Measurement of Antineutrino Oscillation with the Full Detector Configuration at Daya Bay

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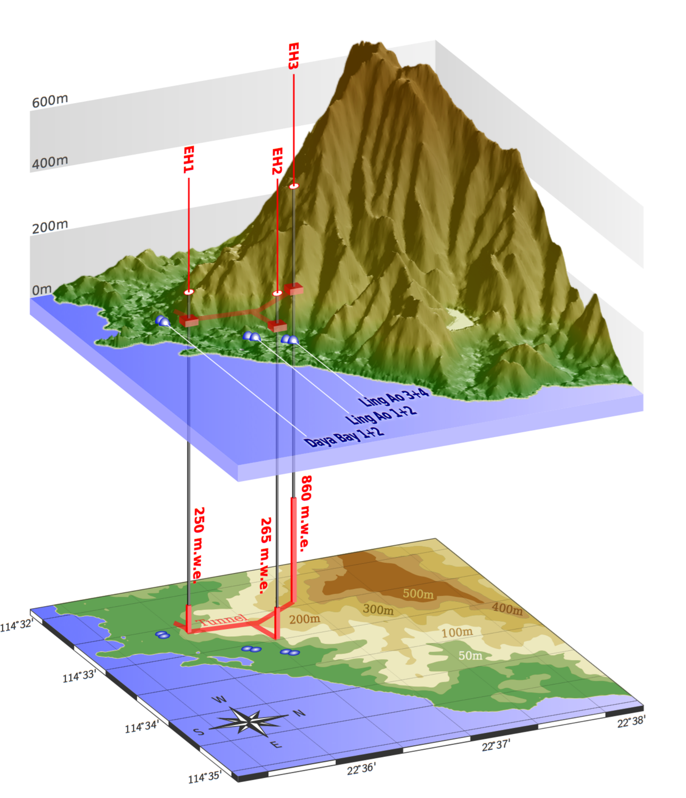
The Daya Bay Experiment



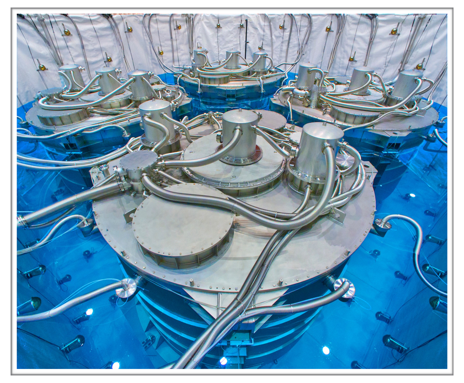
Eight **antineutrino detectors** (ADs) located in three underground experimental halls (EHs). Four ADs positioned in two near halls at short distance from six **nuclear reactor cores**, and four ADs located in the far hall, shielded by 860 mwe overburden.

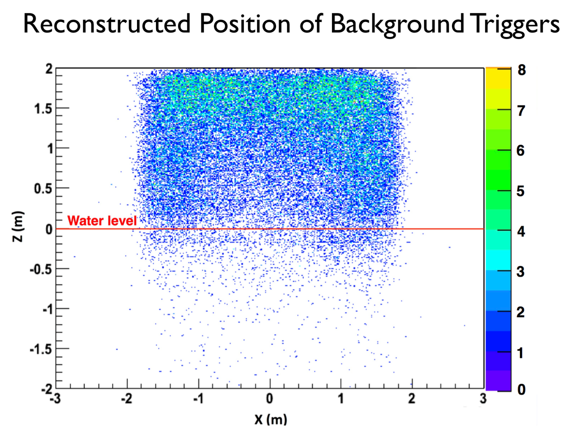
Each EH hosts **functionally identical** ADs inside a muon detector system (water Cerenkov + RPC).

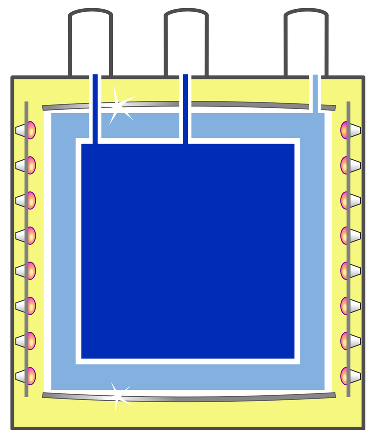
Each AD consists of 3 nested vessels:

- filled with 0.1% **Gd-doped liquid scintillator**
- filled with undoped scintillator (LS)
- filled with mineral oil (MO)

192 8" PMTs are radially positioned in the mineral oil region







Signal & Backgrounds

Inverse Beta Decay $\bar{\nu}_e + p \rightarrow e^+ + n$ — Prompt Energy

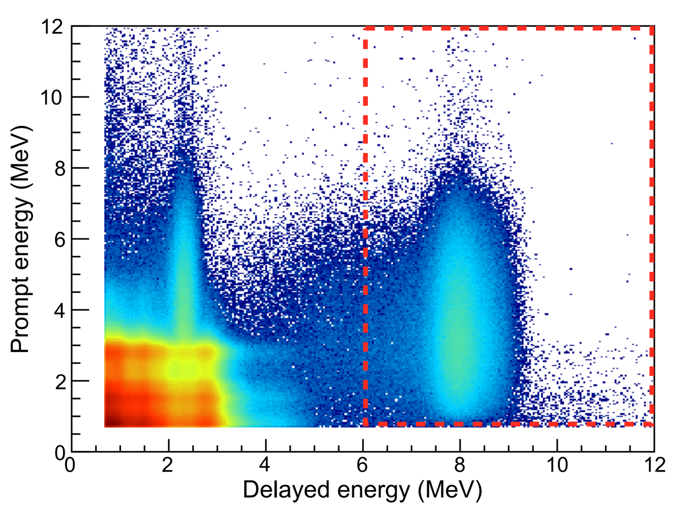
Neutron Capture $\hookrightarrow + Gd \xrightarrow{\tau \approx 28\ \mu s} Gd^* \rightarrow Gd + n\gamma$ — Delayed Energy

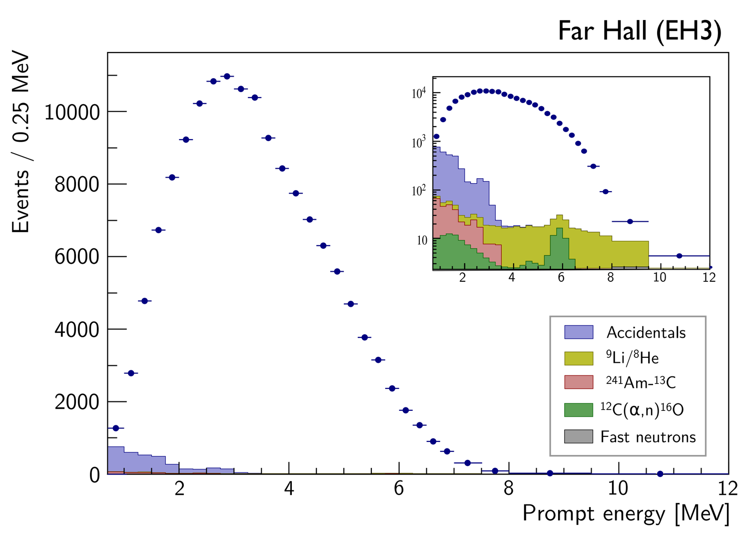
Selection Criteria: $0.7\ \text{MeV} < E_P < 12\ \text{MeV}$

$6\ \text{MeV} < E_D < 12\ \text{MeV}$

$1\ \mu s < (t_D - t_P) < 200\ \mu s$

⊕ Veto to suppress cosmogenic products in case of activity in the muon system





	EH1		EH2		EH3			
	AD1	AD2	AD3	AD8	AD4	AD5	AD6	AD7
IBD candidates	304459	309354	287098	190046	40956	41203	40677	27419
DAQ live time(days)	565.436	565.436	568.03	378.407	562.451	562.451	562.451	372.685
ε_μ	0.8248	0.8218	0.8575	0.8577	0.9811	0.9811	0.9808	0.9811
ε_m	0.9744	0.9748	0.9758	0.9756	0.9756	0.9754	0.9751	0.9758
Accidentals(per day)	8.92 ± 0.09	8.94 ± 0.09	6.76 ± 0.07	6.86 ± 0.07	1.70 ± 0.02	1.59 ± 0.02	1.57 ± 0.02	1.26 ± 0.01
Fast neutron(per AD per day)	0.78 ± 0.12		0.54 ± 0.19		0.05 ± 0.01			
^{9}Li/^{8}He(per AD per day)	2.8 ± 1.5		1.7 ± 0.9		0.27 ± 0.14			
Am-C correlated 6-AD(per day)	0.27 ± 0.12	0.25 ± 0.11	0.27 ± 0.12		0.22 ± 0.10	0.21 ± 0.10	0.21 ± 0.09	
Am-C correlated 8-AD(per day)	0.20 ± 0.09	0.21 ± 0.10	0.18 ± 0.08	0.22 ± 0.10	0.06 ± 0.03	0.04 ± 0.02	0.04 ± 0.02	0.07 ± 0.03
^{13}C(α, n)^{16}O(per day)	0.08 ± 0.04	0.07 ± 0.04	0.05 ± 0.03	0.07 ± 0.04	0.05 ± 0.03	0.05 ± 0.03	0.05 ± 0.03	0.05 ± 0.03
IBD rate(per day)	657.18 ± 1.94	670.14 ± 1.95	594.78 ± 1.46	590.81 ± 1.66	73.90 ± 0.41	74.49 ± 0.41	73.58 ± 0.40	75.15 ± 0.49

Energy Scale Calibration

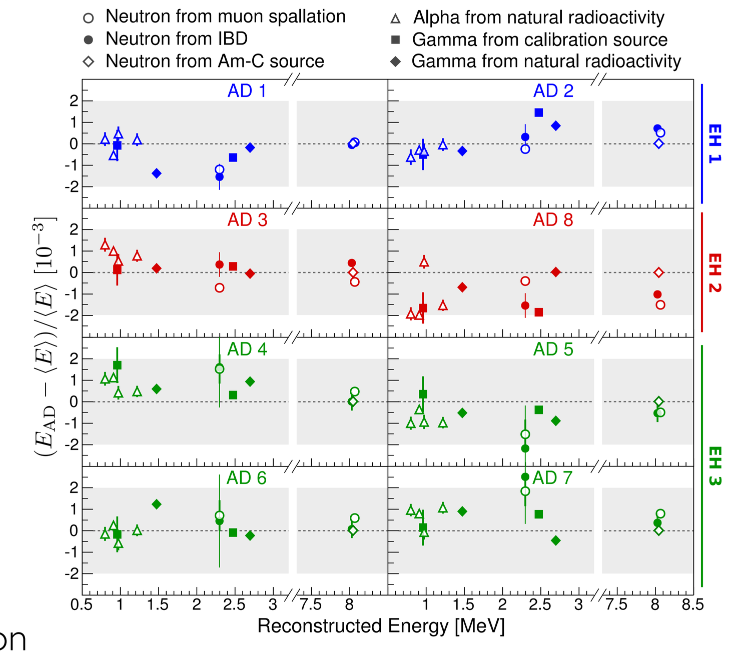
Constrain the energy scale difference among 8ADs

Energy scale calibrated using **Am-C neutron** source at the detector center (n-Gd capture)

Time variation and position dependence corrected using 2.5 MeV gammas from ^{60}**Co** sources

Multiple sources with different spatial distros used to validated **uncertainty** on energy scale

- ^{68}**Ge** gammas at detector center
- Unif. distributed **n from IBD and muon spallation** (both capturing on H and Gd)
- α **particles** from Po and Rn decays in Gd-LS region
- Intrinsic ^{40}K (1.46 MeV gamma) and ^{208}Tl within the Gd-LS region



The uncorrelated relative uncertainty of the energy scale is < 0.2%

Non-Linear Energy Response

Non-linear (NL) energy response originated from:

- particle-dependent **NL light yield of LS**
- charge-dependent **NL in the PMT readout electronics**

} both at the level of 10%

Semi-empirical model accounting for non-linear response contains 4 parameters:

- Birks' constant
- Cherenkov contribution to total light yield

$$f_{\text{scintillator}} = \frac{E_{\text{vis}}}{E_{\text{true}}} \propto f_q(E_{\text{true}}, k_B) + k_C \cdot f_C(E_{\text{true}})$$

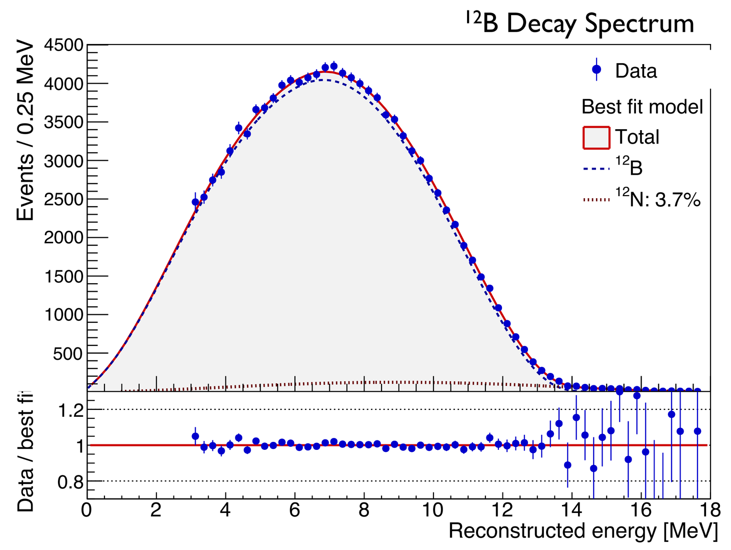
- Amplitude and scale of exponential describing NL electronics response

$$f_{\text{electronics}} = \frac{E_{\text{rec}}}{E_{\text{vis}}} \propto 1 - \alpha \cdot \exp(-E_{\text{vis}}/\tau)$$

Model parameter values obtained from **unconstrained χ2 fit to calibration datasets**:

- **12 gamma lines** from both deployed and naturally occurring sources
- continuous **β- decay** spectrum of ^{12}**B** produced by muon spallation inside the Gd-LS volume

The nominal positron response is derived from the best fit parameters



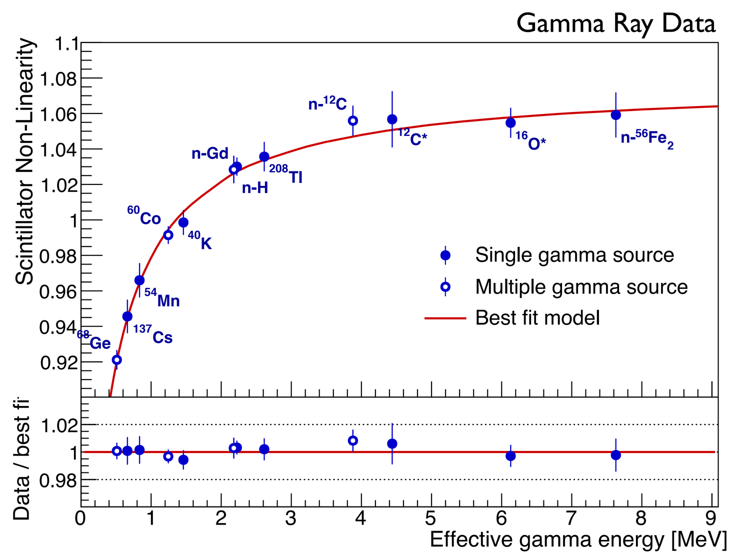
Uncertainty band obtained using other response functions consistent with fitted calibration data within 68% C.L.

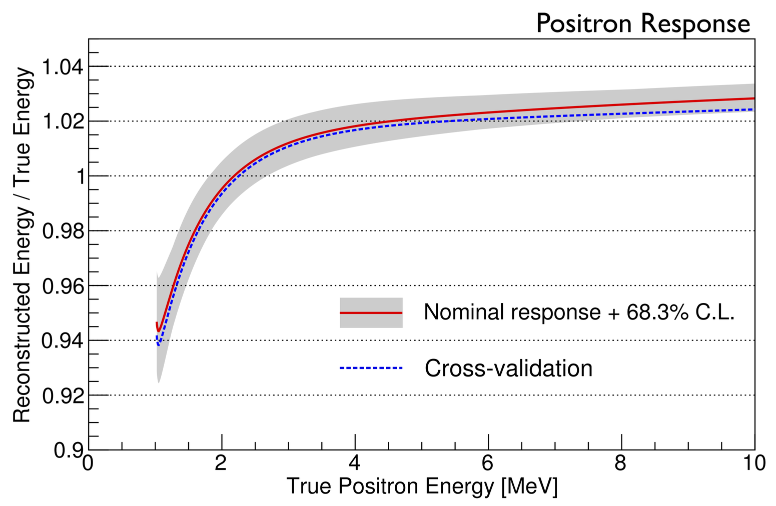
Resulting unc. in absolute energy scale <1%

Cross-check: positron response computed using:

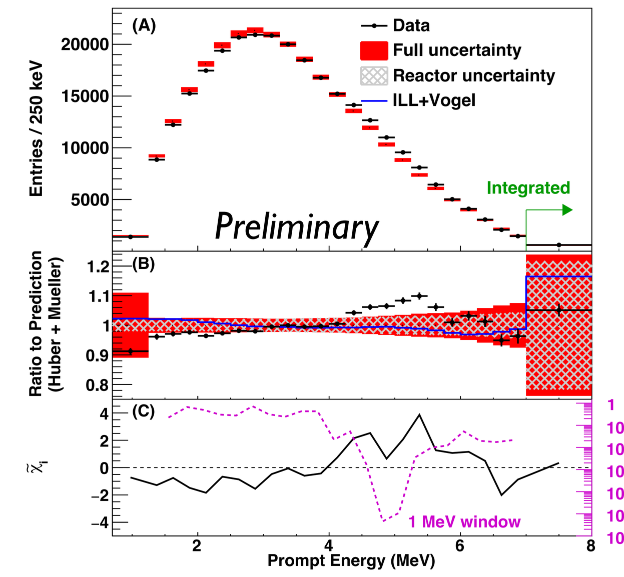
53 MeV cutoff in the Michel electron spectrum from muon decay at rest (1)

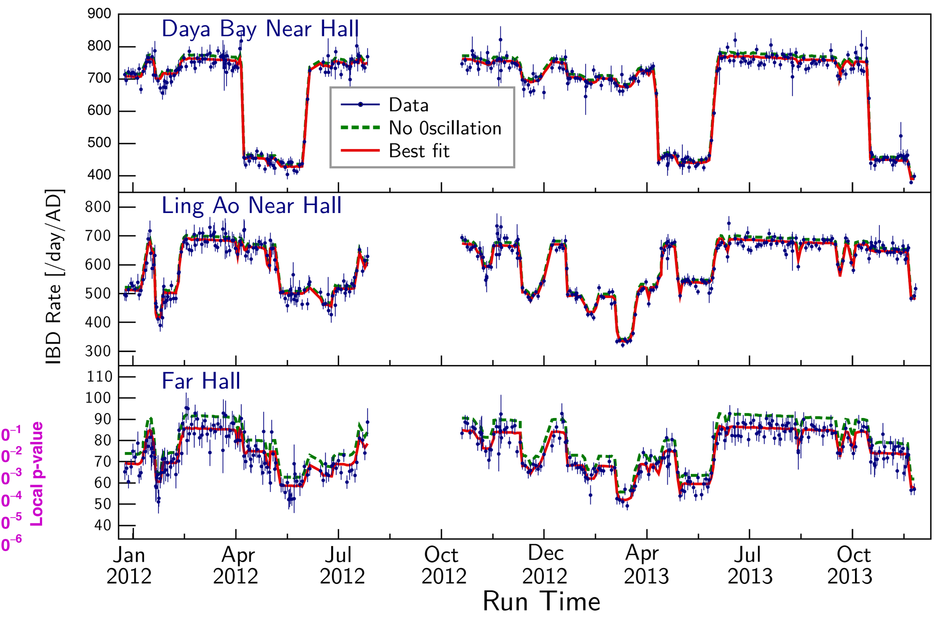
Continuous β+γ spectra from natural bismuth and thallium decays (2)





Near - Far Site Cancellation





Recent precise measurements of the IBD positron energy spectrum disagree with models of reactor ν emission. To measure the oscillation parameters we use a technique for predicting the signal in the far hall based on measurements obtained in the near halls, with **minimal dependence on the on models of the reactor antineutrinos.**

$$\chi^2 = \sum_{i,j} (N^{\text{f}}_j - w_j \cdot N^{\text{n}}_j)(V^{-1})_{ij}(N^{\text{f}}_i - w_i \cdot N^{\text{n}}_i)$$

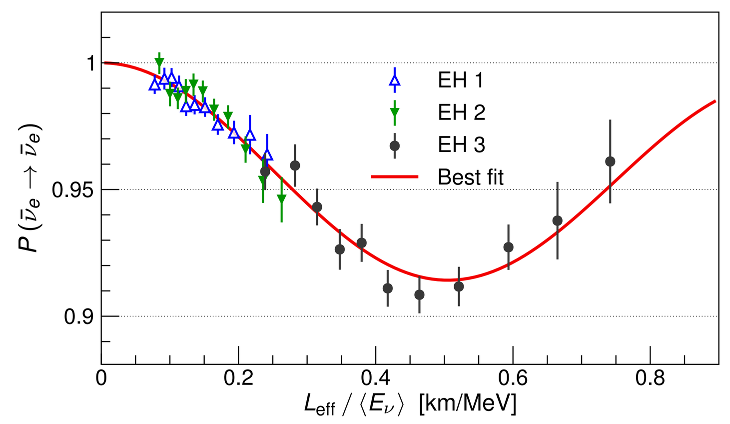
$$w_i^{\text{SR}} = \frac{N^{\text{f}}_i}{N^{\text{n}}_i} = \left(\frac{T^{\text{f}}}{T^{\text{n}}}\right)\left(\frac{\epsilon^{\text{f}}}{\epsilon^{\text{n}}}\right)\left(\frac{L^{\text{n}}}{L^{\text{f}}}\right)^2\left(\frac{P^{\text{f}}_i}{P^{\text{n}}_i}\right)\left(\frac{\phi}{\phi}\right)$$

- N: number of events after bkg sub.
- w: weight accounting for differences between near and far meas.
- T: number of target protons
- ε: efficiency
- L: distance reactor-detector
- P: oscillation probability
- Φ: reactor flux
- V: covariance matrix (stat + sys)

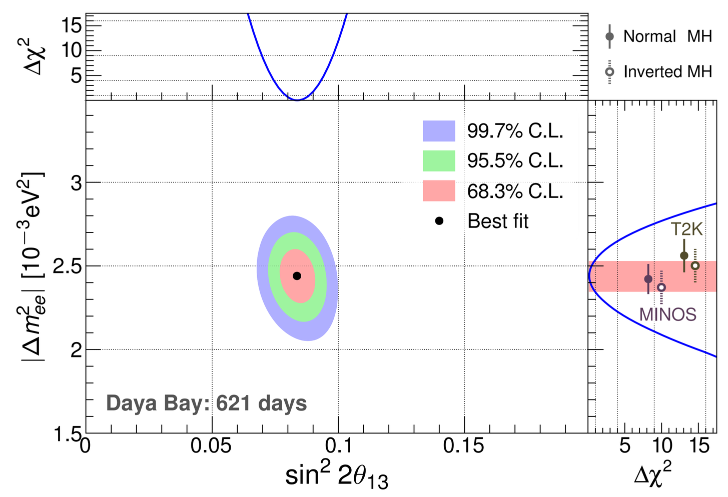
For multiple reactor cores, the weights need to be modified, and the cancellation of the antineutrino flux is no longer exact. However the **impact of the uncertainty in antineutrino flux on the oscillation parameters is ≤ 0.1%**

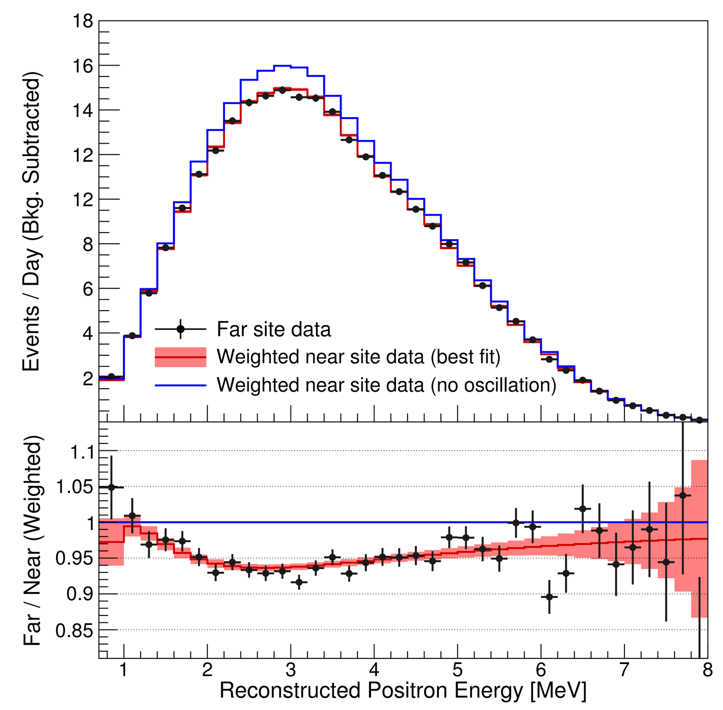
Results

The mass splitting result is consistent with and of comparable precision to measurements obtained from accelerator ν_μ and $\bar{\nu}_\mu$ disappearance (MINOS and T2K).



$\sin^2(2\theta_{13})$ =	0.084 ± 0.005
$\lvert\Delta m^2_{ee}\rvert$ =	$(2.42 \pm 0.11)\ 10^{-3}\ \text{eV}^2$
χ^2/NDF =	134.6 / 146
$\lvert\Delta m^2_{32}\rvert$ (NH) =	$(2.37 \pm 0.11)\ 10^{-3}\ \text{eV}^2$
$\lvert\Delta m^2_{32}\rvert$ (IH) =	$(-2.47 \pm 0.11)\ 10^{-3}\ \text{eV}^2$





More information about this analysis is available at: arXiv: 1505.03456 (accepted by PRL)