Recent Results from Daya Bay:
1) High Energy Reactor Antineutrinos
2)Oscillation parameters
3) Sterile neutrinos

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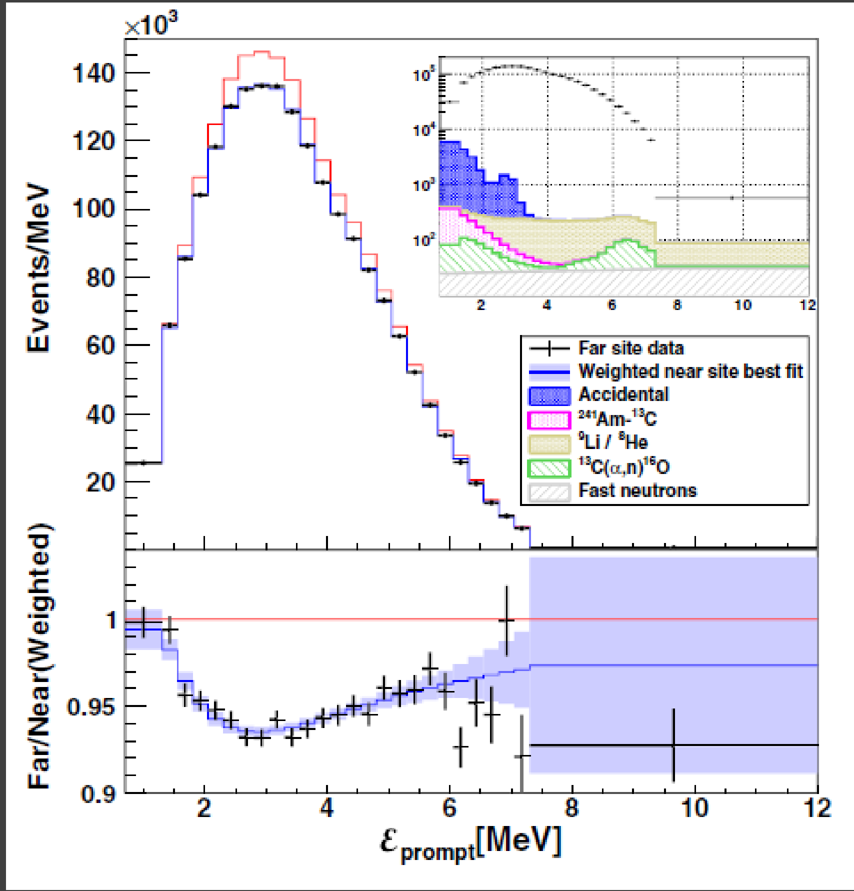
First Measurement of High-Energy Reactor Antineutrinos at Daya Bay

PHYSICAL REVIEW LETTERS 129, 041801 (2022)

First Measurement of > 8 MeV Antineutrinos

- Motivation for > 8 MeV antineutrino
  - No previous measurements from reactor neutrino experiments due to low statistics and low signal/background
  - A background in the search for diffuse supernova neutrino background
  - Benchmark data for beta-decay with high end-point energies, such as ^{88,90}Br and ^{94,96,98}Rb
- The results of first measurement from Daya Bay
  - No > 10 MeV antineutrino hypothesis rejected at 6.2 sigma
  - 29% flux deficit compared to recent model prediction in 8-11 MeV
  - A data-based reference spectrum with antineutrino energy in 7—11 MeV

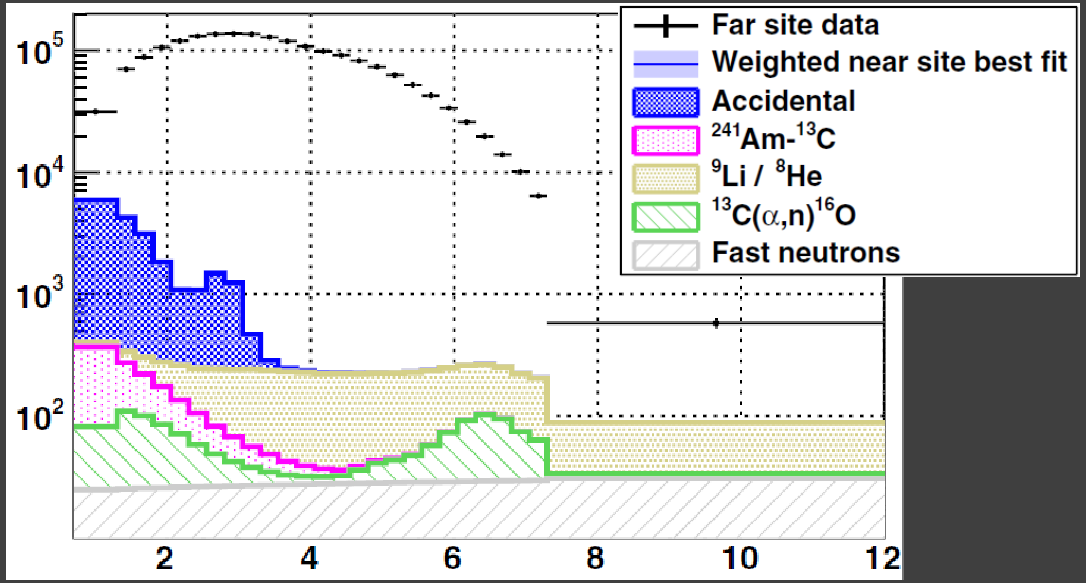


Oscillation measurement in PRL 121, 241805 (2018)
First exploration of the details in 8—12 MeV in the last energy bin with new analysis techniques.

Analysis details in the paper PRL 129, 041801 (2022)

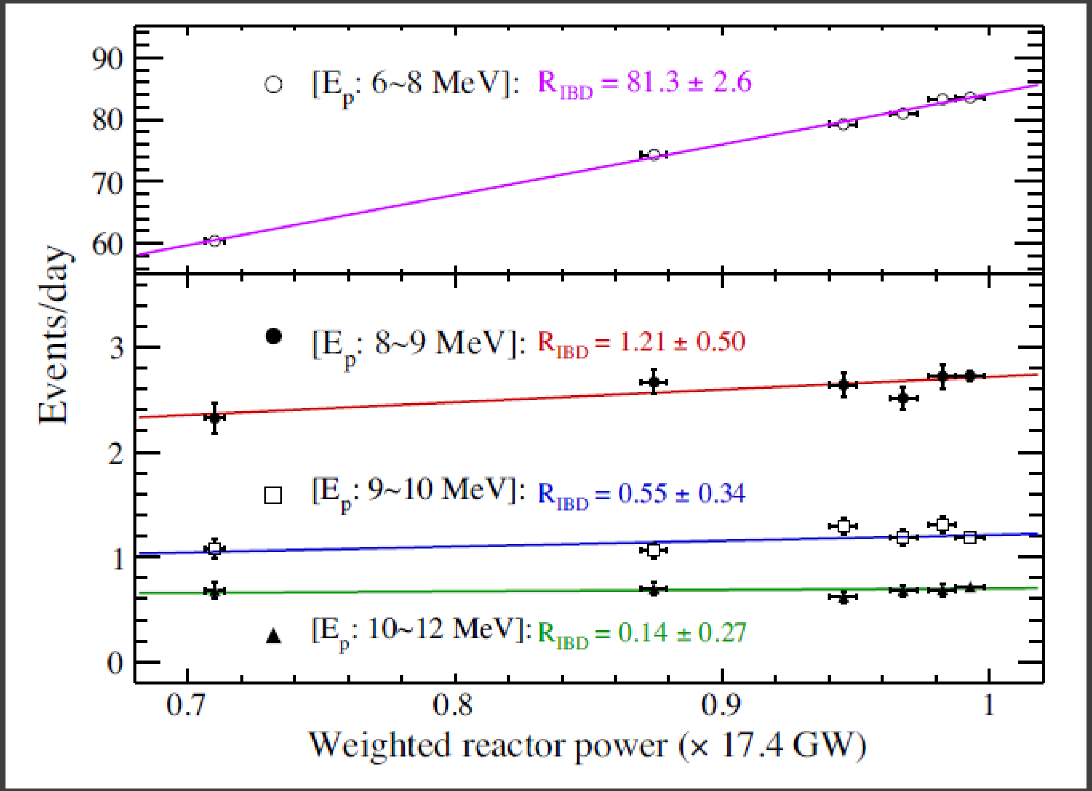
Challenges of the analysis

- Data sample: 1958 days
  - Same IBD selection criteria as that in oscillation analysis
  - 9000 IBD candidates in 8—12 MeV among 4 million in full energy region
- Major backgrounds > 8 MeV
  - cosmogenic $^{9}Li/^{8}He$
  - Fast neutron
- A multivariate analysis is used to separate the signal component from various background components by fitting to the PDFs



$$R = R_{\mathrm{IBD}} P_{\mathrm{reactor}} + R_{\mathrm{bkg}}$$

A simple correlation analysis is unable to find antineutrinos > 8 MeV with significance < 2.5 σ

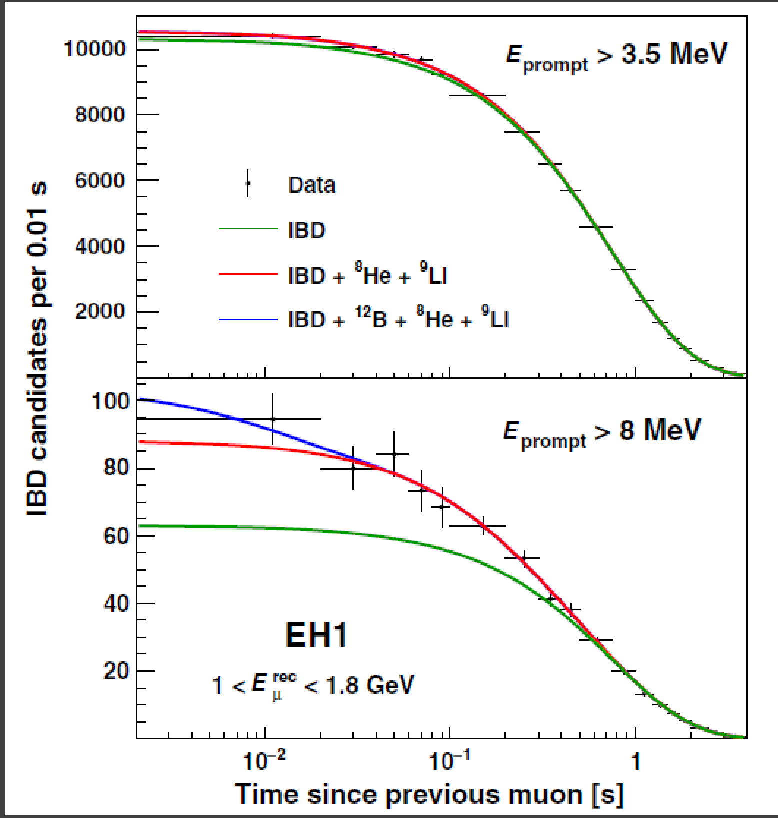


PDFs for signal and background

- A joint PDF for IBD, fast neutron, ^{9}Li/^{8}He
- Time to previous muon PDF: $f_p(\Delta t)$
  - Distinguish ^{9}Li/^{8}He from the other two
  - Has been used in the background estimation for oscillation analysis
  - 8 categories of muons including 4 energy bins w/o accompanying neutron
  - ^{9}Li/^{8}He/^{12}B is correlated with muon
  - IBD and fast neutron (mainly from untagged muons) are uncorrelated with muon

$$F(\boldsymbol{r}; \Delta t, z, w) = \sum_p r_p f_p(\Delta t) h_p(z) k_p(w)$$

p is event type
r_p is the ratio of number of one event type over the total event number



$$f(\Delta t) = \kappa \cdot e^{-\kappa \Delta t}$$

For uncorrelated events, k is $1/R_\mu$
For ^{9}Li/^{8}He, k is $1/R_\mu$ + $1/\tau$
R_μ: muon rate, τ: isotope lifetime

PDFs for signal and background

- Distinguish fast neutron from the other two
- Vertical position PDF: $h_p(z)$
- IBD and $^{9}Li/^{8}He$ is uniform, IBD PDF determined from IBD dominant energy region 2—8 MeV
- Majority of fast neutrons have downward momentum and are near the detector top
- Fast neutron PDF obtained from almost pure sample in 12—20 MeV region

- Distinguish IBD from the other two
- Reactor power PDF: $k_p(w)$
- IBD is proportional to reactor power, while the other two are not

$$F(\boldsymbol{r}; \Delta \boldsymbol{t}, z, w) = \sum_p r_p f_p(\Delta \boldsymbol{t}) h_p(z) k_p(w)$$

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

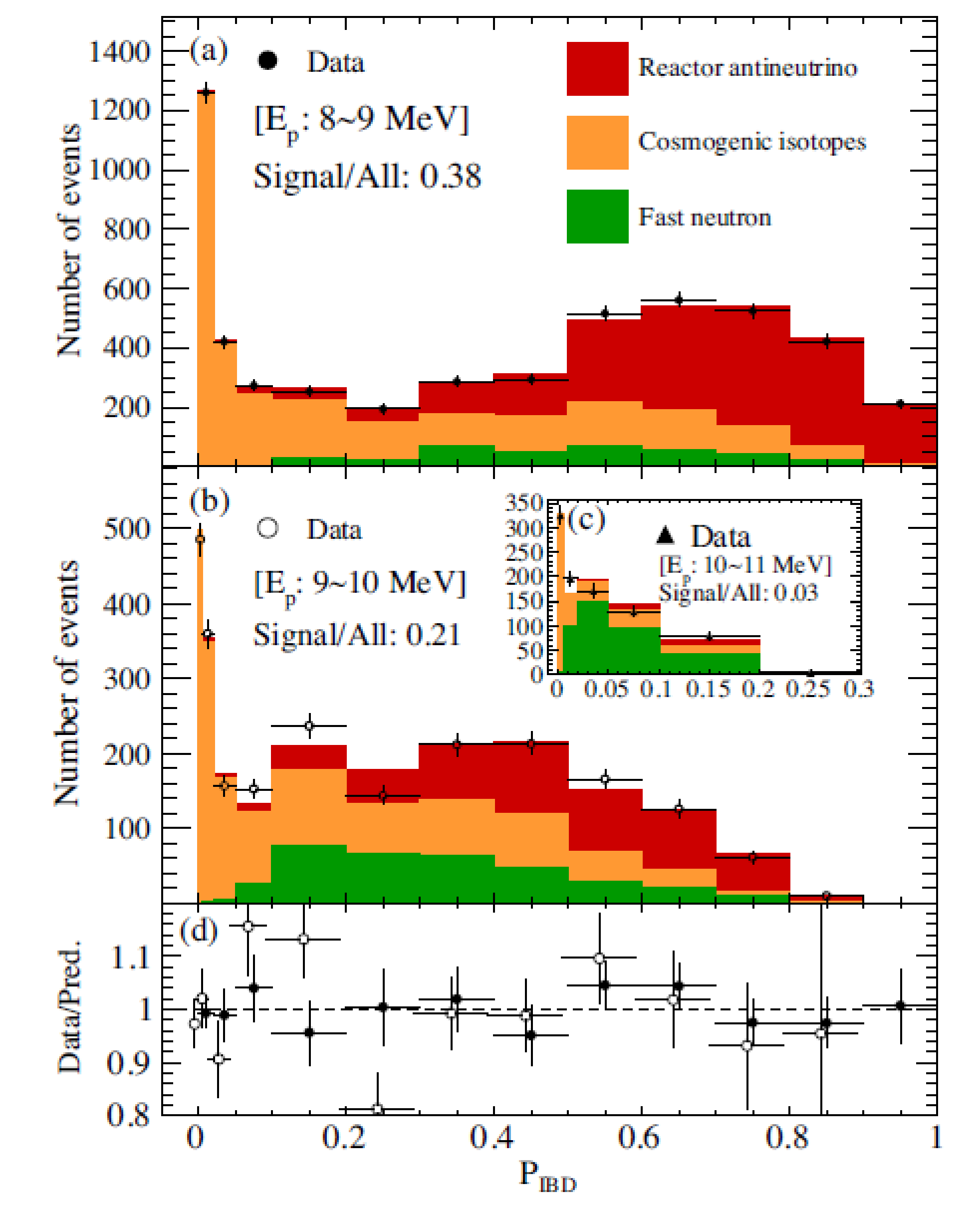
Minimizing a χ^2 to determine the ratio of number of one event type over all in each energy bin

Fitting results

- After minimization, probability of being an IBD signal is calculate

$$P_{\rm IBD} = \frac{r_{\rm IBD} f_{\rm IBD}(\Delta t) h_{\rm IBD}(z) k_{\rm IBD}(w)}{F(r; \Delta t, z, w)}$$

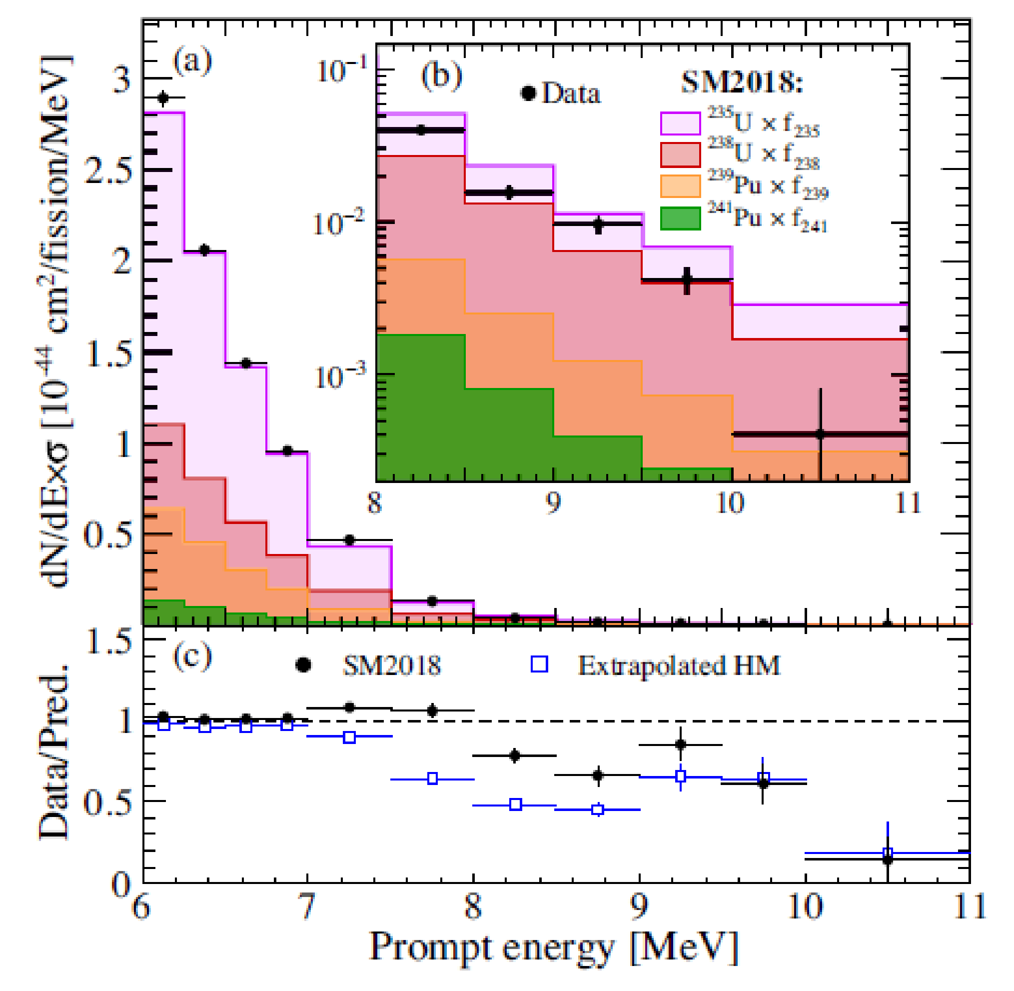
- Good agreement between data and best fit distributions in 8—9 MeV, 9—10 MeV and 10—11 MeV regions
- IBD yields for E> 8 MeV is obtained from the signal component



Comparison with model prediction

- Two models
  - SM2018, extended data provided by authors in PRL123, 022502 (2019)
  - Extrapolated HM, HM model with a polynomial extrapolation from PRC84, 024617 (2011)

- 29% smaller than SM2018 in 8—11 MeV

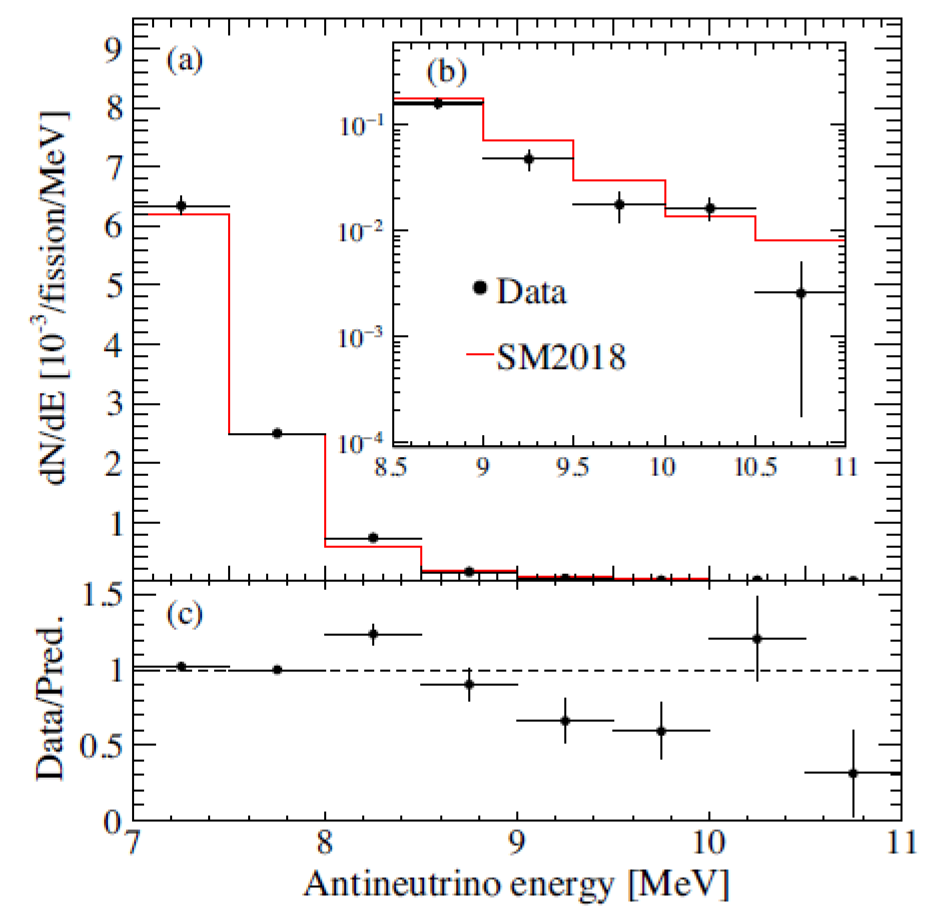


Reference antineutrino spectrum

- A data-based reactor antineutrino energy spectrum is determined with an unfolding technique in 7—11 MeV

Data provided in Supplemental Material in PRL 129, 041801 (2022)

- Similar deficit as in the prompt energy spectrum
- The significance of rejecting the hypothesis of no reactor antineutrinos above 10 MeV is 6.2σ



Precision measurement of reactor antineutrino oscillation at kilometer-scale baselines by Daya Bay

Submitted to PRL, arXiv:2211.14988

The world-leading results for θ_{13} and Δm^2_{32} with the full nGd data sample

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

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)

Improvements

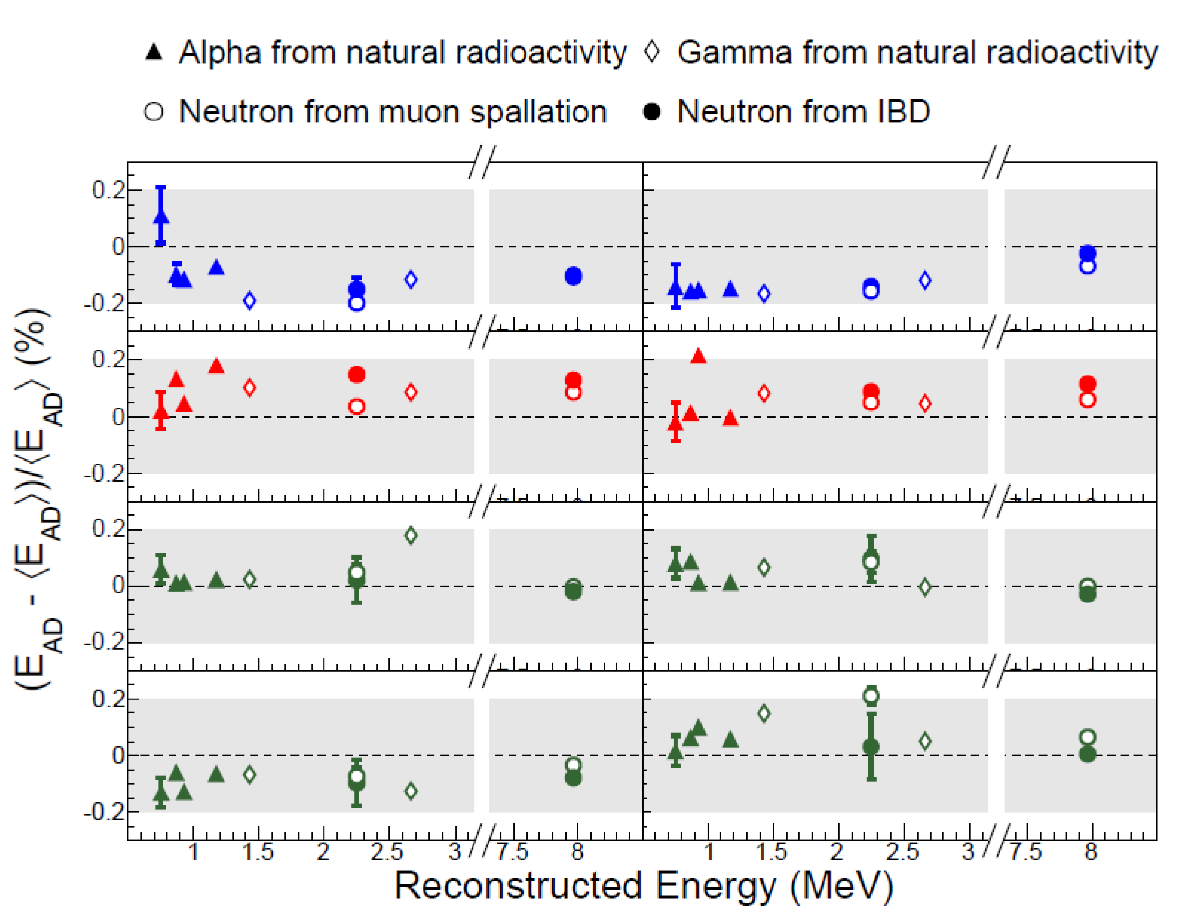
- Full statistics from 24 Dec 2011 to 12 Dec 2020

Year	Calendar days	EH1	EH2	EH3	Total IBDs	
2018 (PRL**121**, 241805)	1958	1,794,417	1,673,907	495,421	3,963,745	
2022 (arXiv:2211.14988)	3158	2,236,810	2,544,894	764,414	5,546,118	40% ↑

- 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

Energy scale

- Gain of photomultiplier tubes
  - Single-photoelectron from dark noise
  - Weekly LED monitoring
- Energy calibration
  - Weekly ^{68}Ge, ^{60}Co, ^{241}Am-^{13}C sources
  - Spallation neutrons
  - Natural radioactivity
- Relative energy scale uncertainty 0.2%

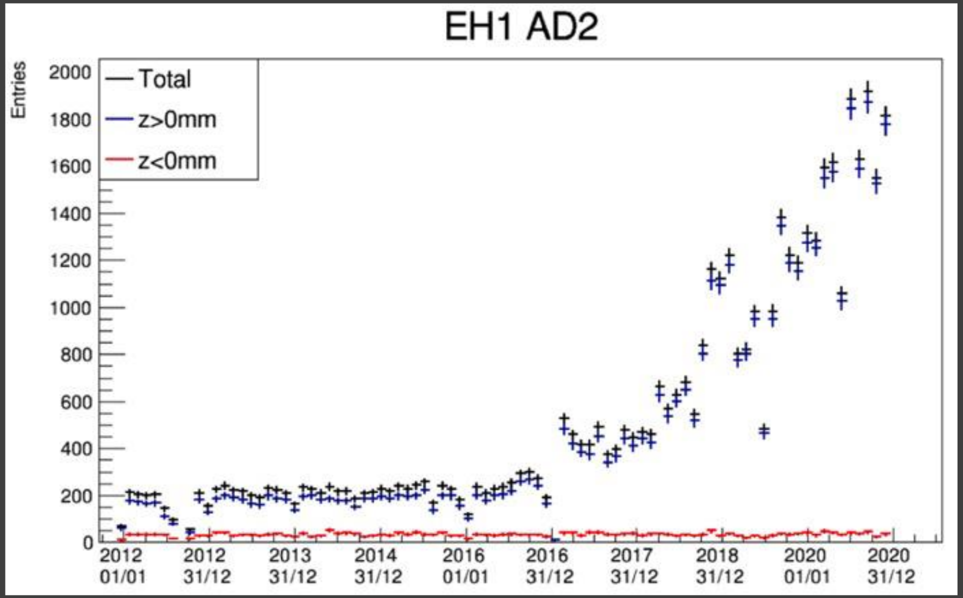


Background

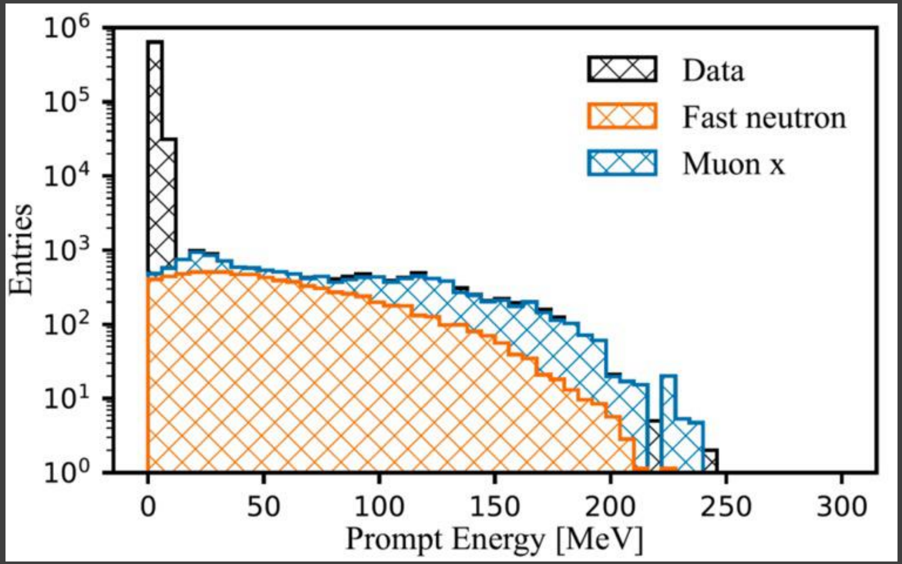
- Uncorrelated background
  - Accidental background
- Correlated background
  - Fast neutron
    - produced outside of the AD but enters the active volume of the antineutrino detector
  - ’Muon-x’
    - associated with untagged muons due to equipment malfunction
  - $^{9}Li/^{8}He$
    - spallation product produced by cosmic-ray muons inside the antineutrino detector
  - ^{241}Am-^{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

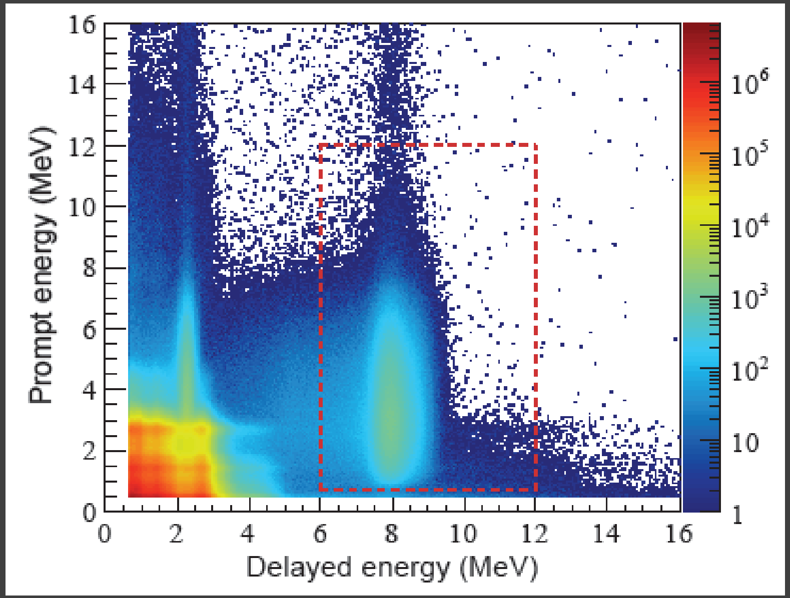


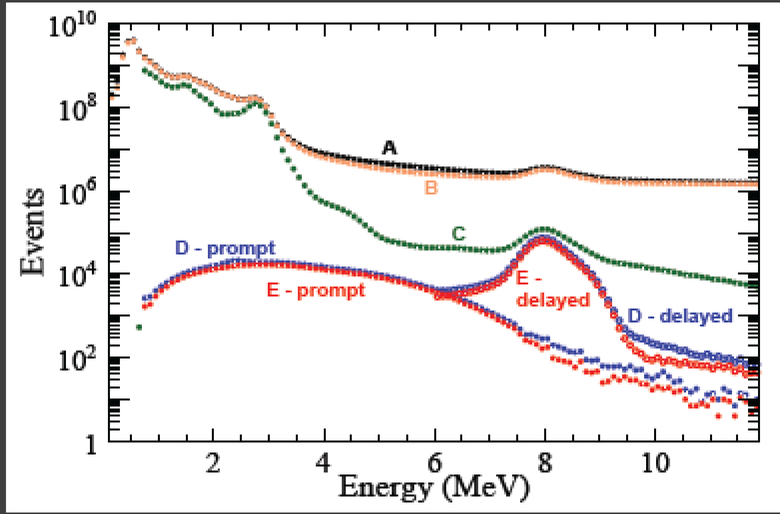
Antineutrino Candidates Selection

- Reject PMT flashers
- Muon veto
- Prompt positron: 0.7 MeV < E_p < 12.0 MeV
- Delayed neutron: 6.0 MeV < E_d < 12.0 MeV
- Neutron capture time: 1 μs < $\Delta t_{p\text{-}d}$ < 200 μs
- Multiplicity: isolated candidate pairs

Detection efficiencies

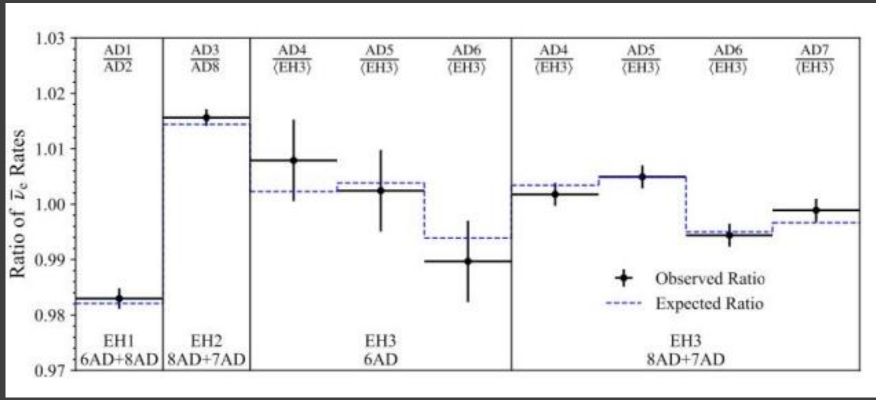
	Efficiency	Correlated	Uncorrelated
Target protons	-	0.92%	0.03%
Flasher cut	99.98%	0.01%	0.01%
Delayed energy cut	92.7%	0.97%	0.08%
Prompt energy cut	99.8%	0.10%	0.01%
Multiplicity cut		0.02%	0.01%
Capture time cut	98.7%	0.12%	0.01%
Gd capture fraction	84.2%	0.95%	0.10%
Spill-in	104.9%	1.00%	0.02%
Livetime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

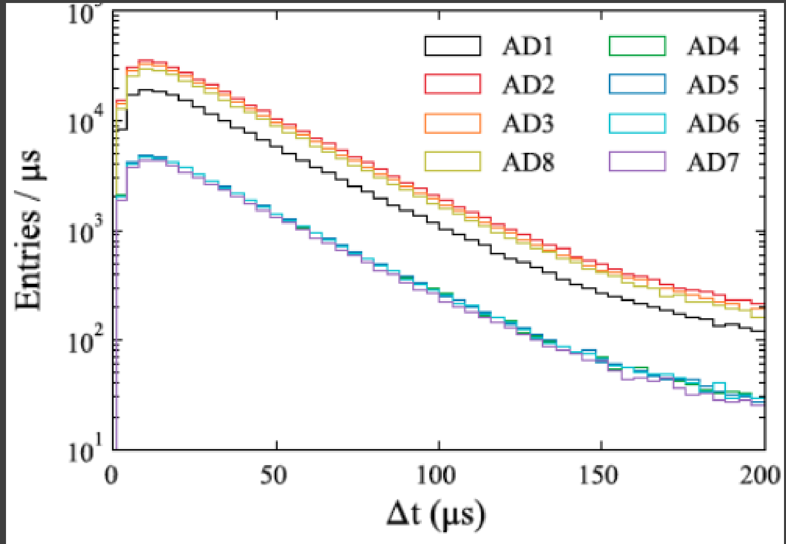


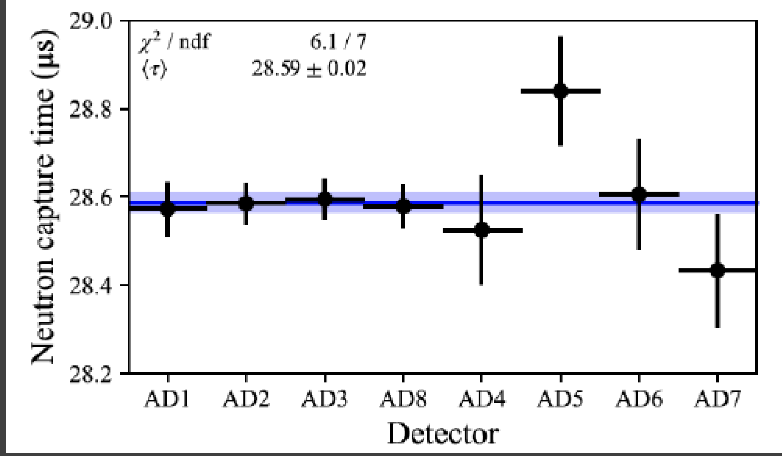


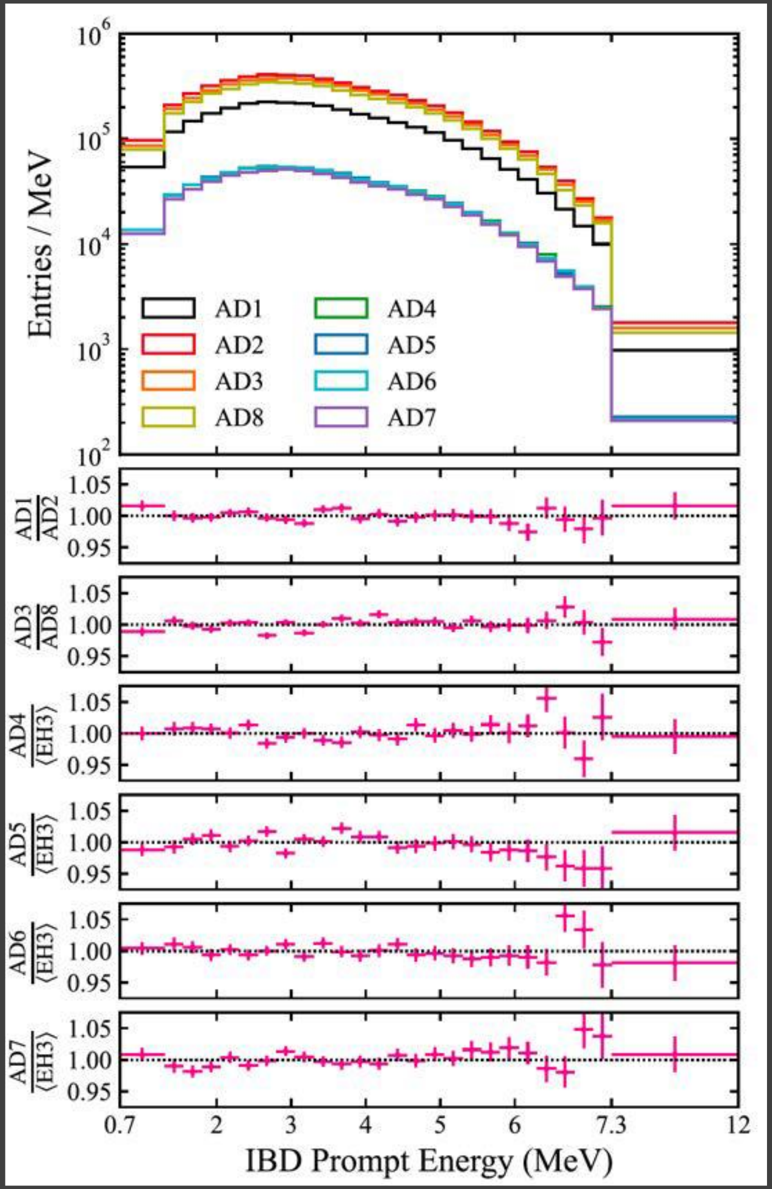
Performance of detectors

- Antineutrino detectors in the same hall have similar performance



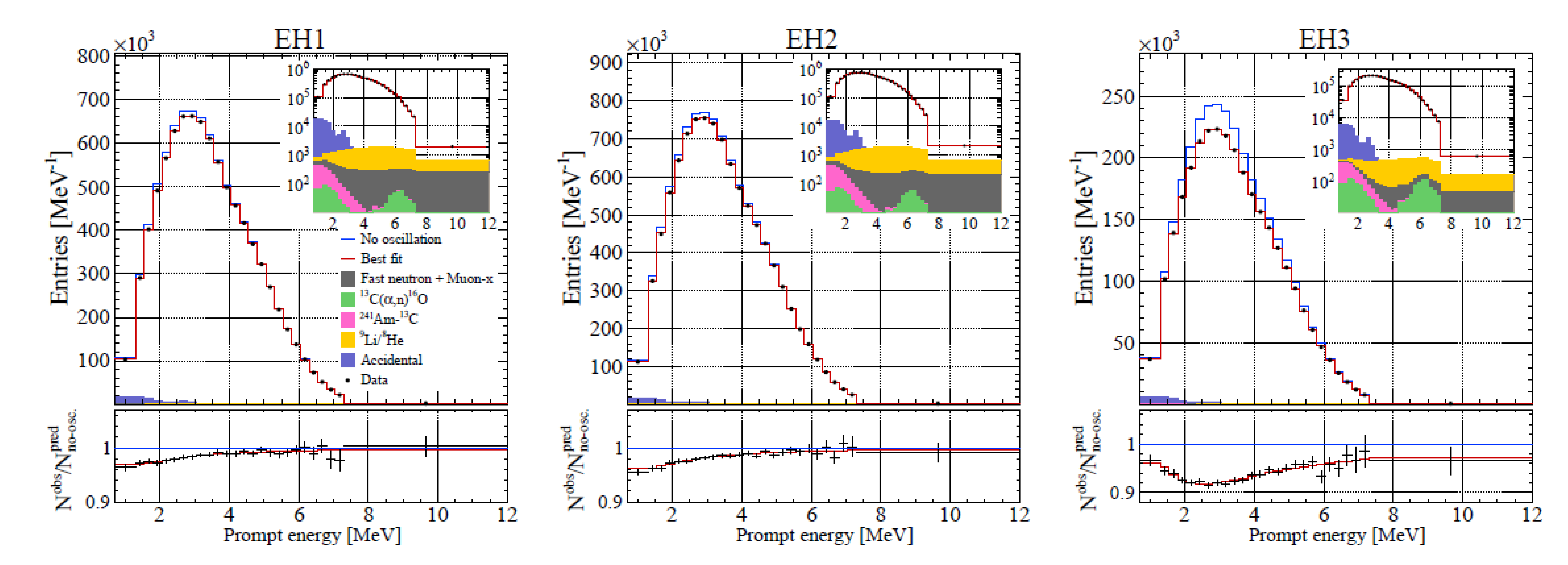




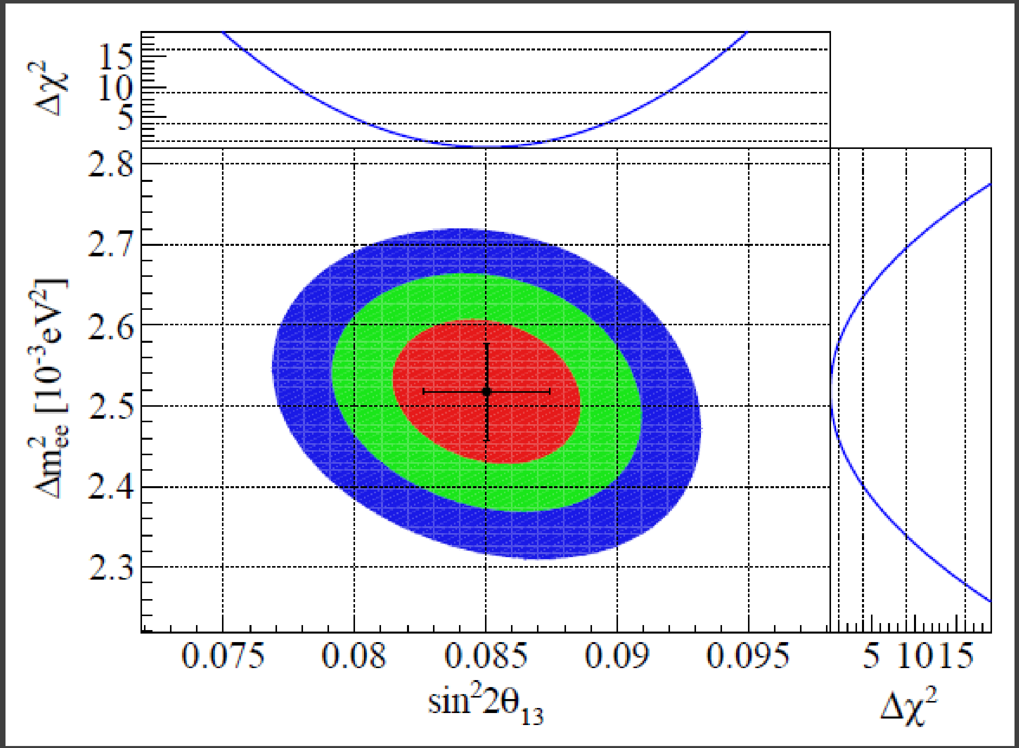


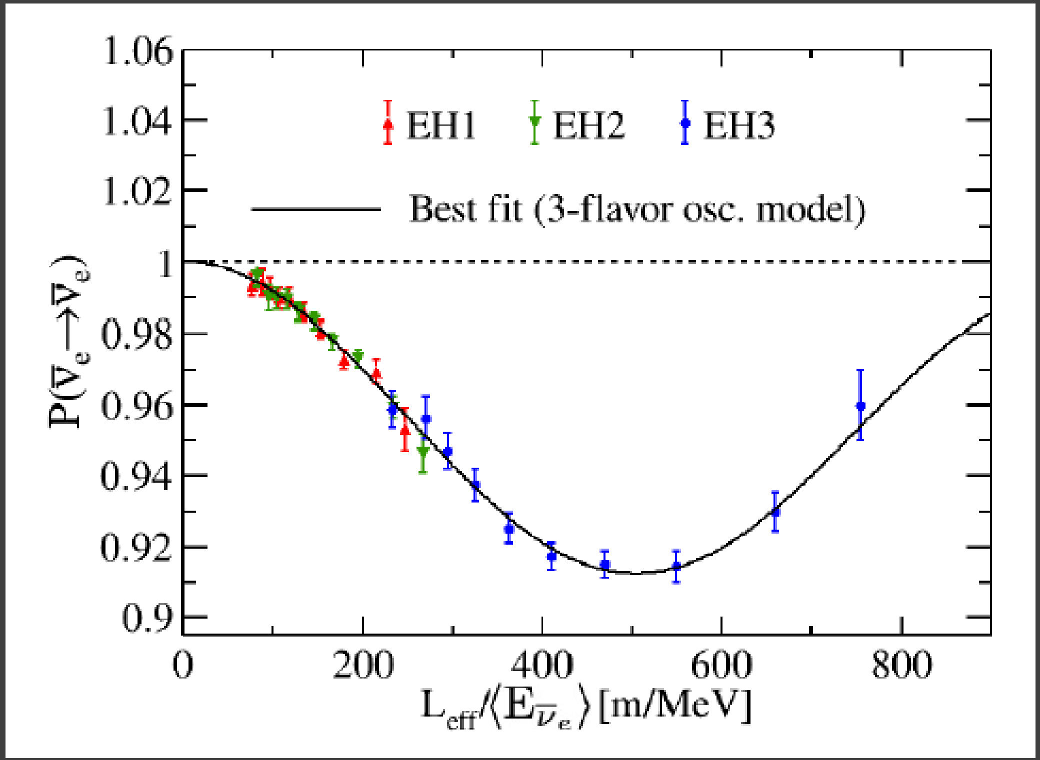
Prompt energy spectrum

- Determine the oscillation by the relative measurement of prompt energy spectra from three EHs
- Spectrum distortions are consistent with three-neutrino oscillation



Oscillation parameters





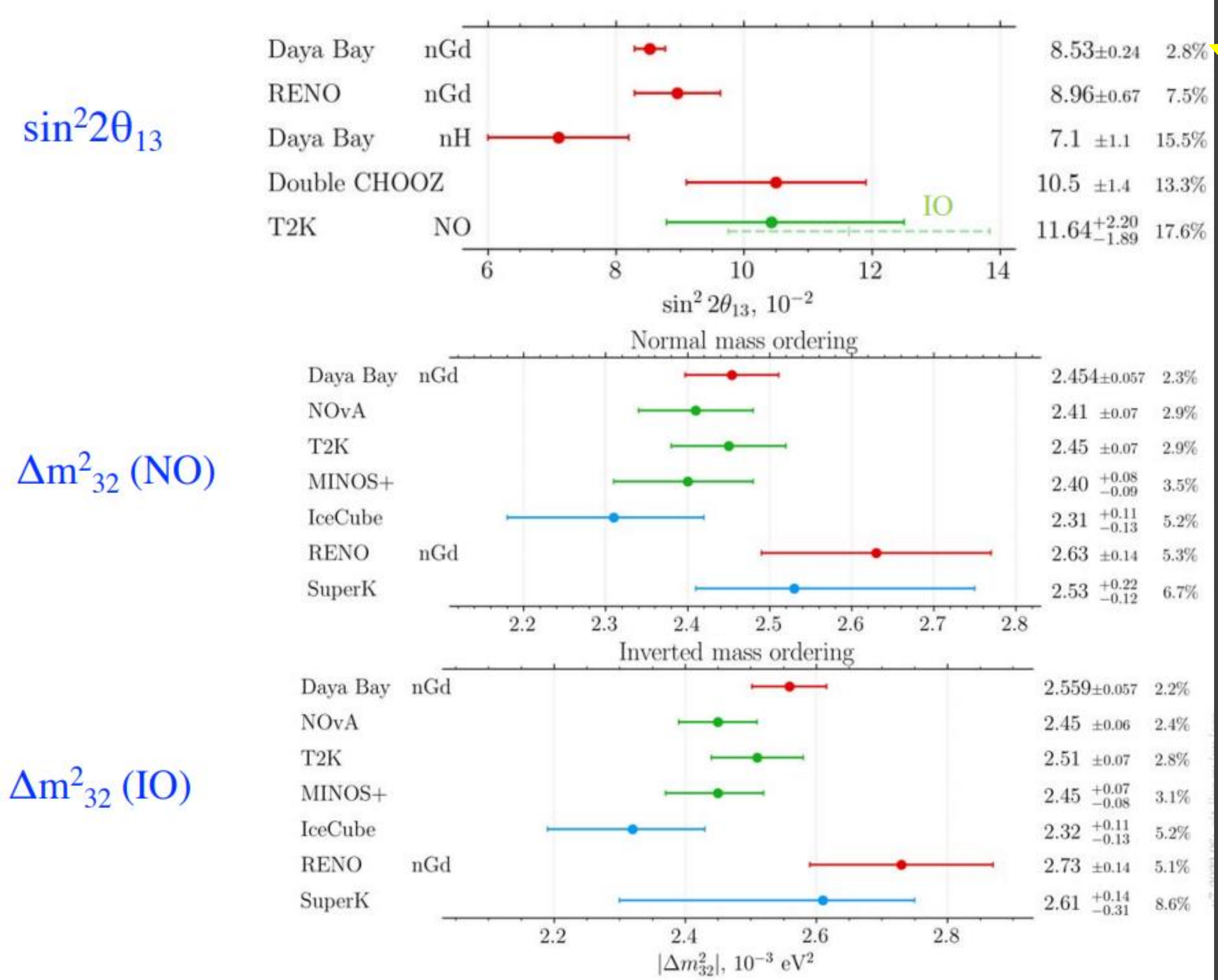
Best-fit results: $\chi^2/\mathrm{ndf} = 559/517$

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

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

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

Present Global Landscape

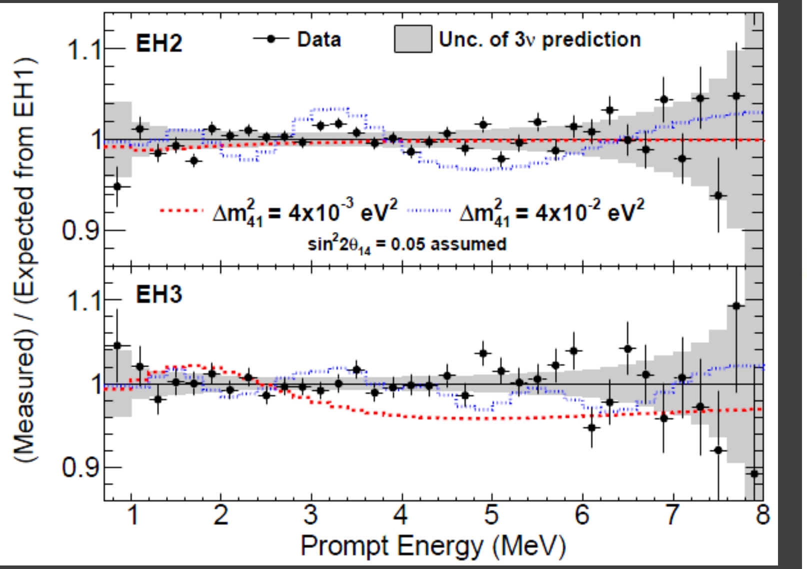


Probably the best measurement in the foreseeable future

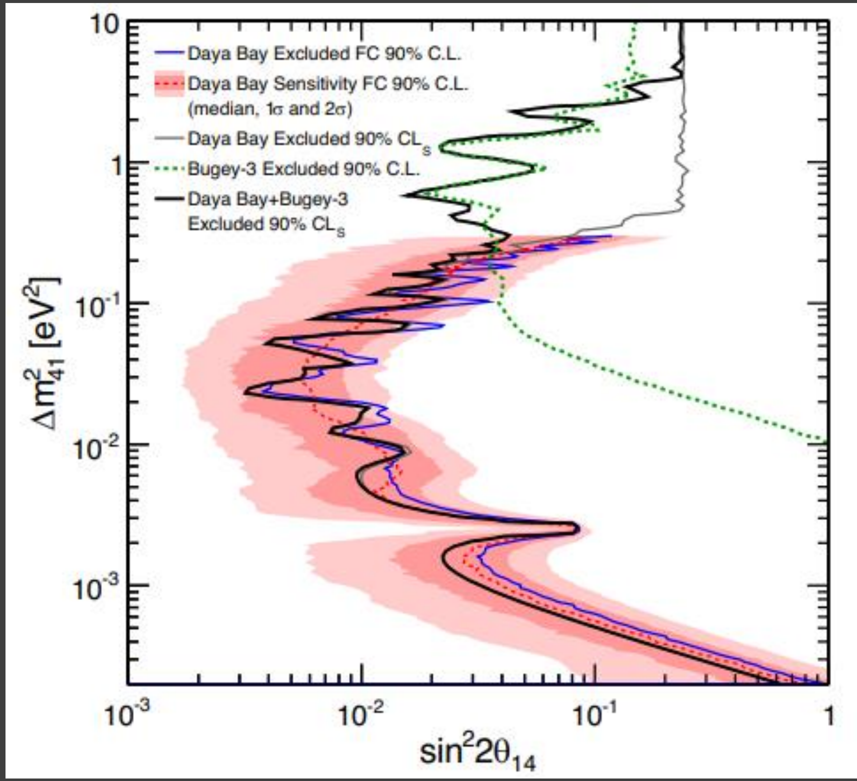
Consistent results from reactor and accelerator/atmospheric experiments

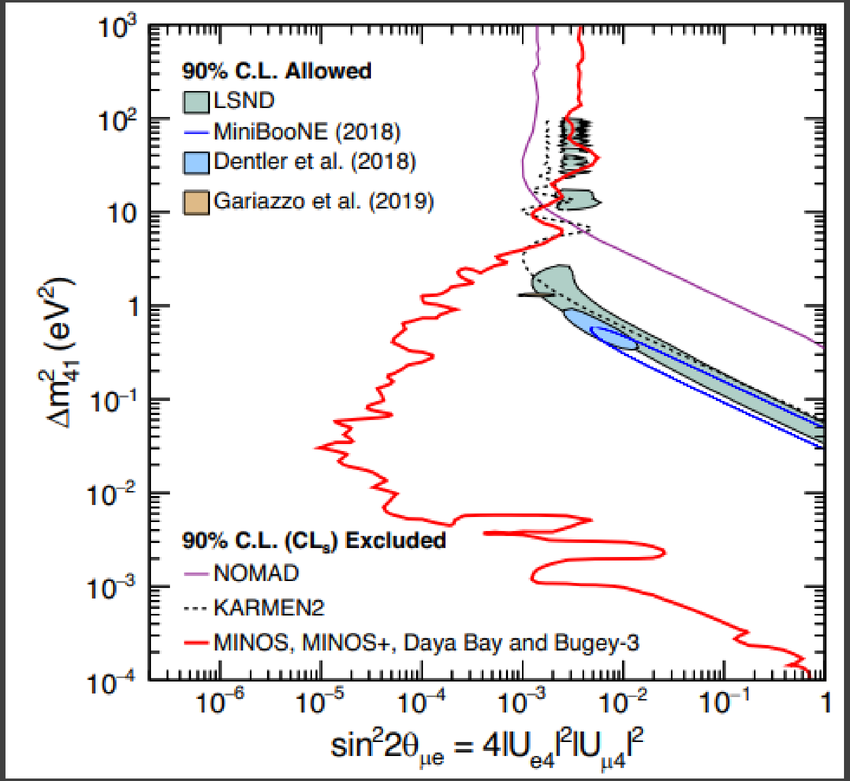
Sterile neutrino search

- A unique opportunity for sterile neutrino searches
  - Sterile neutrino would introduce additional oscillation mode.
  - Relative measurement at multiple baselines of Daya Bay: EH1 (~350 m), EH2 (~500 m), EH3 (~1600 m)
  - Region of 10^{-3} eV^2 < Δm^2_{41} < 0.1 eV^2 explored
- Combined analysis of MINOS, MINOS + , Daya Bay, and Bugey-3, Phys.Rev.Lett. 125 (2020) 7, 071801



1230 days Daya Bay data





Summary

- First measurement of high-energy reactor antineutrinos at Daya Bay
  - No > 10 MeV antineutrino hypothesis is rejected with 6.2 sigma significance
  - A data-based reference spectrum with antineutrino energy in 7—11 MeV
- The world's most precise determination of $\sin^2 2\theta_{13}$

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

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

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

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

- More results with full data set of Daya Bay will come