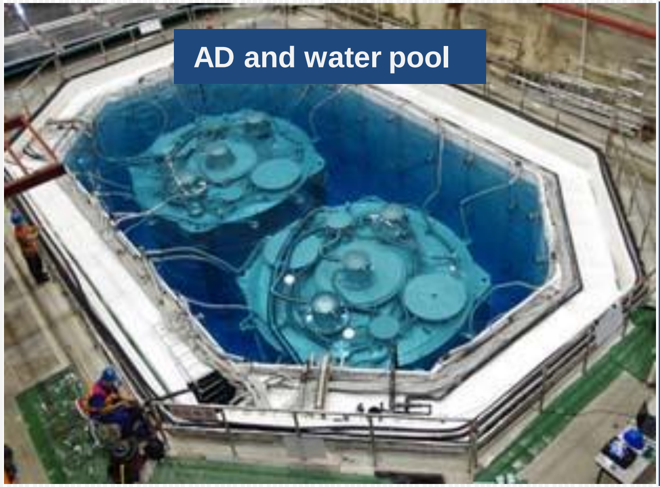
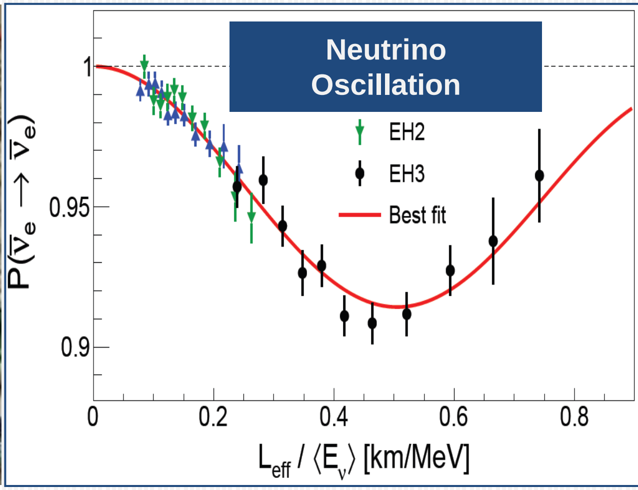




Latest Progress from the Daya Bay Reactor Neutrino Experiment

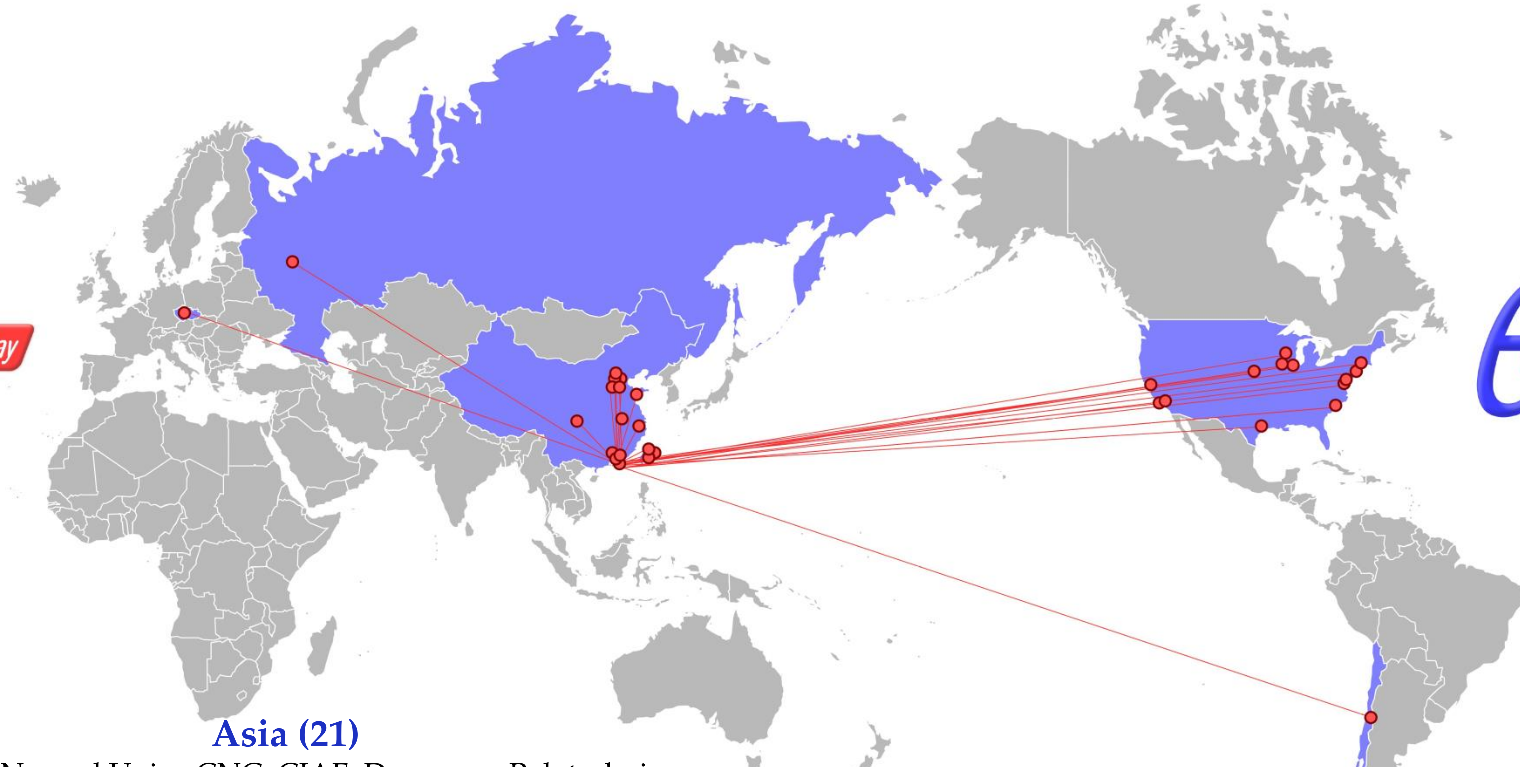
Zhe Wang, Tsinghua University
(on behalf of the Daya Bay Collaboration)

Taup 2015

Sep. 6-12， 2015

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

Daya Bay Collaboration

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Neutrino Mixing and θ_{13}

$$\nu_\alpha = U_{\alpha i}\nu_i \qquad \alpha = e, \mu, \tau \qquad i = 1, 2, 3$$

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

The 3-generation neutrino oscillation theory consists of:

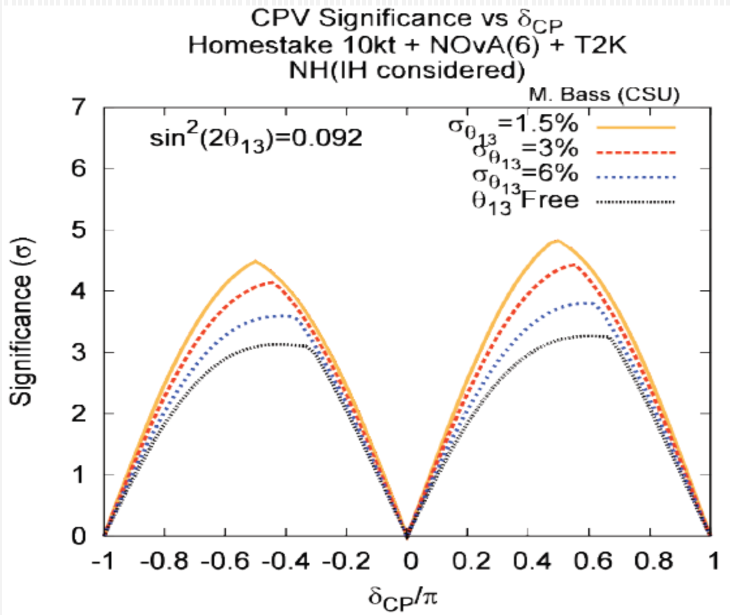
- Three mixing angles
- One Dirac phase (CP phase)
- Two mass squared differences

Unknowns:

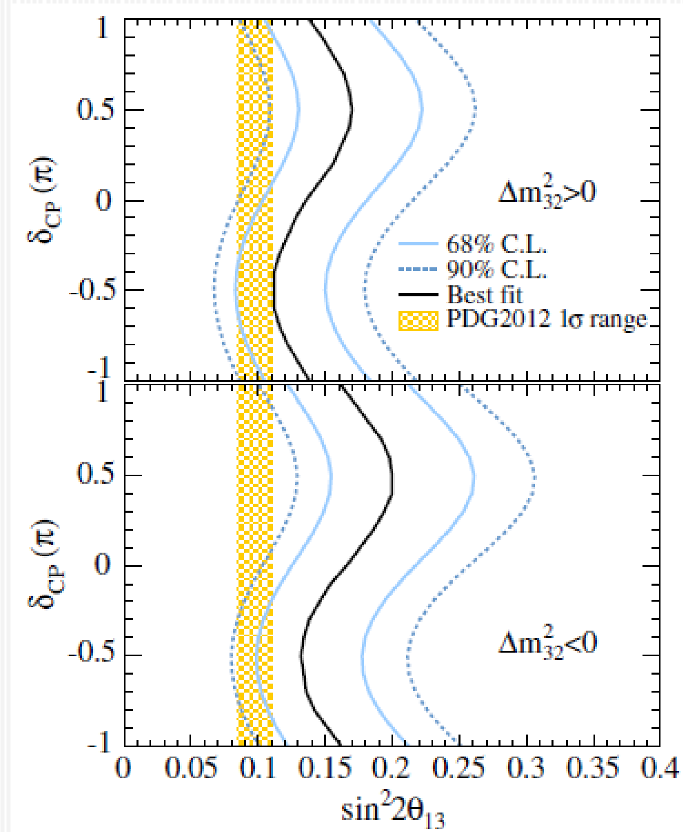
- CP phase
- Sign of one mass squared difference

Precision θ_{13} Measurement

1. Precise θ_{13} is a critical input for neutrino related theories and experiments



arXiv:1309.7961



PRL 112, 061802 (2014)

2. Precise θ_{13} also enable us to search for new physics: sterile neutrinos, reactor antineutrino anomaly, reactor neutrino spectrum, etc.

Measurement Method

- Detection of electron-antineutrino:

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

$$|+H \rightarrow D + \gamma \quad\quad 2.2\text{ MeV} \quad 200\ \mu s$$

$$|+Gd \rightarrow Gd^* \rightarrow Gd + \gamma's \quad 8\text{MeV} \quad 30\ \mu s$$

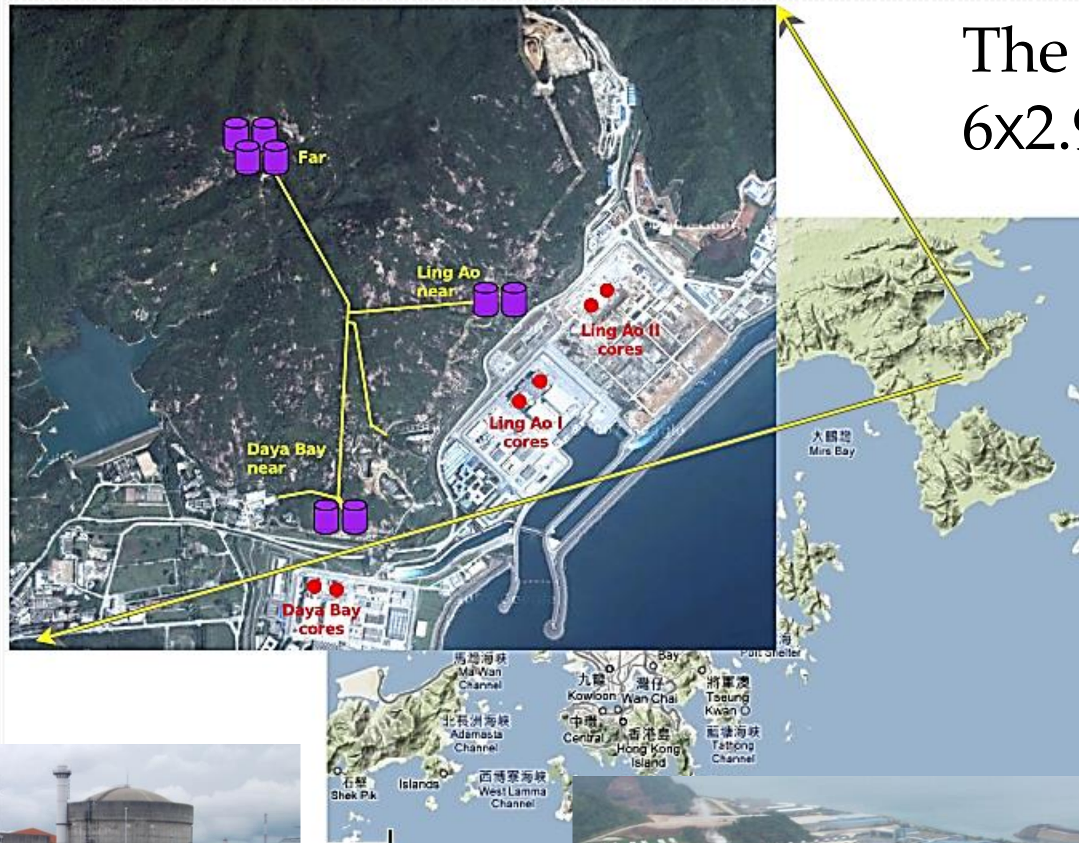
Prompt: e⁺.
Delayed: n capture on H or Gd.

- Extract θ_{13} from
  - Far/Near IBD events ratio, and
  - IBD spectrum distortion of the Far and Near sites

$$\frac{N_{\rm f}}{N_{\rm n}} = \left(\frac{N_{\rm p,f}}{N_{\rm p,n}}\right)\left(\frac{L_{\rm n}}{L_{\rm f}}\right)^2\left(\frac{\epsilon_{\rm f}}{\epsilon_{\rm n}}\right)\left[\frac{P_{\rm sur}(E,L_{\rm f})}{P_{\rm sur}(E,L_{\rm n})}\right]$$

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

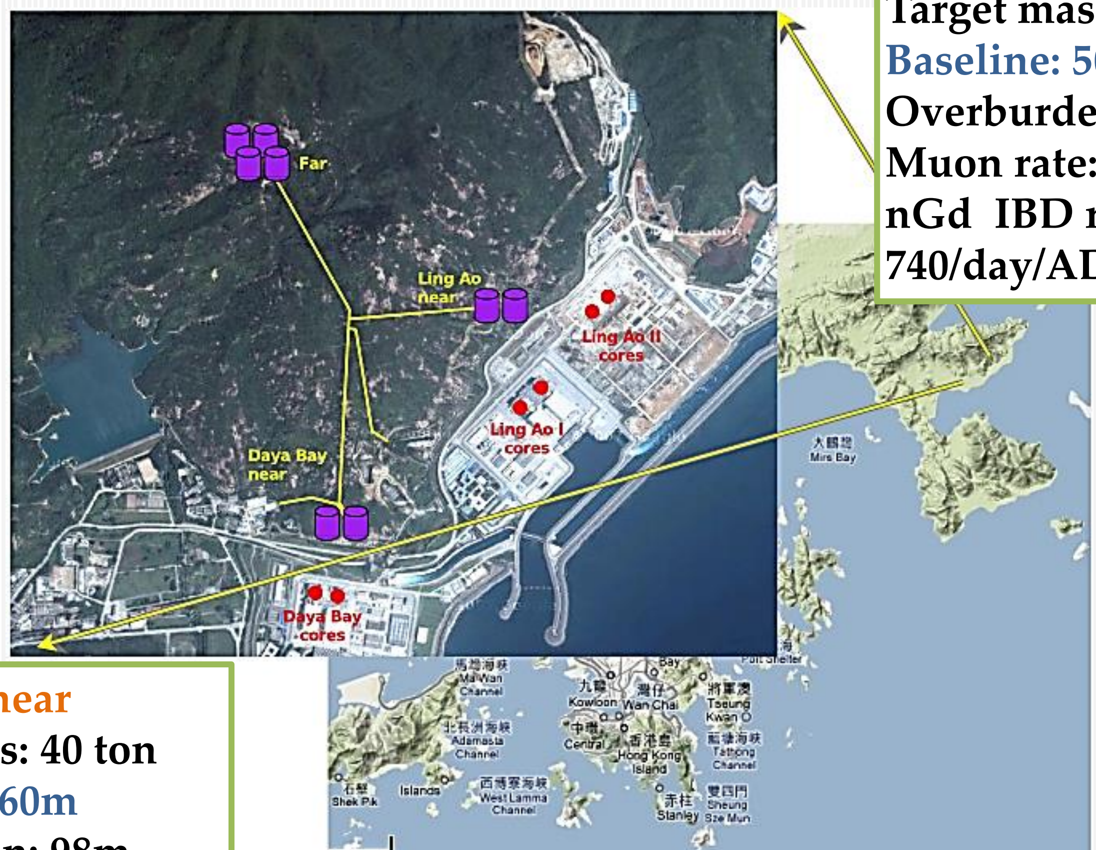
Nuclear Power Plant



The total power 6×2.9 GW_{th}.

Three Experimental Sites

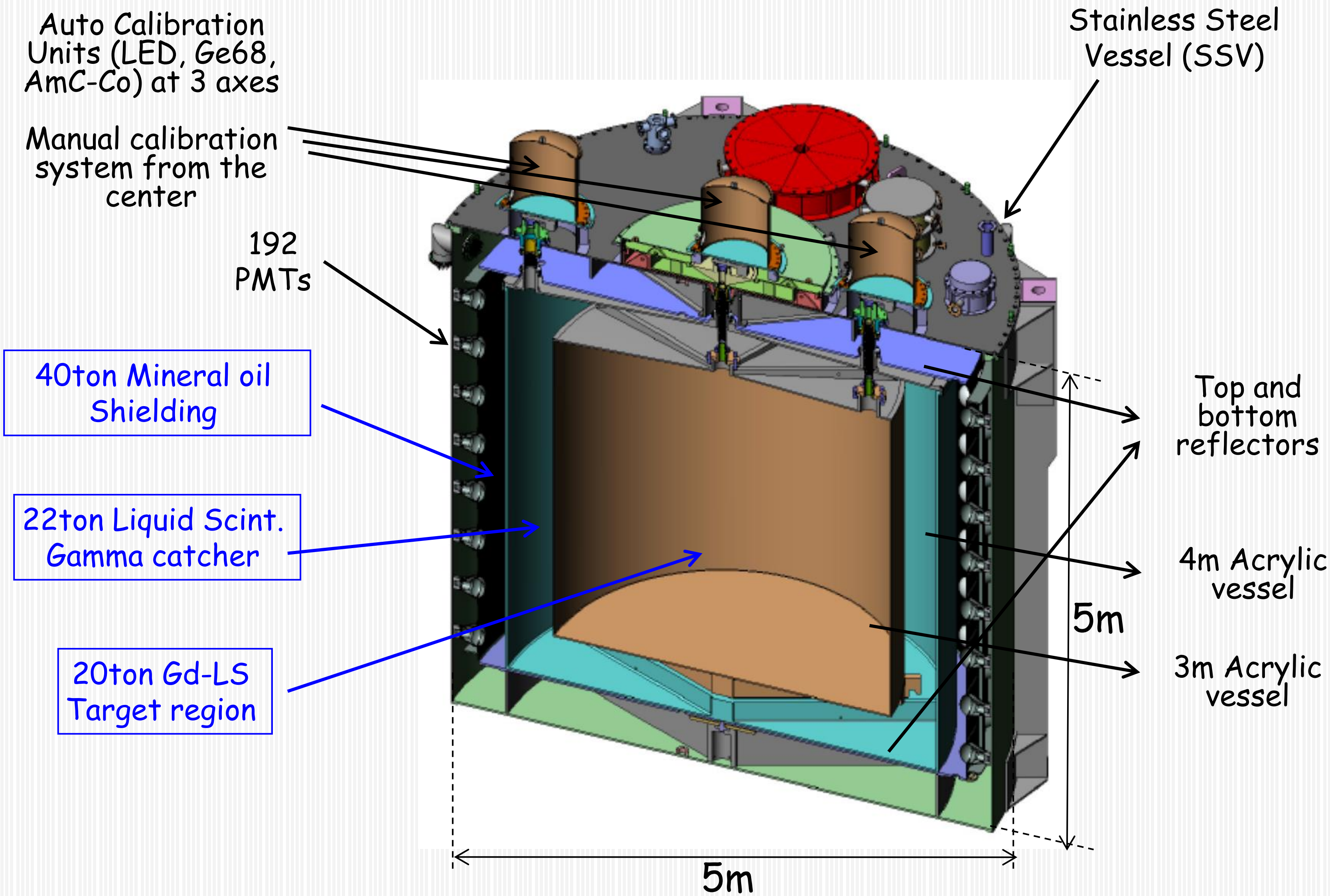
Far
Target mass: 80 ton
1600m to LA, 1900m to DYB
Overburden: 350m
Muon rate: 0.04Hz/m²
nGd IBD rate: 90/day/AD



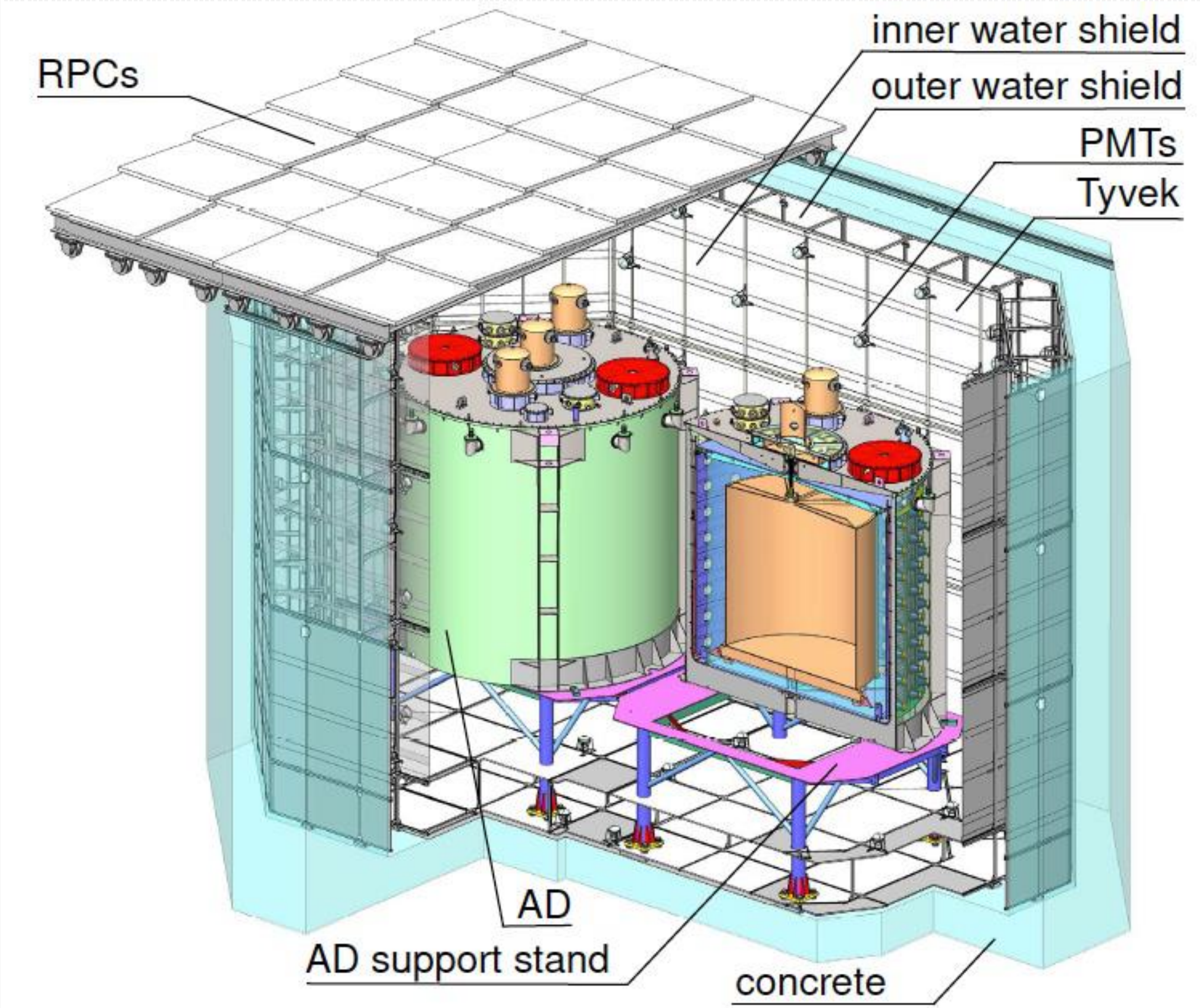
Ling Ao near
Target mass: 40 ton
Baseline: 500m
Overburden: 112m
Muon rate: 0.73Hz/m²
nGd IBD rate: 740/day/AD

Daya Bay near
Target mass: 40 ton
Baseline: 360m
Overburden: 98m
Muon rate: 1.2Hz/m²
nGd IBD rate: 840/day/AD

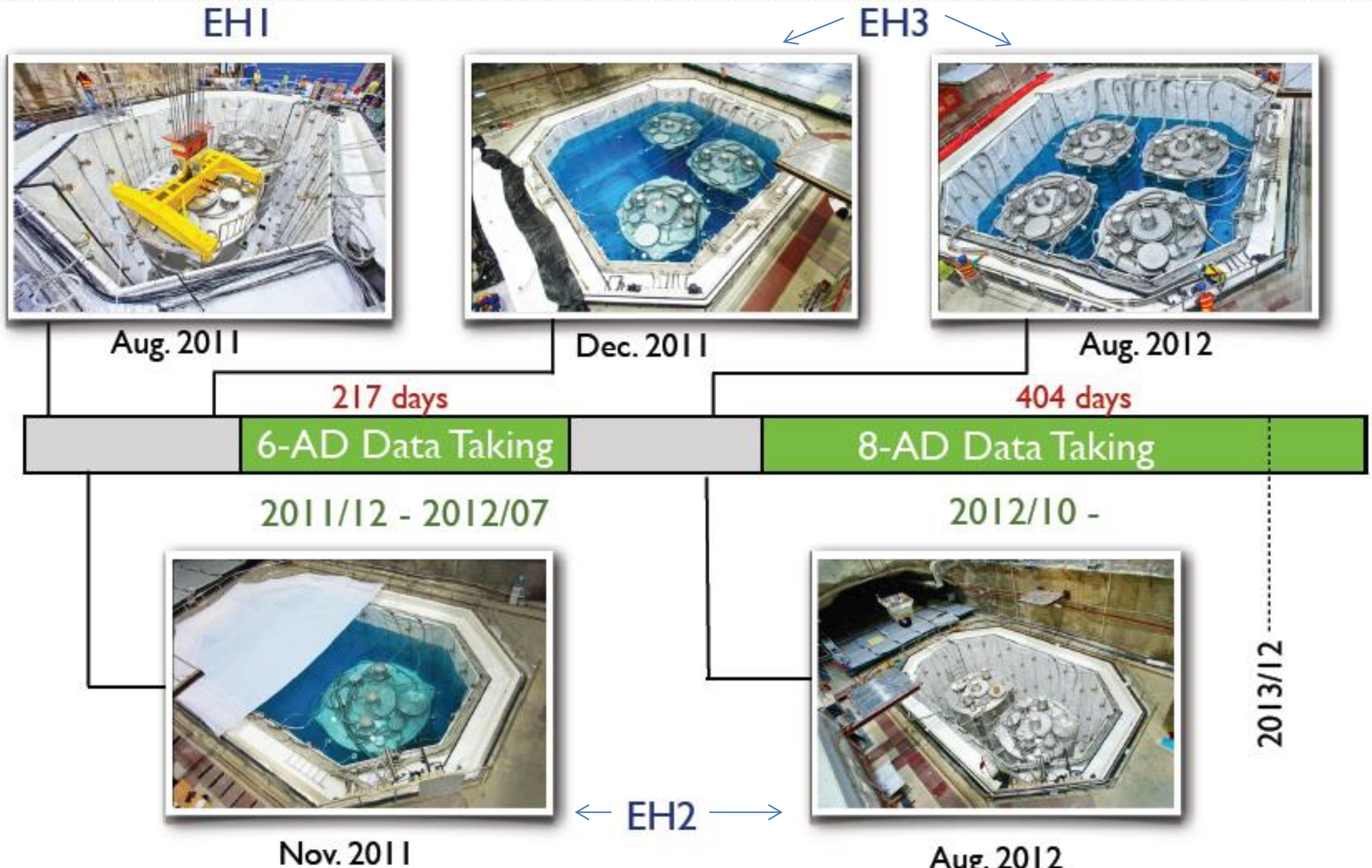
Antineutrino Detector (AD)



Veto System

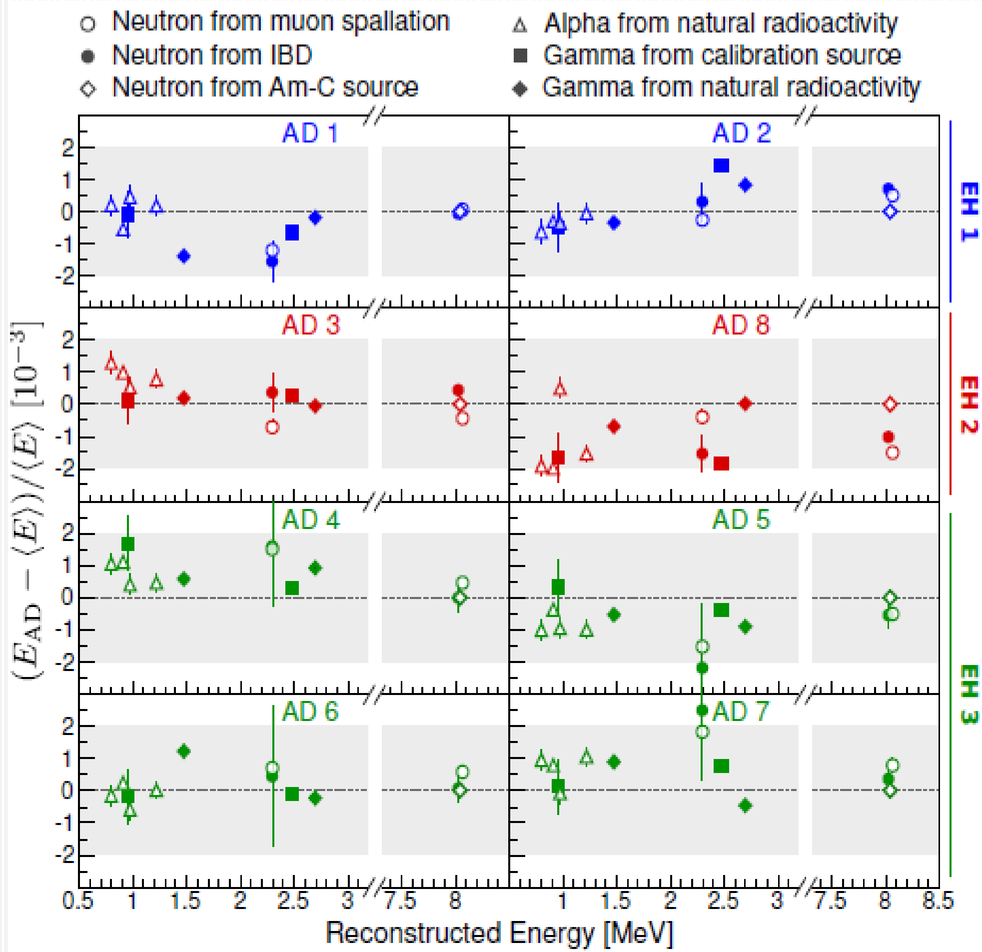

RPCs
inner water shield
outer water shield
PMTs
Tyvek
AD
AD support stand
concrete

Data Collection



Calibration

- **PMT gain**:
  Single electrons from
  Dark noise or LED
- **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

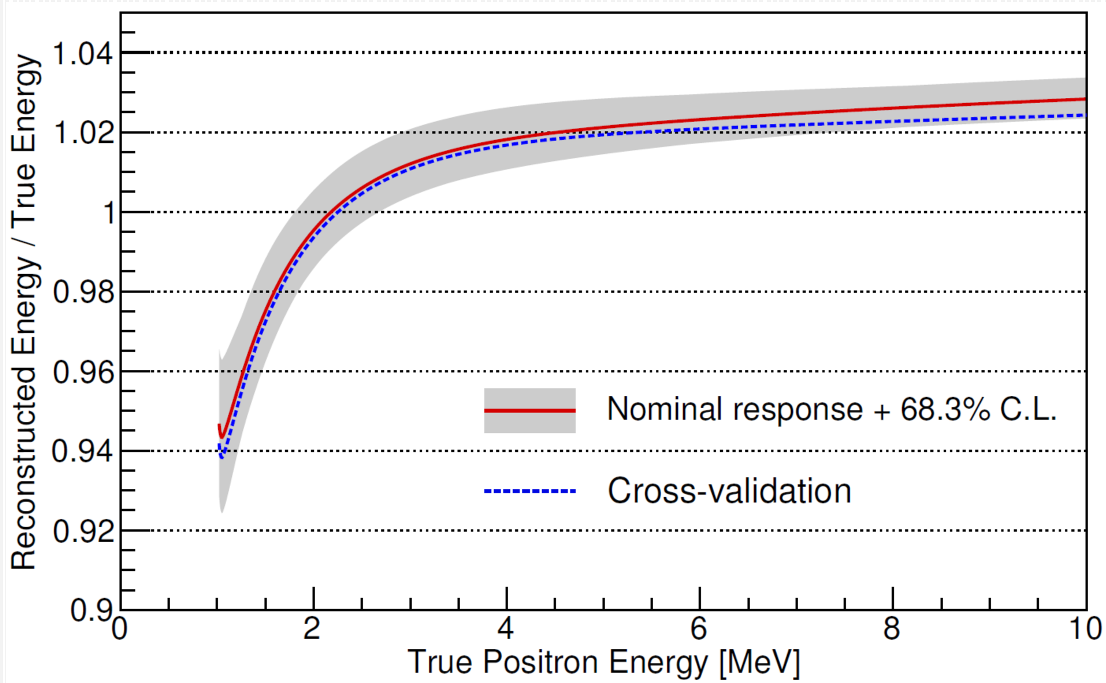
nGd from IBD and muon spallation: Gd-LS region

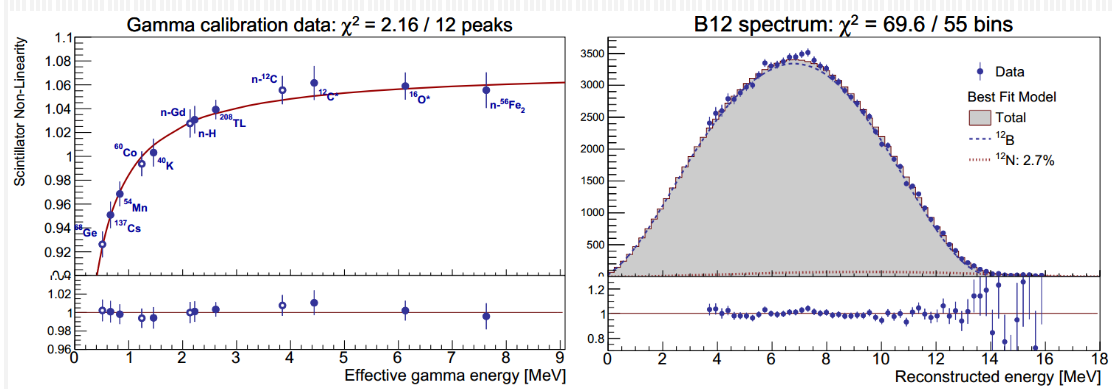
α from polonium decay: Gd-LS vertex cut

^{40}K, ^{208}Tl, nH: 1m vertex cut

Detector Energy Response Model

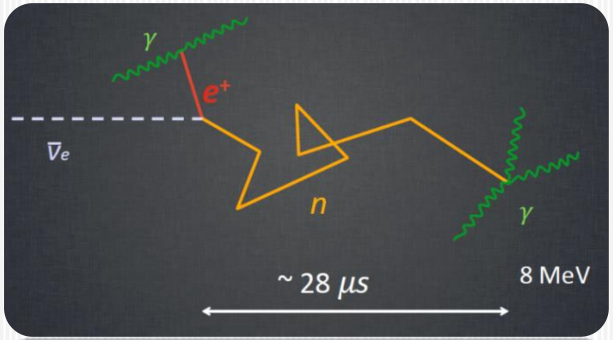
- **Scintillator nonlinearity** : modeled based on Birks' law and Cherenkov fraction
- **Electronics nonlinearity**: modeled based on MC and single channel FADC measurement
- Nominal model: fit to mono-energetic gamma lines and ^{12}B beta-decay spectrum
- Cross-validation model: fit to ^{208}Tl, ^{212}Bi,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





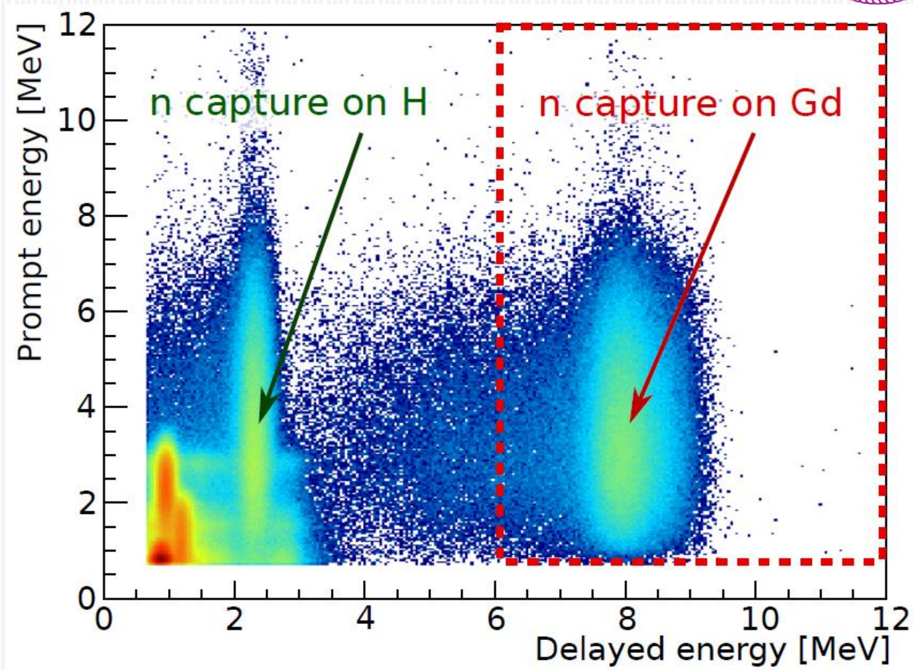
Antineutrino candidates selection

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



- Reject PMT flashers
- **Two-fold coincidence** events
  Time: 1 μs < $\Delta t_{p\text{-}d}$ < 200 μs
  Energy: 0.7 MeV < Ep < 12.0 MeV, 6.0 MeV < Ed < 12.0 MeV

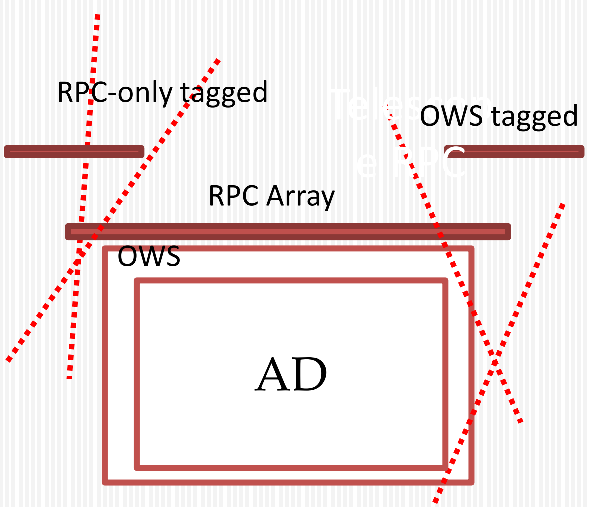
- Muon **anticoincidence**
  Water pool muon: reject 0.6 ms
  AD muon (>20 MeV): reject 1 ms
  AD shower muon (>2.5 GeV): reject 1 s

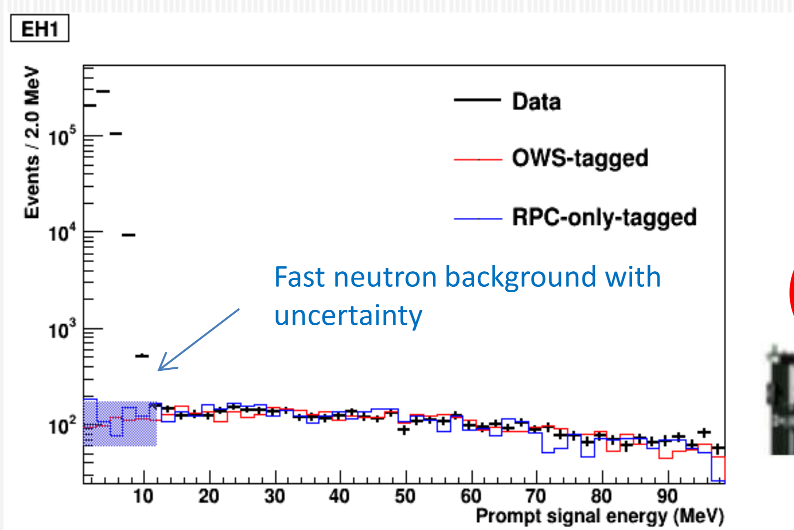


	Efficiency	Correlated Uncertainty	Uncorrelated Uncertainty
Target protons		0.47%	0.03%
Flasher cut	99.98%	0.01%	0.01%
Delayed energy cut	92.7%	0.97%	0.12%
Prompt energy cut	99.81%	0.10%	0.01%
Capture time cut	98.70%	0.12%	0.01%
Gd capture ratio	84.2%	0.95%	0.10%
Spill-in correction	104.9%	1.50%	0.02%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

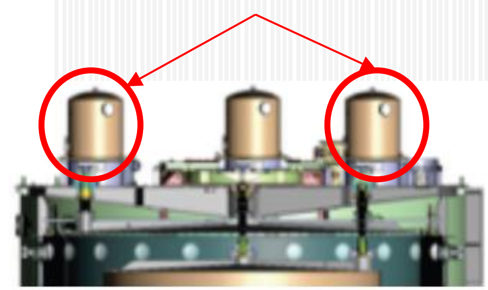
Background Situation

Background	Near	Far	Uncertainty	Method	Improvement
Accidentals	1.4%	2.3%	Negligible	Statistically calculated from uncorrelated singles	Extend to larger data set
$^9Li/^8He$	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



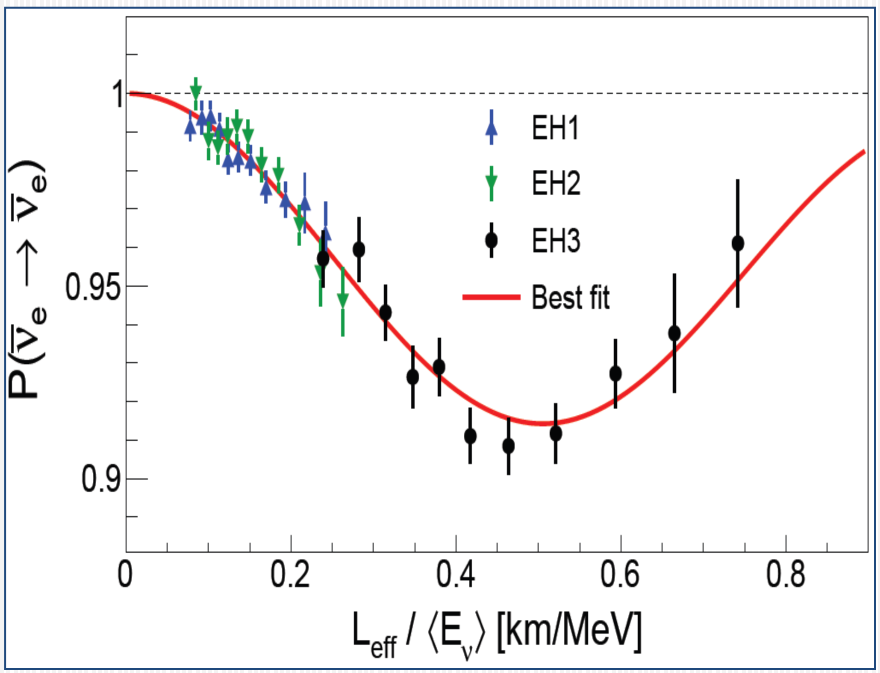
θ_{13} Oscillation Analysis using nGd

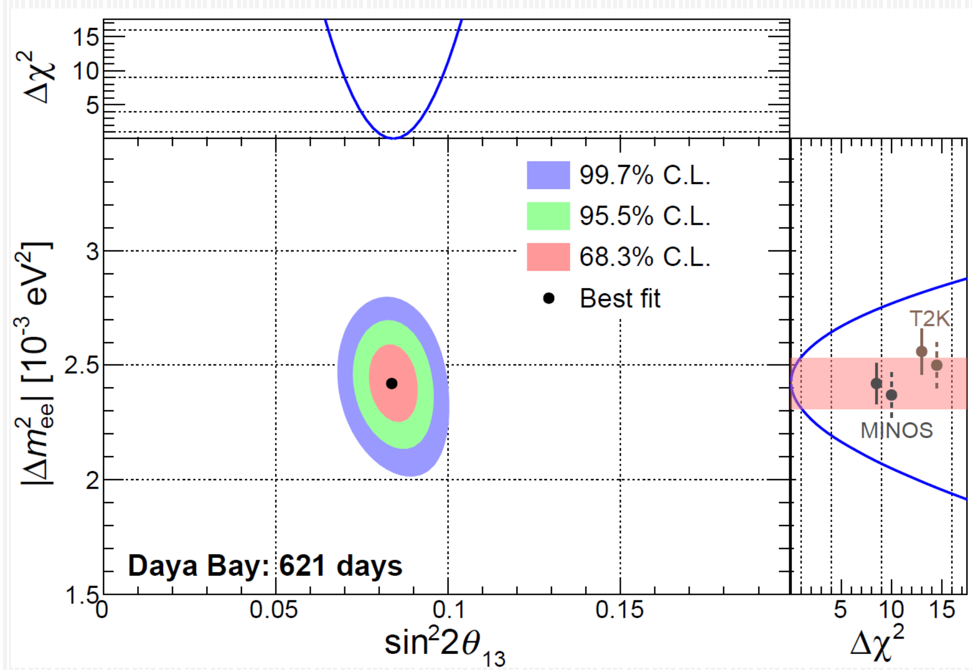
- Far/near relative measurement
- Observed data highly consistent with oscillation interpretation
- Precision of $\sin^2 2\theta_{13}$: **6%**
- Precision of $|\Delta m^2_{ee}|$: **4%**

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

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

arXiv:1505.03456



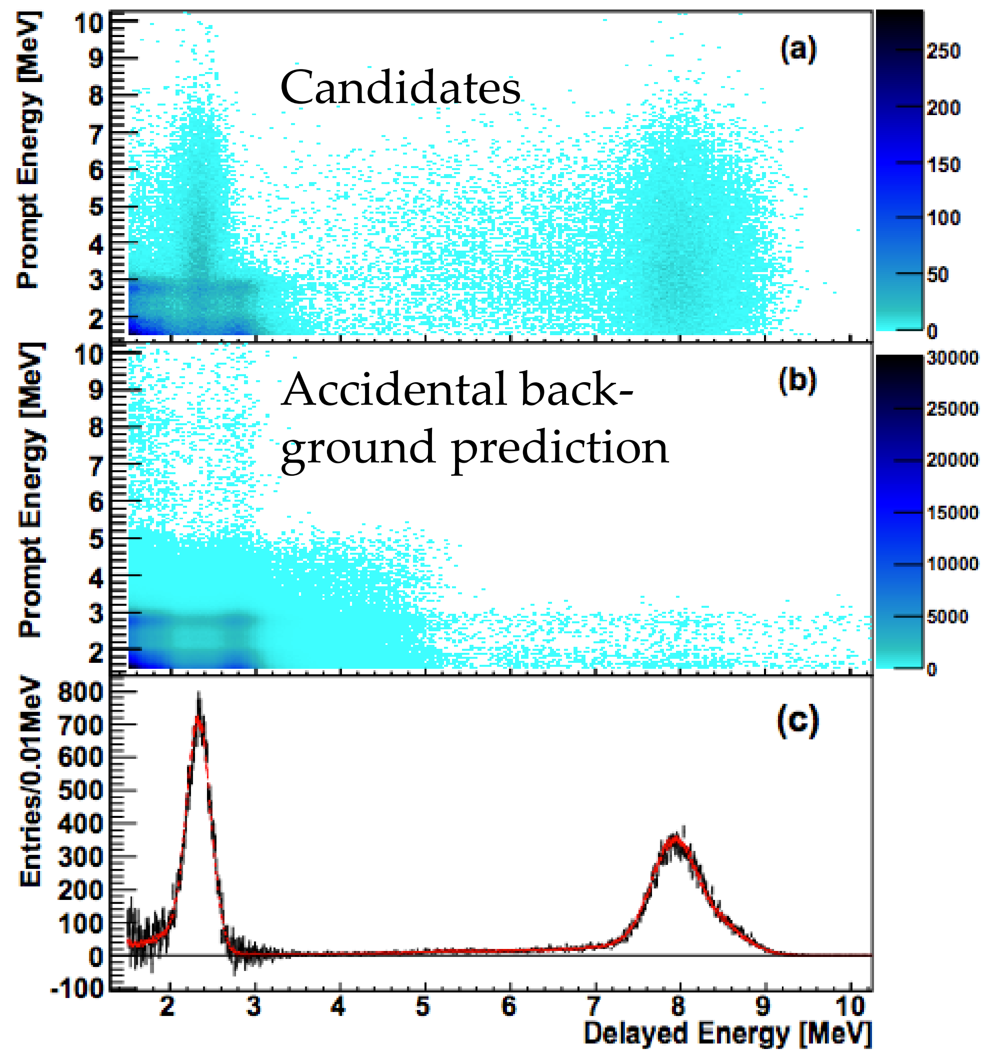


Independent θ_{13} with 6-AD nH sample

- **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

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

PRD 90, 071101 (R) 2014



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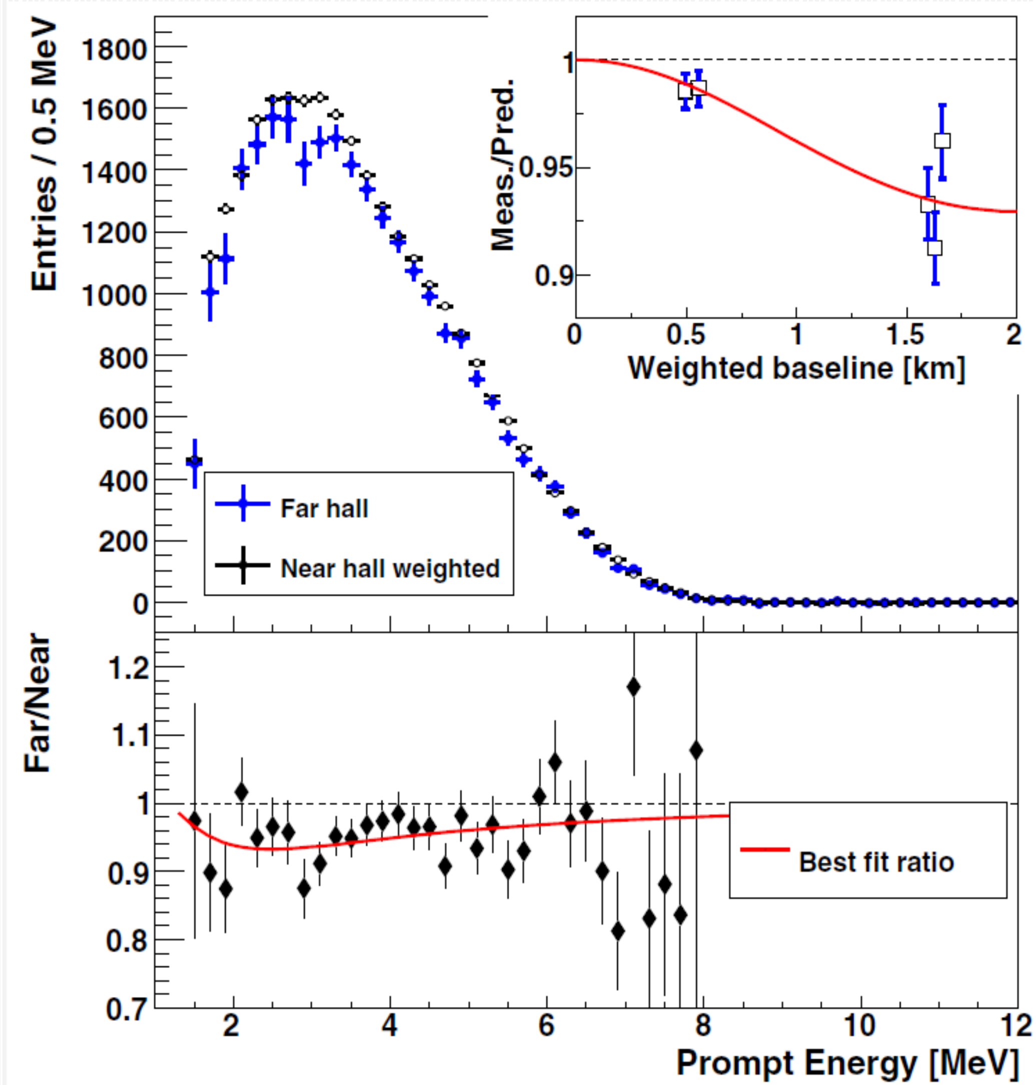
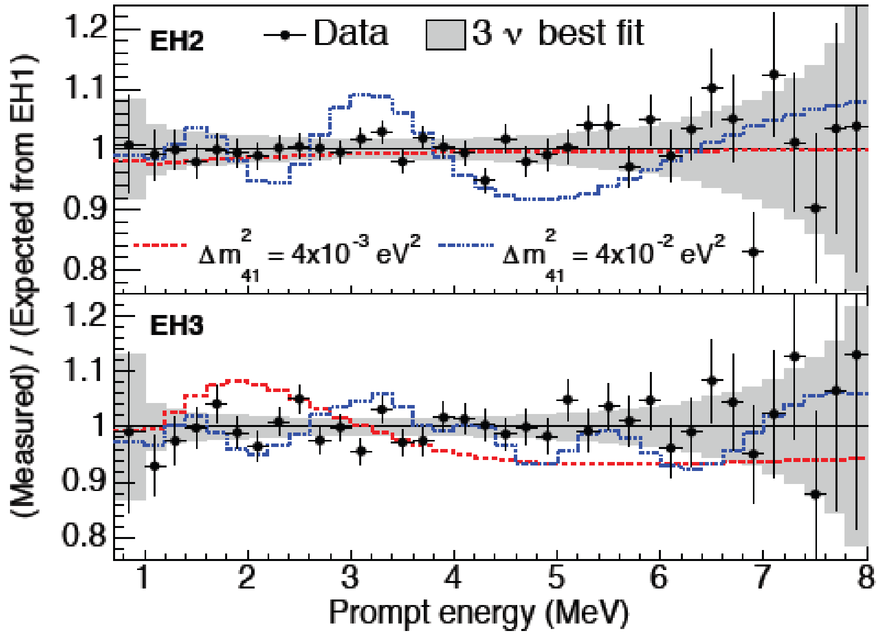


Sterile Neutrino Searches

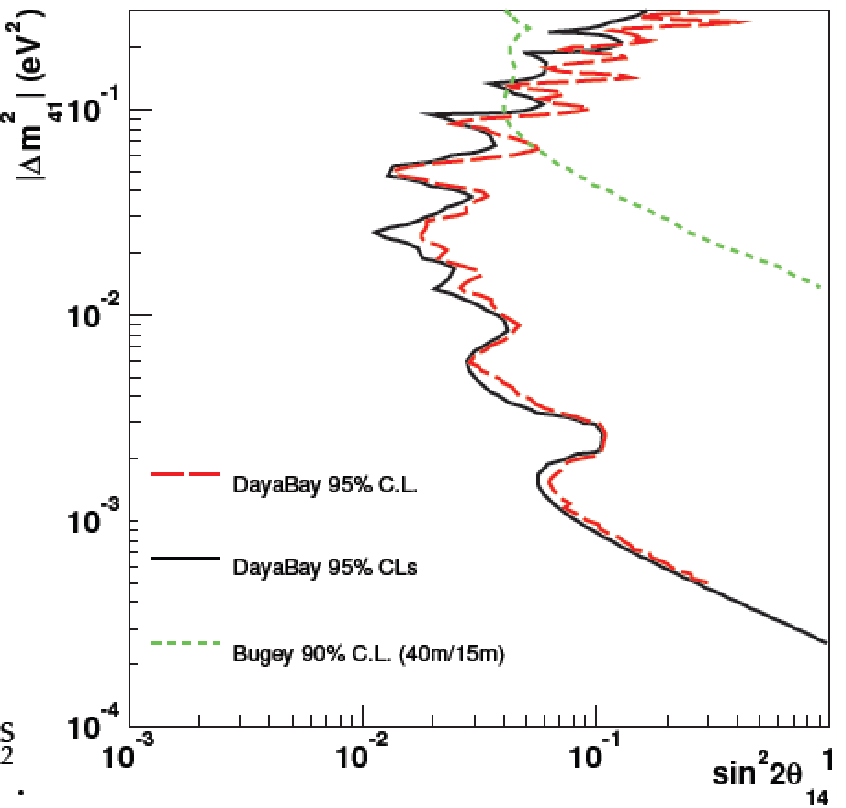
$$P(\bar{\nu}_e \to \bar{\nu}_e) \simeq 1 - \cos^4\theta_{14}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{ee}L}{4E_\nu}\right) - \sin^2 2\theta_{14}\sin^2\left(\frac{\Delta m^2_{41}L}{4E_\nu}\right)$$



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

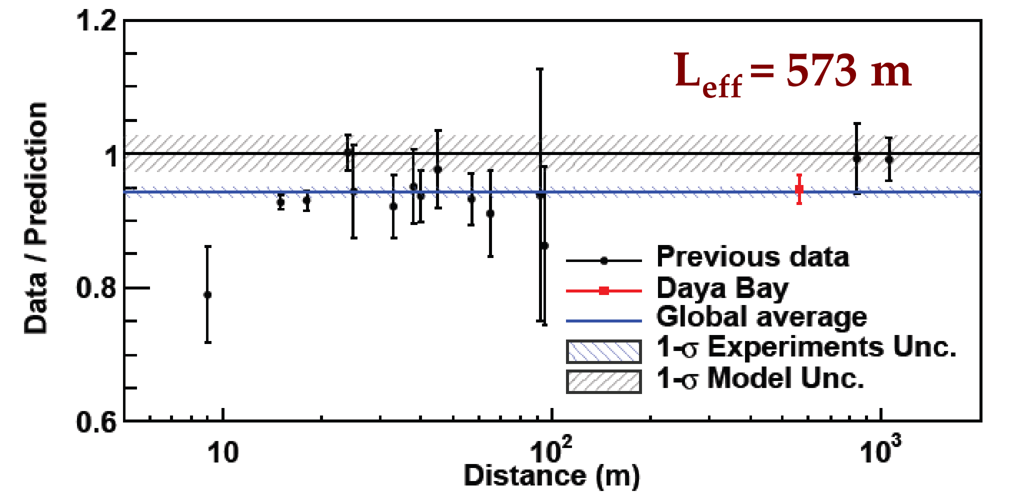
- Daya Bay baselines >350m ⇒ not as sensitive to mass-squared splittings greater than or around 1eV^2



PRL 113, 141802 (2014)

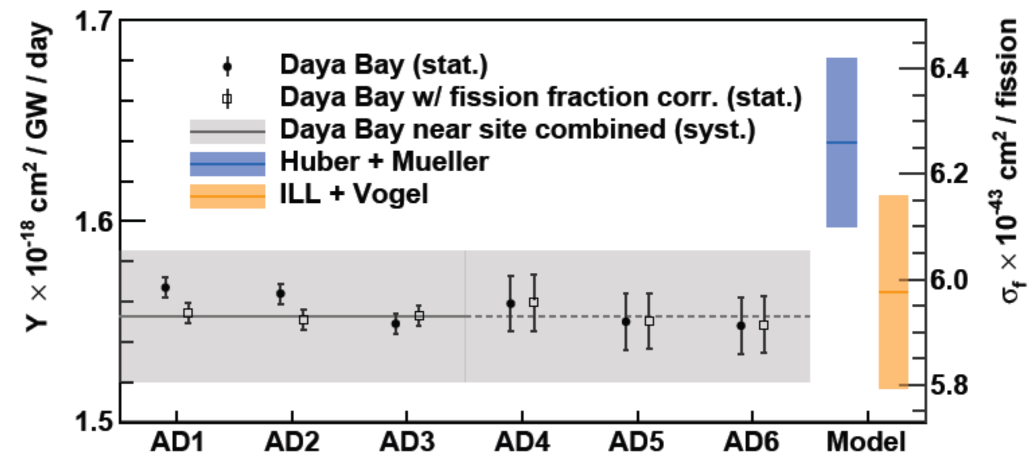
Absolute Reactor Flux Measurement

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



3-AD (near sites) measurement
$Y_0 = 1.553 \times 10^{-18}$ cm²/GW/day
or $\sigma_f = 5.934 \times 10^{-43}$ cm²/fission

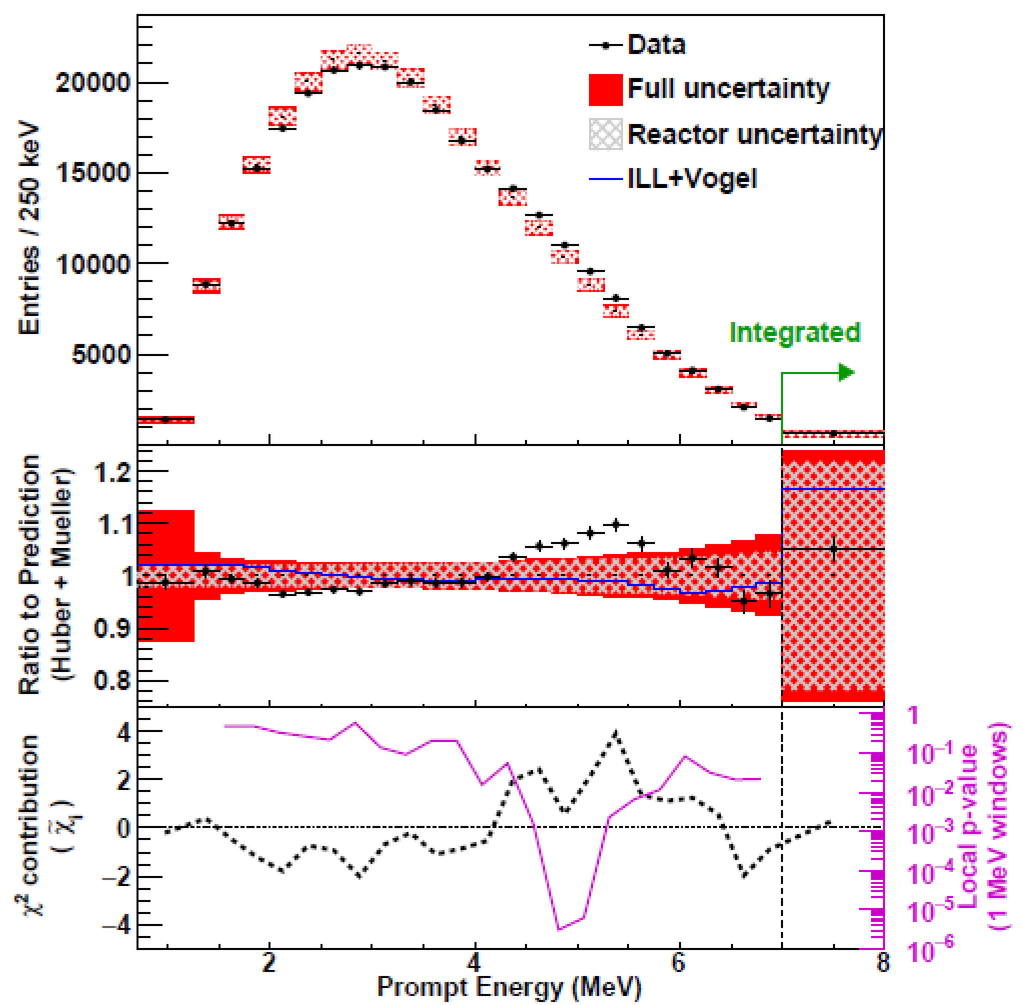
Compare to flux model
Data/Prediction (Huber+Mueller)
0.947 ± 0.022
Data/Prediction (ILL+Vogel)
0.992 ± 0.023



arXiv:1508.04233

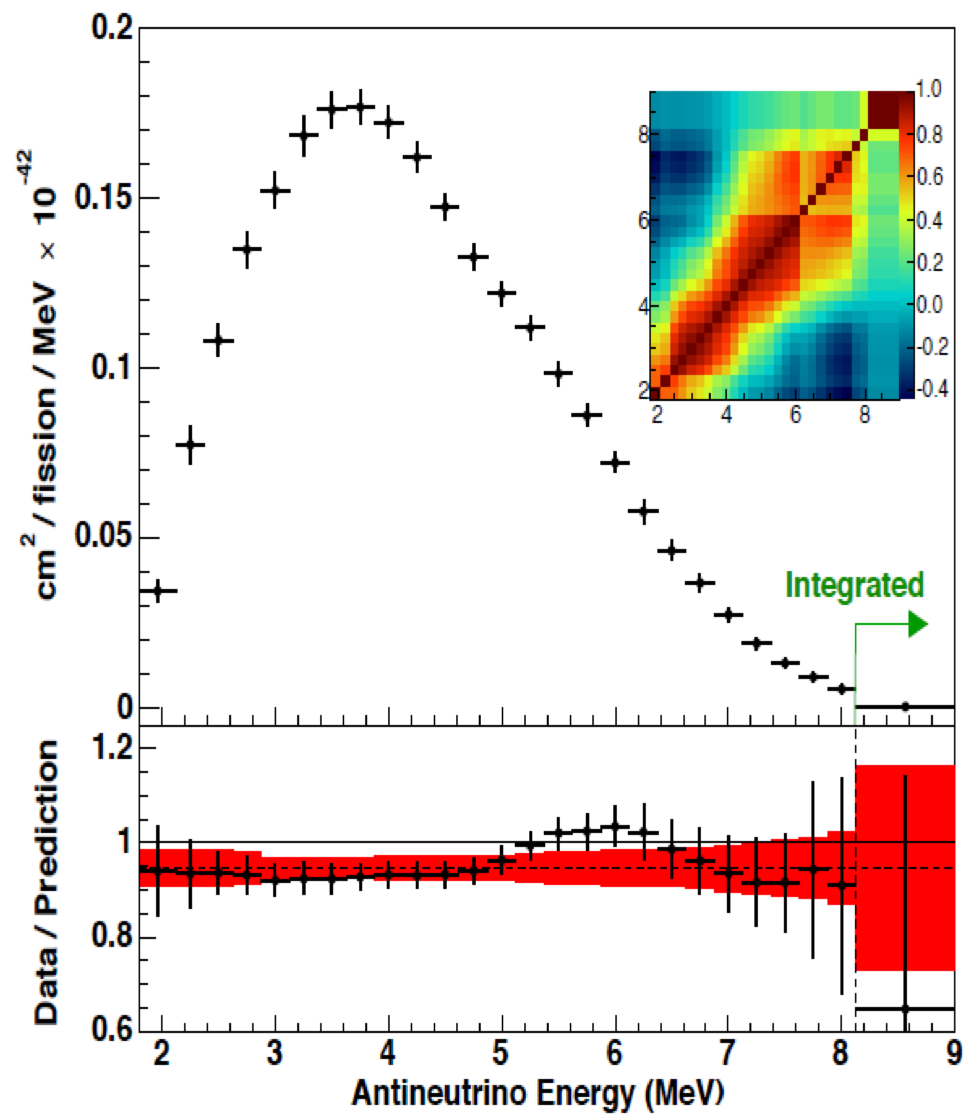
Absolute Positron Spectrum

- The measured positron spectra of IBD events in the three near-hall ADs are combined and compared with the prediction.
- The discrepancy in the 2-MeV window in 4-6 MeV region reached a 4.0σ deviation.



Observable Antineutrino Spectrum

- Extracted a reactor antineutrino spectrum by applying detector response model unfolding
- Can be used directly by future reactor experiments as a reference spectrum
  - more precise than theoretical prediction
  - need small experiment dependent fission fraction corrections



Summary

1. Oscillation analysis using n-captures on Gd with 621 days' data.
   $\sin^2 2\theta_{13}$ precision 6% and $|\Delta m_{ee}^2|$ precision 4%
2. An independent observation of oscillation using n-captures on H with only 6-AD 217 days' data
3. Best limit for sterile neutrinos in Δm^2 of 0.001 – 0.1 eV^2
4. Antineutrino flux measurement is consistent with previous short baseline experiments
5. A local structure (4 σ) around 4-6 MeV is found in positron's detected energy.
6. A generic observable reactor antrineutrino spectrum is extracted.

Thank you.

New results are coming
Stay tuned