The Latest Results from Daya Bay

Zhe Wang, Tsinghua University
(on behalf of the Daya Bay Collaboration)

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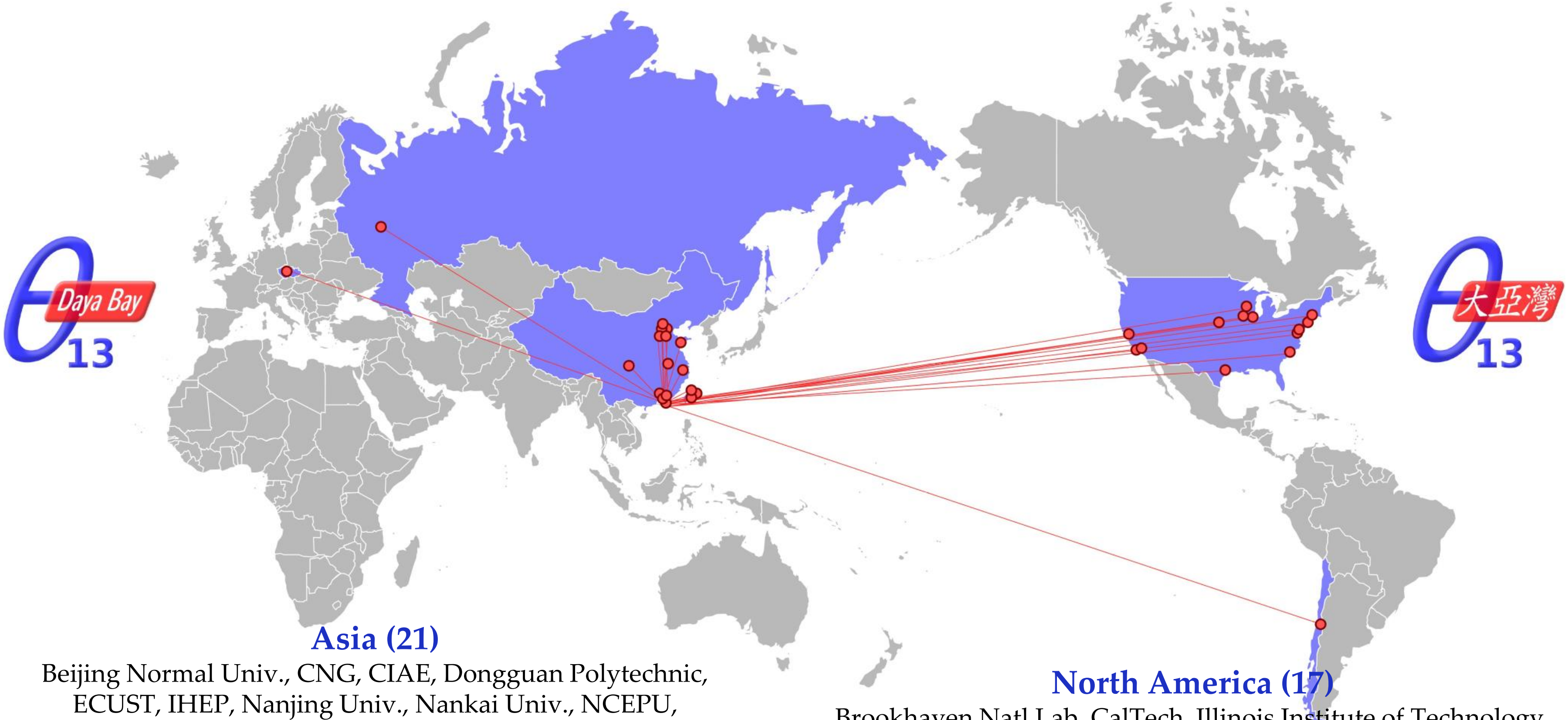
Daya Bay Collaboration

~230 collaborators



Asia (21)

Beijing Normal Univ., CNG, CIAE, Dongguan Polytechnic, ECUST, IHEP, Nanjing Univ., Nankai Univ., NCEPU, Shandong Univ., Shanghai Jiao Tong Univ., Shenzhen Univ., Tsinghua Univ., USTC, Xian Jiaotong Univ., Zhongshan Univ., Chinese Univ. of Hong Kong, Univ. of Hong Kong, National Chiao Tung Univ., National Taiwan Univ., National United Univ.

Europe (2)

Charles University, JINR Dubna

North America (17)

Brookhaven Natl Lab, CalTech, Illinois Institute of Technology, Iowa State, Lawrence Berkeley Natl Lab, Princeton, Rensselaer Polytechnic, Siena College, UC Berkeley, UCLA, Univ. of Cincinnati, Univ. of Houston, UIUC, Univ. of Wisconsin, Virginia Tech, William & Mary, Yale

South America (1)

Catholic Univ. of Chile

Neutrino Mixing, θ_{13} and Beyond

❖ Based on an assumption of three generations, a 3x3 neutrino mixing matrix was proposed – PMNS.

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

1. Precise θ_{13} can provide knowledge of the basic assumptions:
   - Unitarity of PMNS matrix
   - Three generations of neutrinos
2. A critical input for other research, for example:
   - Search for leptonic CP violation
   - Determine the neutrino mass hierarchy
3. With this, other physics can be probed: sterile neutrino, reactor antineutrino anomaly, etc.

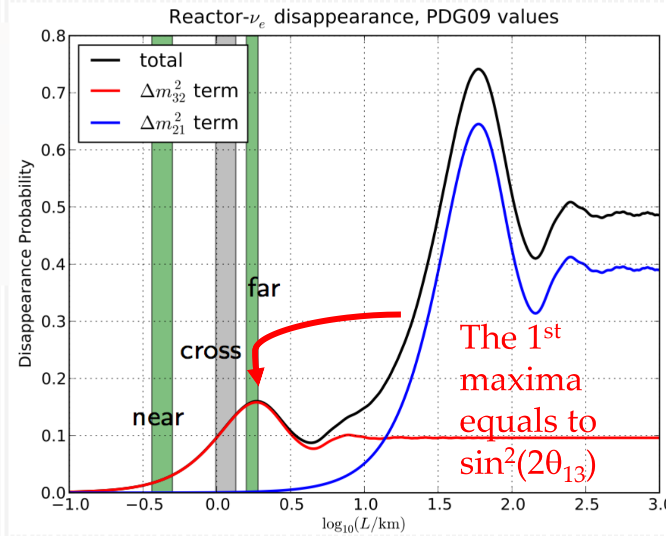
Measurement Method

Detection of anti-electron-neutrino

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

$\rightarrow + p \rightarrow D + \gamma\ (2.2\ MeV)$ (200 μs)

$\rightarrow + Gd \rightarrow Gd^* \rightarrow Gd + \gamma\text{'s}\ (8\ MeV)$ (30 μs)



Extraction of θ_{13}

1. Mixing angle θ_{13} governs overall size of $\bar{\nu}_e$ deficit
2. Effective mass squared difference $|\Delta m^2_{ee}|$ determines deficit dependence on L/E

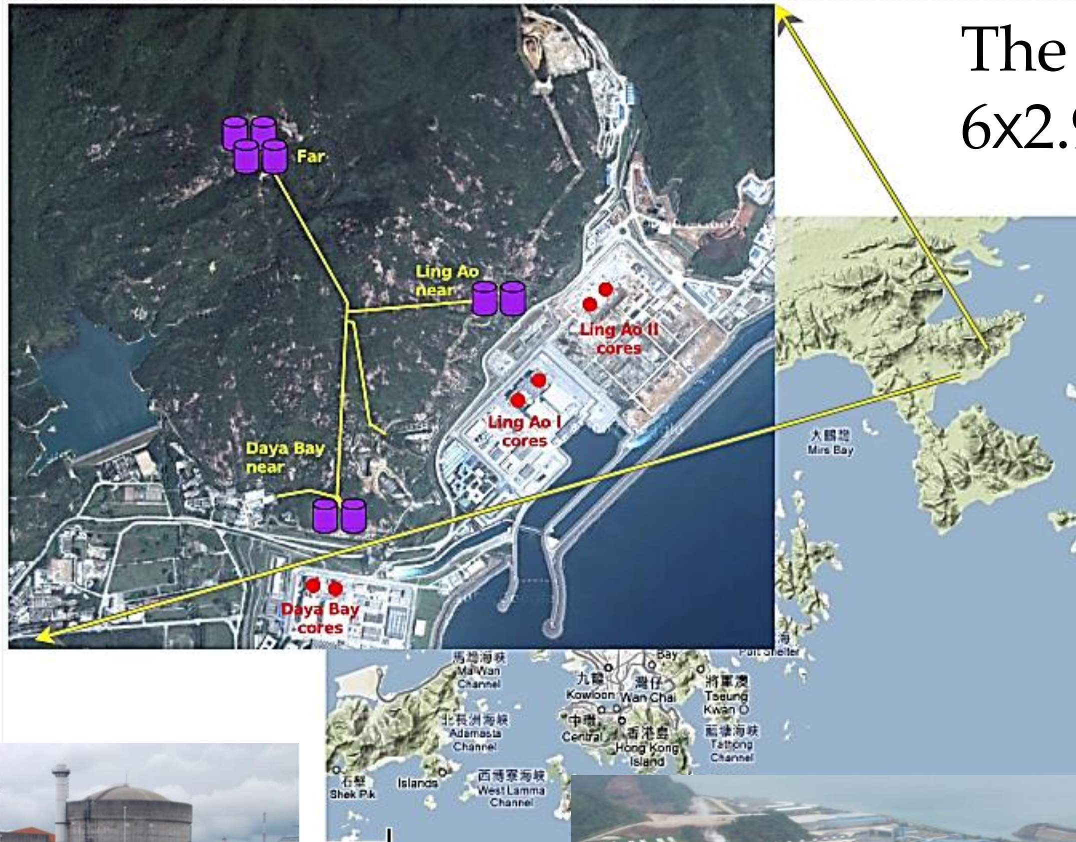
Short Baseline — Long Baseline

$$P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} = 1 - \sin^2 2\theta_{13} \sin^2\left(\Delta m^2_{ee} \frac{L}{4E}\right) - \sin^2 2\theta_{12} \cos^4\theta_{13} \sin^2\left(\Delta m^2_{21} \frac{L}{4E}\right)$$

$$\sin^2(\Delta m^2_{ee} \tfrac{L}{4E}) \equiv \cos^2\theta_{12} \sin^2(\Delta m^2_{31} \tfrac{L}{4E}) + \sin^2\theta_{12} \sin^2(\Delta m^2_{32} \tfrac{L}{4E})$$

Nuclear Power Plant

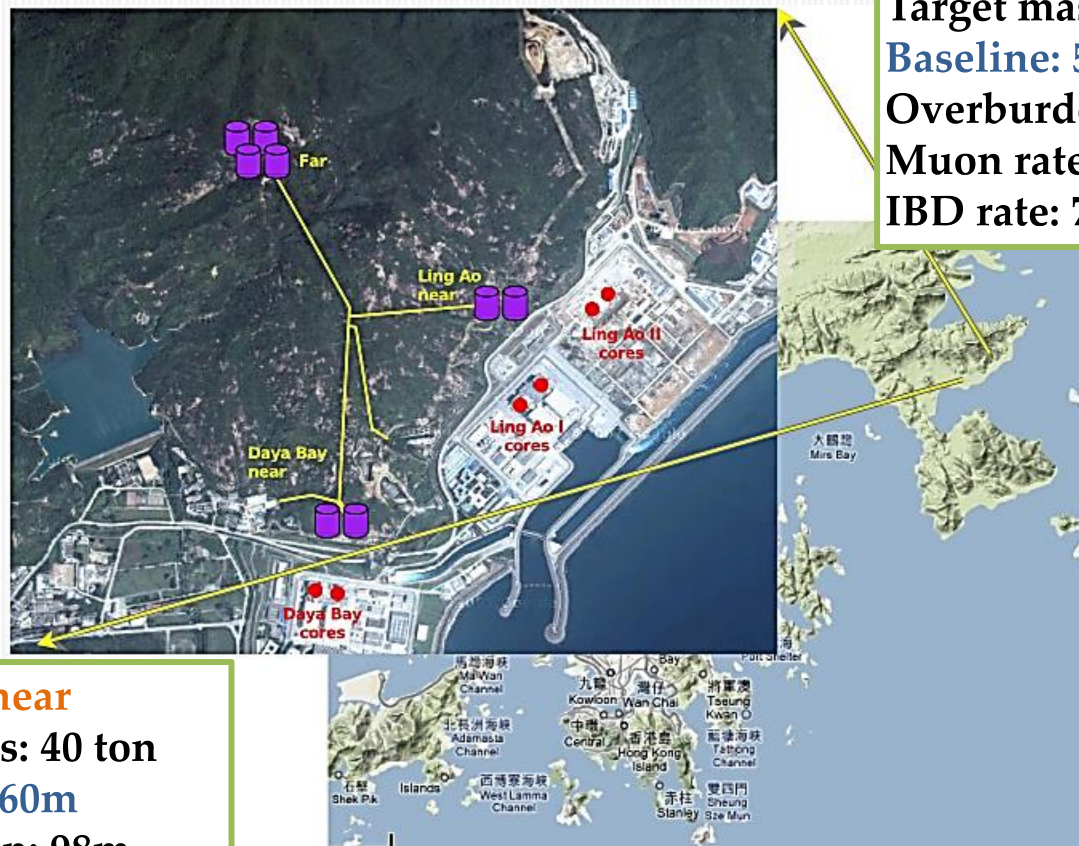
The total power $6 \times 2.9\ GW_{th}$.



Three Experimental Sites

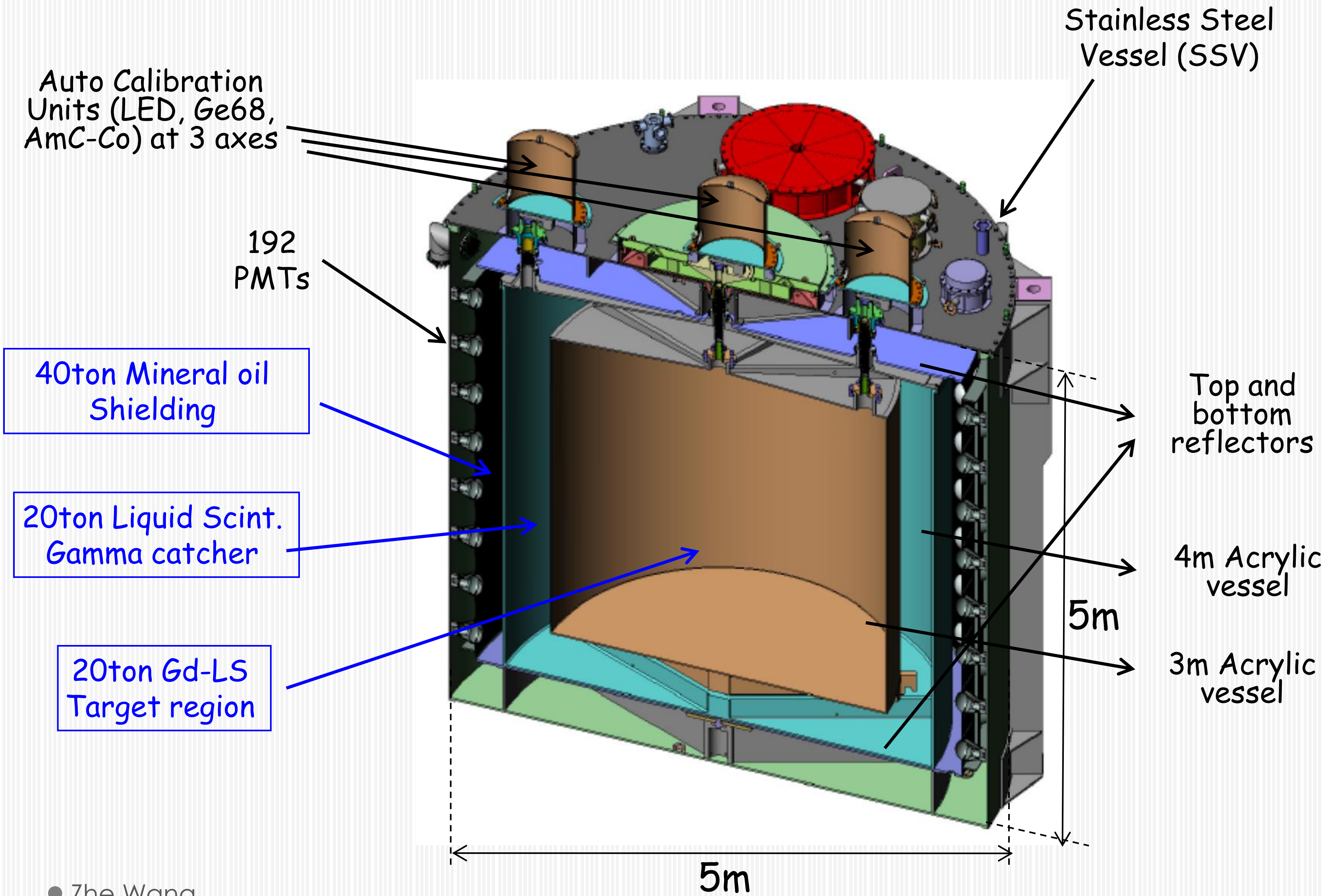
Far
Target mass: 80 ton
1600m to LA, 1900m to DYB
Overburden: 350m
Muon rate: 0.04Hz/m^2
IBD rate: 90/day/AD

Ling Ao near
Target mass: 40 ton
Baseline: 500m
Overburden: 112m
Muon rate: 0.73Hz/m^2
IBD rate: 740/day/AD

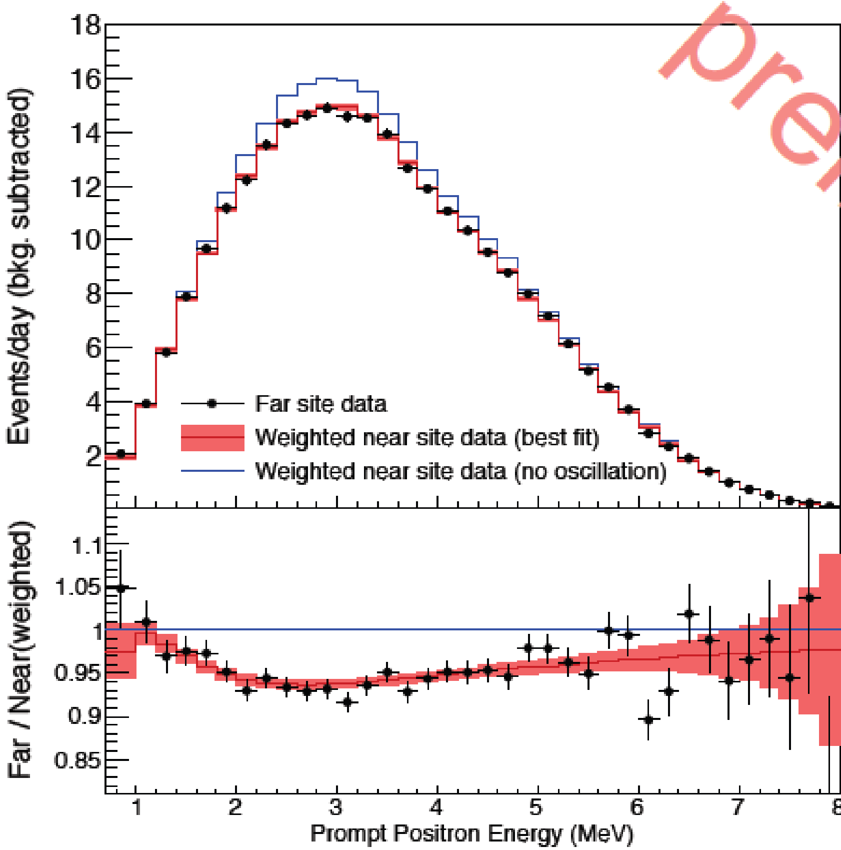


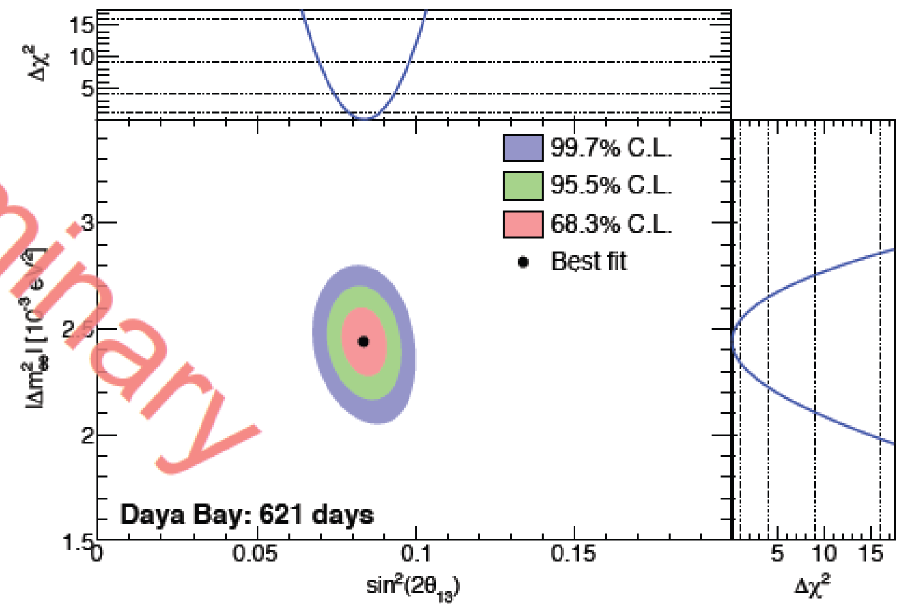
Daya Bay near
Target mass: 40 ton
Baseline: 360m
Overburden: 98m
Muon rate: 1.2Hz/m^2
IBD rate: 840/day/AD

Antineutrino Detector (AD)



θ_{13} Oscillation Analysis using n-Captures on Gd





$$\sin^2 2\theta_{13} = 0.084^{+0.005}_{-0.005}$$

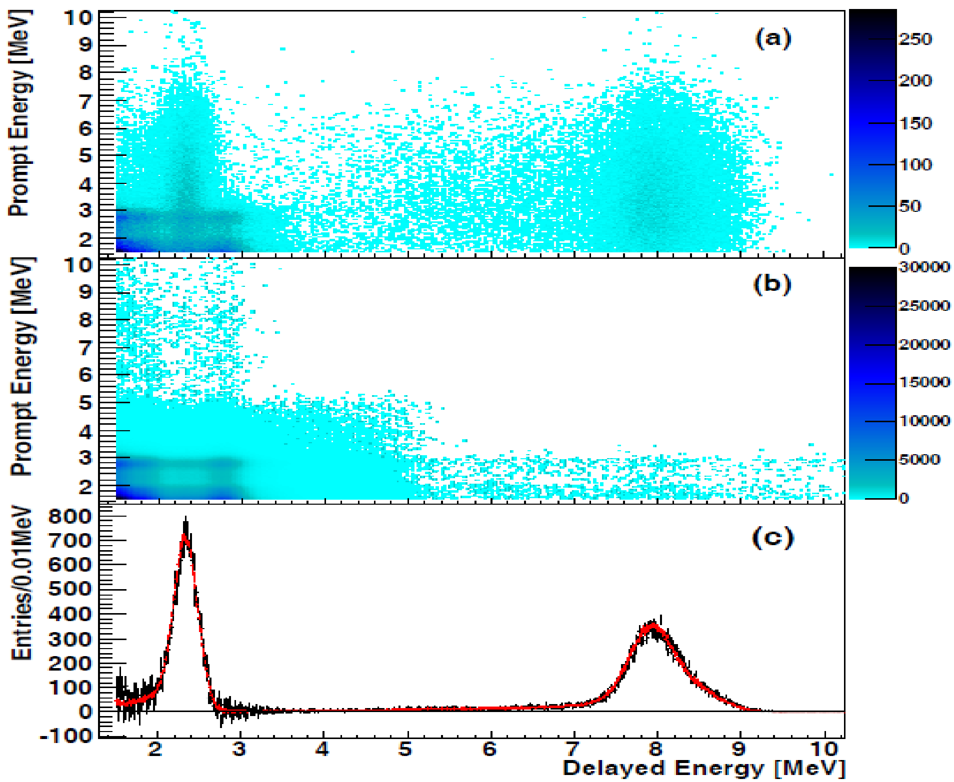
$$|\Delta m^2_{ee}| = 2.44^{+0.10}_{-0.11} \times 10^{-3}\mathrm{eV}^2$$

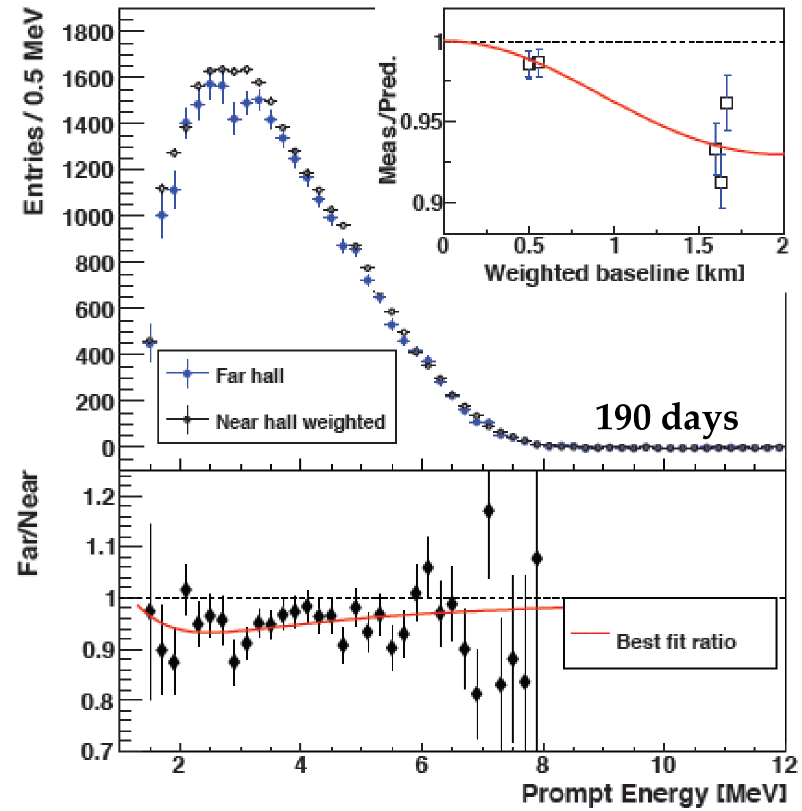
$$\chi^2/NDF = 134.7/146$$

- The far-site expected spectra are predicted based on the near-site observed spectra
- **The current analysis is designed to be (almost) independent of any reactor flux models**

- The most precise $\sin^2 2\theta_{13}$ measurement, ~6%
- The most precise Δm^2_{ee} measurement, comparable to long-baseline muon beam experiments

θ_{13} Oscillation Analysis using n-Captures on H





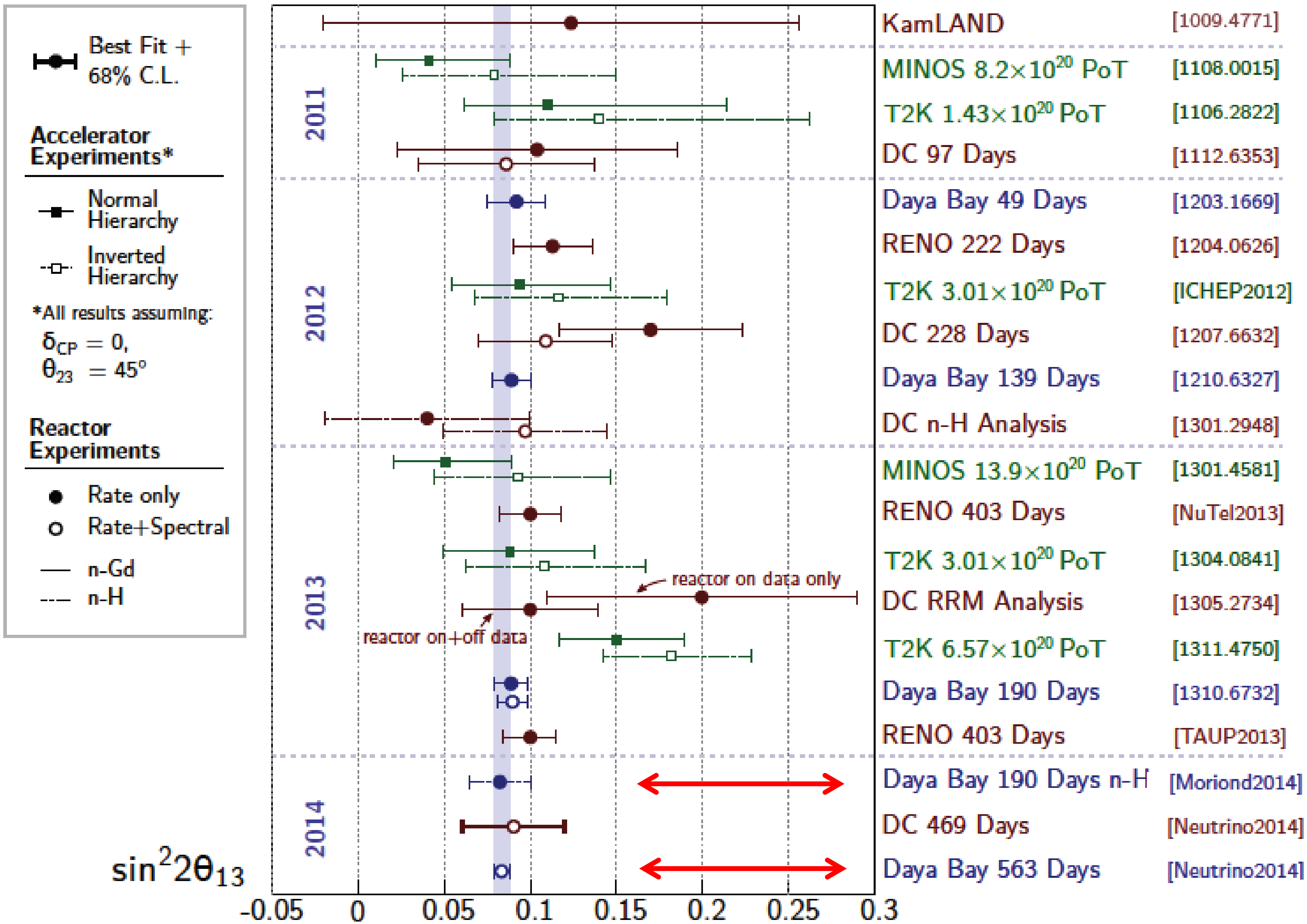
- nH IBD events have lower delayed energy and require longer correlation window thus the accidental rate is much higher, S/N~1 initially. Suppressed by
  - Higher prompt energy cut, >1.5MeV and prompt-delay distance cut <0.5m
  - Statistically subtracted by separation > 2m accidental event spectrum

$\sin^2 2\theta_{13} = 0.083 \pm 0.018$

➡ From the systematic perspective, nH samples are largely independent of nGd samples

➡ nH based analysis shows independently convincing θ_{13} driven oscillation

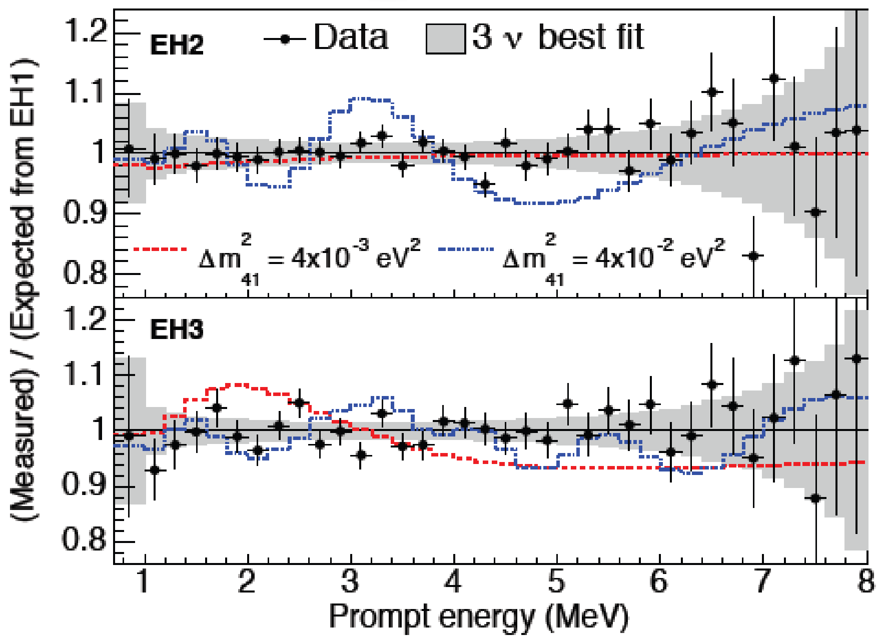
$\sin^2 2\theta_{13}$ Measurement Timeline



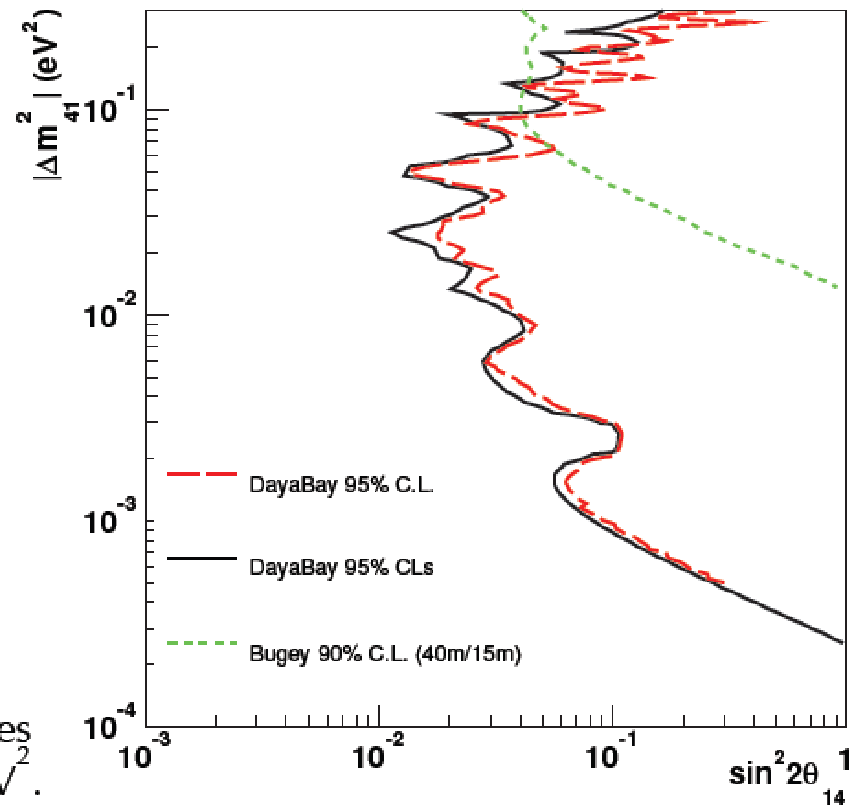
Sterile Neutrino Searches

$$P(\bar{\nu}_e \to \bar{\nu}_e) \simeq 1 - \cos^4\theta_{14}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{ee}L}{4E_\nu}\right) - \sin^2 2\theta_{14}\sin^2\left(\frac{\Delta m^2_{41}L}{4E_\nu}\right)$$

- Daya Bay baselines >350m ⇒ not as sensitive to mass-squared splittings greater than or around 1eV^2



dashed curves assumes $\sin^2 2\theta_{14} = 0.1$



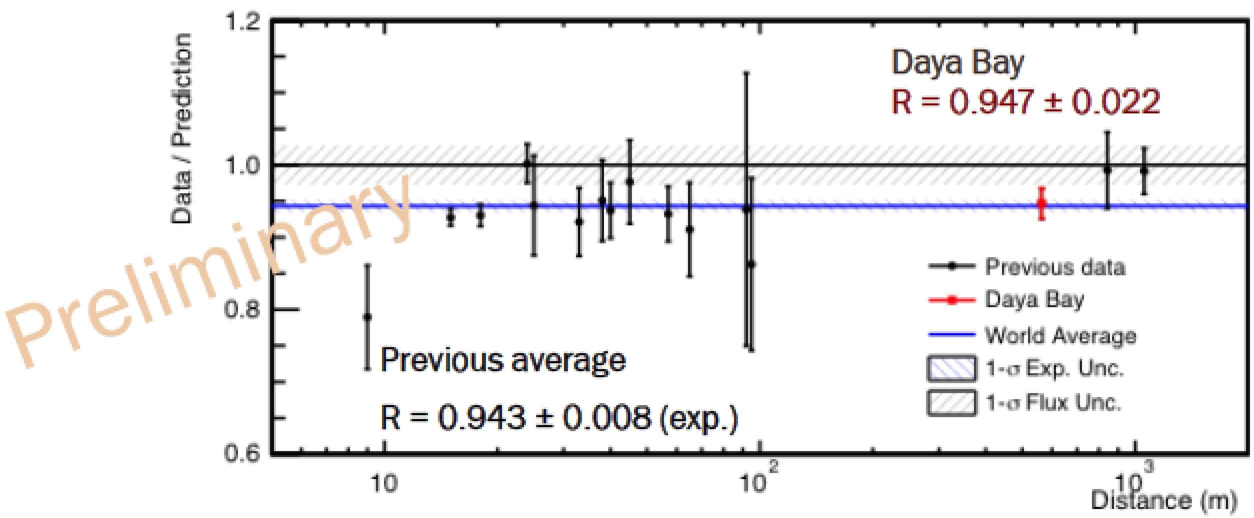
- Daya Bay has multiple baselines whose differences enabled searches in the range of Δm^2~0.01-0.1eV^2. Independent of reactor flux models

Best limit for sterile neutrinos in this range

Absolute Flux Measurement

Daya Bay's reactor antineutrino flux measurement is consistent with previous short baseline experiments.

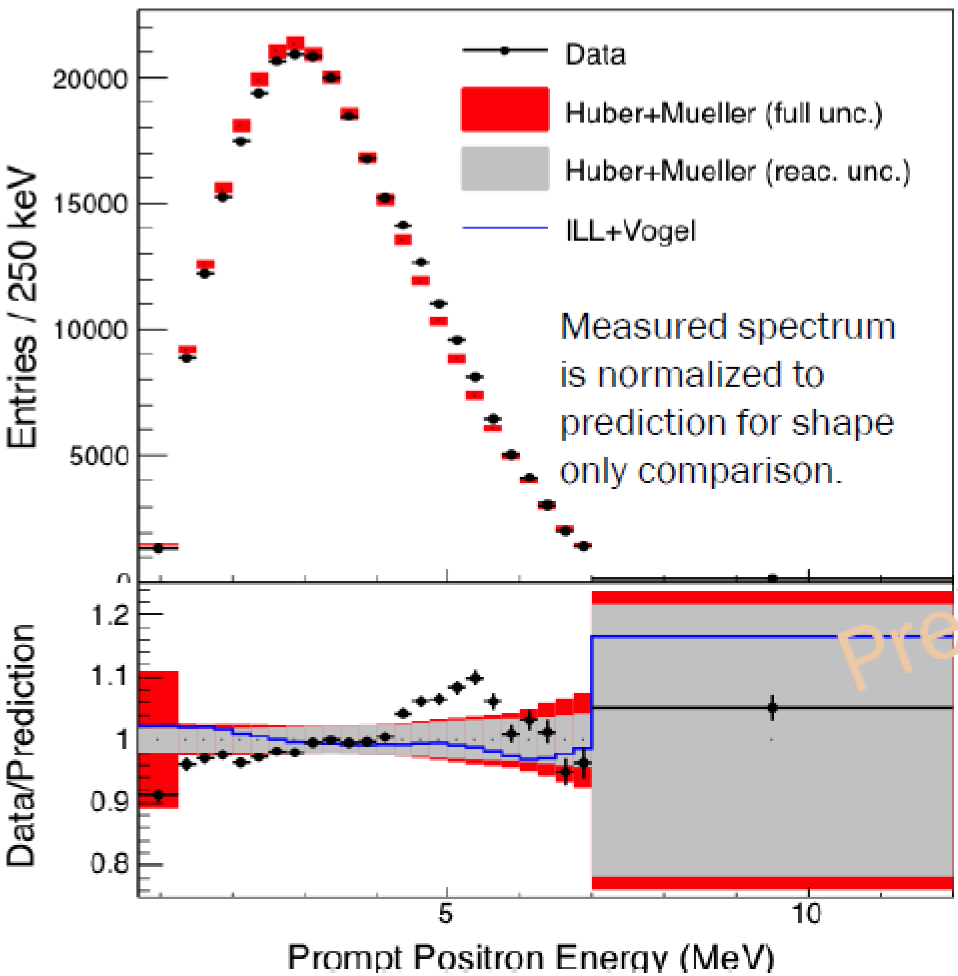
- Global comparison of measurement and prediction (Huber+Mueller):



- Effective baseline of Daya Bay: L_{eff} = 573m
  - Flux weighted detector-reactor distances of 3 ADs in near sites only.
- Effective fission fractions α_k of Daya Bay $^{235}U: ^{238}U: ^{239}Pu: ^{241}Pu$ = 0.586: 0.076: 0.288: 0.050
  - Mean fission fractions from 3 ADs in near sites only.

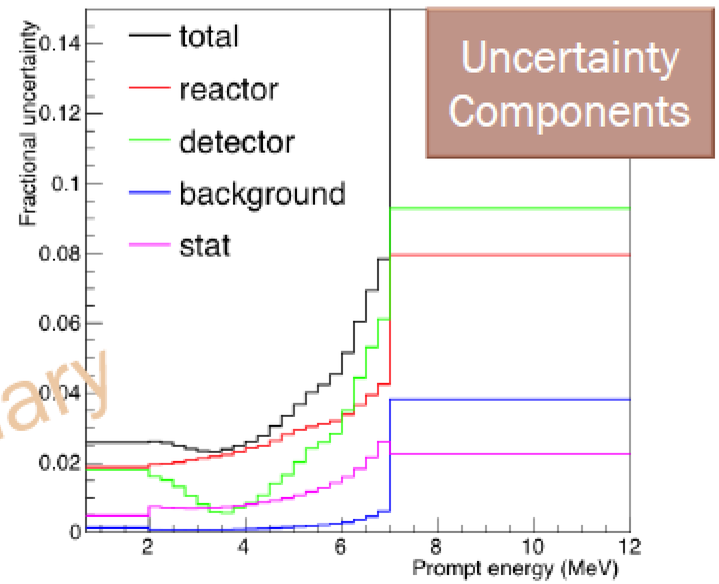
Absolute Positron Spectrum

- The measured positron spectra of IBD events in the three near Hall ADs are combined and compared with the prediction of the same combination.



$$\chi^2 = (N_i^{obs} - N_i^{pred}) V_{ij}^{-1} (N_j^{obs} - N_j^{pred})$$

$$V = V_{stat} + V_{reactor} + V_{detector} + V_{bkgs}$$



X^2/ndf (0.7 < E < 12 MeV)

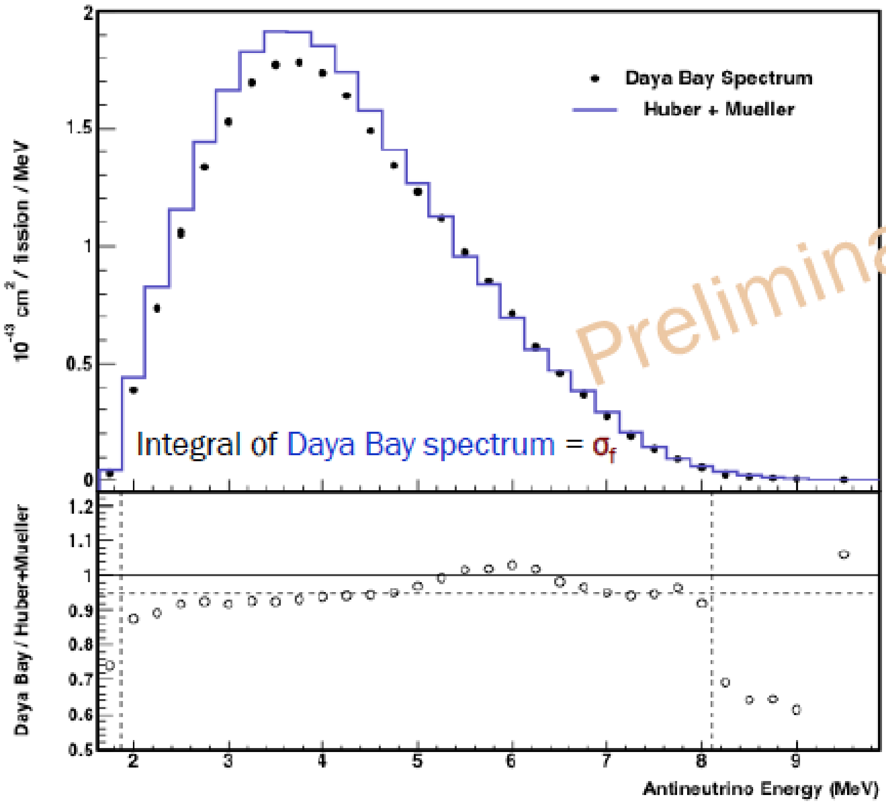
41.4/24

P-value = 0.015, 2.4σ

A question to reactor models

Observable Antineutrino Spectrum

- Extract a generic observable reactor antineutrino spectrum $S_{obs\_\nu}(E_\nu)$:
  - It supplies data outside [2, 8] MeV and could be used for flux and spectrum prediction.



Normalize the unfolded spectrum to *cm²/fission/MeV*.

$$S_{obs\_\bar{\nu}_e}(E_{\bar{\nu}_e}) = \frac{S_{unfolded}(E_{\bar{\nu}_e})}{P_{eff}(E_{\bar{\nu}_e}, L)\cdot N_p \cdot F_{total}}$$

where

N_p is proton number per unit target mass;

$P_{eff}(E_{\bar{\nu}_e}, L)$ is suvival probability of $\bar{\nu}_e$ weighted by flux;

F_{total} is total number of fissions of all reactors.

$$S_{pred\_\bar{\nu}_e}(E) = (\sum_k \alpha_k S_k(E) + c^{ne}(E) + SNF(E))\cdot \sigma_{IBD}(E)$$

where

α_k are the effective fission fractions of Daya Bay

- Compare Daya Bay spectrum $S_{obs\_\nu}(E_\nu)$ and Huber+Mueller Prediction $S_{pred\_\nu}(E_\nu)$:
  - Same rate deficit as flux measurement, and same shape deviation structure as in comparison of positron spectrum.

Summary

1. Oscillation analysis using n-captures on Gd with 563 days' data. Most precise measurement of $\sin^2 2\theta_{13}$, 6%
2. An independent oscillation analysis using n-captures on H with 190 days' data
3. Best limit for sterile neutrinos in Δm^2 of 0.001 – 0.1 eV^2
4. Absolute antineutrino flux measurement is consistent with previous short baseline experiments
5. The absolute positron spectrum measurement is not consistent (~2.4 σ) with prediction of different reactor antineutrino models.
6. A generic observable reactor antrineutrino spectrum is extracted.

Thank you.