Recent Progress from Daya Bay

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On behalf of the Daya Bay Collaboration

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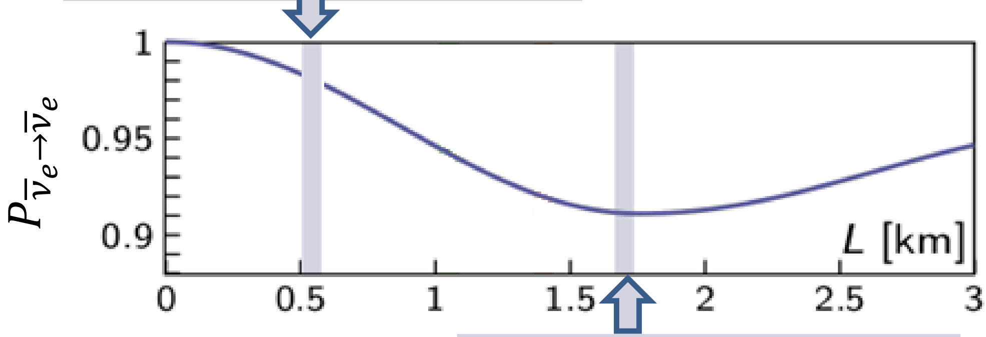
Daya Bay Experiment Layout

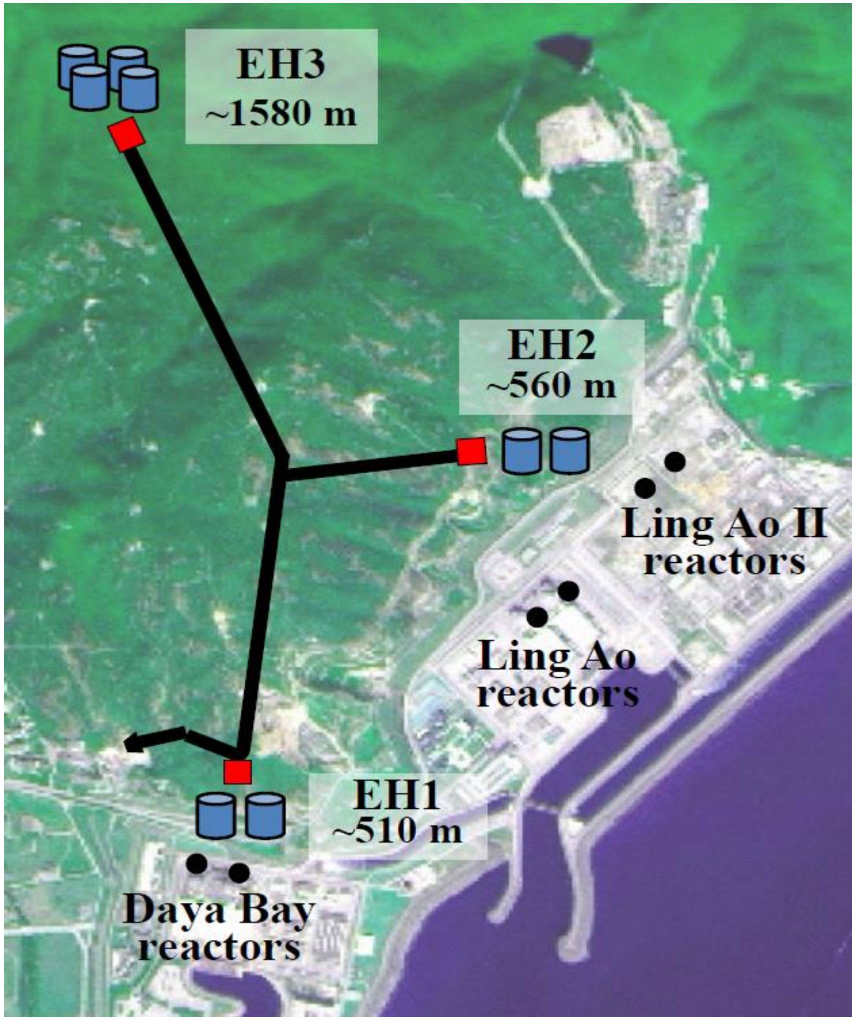
$\overline{\nu}_e$ from six 2.9 $\mathrm{GW_{th}}$ reactors are detected at two near and one far experiment sites

Near halls constrain reactor $\overline{\nu}_e$ flux

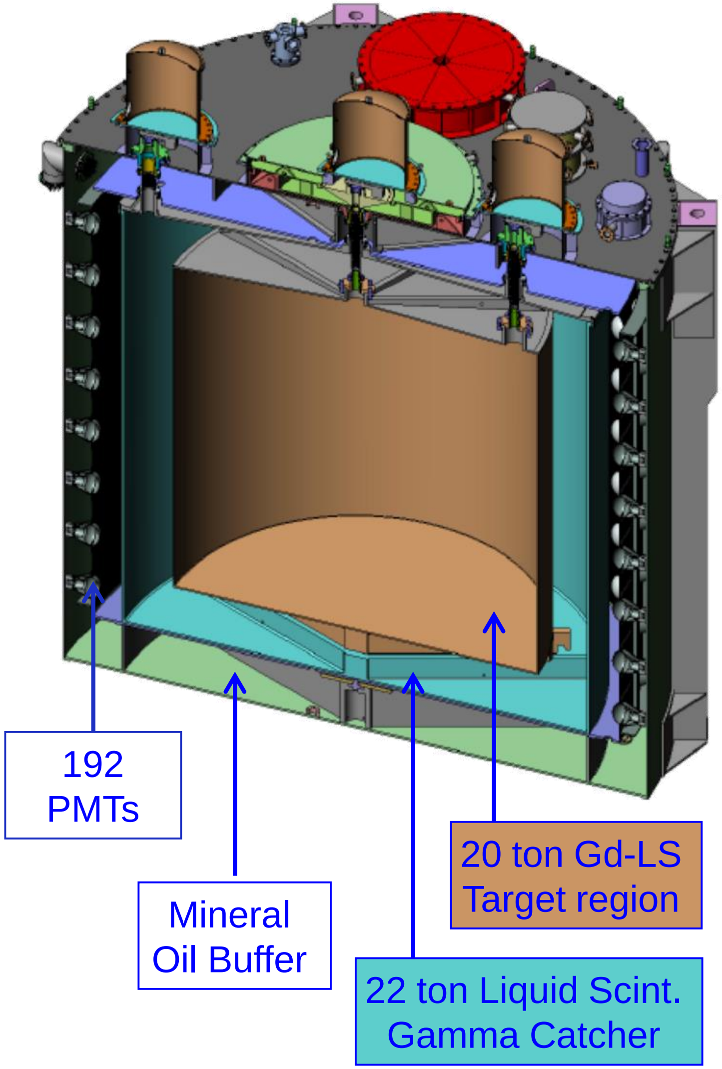


Far hall measures $\overline{\nu}_e$ disapperance

$$P_{\overline{\nu}_e\to\overline{\nu}_e} \sim 1-\sin^2 2\theta_{13}\sin^2\left(\Delta m^2_{ee}\frac{L}{4E}\right)$$



Antineutrino Detector (AD)



- Inner 20 ton gadolinium-doped liquid scintillator (Gd-LS) as the target
- Surrounding volume is 22 ton liquid scintillator (LS) to improve the efficiency of detecting gammas escaping the inner target
- Outer buffer volume of mineral oil to shield against radiation entering the LS.

Antineutrino Detection

Reactor $\overline{\nu}_e$ are detected via Inverse Beta Decay (IBD)

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

$$+H \rightarrow D + \gamma$$ 2.2 MeV, ~200 μs

$$+Gd \rightarrow Gd^* \rightarrow \gamma' s$$ ~8 MeV, ~30 μs

- **Prompt event:** e^+ deposits energy and annihilates
- **Delayed event:** n thermalizes and captured on H or Gd
- **Two IBD samples:** nH and nGd

Recent progess from Daya Bay

1. nGd shape analysis

   arXiv:1505.03456 [hep-ex]

   accepted by Phys. Rev. Lett.
   - 6+8 AD (621 days)
   - ***~4 times more statistics*** than our latest published results

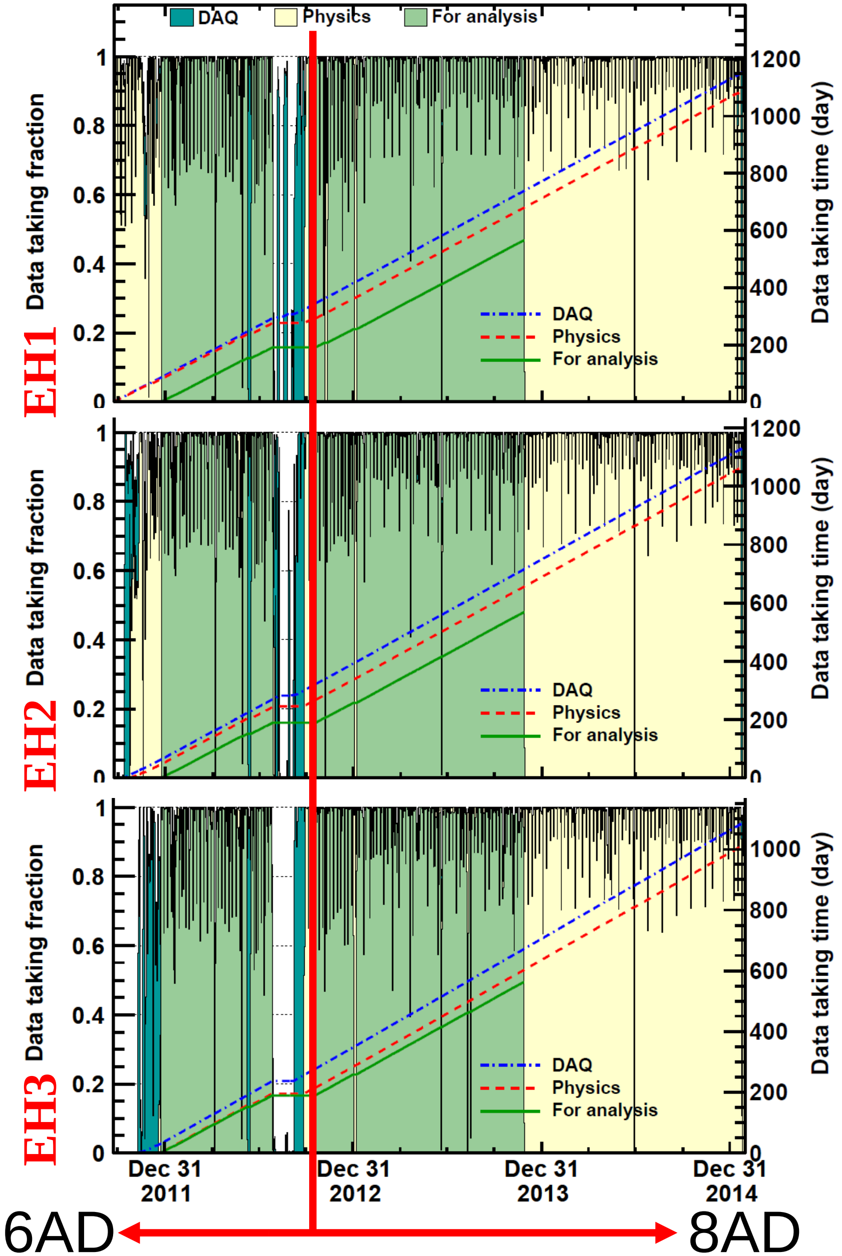
2. nH rate analysis

   Phys. Rev. D90, 071101(R) (2014)
   - 6AD (217 days)

3. Light sterile neutrino search

   Phys. Rev. Lett. 113, 141802 (2014)
   - 6AD (217 days)

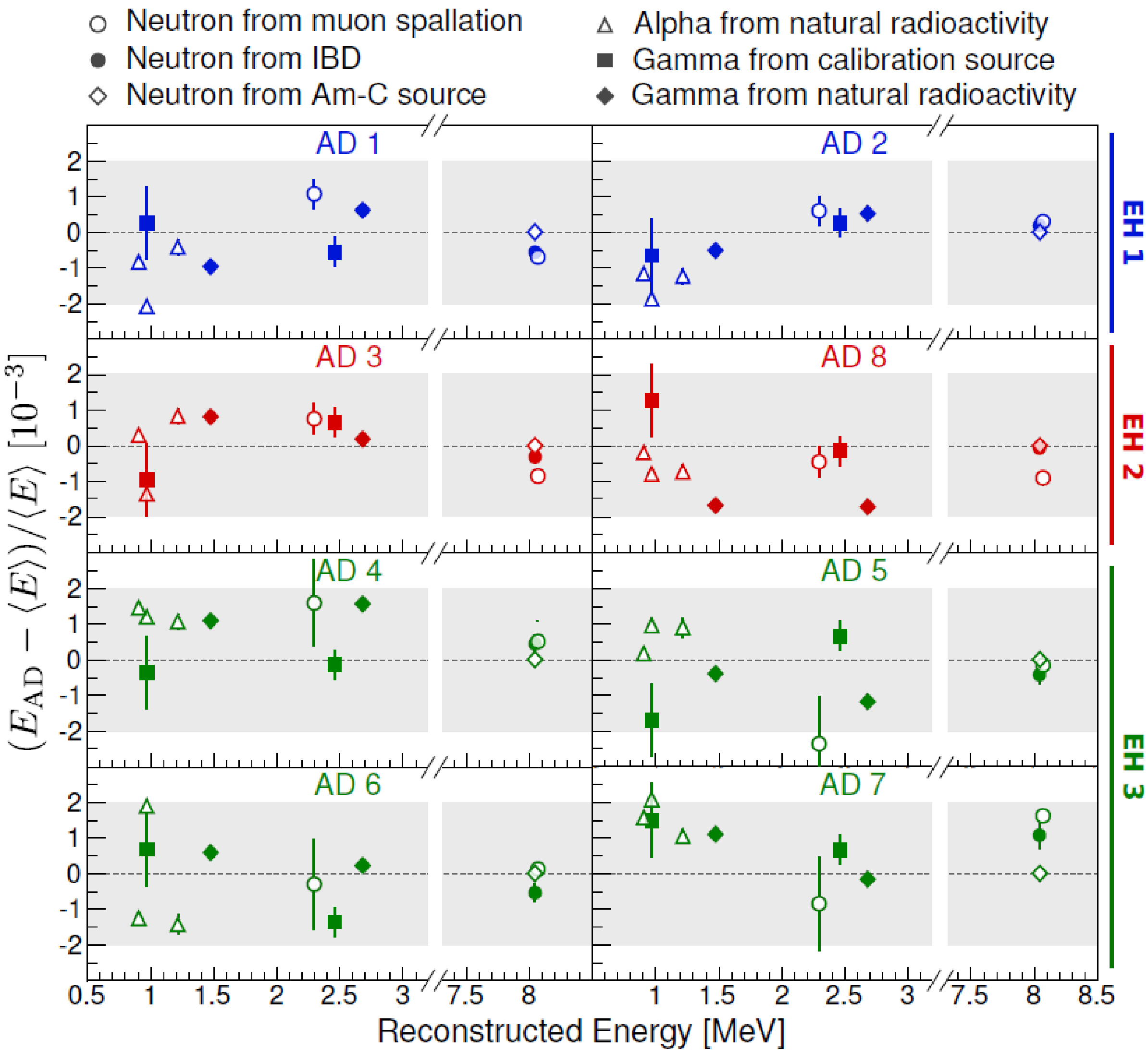
4. Reactor antineutrino flux and spectrum measurement
   - 6AD (217 days)



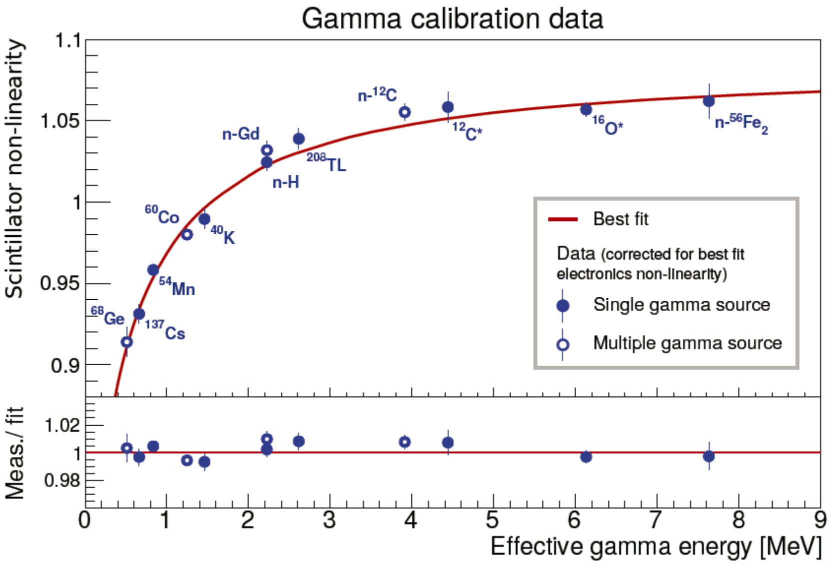
Energy Calibration

- Relative energy scale variations between detectors < 0.2% for the entire energy range

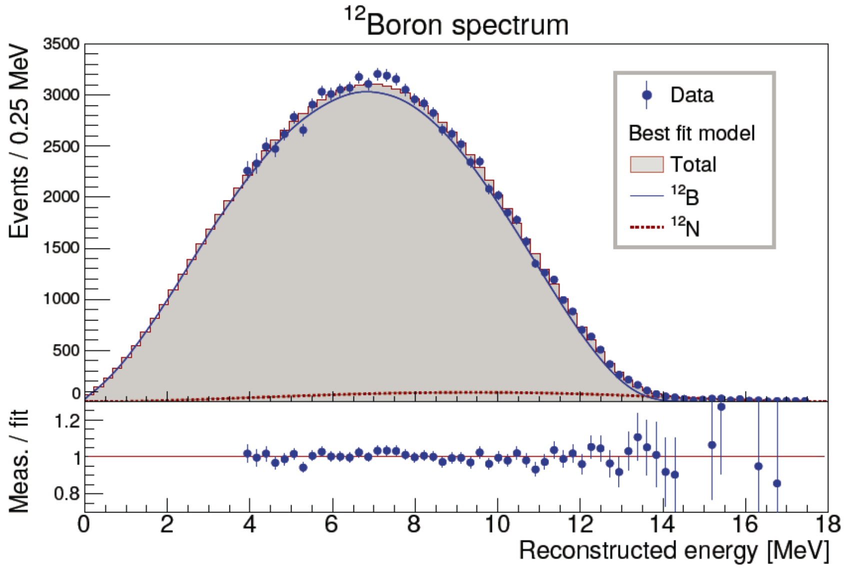
- 43% reduction wrt. our previous spectral analysis publication (*PRL 112, 061801 (2014)*)
  - By the improvements in the corretion of postion and time dependence of energy scale



Energy Non-linearity



Gamma calibration data

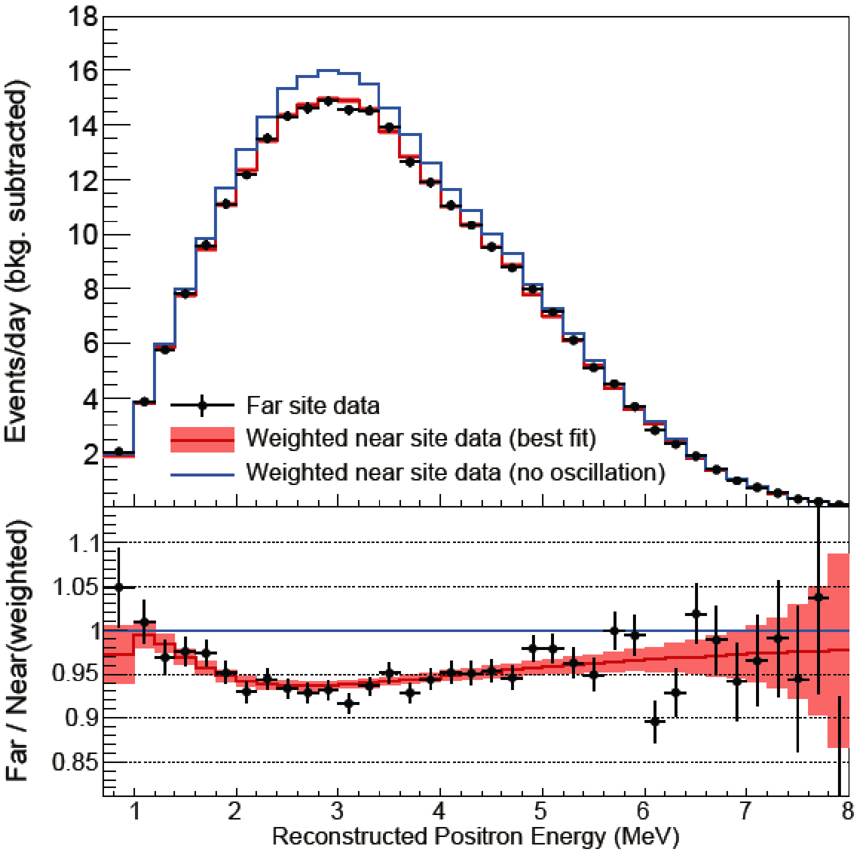


^{12}Boron spectrum

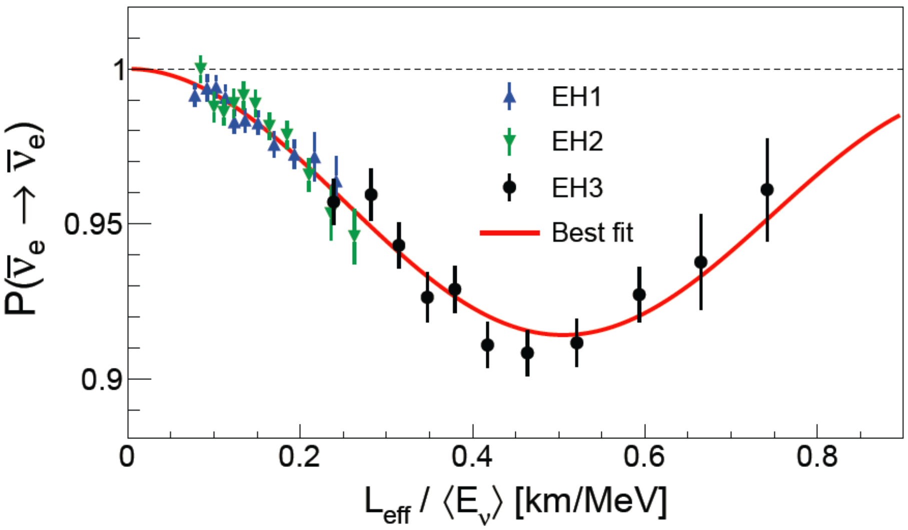
- Two primary sources of non-linearity
  - Scintillator response: scintillator quenching (Birks' law) and Cherenkov light
  - PMT readout electronics response

- Model constrained by fit to mono-energetic gamma peaks and ^{12}B beta-decay spectum

Oscillation Measurement



- Relative comparsion of near and far site data
- Data hightly consistent with oscillation interpretation

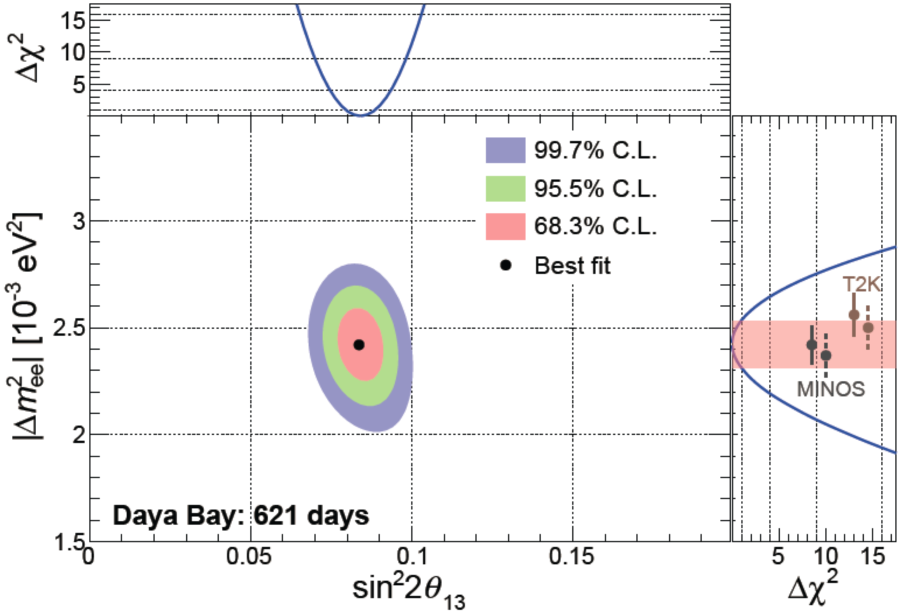


nGd Spectral Analysis Result

- Most presise measurement of $\sin^2 2\theta_{13}$ (6%)
- Measurement of effective mass splitting $|\Delta m^2_{ee}|$ reaches 4%
  - ○ Consistent with muon neutrino disappearance experiments
  - ○ Comparable precision

$$\sin^2 2\theta_{13} = 0.084 \pm 0.005$$

$$|\Delta m^2_{ee}| = (2.42 \pm 0.11) \times 10^{-3} \mathrm{eV}^2$$



arXiv:1505.03456 [hep-ex]

Accepted by Phys. Rev. Lett.

Independent Measurement of θ_{13} using nH

Features

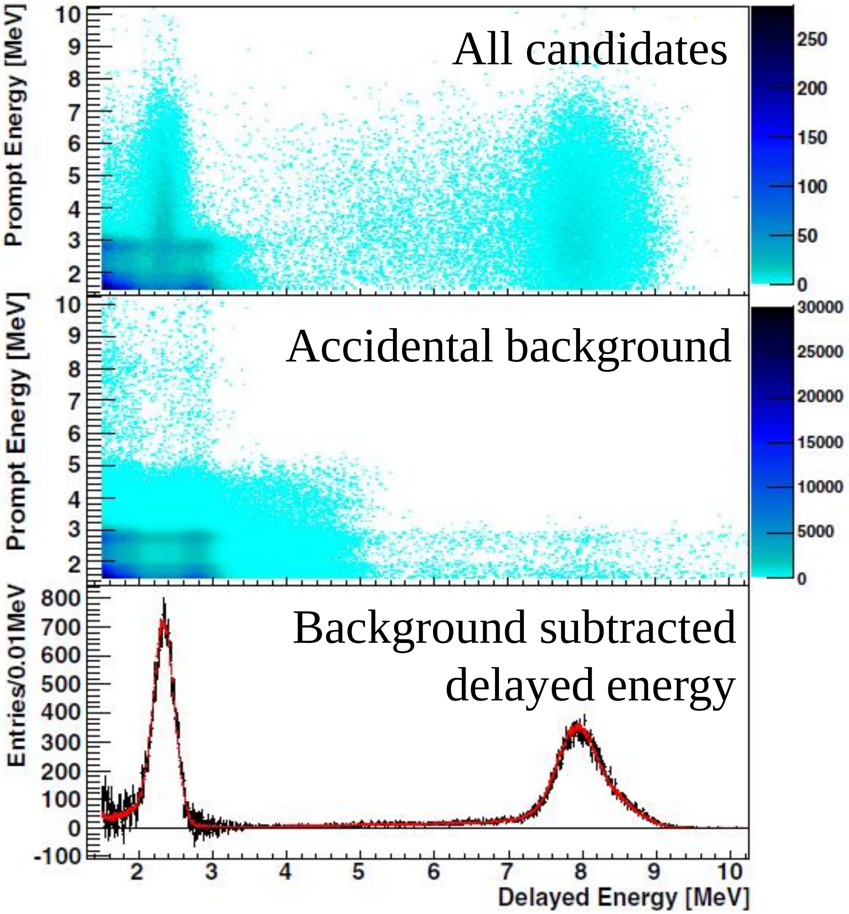
- Comparable statistics to the nGd sample
- Independent measurement: different systematic uncertainties from nGd analysis
- Technique applicable to future large scale experiments (e.g. JUNO)

Challenges

- Larger accidental background due to natural radioactivity
- Events concentrated in gamma catcher (LS)

Strategy

- Remove low-energy events (<1.5 MeV)
- Require prompt-delayed distance < 0.5 m
- Data-driven systematic measurements

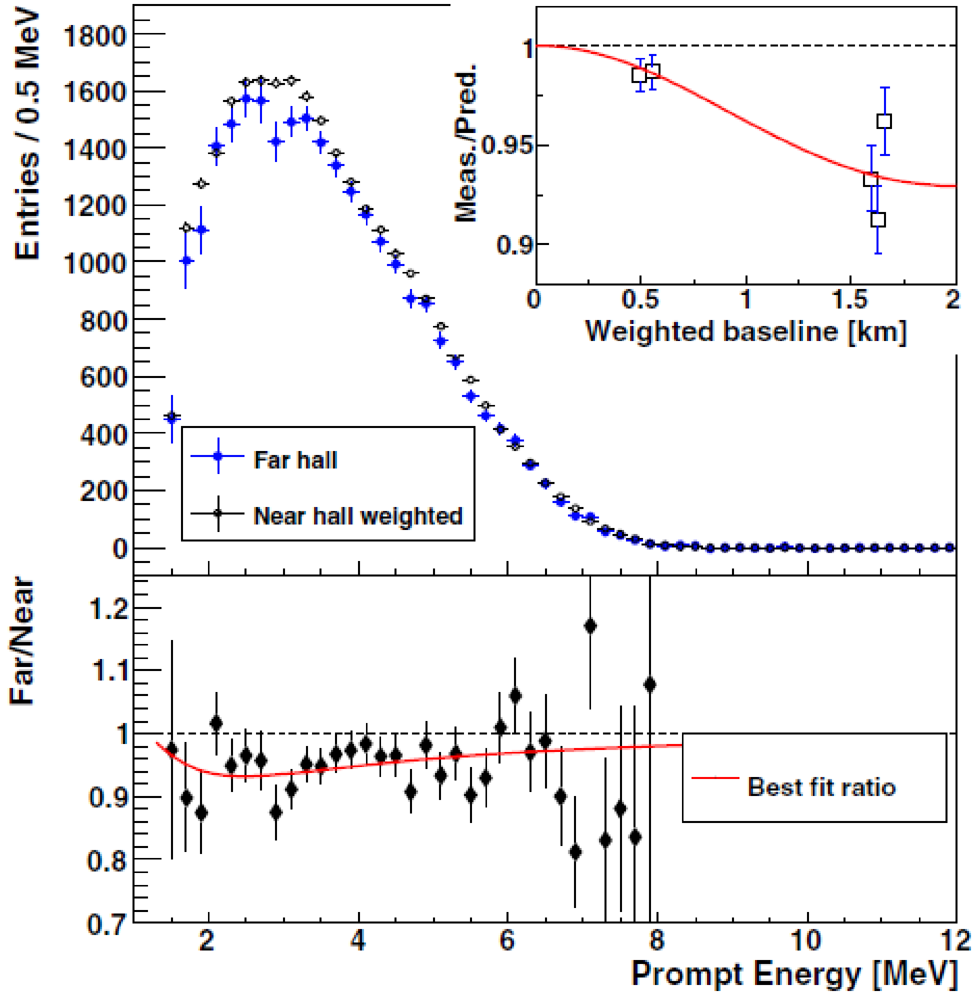


nH Analysis Result

- 217 days of 6AD data
- χ^2 fitting with pull terms, nH rate analysis gives

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

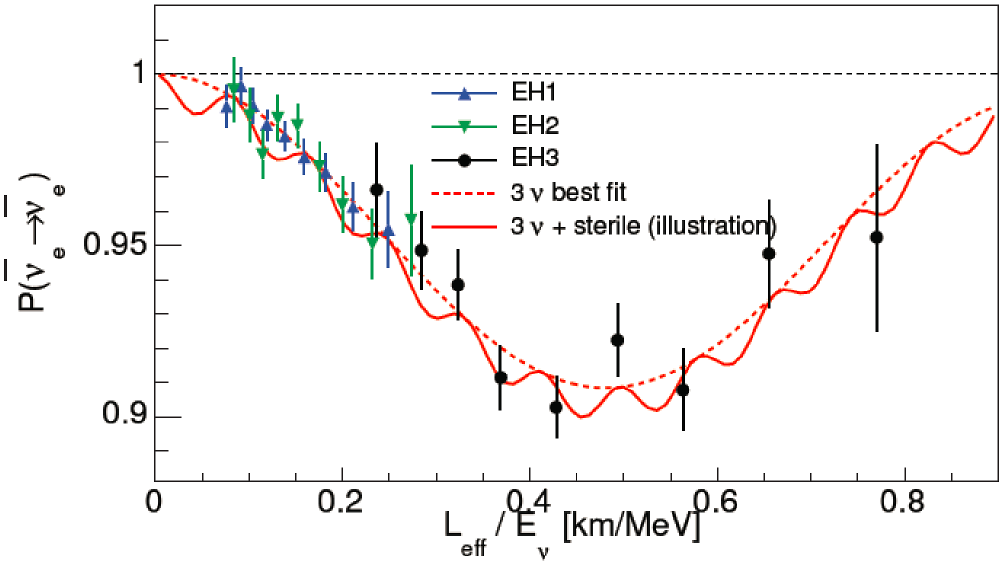
  with $\chi^2/\mathrm{ndf} = 4.5/4$
  - $\Delta\chi^2 = 20$ when θ_{13} is set to 0
- Consistent result with nGd analysis



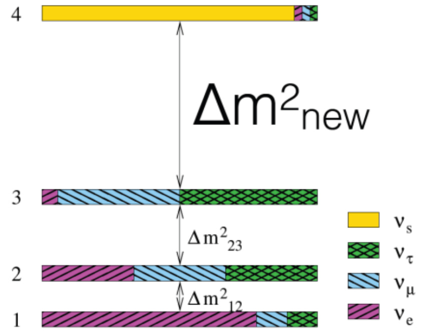
Phys. Rev. D90, 071101(R) (2014)

Search for Light Sterile Neutrino

- A unique opportunity for sterile neturino searches
  - Light sterile neutrinos could introduce additional mode of oscillation
  - Relative measurement at multiple baselines (EH1/2/3)



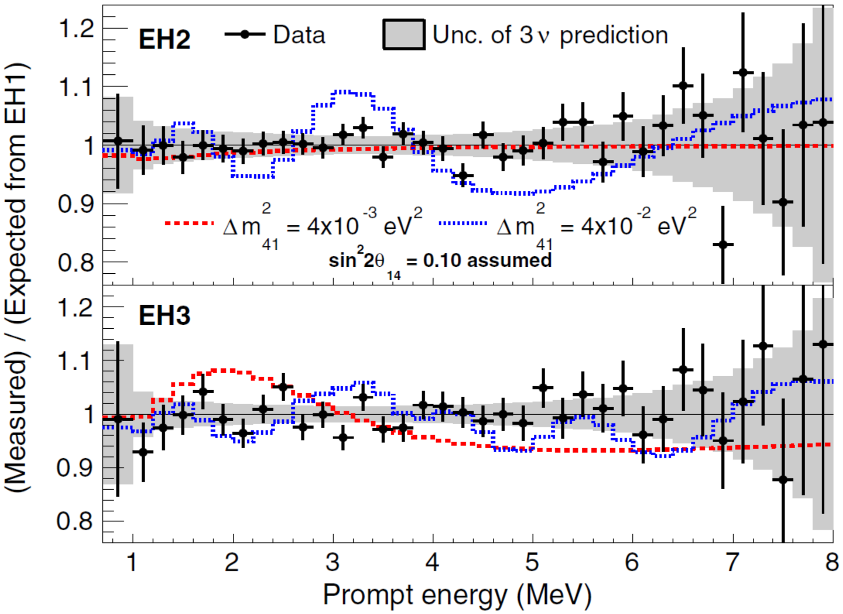
“3+1 model”

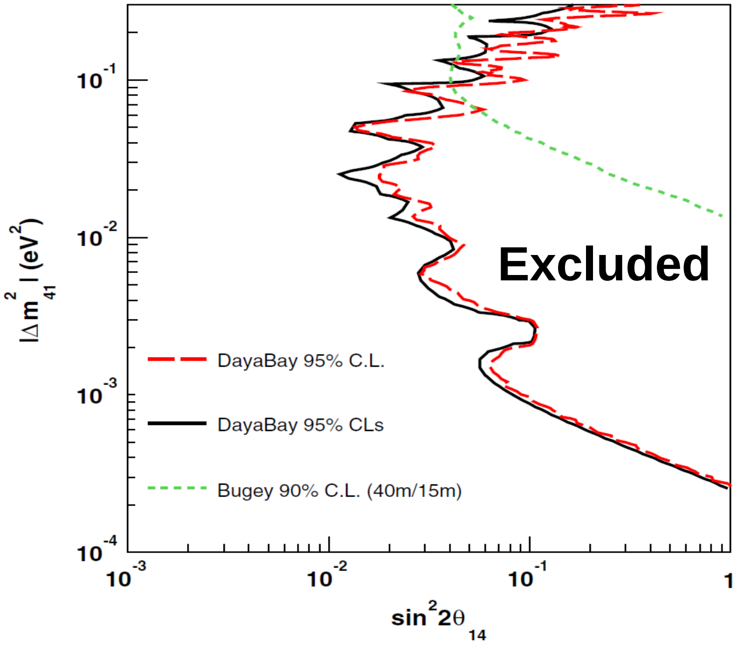


$$P(\bar{\nu}_e \to \bar{\nu}_e) \simeq 1 - \cos^4\theta_{14}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{ee}L}{4E_\nu}\right)$$

$$-\boxed{\sin^2 2\theta_{14}}\sin^2\left(\frac{\boxed{\Delta m^2_{41}}L}{4E_\nu}\right)$$

Sterile Neutrino Search Result



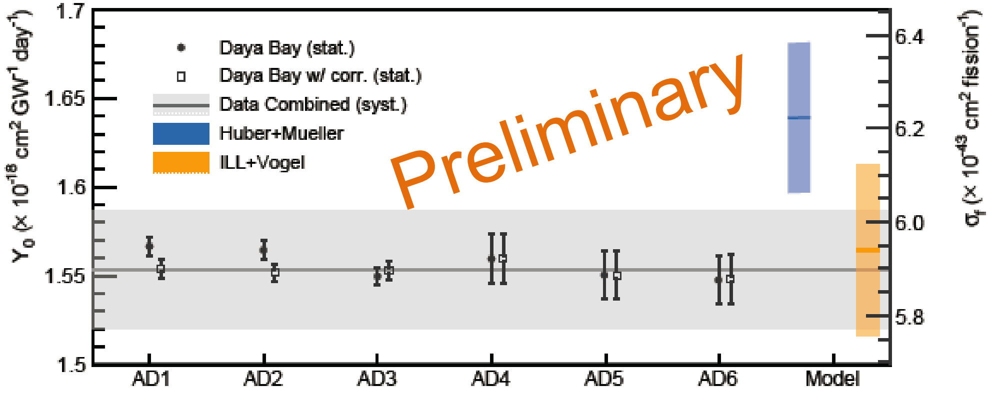


- No significant signal observed, consistent with 3-neutrino model
- Set most stringent limits on $\sin^2 2\theta_{14}$ at $\left|m^2_{41}\right| < 0.1\ \mathrm{eV}^2$

Phys. Rev. Lett. 113, 141802 (2014)

Reactor Antinuetrino Flux and Spectrum

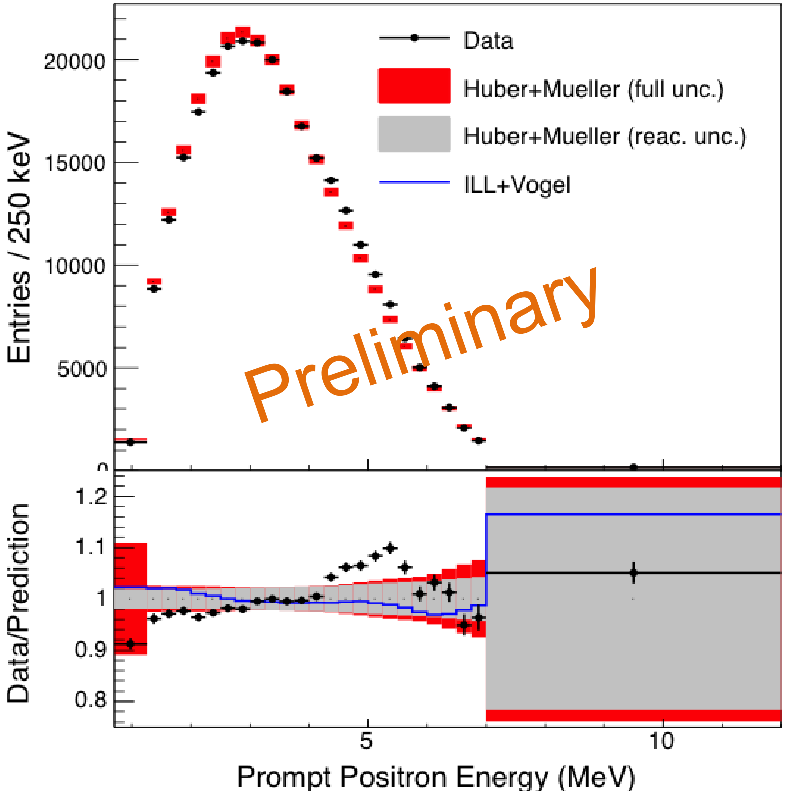
Flux



- Consistent with previous short baseline experiments
- Measured IBD rate / predicted
  - 0.947 ± 0.022 (Huber+Mueller)
  - 0.992 ± 0.023 (ILL+Vogel)

Publication in Preparation

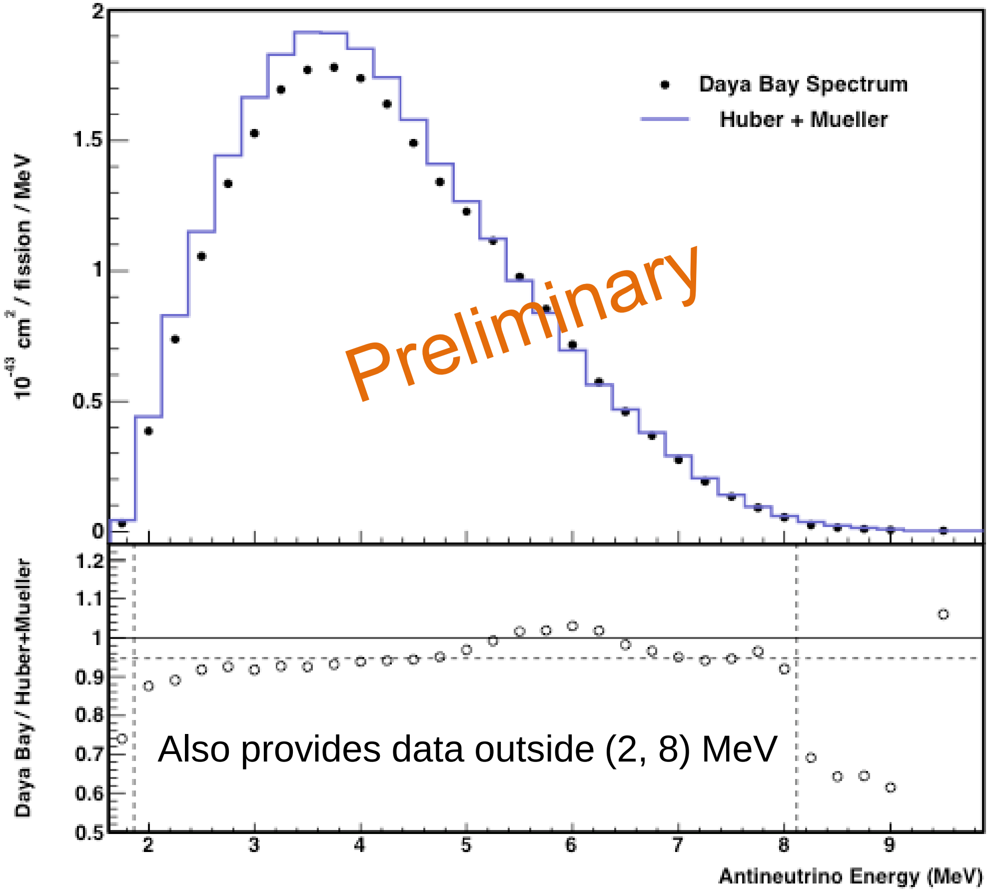
Spectrum



- Spectral shape is not consistent with models, especially between 4-6 MeV.

Reactor Antinuetrino Flux and Spectrum

- A reactor $\overline{\nu}_e$ spectrum [cm^2/fission/MeV] is extracted from the measured prompt-energy spectrum
- Enables model-independent predictions of reactor $\overline{\nu}_e$ spectra.



Also provides data outside (2, 8) MeV

Summary

- nGd spectral analysis results with 621 days of 6+8AD data

$$\sin^2 2\theta_{13} = 0.084 \pm 0.005$$

$$|\Delta m^2_{ee}| = (2.42 \pm 0.11) \times 10^{-3} \mathrm{eV}^2$$

- Independent measurement using nH with 217 days of 6AD data

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

- Most stringent limits on sterile neutrino for $\left|m^2_{41}\right| < 0.1\ \mathrm{eV}^2$
- Precision measurement of reactor antinuetirno flux and spectrum
- More results coming soon

Thank you！

Three Neutrino Oscillation: PMNS Matrix

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U_{\alpha,i}\,|\nu_i\rangle$$

How they interact

How they propagate

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

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

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