Latest Results On Neutrino Oscillation Parameters From Daya Bay

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(On behalf of the Daya Bay Collaboration)

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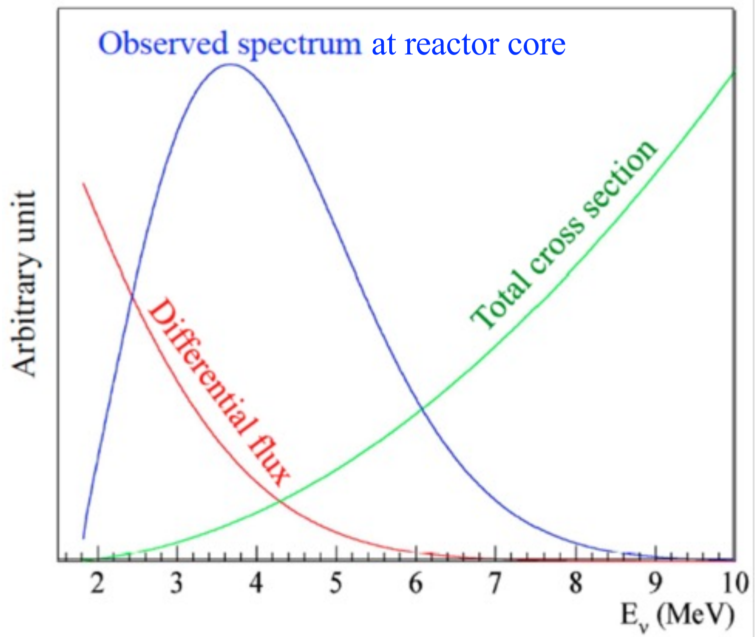
The Daya Bay Collaboration

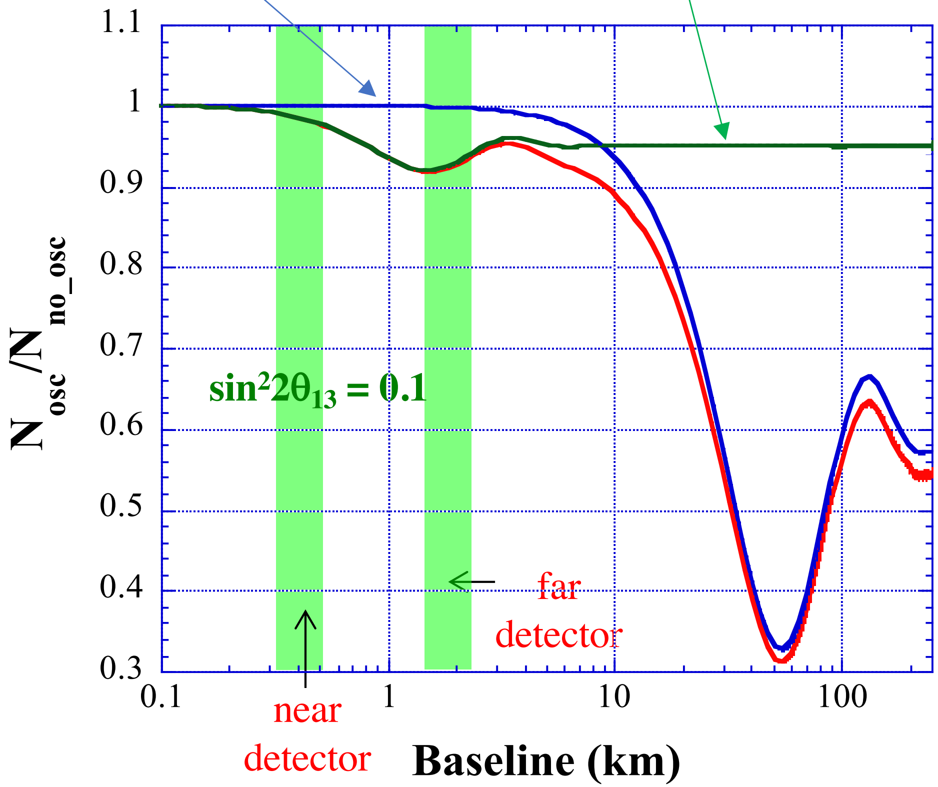
About 200 members
from
Chile, China, Czech Republic, Hong Kong, Russia, Taiwan and USA

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

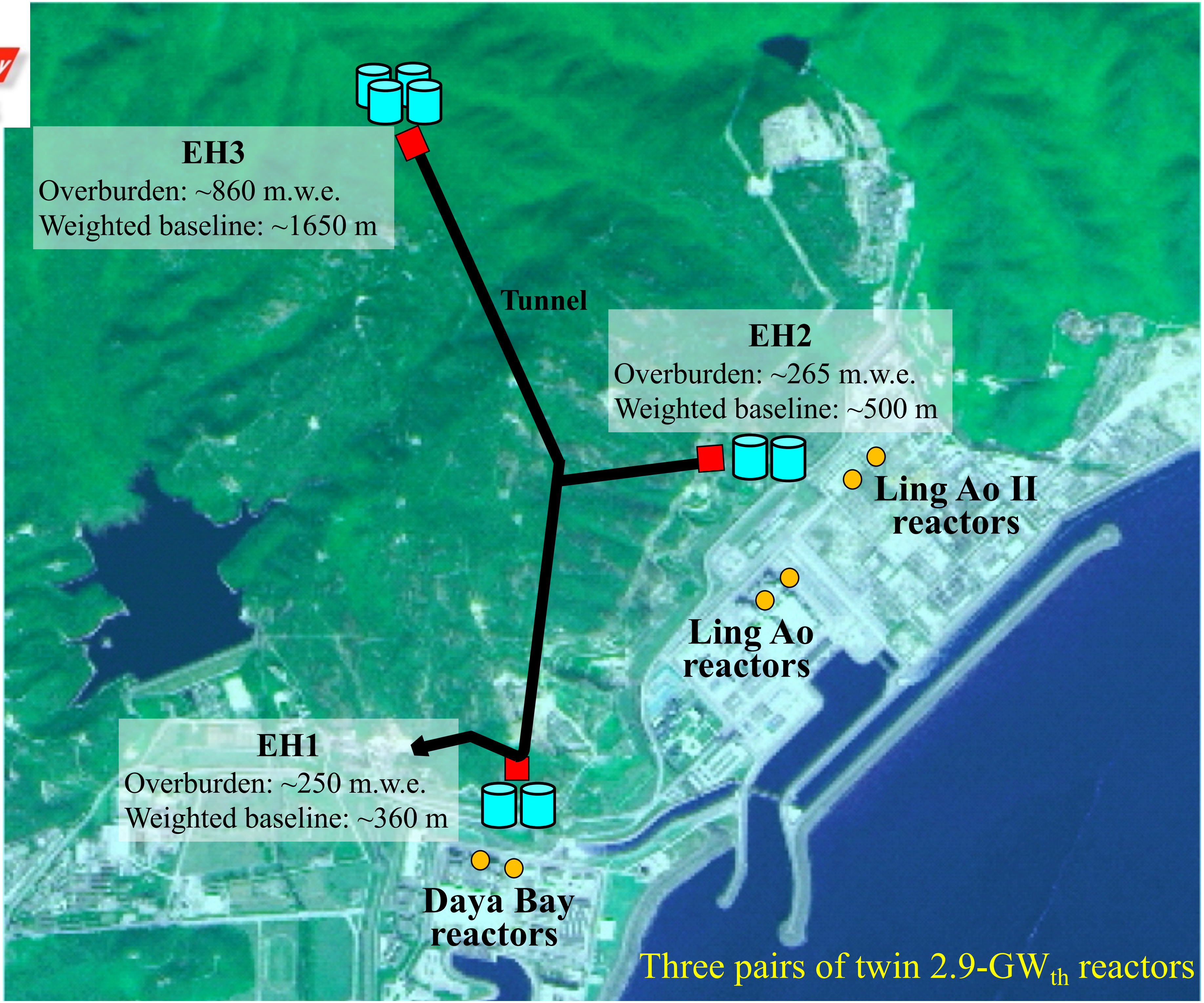
- Survival probability:

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





- Lower systematic uncertainties by performing relative measurements with Far/Near ratios


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

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

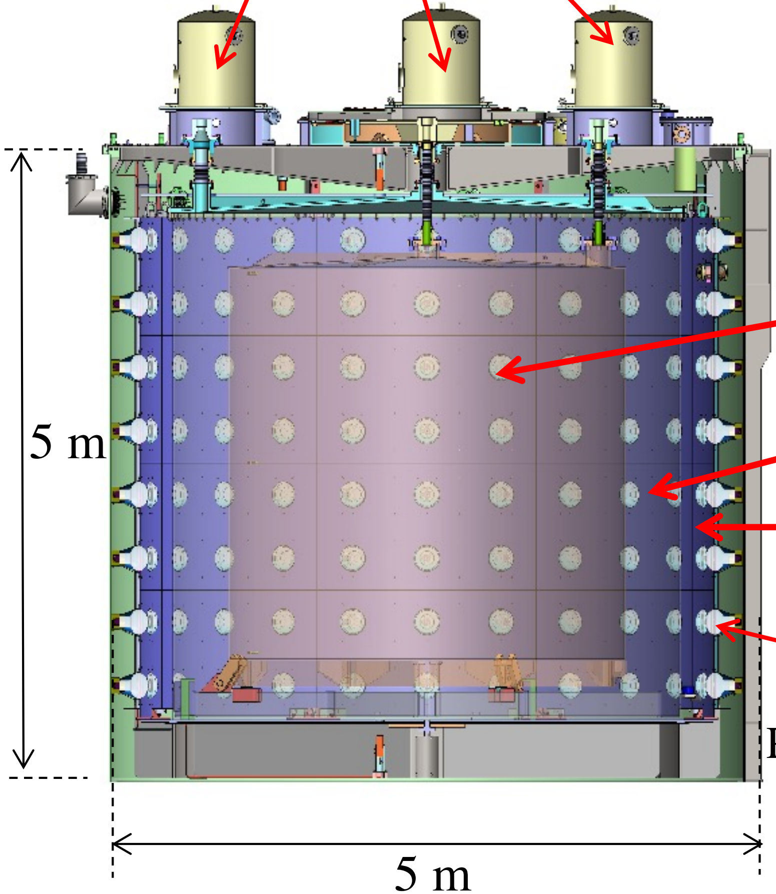
~180 μs: $\rightarrow + p \rightarrow d + \gamma$ (2.2 MeV)

$\rightarrow + Gd \rightarrow Gd^*$

~30 μs for 0.1% Gd: $\rightarrow Gd + \gamma$'s (~8 MeV)

main focus of this talk

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



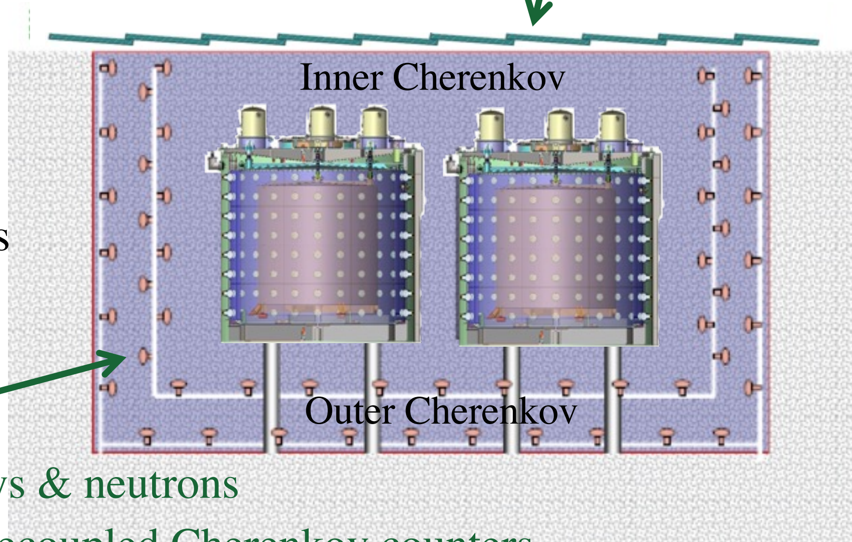
20-t 0.1% Gd-loaded liquid scintillator (target)

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



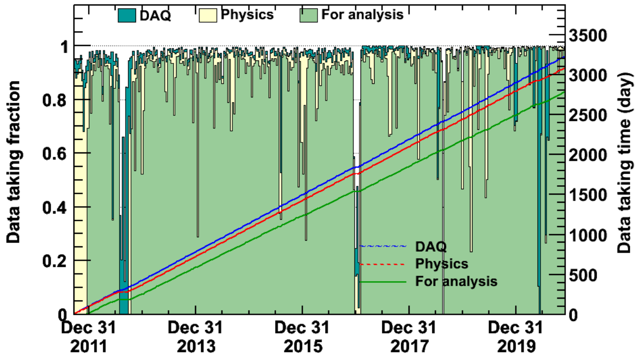
2.5-m water:
- Attenuates gamma rays & neutrons
- Forms two optically decoupled Cherenkov counters

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

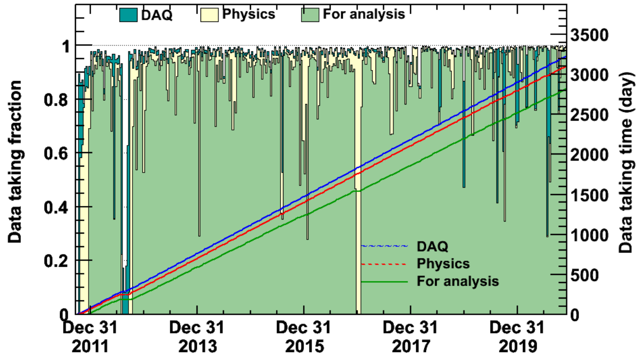
Data Collection

- Operational statistics:

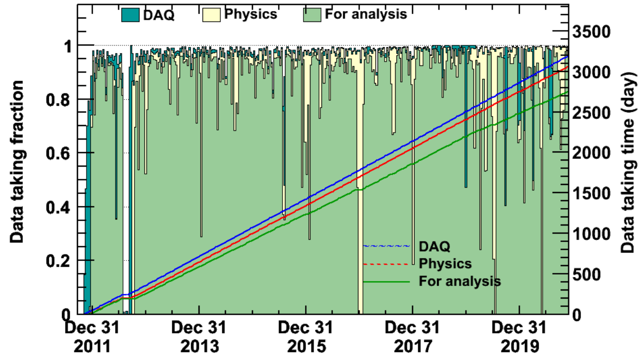
EH1



EH2



EH3



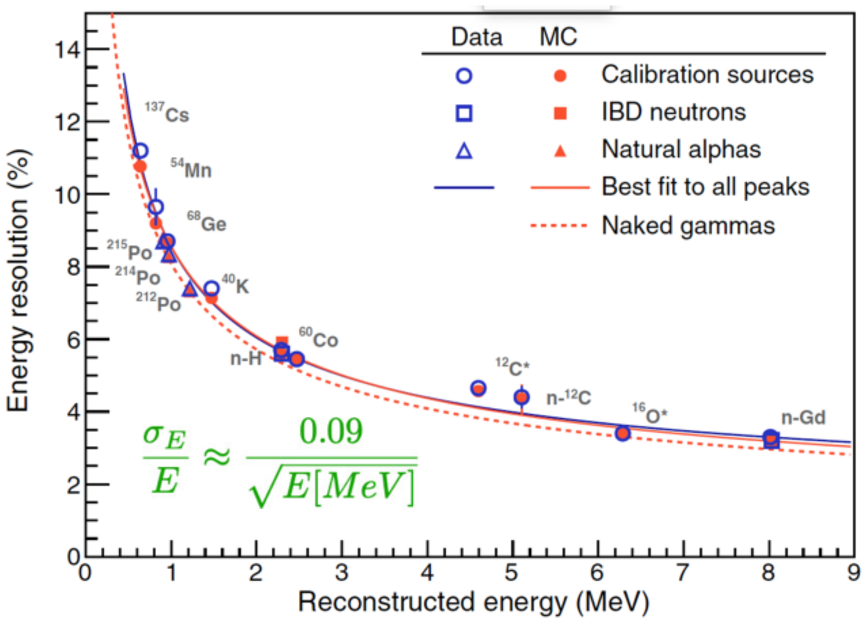
- Three physics runs:

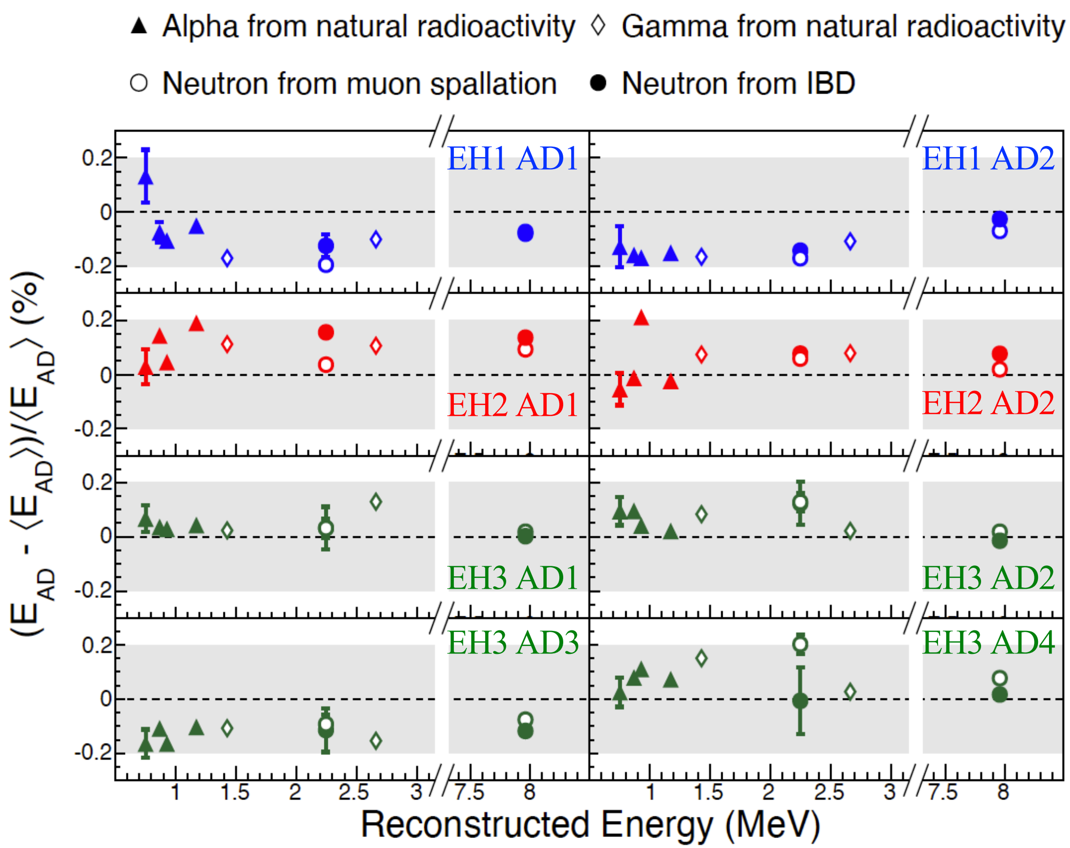
Configuration	EH1	EH2	EH3	Start date – End date	Duration (Days)
6-AD	2	1	3	24 Dec 2011 – 28 July 2012	217
8-AD	2	2	4	19 Oct 2012 – 20 Dec 2016	1524
7-AD	1	2	4	26 Jan 2017 – 12 Dec 2020	1417
Total					**3158**

- Data available for analyses: ~2700 days

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



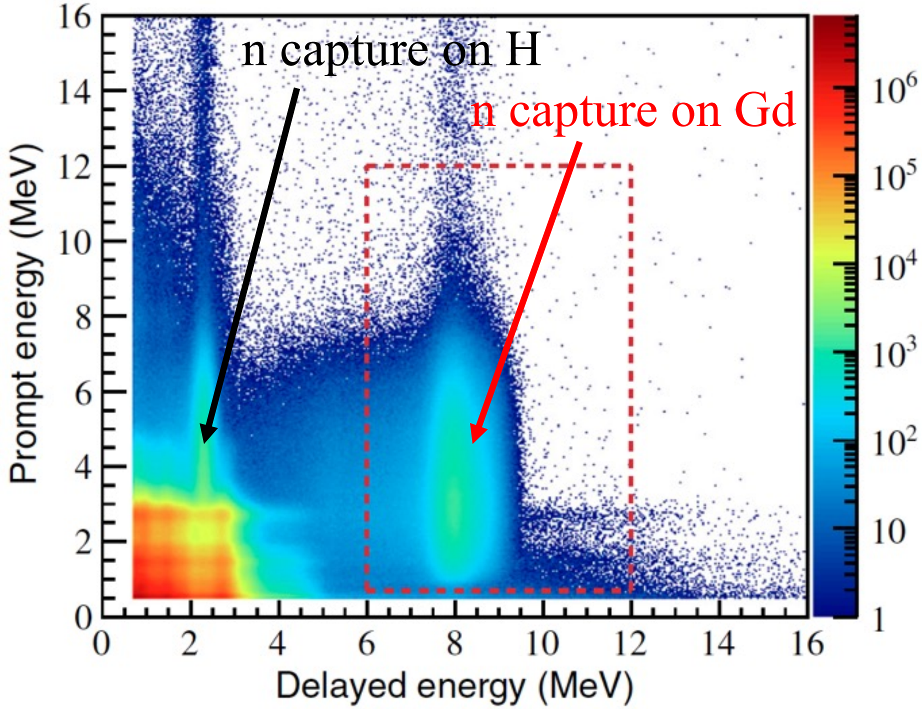


Relative uncertainty in energy scale: ~0.2%

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

PRD**95** (2017) 072006

- 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

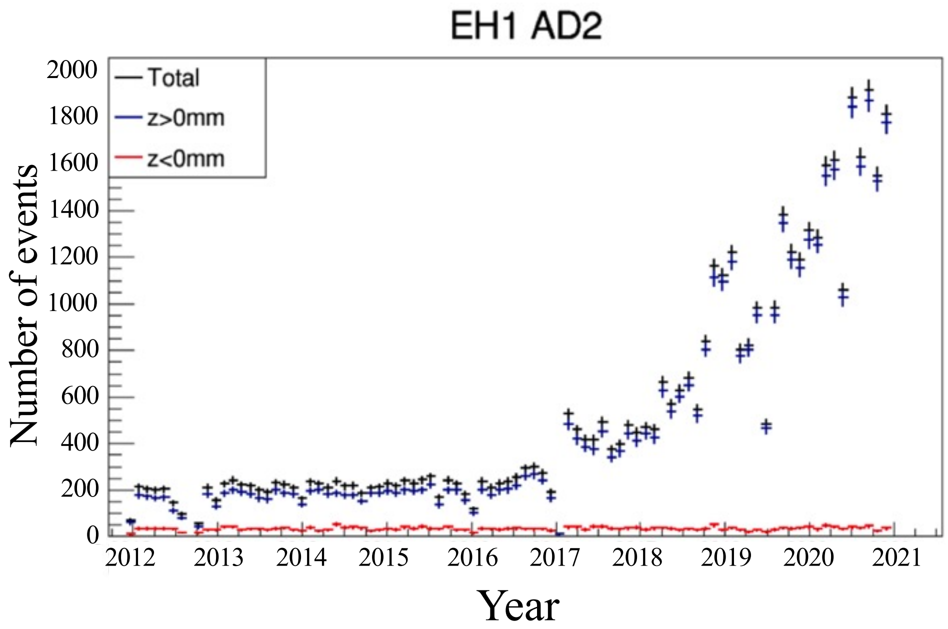
	Efficiency	Correlated	Uncorrelated
Target protons	-	0.92%	0.03%
Flasher cut	99.98%	0.01%	0.01%
Delayed energy cut	92.7%	0.97%	0.08%
Prompt energy cut	99.8%	0.10%	0.01%
Multiplicity cut		0.02%	0.01%
Capture time cut	98.7%	0.12%	0.01%
Gd capture fraction	84.2%	0.95%	0.10%
Spill-in	104.9%	1.00%	0.02%
Livetime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

Background

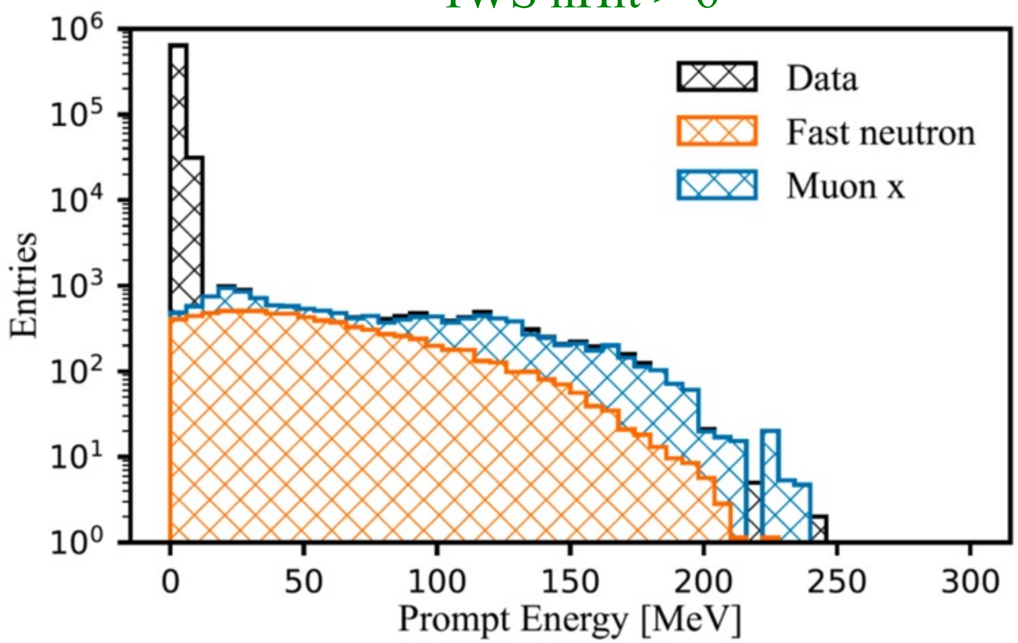
- Uncorrelated background
  - Accidental
- Correlated background
  - Fast neutron
    - produced outside of the AD but enters the active volume of the AD
  - 'Muon-x'
    - associated with untagged muons due to equipment malfunction
  - $^{9}Li/^{8}He$
    - spallation product produced by cosmic-ray muons inside the AD
  - $^{241}Am\text{-}^{13}C$
    - neutron calibration source resides inside the ACU
    - minor background
  - $^{13}C(\alpha,n)^{16}O$
    - α from decay of natural radioactive isotope in the liquid scintillator
    - insignificant background

Muon-x Background

- Gradual failure of PMTs or high-voltage channels in the inner water Cherenkov counter (IWS) 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-x events
  - Extend cut on E_{prompt} from 12 MeV to 250 MeV to determine the rate and spectrum for fast neutron and muon x together

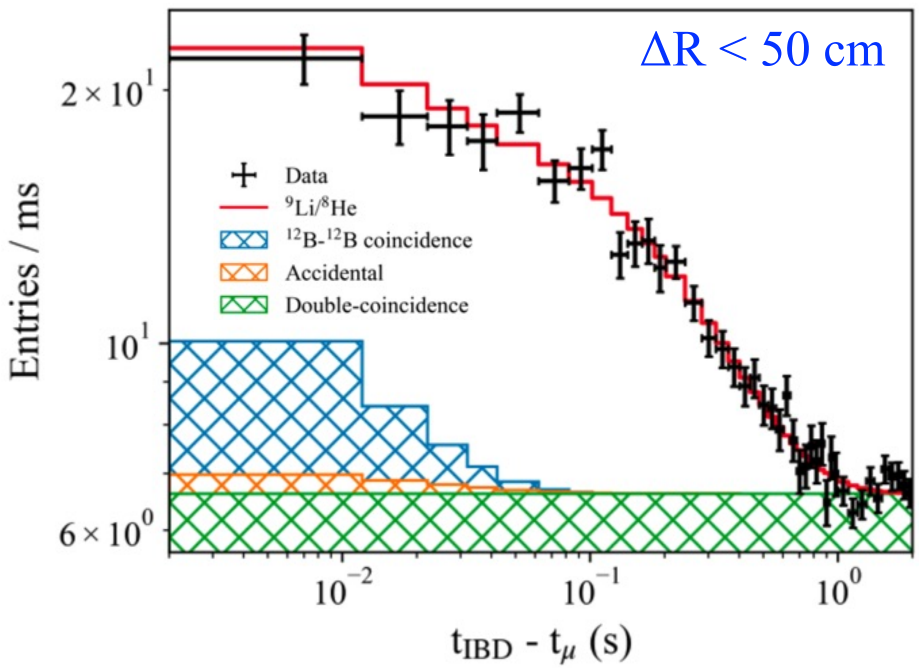


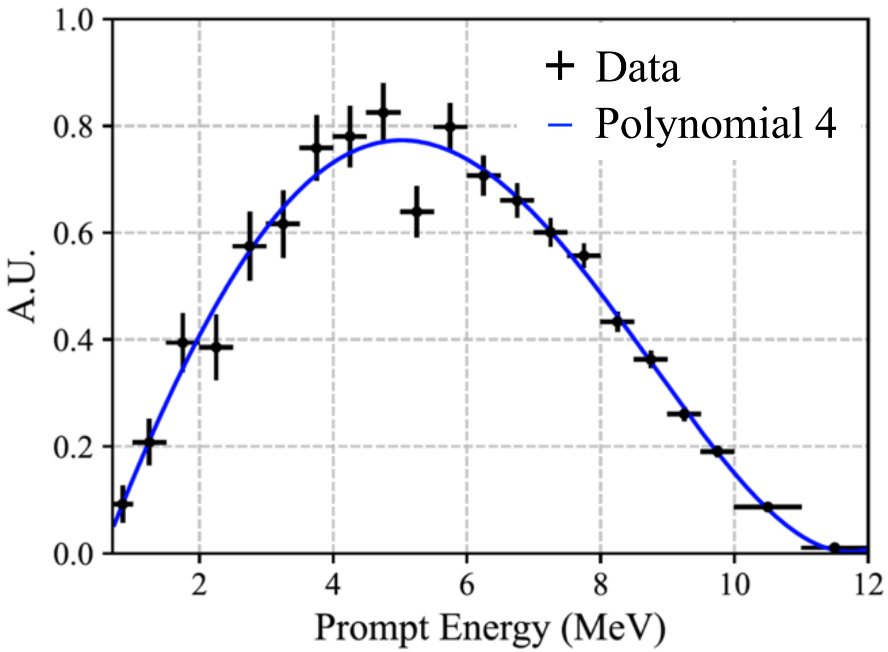
IWS nHit > 6



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

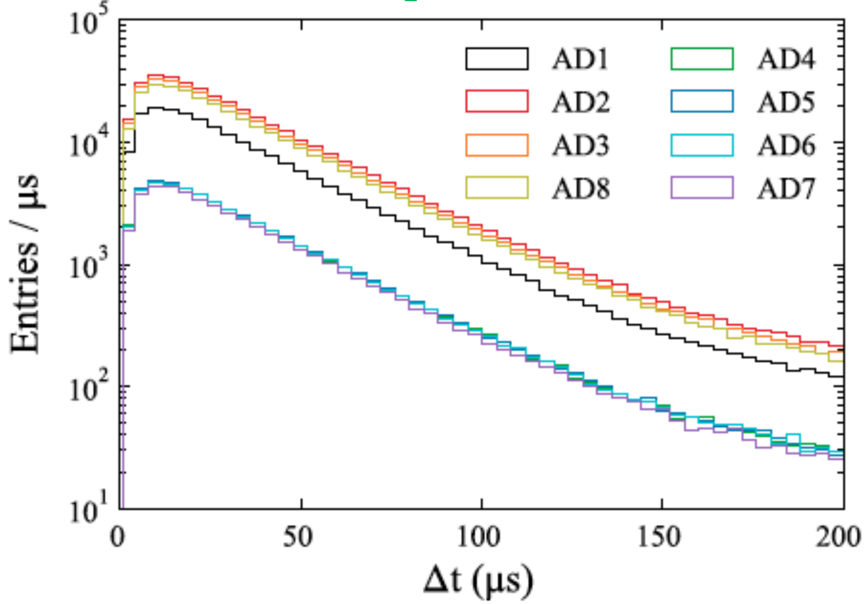


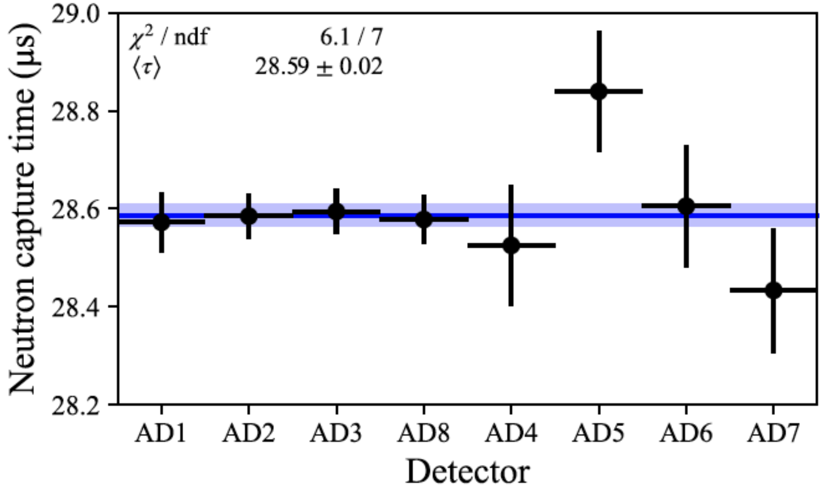


Performance of Antineutrino Detectors

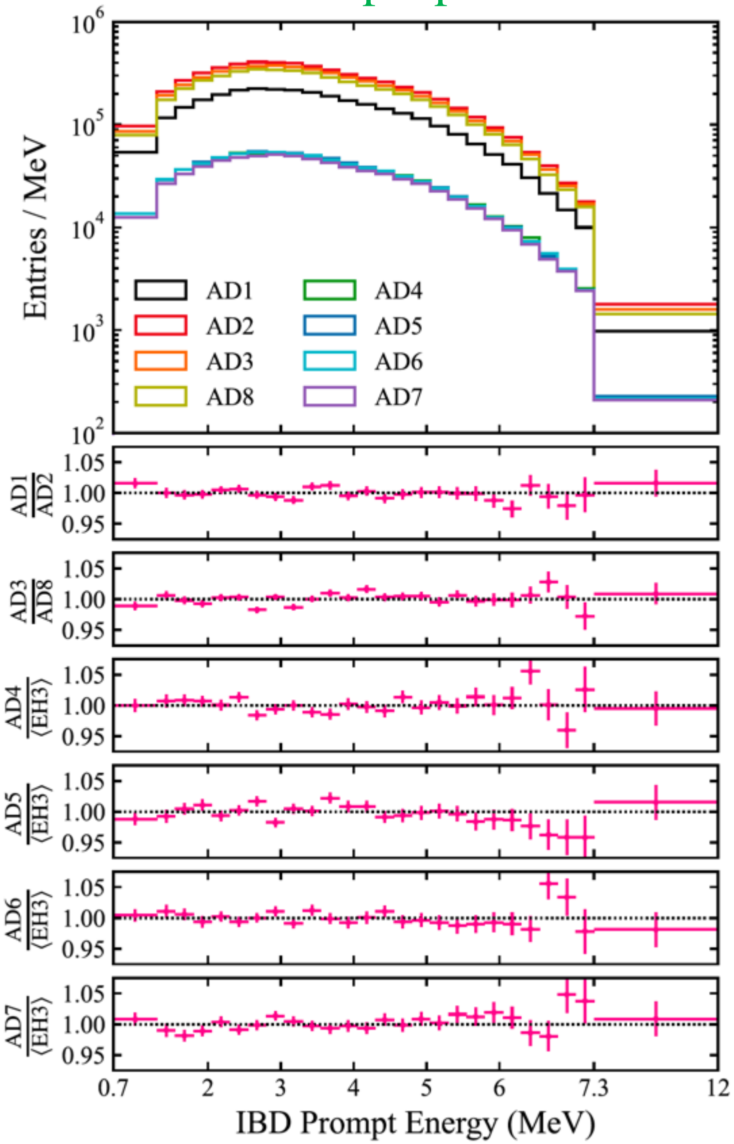
IBD candidates including background (< 2%)

Capture time





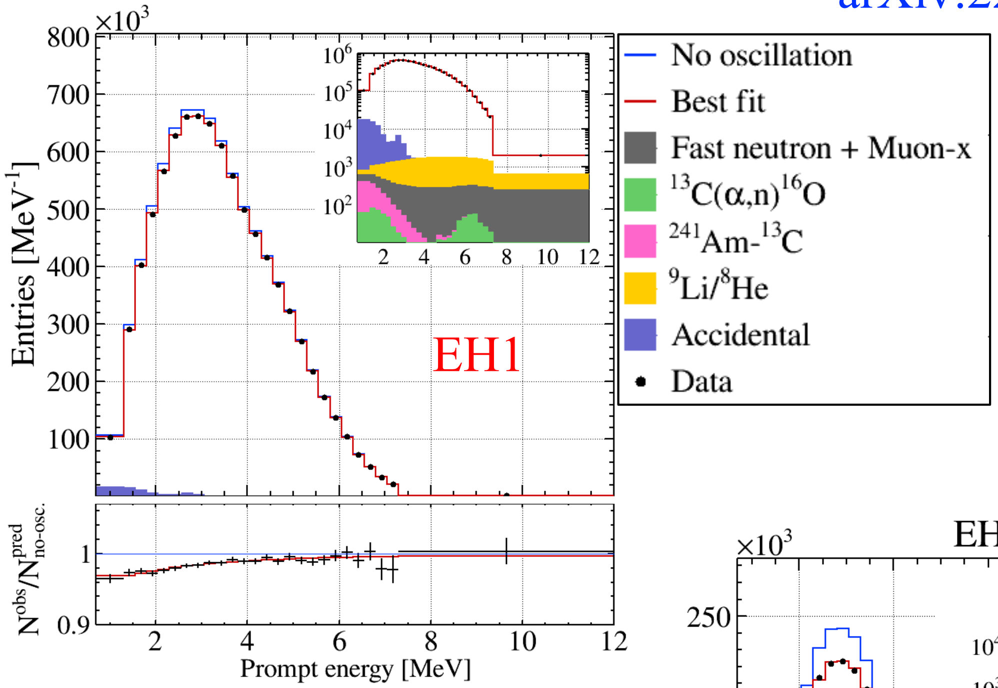
Prompt spectrum



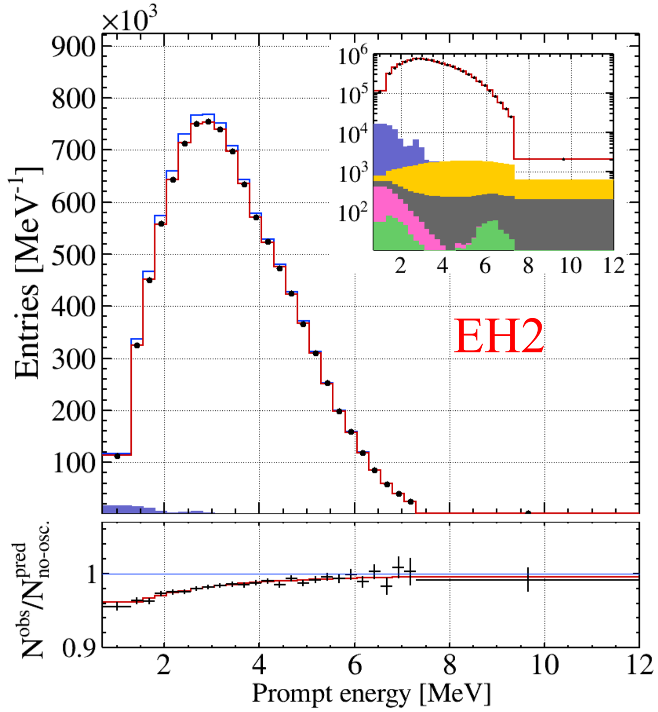
Antineutrino detectors in the same hall have similar performance

Prompt-energy Spectra

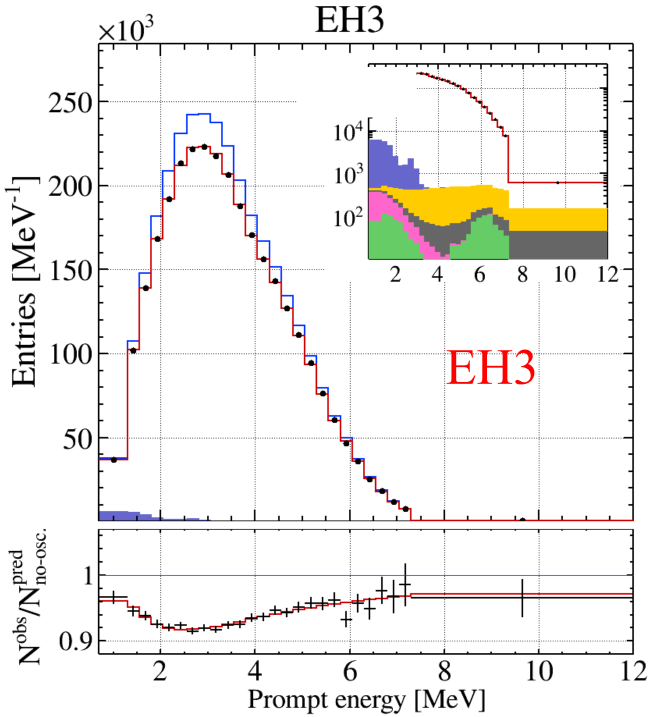
arXiv:2211.14988



2,236,810 IBD events



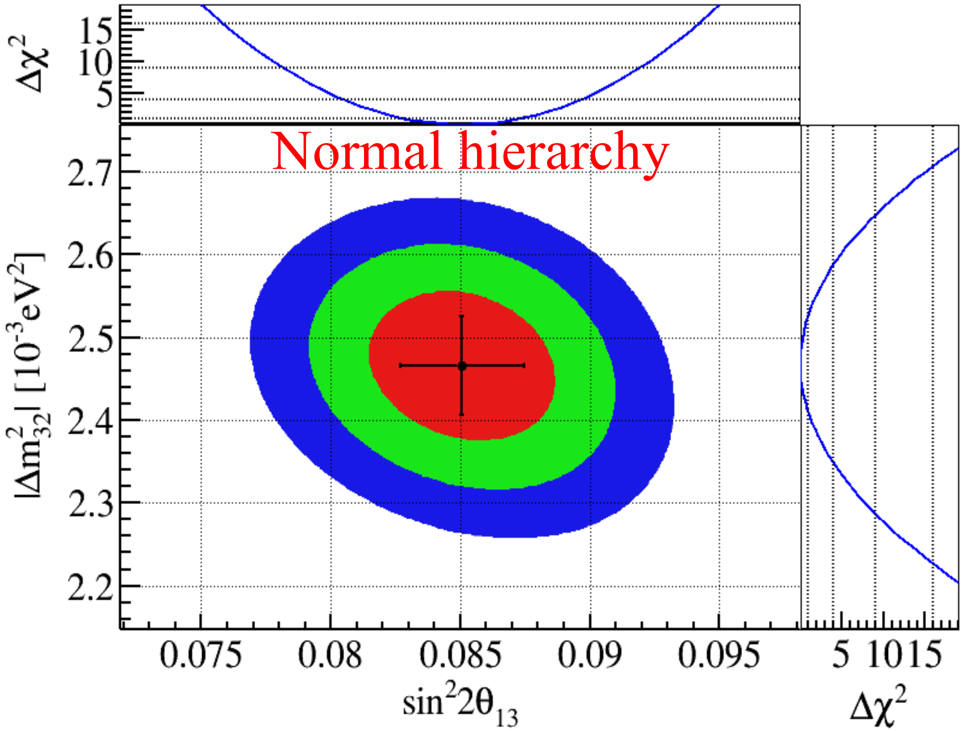
2,544,894 IBD events

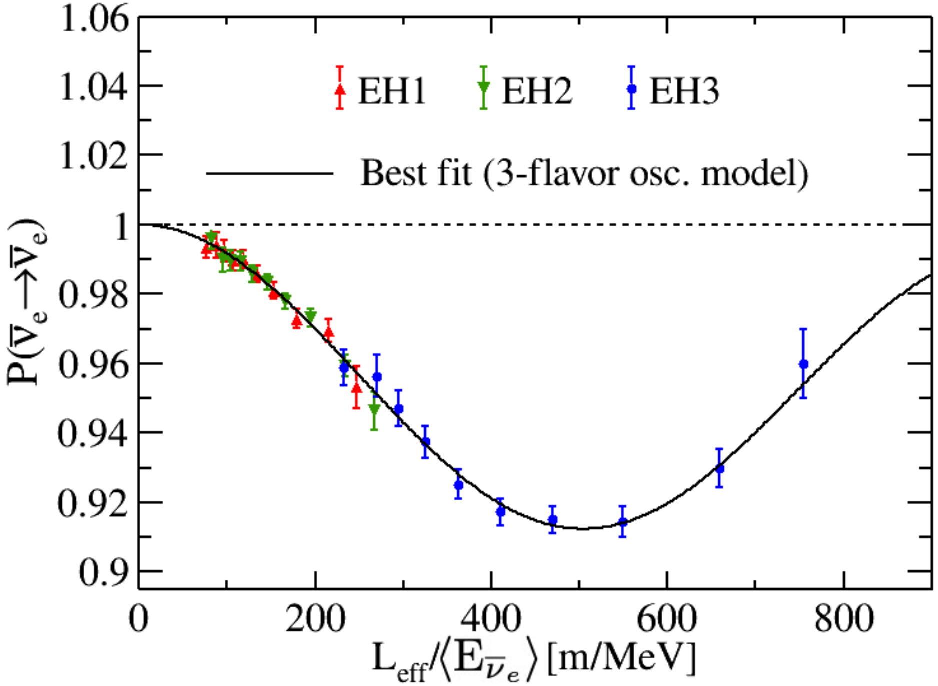


764,414 IBD events

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

arXiv:2211.14988





Best-fit results: $\chi^2/\text{ndf} = 559/517$

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

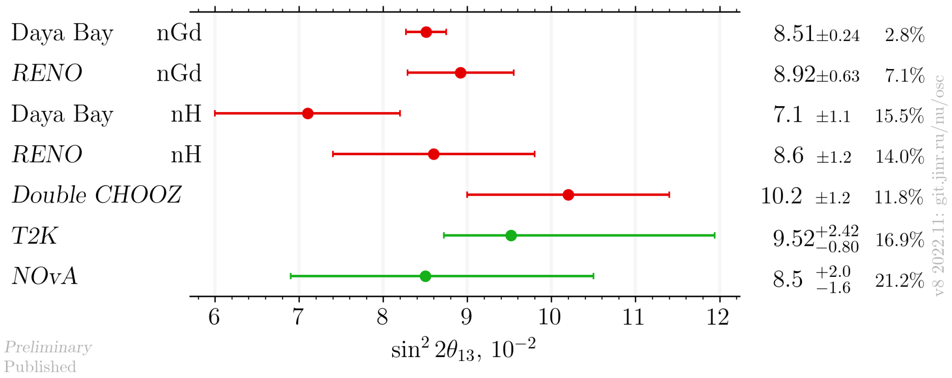
Normal hierarchy: $$\Delta m^2_{32} = +\left(2.466^{+0.060}_{-0.060}\right) \times 10^{-3}\text{eV}^2$$ (2.4% precision)

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

Present Global Landscape

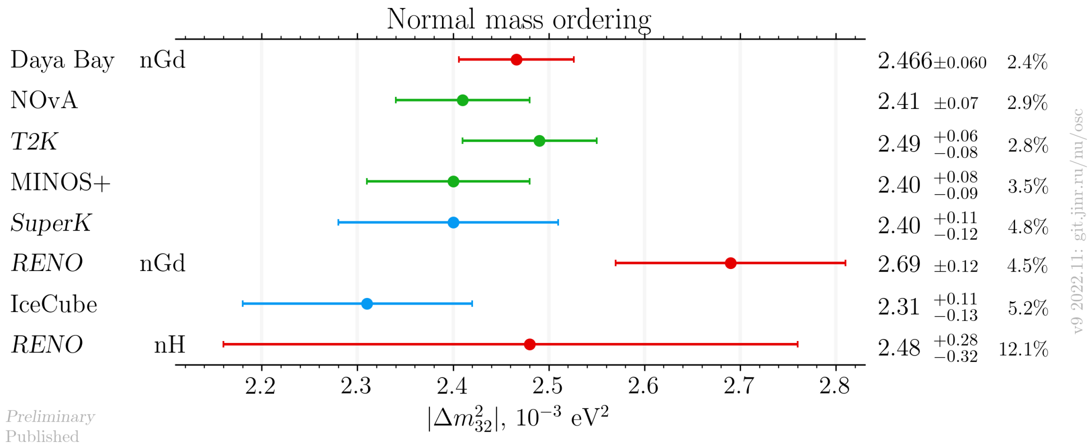
Compare Daya Bay's current results with other measurements

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

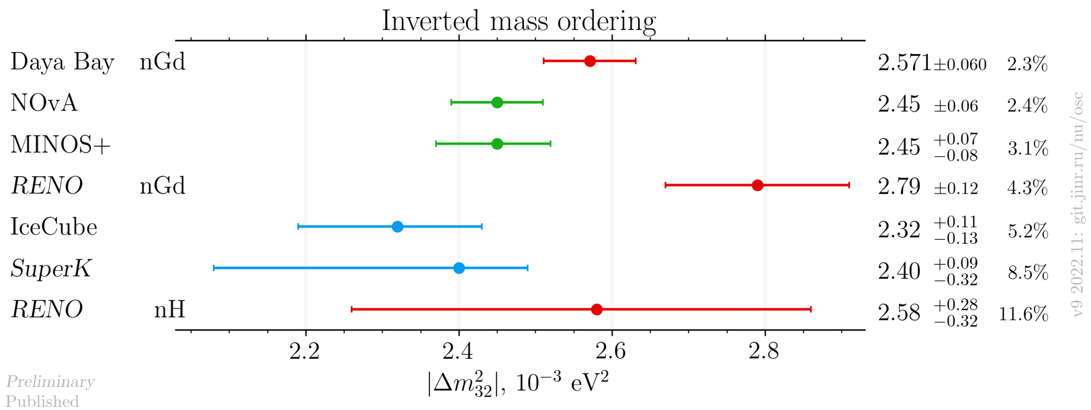


Probably the best measurement for a while

Δm^2_{32} (NO)



Δm^2_{32} (IO)



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

Summary

- Daya Bay
  - Finished data taking on 12 December 2020
  - Acquired world's largest sample of reactor antineutrinos to date

    5.5 million IBD events with neutron captured on Gd
  - Obtains the world's most precise determination of $\sin^2 2\theta_{13}$

$$\sin^2 2\theta_{13} = 0.0851^{+0.0024}_{-0.0024}$$

  - Provides one of the best measurements of $|\Delta m^2_{32}|$

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

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

  - Will have more results to be presented in the future, for example,
    - Updated results on oscillation parameters with neutron captured on H samples