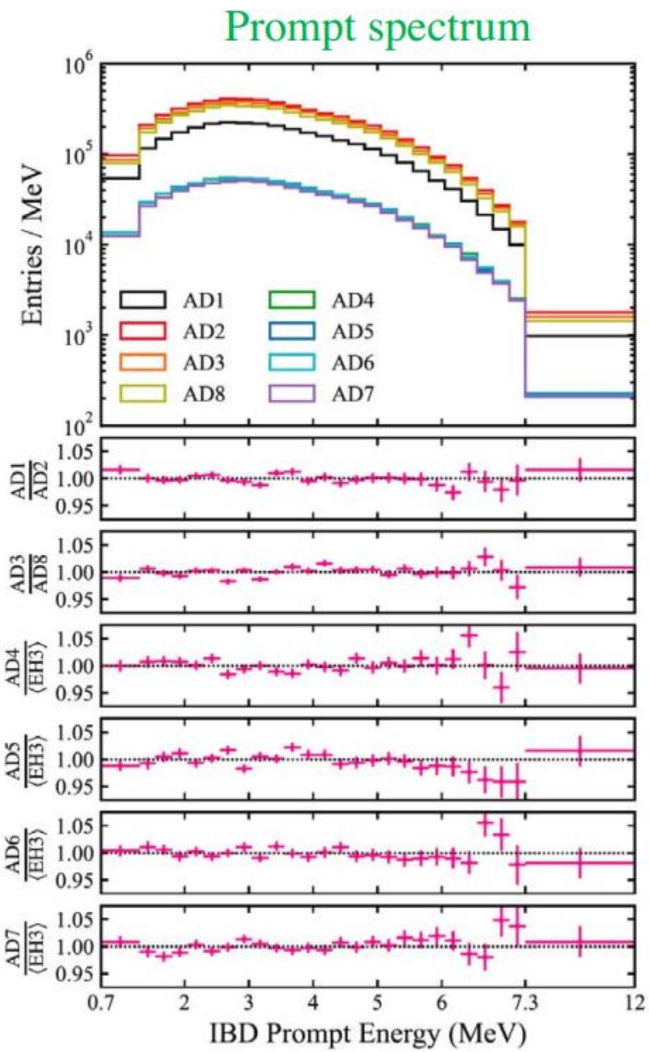


■Performance of Antineutrino Detectors

- IBD candidates including background (< 3%)



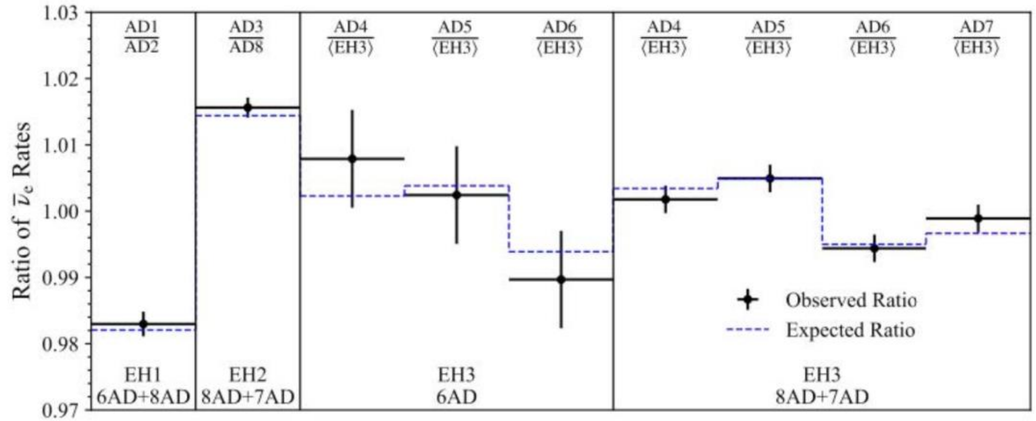




- Antineutrino detectors in the same hall have similar performance

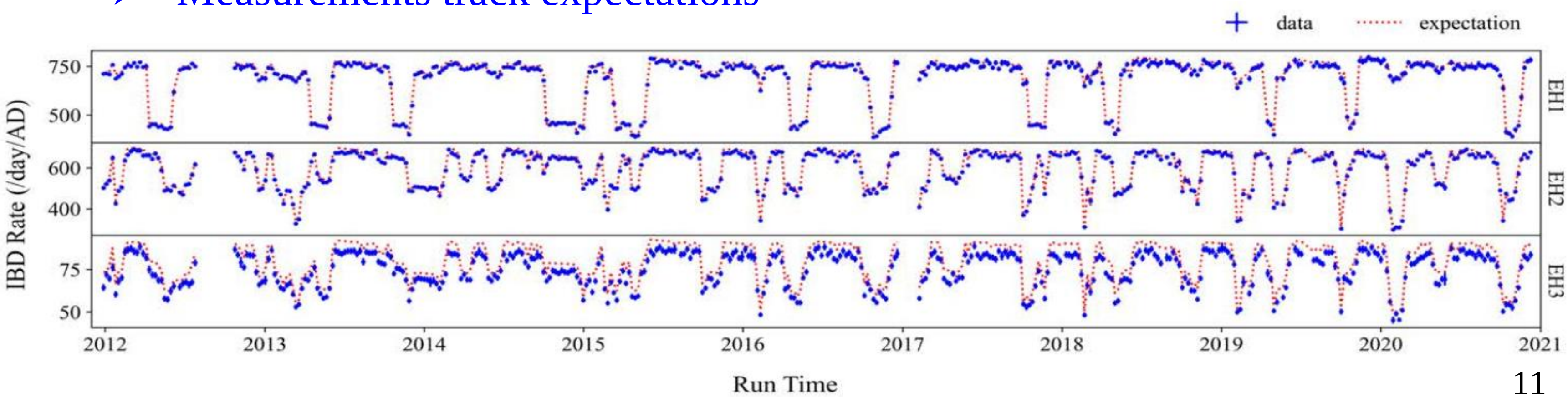
■IBD Rate (background subtracted)

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

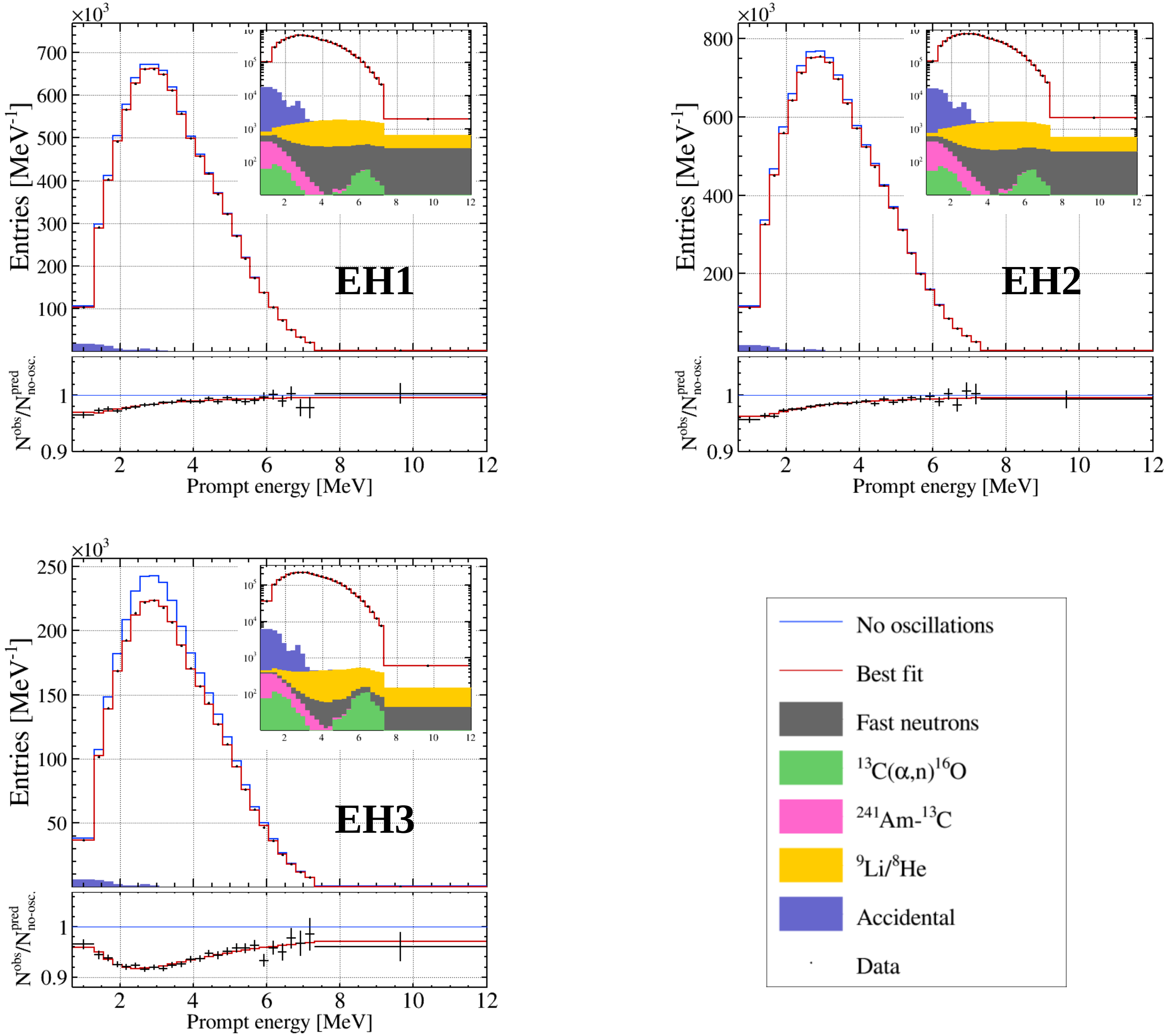


Errors include relative detection efficiency of 0.13%

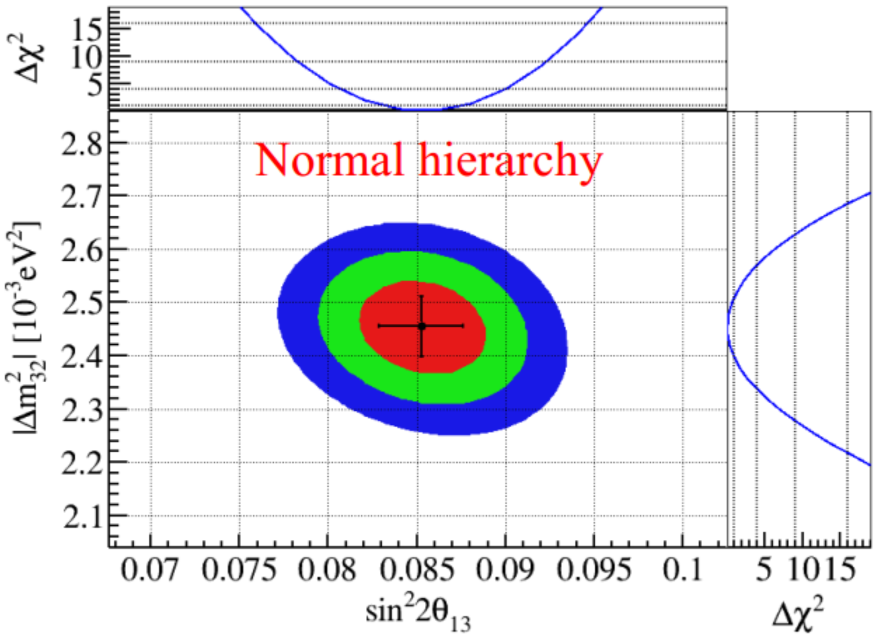
- Correlation with operation of reactors
  - ➢ Expectation based on weekly reactor operational information
  - ➢ Measurements track expectations

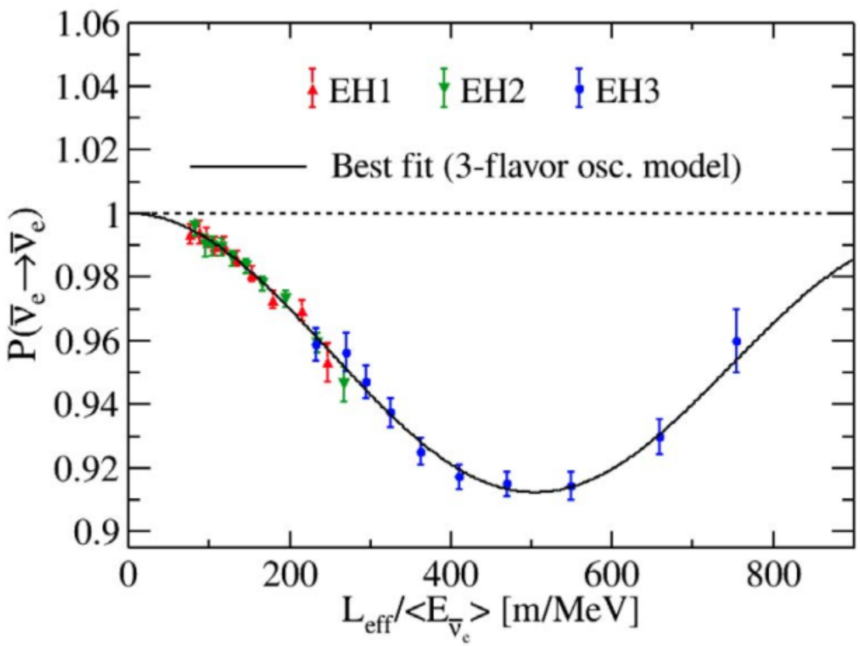


■Prompt-energy Spectra



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

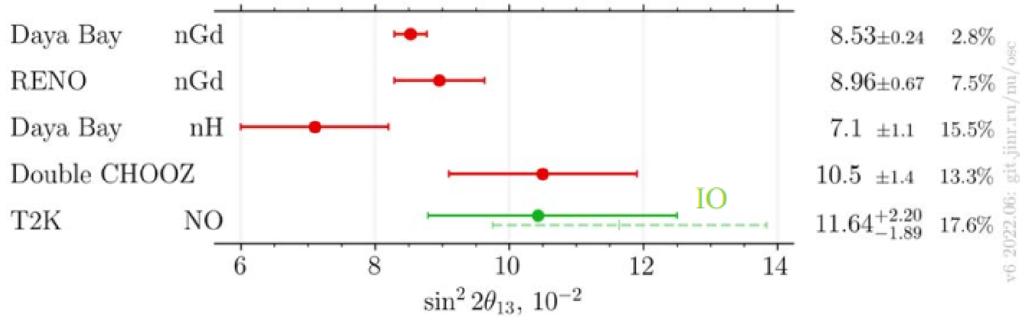
Inverted hierarchy: $\Delta m^2_{32} = -\left(2.559^{+0.057}_{-0.057}\right) \times 10^{-3}\ \mathrm{eV}^2$

(2.3% precision)

■Present Global Landscape

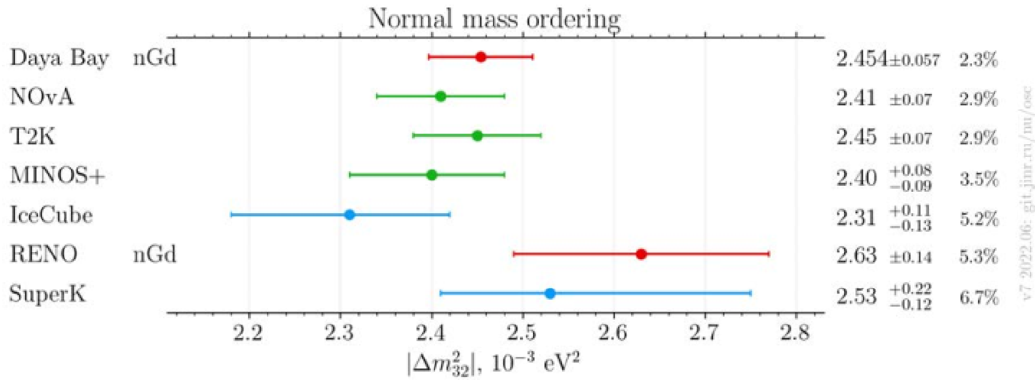
- Compare Daya Bay’s current results with published results

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

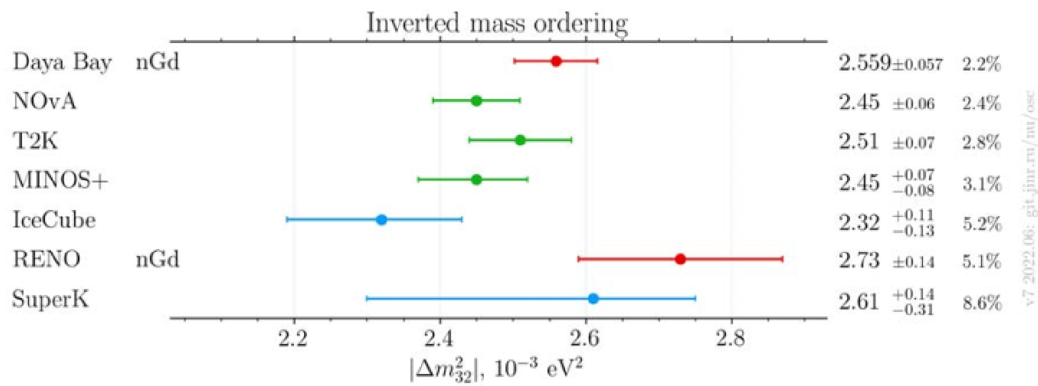


Will likely be the best measurement in the foreseeable future

Δm^2_{32} (NO)



Δm^2_{32} (IO)



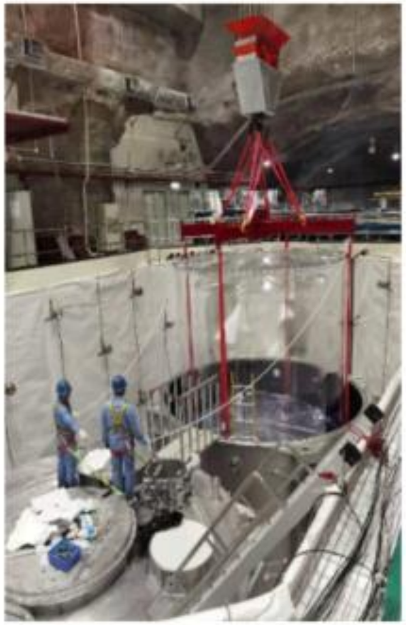
Summary

- **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 $\bar{\nu}_e$
  - 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

■Backup

Brief History of Onsite Operation

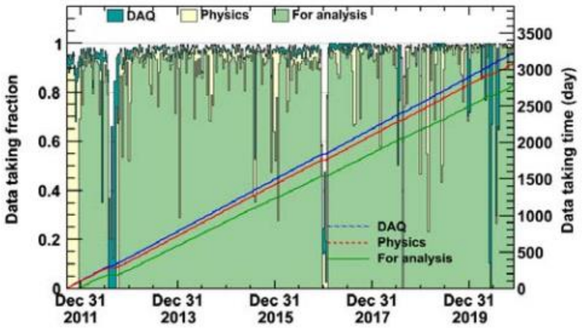
- Detector commissioning on 15 August 2011
- Collection of physics data began on 24 Dec 2011
- Collection of physics data ended on 12 Dec 2020
- Decommissioning: 12 Dec 2020 – 31 Aug 2021



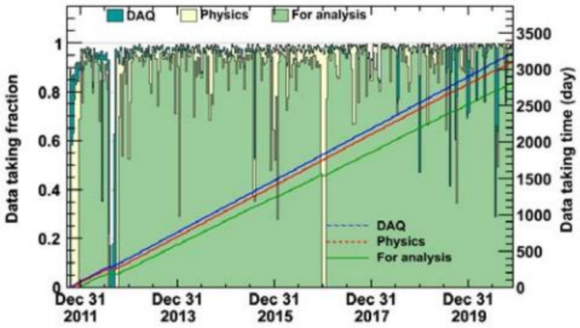
Data Acquisition

- Operational statistics:

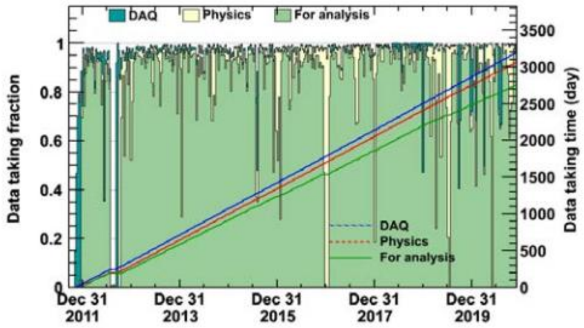
EH1



EH2



EH3



- Three physics runs:

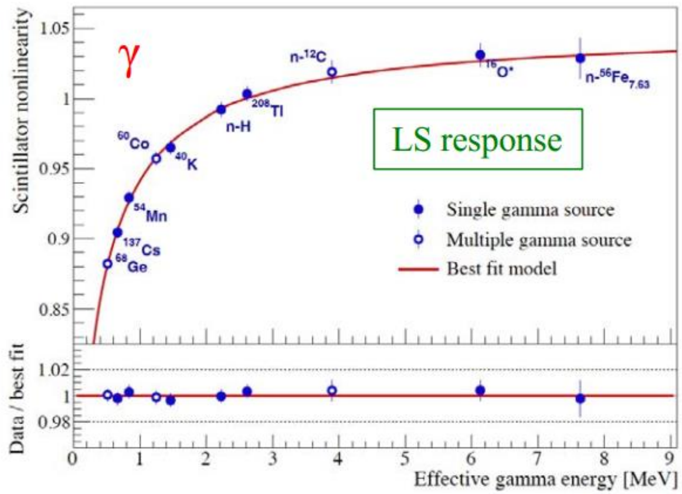
Configuration	EH1	EH2	EH3	Start date – End date	Duration (Days)
6-AD	2	1	3	24 Dec 2011 – 28 July 2012	217
8-AD	2	2	4	19 Oct 2012 – 26 Dec 2016	1524
7-AD	1	2	4	26 Jan 2017 – 12 Dec 2020	1417
Total					**3158**

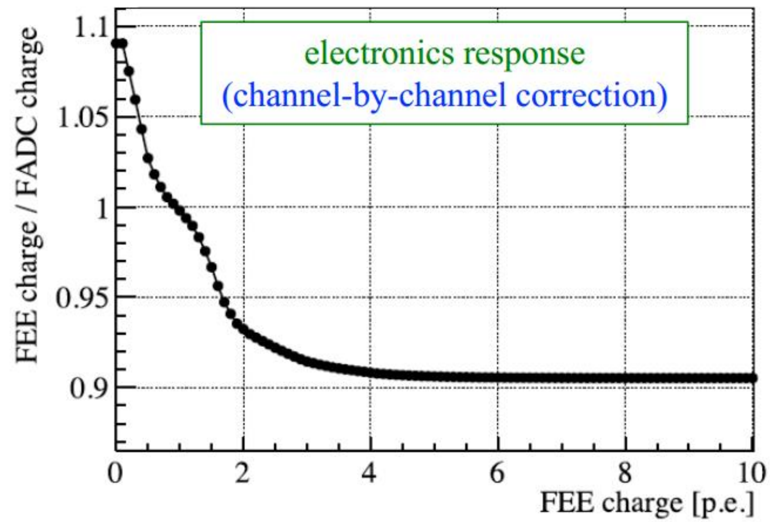
- Data available for analyses: ~2700 days

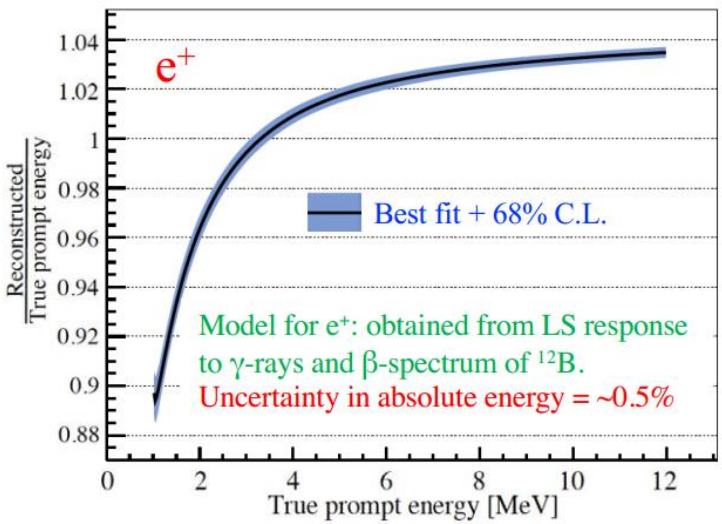
■Non-linear Energy Response

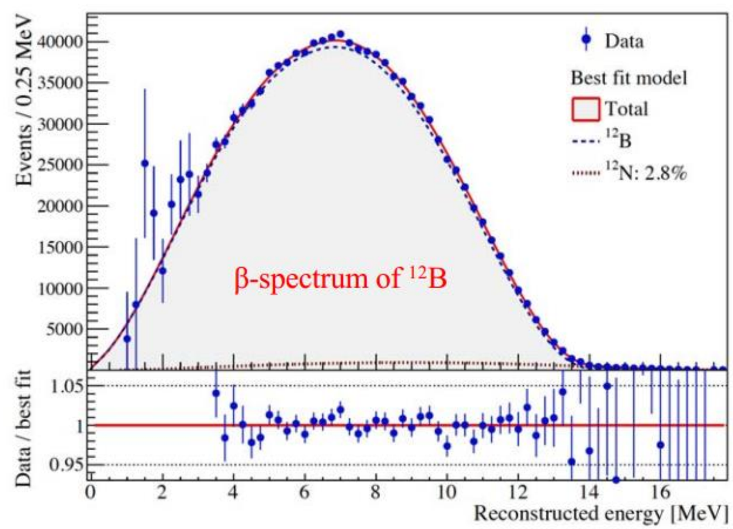
- Due to nature of liquid scintillator (LS) and charge measurement of electronics

NIM A**940** (2019) 230



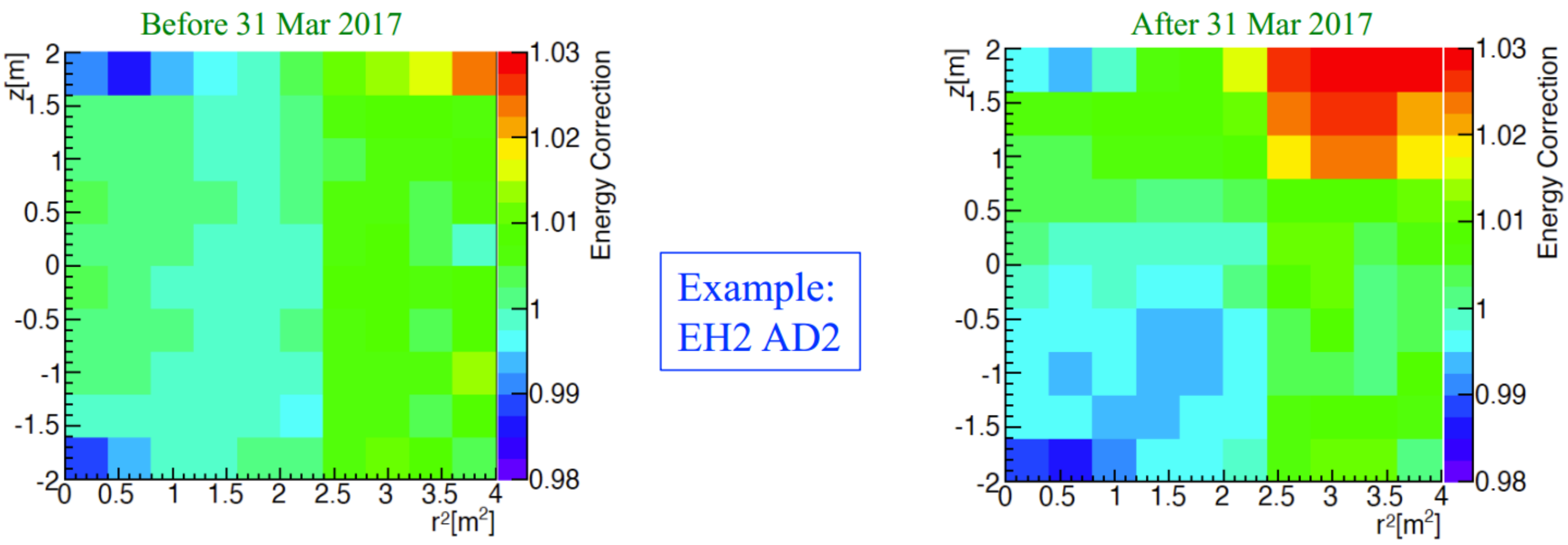






■Improved Nonuniformity of Energy Scale

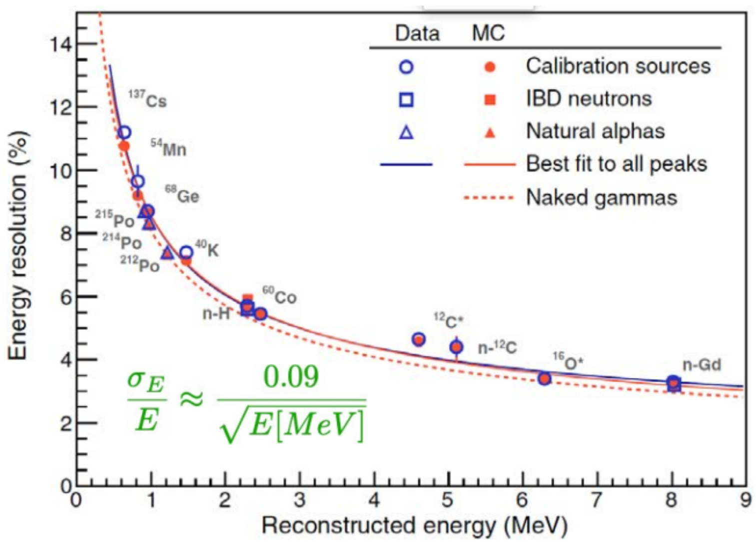
- Additional non-uniformity on top of already-corrected geometric nonuniformity
  - ➢ Residual effect of the Earth magnetic field
  - ➢ Dead PMTs or high-voltage supply channels
- Corrections
  - ➢ Use γ's from spallation-neutron capture on Gd and α's from natural radioactive isotopes
  - ➢ Time dependent,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

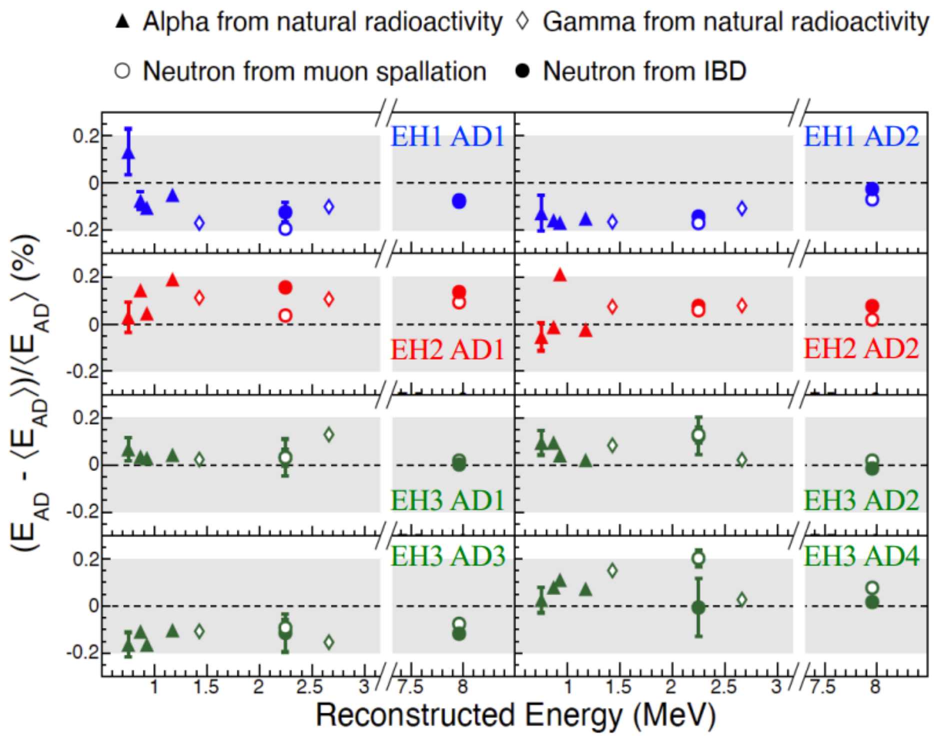


- The largest additional correction is about 3%

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



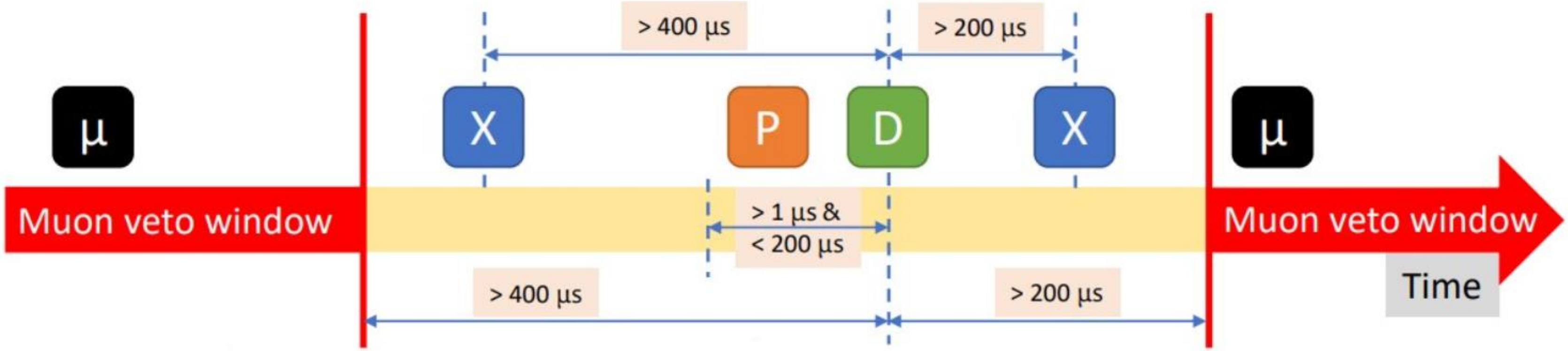


Relative uncertainty in energy scale: ~0.2%

■Details of IBD Selection

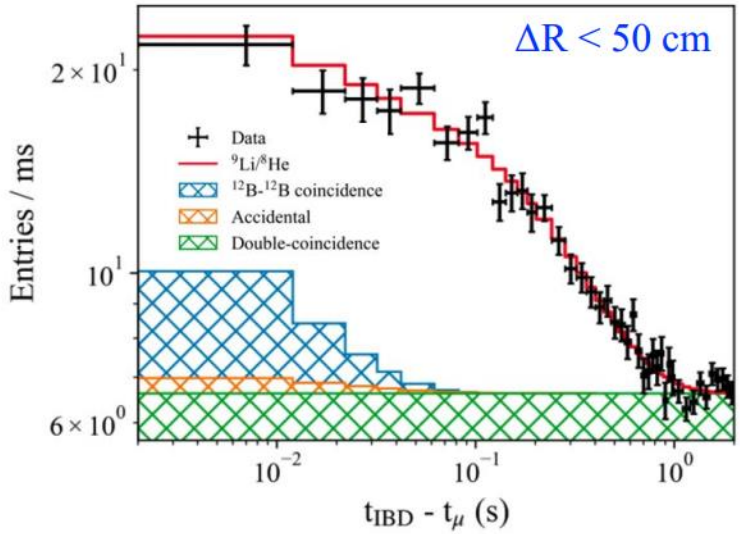
P = Prompt-like signal; D = Delayed-like signal; X = Non-muon signal

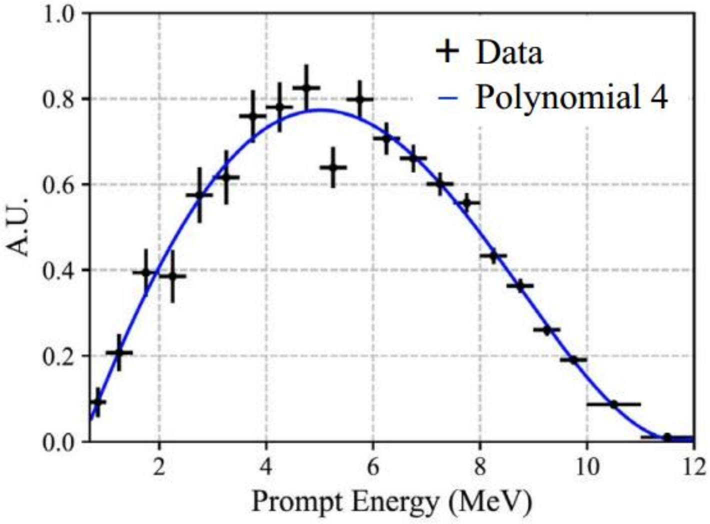
Muon veto	Water pool muon	Veto [-2 μs, 200 μs] after NHIT > **12** in OWS or IWS		
	AD muon	Veto [-2 μs, 1 ms] after > **20 MeV** signal in AD		
	AD shower	Veto [-2 μs, 0.4 s] after > **2 GeV** signal in AD		
	IWS muon veto	Veto [-2 μs, 10 μs] after **6** < NHIT ≤ **12** in IWS		
Flasher cut		Standard, DocDB-7424	Residual, DocDB-12462	
Energy cut		0.7 ≤ P ≤ 12 MeV	6 ≤ D ≤ 12 MeV	0.7 ≤ X ≤ 20 MeV
Decoupled Multiplicity Cut (DMC)	Full DMC for post-6AD period	Each D	One P within (-200 μs, -1 μs) && no X within (-400 μs, 200 μs)	
			Time to last muon veto window > 400 μs	
			Time to next muon veto window > 200 μs	



■ ^{9}Li/^{8}He Background

- ^{9}Li/^{8}He
  - ➢ 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



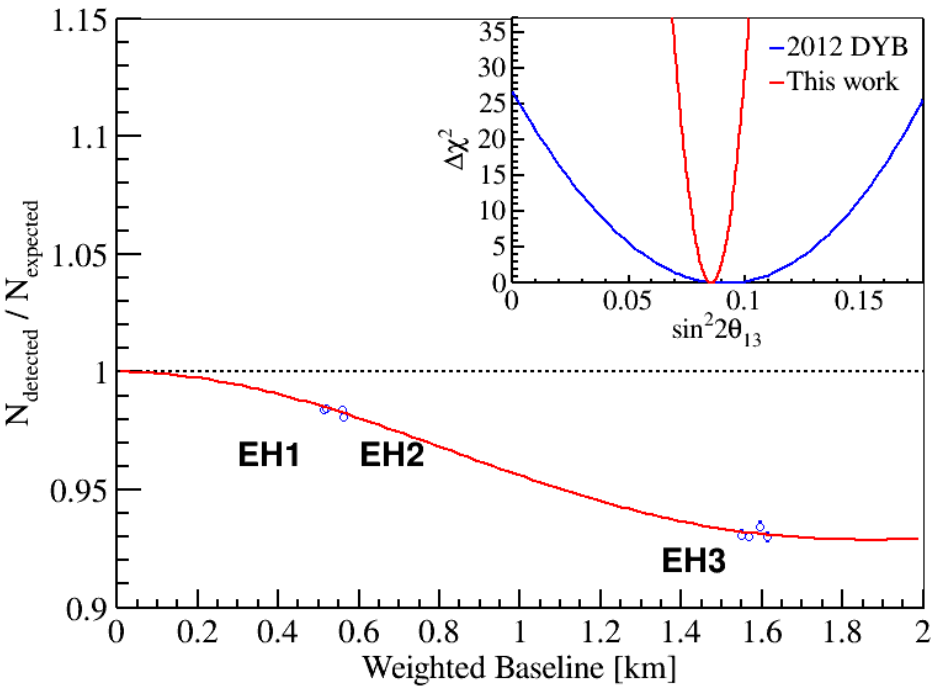


Summary Table

	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 [AD^{-1} 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

■Rate-only Fitting Results

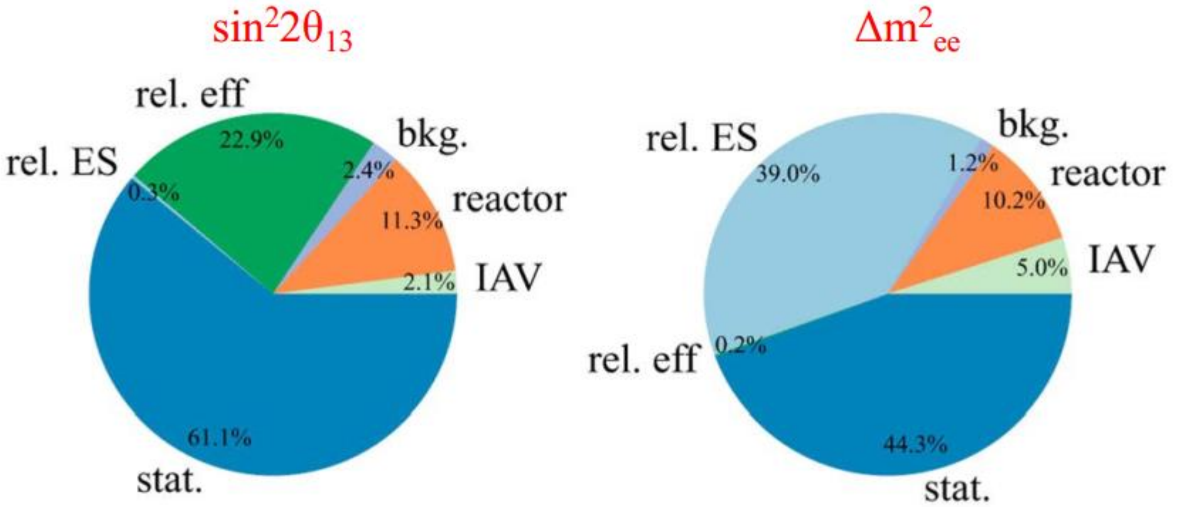
rate-only	$\sin^2 2\theta_{13}$	χ^2_{min} / NDF
1-stage	$0.0853^{+0.0027}_{-0.0027}$	3.4 / 6
3-stage	$0.0854^{+0.0027}_{-0.0027}$	17.3 / 19



■Error Budget

Based on Asimov sample

Add-on method:



Subtraction method: