Recent results from Daya Bay

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On behalf of the Daya Bay collaboration

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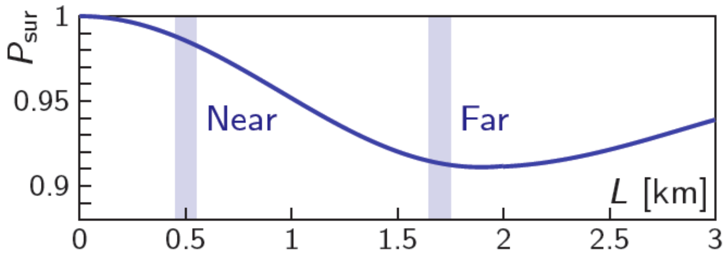
Daya Bay experiment

- Disappearance of reactor antineutrino: $\bar{\nu}_e \rightarrow \bar{\nu}_e$

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

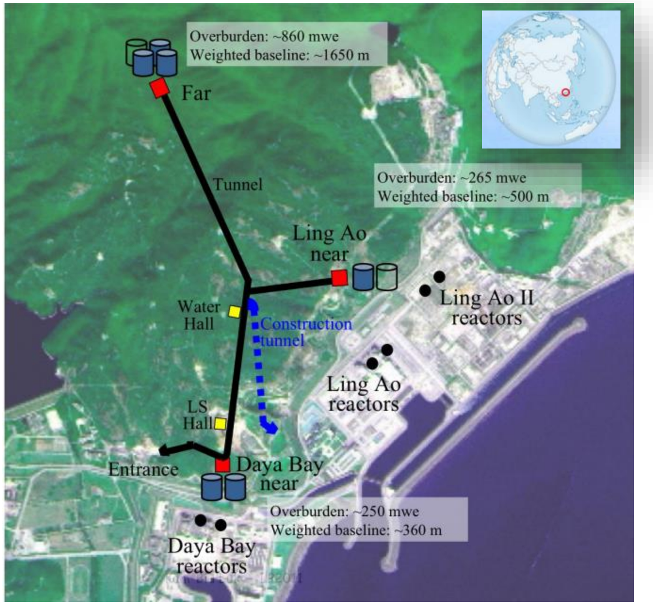


$$\sin^2\Delta_{ee} \equiv \cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}$$

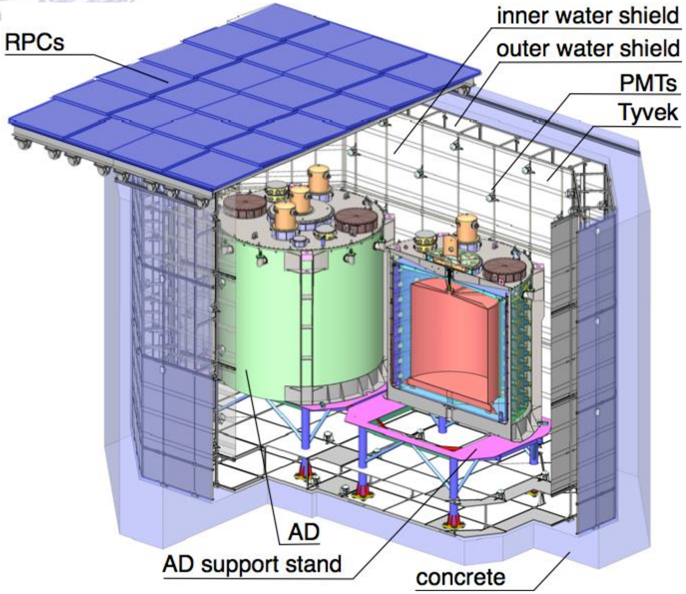
$$\Delta_{ji} \equiv 1.267\Delta m^2_{ji}(\mathrm{eV}^2)[L(\mathrm{m})/E(\mathrm{MeV})]$$

Only valid for short baseline

- Latest θ_{13} result with the full detector configuration, *arXiv:1505.03456*
- Measurement of reactor antineutrino flux and spectrum, *paper in preparation*
- Independent θ_{13} measurement with nH, *PRD 90, 071101(R) (2014)*
- Search for light sterile neutrinos, *PRL 113, 141802 (2014)*

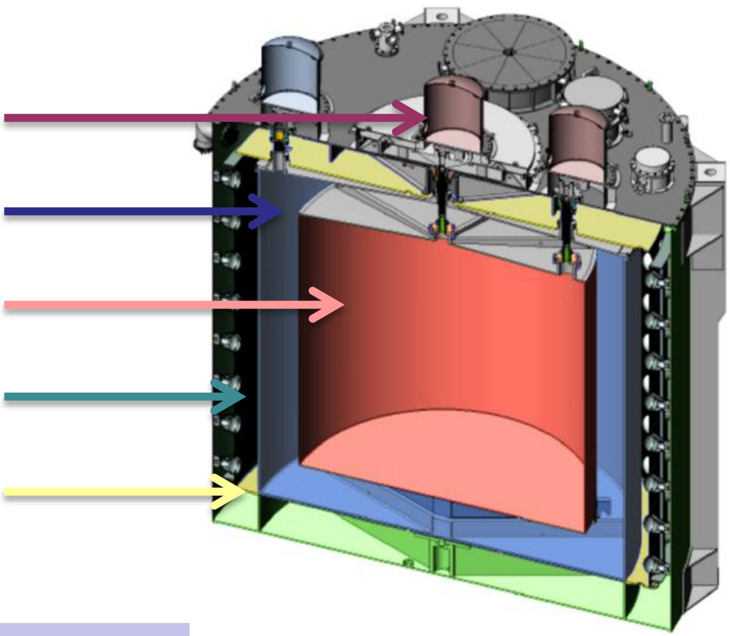


Daya Bay detectors

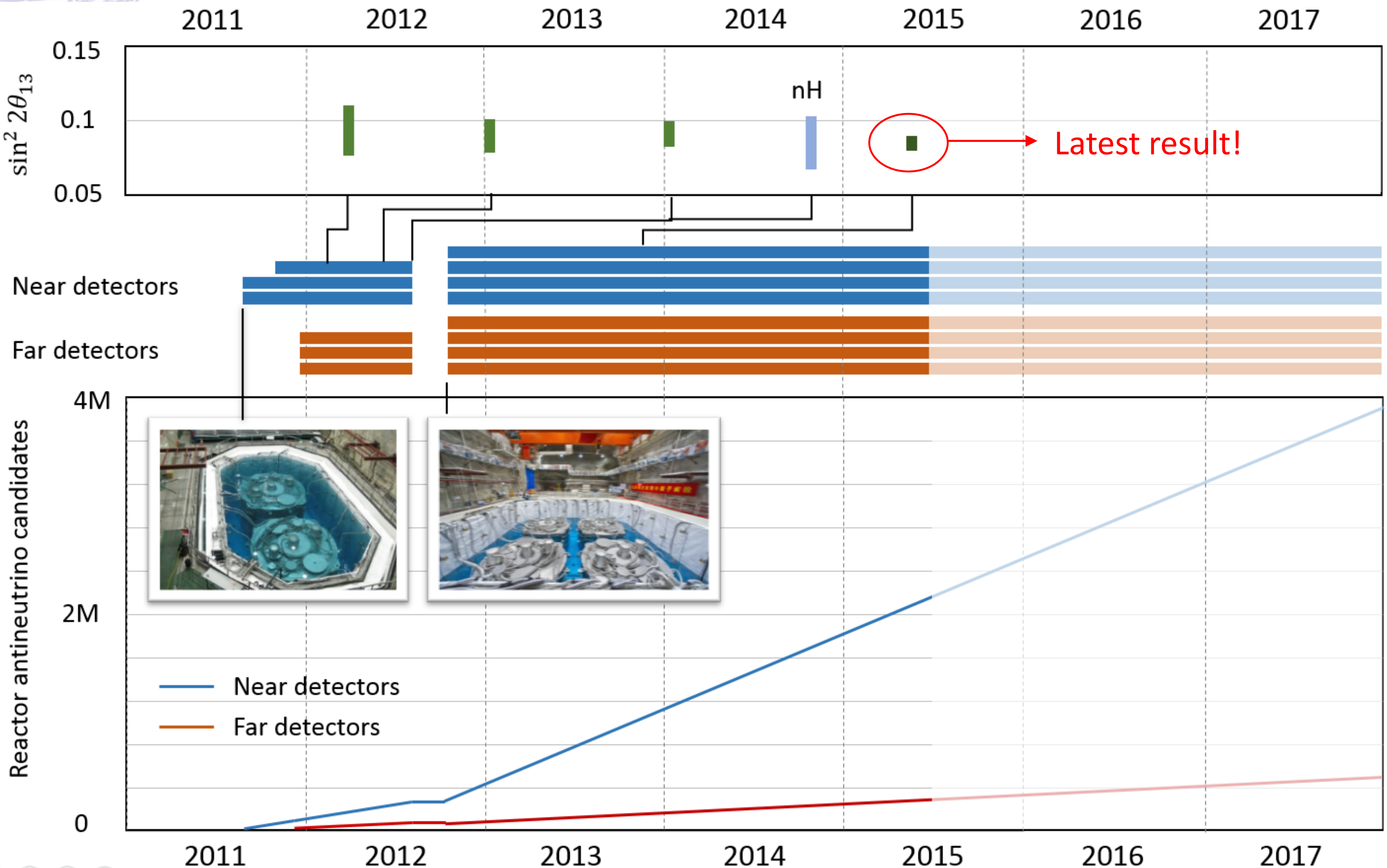


- 8 functionally identical antineutrino detector (AD) modules to reduce uncorrelated systematic uncertainties
- 3 independent detectors (RPC+IWS+OWS) form muon veto system at each site

- Calibration units
- Liquid scintillator
- Gd-doped liquid scintillator
- Mineral oil
- Top and bottom reflectors

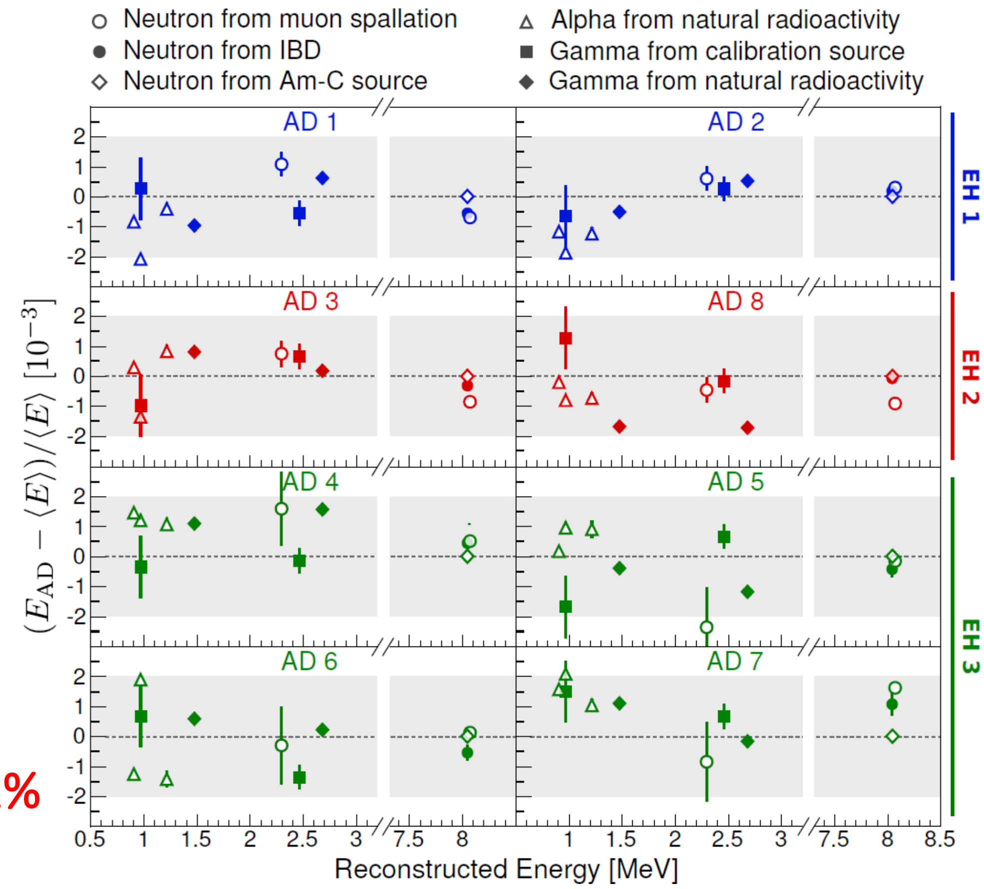


Operation history



Energy calibration

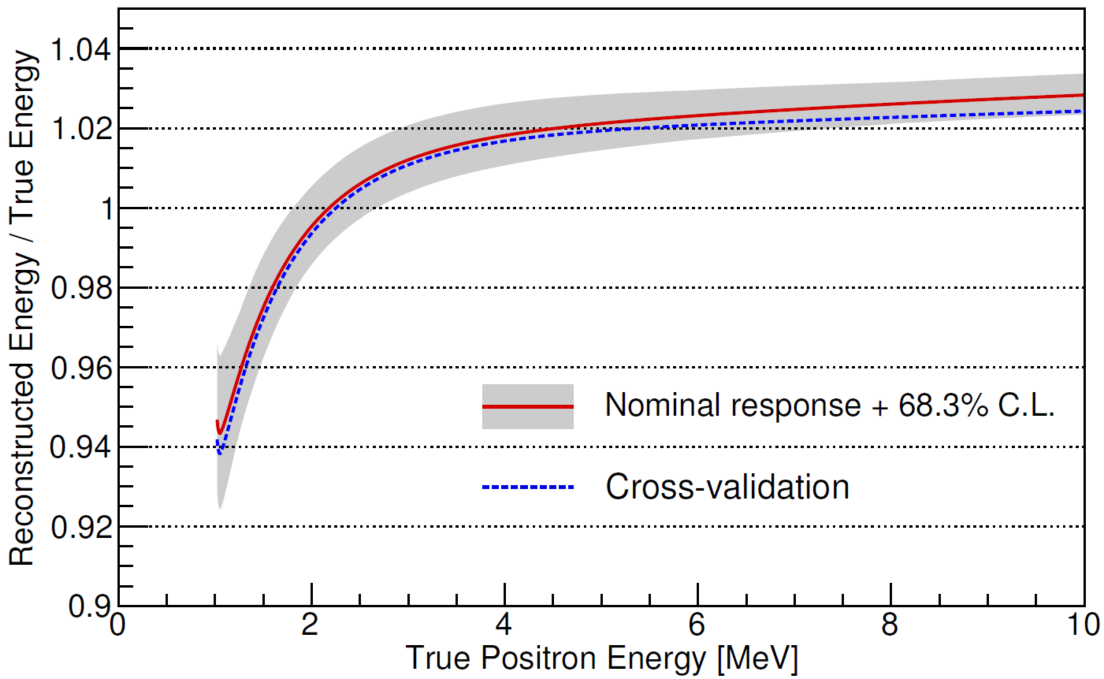
- **PMT gain**:
  Single electrons from photocathode
- **Absolute energy scale**:
  AmC at detector center
- **Time variation**:
  ^{60}Co at detector center
- **Non-uniformity**:
  ^{60}Co at different positions
- **Alternative calibration**:
  nGd from muon spallation

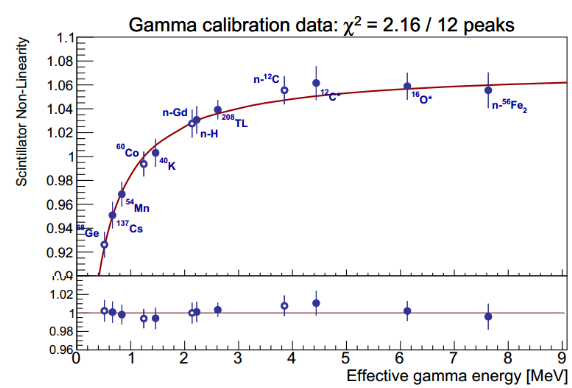


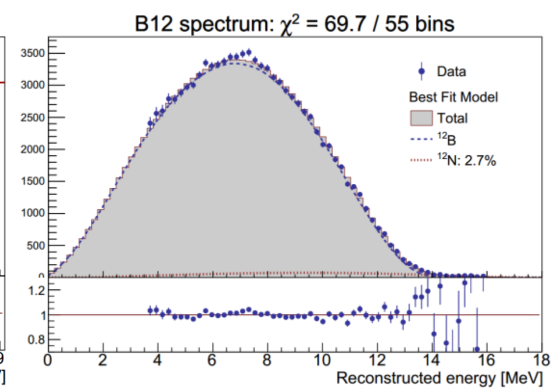
- **Relative energy scale uncertainty**: 0.2%
  - ^{68}Ge, ^{60}Co, AmC: detector center
  - nGd from IBD and muon spallation: Gd-LS region
  - α from polonium decay: Gd-LS vertex cut
  - ^{40}K, ^{208}Tl, nH: 1m vertex cut

Detector energy response model

- **Scintillator nonlinearity** : modeled based on Birks' law and Cherenkov fraction
- **Electronics nonlinearity**: modeled based on MC and single channel FADC measurement
- Nominal model: fit to mono-energetic gamma lines and ^{12}B beta-decay spectrum
- Cross-validation model: fit to ^{208}Th, ^{212}Bi, ^{214}Bi beta-decay spectrum, Michel electron
- Uncertainty <1% above 2MeV

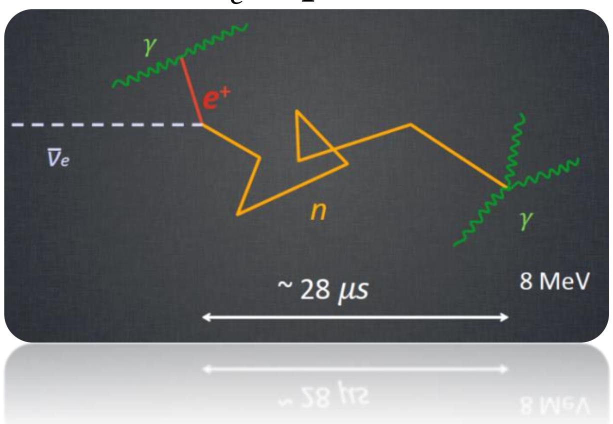




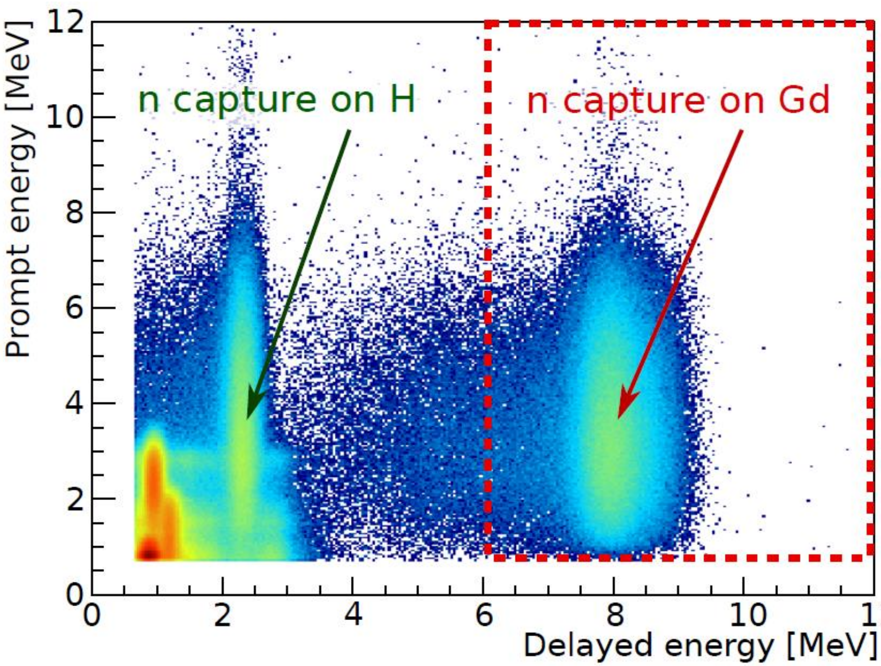


Antineutrino candidates selection

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



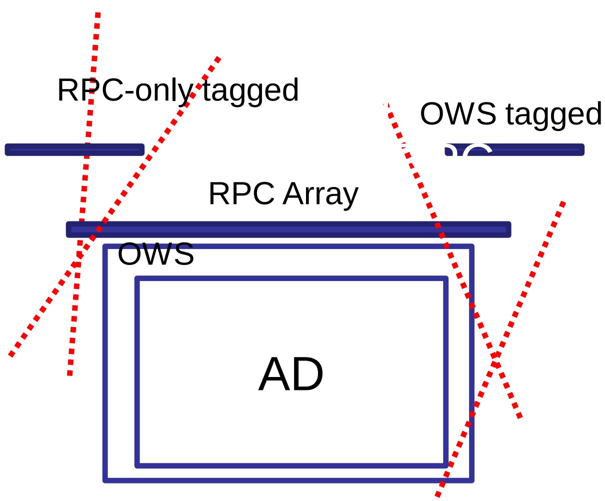
- Reject PMT flashers
- **Coincidence** in energy and time with multiplicity=2
  - **Energy**: 0.7 MeV < Ep < 12.0 MeV, 6.0 MeV < Ed < 12.0 MeV
  - **Time**: 1 μs < $\Delta t_{p\text{-}d}$ < 200 μs
- Muon **anticoincidence**
  - Water pool muon: reject 0.6 ms
  - AD muon (>20 MeV): reject 1 ms
  - AD shower muon (>2.5 GeV): reject 1 s

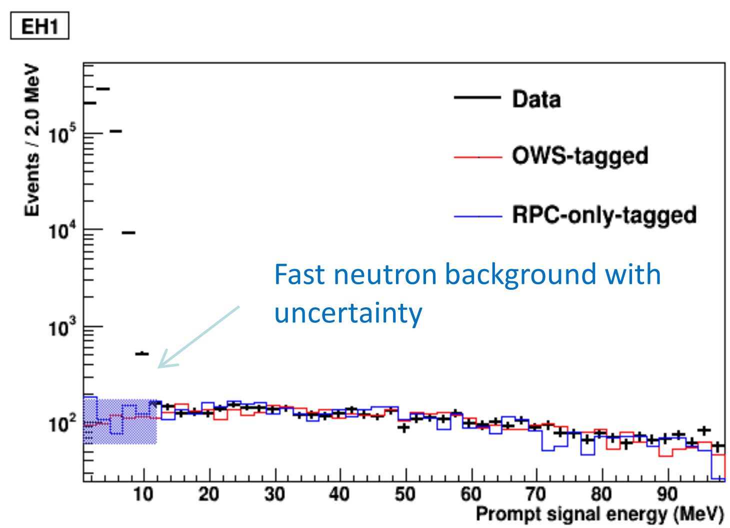


	Efficiency	Correlated Uncertainty	Uncorrelated Uncertainty
Target protons		0.47%	0.03%
Flasher cut	99.98%	0.01%	0.01%
Delayed energy cut	92.7%	0.97%	0.12%
Prompt energy cut	99.81%	0.10%	0.01%
Capture time cut	98.70%	0.12%	0.01%
Gd capture ratio	84.2%	0.95%	0.10%
Spill-in correction	104.9%	1.50%	0.02%
Combined	80.6%	2.1%	0.2%

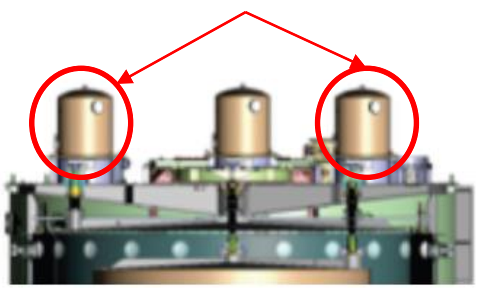
Background

Background	Near	Far	Uncertainty	Method	Improvement
Accidentals	1.4%	2.3%	Negligible	Statistically calculated from uncorrelated singles	Extend to larger data set
$^{9}Li/^{8}He$	0.4%	0.4%	~50%	Measured with after-muon events	Extend to larger data set
Fast neutron	0.1%	0.1%	~30%	Measured from RPC+OWS tagged muon events	Model independent measurement
AmC source	0.03%	0.2%	~50%	MC benchmarked with single gamma and strong AmC source	Two sources are taken out in Far site ADs
Alpha-n	0.01%	0.1%	~50%	Calculated from measured radioactivity	Reassess systematics





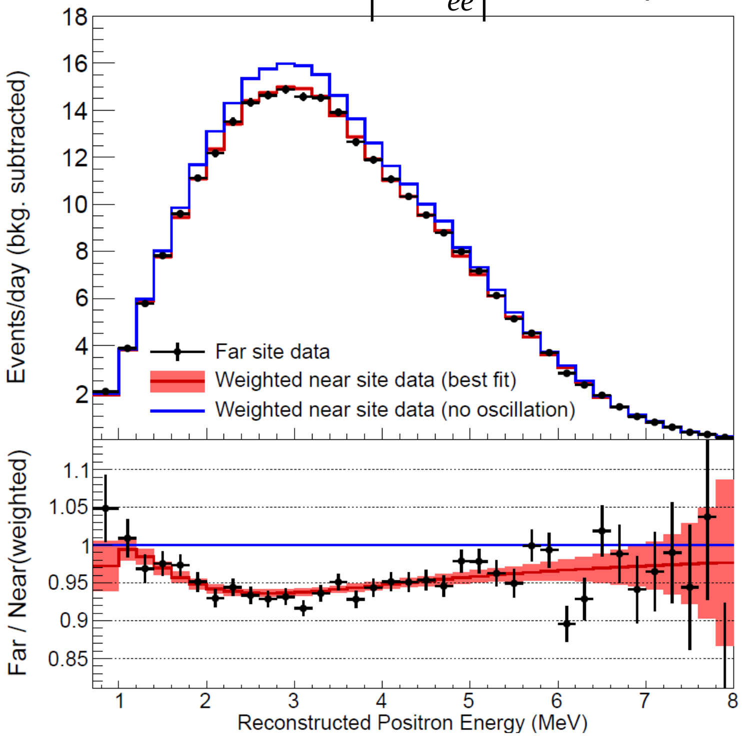
Take out two AmC sources

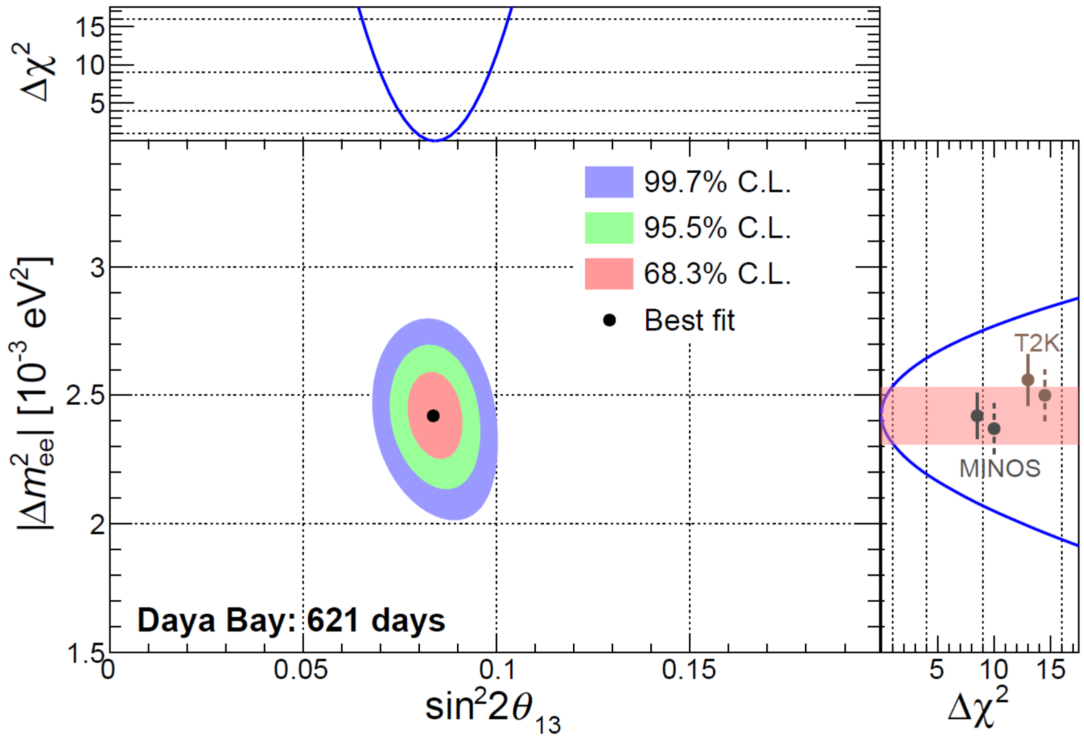


Oscillation analysis

- Far/near relative measurement
- Observed data highly consistent with oscillation interpretation
- Precision of $\sin^2 2\theta_{13}$: 10% → 6%
- Precision of $\left|\Delta m^2_{ee}\right|$: 8% → 4%

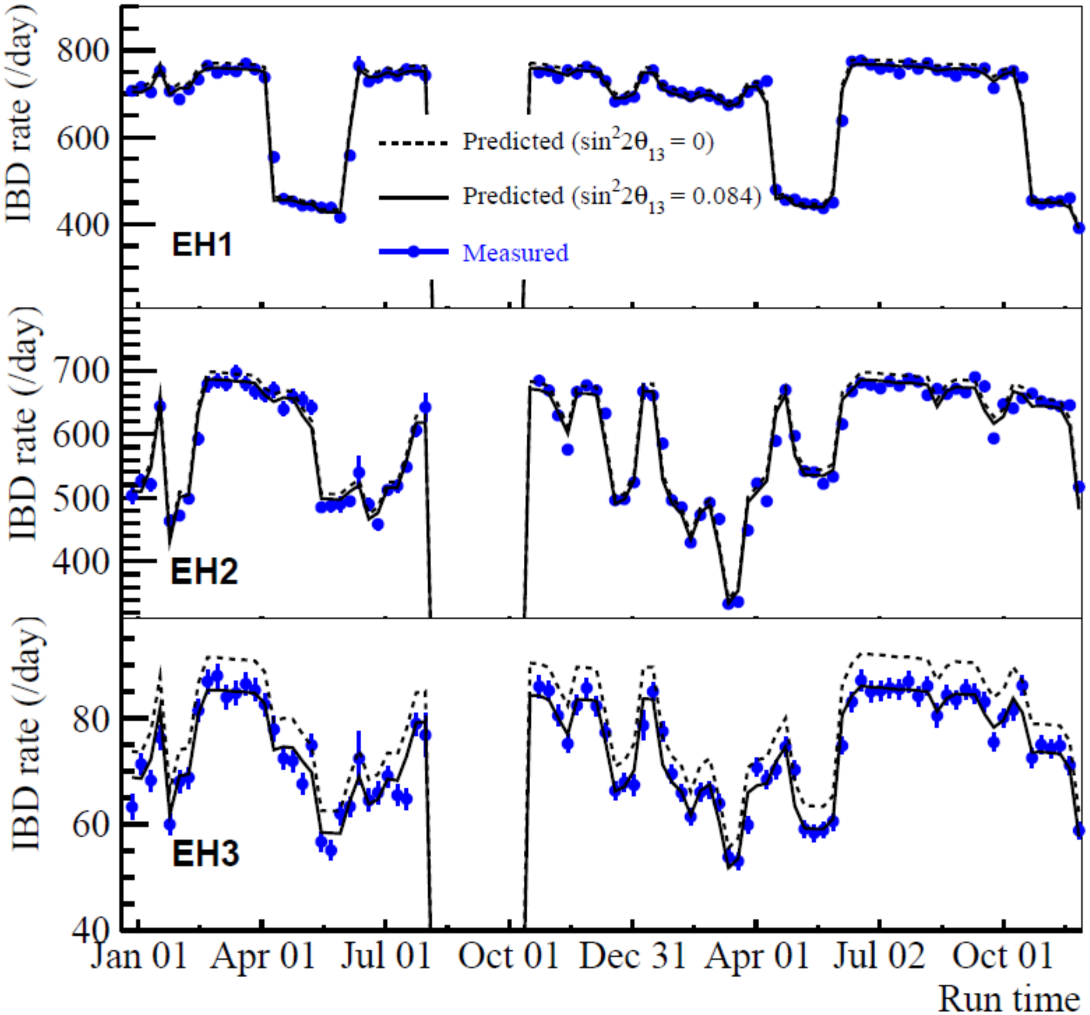
$$\sin^2 2\theta_{13} = 0.084 \pm 0.005$$
$$\left|\Delta m^2_{ee}\right| = \left(2.42 \pm 0.11\right) \times 10^{-3}\,\mathrm{eV}^2$$

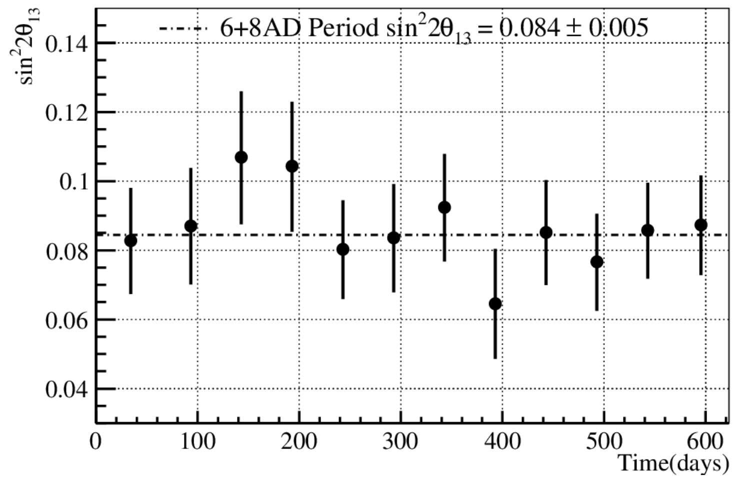




$\Delta m^2_{ee} \sim \Delta m^2_{32} \pm 5.2 \times 10^{-5}$ [eV²]

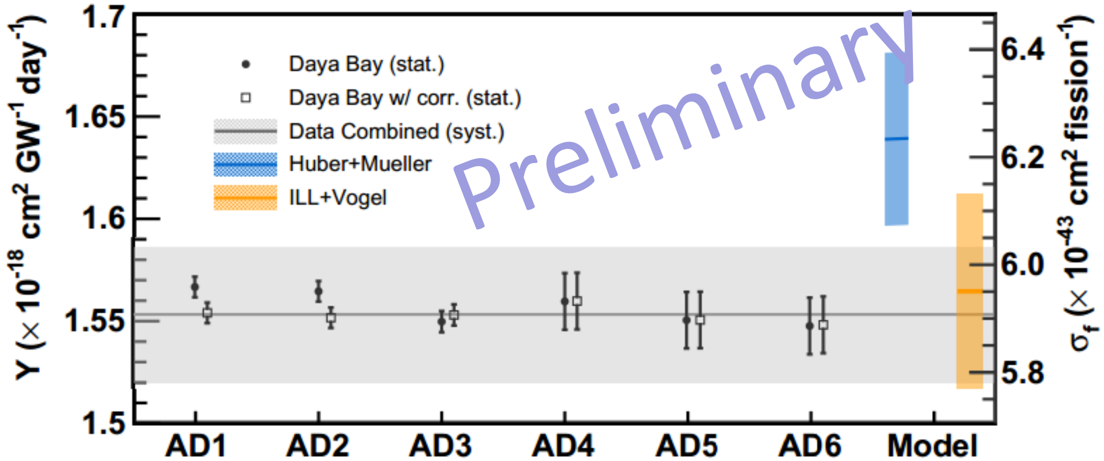
Time variation of rate deficit



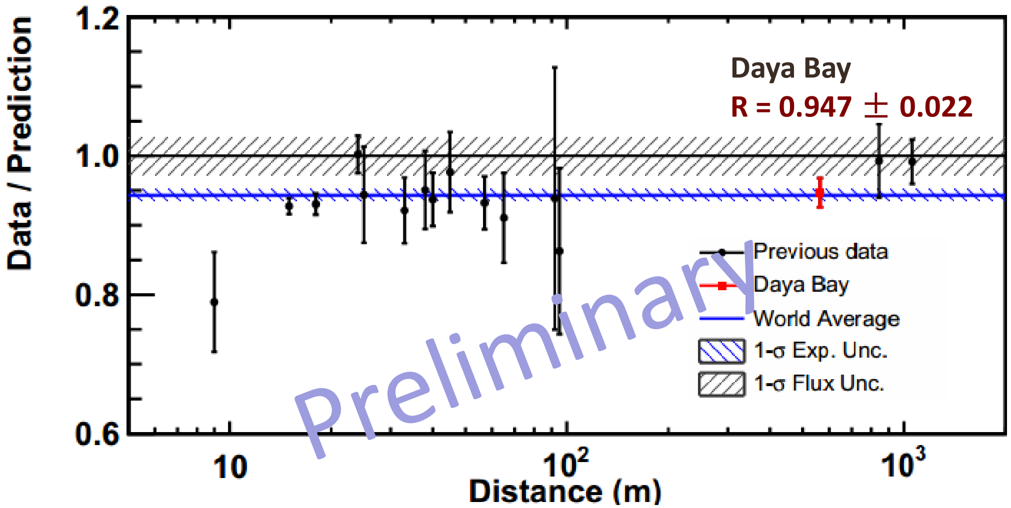


- IBD rate highly correlated with reactor prediction
- Consistent rate deficit as a function of time

Reactor antineutrino flux



Measured IBD events (background subtracted) in each detector are normalized to *cm²/GW/day* (**Y_0**) and *cm²/fission* (**σ_f**).



Global comparison of measurement and prediction (Huber+Mueller)

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

3-AD (near sites) measurement

$Y_0 = 1.553 \times 10^{-18}$

$\sigma_f = 5.934 \times 10^{-43}$

Compare to flux model

Data/Prediction (Huber+Mueller)

0.947 ± 0.022

Data/Prediction (ILL+Vogel)

0.992 ± 0.023

Effective baseline (near sites)

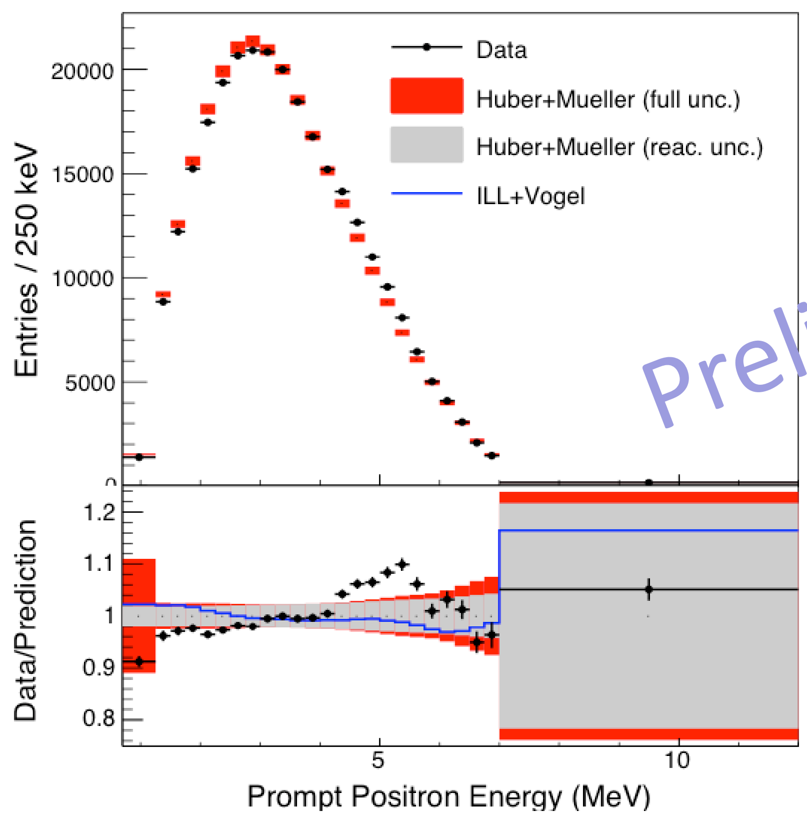
$L_{eff} = 573$m

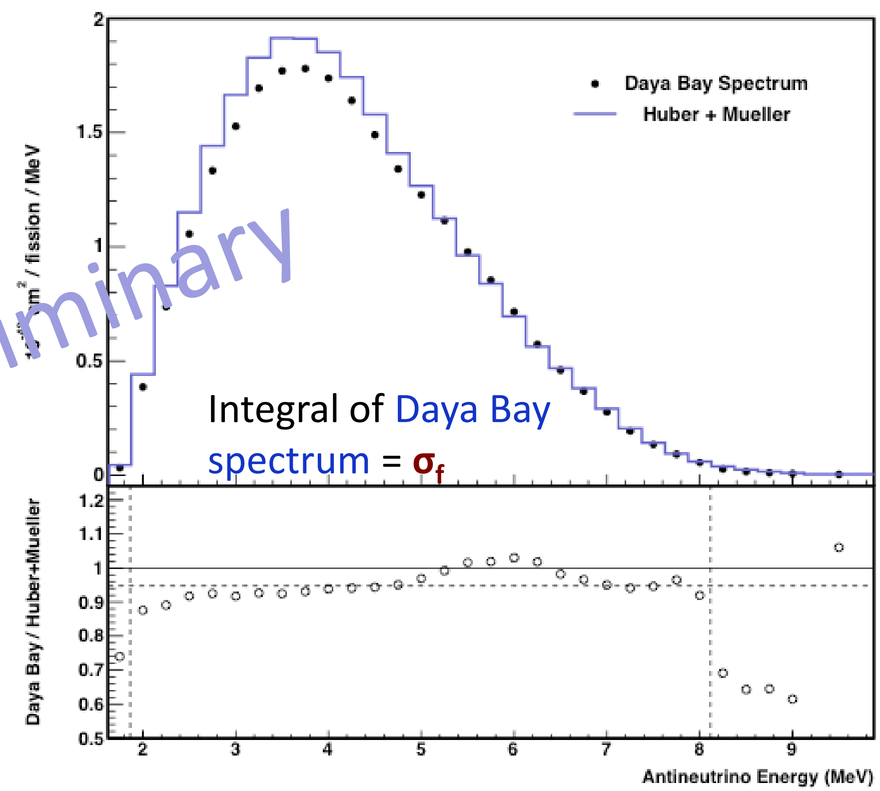
Effective fission fractions α_k

^{235}U	^{238}U	^{239}Pu	^{241}Pu
0.586	0.076	0.288	0.050

Reactor antineutrino spectrum

- Absolute positron spectral shape is NOT consistent with the prediction. A bump is observed in 4-6 MeV (~4σ discrepancy).
- Extract a generic observable reactor antineutrino spectrum by removing the detector response



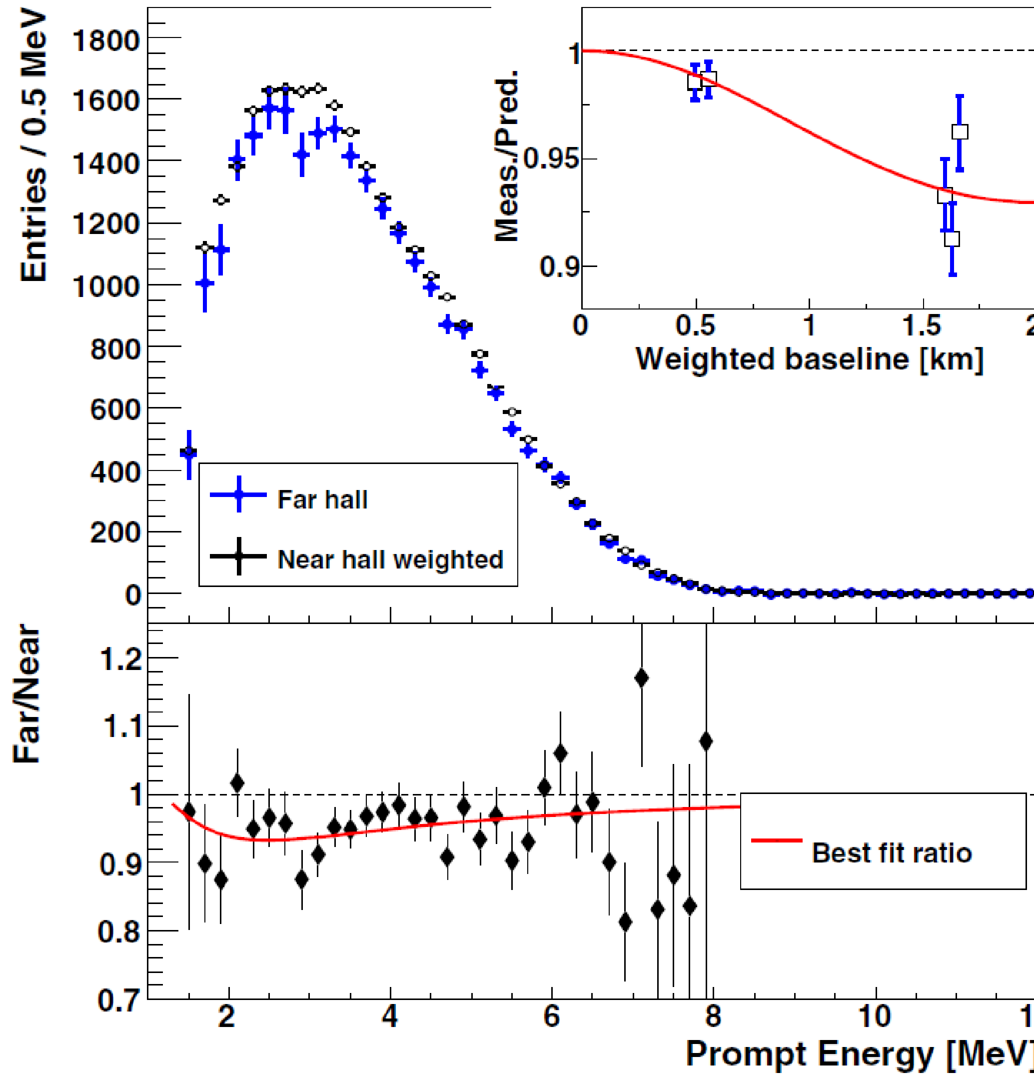


Independent θ_{13} measurement with nH

- **Key features**: independent statistics, different systematics
- **Challenges**: high accidental background because of longer capture time and lower delayed energy
- **Strategy**: raise prompt energy cut (>1.5MeV) and require prompt to delay distance cut (<0.5m)
- **Oscillation analysis** of rate deficit using 217 days of 6AD data

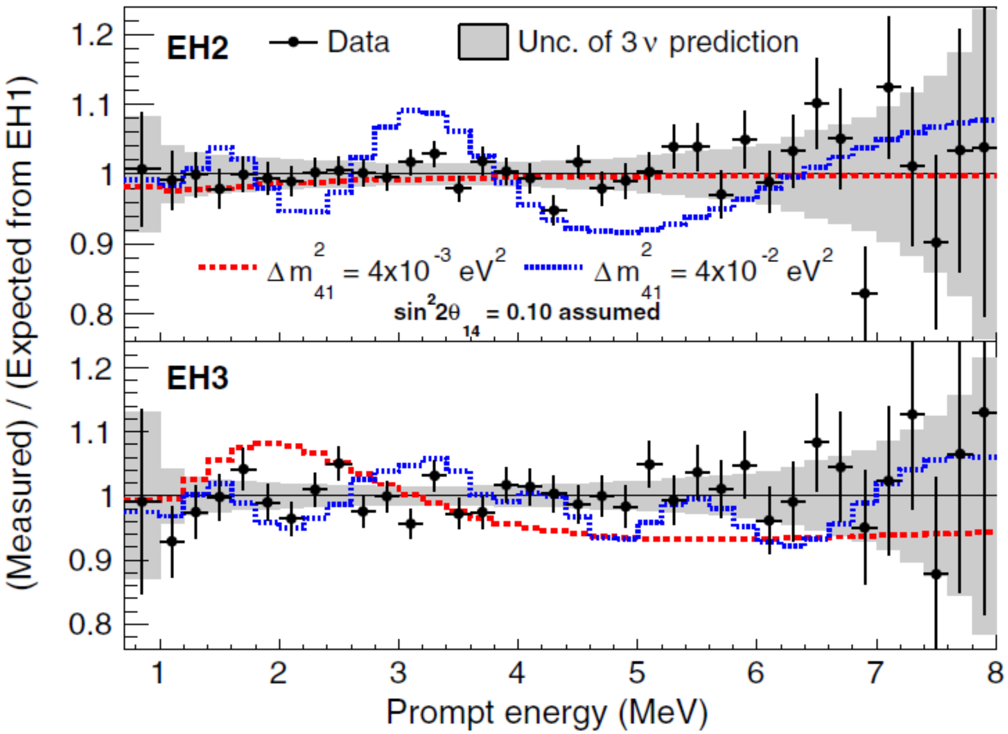
$$\sin^2 2\theta_{13} = 0.083 \pm 0.018$$

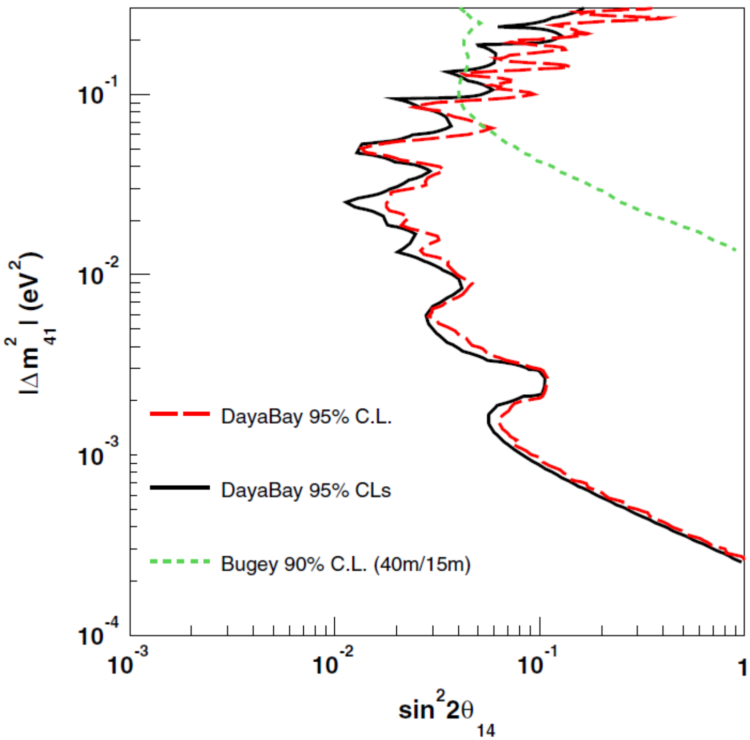
- **Spectral analysis** in progress



Search for light sterile neutrinos

- An unique opportunity for sterile neutrino searches
  - Sterile neutrino would introduce additional oscillation mode.
  - Relative measurement at multiple baselines: EH1 (~350m), EH2 (~500m), EH3 (~1600m)
- Oscillation analysis
  - No significant signal observed, consistent with 3-flavor neutrino oscillation.
  - Set most stringent limit at 10^{-3} $eV^2 < \Delta m^2_{41} < 0.1$ eV^2

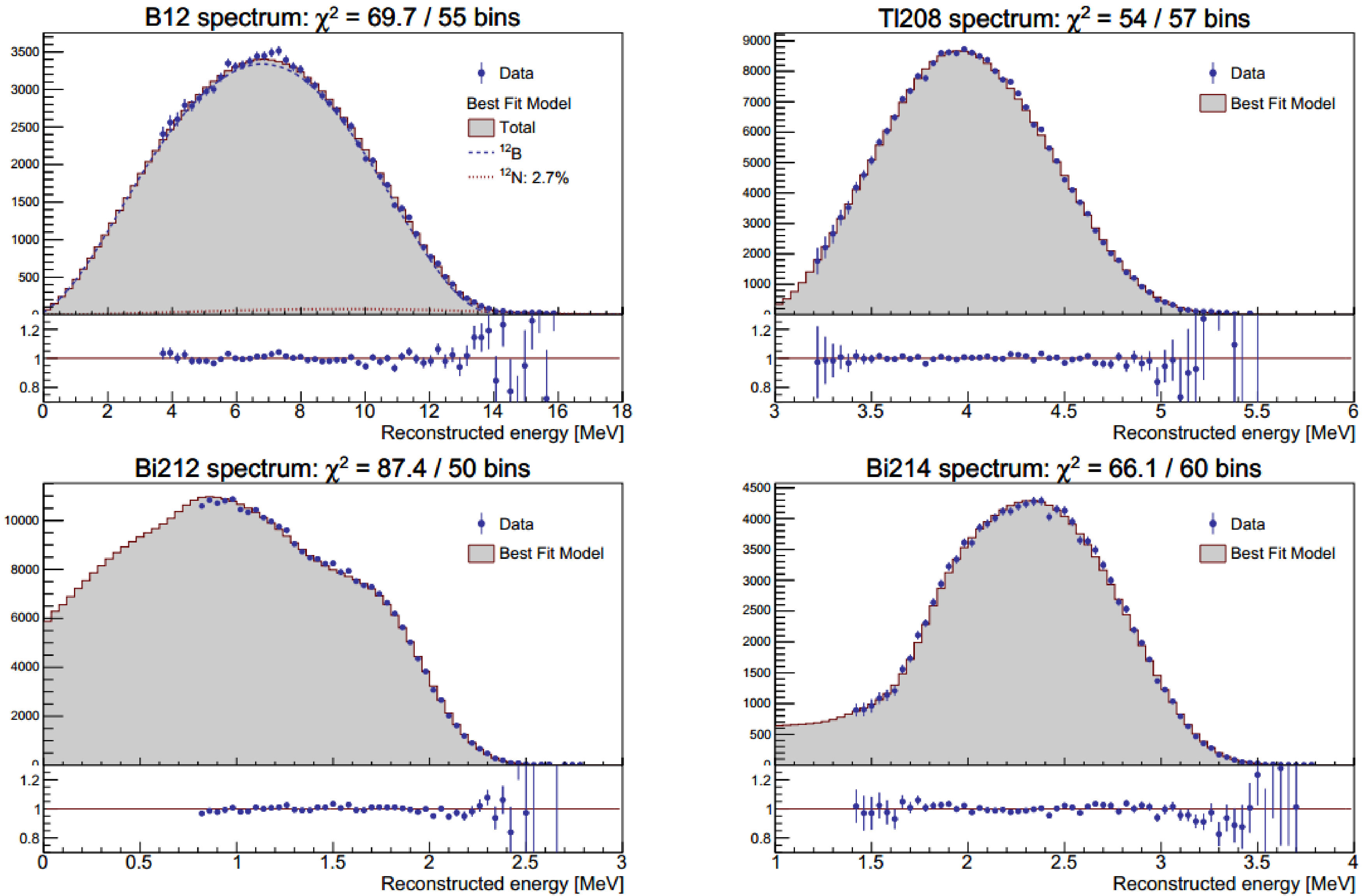




Summary

- Daya Bay updated reactor antineutrino analysis with the full detector configuration
  - Most precision measurement of $\sin^2 2\theta_{13}$: 6%
  - Most precision measurement of $|\Delta m^2_{ee}|$ in the electron antineutrino disappearance channel: 4%
- Precision measurement on reactor antineutrino flux and spectrum
  - Flux is consistent with previous short baseline experiments
  - Spectrum is NOT consistent with prediction at 4σ level in 4-6 MeV (5-7 MeV) positron (antineutrino) energy region
- Confirmed reactor antineutrino disappearance and measured $\sin^2 2\theta_{13}$ independently with nH sample
- Set new limit to light sterile neutrinos

backup

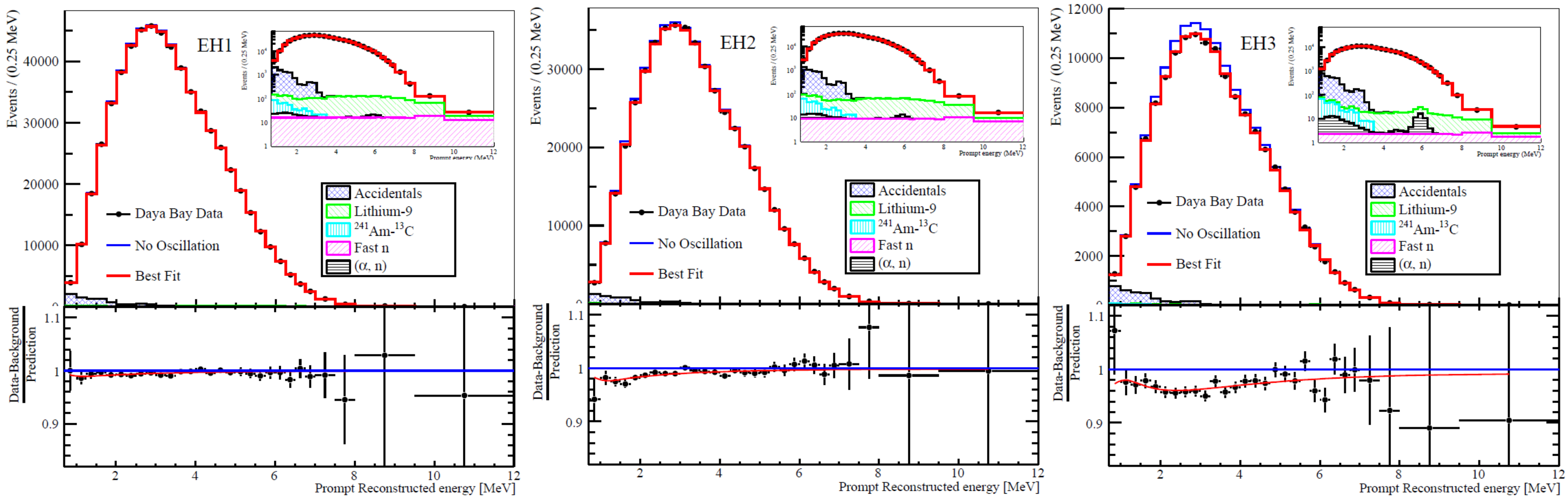

B12 spectrum: χ^2 = 69.7 / 55 bins
Data
Best Fit Model
Total
^{12}B
^{12}N: 2.7%
Reconstructed energy [MeV]
Tl208 spectrum: χ^2 = 54 / 57 bins
Data
Best Fit Model
Reconstructed energy [MeV]
Bi212 spectrum: χ^2 = 87.4 / 50 bins
Data
Best Fit Model
Reconstructed energy [MeV]
Bi214 spectrum: χ^2 = 66.1 / 60 bins
Data
Best Fit Model
Reconstructed energy [MeV]

Data table

	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

TABLE I. Summary of signal and backgrounds. Rates are corrected for the muon veto and multiplicity selection efficiencies $\varepsilon_\mu \cdot \varepsilon_m$. The measured ratio of the IBD rates in AD1 and AD2 (AD3 and AD8 in the 8-AD period) was 0.981±0.004 (1.019±0.004) while the expected ratio was 0.982 (1.012).

Signal and background spectrum



oscillation