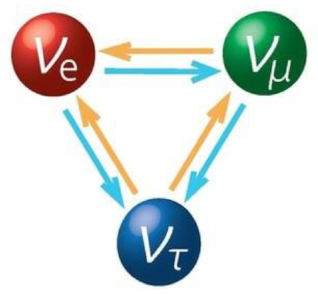
Neutrino Mixing at Daya Bay: $\sin^2 2\theta_{13}$ and Δm^2_{ee} from Neutron Capture on Gadolinium

Matt Kramer (UC Berkeley), on behalf of the **Daya Bay Collaboration**

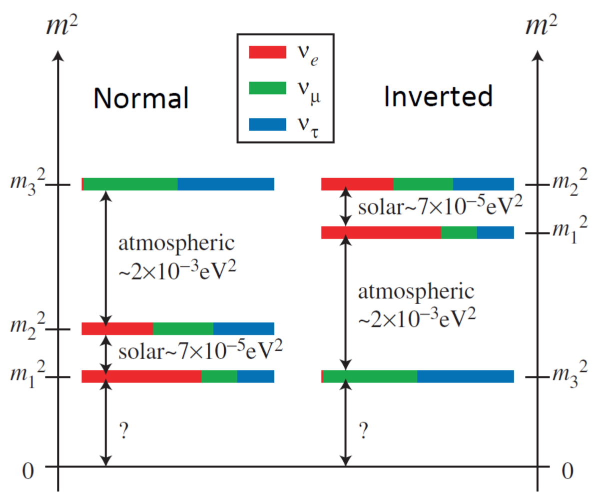
Reactor Neutrino Mixing



Neutrino mass states $|\nu_i\rangle \neq$ flavor (weak interaction) states $|\nu_\alpha\rangle$:

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U^*_{\alpha i} |\nu_i\rangle$$

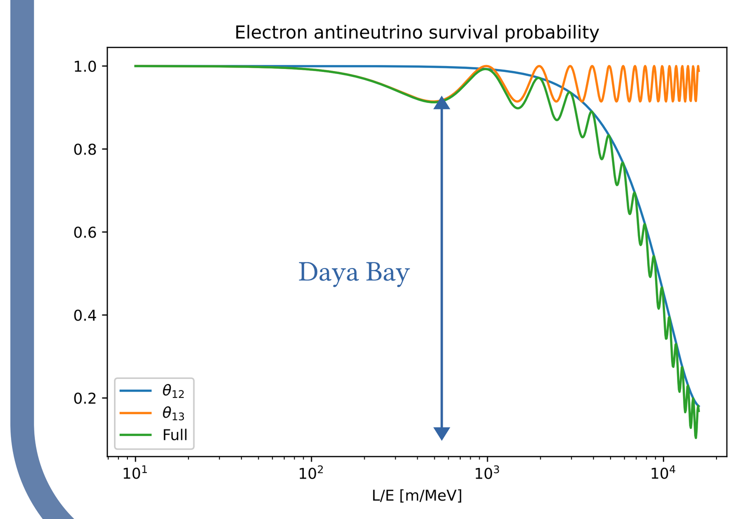
$$U = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{Atmospheric } \theta_{23} \approx 45^\circ} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix}}_{\text{Reactor } \theta_{13} \approx 9^\circ} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar } \theta_{12} \approx 34^\circ} \quad \begin{pmatrix} c_{ij} \equiv \cos\theta_{ij} \\ s_{ij} \equiv \sin\theta_{ij} \end{pmatrix}$$



Via **disappearance of reactor antineutrinos**, Daya Bay was the first experiment to measure θ_{13}.

Letting $\Delta_{ij} \simeq 1.267 \Delta m^2_{ij} L/E\ [\mathrm{eV^2\ m\ MeV^{-1}}]$:

$$\begin{aligned} P(\bar\nu_e \to \bar\nu_e) &= 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} \\ &\quad - \sin^2 2\theta_{13} \times \\ &\quad (\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}) \\ &\simeq 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} \\ &\quad - \sin^2 2\theta_{13}\sin^2\Delta_{ee} \end{aligned}$$



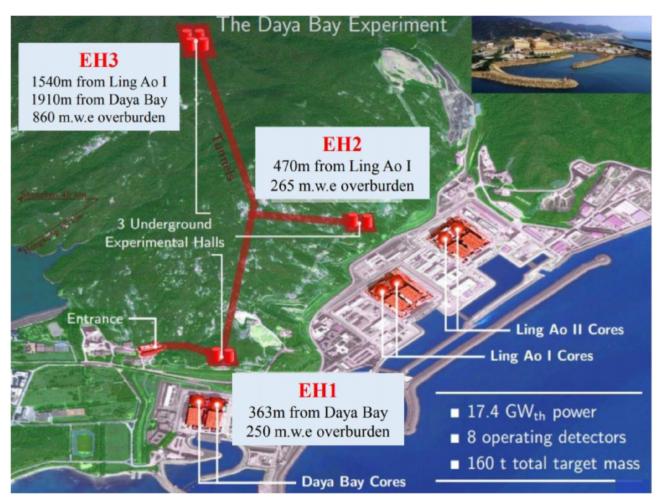
Daya Bay is not sensitive to the difference between Δm^2_{31} and Δm^2_{32}. Thus we have defined the effective mass splitting

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

Δm^2_{ee} is independent of whether mass hierarchy is "normal" (NH) or "inverted" (IH). Once we know:

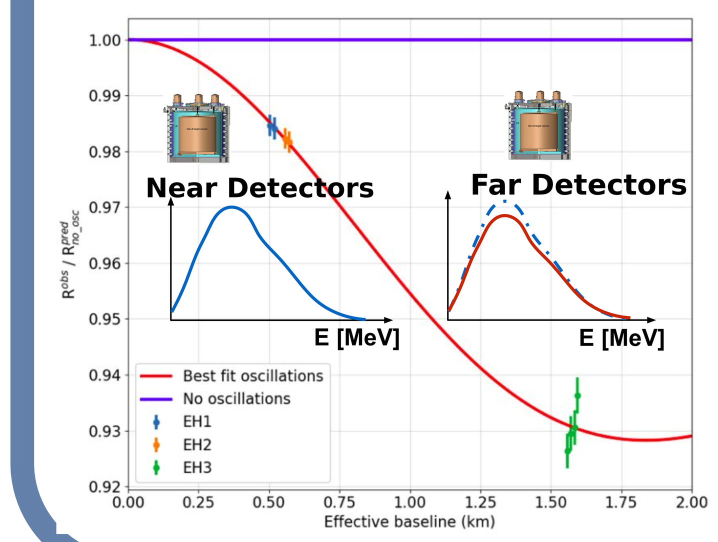
$$\Delta m^2_{31} \simeq \Delta m^2_{ee} \pm 2.3 \times 10^{-5}\ \mathrm{eV^2} \quad (+\mathrm{NH}\ /\ -\mathrm{IH})$$
$$\Delta m^2_{32} \simeq \Delta m^2_{ee} \mp 5.2 \times 10^{-5}\ \mathrm{eV^2} \quad (-\mathrm{NH}\ /\ +\mathrm{IH})$$

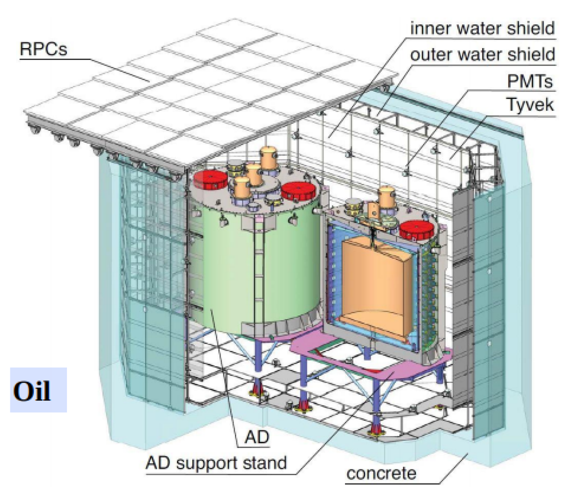
Daya Bay Experiment



Together, the Daya Bay and Ling Ao I & II nuclear power plants produce 17.6 $\mathrm{GW_{th}}$, releasing ~ 10^{21} $\bar\nu_e$ / sec

Using 8 essentially identical antineutrino detectors (ADs) in 1 "far" and 2 "near" experimental halls (EHs), disappearance is measured. Use of the near halls allows for cancellation of uncertainties related to reactor flux and detection efficiency.



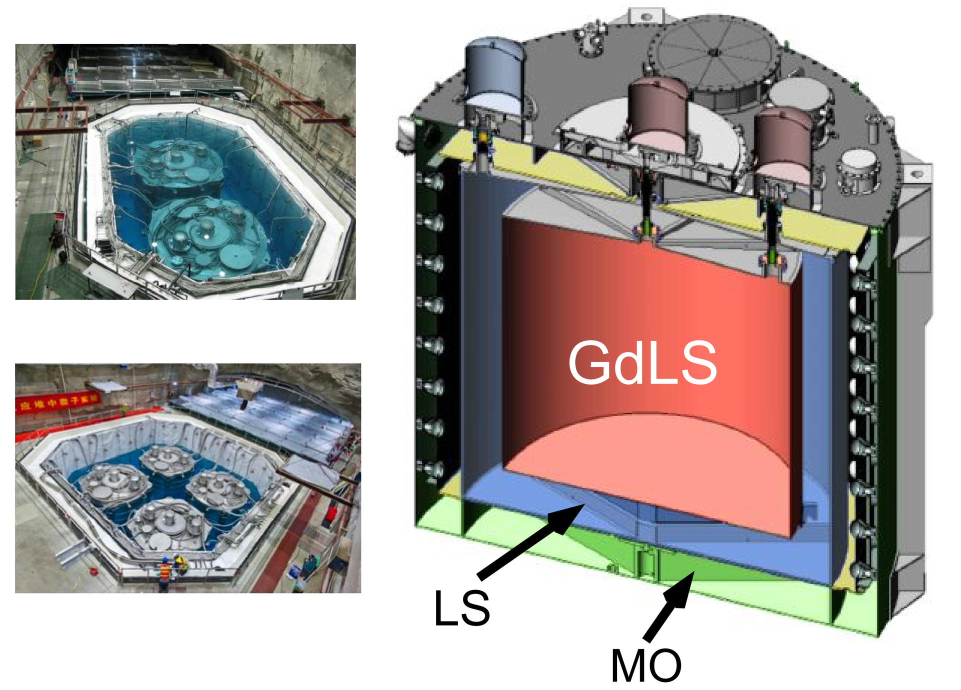


The halls are nestled under a mountain. In each hall, the ADs are submerged in a water pool for shielding and detection of cosmic ray muons.

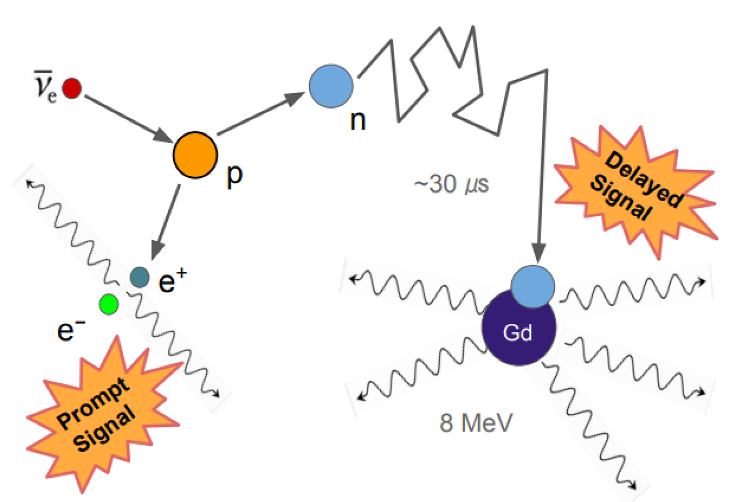
Antineutrino Detectors

Each AD contains 192 photomultipler tubes (PMTs) and is divided into 3 zones:

- Gadolinium-doped liquid scintillator (GdLS)
  - Target volume (20 tons)
- Liquid scintillator (LS)
  - γ catcher (21 tons)
- Mineral oil
  - Buffer hosting PMTs (40 tons)



$$\bar\nu_e + p \to e^+ + n$$



Antineutrinos are detected via the inverse beta decay (IBD) process.

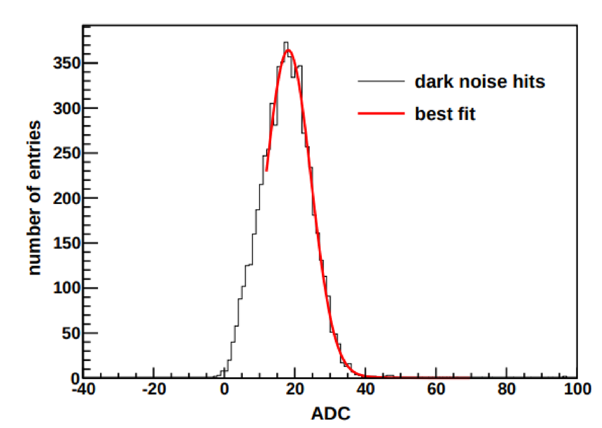
Gadolinium has a high neutron capture cross section and energy (~8 MeV), giving a double coincidence signature with low backgrounds.

$$E_{\mathrm{prompt}} \simeq E_{\bar\nu} - 0.8\ \mathrm{MeV}$$

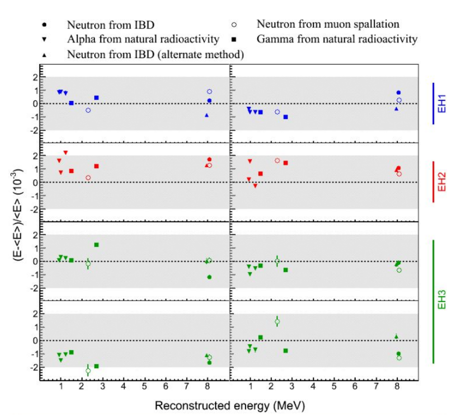
Calibration and Reconstruction

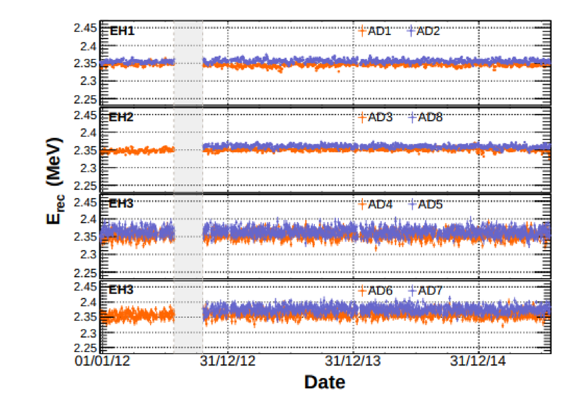
Calibration begins with measurement of the *gain* (observed charge per photoelectron) of each PMT

"Dark noise" (thermal photoelectron emission) is continuously measured in order to obtain the gain from a fit to the peak (~daily)

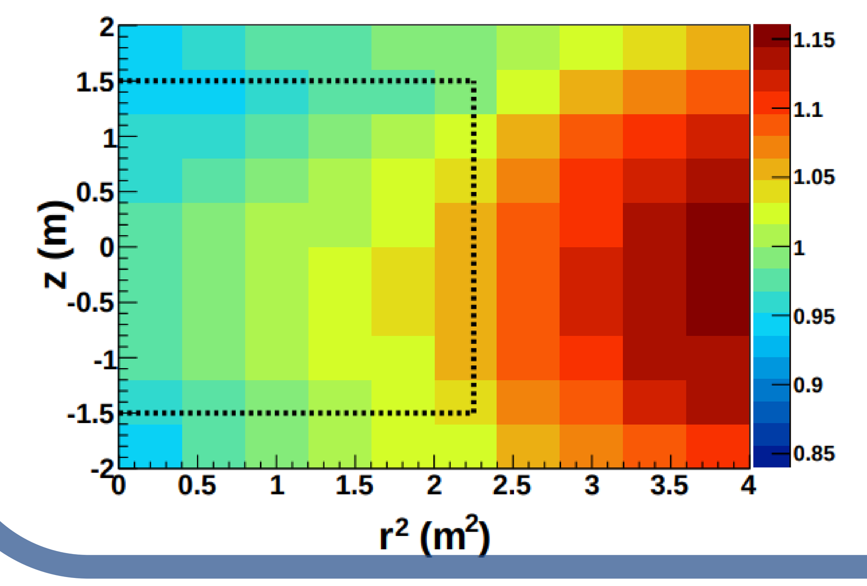


The next step is to measure the *energy scale* (photoelectrons per MeV) of each AD, by fitting the ~8 MeV Gd-capture peak from spallation neutrons produced by cosmic rays. (An independent method using ^{60}Co calibration runs gives consistent results.) This calibration produces excellent consistency between ADs and stability across time.

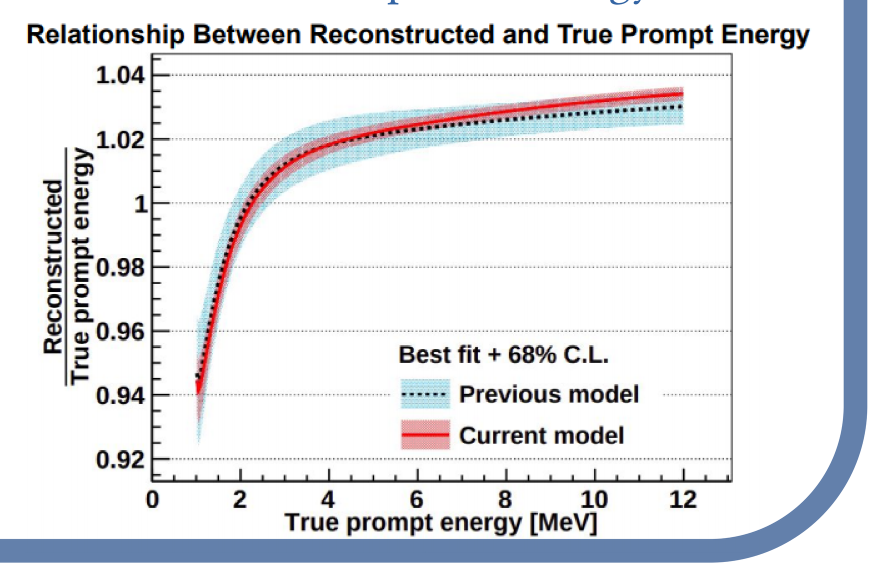




An additional correction is applied to account for the geometric nonuniformity of the ADs.



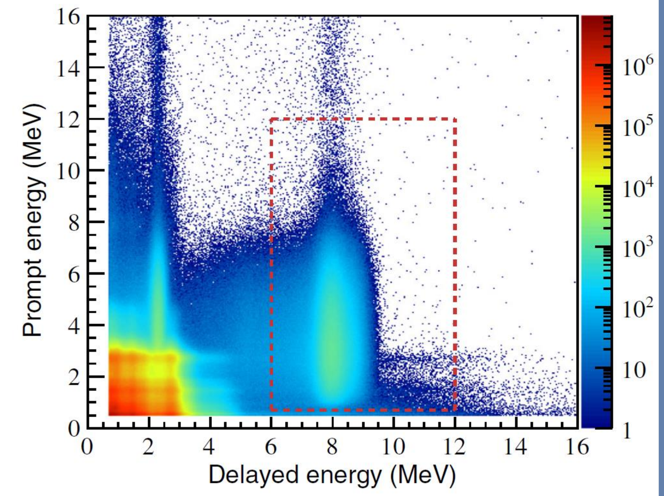
Finally, we correct for the nonlinear response of the scintillator in order to obtain the true deposited energy.



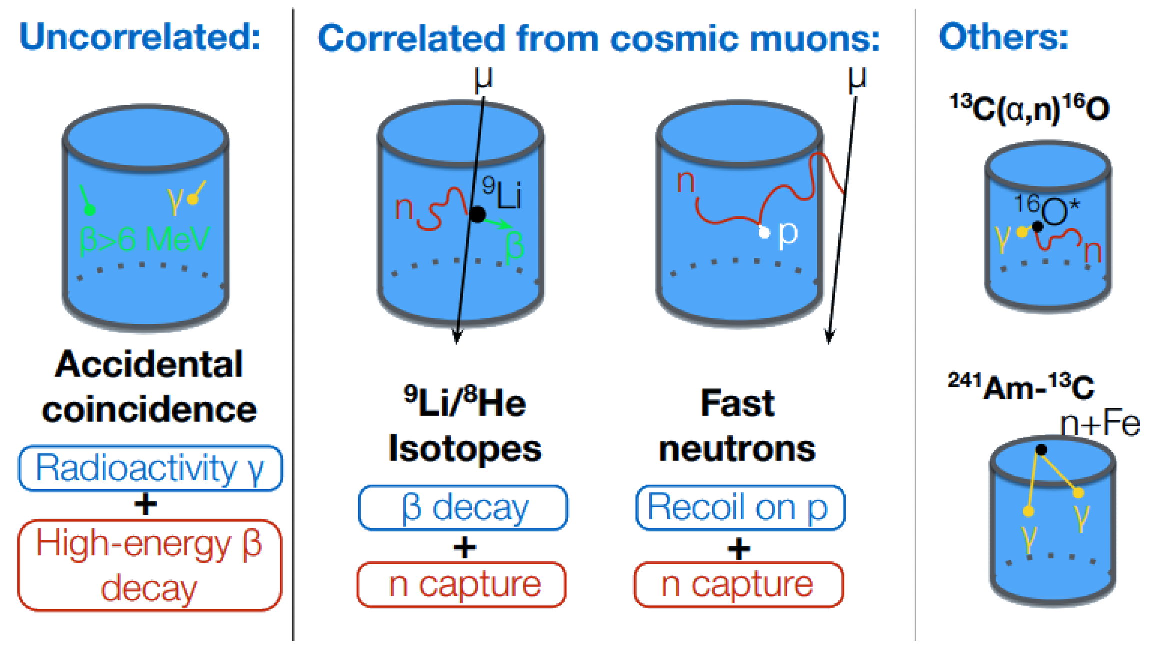
Signal and Background

After a muon veto is applied, IBD candidates are selected based on reconstructed energy and time separation.

Prompt energy: 0.7–12 MeV
Delayed energy: 6–12 MeV
Time separation: 1–200 μs



Five types of backgrounds are present. Their rates are separately measured, and their scaled spectra are subtracted from the IBD prompt spectra. The total background rate of <2% contributes <0.15% uncertainty to the IBD rate.



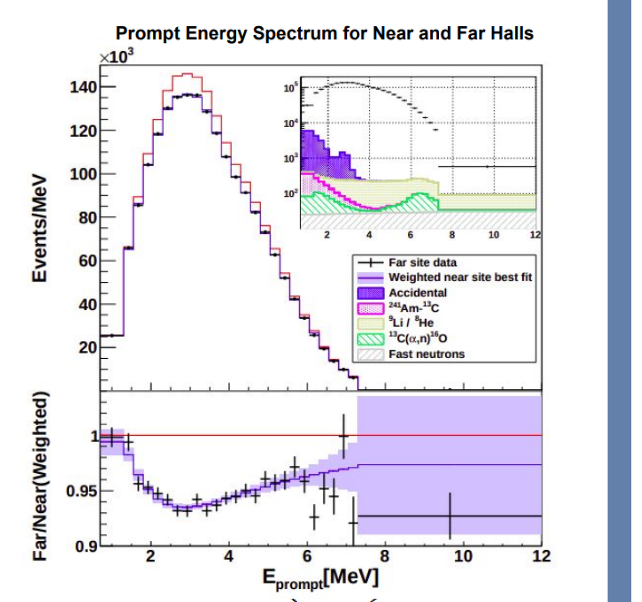
Oscillation Fit

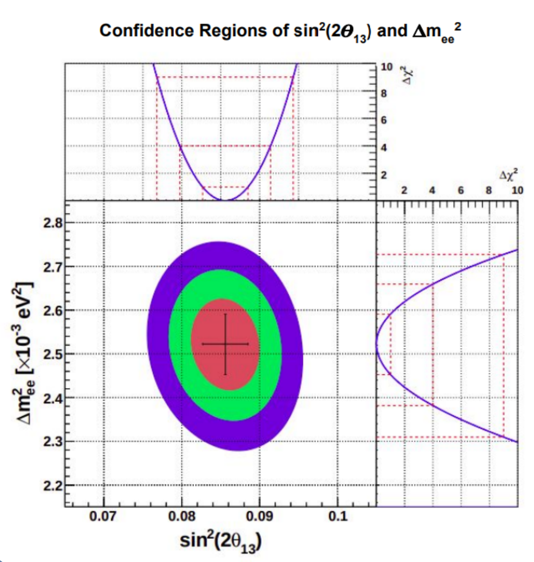
After background subtraction, the ratios of the far and near spectra are fit to the oscillation probability function:

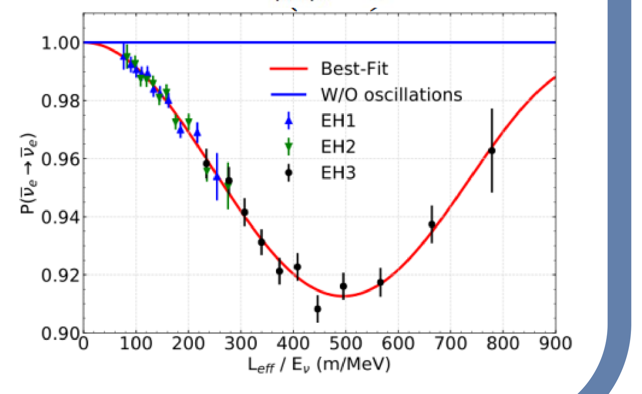
$$\sin^2 2\theta_{13} = 0.0856 \pm 0.0029 \qquad \Delta m^2_{ee} = (2.522^{+0.068}_{-0.070}) \times 10^{-3}\ \mathrm{eV^2}$$
$$\Delta m^2_{32} = +(2.471^{+0.068}_{-0.070}) \times 10^{-3}\ \mathrm{eV^2} \quad (\mathrm{NH})$$
$$\Delta m^2_{32} = -(2.575^{+0.068}_{-0.070}) \times 10^{-3}\ \mathrm{eV^2} \quad (\mathrm{IH})$$

World's most precise measurement of $\sin^2 2\theta_{13}$. Improved final measurement (~3%) will be world's best for foreseeable future.

Δm^2_{32} precision is comparable to accelerator neutrino measurements; value is in agreement.







D. Adey et al. (The Daya Bay Collaboration), Phys. Rev. Lett. 121, 241805 (2018)