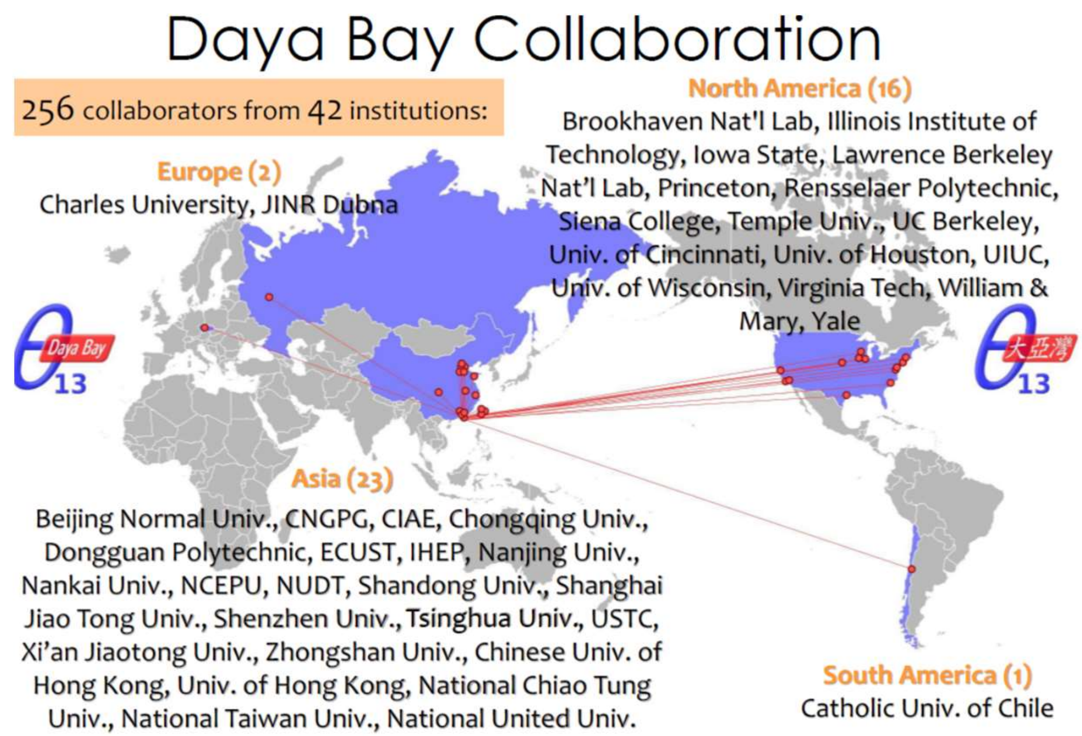
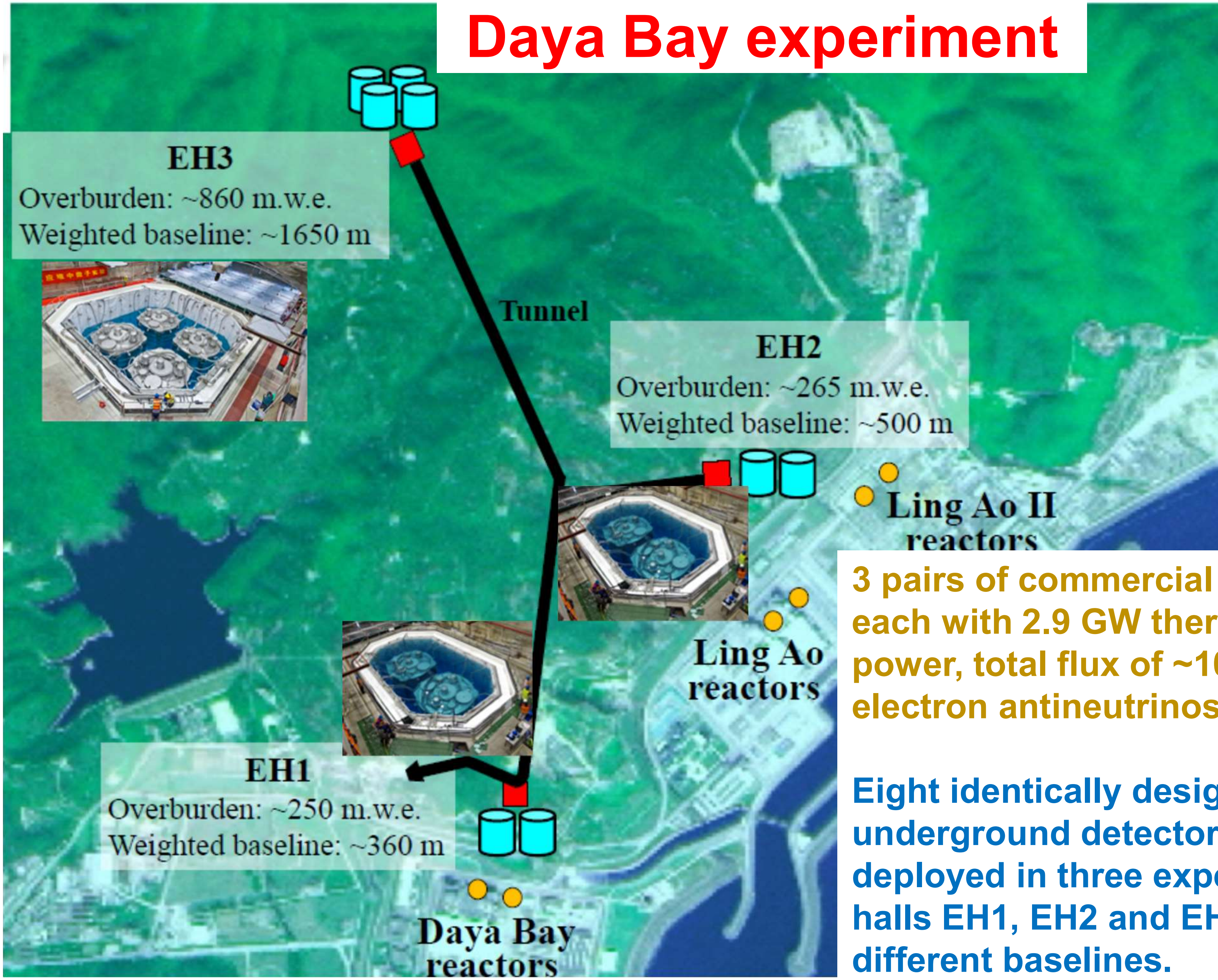
Recent results from the Daya Bay experiment

Rupert Leitner, Charles University, Prague
on behalf of Daya Bay Collaboration

The Daya Bay is an international reactor anti-neutrino experiment located in southern China near commercial nuclear power plants.



Daya Bay experiment



3 pairs of commercial reactors, each with 2.9 GW thermal power, total flux of $\sim 10^{21}$ electron antineutrinos / s

Eight identically designed underground detectors deployed in three experimental halls EH1, EH2 and EH3 at different baselines.

Detectors

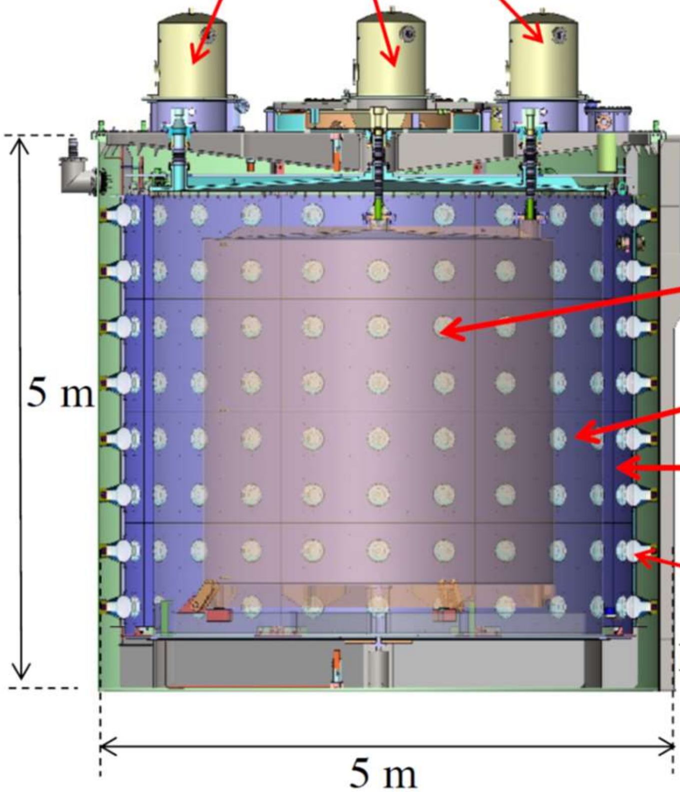
- Detect inverse β-decay reaction (IBD):

prompt | delayed

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

~180 μs
$$\hookrightarrow + p \rightarrow d + \gamma\ (2.2\ \text{MeV})$$
$$\hookrightarrow + Gd \rightarrow Gd^*$$
~30 μs for 0.1% Gd
$$\hookrightarrow Gd + \gamma\text{'s}\ (\sim 8\ \text{MeV})$$

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



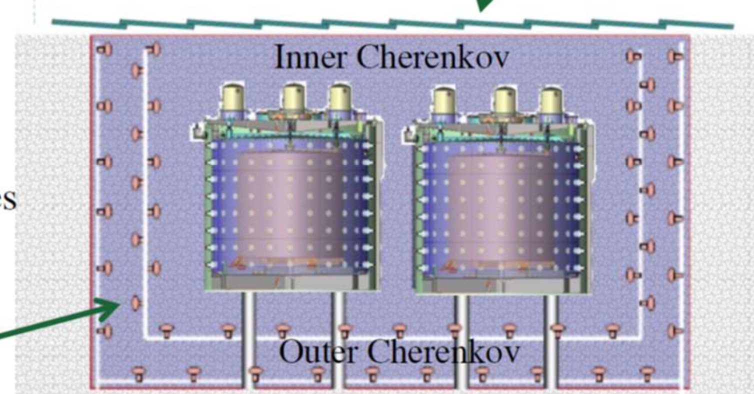
20-t 0.1% Gd-loaded liquid scintillator (target)

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 sets analyzed

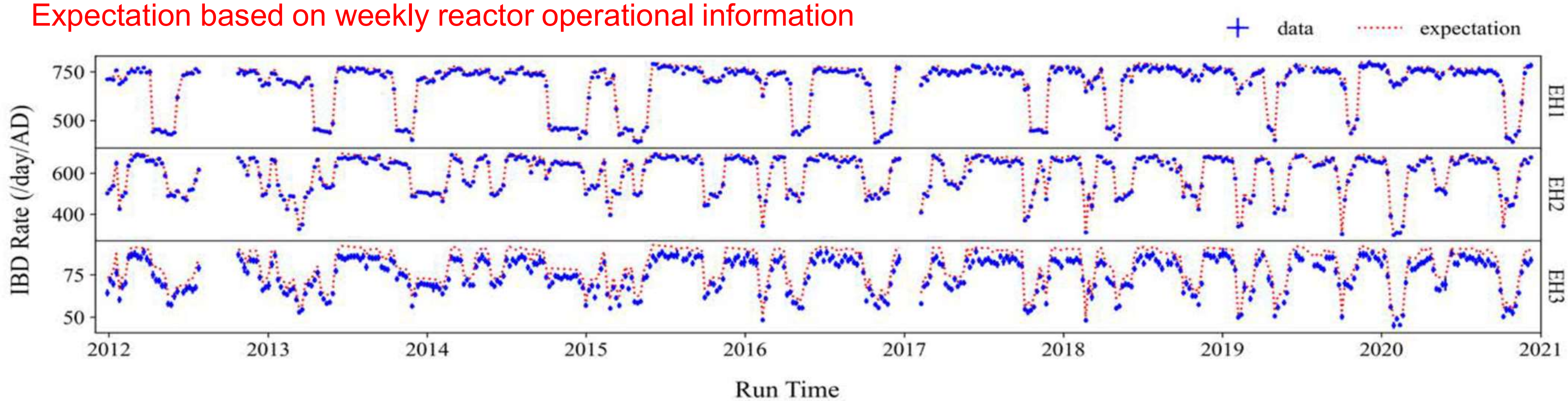
Three physics runs. Data available for analyses ~2700 days

	EH1	EH2	EH3	Start date – End date
6-AD	2	1	3	Dec 2011 – July 2012
8-AD	2	**2**	**4**	Oct 2012 – Dec 2016
7-AD	**1**	2	4	Jan 2017 – Dec 2020

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

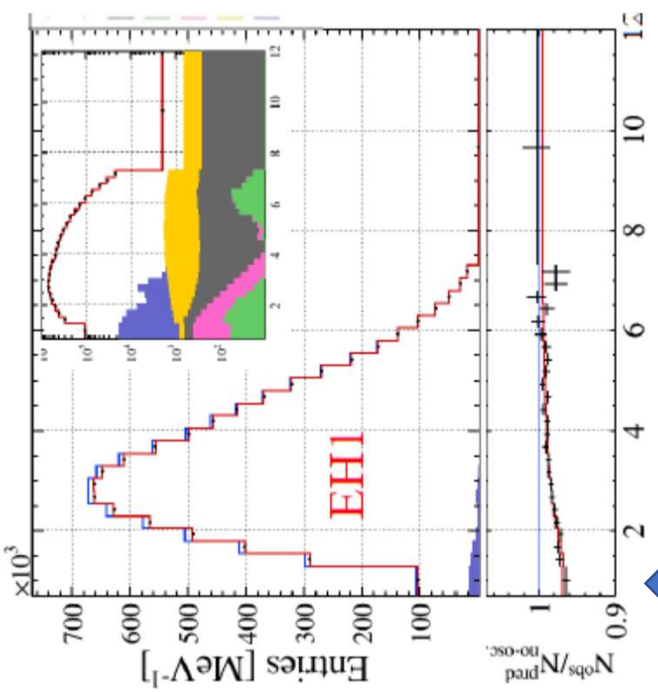
Correlation with operation of reactors.

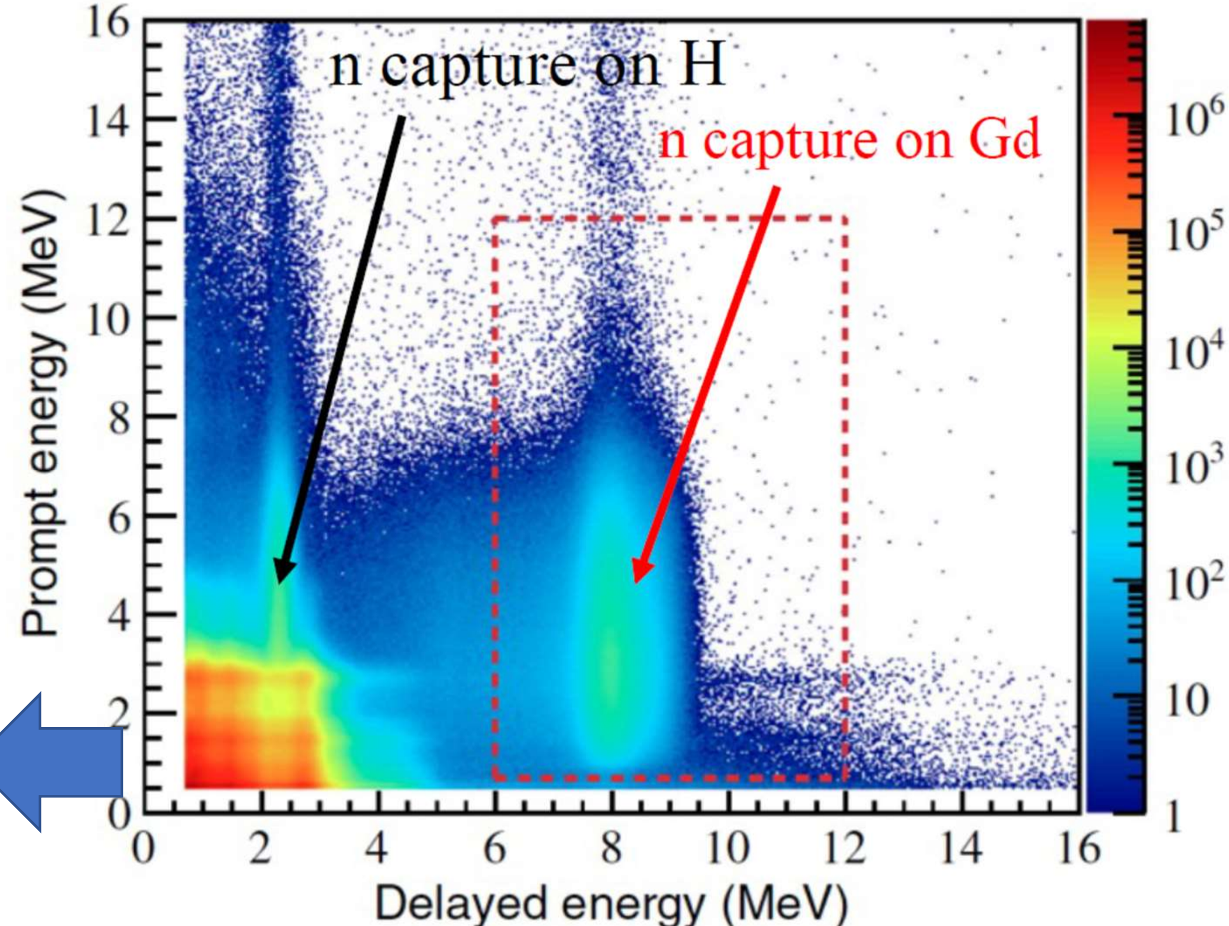
Expectation based on weekly reactor operational information



A selection of events from the measurement of the coincidence of the prompt and delayed signals

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





Energy resolution

Gain of photomultiplier tubes

- Single-photoelectron dark noise
- Weekly LED monitoring

Energy calibration

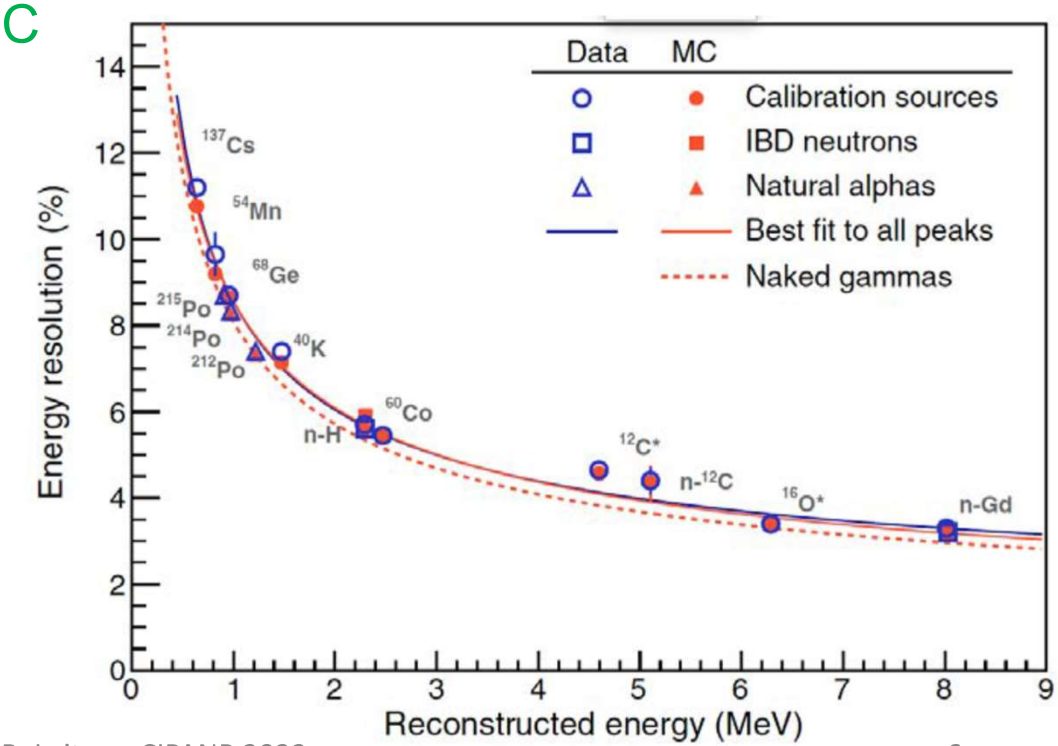
- Weekly ^{68}Ge, ^{60}Co, ^{241}Am-^{13}C
- Spallation neutrons
- Natural radioactivity

Nonuniformity corrections

Relative uncertainty in energy scale: ~0.2%
Uncertainty in absolute energy ~0.5%

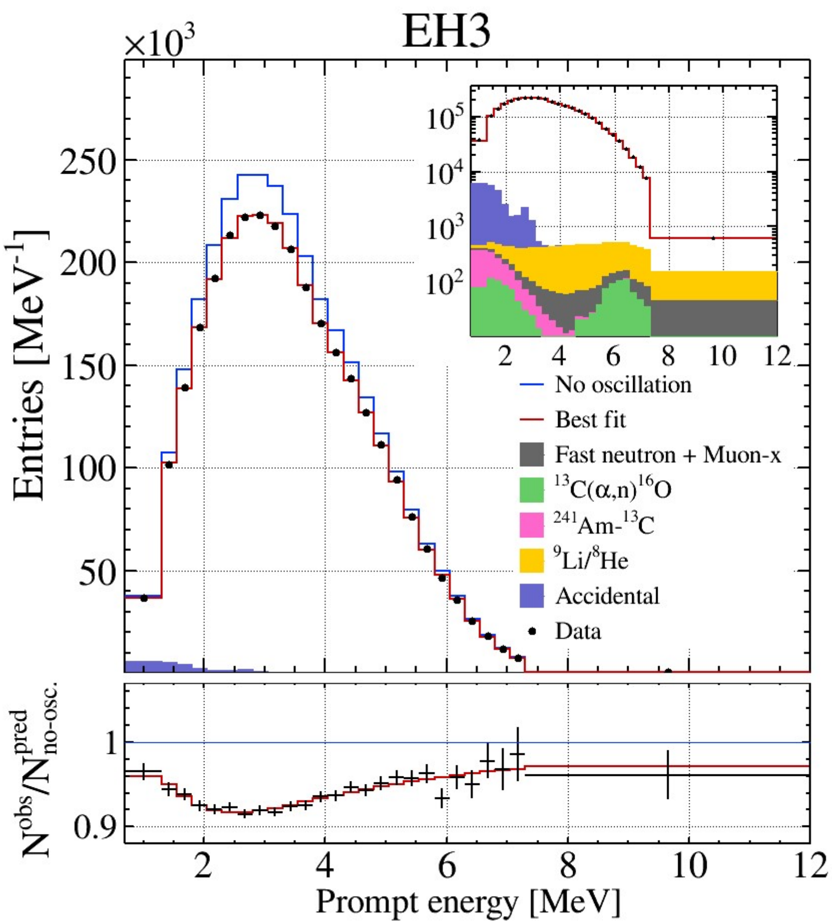
Energy resolution

$$\frac{\sigma_E}{E} \approx \frac{0.09}{\sqrt{E[MeV]}}$$



Energy spectrum measured in far hall EH3

Due to oscillations, the measured spectrum in EH3 shows a deficit compared to the spectrum predicted from measurements in EH1 and EH2.



Background

Uncorrelated background

Accidental

Correlated background

^{9}Li/^{8}He spallation product produced by cosmic-ray muons inside the antineutrino detector AD

Fast neutrons+Muon-x neutrons produced outside of the AD but enters the active volume of the AD + muon decay and spallation products

^{241}Am-^{13}C neutron calibration source resides inside the calibration unit ACU

^{13}C(α,n)^{16}O α from decay of natural radioactive isotope in the liquid scintillator

Electron (anti)neutrino disappearance does not depend on CP violating phase δ, nor mixing angle θ_{23}, matter effect is negligible.

$$P^{3x3}_{\overline{\nu}e\to\overline{\nu}e} = 1 - \cos^4\theta_{13}\sin^2(2\theta_{12})\sin^2\left(\frac{\Delta m^2_{21}}{4\hbar c}\frac{L}{E}\right)$$

Sub-percent contribution at the first local minimum.

$$-\sin^2(2\theta_{13})\left(\cos^2\theta_{12}\sin^2\left(\frac{\Delta m^2_{31}}{4\hbar c}\frac{L}{E}\right) + \sin^2\theta_{12}\sin^2\left(\frac{\Delta m^2_{32}}{4\hbar c}\frac{L}{E}\right)\right)$$

Oscillation amplitude $\sim\sin^2(2\theta_{13})$

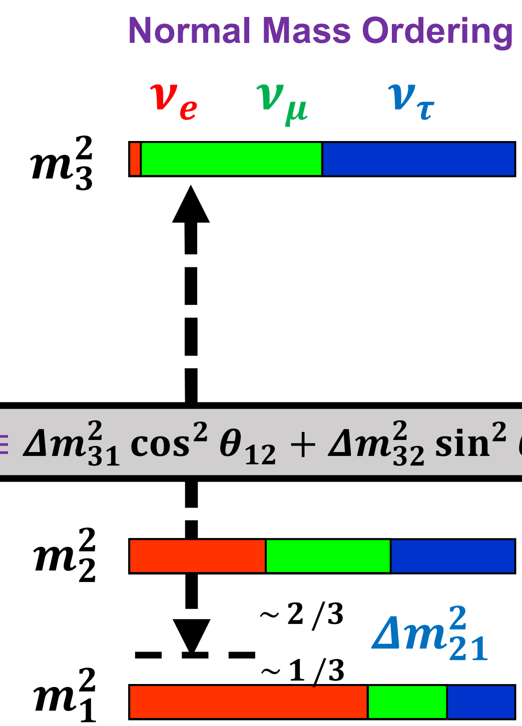
Daya Bay also measures large mass splitting Δm^2_{32}

$$P^{3x3}_{\overline{\nu}e\to\overline{\nu}e}$$

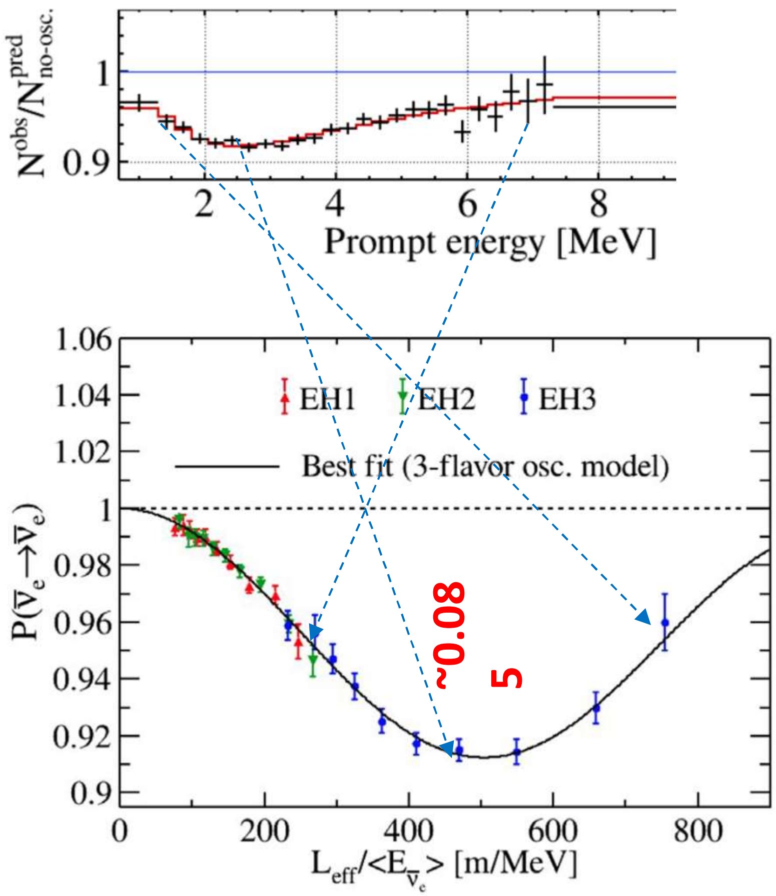
$$\cong 1 - \cos^4\theta_{13}\sin^2(2\theta_{12})\sin^2\left(\frac{\Delta m^2_{21}}{4\hbar c}\frac{L}{E}\right)$$

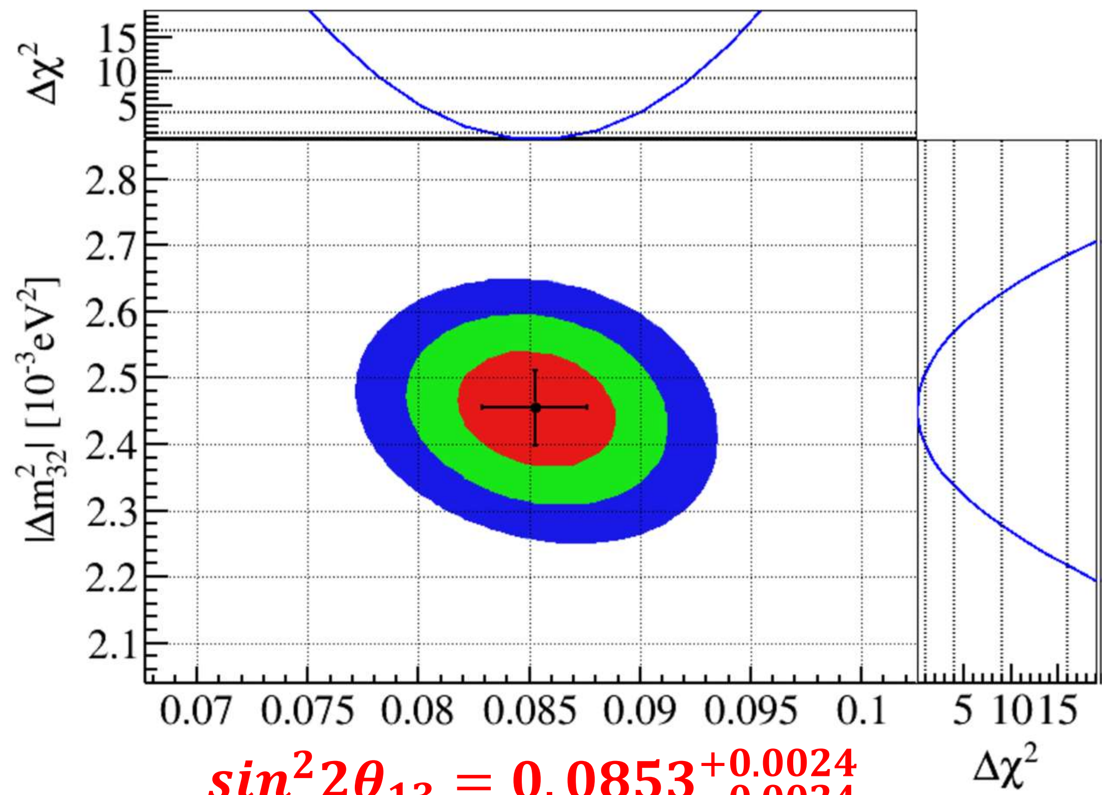
$$-\sin^2(2\theta_{13})\sin^2\left(\frac{\Delta m^2_{ee}}{4\hbar c}\frac{L}{E}\right)$$

$$\Delta m^2_{ee} \equiv \Delta m^2_{31}\cos^2\theta_{12} + \Delta m^2_{32}\sin^2\theta_{12}$$



New Daya Bay results 2022





$$\sin^2 2\theta_{13} = 0.0853^{+0.0024}_{-0.0024}$$

Normal Mass Ordering

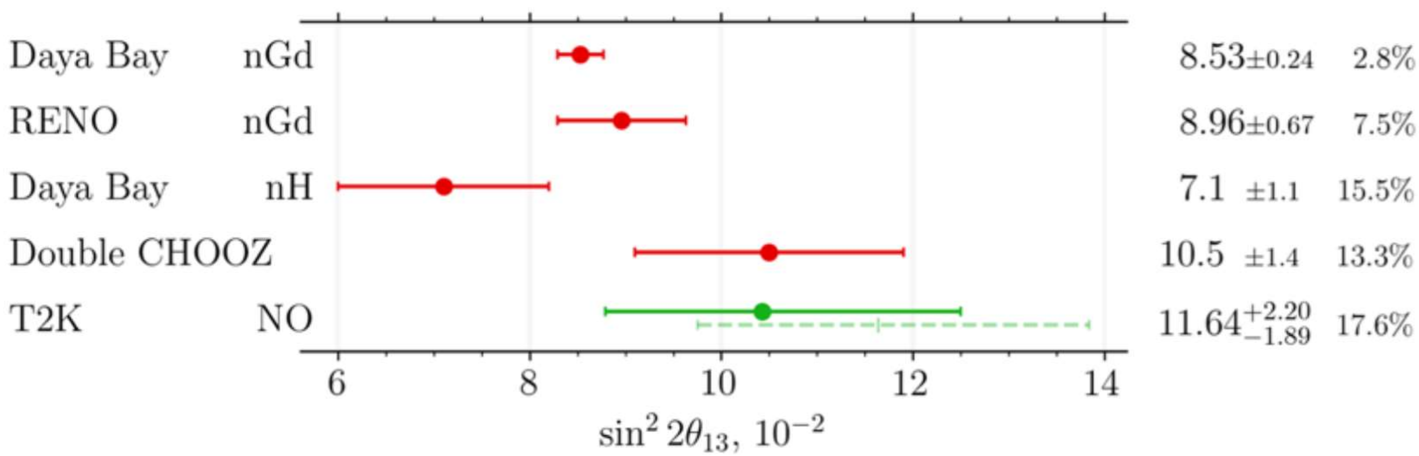
$$\Delta m^2_{32} = +\left(2.454^{+0.057}_{-0.057}\right) \times 10^{-3}\ \text{eV}^2$$

Inverted Mass Ordering

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

Importance of precise measurement of θ13

$$sin^2 2\theta_{13} = 0.0853^{+0.0024}_{-0.0024}$$



1. We know precisely the electron neutrino content in the $\boldsymbol{m_3}$ mass eigenstate.

$$|U_{e3}|^2 \equiv \sin^2\theta_{13} = (\mathbf{2.18 \pm 0.06})\%$$

2. $\boldsymbol{\theta_{13}}$ is also measured via an appearance of electron (anti)neutrinos in accelerator muon (anti)neutrino beams. Measured appearance probability in these experiments

$$\boldsymbol{P^{3x3}_{\bar{\nu}\mu\to\bar{\nu}e}}(\theta_{13}, \delta,\ \mathrm{NO/IO},\ \theta_{23} \lesseqgtr 45^o)$$

is the function of θ_{13} but also of yet unknown CP violating phase δ, neutrino mass ordering and the octant of θ_{23}.

Input of the value of $\boldsymbol{\theta_{13}}$ from reactor neutrino experiments will shed light on yet unknown variables of neutrino mixing.

3. The effect of CP violation in neutrino oscillations is proportional to $\cos(\theta_{13})\sin(2\theta_{13})$ The CP violation can be direcly measured as the difference:

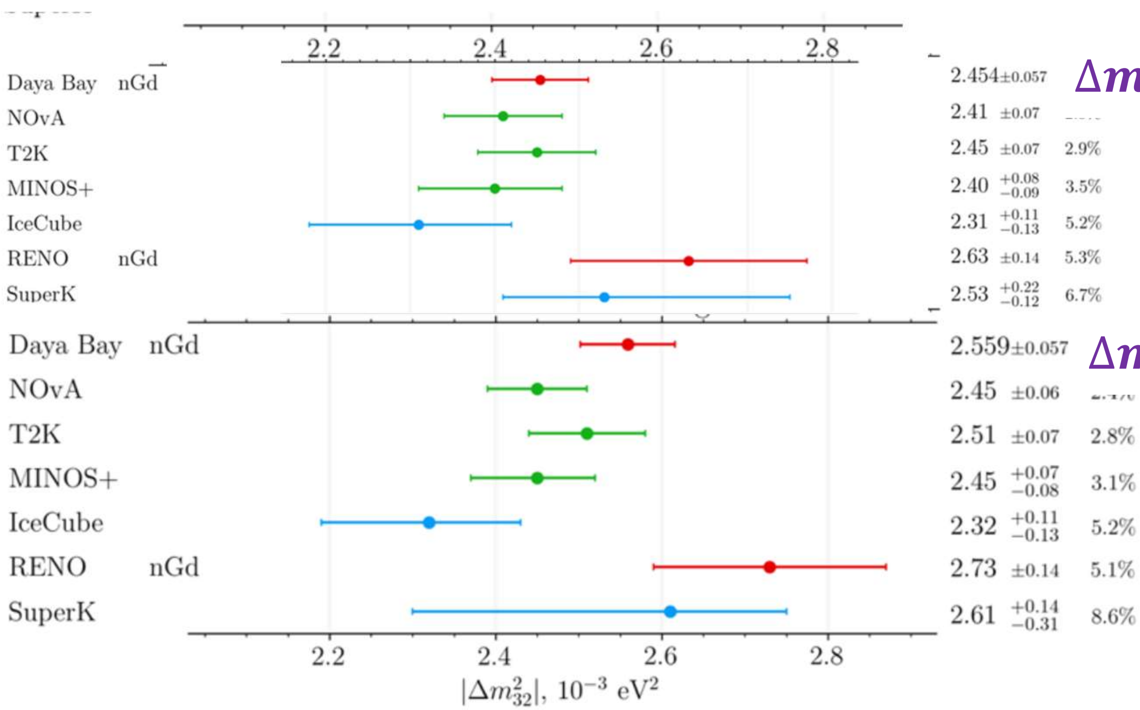
$$\boldsymbol{P_{\bar{\nu}\mu\rightarrow\bar{\nu}e} - P_{\nu\mu\rightarrow\nu e}}$$

$$= \sin(\delta)\, 2\cos(\theta_{13})\sin(2\theta_{13})\sin(2\theta_{12})\sin(2\theta_{23})\, sin\left(\frac{\Delta m^2_{21}}{4\hbar c}\frac{L}{E}\right) sin\left(\frac{\Delta m^2_{31}}{4\hbar c}\frac{L}{E}\right) sin\left(\frac{\Delta m^2_{32}}{4\hbar c}\frac{L}{E}\right)$$

$$= \boldsymbol{sin(\delta)} \quad \boldsymbol{0.53} \quad \boldsymbol{0.052(1st\ maximum)} \quad \boldsymbol{0.156(2nd\ maximum)}$$

The very precise measurement of $\boldsymbol{\theta_{13}}$ means that the relative contribution of $\boldsymbol{\theta_{13}}$ to the uncertainty of the 0.53 value is similar to that of much larger mixing angles $\boldsymbol{\theta_{12}}$ and $\boldsymbol{\theta_{23}}$.

Precise measurement of Δm^2_{32}



$\Delta m^2_{32} = +\left(2.454^{+0.057}_{-0.057}\right) \times 10^{-3}$ eV²

Normal Mass Ordering

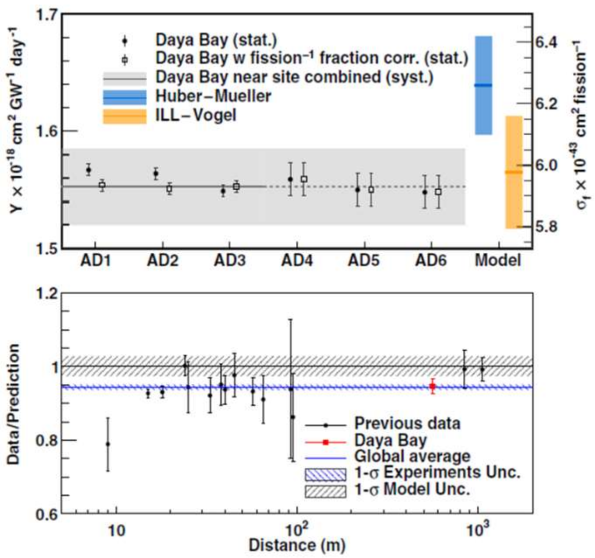
$\Delta m^2_{32} = +\left(2.559^{+0.057}_{-0.057}\right) \times 10^{-3}$ eV²

Inverted Mass Ordering

Daya Bay measures the Δm^2_{32} value most precisely with similar uncertainties to NOvA, T2K and MINOS.

The uncertainty 5.7×10^{-5} eV² is even 25% smaller than the smallest neutrino mass difference $\Delta m^2_{21} = 7.53 \times 10^{-5}$ eV²

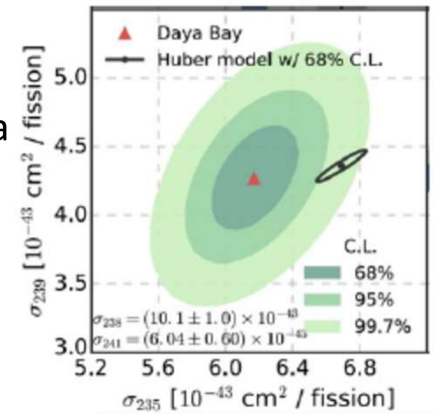
Reactor antineutrino flux



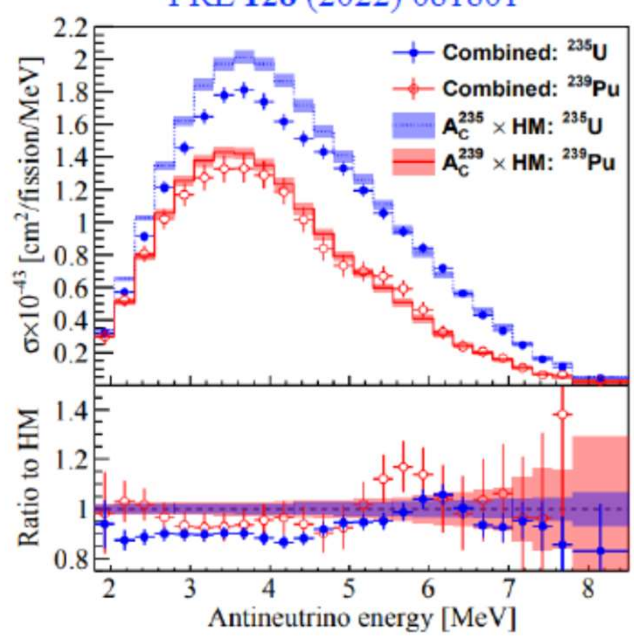
Daya Bay measures the absolute flux of reactor anti-neutrinos very precisely. The Huber-Mueller (HM) model predicted a value about 5% greater.

Measurements made it possible to separate the antineutrino flux from ^{235}U and ^{239}Pu separately. The result showed that for ^{239}Pu the model predicts a value about 1% larger, but for ^{235}U it predicts a value about 8% larger. However, measurement uncertainties could not rule out this model for ^{235}U.

PRL **118** (2017) 251801



PRL **128** (2022) 081801



The new result is a combination of the **Daya Bay** (^{235}U and ^{239}Pu) and **PROSPECT** (^{235}U) experiments. These results show good agreement of the HM model with the ^{239}Pu data but **significantly disfavor the model for ^{235}U .**

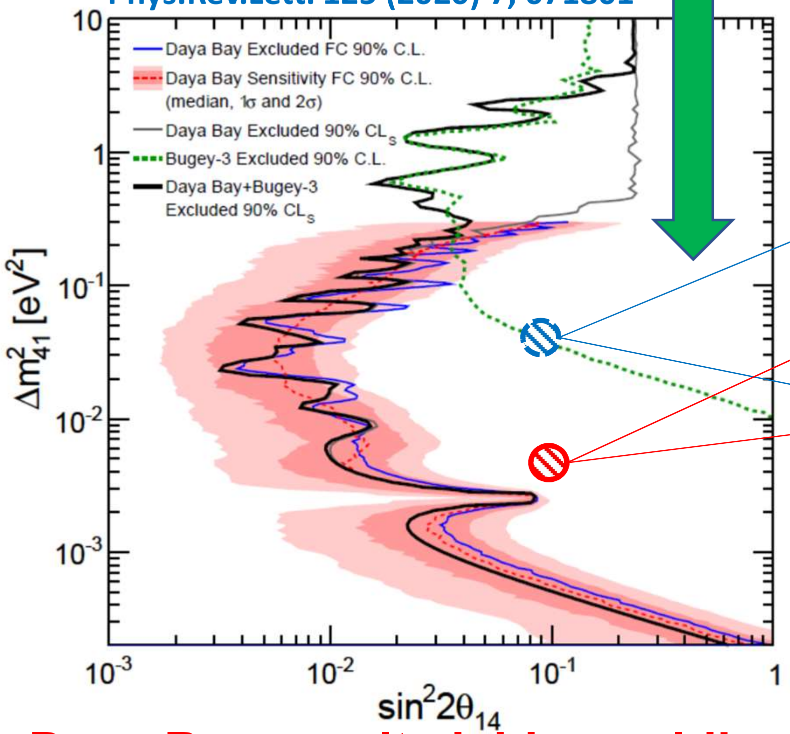
Light sterile neutrino searches

Fourth neutrino mass eigenstate m_4 imply three additional mixing angles θ_{14}, θ_{24} and θ_{34}, two additional CP violating Dirac phases.

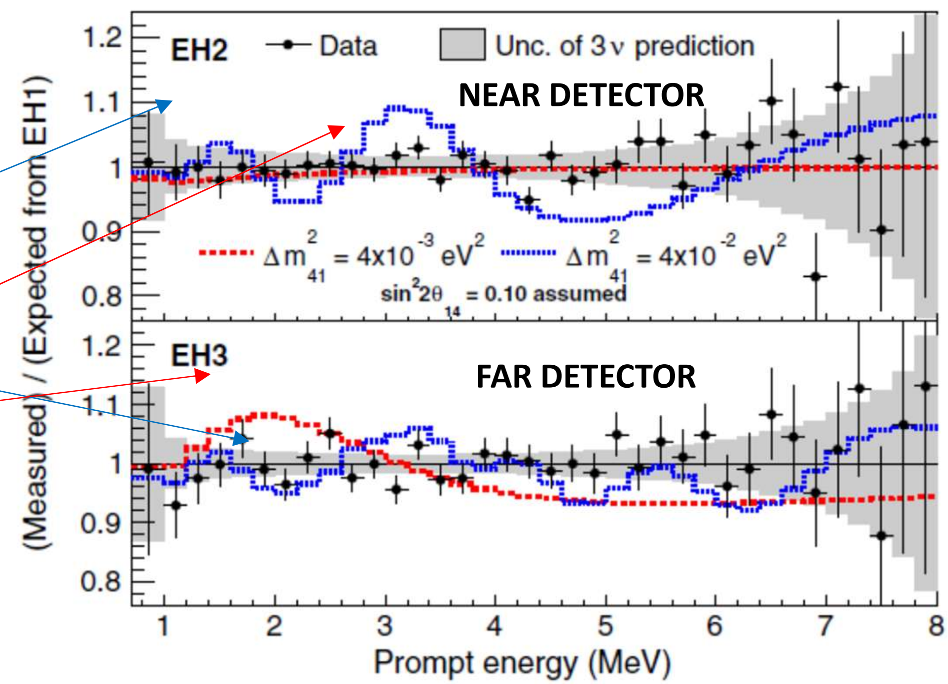
Electron antineutrino disappearance depends only on the value of θ_{14}

Excluded region is on right part of the plot

Phys.Rev.Lett. 125 (2020) 7, 071801



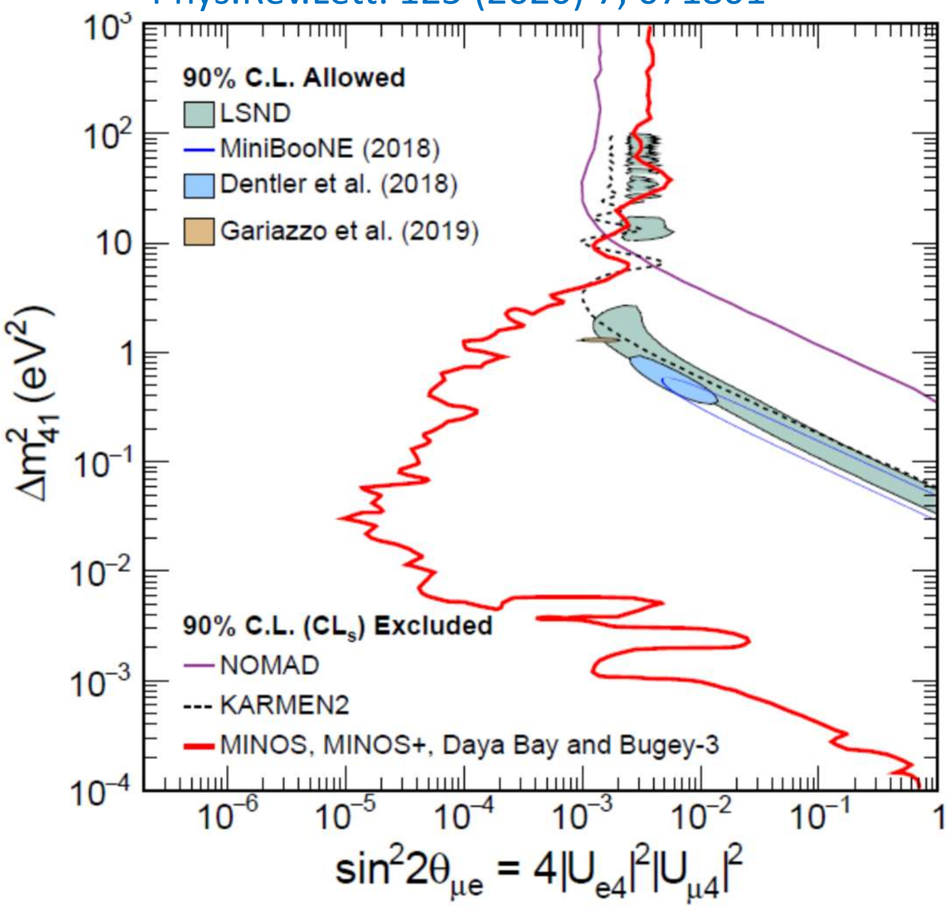
Possible effect on measured spectra:



Daya Bay result yields world's most stringent limits on θ_{14} for $\Delta m^2_{41} < 0.1$ eV^2

Similarly, the search for sterile neutrinos in muon neutrino experiments sets a limit in the Δm^2_{41} $U^2_{\mu 4}$ plane.

Phys.Rev.Lett. 125 (2020) 7, 071801



By combining the electron and muon neutrino disappearance data, a limit can be placed on the Δm^2_{41} .vs. product U^2_{e4} $U^2_{\mu 4}$

Observations of the oscillations of muon neutrinos to electron neutrinos, which cannot be described by the three types of neutrinos, are proportional to this product U^2_{e4} $U^2_{\mu 4}$

Combined results of electron (Daya Bay, Bugey-3) and muon (MINOS, MINOS+) excluded the LSND and MiniBooNE allowed regions for Δm^2_{41} < 1.2 eV².

Summary

The 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 $|\Delta m^2_{32}|$ with the uncertainty smaller than Δm^2_{21}

- Yields leading results on absolute reactor neutrino flux and light sterile neutrino searches

- Will have more results to be presented in the future, for example updated results on oscillation parameters with nH samples.