Daya Bay oscillation results with full dataset

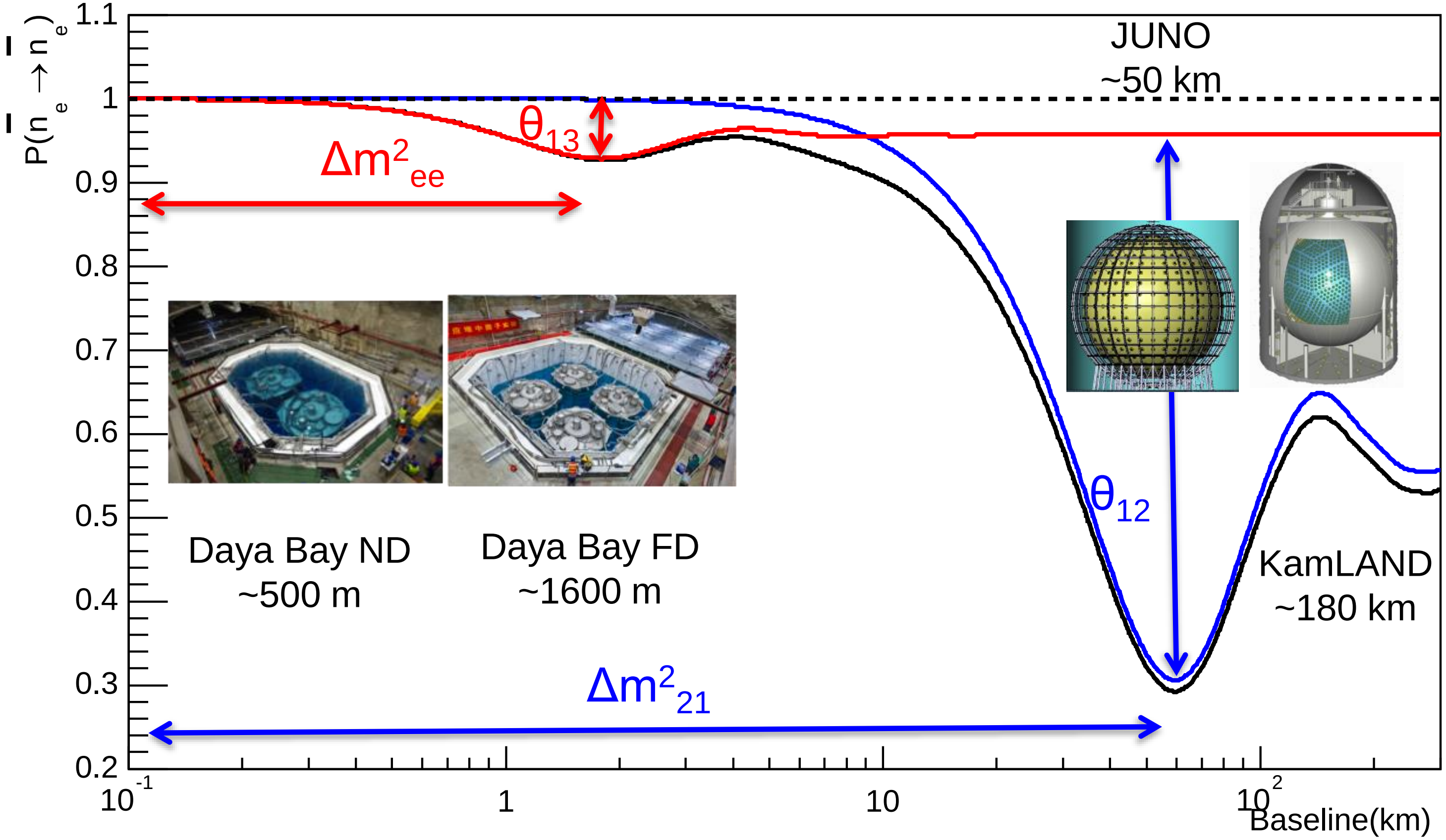
Vít Vorobel, Charles University, Prague
on behalf of Daya Bay Collaboration

Reactor anti-neutrino oscillation

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

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

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



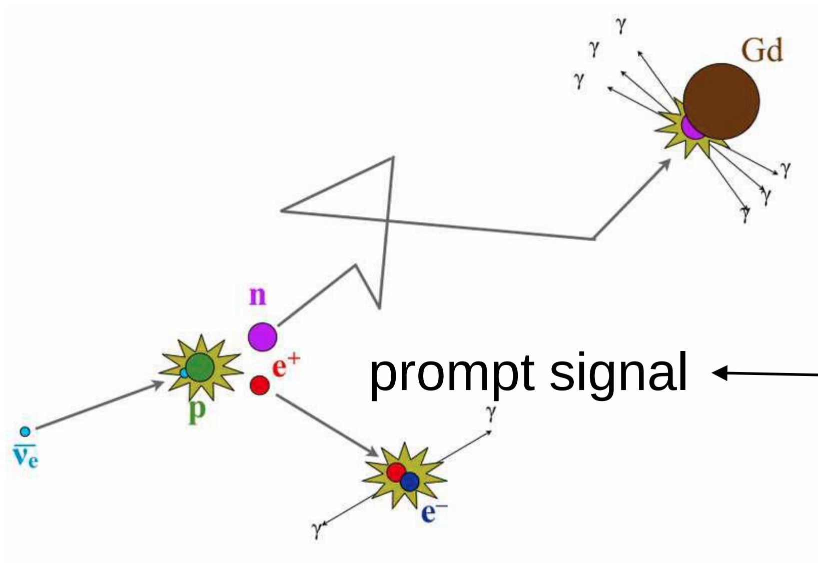
Detection of $\bar{\nu}_e$

Inverse beta-decay (IBD) in Gd-doped liquid scintillator:

$$\overline{\nu_e} + p \rightarrow e^+ + n$$

$\rightarrow + \text{p} \rightarrow \text{D} + \gamma(2.2\ \text{MeV})$ (t~180 μs)

$\rightarrow + \text{Gd} \rightarrow \text{Gd}^* \rightarrow \text{Gd} + \gamma\text{'s}(8\ \text{MeV})$ (t~30 μs)



delayed signal

prompt signal

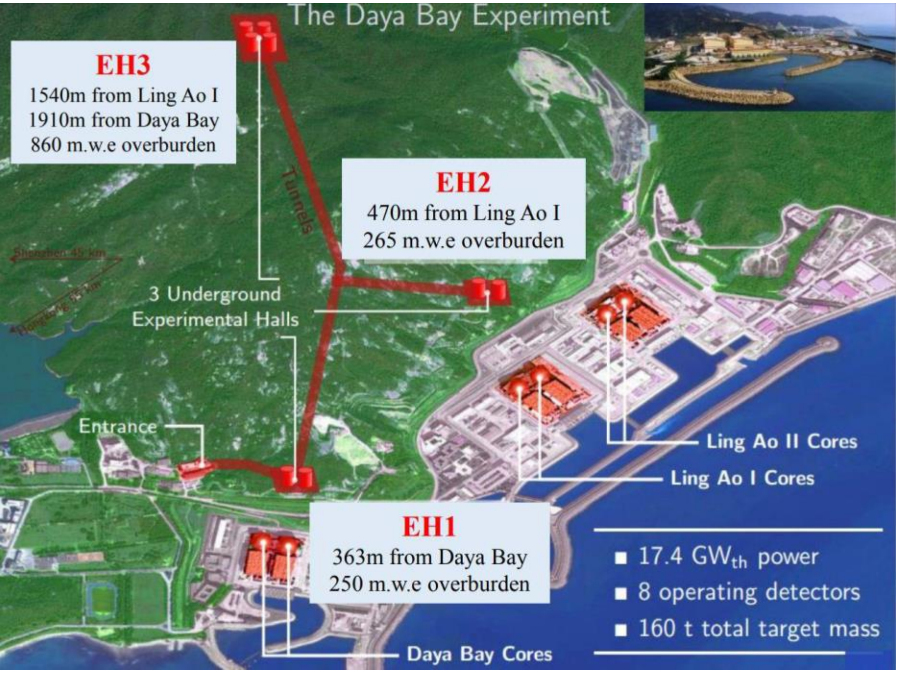
Coincidence

$E_{\bar{\nu}} \approx T_{e+} + T_n + (m_n - m_p) + m_{e+} \approx T_{e+} + 1.8$ MeV (threshold)

$E_{prompt} = T_{e+} + 2m_e$ (annihilation gammas)

$E_{\bar{\nu}} \approx E_{prompt} + 0.8$ MeV

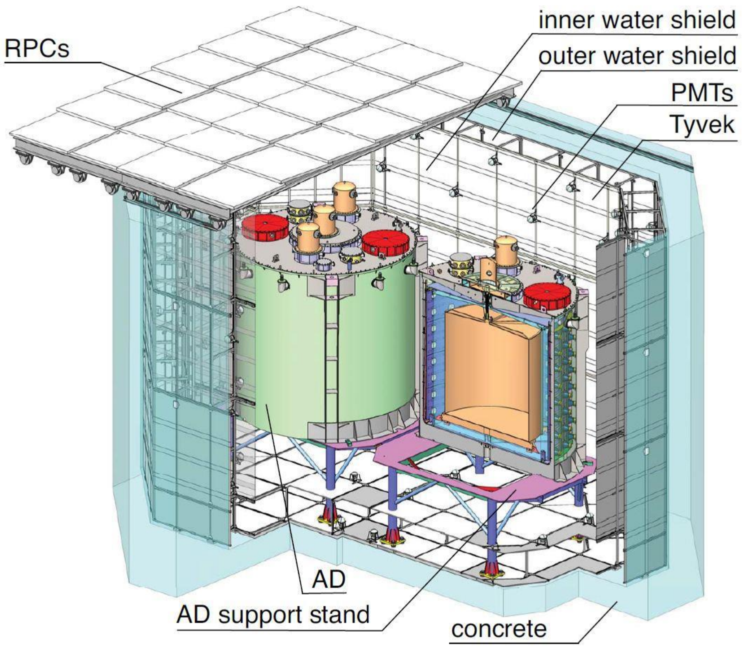
Daya Bay experiment



6 low enriched uranium (LEU) commercial reactors, each with 2.9 GW thermal power.

Eight identically designed underground detectors deployed at different baselines

The largest dataset (~6 million) of reactor antineutrinos collected from December 2011 to December 2022.



Zone	Mass	Liquid	Purpose
Inner acrylic vessel	20 t	Gd-doped liquid scintillator	**Anti-neutrino target**
Outer acrylic vessel	20 t	Liquid scintillator	Gamma catcher (from target zone)
Stainless steel vessel	40 t	Mineral Oil	Radiation shielding

- Outer layer of water Čerenkov detector is 1 m thick, inner layer >1.5 m.
- 4-layer RPC modules above pool

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 (this talk, poster #715)

2. Joint spectral determination of reactor antineutrinos from ^{235}U and ^{239}Pu fission of Daya Bay and PROSPECT (next talk)

3. First measurement of high-energy reactor antineutrinos with energy between 8 MeV and 11 MeV (next talk, poster #469)

Recent results from Daya Bay in the poster session:

- Daya Bay neutrino oscillation results based on neutron captured on Hydrogen (poster #851)

Another research in Daya Bay:

- Muon modulation study (poster #979)
- Search For Electron-Antineutrinos Associated With Gravitational-Wave Events at Daya Bay (poster #850)

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

Full Dataset

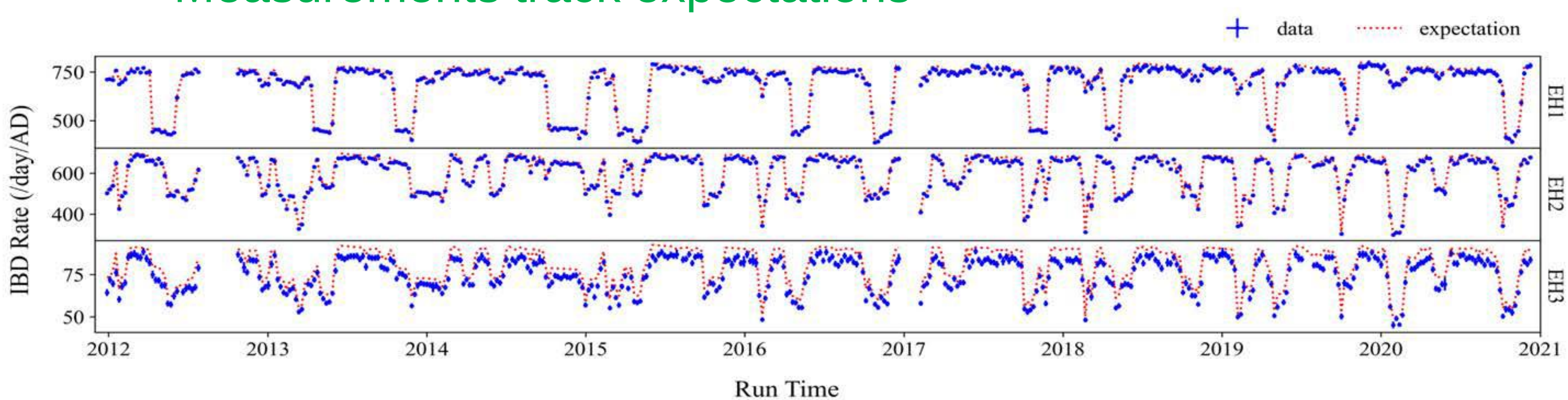
Three physics runs:

Configuration	EH1	EH2	EH3	Start data – End data	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

Correlation with operation of reactors

- Expectation based on weekly reactor operational information
- Measurements track expectations



Energy Scale

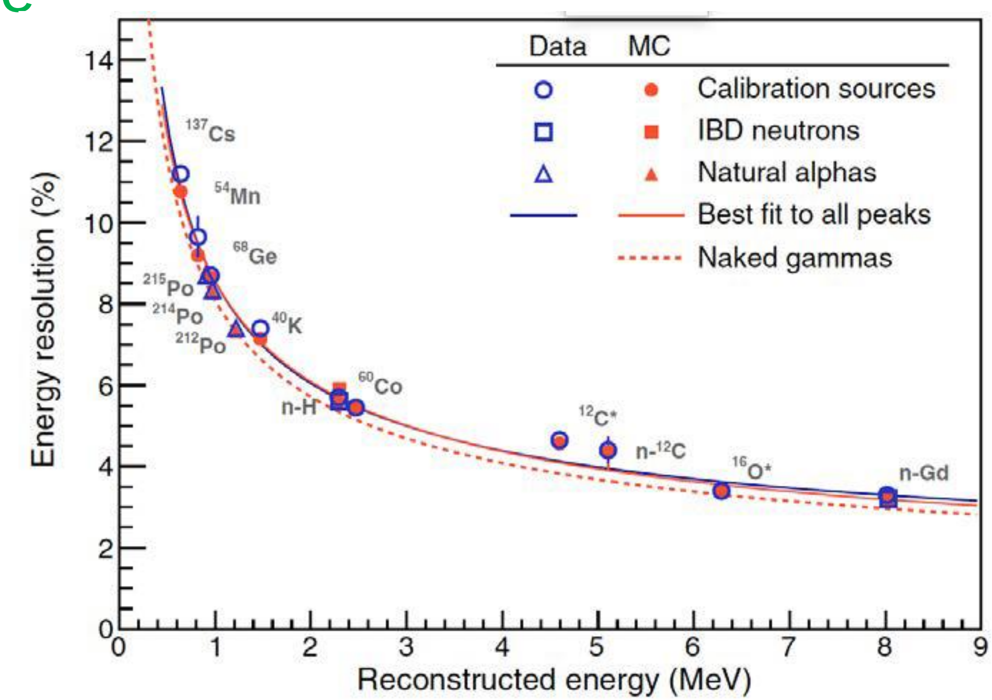
Gain of photomultiplier tubes

- Single-photoelectron dark noise
- Weekly LED monitoring

Energy calibration

- Weekly ^{68}Ge, ^{60}Co, ^{241}Am-^{13}C
- Spallation neutrons
- Natural radioactivity

Nonuniformity corrections



Relative uncertainty in energy scale: ~0.2%

Uncertainty in absolute energy ~0.5%

Energy resolution $\frac{\sigma_E}{E} = \frac{0.09}{\sqrt{E[MeV]}}$

Background

Uncorrelated background

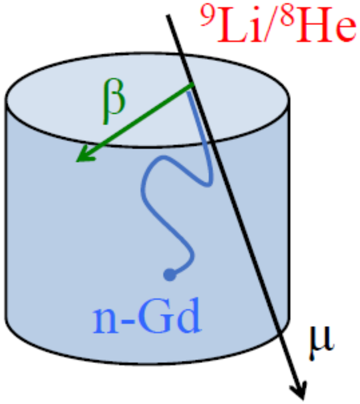
- Accidental

Correlated background

- Fast neutron
  - produced outside of the AD but enters the active volume of the AD
- $^{9}Li/^{8}He$ new approach
  - 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

$^9Li/^8He$ Background



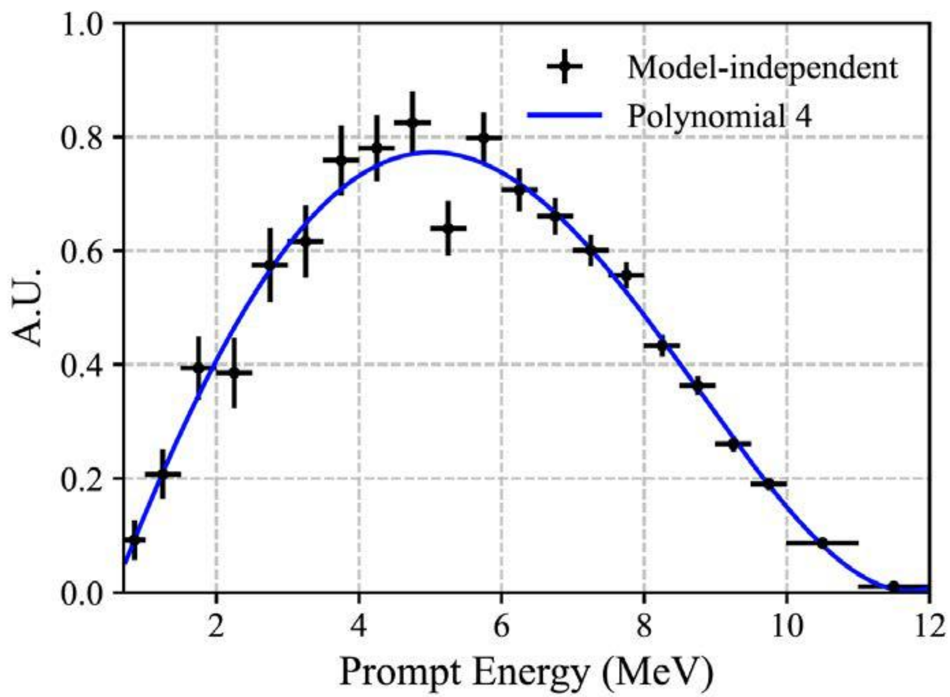
β-n decay

- τ_{Li} = 257.2 ms
- τ_{He} = 171.7 ms

Perform a multi-dimensional fit using

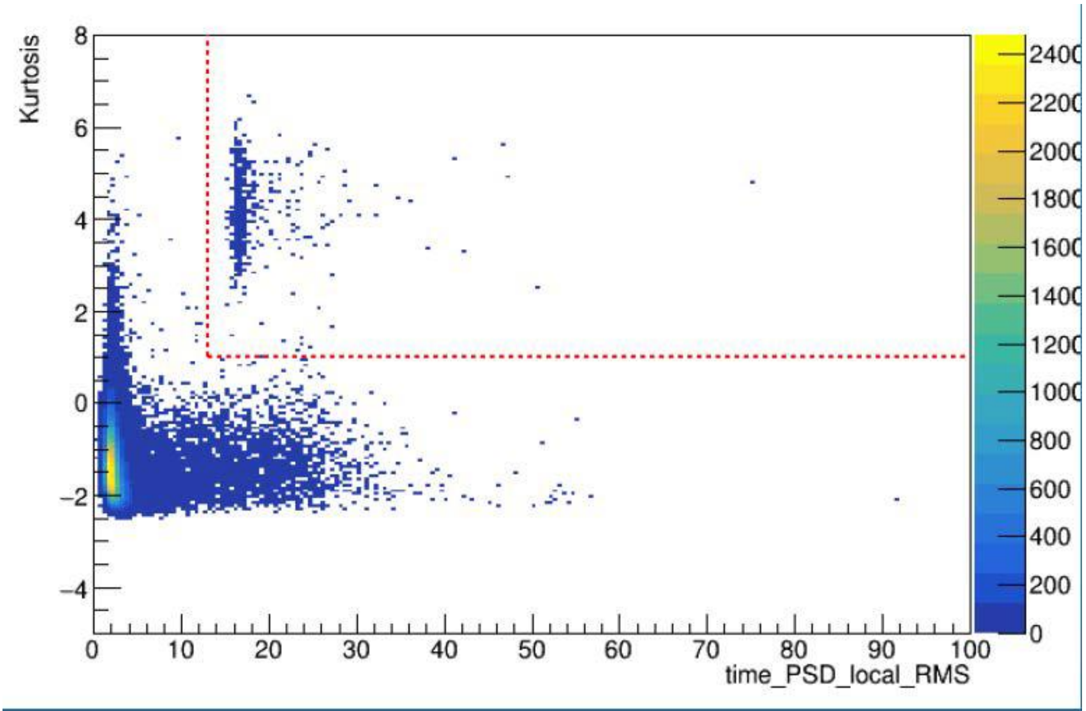
- Time interval after the preceding muon ($t_{IBD} - t_{\mu}$)
- Prompt energy (E_{prompt})
- Distance between the prompt and delayed signals (ΔR)
- Low-energy (E_{vis} < 2 GeV) and high-energy (E_{vis} > 2 GeV)

muon samples from all three halls simultaneously



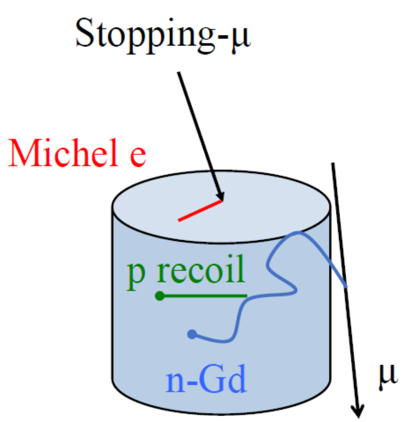
Residual flashers rejection

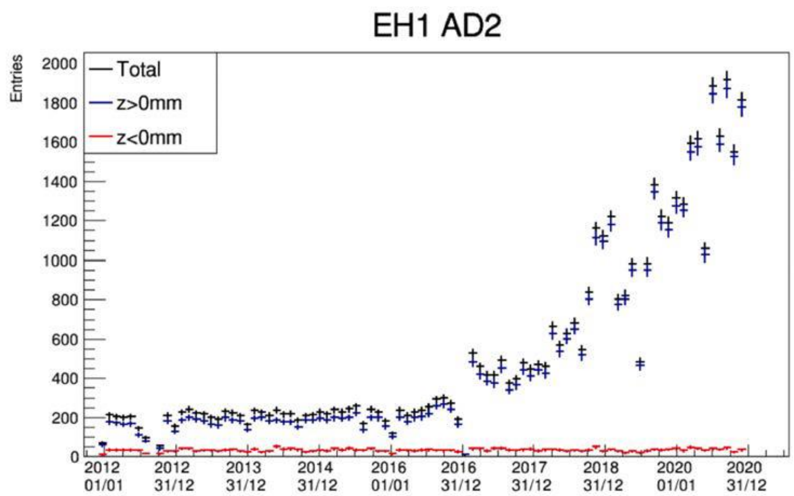
- Residual flashers located near the top of some ADs
- Removed by cutting on Kurtosis and time_PSD_local_RMS
- After rejecting residual flashers,
  - Contamination in the IBD sample is negligible
  - Retain 99.997% of the IBD candidates



Fast neutrons and Muon-x Background

- Fast spallation neutrons generated outside of the water pool
- Muon decays and additional spallation (muon-x) on top of ADs
  - negligible before 2017, become considerable after the gradual failure of water pool PMT or high-voltage channels in the inner water Cherenkov counter (IWS) in the water pool
- Lower the hit multiplicity of PMTs (nHit) in IWS from 12 to 6 to tag muons
  - Reject about 80% of muon decays with < 0.1% livetime loss
- Remaining Muon-x is estimated together with fast neutrons
  - Extend cut on E_{prompt} from 12 MeV to 250 MeV spectrum for fast neutrons and muon-x





Selection of ν_e Candidates

Remove flashing PMT events

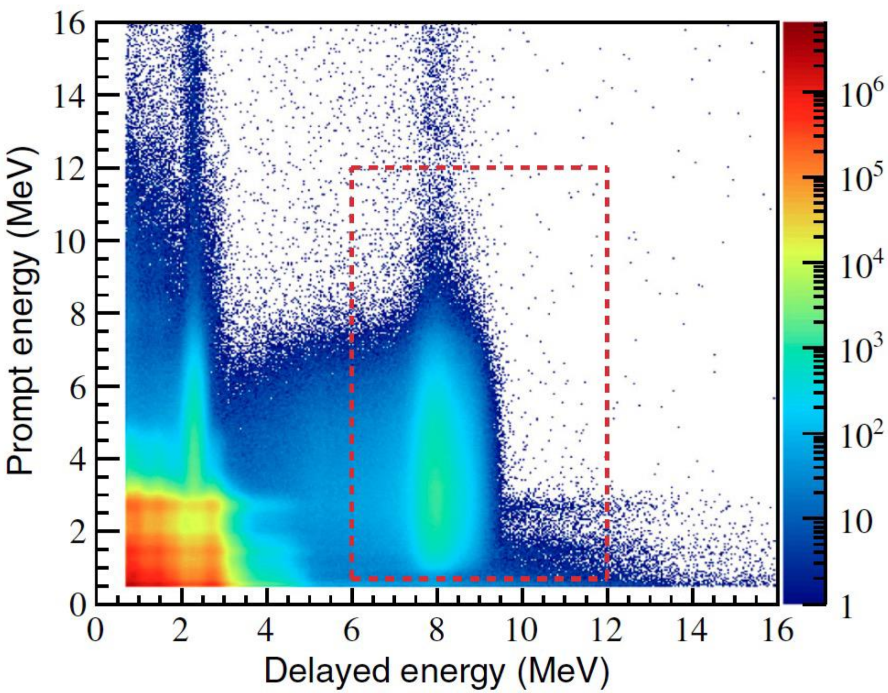
Veto muon events

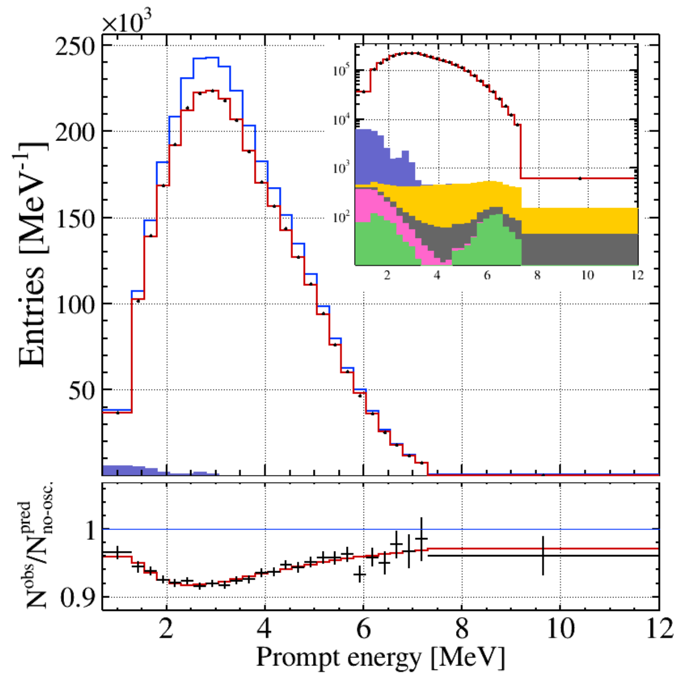
Require 0.7 MeV < E_{prompt} < 12 MeV, 6 MeV < $E_{delayed}$ < 12 MeV

Neutron capture time: 1 μs < Δt < 200 μs

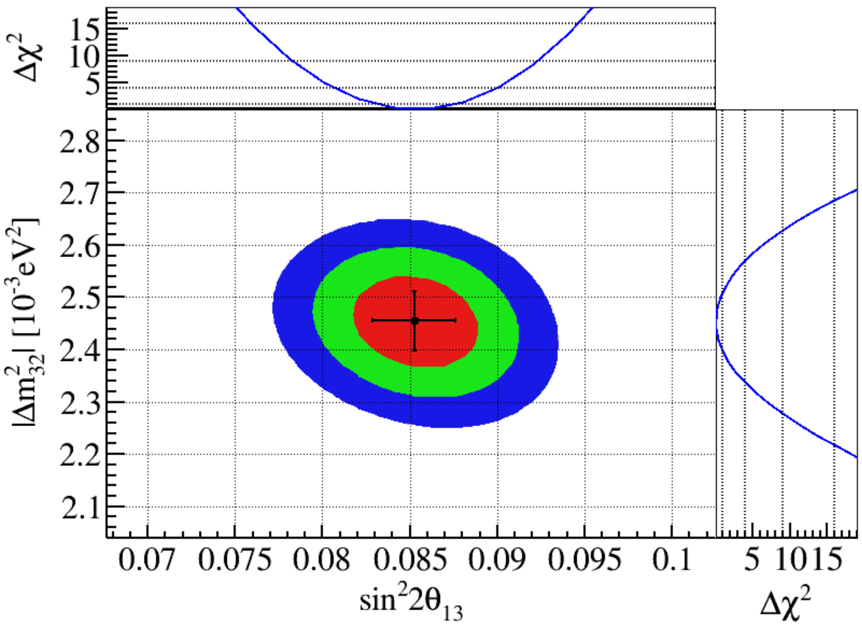
Multiplicity cut: select time-isolated energy pairs

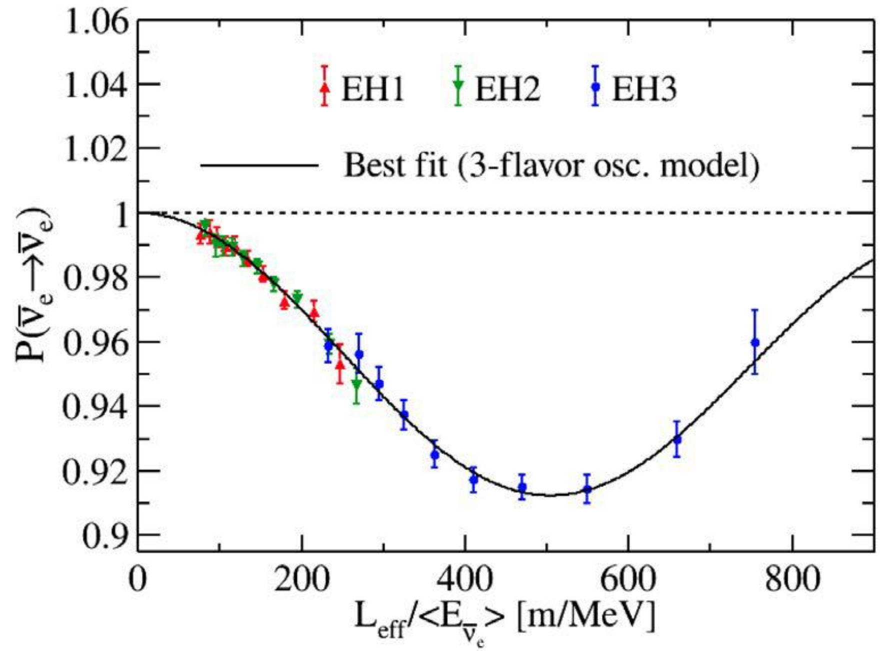
PRD95 (2017) 072006





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





Best-fit results:

$$\chi^2/ndf = 559/518$$

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

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

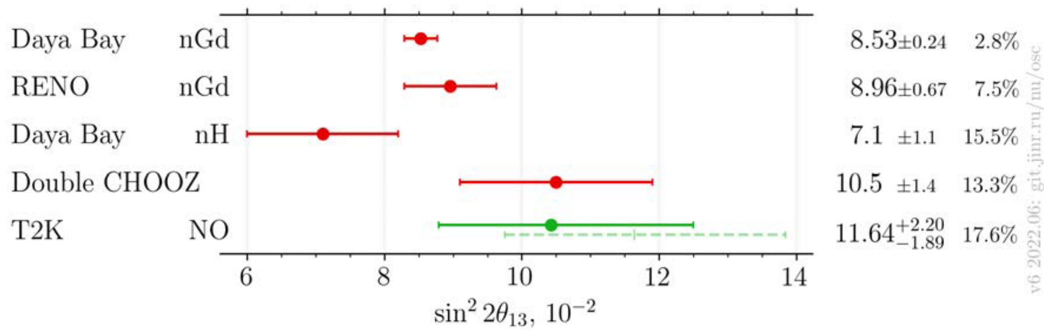
(2.3% precision)

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

Present Global Landscape

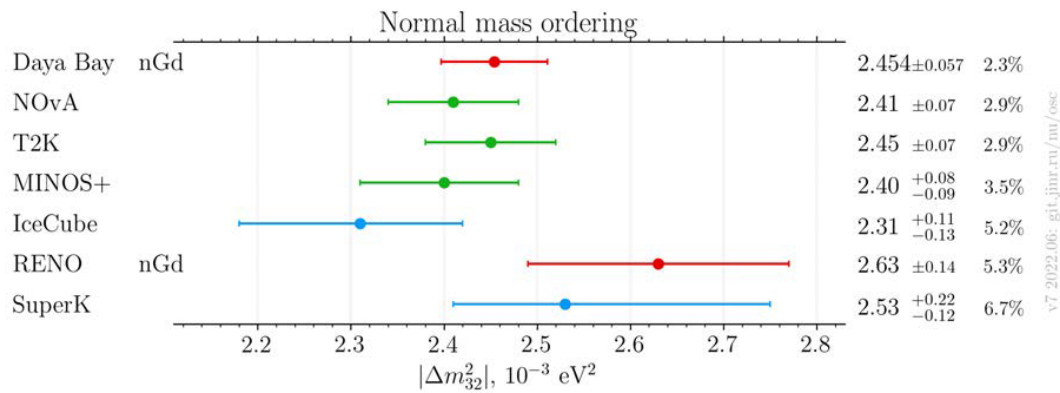
Compare Daya Bay's current results with published results

$sin^2 2\theta_{13}$

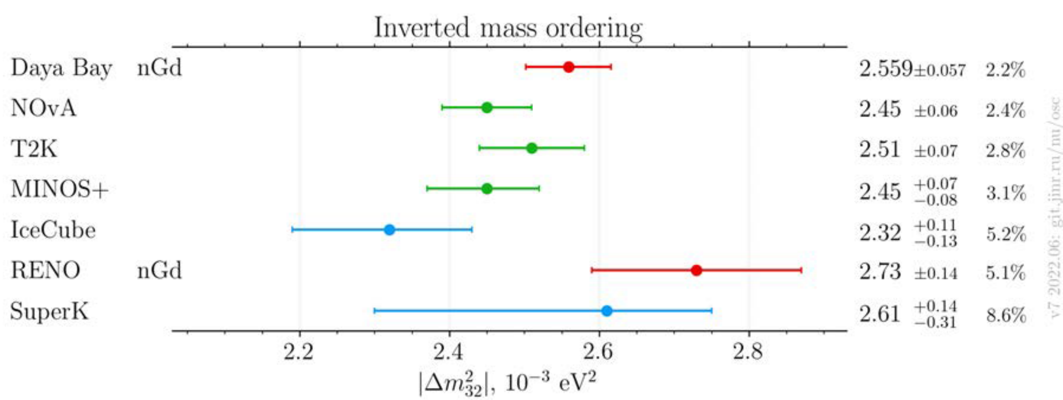


Will likely be the best measurement in the foreseeable future

Δm^2_{32} (NO)



Δm^2_{32} (IO)



Summary

Daya Bay experiment

- 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 ν_e,
    - Evolution of absolute reactor ν_e flux and spectrum.
- Will have more results to be presented in the future, for example
    - Updated results on oscillation parameters with nH samples.