XVI International Workshop on Neutrino Telescopes

2-6 March 2015 *Palazzo Franchetti, Istituto Veneto di Scienze, Lettere ed Arti*

Recent results from Daya Bay

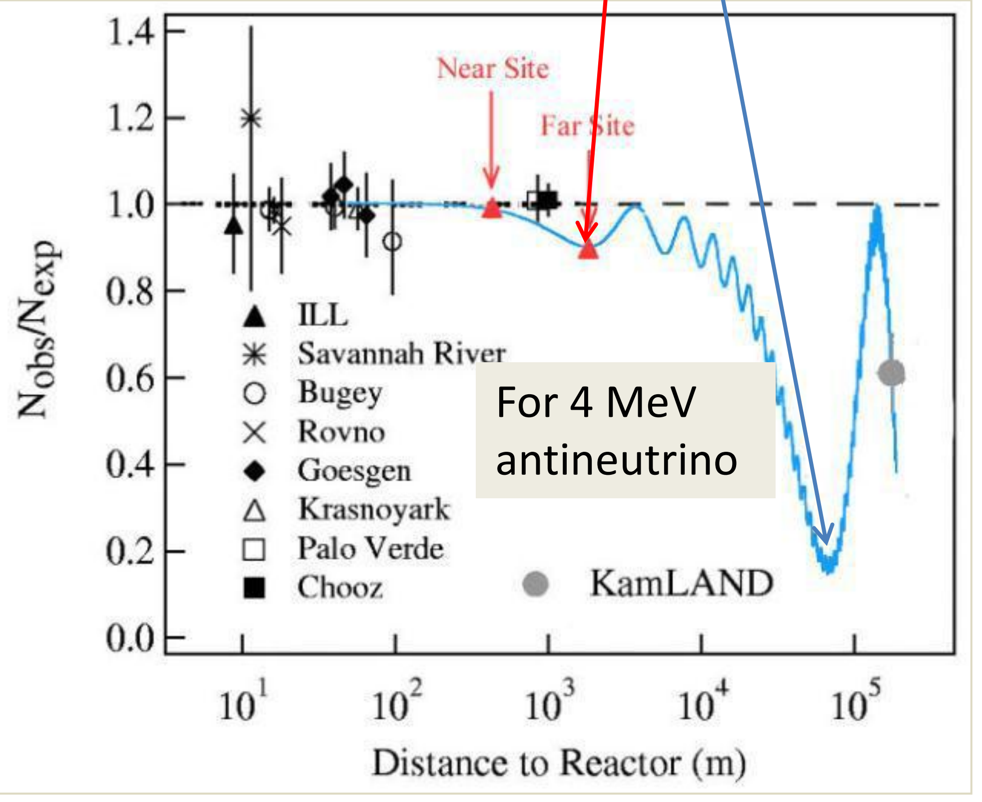
Liang Zhan (Institute of High Energy Physics)

On behalf of the Daya Bay Collaboration

Reactor antineutrino oscillation

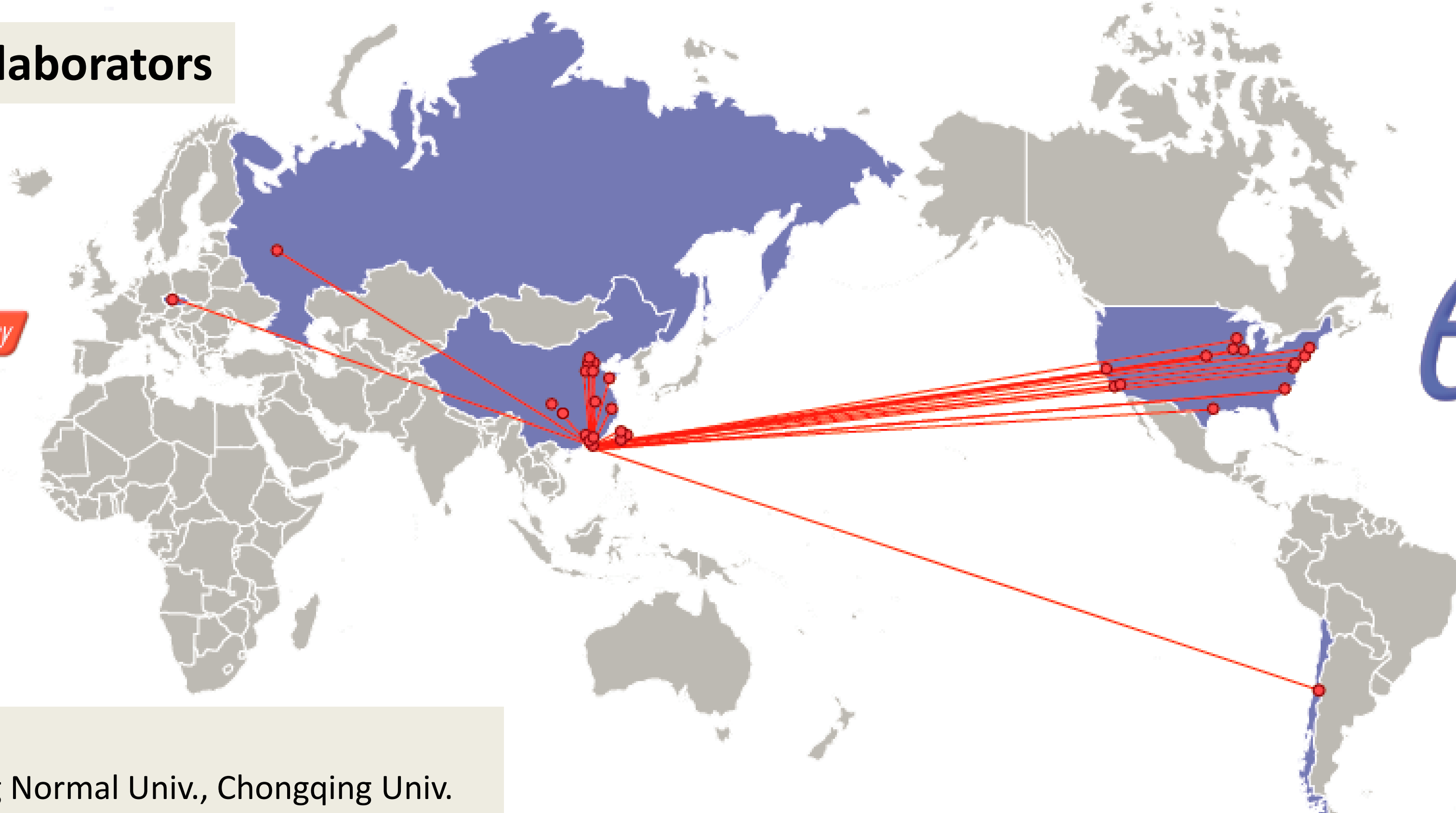
- Reactor as $\overline{\nu}_e$ source
  - Free and pure
  - No dependence on CP phase or matter effect at short baseline
- Precision measurement of θ_{13} at Daya Bay
  - Large thermal power (6x2.9 GW_{th}) and target mass (8x20 kt)
  - Near/far relative measurement to reduce reactor related errors
  - Identically designed multiple detectors to verify and reduce detector related errors
  - Good shielding and enough overburden to reduce backgrounds

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



The Daya Bay Collaboration

~230 collaborators



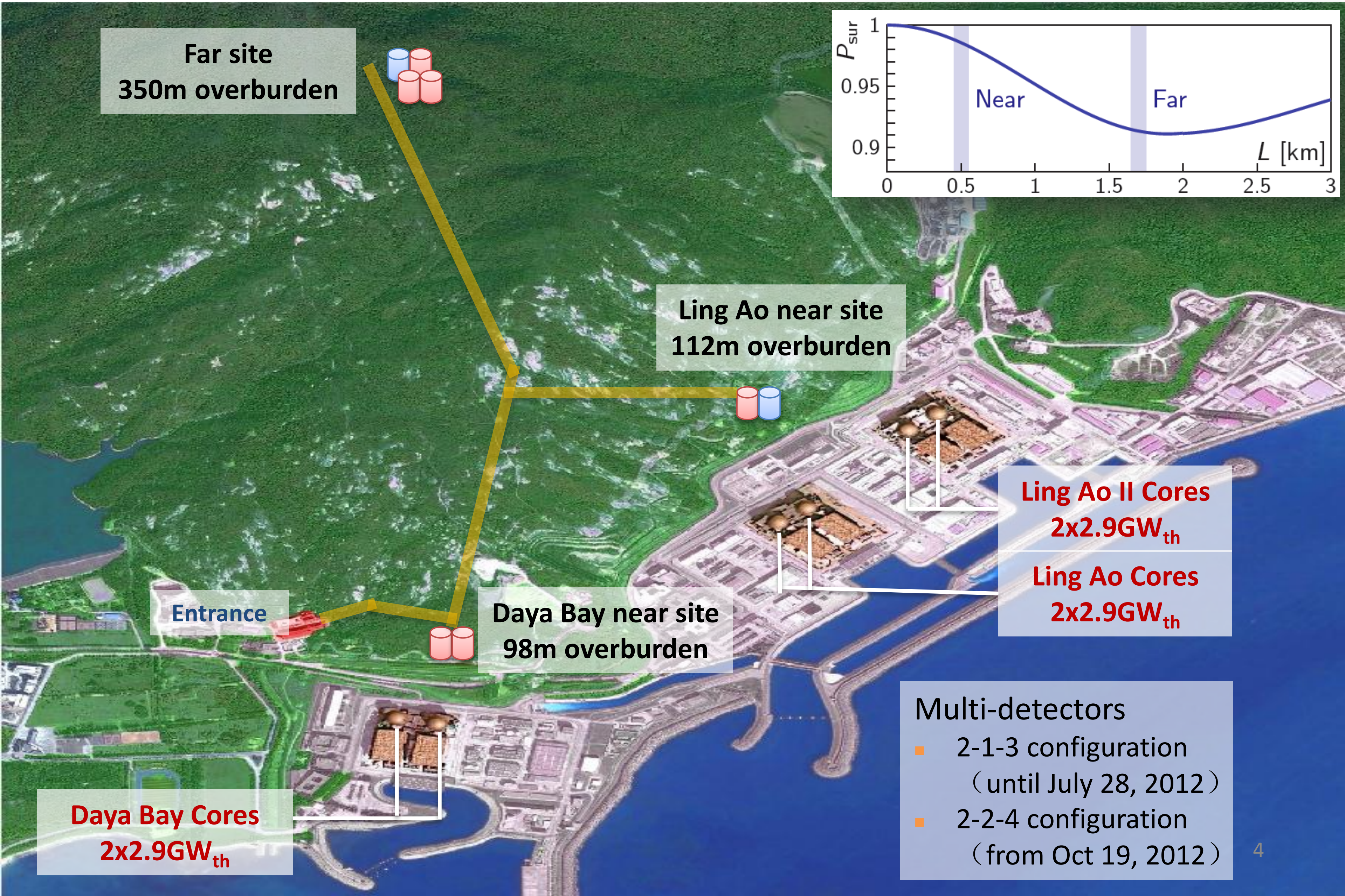
Asia (22)
IHEP, Beijing Normal Univ., Chongqing Univ. Chengdu Univ. of Sci. and Tech., CGNPG,CIAE, Dongguan Univ. of Tech., Nanjing Univ., Nankai Univ., NCEPU, Shandong Univ., Shanghai Jiao tong Univ., Shenzhen Univ., Tsinghua Univ., USTC, Xi'an Jiaotong Univ., Zhongshan Univ., Univ. of Hong Kong, Chinese Univ. of Hong Kong, National Taiwan Univ., National Chiao Tung Univ., National United Univ.

North America (17)
BNL, Caltech, LBNL, Iowa State Univ., Illinois Inst. Tech., Princeton, RPI, UC-Berkeley, UCLA, Univ. of Cincinnati, Univ. of Houston, Univ. of Wisconsin, William & Mary, Virginia Tech., Univ. of Illinois-Urbana-Champaign, Siena , Temple Univ, Yale

Europe (2)
JINR, Dubna, Russia; Charles University, Czech Republic

South America (1)
Catholic Univ. of Chile

The Daya Bay experiment

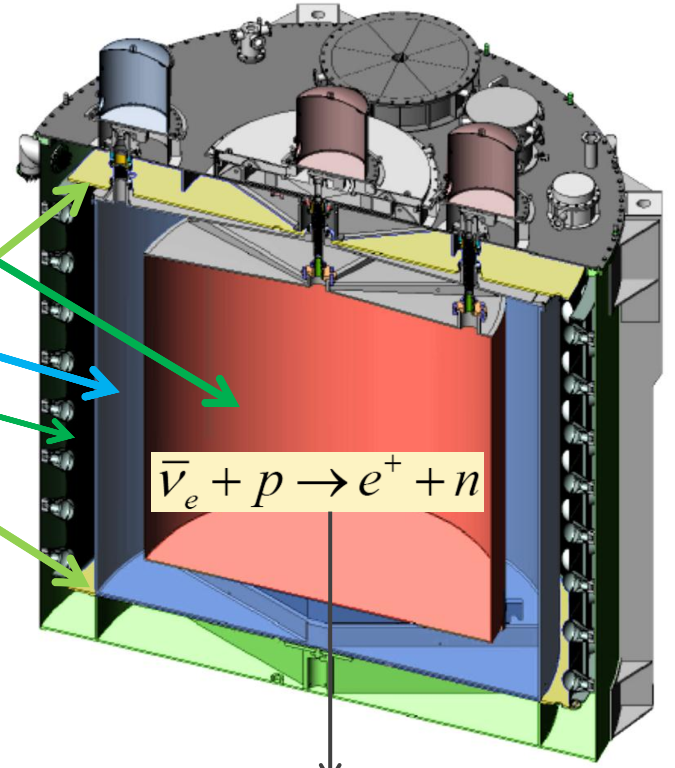


Multi-detectors

- 2-1-3 configuration （until July 28, 2012）
- 2-2-4 configuration （from Oct 19, 2012）

Antineutrino detector

- Three zones structure:
  - Target: 20 t 0.1% Gd-loaded scintillator
  - γ-catcher: 20 t scintillator
  - Buffer shielding: mineral oil
- Top and bottom optical reflectors double the photon coverage.
- 192 8'' PMTs collect ~160 p.e./MeV

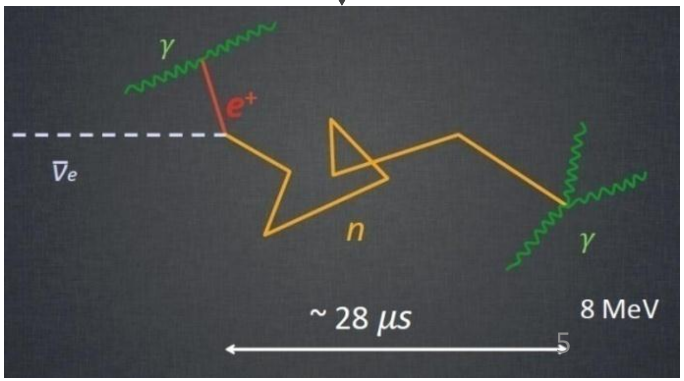


8 identically designed detectors to reduce systematic uncertainties

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

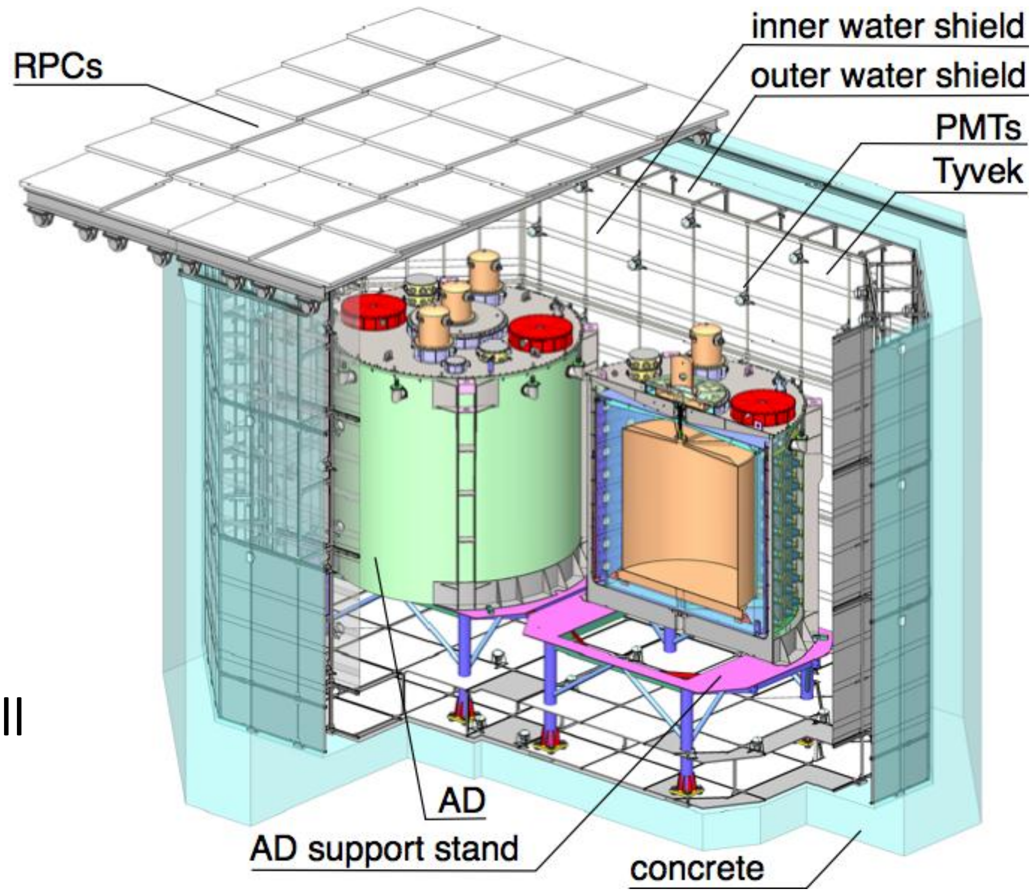
Target mass

efficiency

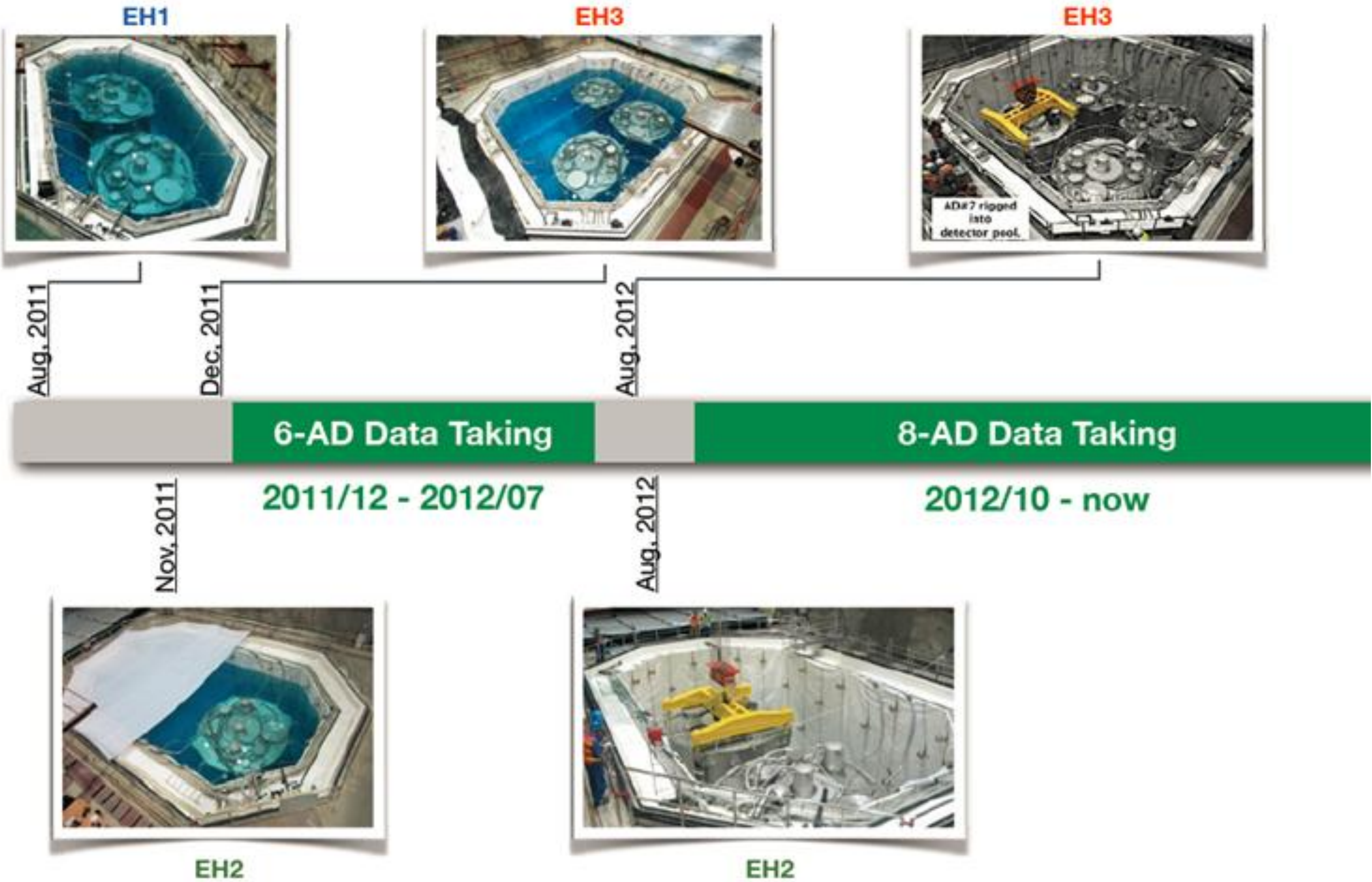


Muon veto system

- Water Cherenkov detector
  - Two layers: inner (> 1.5m) and outer (1m) layers
  - Also for shielding
  - 288 8” PMTs in each near hall
  - 384 8” PMTs in Far Hall
- 4-layer RPC modules above pool
  - 54 modules in each near hall
  - 81 modules in Far hall
  - 2 telescope modules/hall

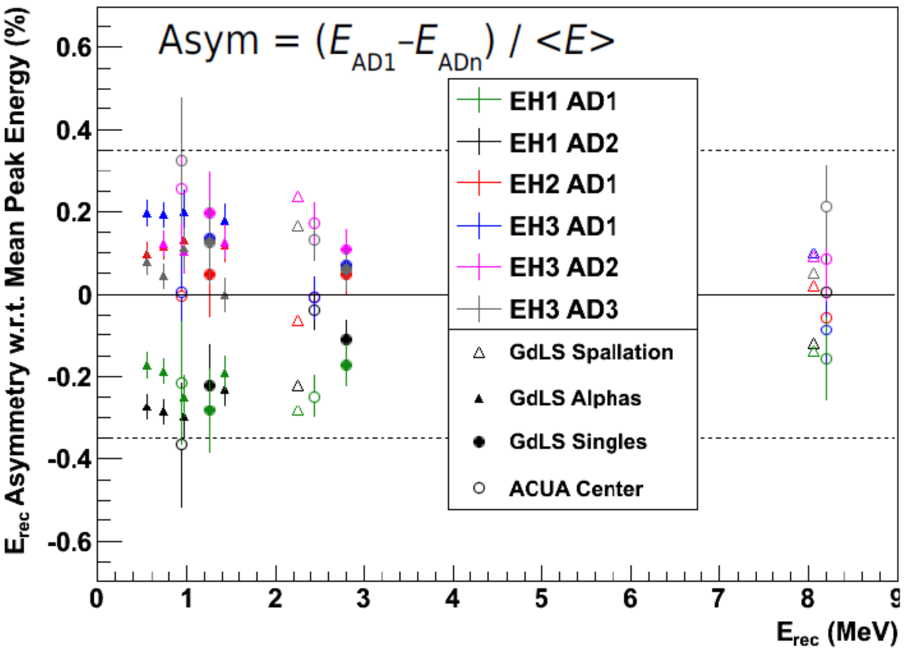


Timeline of detector installation

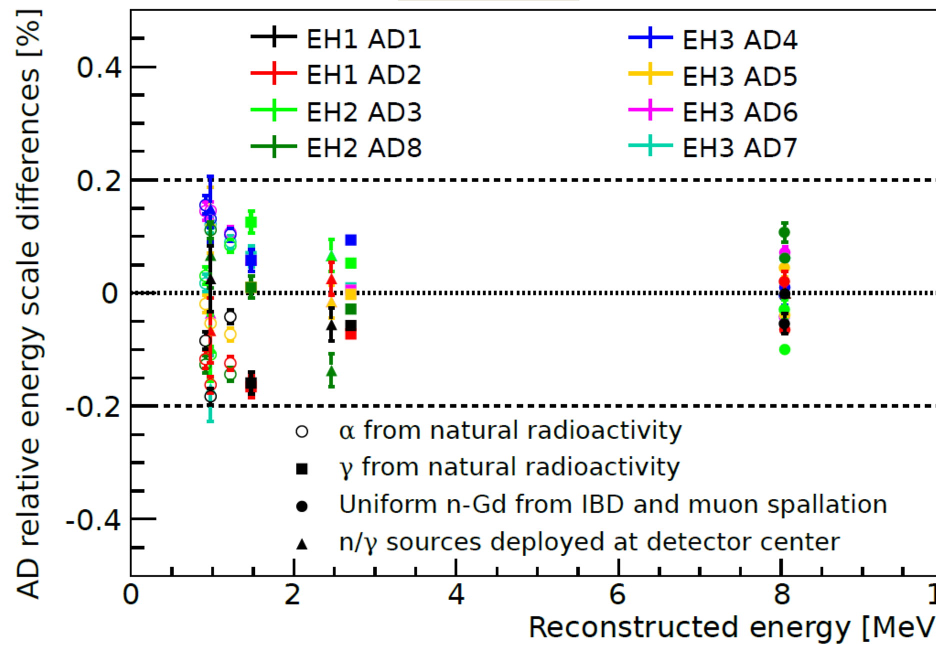


Relative energy scale

6AD



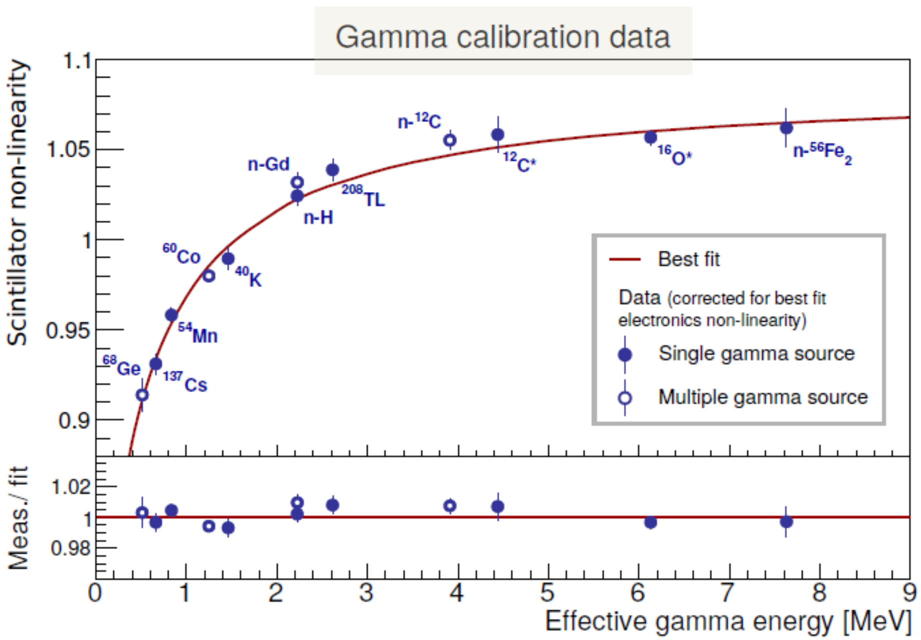
6+8AD

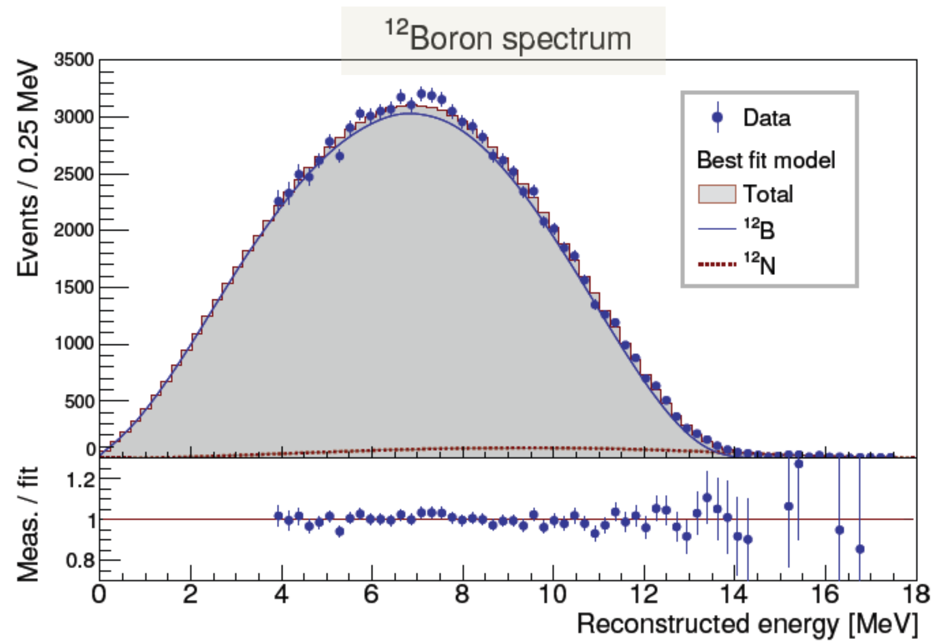


ACU: ^{60}Co, ^{68}Ge, AmC
Spallation: nGd, nH
Gamma: ^{40}K, ^{208}Tl
Alpha: ^{212}Po, ^{214}Po, ^{216}Po

- < 0.2% variation in reconstructed energy between ADs
- Improved from 0.35% in 2013 which was between 6 detectors.

Energy non-linearity calibration



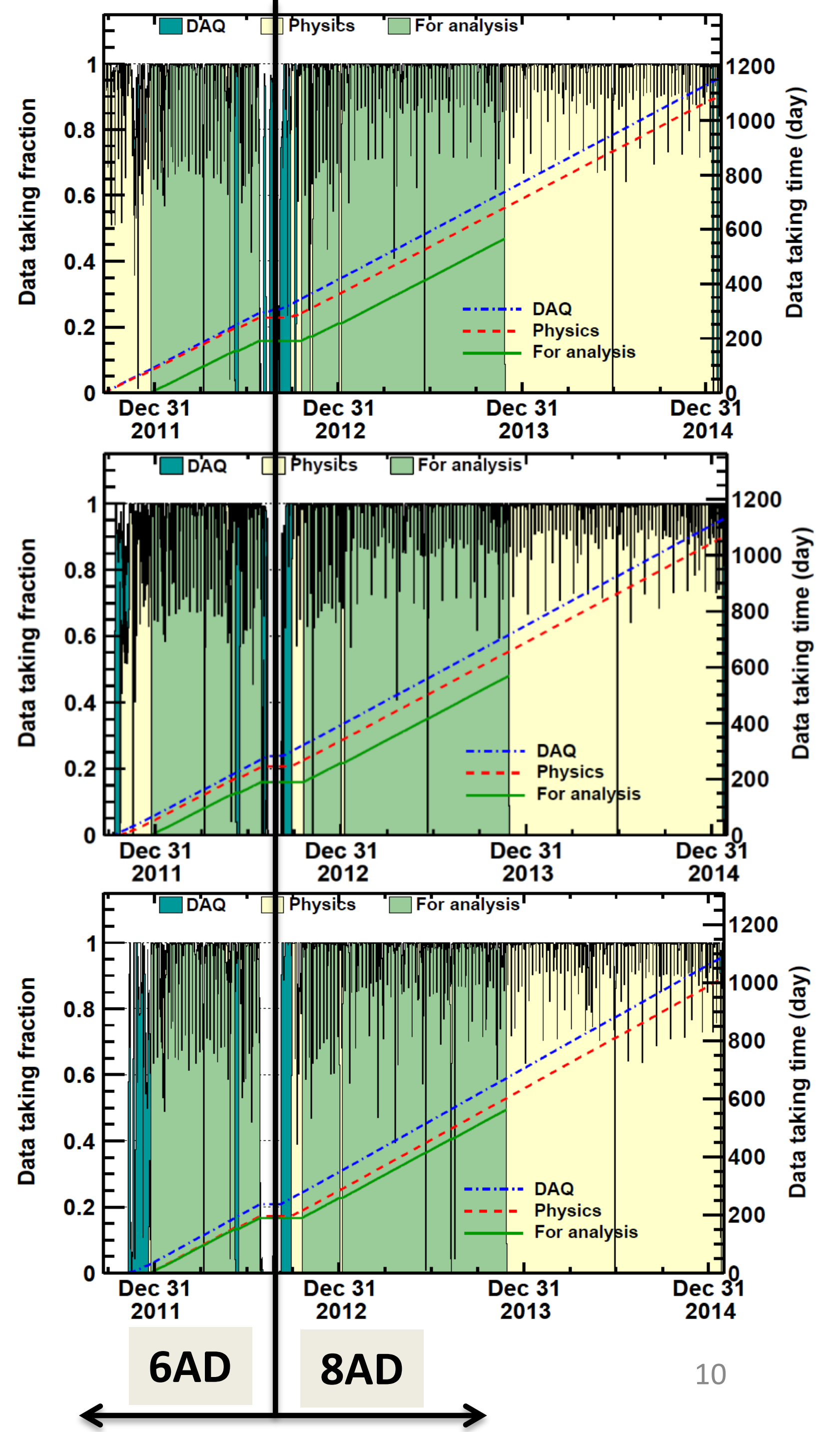


- Two major sources of non-linearity
  - Scintillator response: modeled with Birks' law and Cherenkov fraction
  - Electronics response: modeled with MC and single channel FADC measurement
- Combined fit to mono-energetic gamma lines and ^{12}B beta-decay spectrum
- Validation with ^{208}Th, ^{214}Bi beta-decay spectrum, Michel electron spectrum, and scintillator quenching measurement using neutron beams and Compton scattering electrons.

Analysis data set

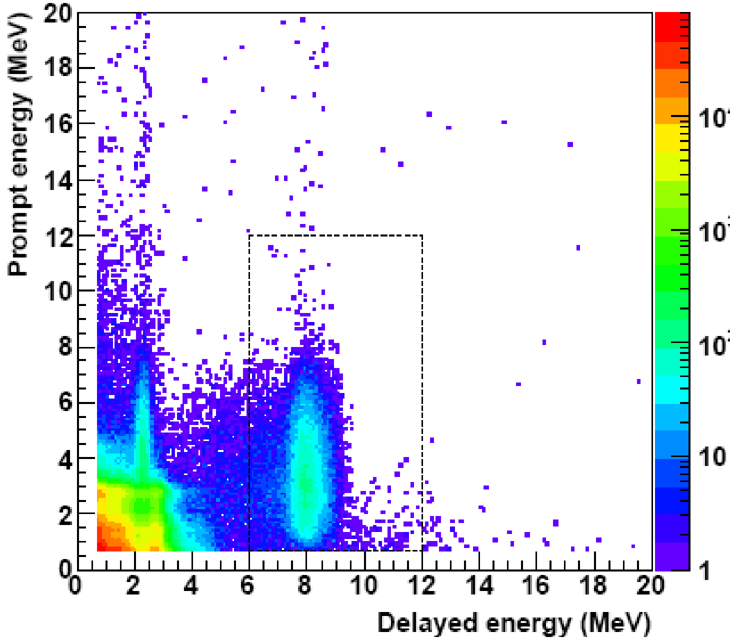
- 6AD period (217 days)
  - 2011/12/24 - 2012/07/28
- 8AD period (404 days)
  - 2012/10/19 - 2013/11/27
- Past oscillation results
  - θ_{13}, *PRL.* ***108****, 171803 (2012)* [55 days]
  - θ_{13}, *CPC* ***37****, 011001 (2013)* [139 days]
  - θ_{13} & Δm^2_{ee}, *PRL.* ***112****, 061801 (2014)* [217 days]

- Latest analysis :
  - 6+8 AD combined nGd θ_{13} analysis [621 days]
  - 6AD absolute reactor flux and spectrum measurement [217 days]
  - 6AD nH θ_{13} rate analysis, *PRD* ***90****, 071101(R) (2014)* [217 days]
  - 6AD light sterile neutrino search, *PRL* ***113****, 141802 (2014)* [217 days]

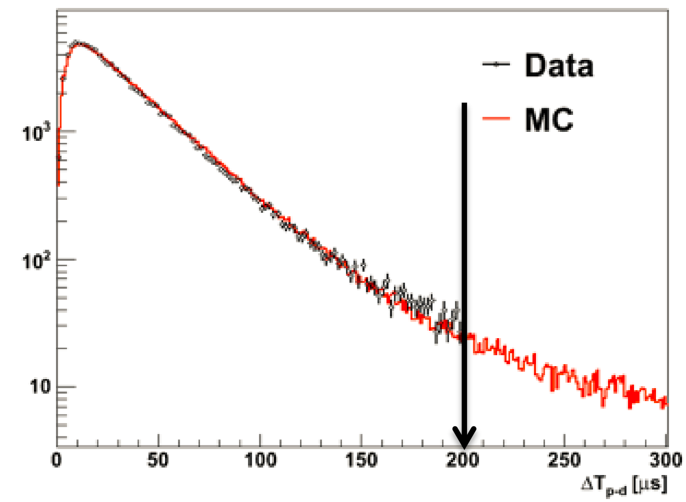


Antineutrino candidates selection (IBD)

- Reject PMT flashers
- Muon veto
  - Water pool muon: reject 0.6 ms
  - AD muon (>20 MeV): reject 1 ms
  - AD shower muon (>20 GeV): reject 1 s
- Prompt positron: 0.7 MeV < E_p < 12.0 MeV
- Delayed neutron: 6.0 MeV < E_d < 12.0 MeV
- Neutron capture time: 1 μs < $\Delta t_{p\text{-}d}$ < 200 μs
- Multiplicity: isolated candidate pairs

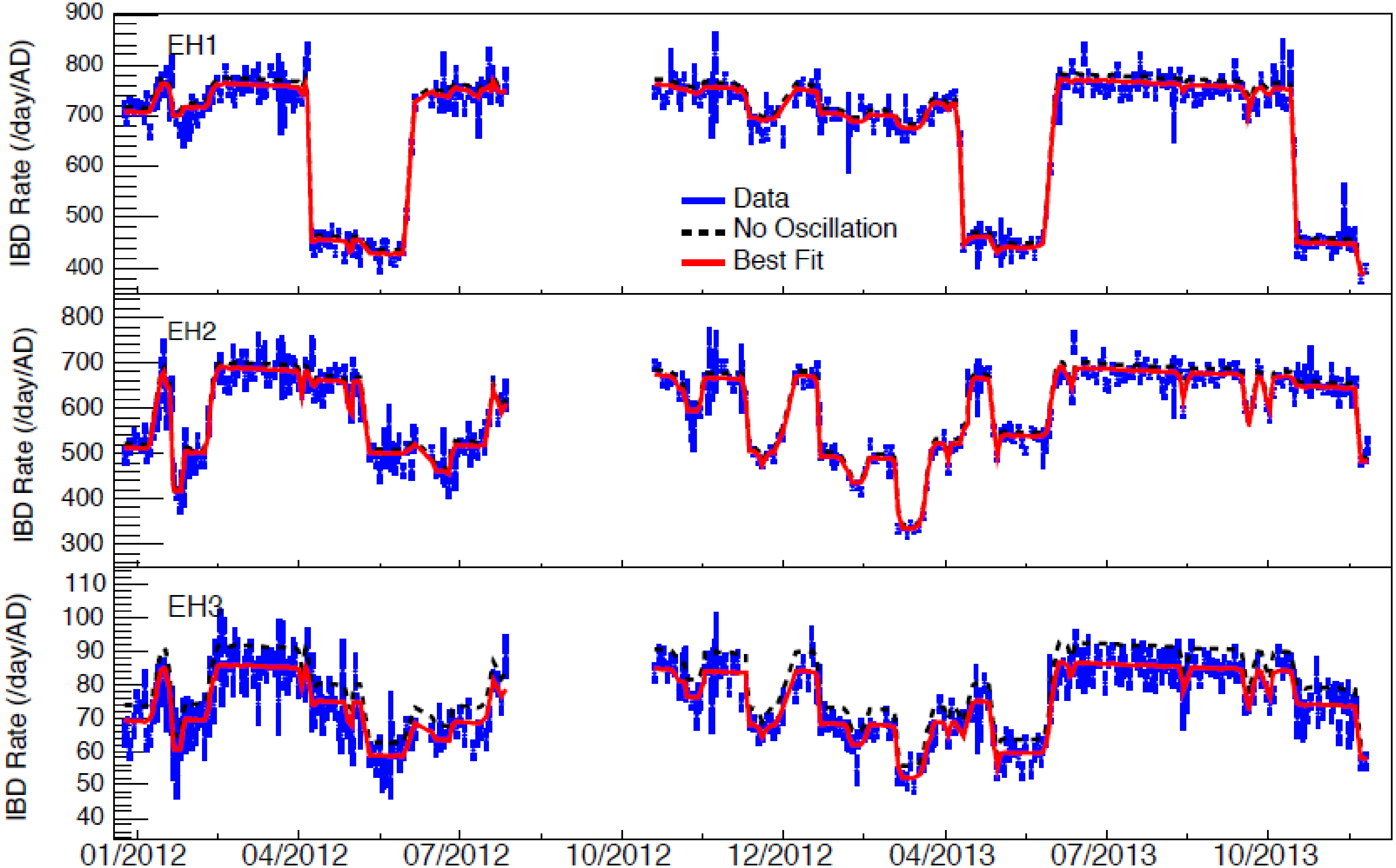


	Efficiency	Uncertainty	
		Correlated	Uncorrelated
Target Protons		0.47%	0.03%
Flasher cut	99.98%	0.01%	0.01%
Delayed Energy cut	92.7%	0.97%	0.12%
Prompt Energy cut	99.81%	0.10%	0.01%
Capture time cut	98.70%	0.12%	0.01%
Gd capture ratio	84.2%	0.95%	0.10%
Spill-in correction	104.9%	1.50%	0.02%
Combined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



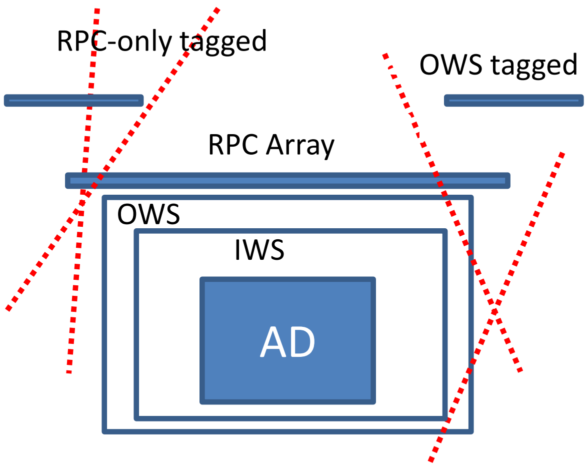
IBD rate versus time

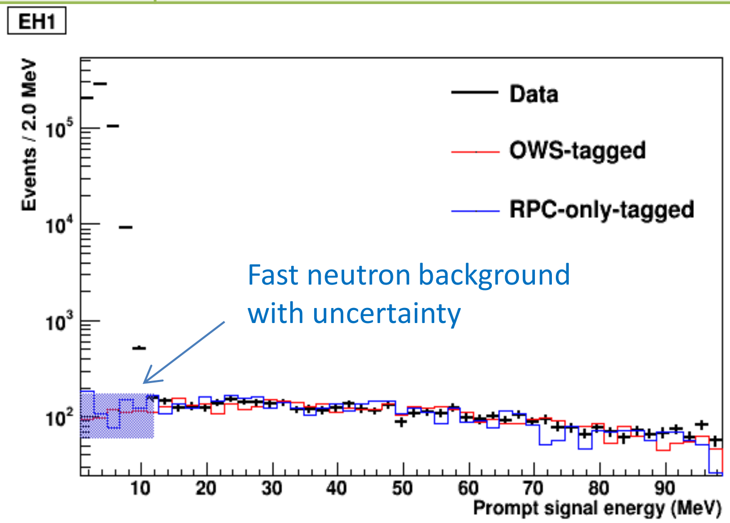
Over 1 million antineutrino interactions detected!



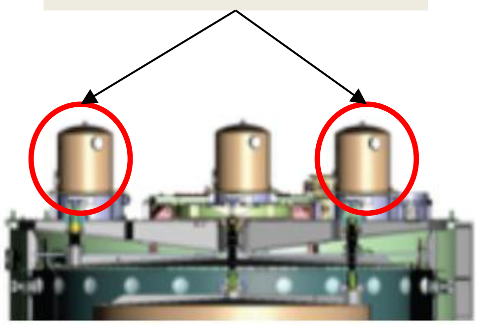
Background budget

Background	Near	Far	Uncertainty	Method	Comment
Accidentals	1.4%	2.3%	Negligible	Statistically calculated from uncorrelated singles	Same as before
9Li/8He	0.4%	0.4%	~50%	Measured with after-muon events	Same as before
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	Same as before





AmC source taken out



Data summary

Preliminary

6AD period

	AD1	AD2	AD3	AD4	AD5	AD6
IBD candidates	101998	103137	93742	13889	13814	13645
DAQ live time(day)	190.989		189.623	189.766		
ε_μ	0.8234	0.8207	0.8576	0.9811	0.9811	0.9808
ε_m	0.9741	0.9745	0.9757	0.9744	0.9742	0.974
Accidentals(/day)	9.53 ± 0.10	9.29 ± 0.10	7.40 ± 0.08	2.93 ± 0.03	2.87 ± 0.03	2.81 ± 0.03
Fast neutron(/day)	0.78 ± 0.12		0.54 ± 0.19	0.05 ± 0.01		
9Li/8He(/day)	2.8 ± 1.5		1.7 ± 0.9	0.27 ± 0.14		
AmC correlated(/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
$^{13}C(\alpha, n)^{16}O$(/day)	0.08 ± 0.04	0.07 ± 0.04	0.05 ± 0.03	0.05 ± 0.03	0.05 ± 0.03	0.05 ± 0.03
IBD rate(/day)	652.38 ± 2.58	662.02 ± 2.59	580.84 ± 2.14	73.04 ± 0.67	72.71 ± 0.67	71.88 ± 0.67
side-by-side ibd rate ratio	0.985 ± 0.005					

8AD period

	AD1	AD2	AD3	AD8	AD4	AD5	AD6	AD7
IBD candidates	202461	206217	193356	190046	27067	27389	27032	27419
DAQ live time(day)	374.447		378.407		372.685			
ε_μ	0.8255	0.8223	0.8574	0.8577	0.9811	0.9811	0.9808	0.9811
ε_m	0.9746	0.9749	0.9759	0.9756	0.9762	0.976	0.9757	0.9758
Accidentals(/day)	8.62 ± 0.09	8.76 ± 0.09	6.43 ± 0.07	6.86 ± 0.07	1.07 ± 0.01	0.94 ± 0.01	0.94 ± 0.01	1.26 ± 0.01
Fast neutron(/day)	0.78 ± 0.12		0.54 ± 0.19		0.05 ± 0.01			
9Li/8He(/day)	2.8 ± 1.5		1.7 ± 0.9		0.27 ± 0.14			
AmC correlated(/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
$^{13}C(\alpha, n)^{16}O$(/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(/day)	659.58 ± 2.12	674.36 ± 2.14	601.77 ± 1.67	590.81 ± 1.66	74.33 ± 0.48	75.40 ± 0.49	74.44 ± 0.48	75.15 ± 0.49
side-by-side ibd rate ratio	0.978 ± 0.004		1.019 ± 0.004					

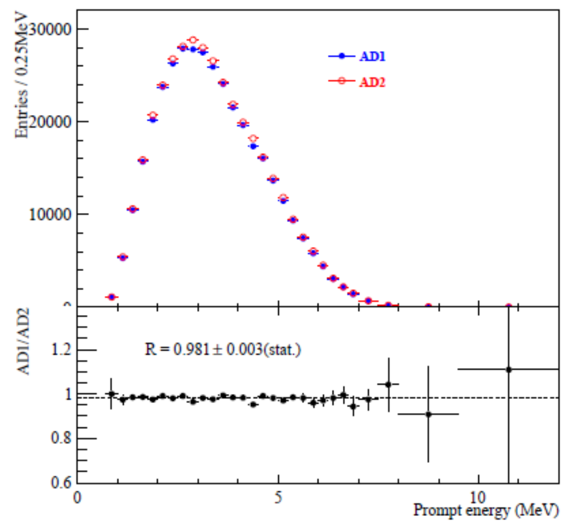
Consistent rate for side-by-side detectors

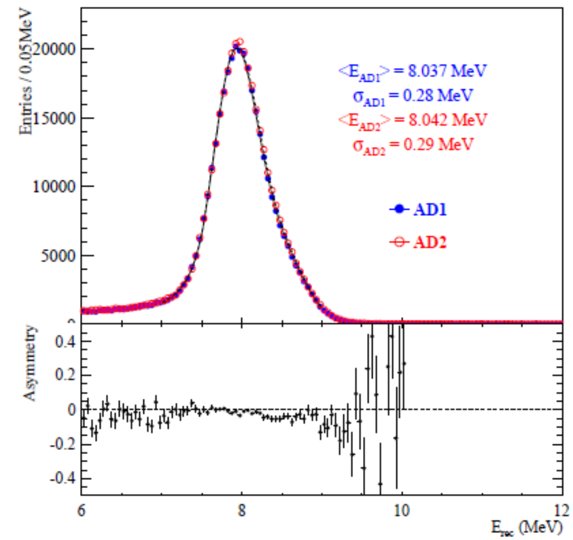
Consistent spectrum for side-by-side detectors

Positron spectrum | Neutron capture spectrum

AD1/AD2 (6+8AD data)
Expected: 0.982
Measured: 0.981±0.004

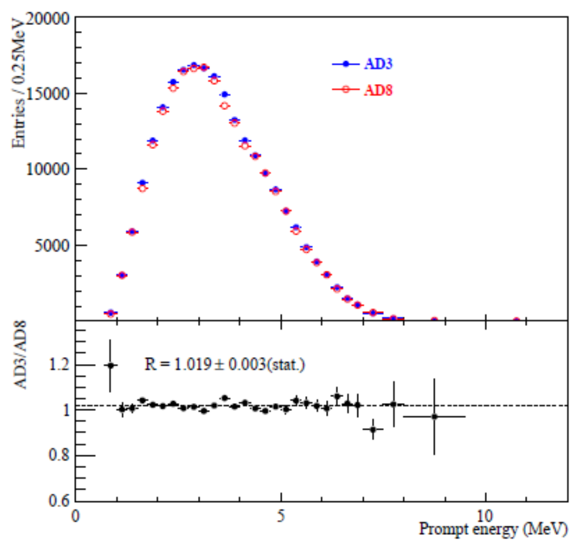
EH1

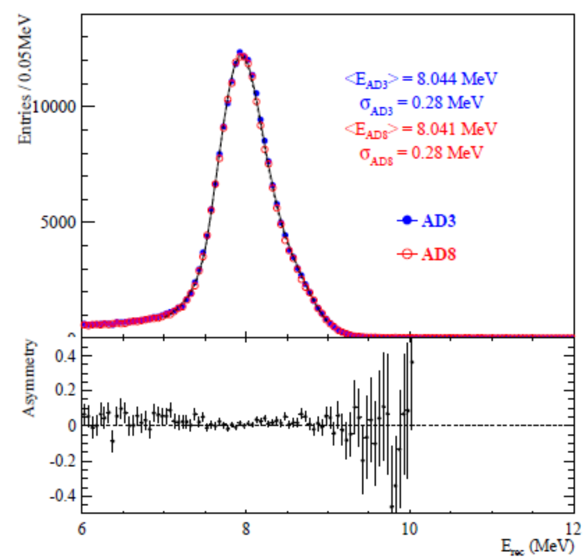




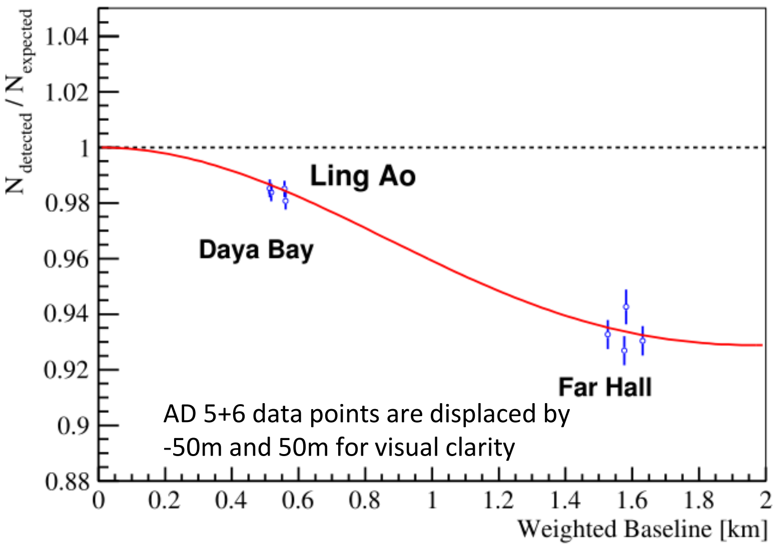
AD3/AD8 (8AD data)
Expected: 1.012
Measured: 1.019±0.004

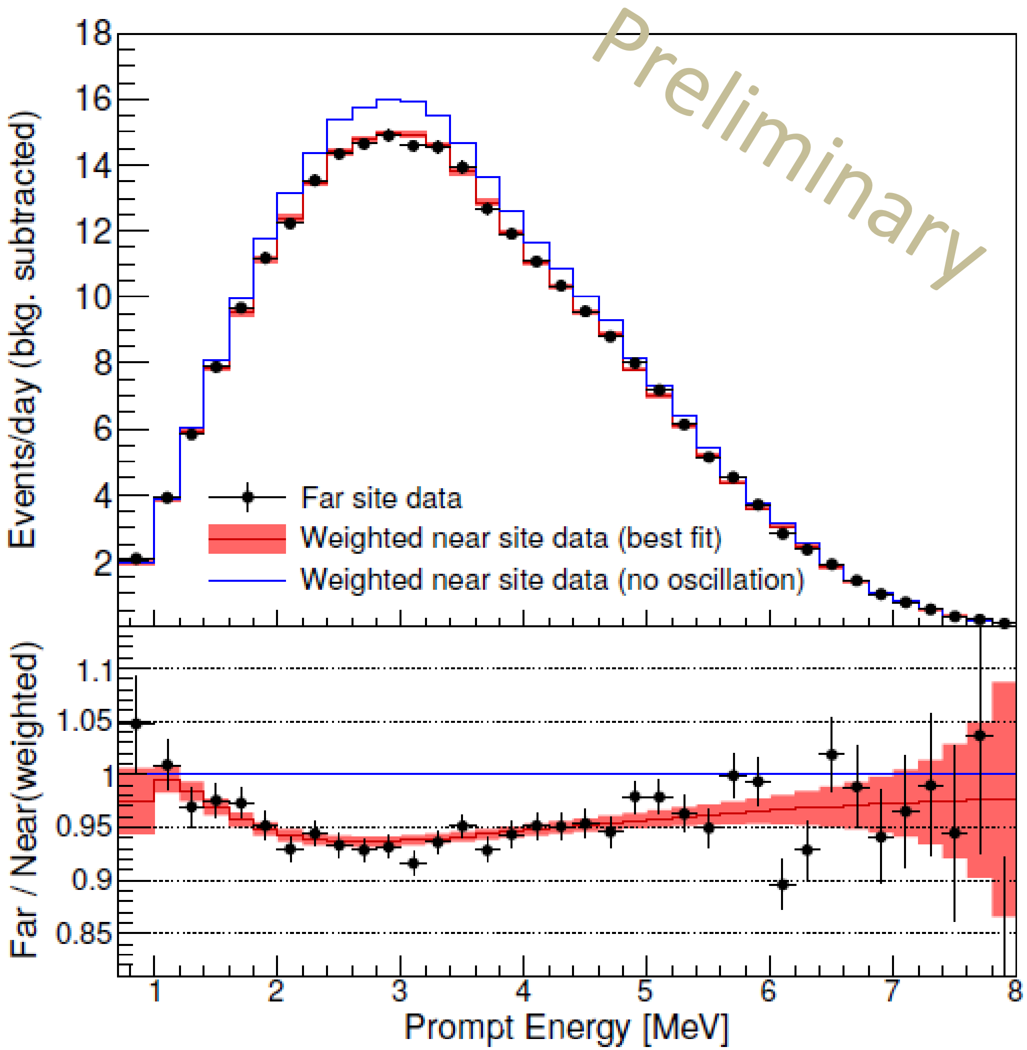
EH2





Rate deficit and spectrum distortion





- Near/Far relative measurement
- Observed data highly consistent with oscillation interpretation

Oscillation results

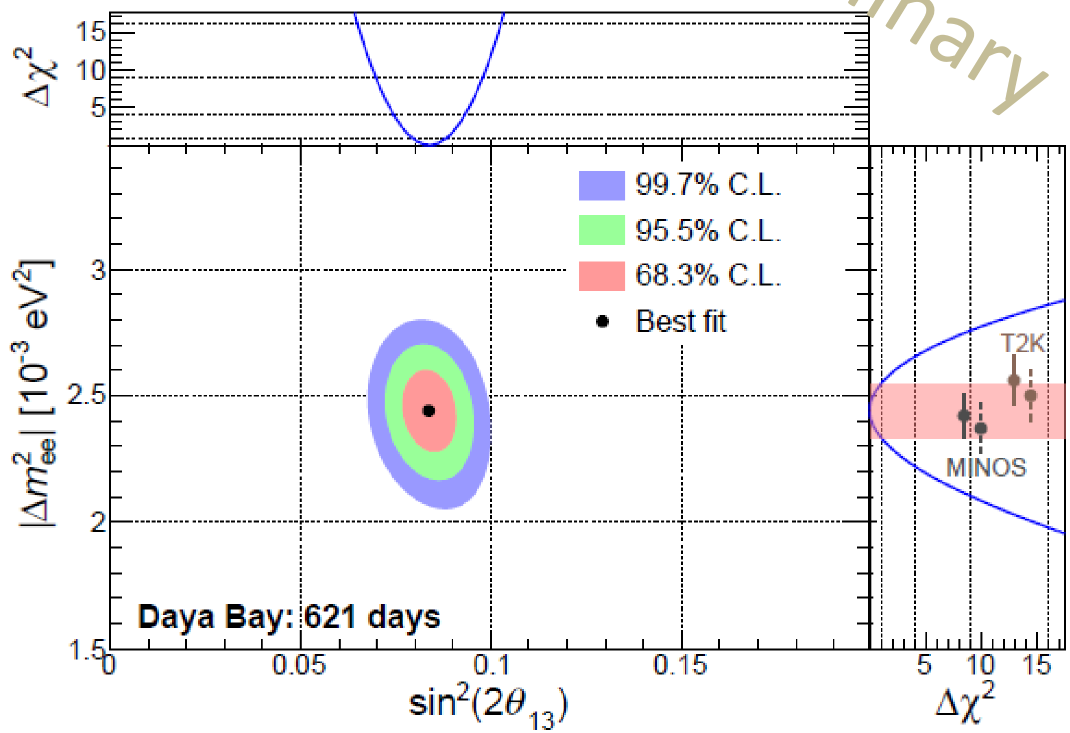
Preliminary

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

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

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

- Most precise measurement of $\sin^2 2\theta_{13}$ (6%)
- Most precise measurement of Δm^2_{ee} in the electron neutrino disappearance channel (4%)
  - Consistent with the muon neutrino disappearance experiments
  - Comparable precision

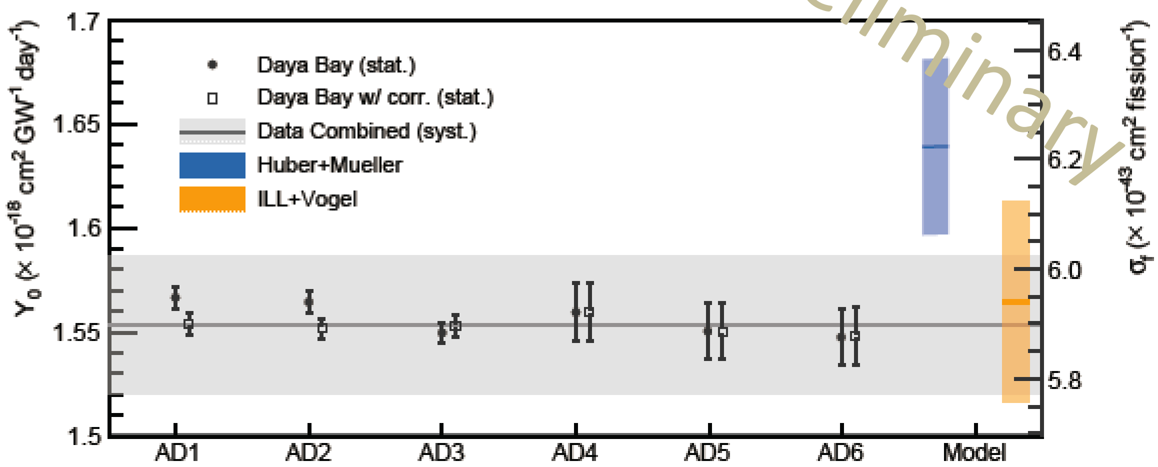


MINOS: PRL, **112**, 191801 (2014)
T2K: PRL, **112**, 181801 (2014)

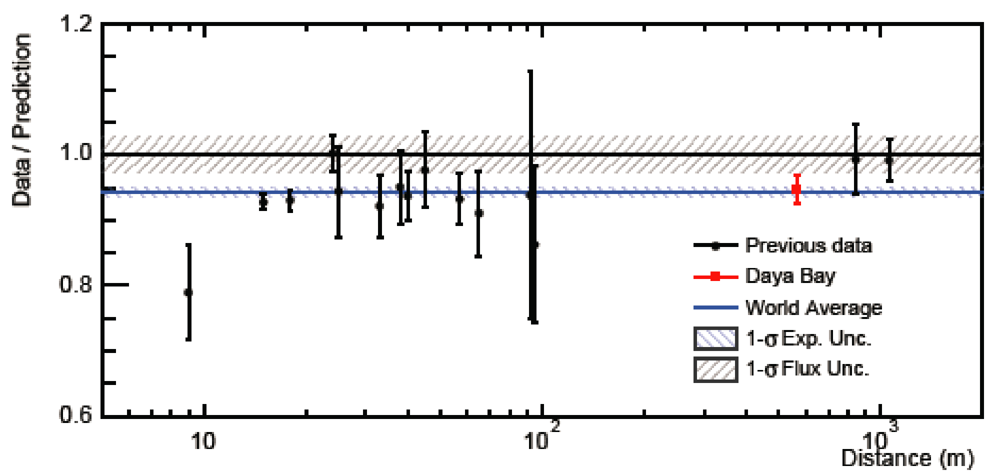
Publication in preparation

Absolute reactor flux measurement

- Measured reactor flux (Y and σ_f) consistent between 6 ADs
- Data/Prediction is consistent with previous short baseline experiments (reactor flux anomaly)



^{235}U : ^{238}U : ^{239}Pu : ^{241}Pu	0.586 : 0.076 : 0.288 : 0.050
IBD Yield	
Y (cm^2/GW/day)	$(1.55 \pm 0.04) \times 10^{-18}$
σ_f (cm^2/fission)	$(5.93 \pm 0.14) \times 10^{-43}$
Data / Prediction	
R (Huber+Mueller)	0.946 ± 0.022
R (ILL+Vogel)	0.991 ± 0.023

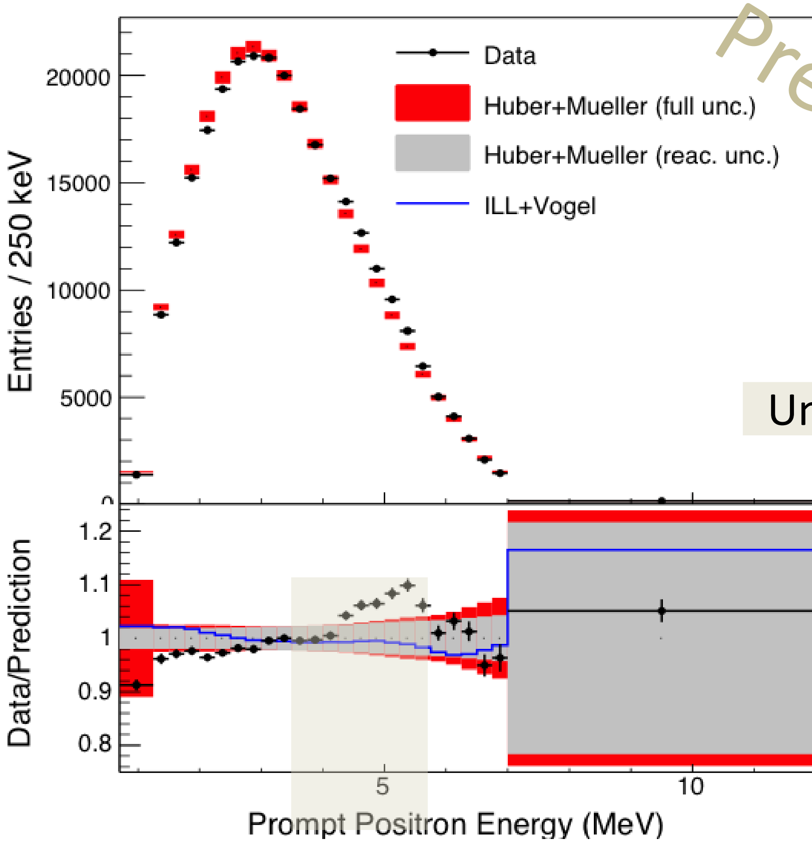


Publication in preparation

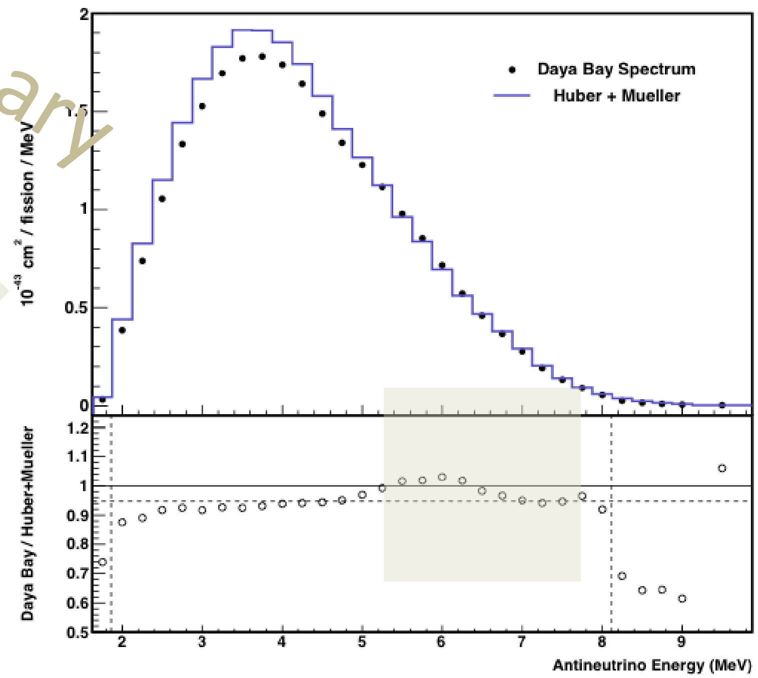
Absolute spectral shape measurement

- Absolute spectral shape is NOT consistent with the prediction. A bump is observed in 4-6 MeV.

- Another way to precisely measure antineutrino spectrum
  - IBD prompt spectrum ➔ antineutrino spectrum
  - Beta decay spectrum ➔ antineutrino spectrum (Huber, Mueller, ILL)



Unfolding



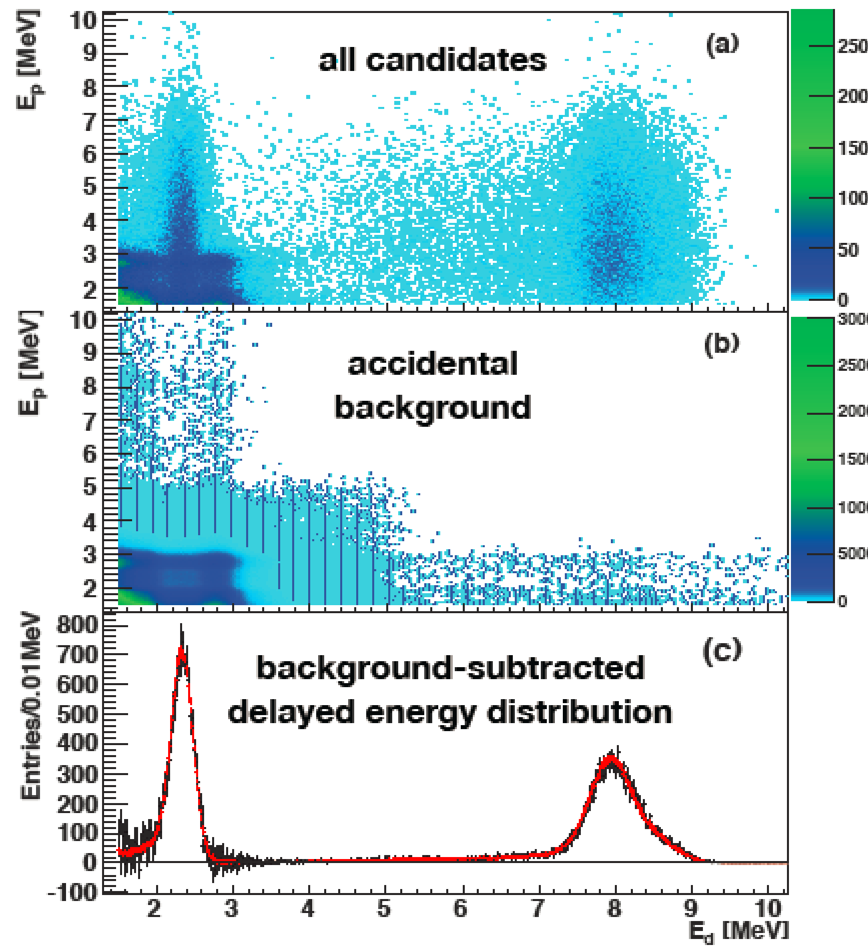
Publication in preparation

Independent θ_{13} measurement through nH

- Key feature
  - High statistics (additional 20 ton LS target per AD)
  - Different systematic uncertainties from nGd analysis
- Challenges
  - High accidental background
    - Longer capture time
    - Lower delayed energy
- Strategy
  - Raise prompt energy cut (>1.5MeV)
  - Require prompt to delay distance cut (<0.5m)

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

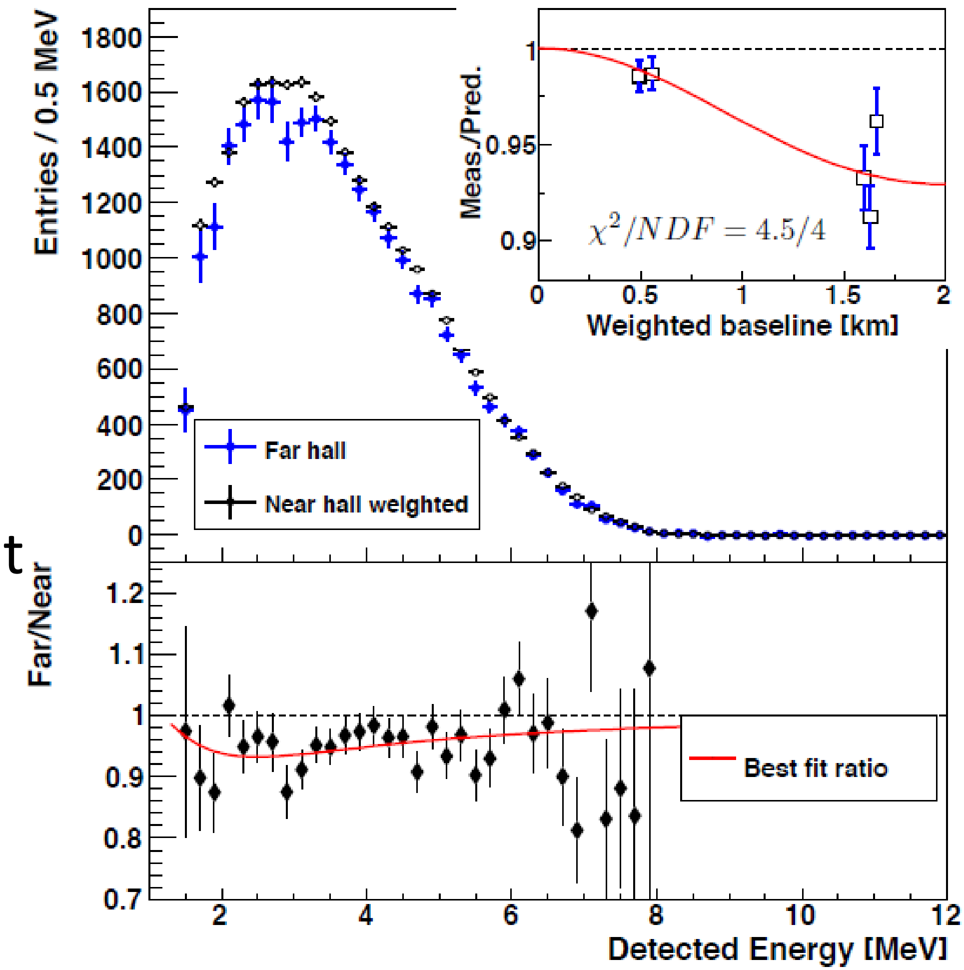
$+H \rightarrow D + \gamma$	2.2 MeV	200 μs
$+Gd \rightarrow Gd^* \rightarrow Gd + \gamma's$	8MeV	30 μs



nH analysis result

- Full 6AD data (217 days)
- Rate analysis measures

  $\sin^2 2\theta_{13} = 0.083 \pm 0.018$
- An independent and consistent result with nGd analysis
- Another precise measurement of $\sin^2 2\theta_{13}$
- Spectrum distortion is consistent with oscillation explanation.
  - Spectral shape analysis in progress

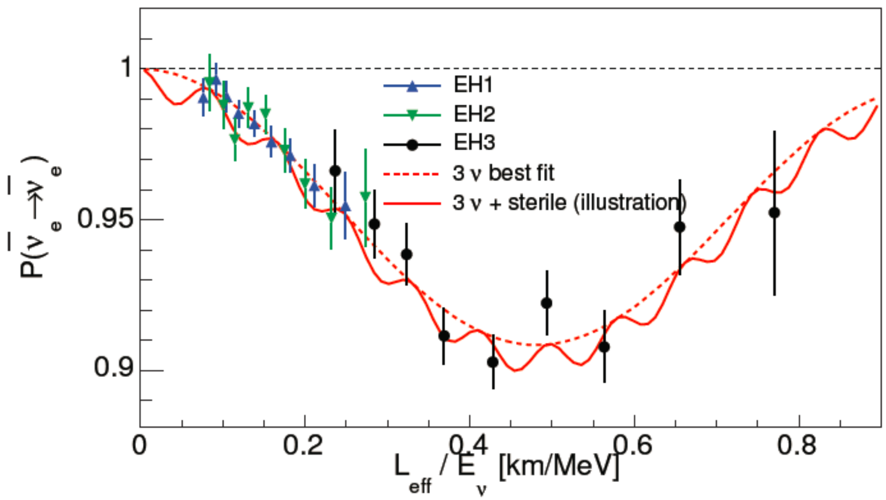


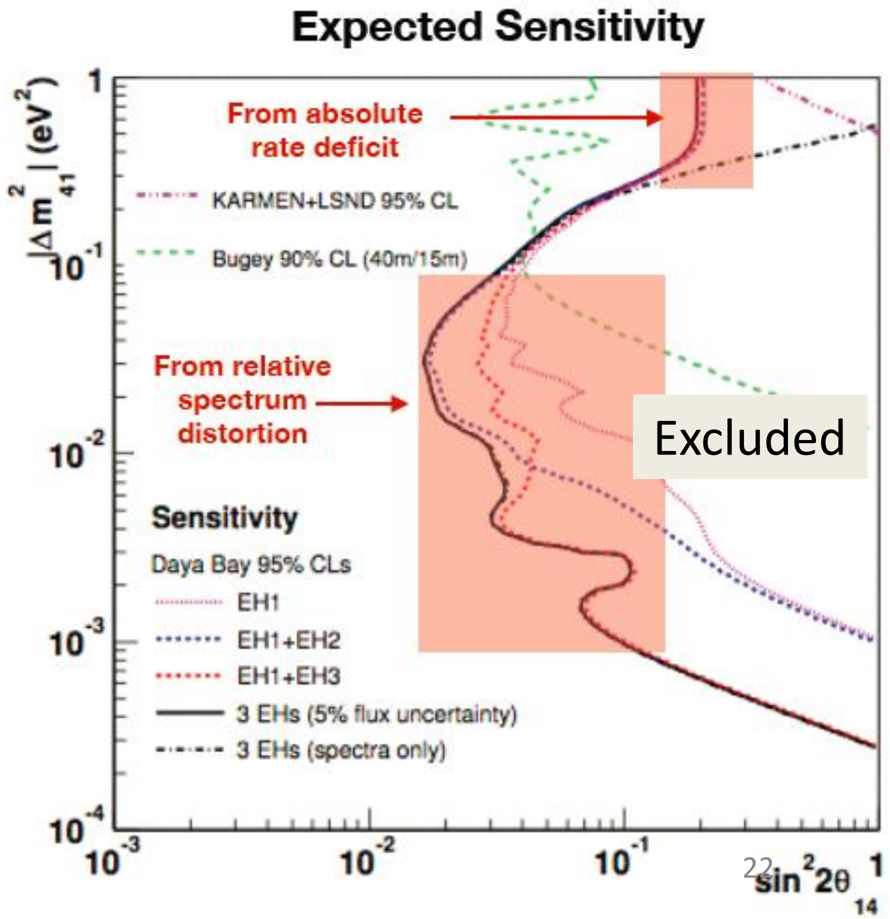
*PRD **90**, 071101(R) (2014)*

Search for light sterile neutrino

- An unique opportunity for sterile neutrino searches
  – Sterile neutrino would introduce additional oscillation mode.
  – Relative measurement at multiple baselines of Daya Bay: EH1 (~350 m), EH2 (~500 m), EH3 (~1600 m)
  – Region of 10^{-3} eV^2 < Δm^2_{41} < 0.1 eV^2 explored

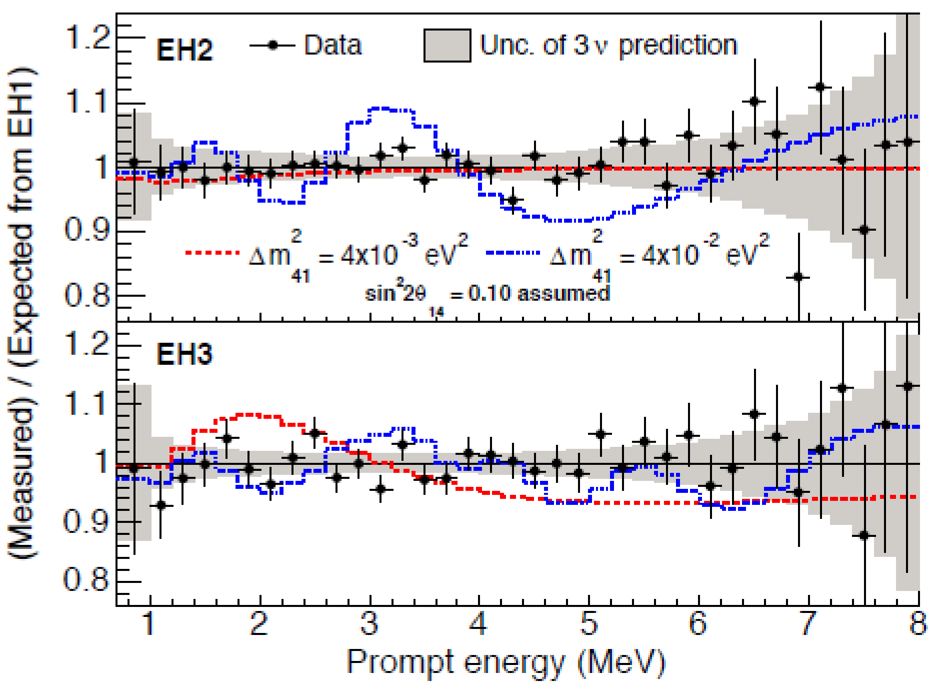
$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \simeq 1 - \cos^4\theta_{14}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{ee}L}{4E_\nu}\right) - \sin^2 2\theta_{14}\sin^2\left(\frac{\Delta m^2_{41}L}{4E_\nu}\right)$$

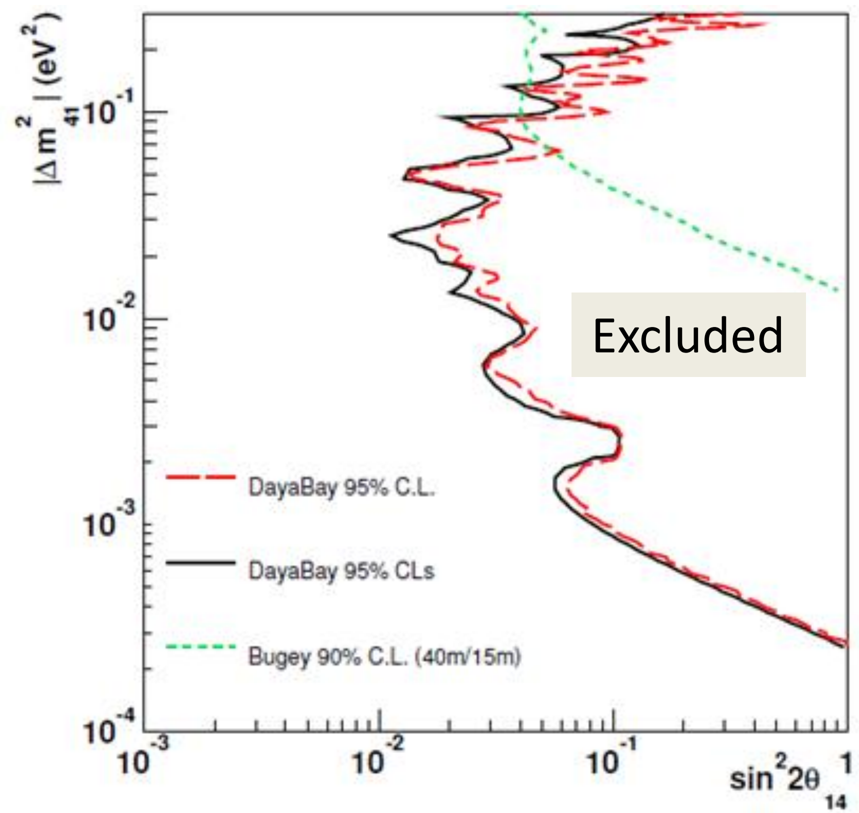




Sterile neutrino search results

- Full 6AD data (217 days)
- No significant signal observed, consistent with 3-flavor neutrino oscillation.
- Set most stringent limit at 10^{-3} eV^2 < Δm^2_{41} < 0.1 eV^2





*PRL **113**, 141802 (2014)*

Summary

- High precision measurement with 621 days of data

$$\sin^2 2\theta_{13} = 0.084^{+0.005}_{-0.005}$$
$$|\Delta m^2_{ee}| = 2.44^{+0.10}_{-0.11} \times 10^{-3} (eV^2)$$

- The precision of both $\sin^2 2\theta_{13}$ and Δm^2_{ee} is expected to be further improved to 3% by the end of 2017.
- Many other analysis carried out
  - Precision measurement of reactor flux and spectrum
  - An independent oscillation analysis using nH captures
  - Search for light sterile neutrino
- Stay tuned for future results!