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Latest Results on the Measurement of Reactor Antineutrino Oscillation at Daya Bay

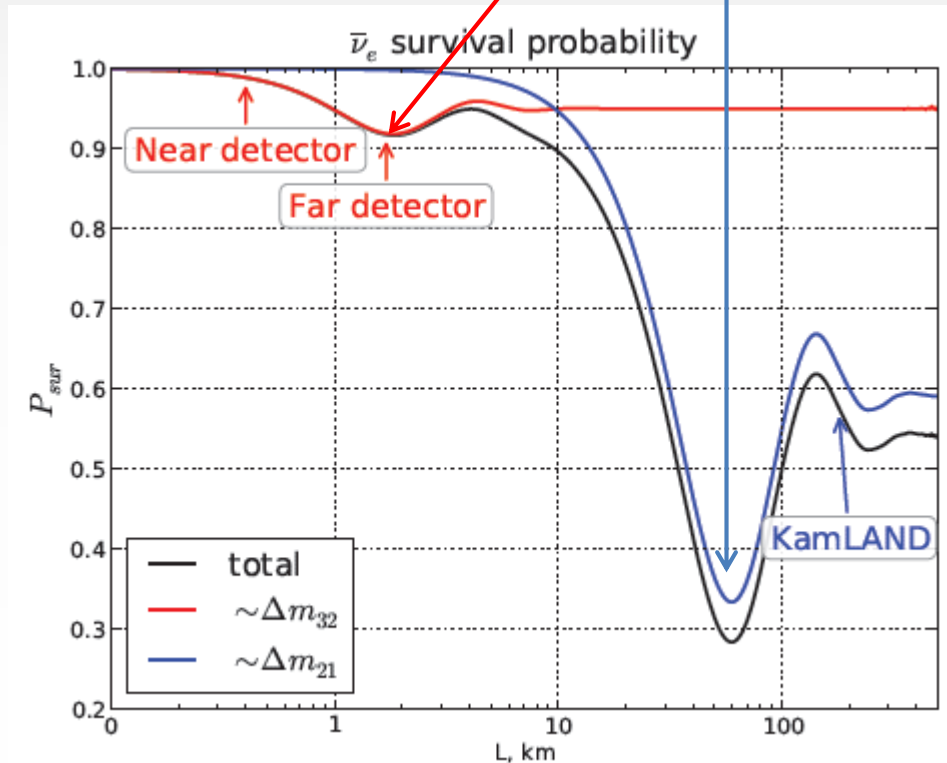


Liang Zhan, *Institute of High Energy Physics, Beijing*
for the Daya Bay Collaboration

Daya Bay Basics

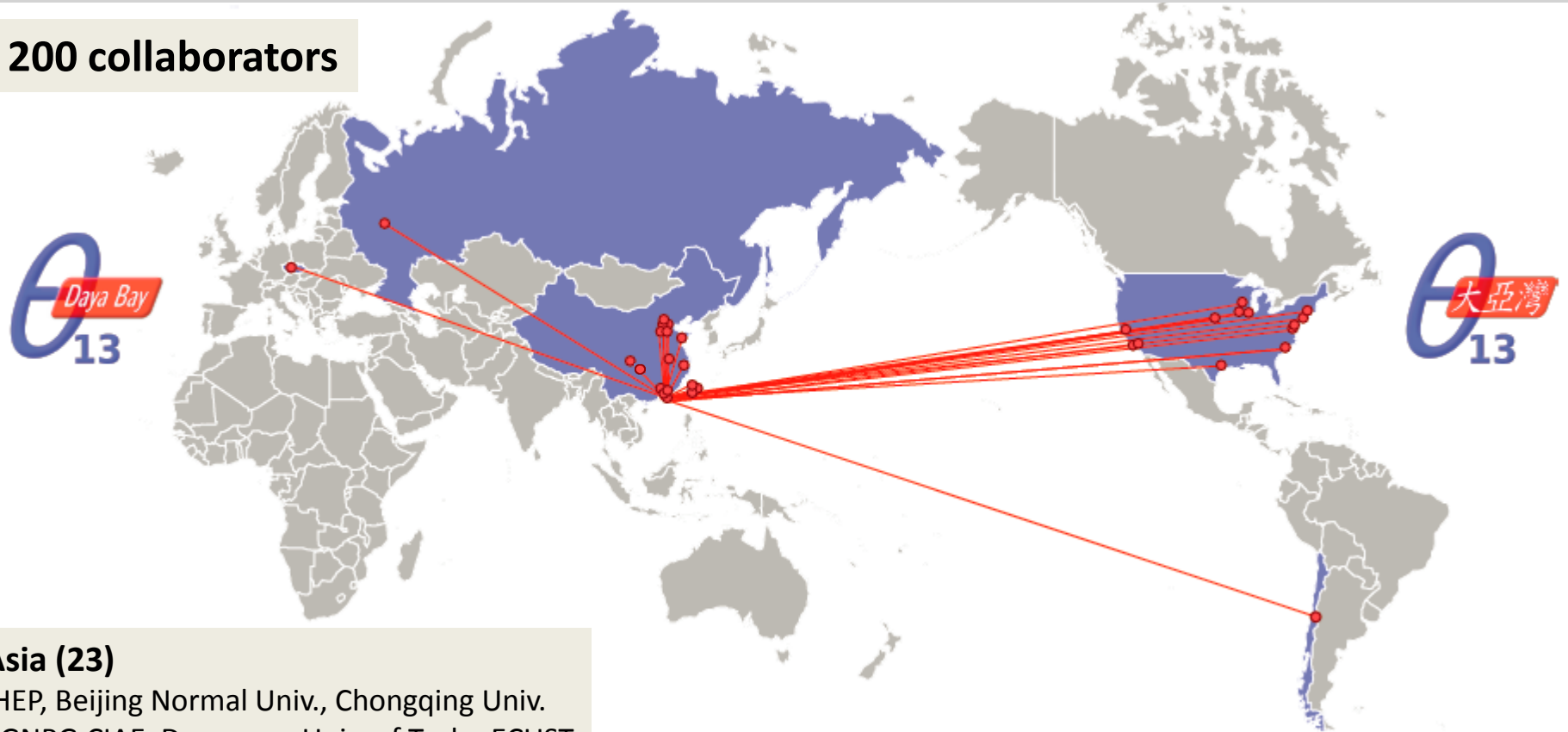
- Reactor as $\bar{\nu}_e$ source
 - Free and pure
 - No dependence on CP phase or matter effect at short baseline
- Key features of Daya Bay
 - Large thermal power ($6 \times 2.9 \text{ GW}_{\text{th}}$) and target mass ($8 \times 20 \text{ ton}$)
 - Near/far relative measurement to reduce reactor related errors
 - Identically designed multiple detectors to verify and reduce detector related errors
 - Good shielding and enough overburden to reduce backgrounds

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



The Daya Bay Collaboration

~ 200 collaborators



Asia (23)

IHEP, Beijing Normal Univ., Chongqing Univ.
CGNPG, CIAE, Dongguan Univ. of Tech., ECUST,
Nanjing Univ., Nankai Univ., NCEPU, NUDT,
Shandong Univ., Shanghai Jiao tong Univ.,
Shenzhen Univ., Tsinghua Univ., USTC, Xi'an
Jiaotong Univ., Zhongshan Univ., Univ. of
Hong Kong, Chinese Univ. of Hong Kong,
National Taiwan Univ., National Chiao Tung
Univ., National United Univ.

North America (15)

BNL, LBNL, Iowa State Univ., Illinois Inst. of
Tech., Princeton, Siena College, Temple
Univ, UC-Berkeley, Univ. of Cincinnati, Univ.
of Houston, Univ. of Illinois-Urbana-
Champaign, Univ. of Wisconsin, Virginia
Tech., William & Mary, Yale

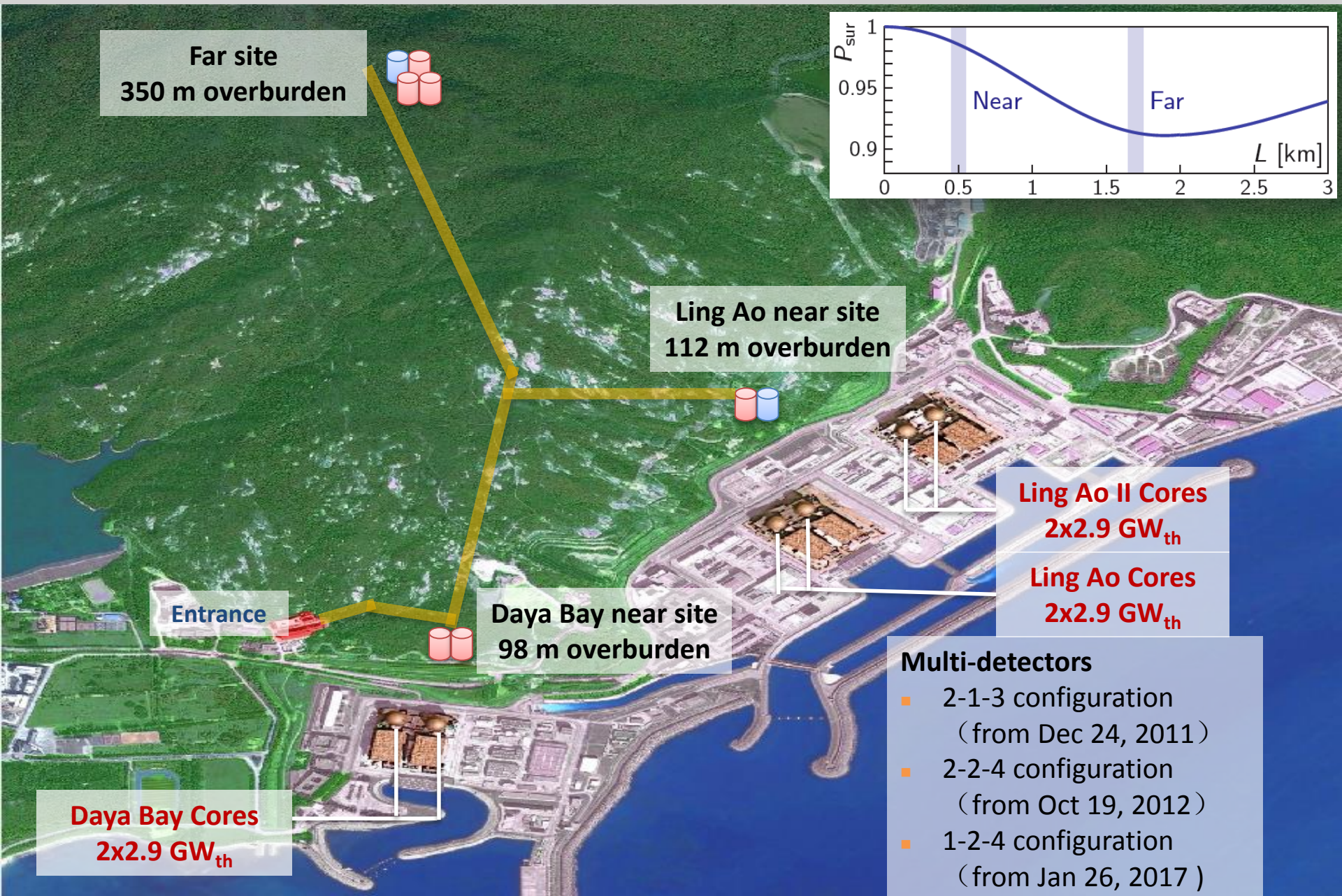
Europe (2)

JINR, Dubna, Russia; Charles
University, Czech Republic

South America (1)

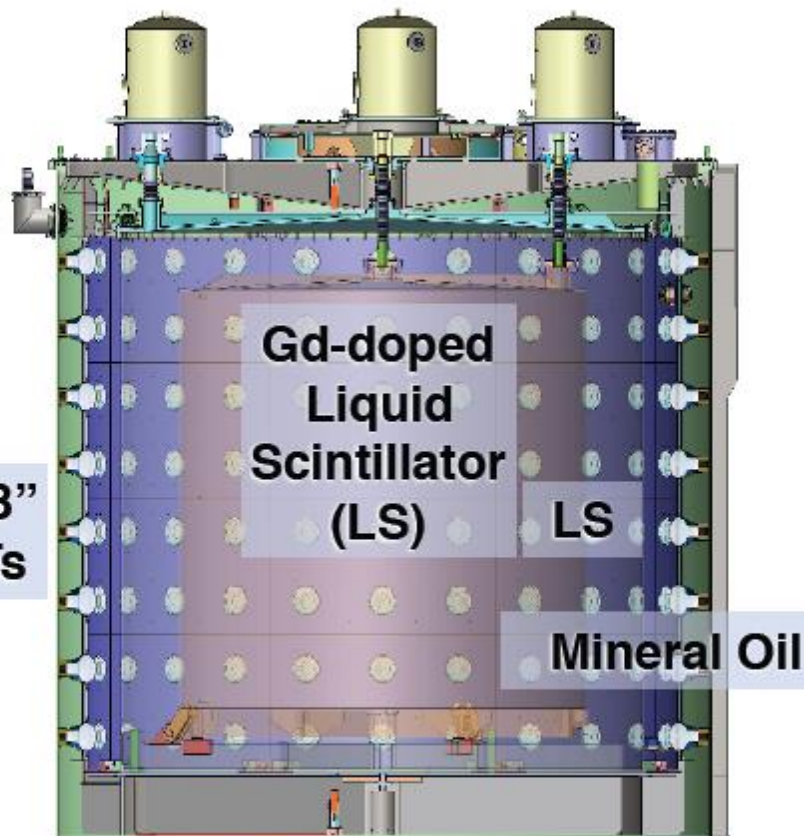
Catholic Univ. of Chile

The Daya Bay Experiment

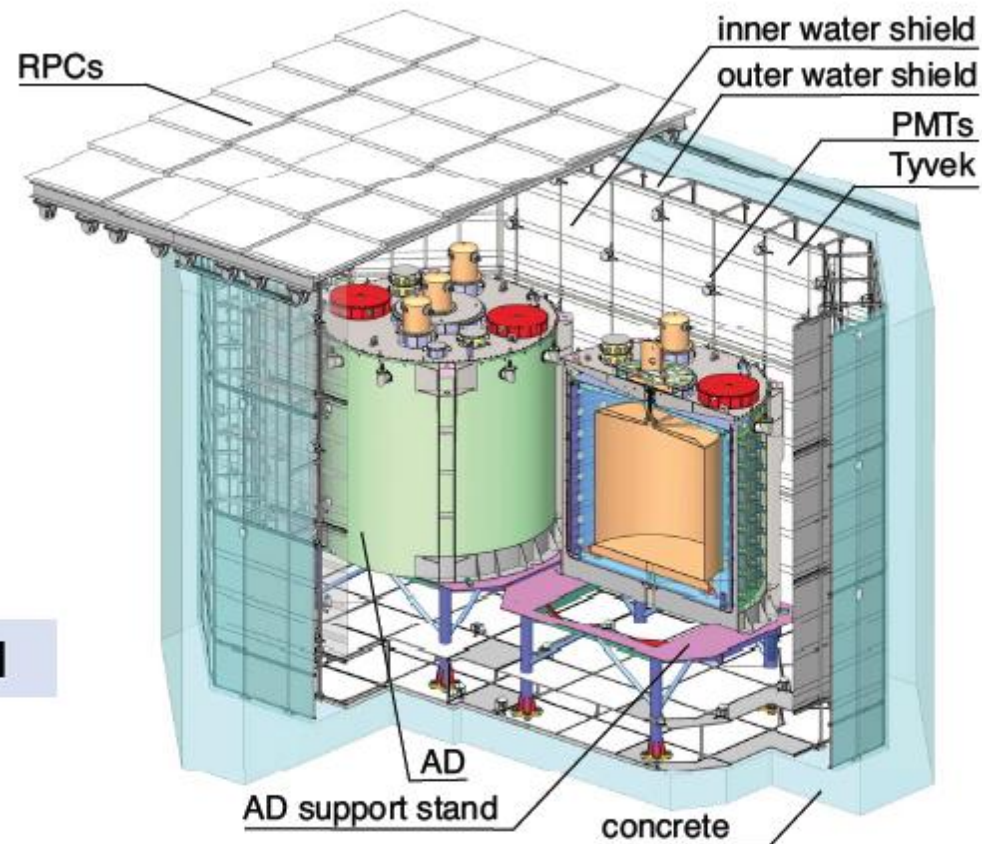


Daya Bay Detectors

- Three-zone Antineutrino Detectors NIM A **811**, 133 (2016)
- Water pool + RPC veto NIM A **773**, 8 (2015)



Energy resolution:
 $\sigma_E/E \approx 8.5\%/ \sqrt{E[\text{MeV}]}$

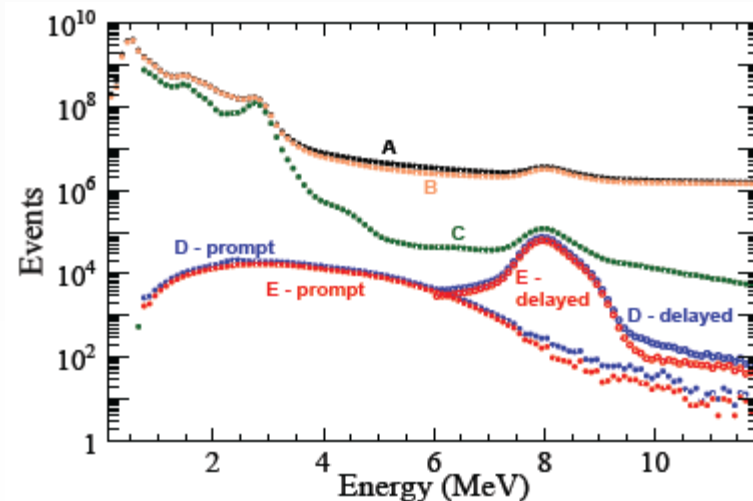
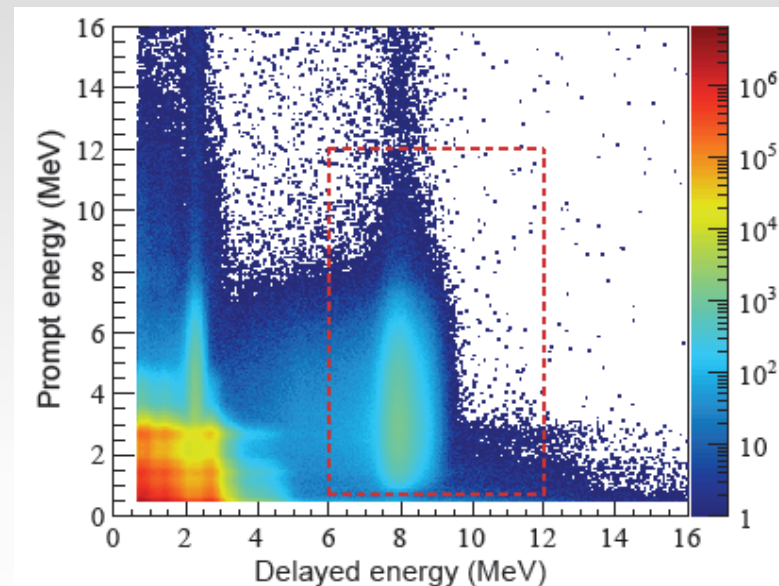


Double purpose: shield the ADs
and veto cosmic ray muons

Antineutrino Candidates Selection

- Reject PMT flashers
- Muon veto
- Prompt positron: $0.7 \text{ MeV} < E_p < 12.0 \text{ MeV}$
- Delayed neutron: $6.0 \text{ MeV} < E_d < 12.0 \text{ MeV}$
- Neutron capture time: $1 \mu\text{s} < \Delta t_{p-d} < 200 \mu\text{s}$
- Multiplicity: isolated candidate pairs

	Efficiency	Uncertainty	
		Correlated	Uncorrelated
Target protons	-	0.92%	0.03%
Flasher cut	99.98%	0.01%	0.01%
Prompt Energy cut	99.8%	0.10%	0.01%
Multiplicity cut	-	0.02%	0.01%
Capture time cut	98.7%	0.12%	0.01%
Delayed neutron cut	81.48%	0.74%	0.13%
Live time	-	0.002%	0.01%
Combined	80.2%	1.2%	0.13%



Data Set

- Summary of 1958-day data set

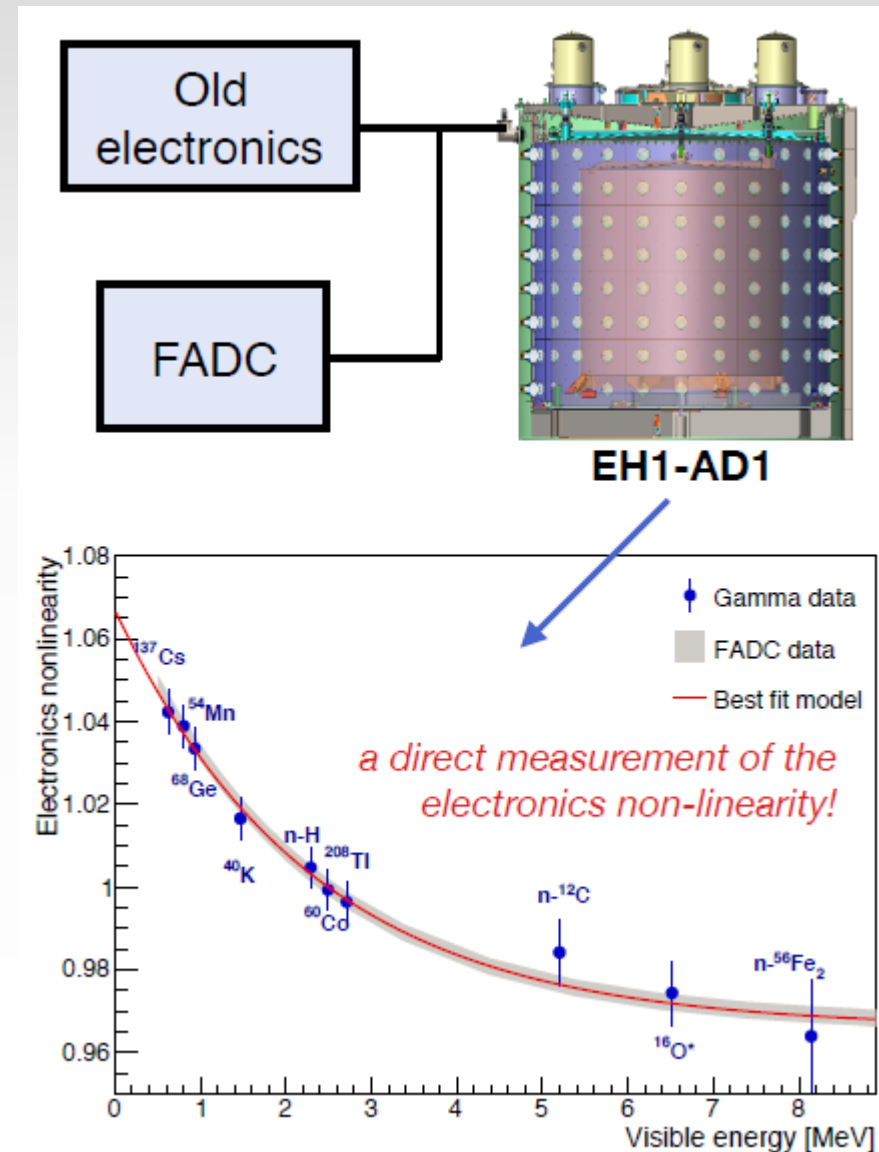
	EH1		EH2		EH3			
	AD1	AD2	AD3	AD8	AD4	AD5	AD6	AD7
$\bar{\nu}_e$ candidates	830036	964381	889171	784736	127107	127726	126666	113922
DAQ live time (days)	1536.621	1737.616	1741.235	1554.044	1739.611	1739.611	1739.611	1551.945
ε_μ	0.8261	0.8221	0.8576	0.8568	0.9831	0.9831	0.9829	0.9833
ε_m	0.9744	0.9748	0.9758	0.9757	0.9761	0.9760	0.9758	0.9758
Accidentals (day^{-1})	8.27 ± 0.08	8.12 ± 0.08	6.00 ± 0.06	5.86 ± 0.06	1.06 ± 0.01	1.00 ± 0.01	1.03 ± 0.01	0.86 ± 0.01
Fast neutron ($\text{AD}^{-1} \text{ day}^{-1}$)	0.79 ± 0.10		0.57 ± 0.07		0.05 ± 0.01			
${}^9\text{Li}/{}^8\text{He}$ ($\text{AD}^{-1} \text{ day}^{-1}$)	2.38 ± 0.66		1.59 ± 0.49		0.19 ± 0.08			
Am-C correlated 6-AD (day^{-1})	0.29 ± 0.13	0.27 ± 0.12	0.30 ± 0.14		0.24 ± 0.11	0.23 ± 0.10	0.23 ± 0.10	
Am-C correlated 8-AD (day^{-1})	0.15 ± 0.07	0.14 ± 0.06	0.12 ± 0.05	0.13 ± 0.06	0.04 ± 0.02	0.03 ± 0.02	0.03 ± 0.02	0.04 ± 0.02
${}^{13}\text{C}(\alpha, n){}^{16}\text{O}$ (day^{-1})	0.08 ± 0.04	0.06 ± 0.03	0.04 ± 0.02	0.06 ± 0.03	0.04 ± 0.02	0.04 ± 0.02	0.04 ± 0.02	0.04 ± 0.02
$\bar{\nu}_e$ rate (day^{-1})	659.36 ± 1.00	681.09 ± 0.98	601.83 ± 0.82	595.82 ± 0.85	74.75 ± 0.23	75.19 ± 0.23	74.56 ± 0.23	75.33 ± 0.24

Experiment halls	EH1	EH2	EH3
Statistical uncertainty	0.07%	0.08%	0.14%
Background/Signal	1.8%	1.4%	1.9%
$\Delta\text{B}/\text{S}$	0.11%	0.09%	0.12%

- More than 3.9 million antineutrino candidates, > 60% increase of statistics compared with the previous result

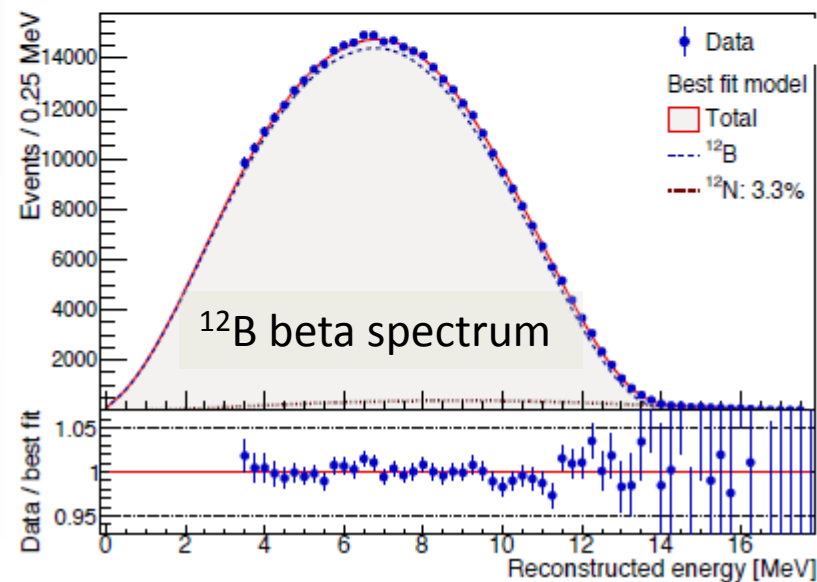
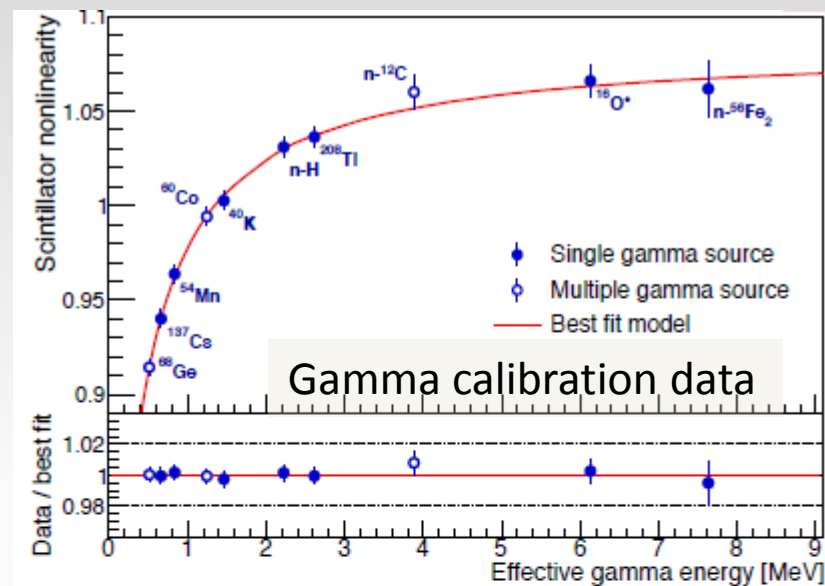
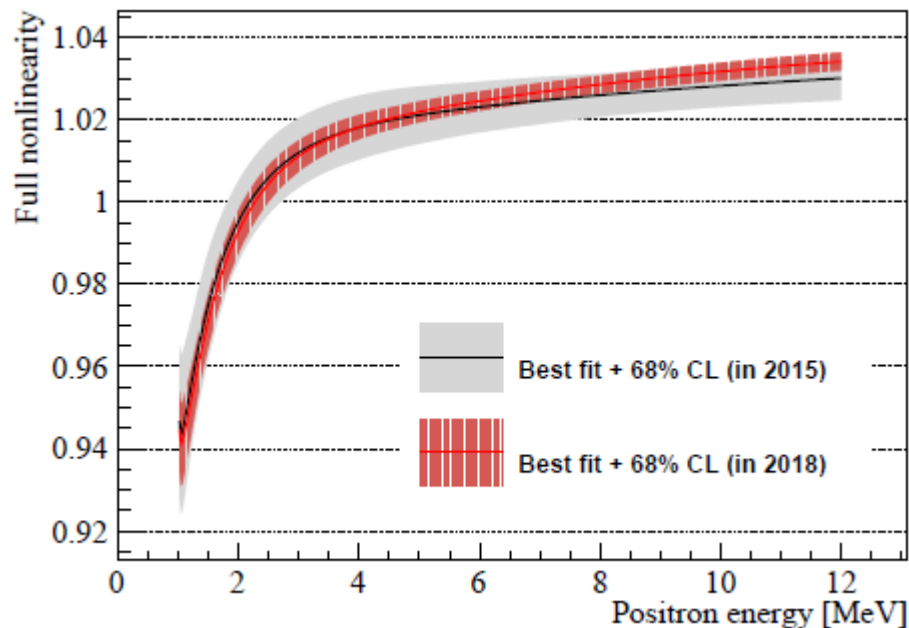
Improved Energy-Scale Calibration

- Energy scale is nonlinear due to two major sources
 - Scintillation quenching + Cherenkov light
 - Electronics response
- Carried out two key measurements
 - End of 2015: installation of a full FADC readout system in EH1-AD1, taking data simultaneously with standard electronics
 - Early 2017: deployment of ^{60}Co calibration sources with different encapsulating materials, to constrain optical shadowing effects



Energy Nonlinearity Model

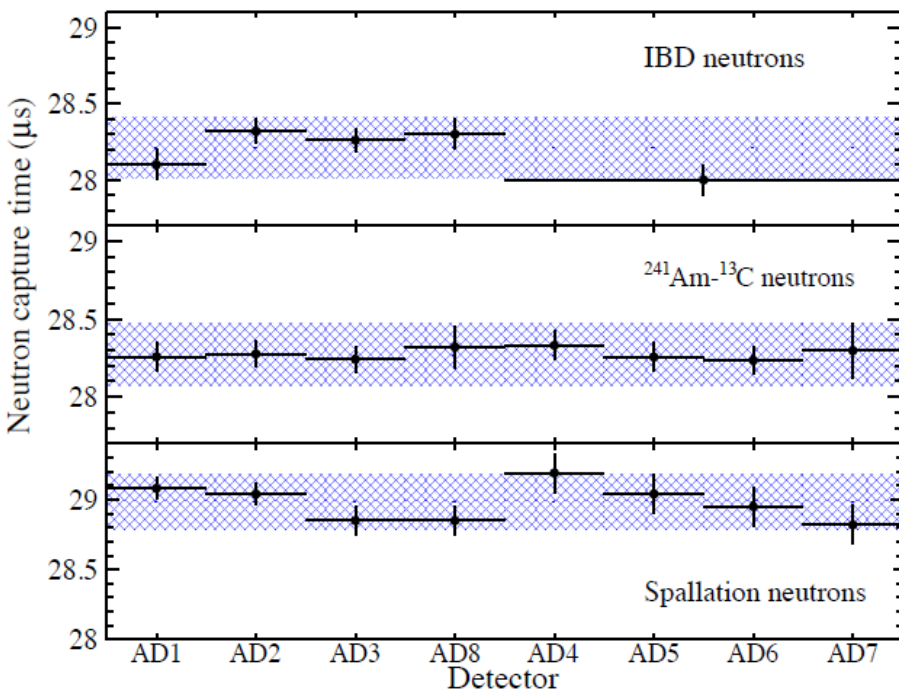
- Model built by combined fit to mono-energetic gamma lines and ^{12}B beta-decay spectrum
- Uncertainty reduced to be $\sim 0.5\%$ from previous $\sim 1.0\%$



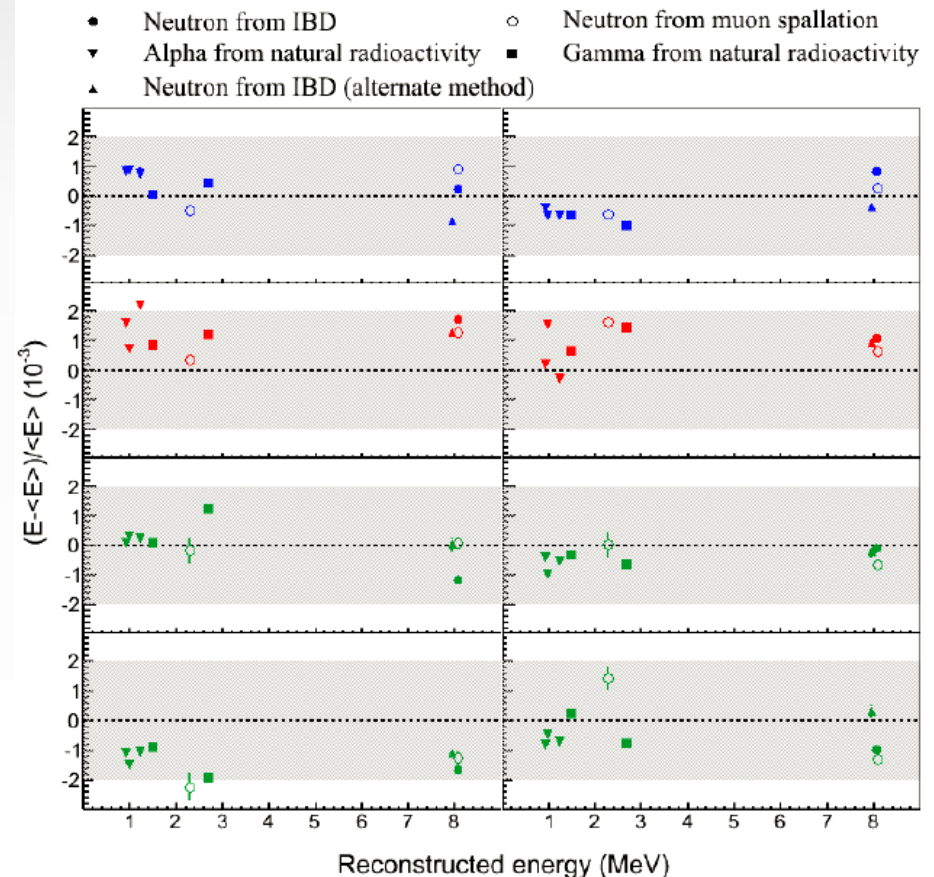
Relative Detection Efficiency

- Achieve a relative detection-efficiency uncertainty of 0.13%

Neutron capture time difference $\pm 2\mu\text{s}$
→ relative Gd capture fraction
uncertainty < 0.1%



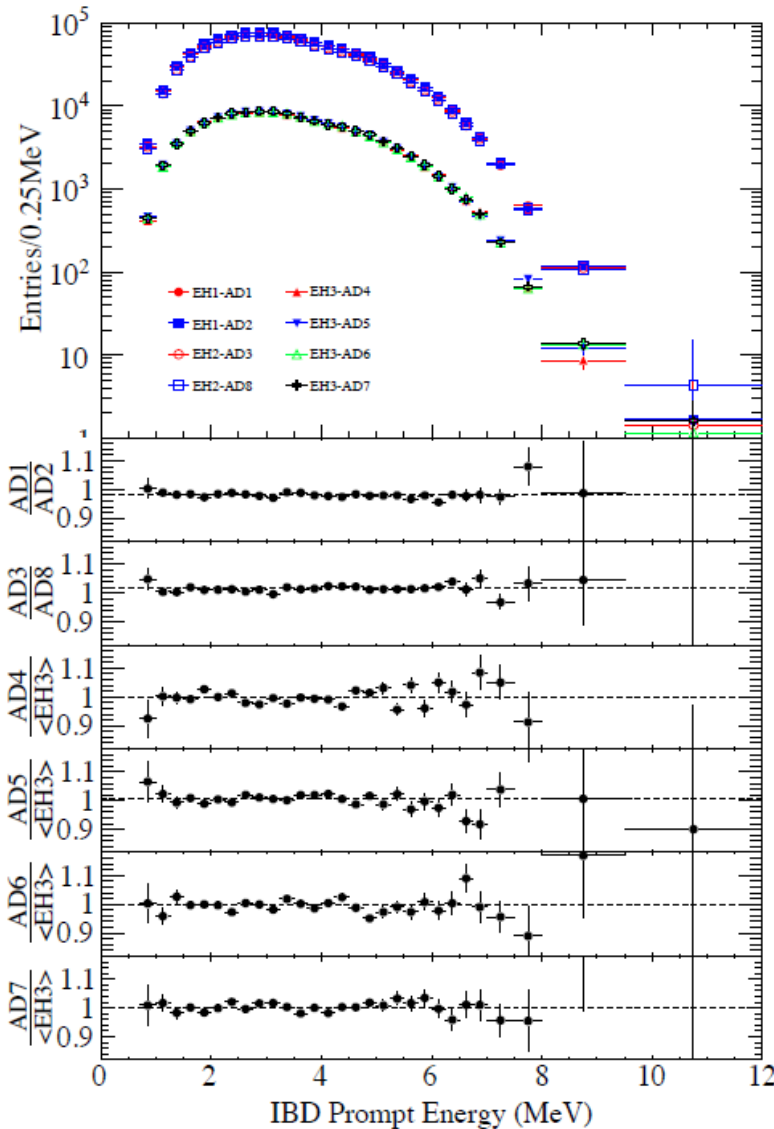
Relative energy scale uncertainty < 0.2%



Side-by-side Comparison

prompt energy spectrum

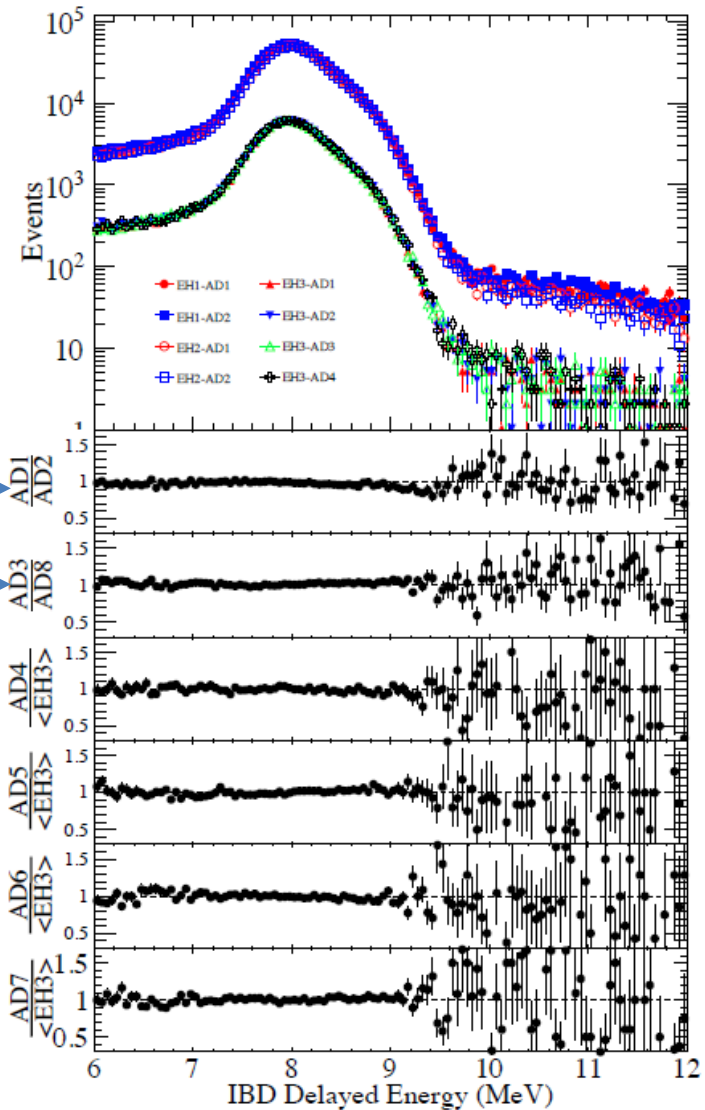
Delayed energy spectrum



EH1

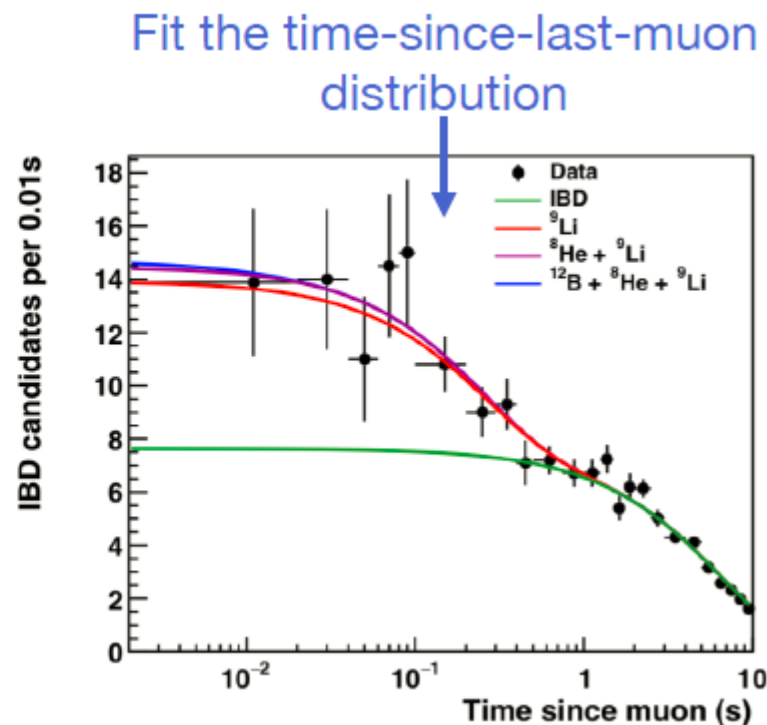
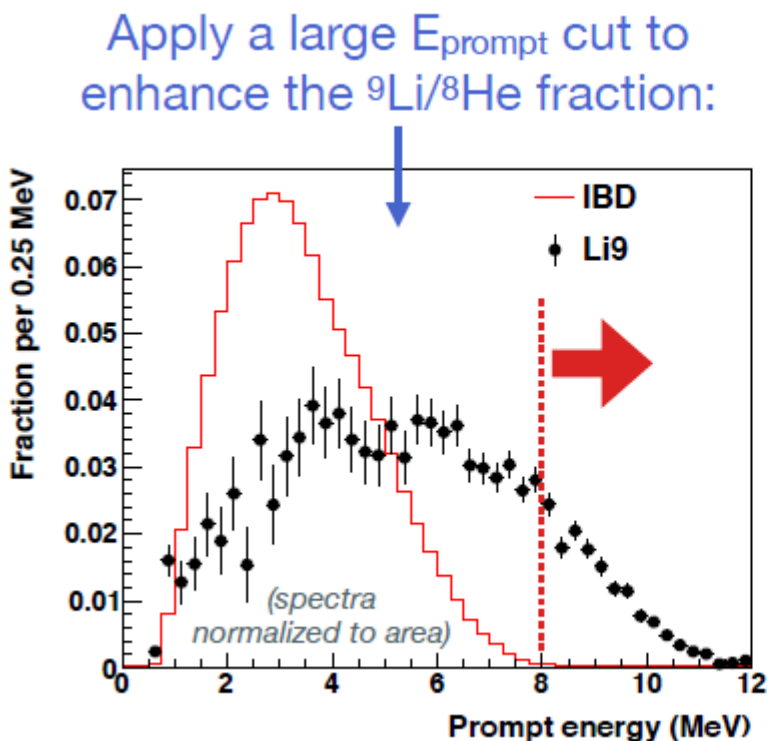
EH2

EH3



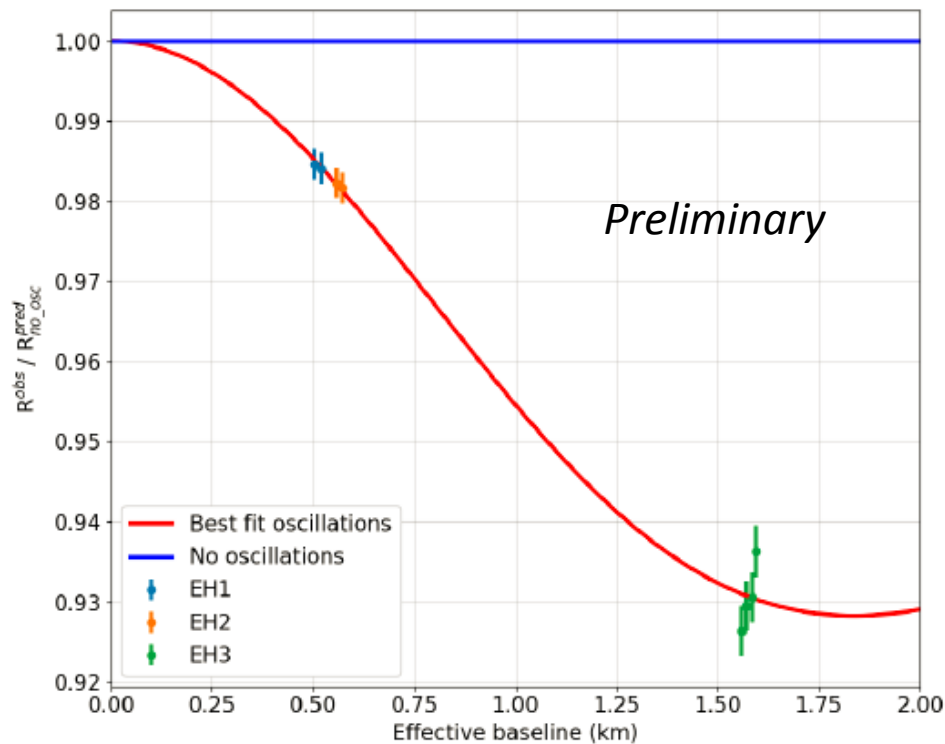
Improved ${}^9\text{Li}/{}^8\text{He}$ Estimation

- ${}^9\text{Li}/{}^8\text{He}$ β -n decay is the dominant background produced by cosmogenic muons.
- Uncertainty of ${}^9\text{Li}/{}^8\text{He}$ reduced from 50% to 30% by new analysis method and larger data sample

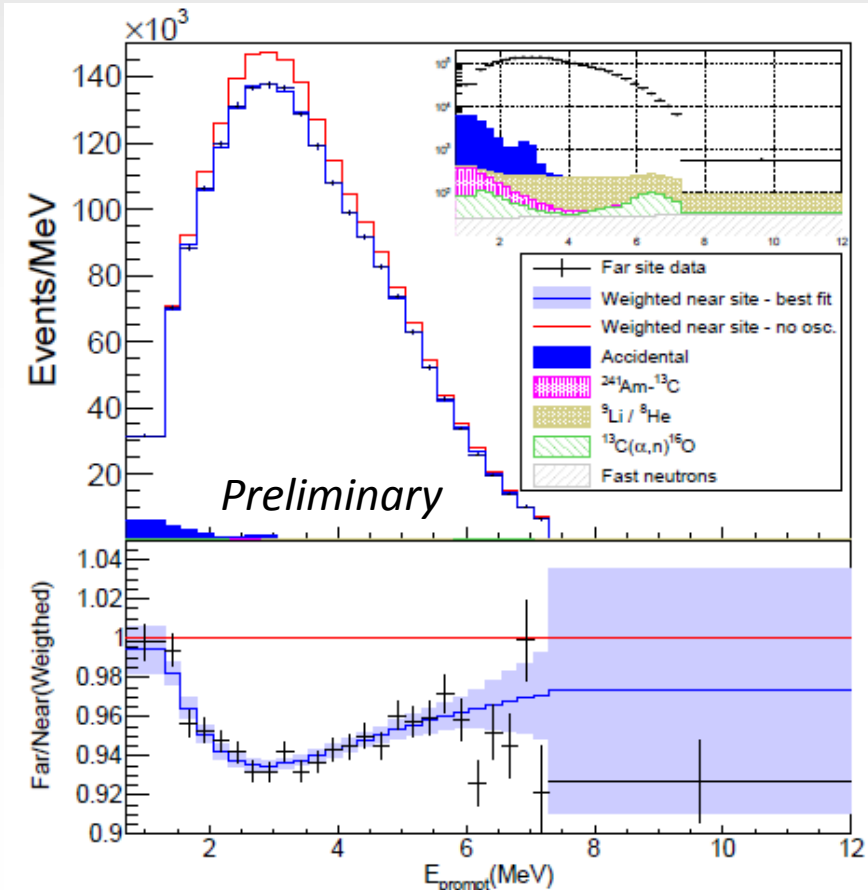


Oscillation Results with 1958 Days

- The measured rate deficit and the spectrum distortion are consistent with three-neutrino framework.



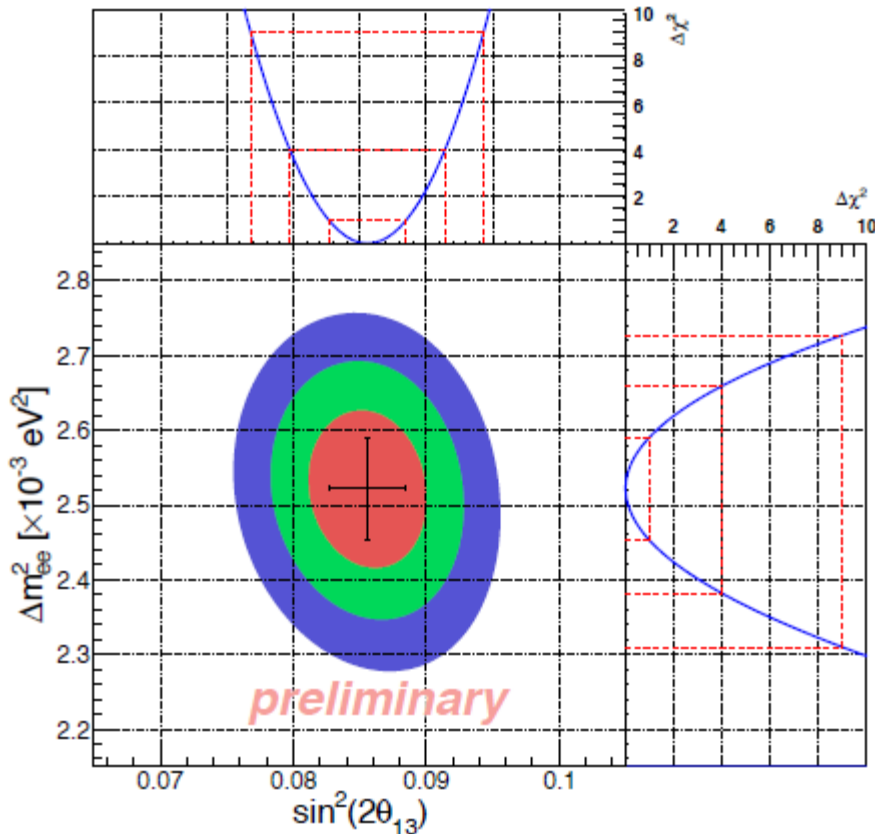
Rate-only $\chi^2/ndf = 8.8/6$



Rate+shape $\chi^2/ndf = 148/154$

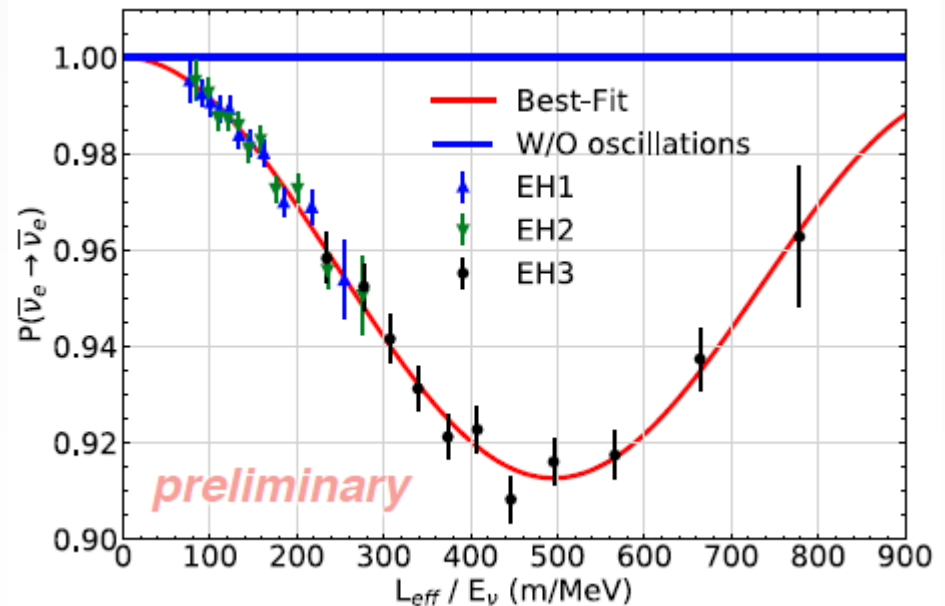
Oscillation Results with 1958 Days

- $\sin^2 2\theta_{13}$ uncertainty is 3.4% and $|\Delta m^2_{ee}|$ uncertainty is 2.8%
- Statistical uncertainty contributes 60% for $\sin^2 2\theta_{13}$ and 50% for $|\Delta m^2_{ee}|$



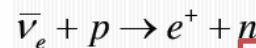
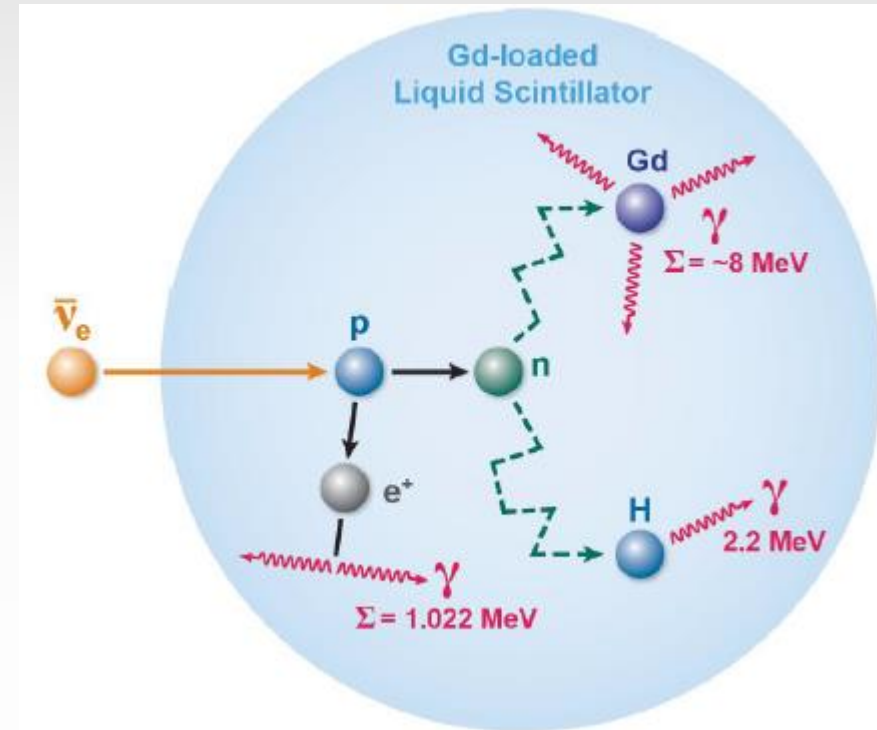
$$\sin^2 2\theta_{13} = 0.0856 \pm 0.0029$$

$$|\Delta m^2_{ee}| = (2.52 \pm 0.07) \times 10^{-3} \text{ eV}^2$$



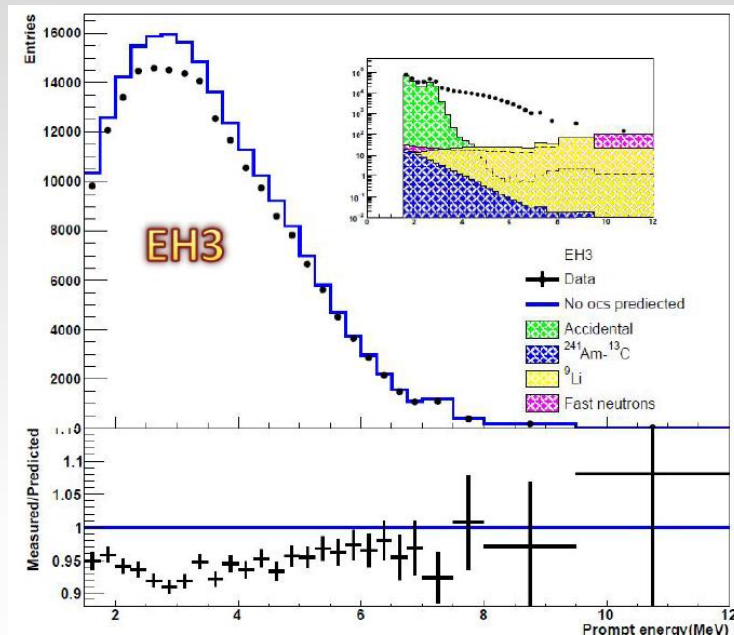
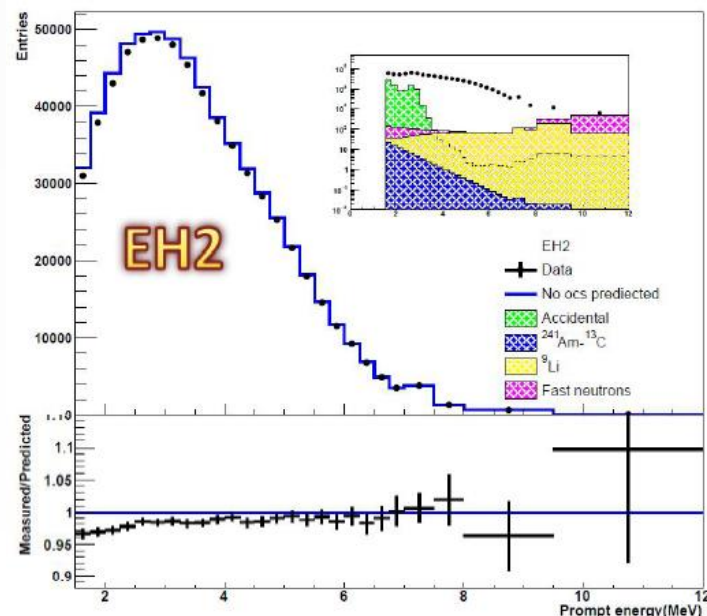
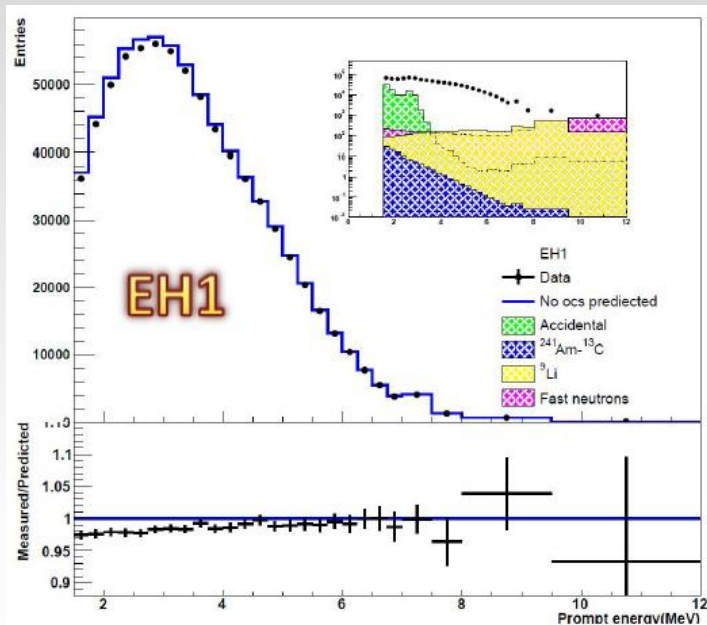
An Independent Measurement of Oscillation

- Select nH capture events as another tag for antineutrino candidates
- Key feature
 - High statistics (additional 20 ton LS target per AD)
 - Different systematic uncertainties from nGd analysis
- Challenges
 - High accidental background
 - Large energy leakage
- Strategy
 - Raise prompt energy cut (> 1.5 MeV)
 - Require prompt to delay distance cut (< 0.5 m)



$+H \rightarrow D + \gamma$	2.2 MeV	200 μs
$+Gd \rightarrow Gd^* \rightarrow Gd + \gamma's$	8MeV	30 μs

nH Spectrum Measurement



- Clear spectrum distortion observed.
- The oscillation analysis result will be released soon.

Details in poster (E_51) by Chao Li

Summary

- The most precise $\sin^2 2\theta_{13}$ measurement in the world

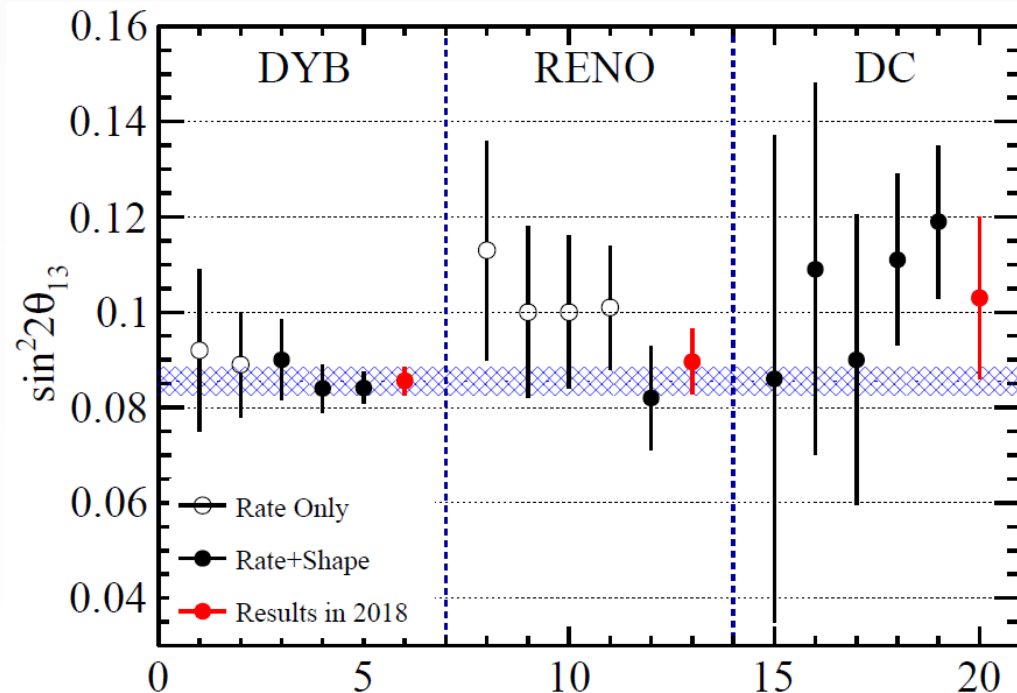
$$\sin^2 2\theta_{13} = 0.0856 \pm 0.0029$$

$$|\Delta m_{ee}^2| = (2.52 \pm 0.07) \times 10^{-3} \text{ eV}^2$$

Article in
preparation

- An independent measurement of oscillation by spectral analysis of nH sample will be released soon.

- Daya Bay will run until 2020 and will achieve <3% precision on $\sin^2 2\theta_{13}$



Thanks!