on behalf of the Daya Bay Collaboration

Recent Results From Daya Bay

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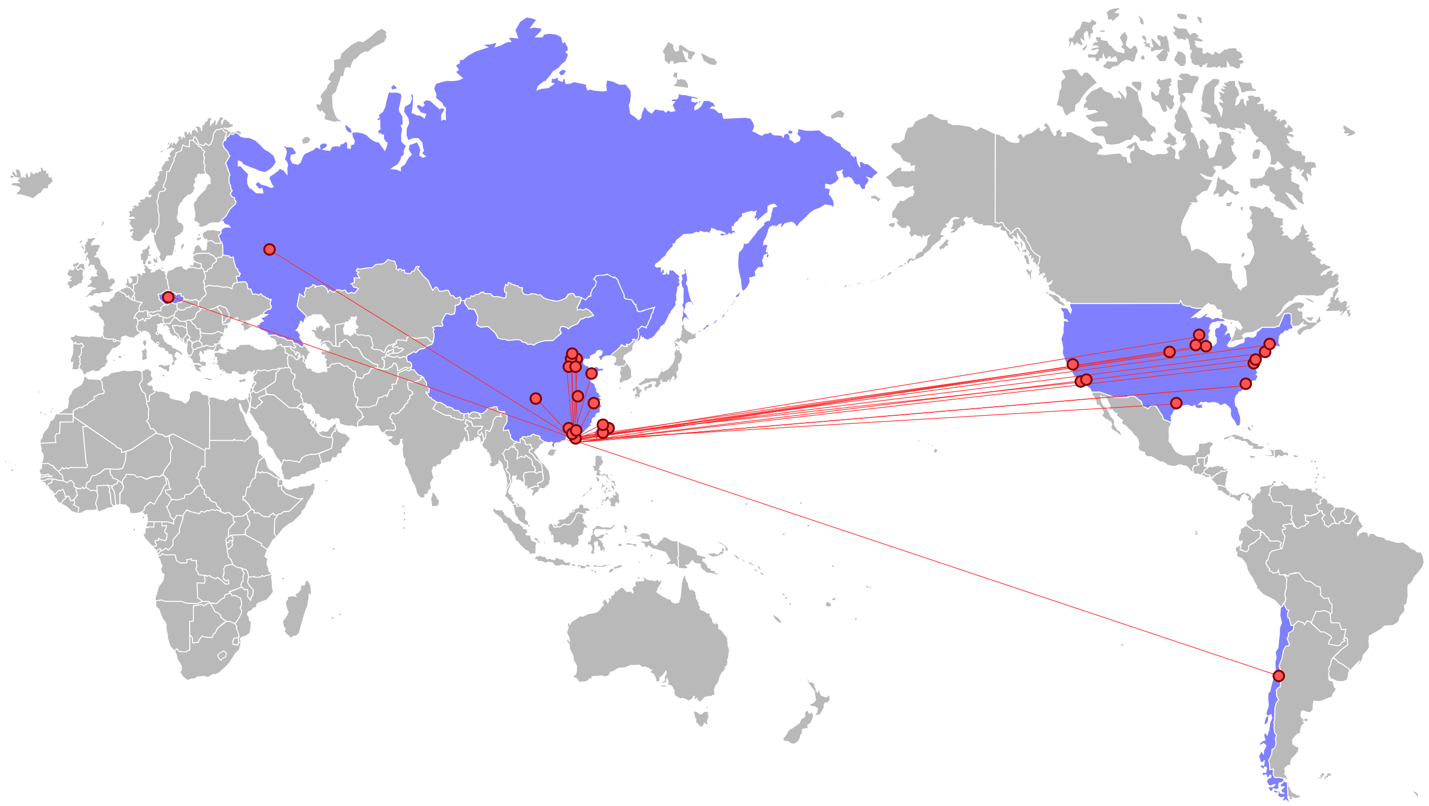
BROOKHAVEN NATIONAL LABORATORY

Neutrino 2014, Boston, 6/3/2014

The Daya Bay Collaboration



Asia (21)

IHEP, Beijing Normal 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, **LBNL, Iowa State Univ., RPI,** Illinois Inst. Tech., Princeton, 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

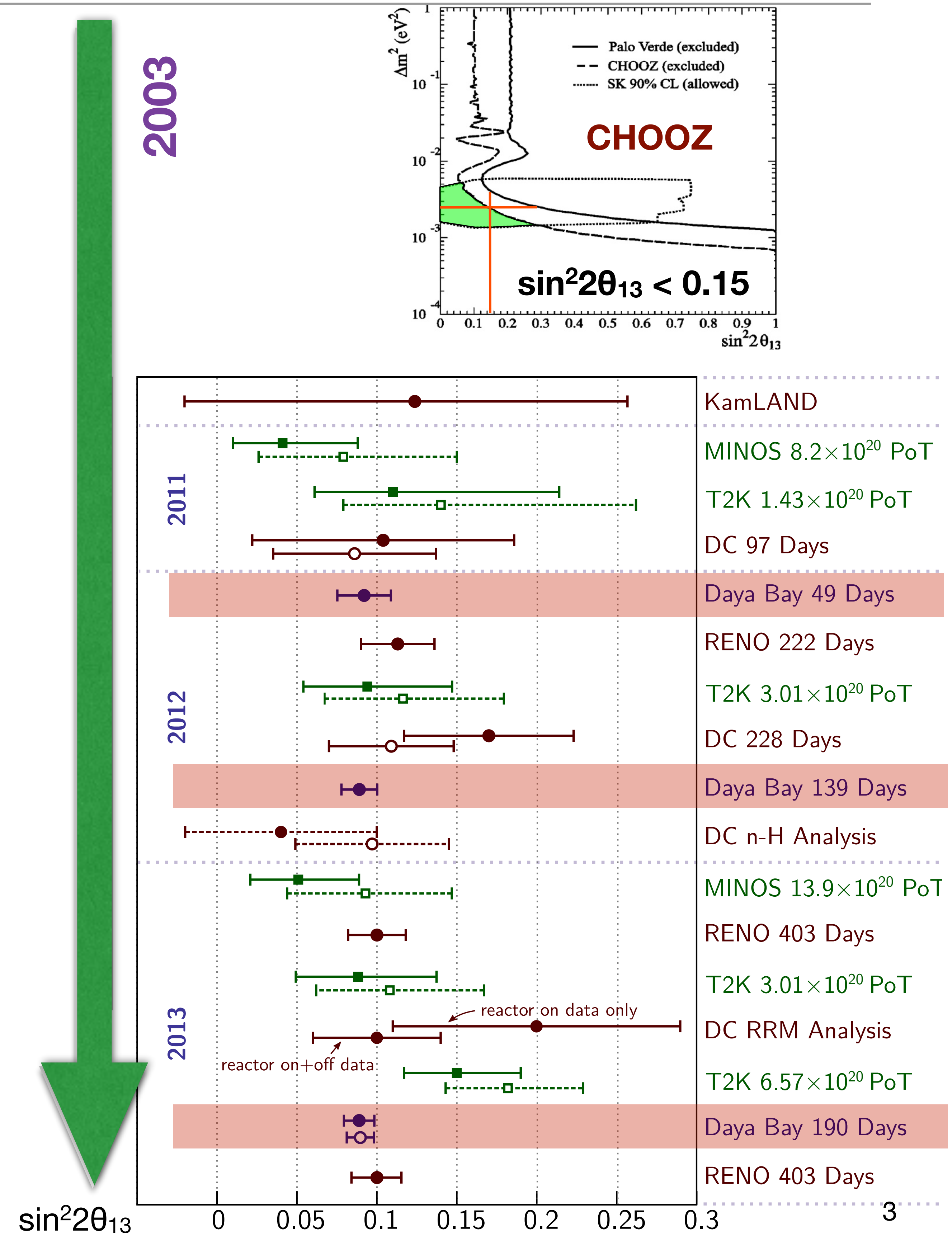
South America (1)

Catholic Univ. of Chile

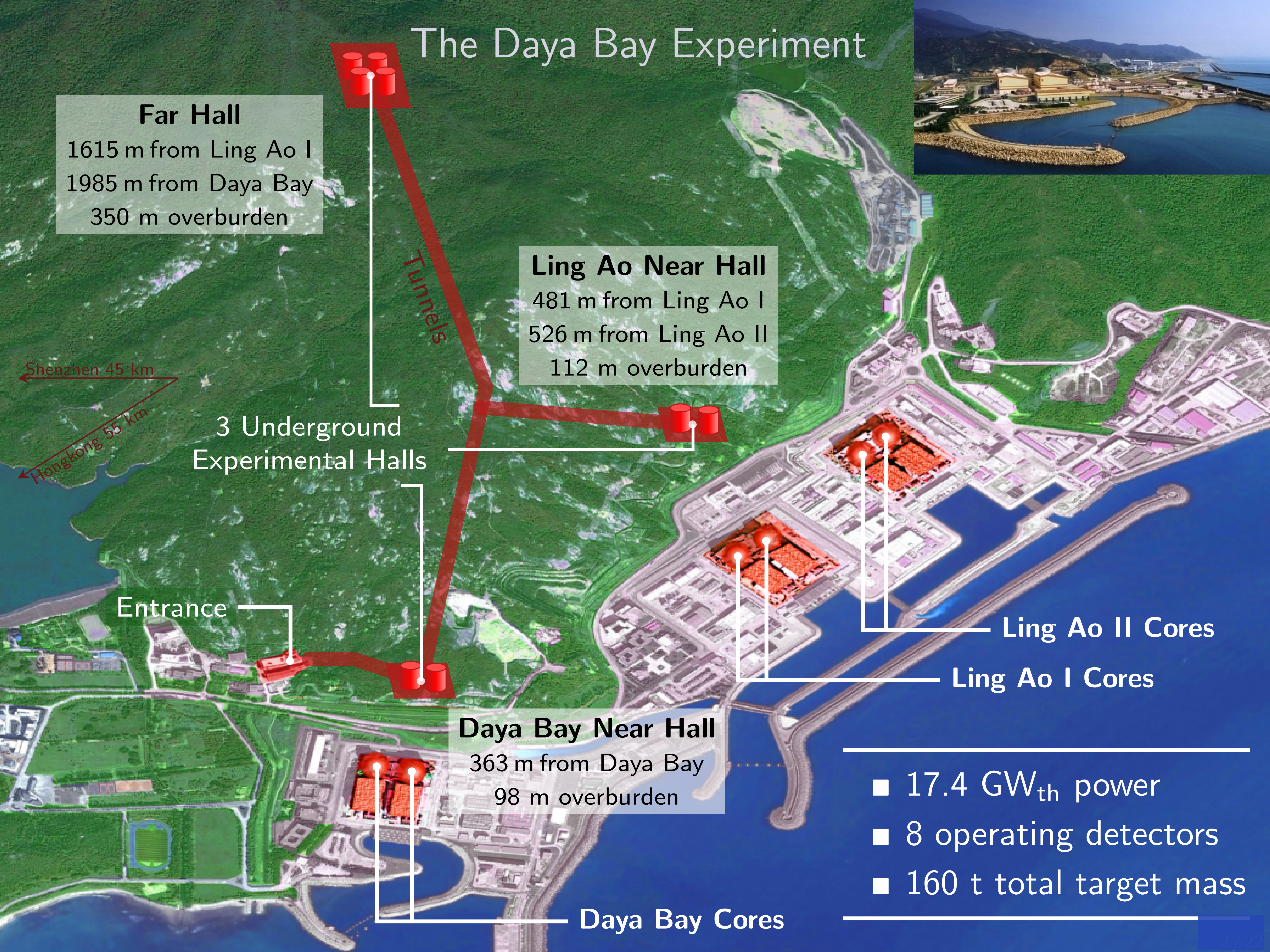
~230 collaborators

Precision Measurement of θ_{13}

- Nature is kind to give us a relatively large θ_{13} ($\sin^2 2\theta_{13} \sim 0.1$)
- Daya Bay was designed to discover $\sin^2 2\theta_{13} < 0.01$ at 90% C.L. Now turning into a precision experiment
  - **Statistics**: powerful reactors (17.6 GW_{th}) + large detectors (80 ton at Far site)
  - **Reactor-related uncertainty**: Far/Near relative measurement
  - **Detector-related uncertainty**: multiple functionally identical detectors (4 Near + 4 Far)
  - **Background**: deep underground (860 m.w.e at far site)

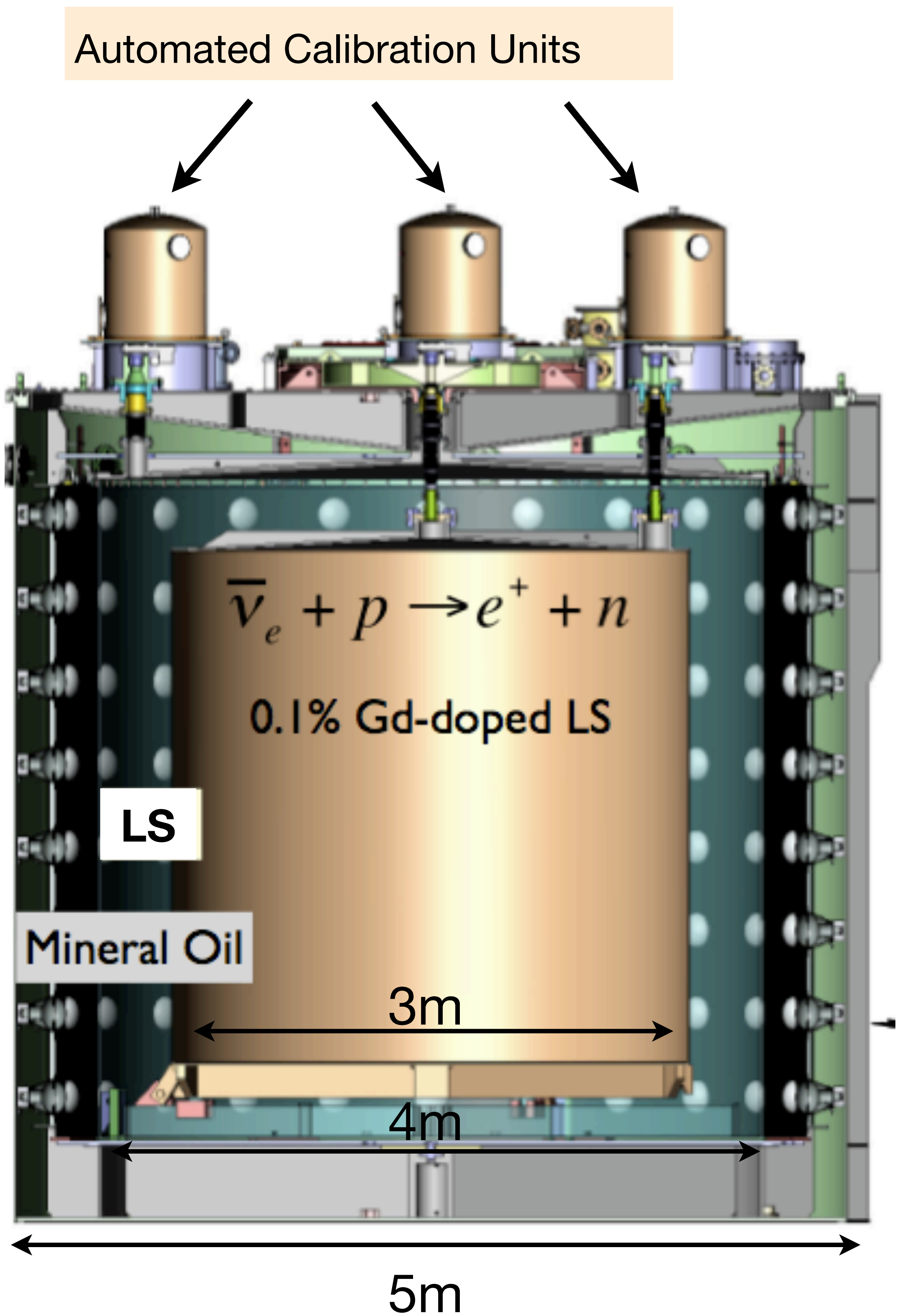


The Daya Bay Experiment



- 17.4 GW_{th} power
- 8 operating detectors
- 160 t total target mass

Anti-neutrino Detector (AD)



8 functionally identical detectors

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

Each detector has 3 nested cylindrical zones separated by Acrylic Vessels:

- **Inner: 20 tons Gd-doped LS (target volume)**
- Mid: 20 tons LS (gamma catcher)
- Outer: 40 tons mineral oil (buffer)

Each detector has:

- 192 8-inch Photomultipliers (PMTs)
- Optical reflectors at top/bottom of cylinder
- - effectively 12% photocoverage
- ~ 160 photoelectrons / MeV
- ~ 8%/√E (MeV) energy resolution

Muon Veto System

Multiple muon veto detectors
2.5m thick two-sector active water shield and RPC

Water Cherenkov

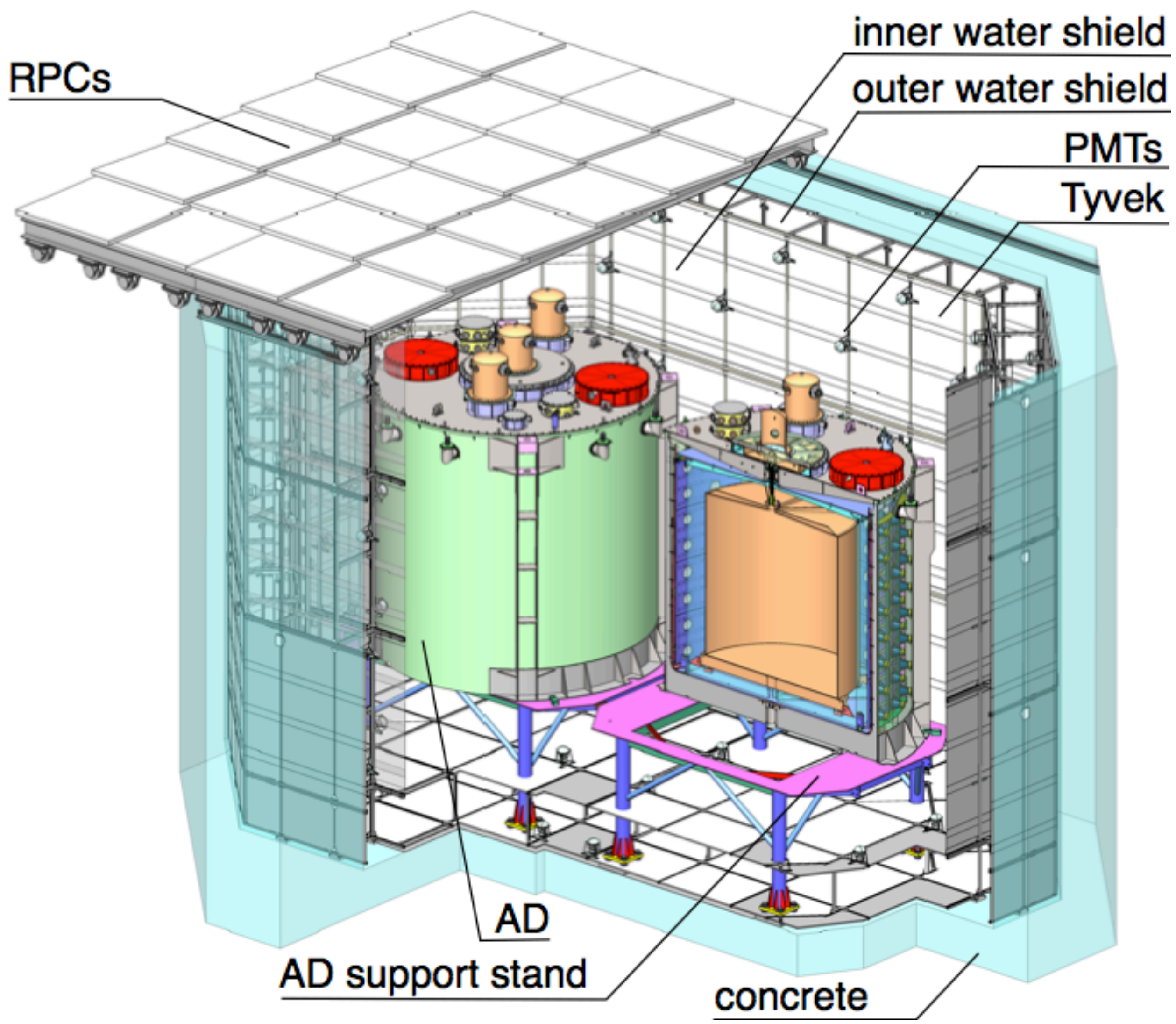
- Detectors submerged in water shielded against external neutrons and gammas

- Optically separated with Tyvek sheets into inner / outer region for better muon tracking

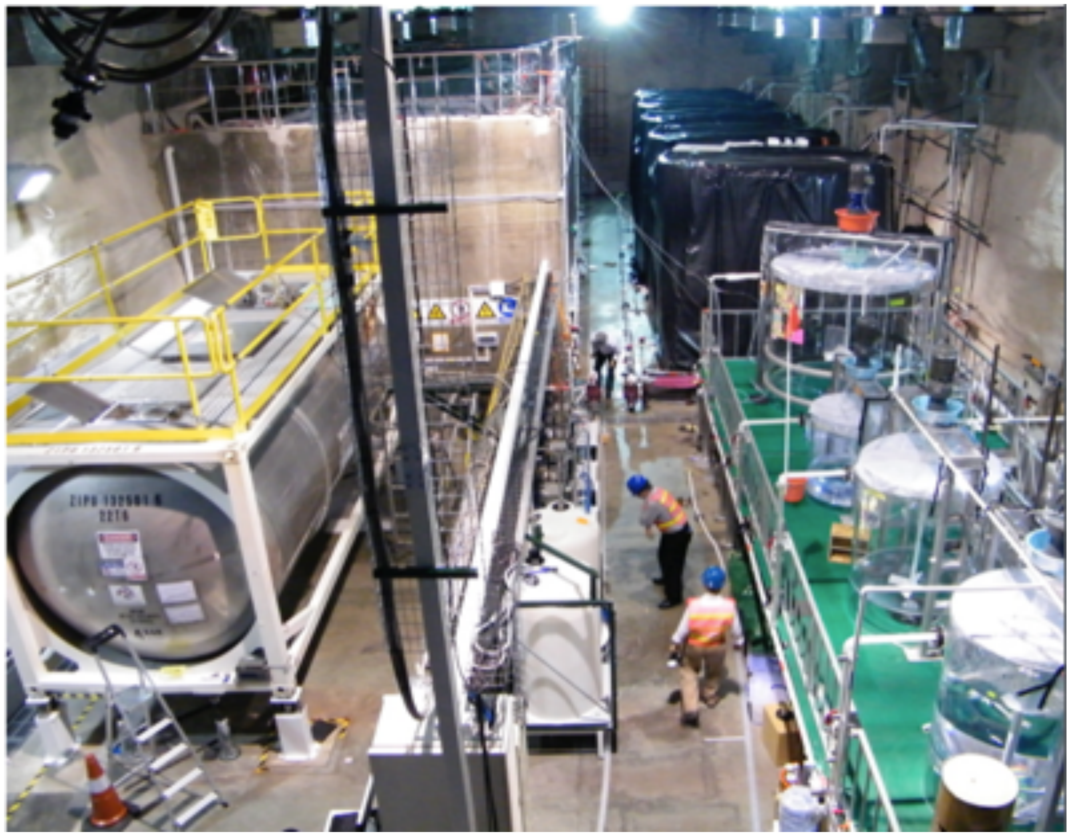
- 8-inch PMTs mounted on frames, 288 @Near, 384 @Far

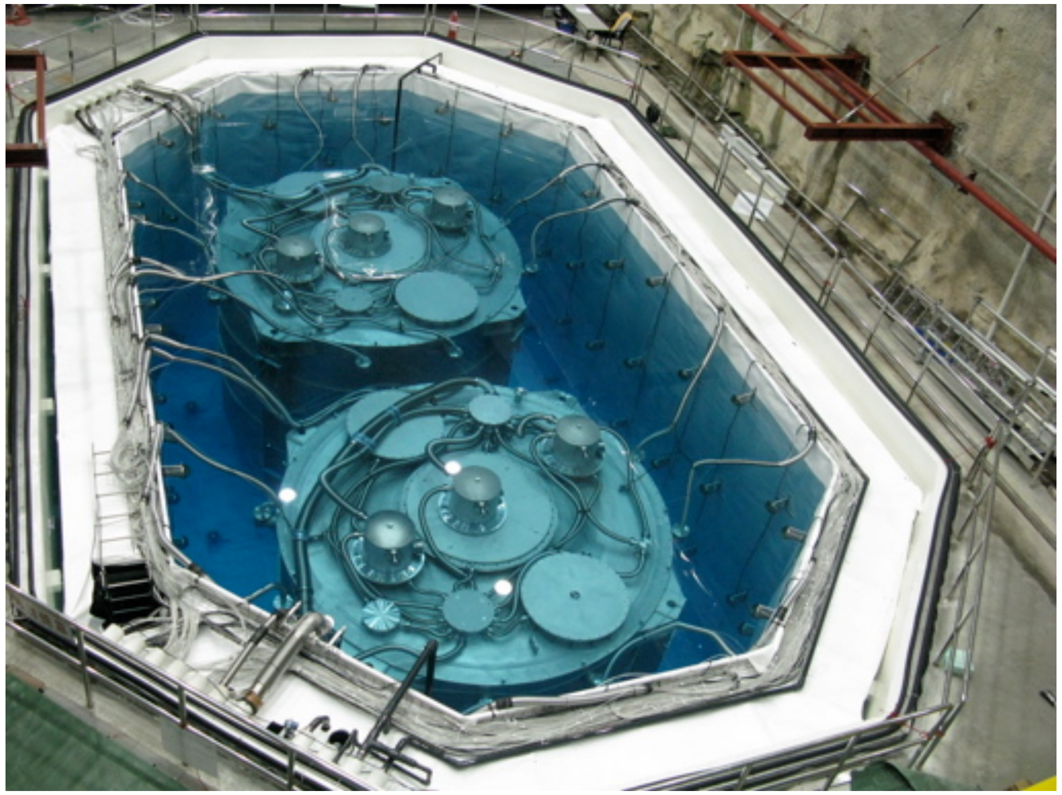
Resistive Plate Chamber (RPC)

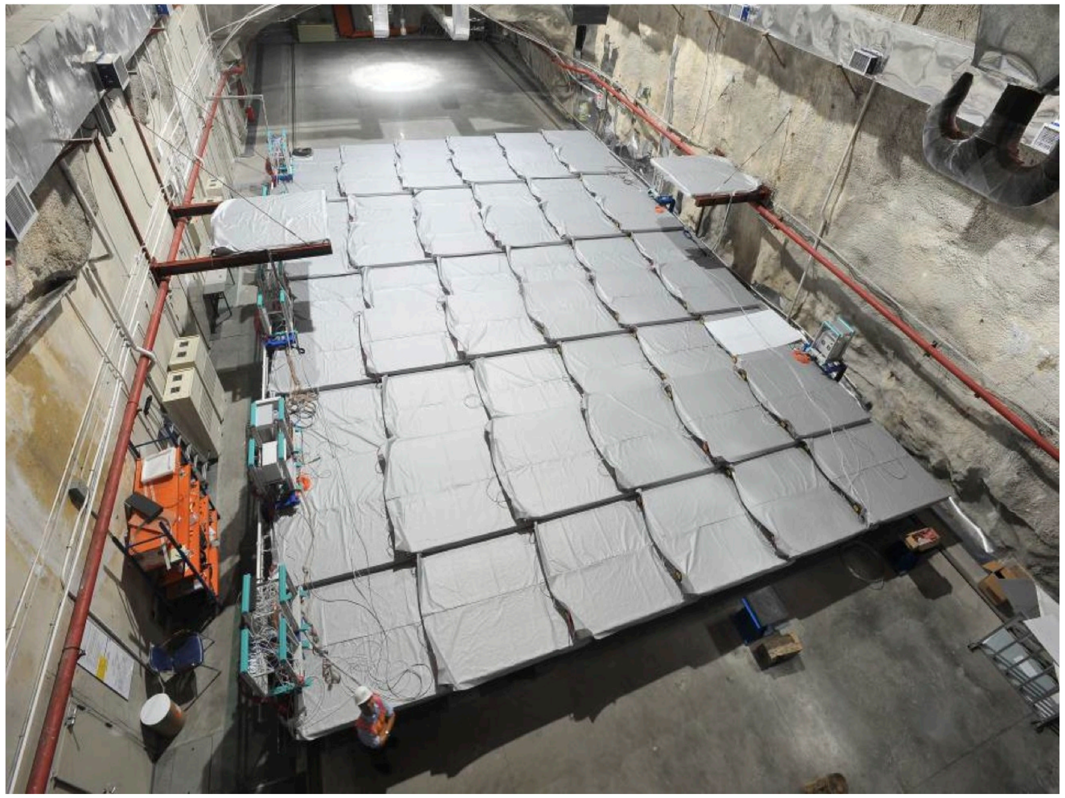
- Independent muon tagging
- Retractable roof above pool
- 54 modules @Near, 81 @Far



Antineutrino Detector Installation

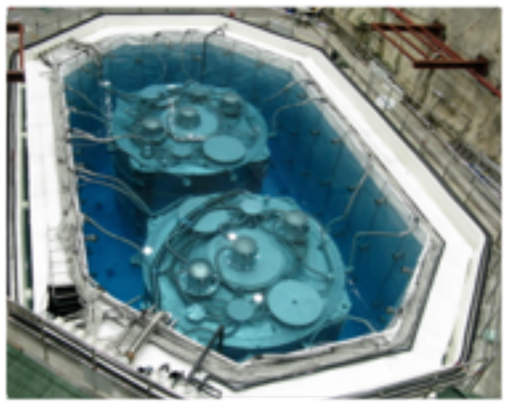




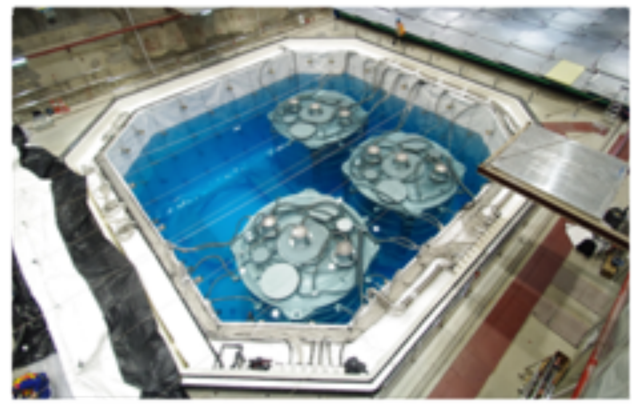


The Timeline of Detector Installation

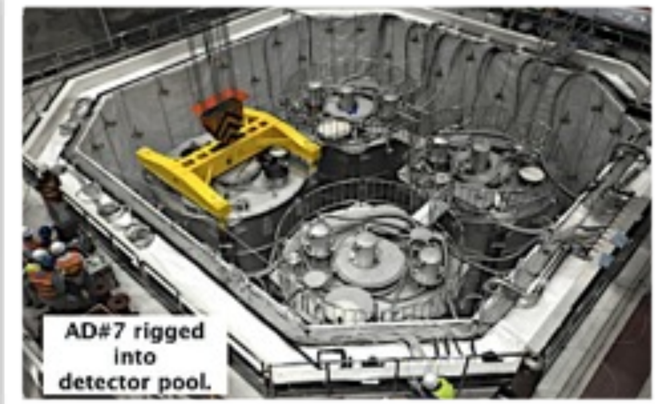
EH1



EH3



EH3



Aug, 2011

Dec, 2011

Aug, 2012

6-AD Data Taking

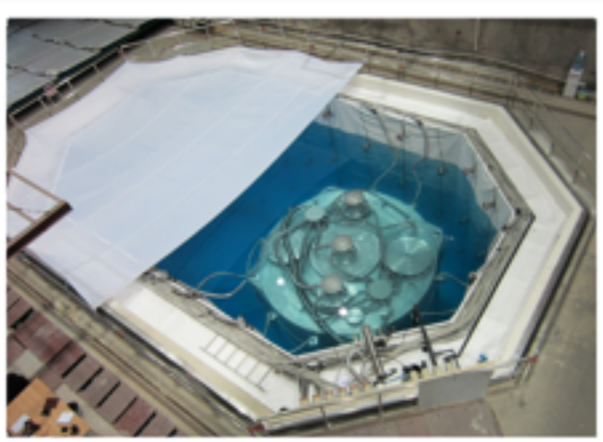
8-AD Data Taking

Nov, 2011

2011/12 - 2012/07

Aug, 2012

2012/10 - now



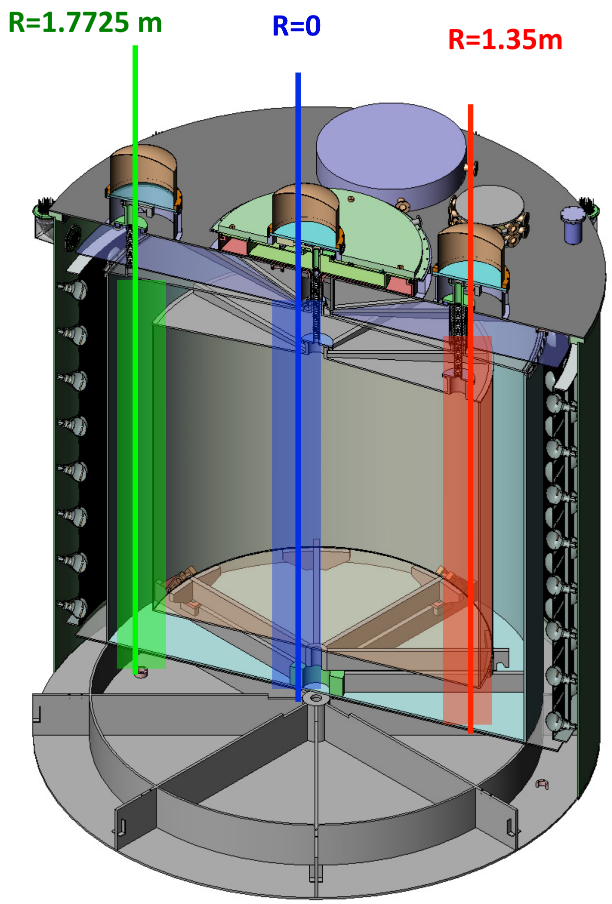
EH2

EH2

Calibration System

3 Automated Calibration Units (ACUs) per detector

- 3 sources for each z axis on a turntable (position accuracy < 7 mm)



- 10 Hz **^{68}Ge** (2 x 0.511 MeV γ's)
- 100 Hz **^{60}Co** gamma source (1.173 + 1.332 MeV γ's) + 0.7 Hz **^{241}Am^{13}C** neutron source (3.5 MeV n without γ)
- **LED** diffuser ball for PMT gain and timing

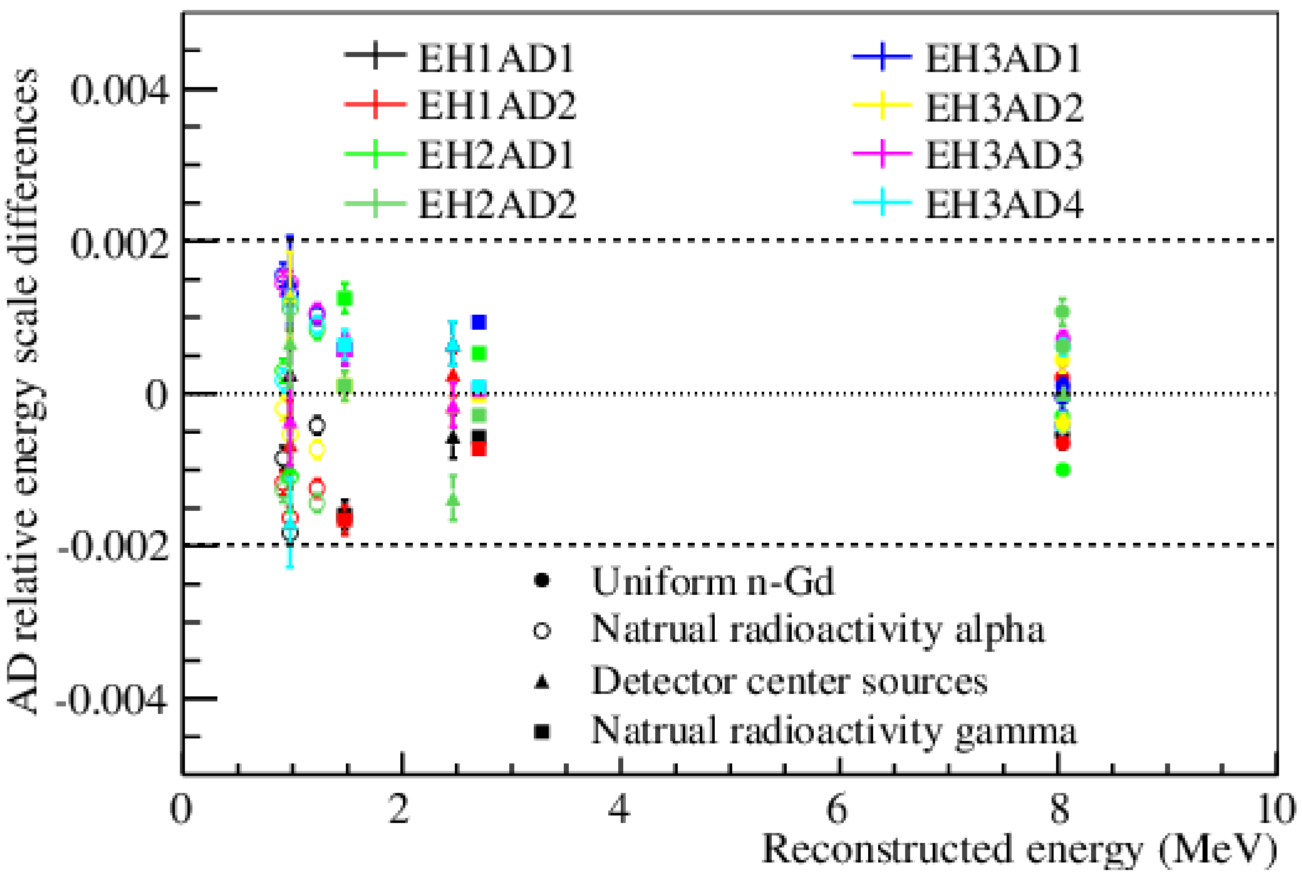
Manual Calibration System (one-time)

- MCS installed on AD#1 in summer 2012
- ^{60}Co + ^{239}Pu^{13}C composite source
- 4π deployment

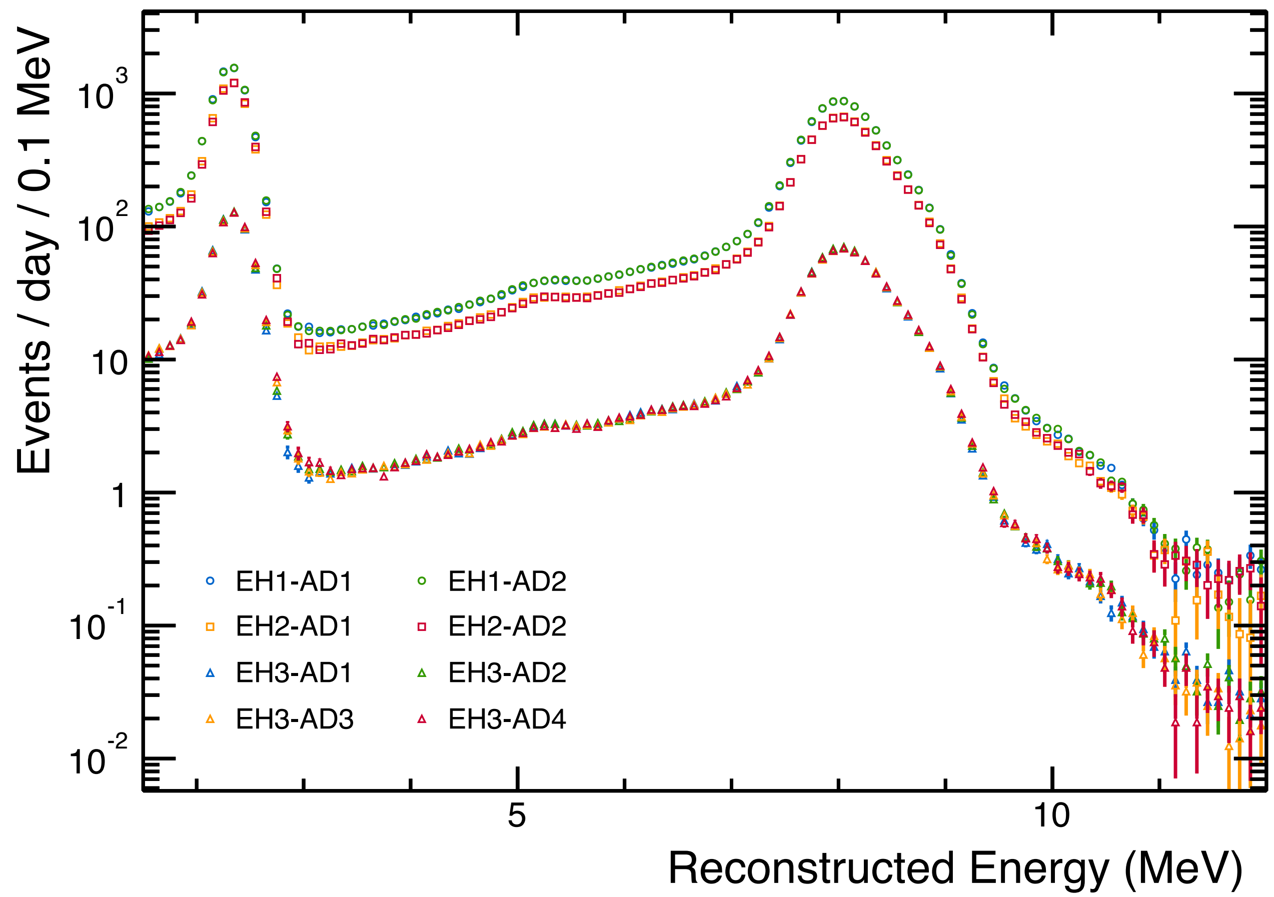
- **Simultaneous, fully-automated weekly deployment for all 8 ADs**
- Special calibration campaign during summer 2012 with temporary sources
  - ^{137}Cs, ^{54}Mn, ^{40}K, ^{241}Am^{9}Be, ^{239}Pu^{13}C
- Also have methods to calibrate **in-situ**
  - PMT gains: dark noise
  - Energy (light-yield): spallation neutron

Relative Energy Scale

ACU: ^{60}Co, ^{68}Ge, AmC
Spallation: nGd, nH
Gamma: ^{40}K, ^{208}Tl
Alpha: ^{212}Po, ^{214}Po, ^{215}Po

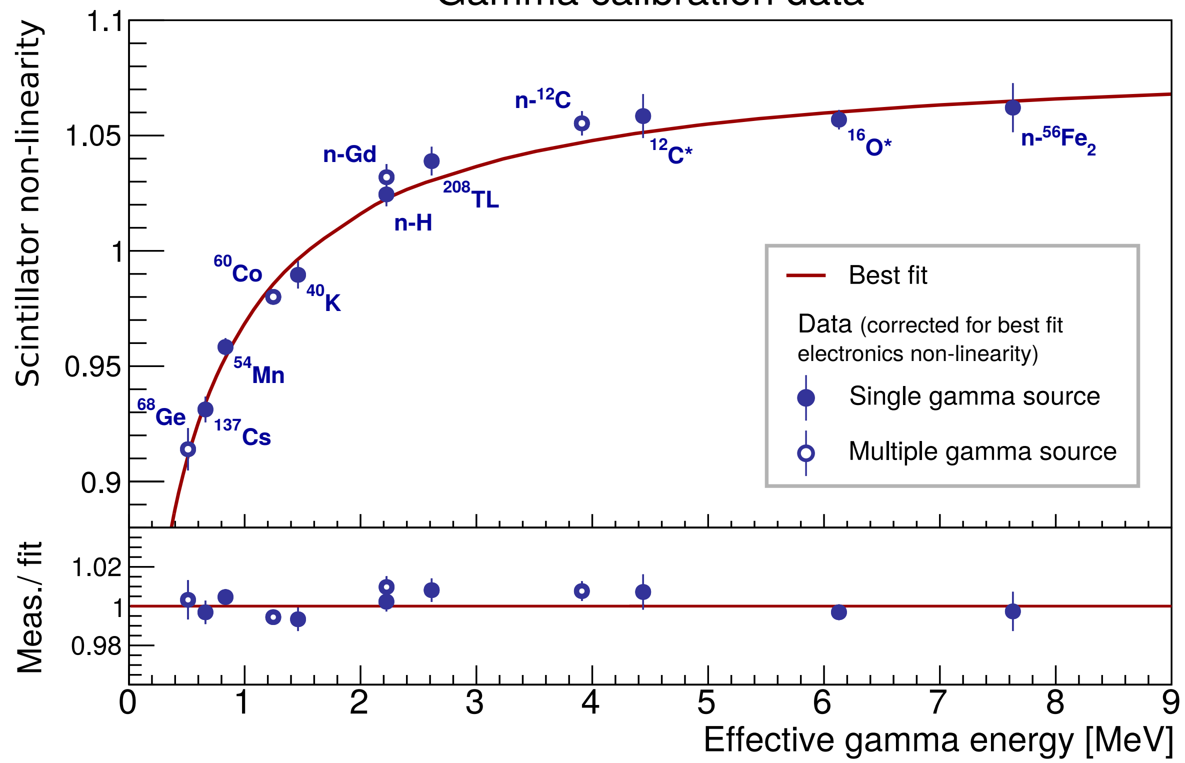


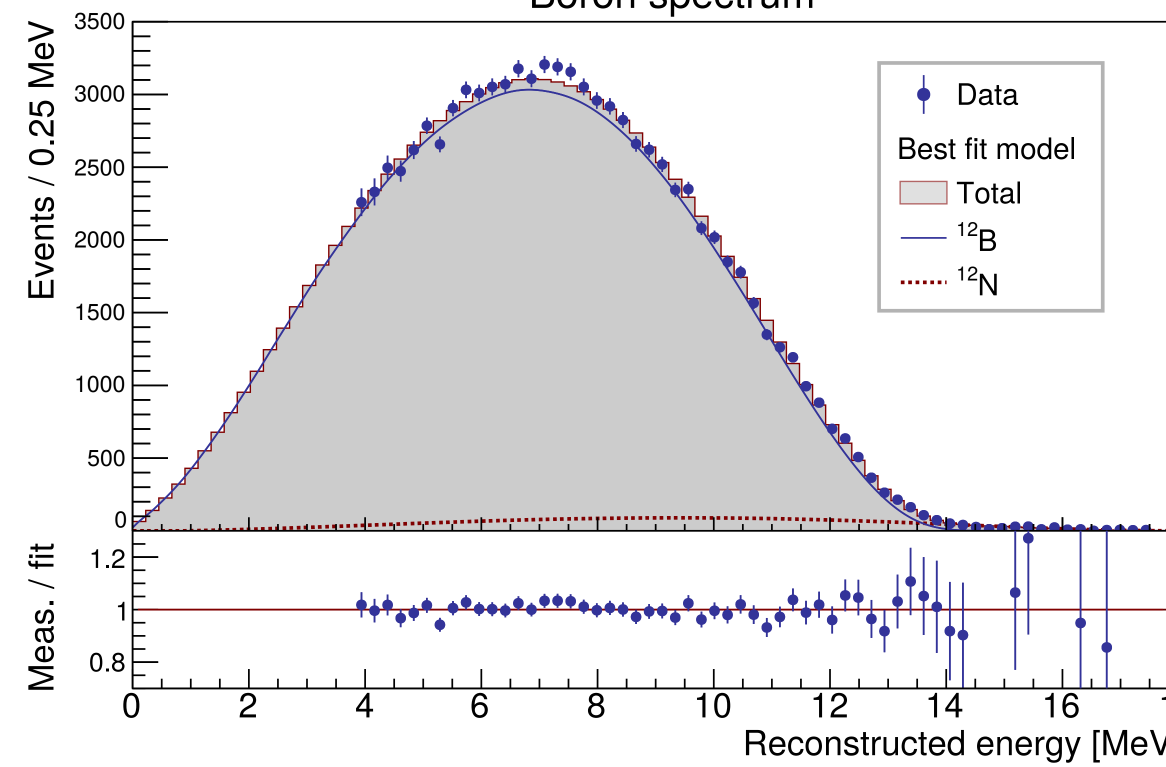
spallation neutron capture spectrum



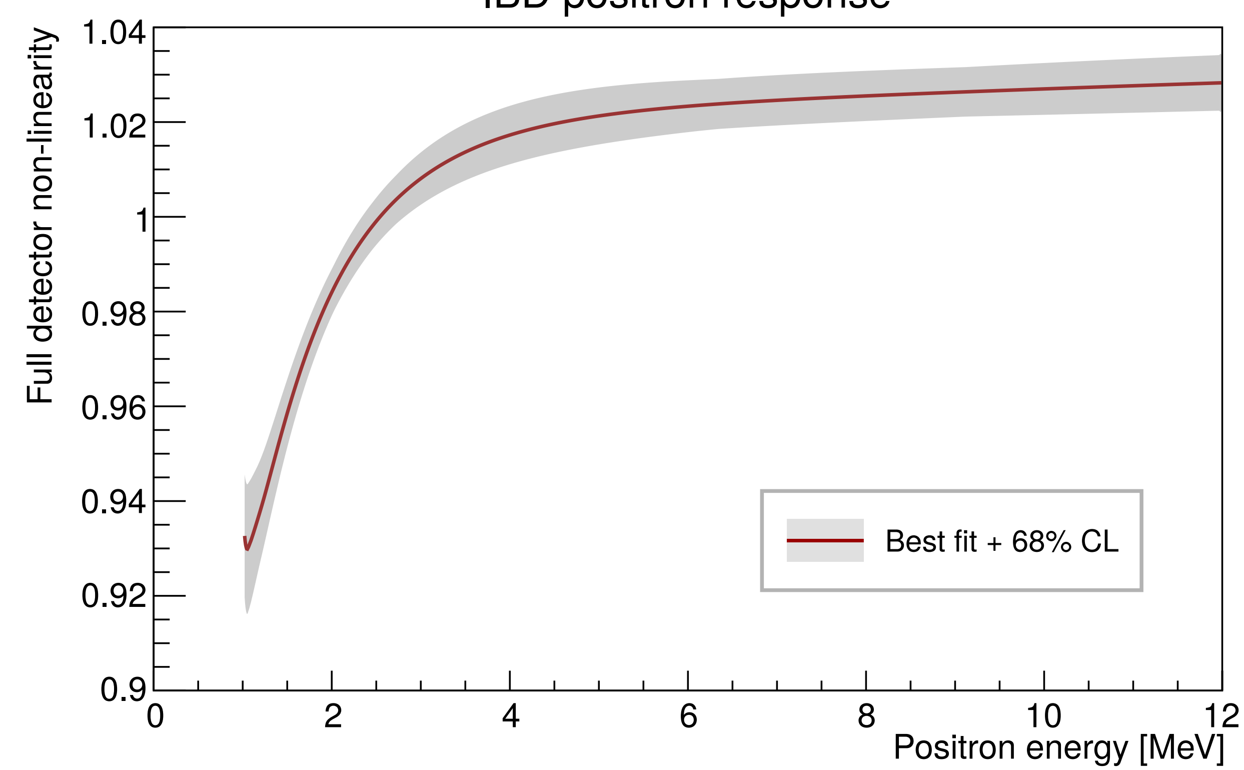
< 0.2% variation in reconstructed energy between ADs

Energy Nonlinearity Calibration





- Two major sources of non-linearity
  - **scintillator response:** modeled with Birks formula and Cherenkov fraction
  - **electronics:** modeled with MC and single channel FADC measurement
- Combined fit with mono-energetic gamma peaks and ^{12}B beta-decay spectrum
- Cross-validated with ^{214}Bi, ^{208}Tl beta-decay spectrum, Michel electron spectrum and standalone bench-top Compton scattering measurement.



< 1% uncertainty (correlated among all detectors)

Analysis Results

Using Combined 6+8AD period (621 days):

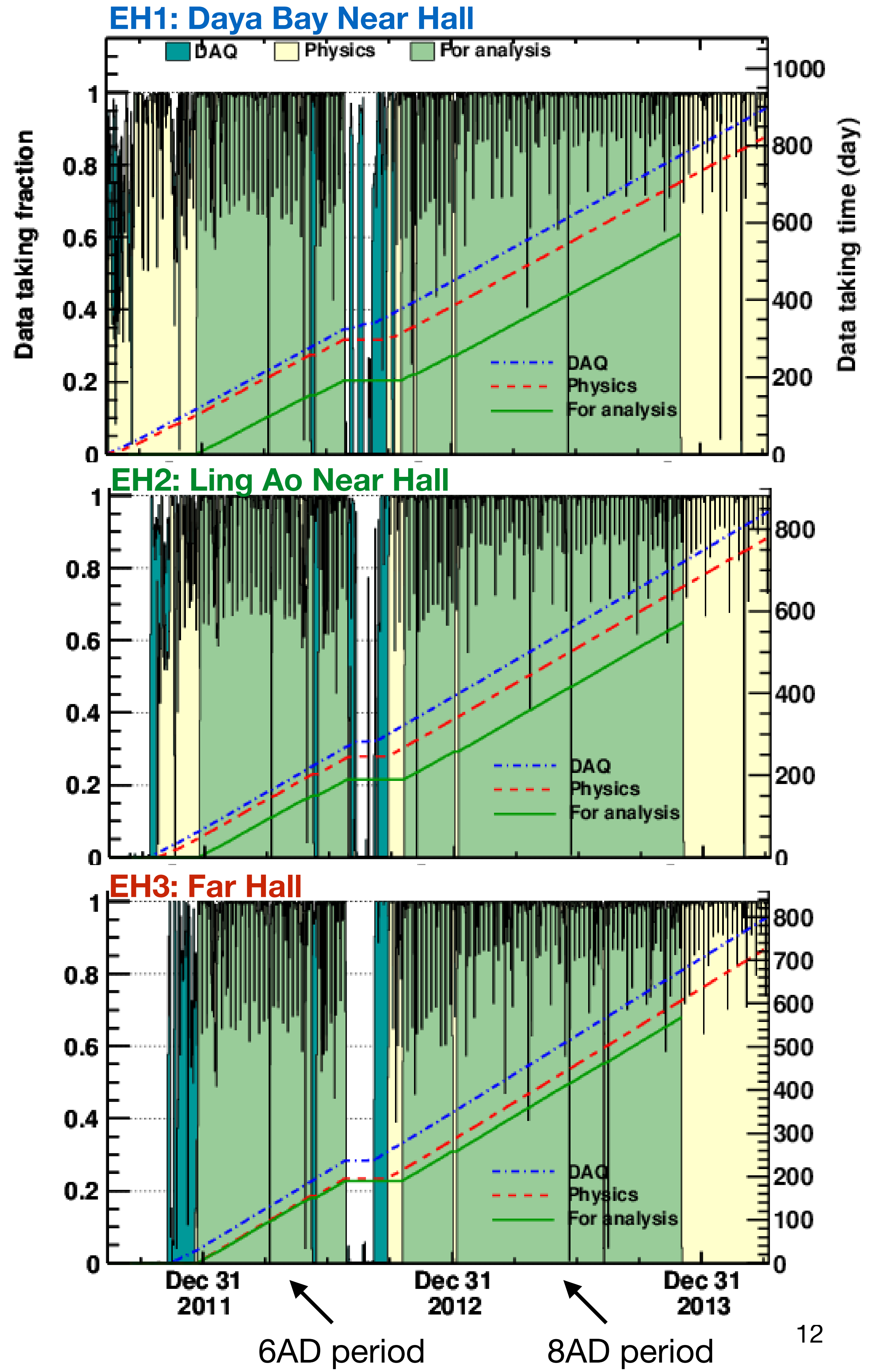
- Oscillation analysis: $\sin^2 2\theta_{13}$ and Δm^2_{ee}
  - 4 times more statistics than our previously published results (*PRL 112, 061801 (2014)*)

Using 6-AD period (217 days):

- Absolute flux of reactor antineutrino
- Independent measurement of $\sin^2 2\theta_{13}$ using neutron capture on hydrogen
- Light sterile neutrino search

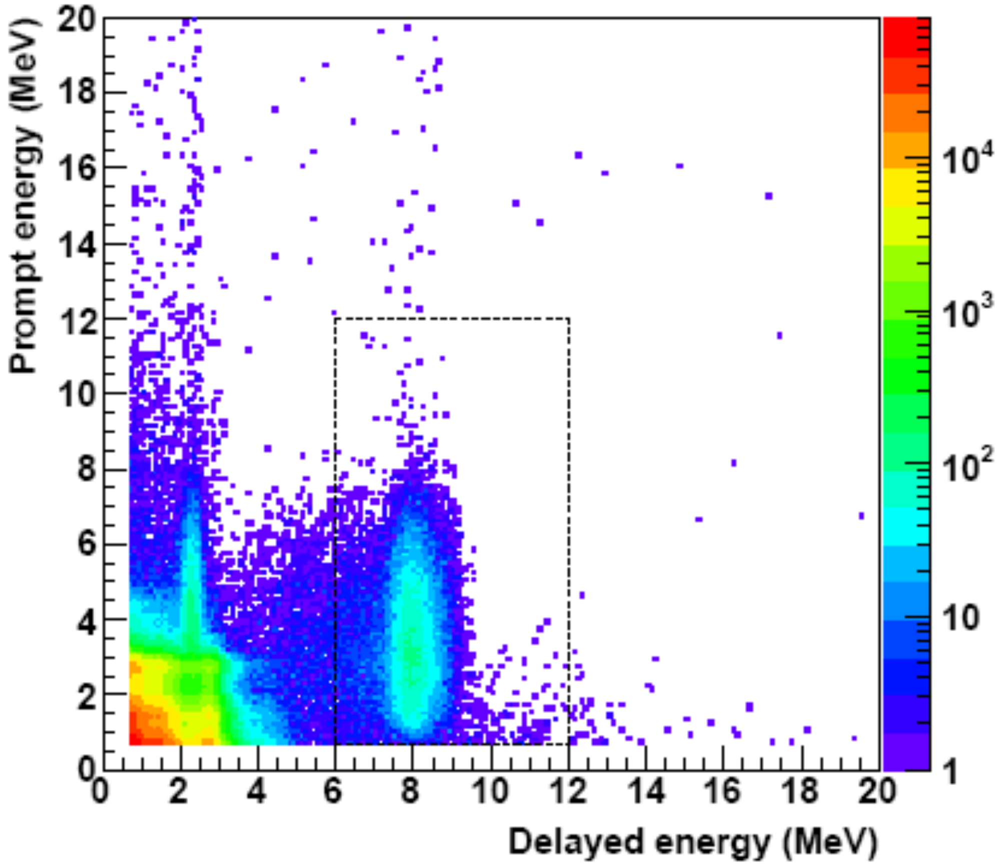
6-AD period: 2011/12/24 - 2012/07/28

8-AD period: 2012/10/19 - 2013/11/27

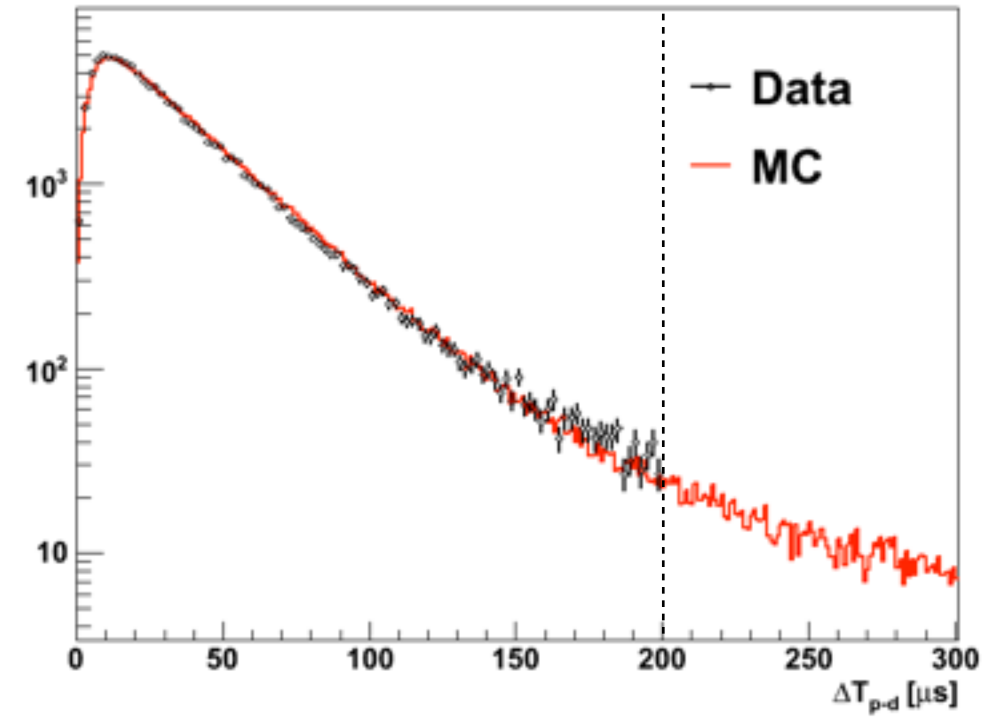


Antineutrino Candidate Selection

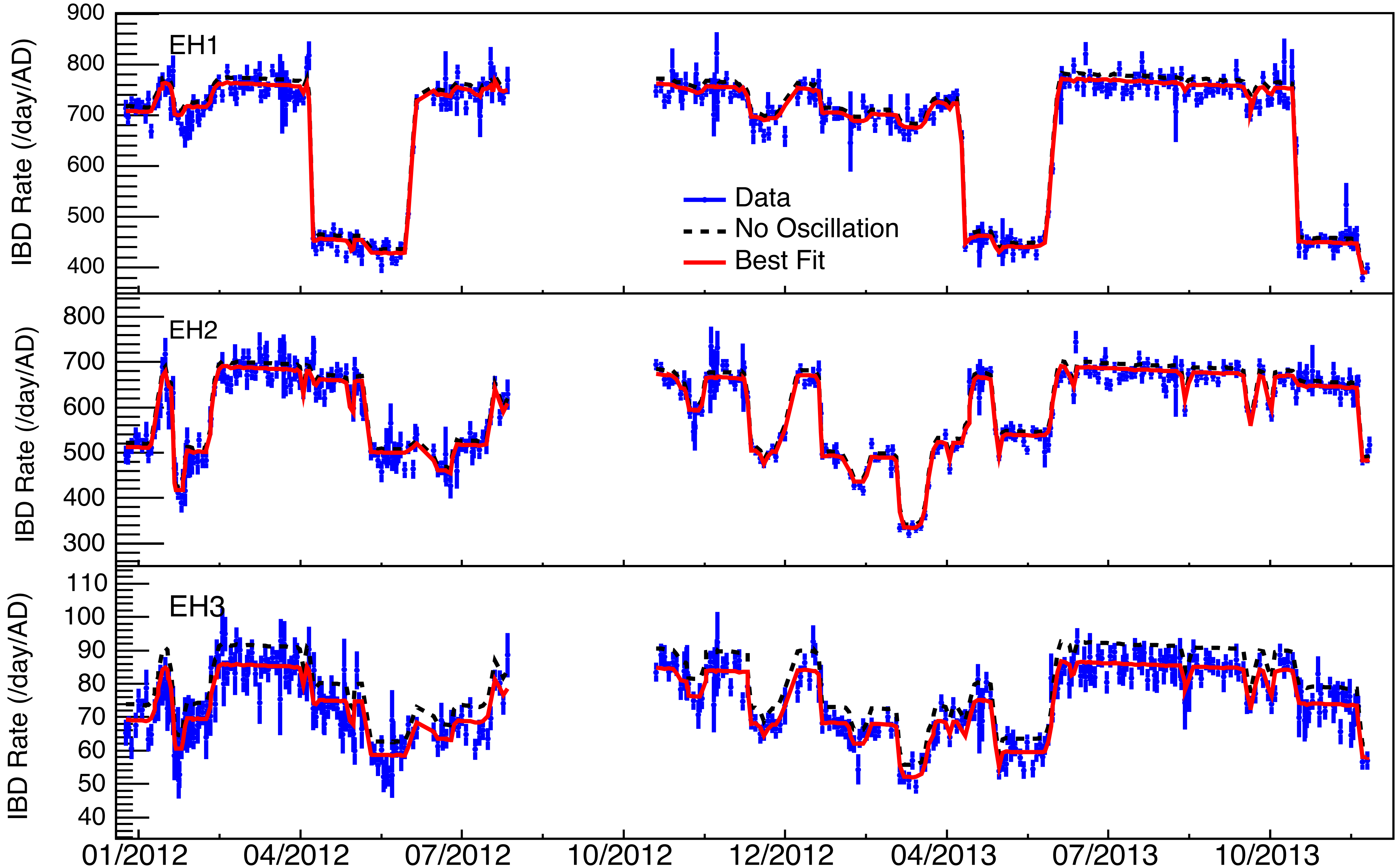
- Reject PMT flashers
- Muon veto:
  - Water pool Muon: reject 0.6ms
  - AD Muon (>20 MeV): reject 1 ms
  - AD Shower Muon (>2.5 GeV): reject 1s
- Prompt positron Energy: 0.7 MeV < Ep < 12 MeV
- Delayed neutron Energy: 6 MeV < Ed < 12 MeV
- Neutron Capture time: 1 us < Δt < 200 us
- Multiplicity cut: only select isolated candidate pairs



	Efficiency	Uncertainty Correlated	Uncertainty 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%

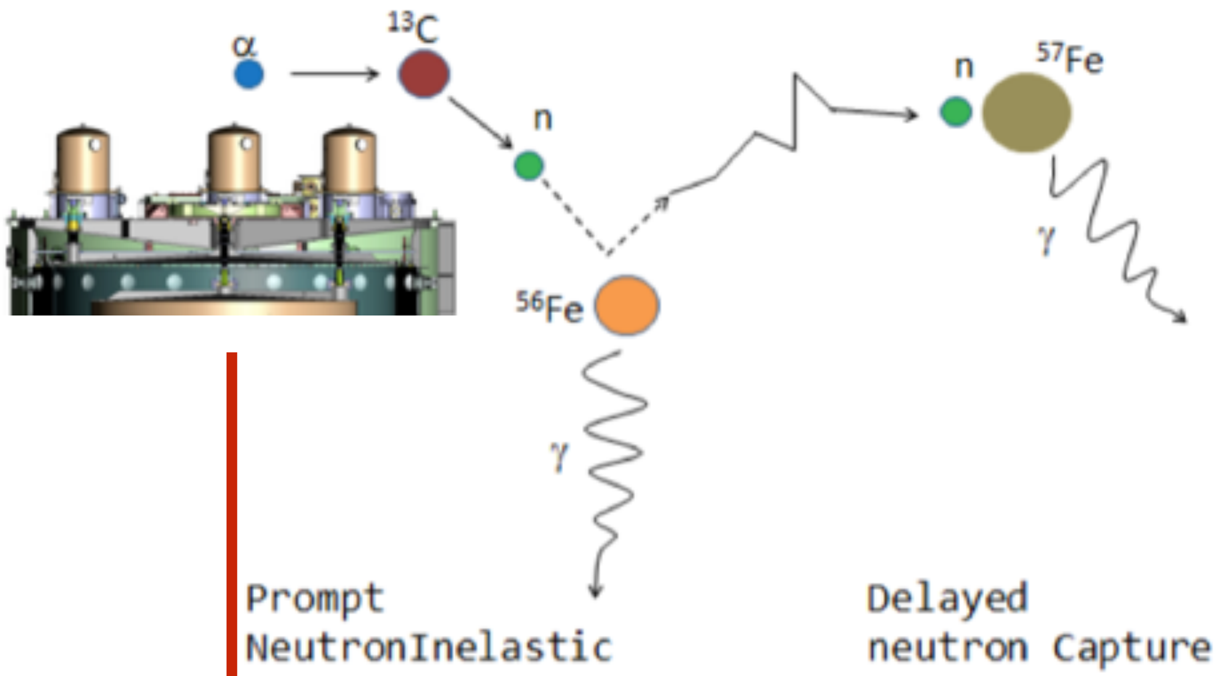


Over 1 million antineutrino interactions!!
(150k at the far site)

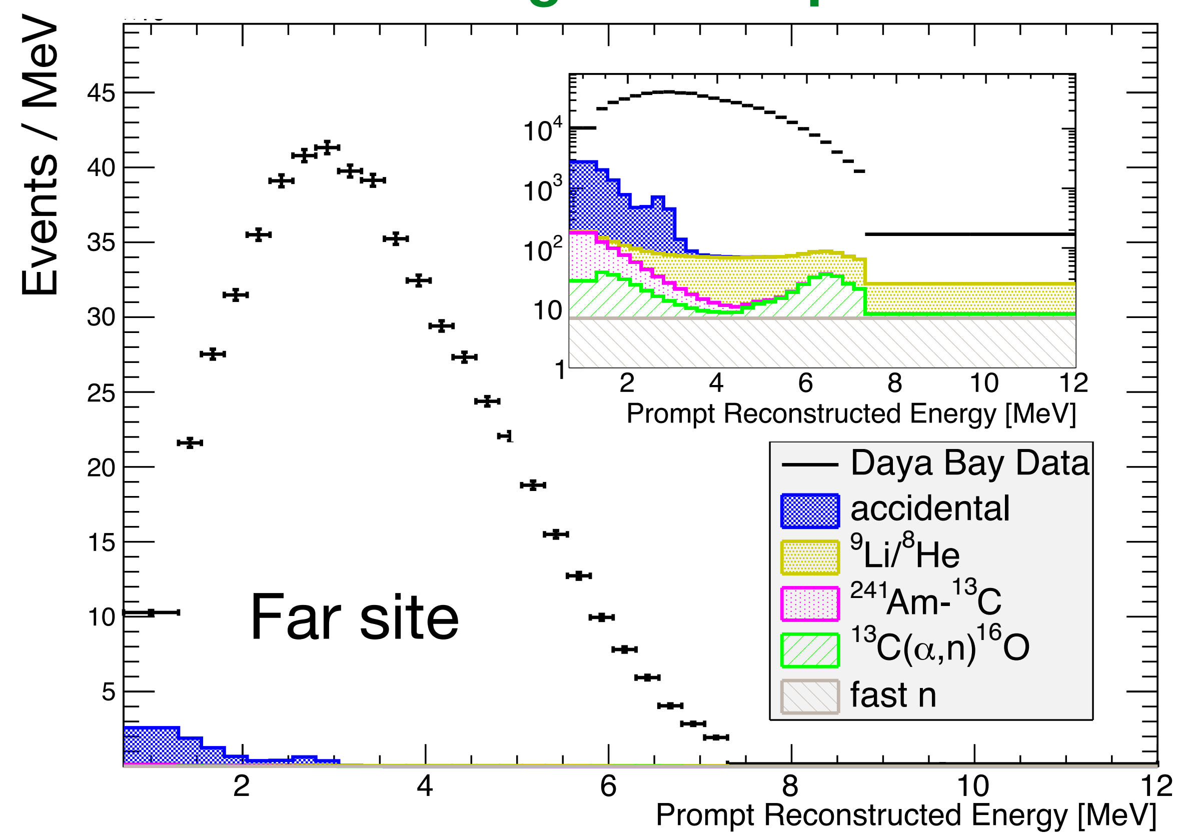


Detected rate strongly correlated with reactor flux

Background Budget



a low background experiment



Background	Near	Far	Uncertainty	Method
Accidentals	1.4%	2.3%	negligible	statistically calculated from uncorrelated singles
AmC source	0.03%	0.2%	~50%	MC benchmarked with single gamma and strong AmC source
Li-9 / He-8	0.4%	0.4%	~50%	measured with after-muon events
Fast neutron	0.1%	0.1%	~30%	measured from AD/water/RPC tagged muon events
Alpha-n	0.01%	0.1%	~50%	calculated from measured radioactivity

Data Summary

preliminary

6-AD 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 ± 0.1	0.21 ± 0.1	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					

8-AD Period

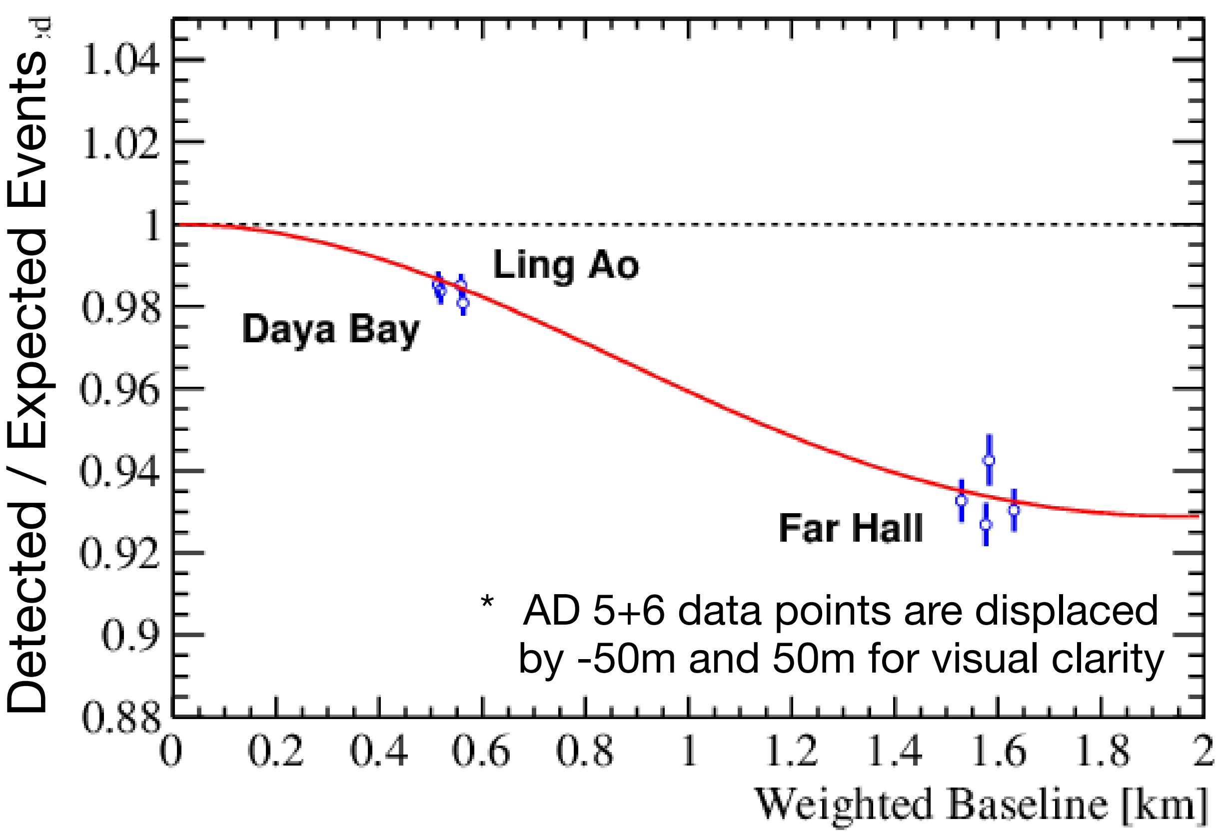
	AD1	AD2	AD3	AD8	AD4	AD5	AD6	AD7
IBD candidates	202461	206217	193356	190046	27067	27389	27032	27419
DAQ live time(day)	374.447		378.407			372.685		
ε_μ	0.8255	0.8223	0.8574	0.8577	0.9811	0.9811	0.9808	0.9811
ε_m	0.9746	0.9749	0.9759	0.9756	0.9762	0.976	0.9757	0.9758
Accidentals(/day)	8.62 ± 0.09	8.76 ± 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 ± 0.02
$^{13}C(\alpha,n)^{16}O$(/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					

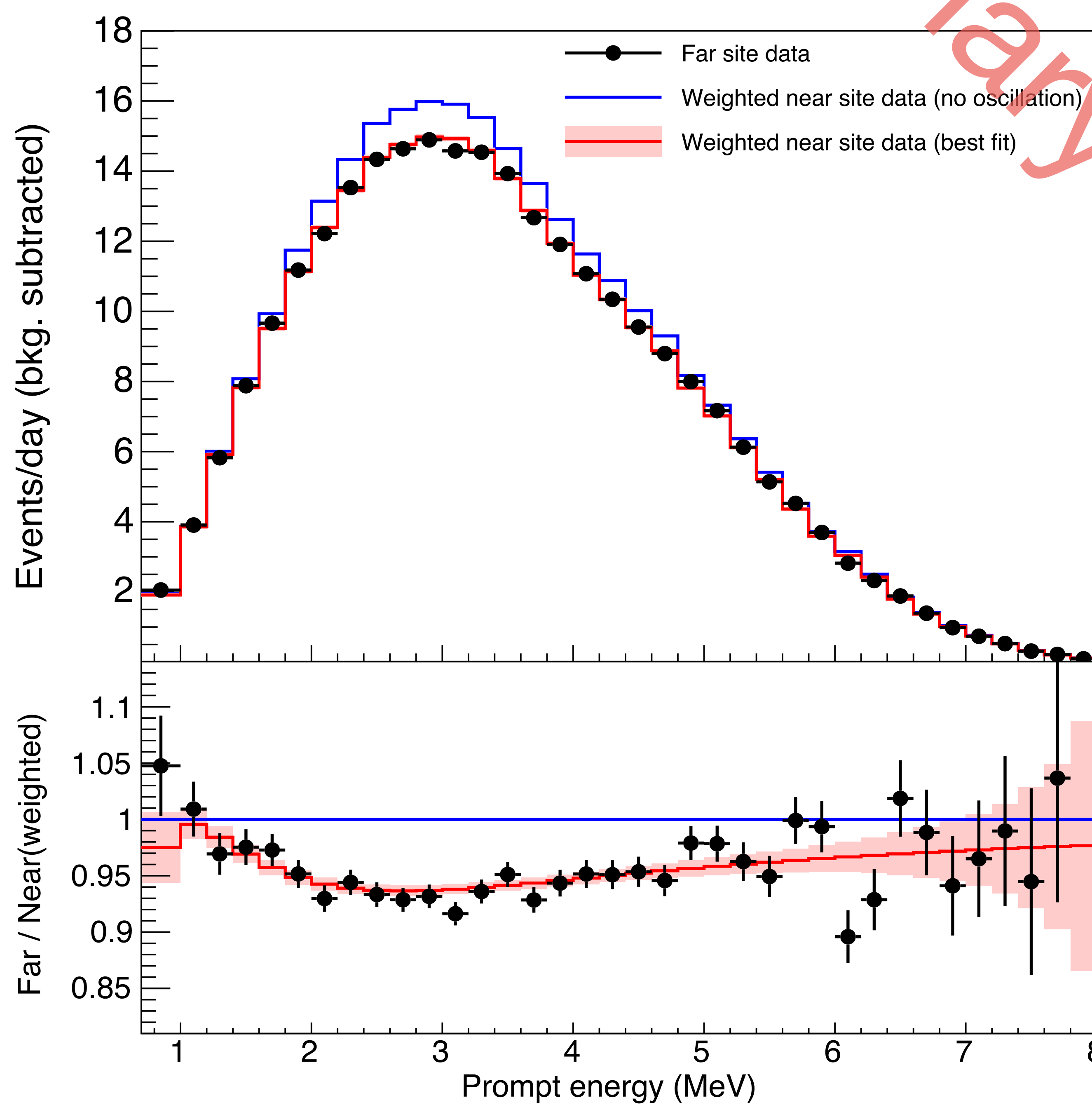
Expected: AD1/AD2 = 0.982; AD3/AD8 = 1.012

consistent rate for side-by-side detectors

Far v.s. Near Comparison

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





The observed relative rate deficit and relative spectrum distortion are highly consistent with oscillation interpretation

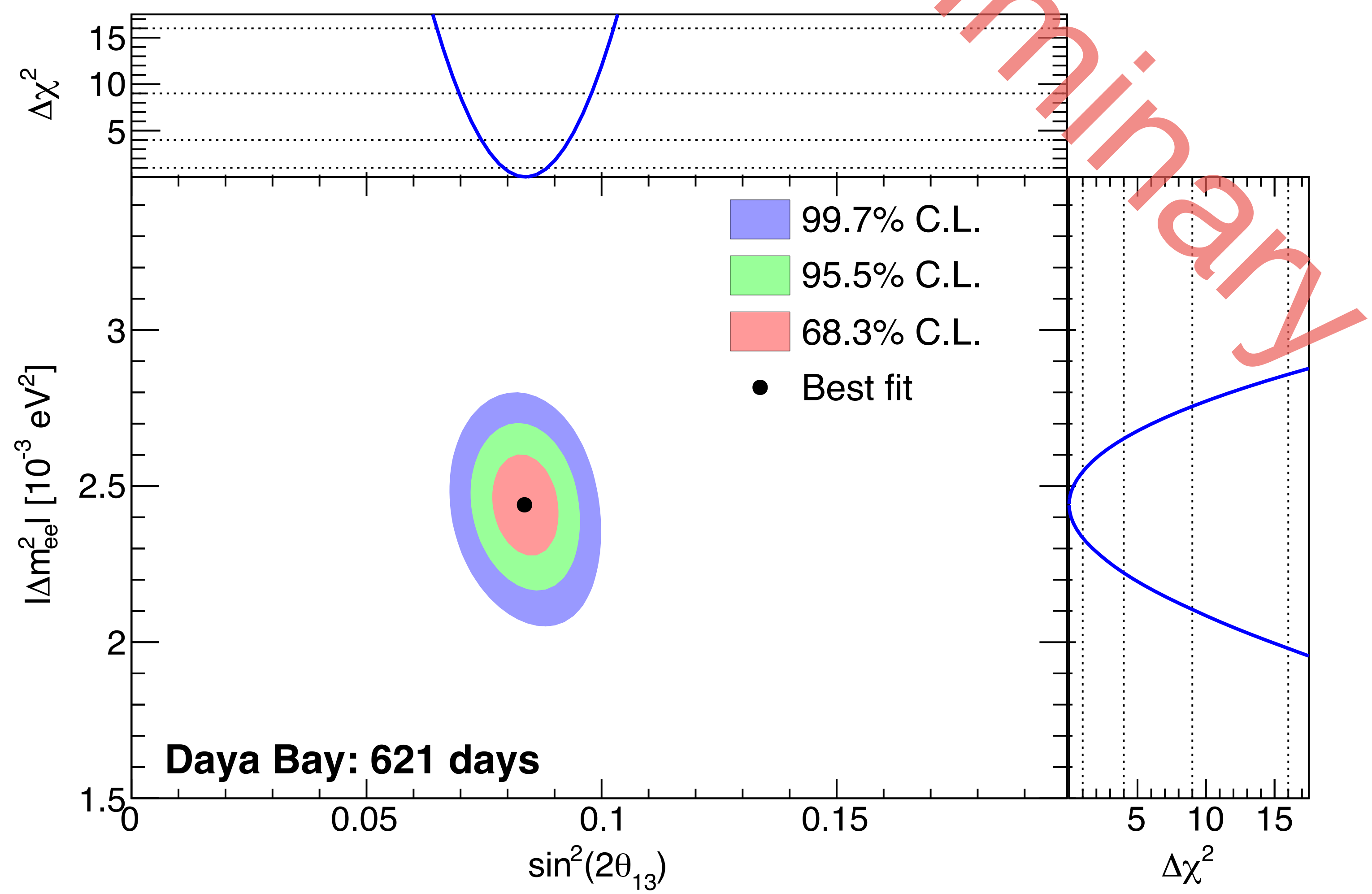
Oscillation Results

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

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

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

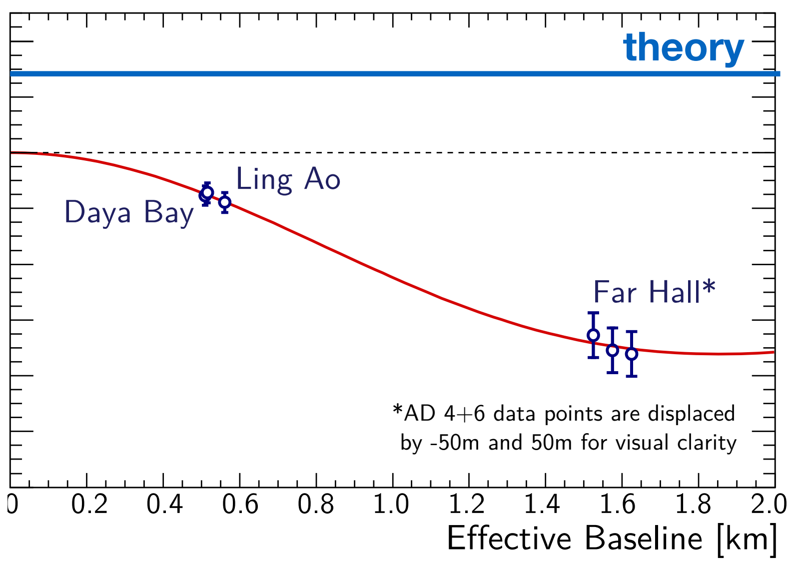
- **Most precise measurement of $\sin^2 2\theta_{13}$**, precision reached < 6%
- **Most precise measurement of Δm^2_{ee} in the electron neutrino disappearance channel**
  - consistent with the muon neutrino disappearance experiments
  - comparable precision

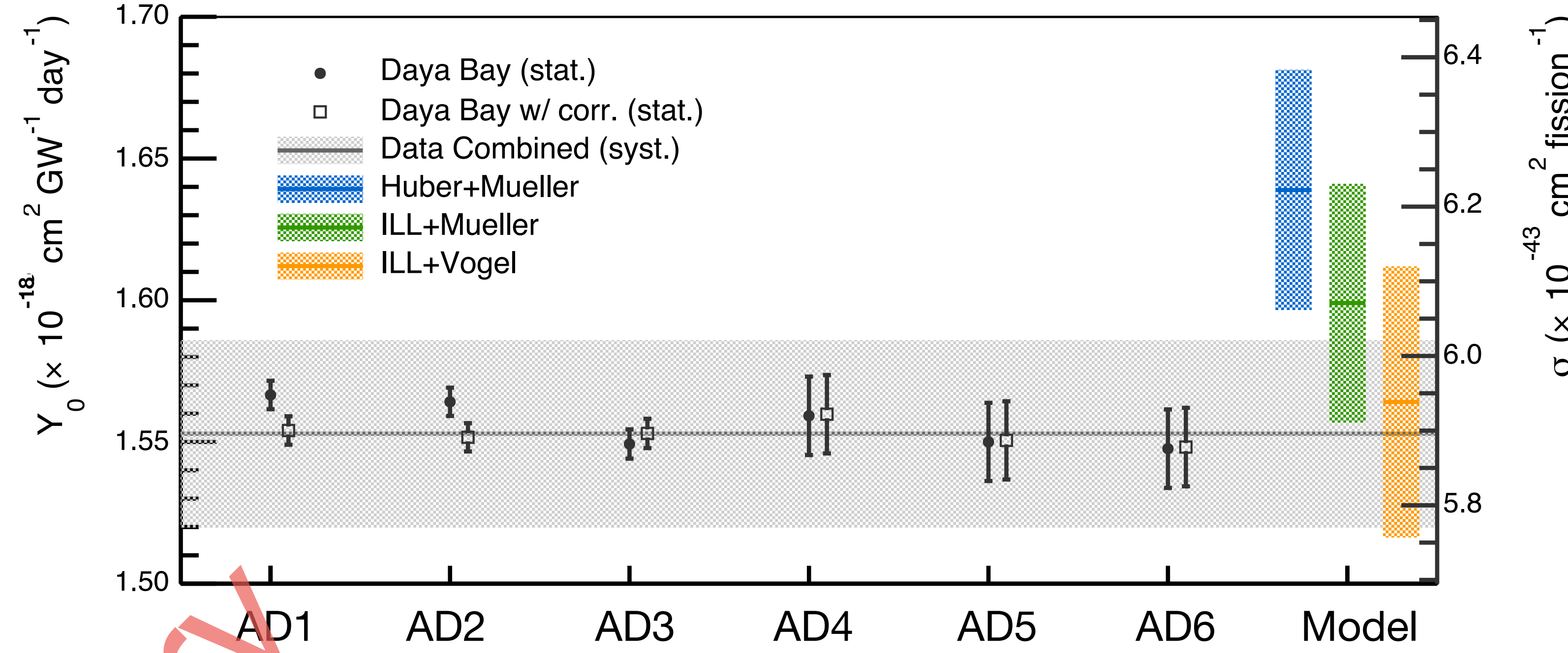


	Normal MH Δm^2_{32} [10^{-3}eV^2]	Inverted MH Δm^2_{32} [10^{-3}eV^2]
From Daya Bay Δm^2_{ee}	$2.39^{+0.10}_{-0.11}$	$-2.49^{+0.10}_{-0.11}$
From MINOS $\Delta m^2_{\mu\mu}$	$2.37^{+0.09}_{-0.09}$	$-2.41^{+0.11}_{-0.09}$

A. Radovic, DPF 2013

Absolute Reactor Antineutrino Flux





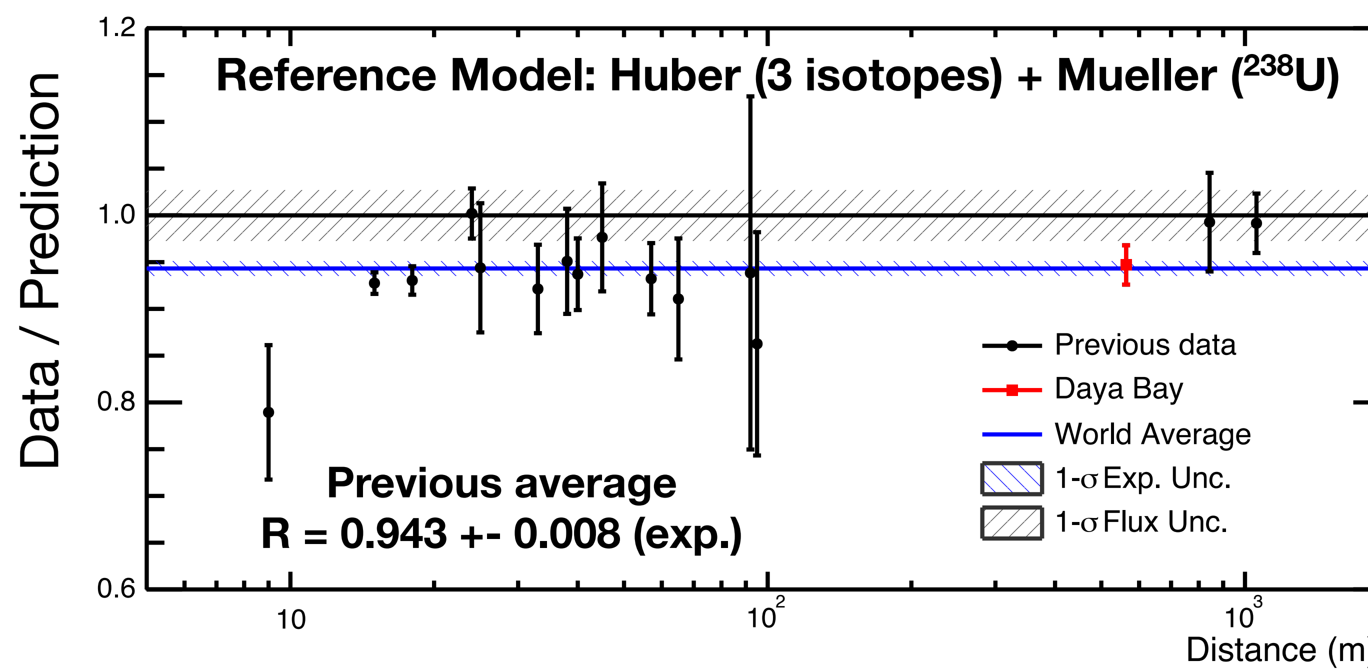
preliminary

Flux Measurement Uncertainty

	Uncertainty
statistics	0.2%
θ_{13}	0.2%
reactor	0.9%
detector efficiency	2.1%
Total	2.3%

^{235}U : ^{238}U : ^{239}Pu : ^{241}Pu	0.586 : 0.076 : 0.288 : 0.050
Y_0 (cm^2 GW^{-1} day^{-1})	1.553×10^{-18}
σ_f (cm^2 fission^{-1})	5.934×10^{-43}
Data / Prediction (Huber+Mueller)	0.947 ± 0.022
Data / Prediction (ILL+Vogel)	0.992 ± 0.023

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

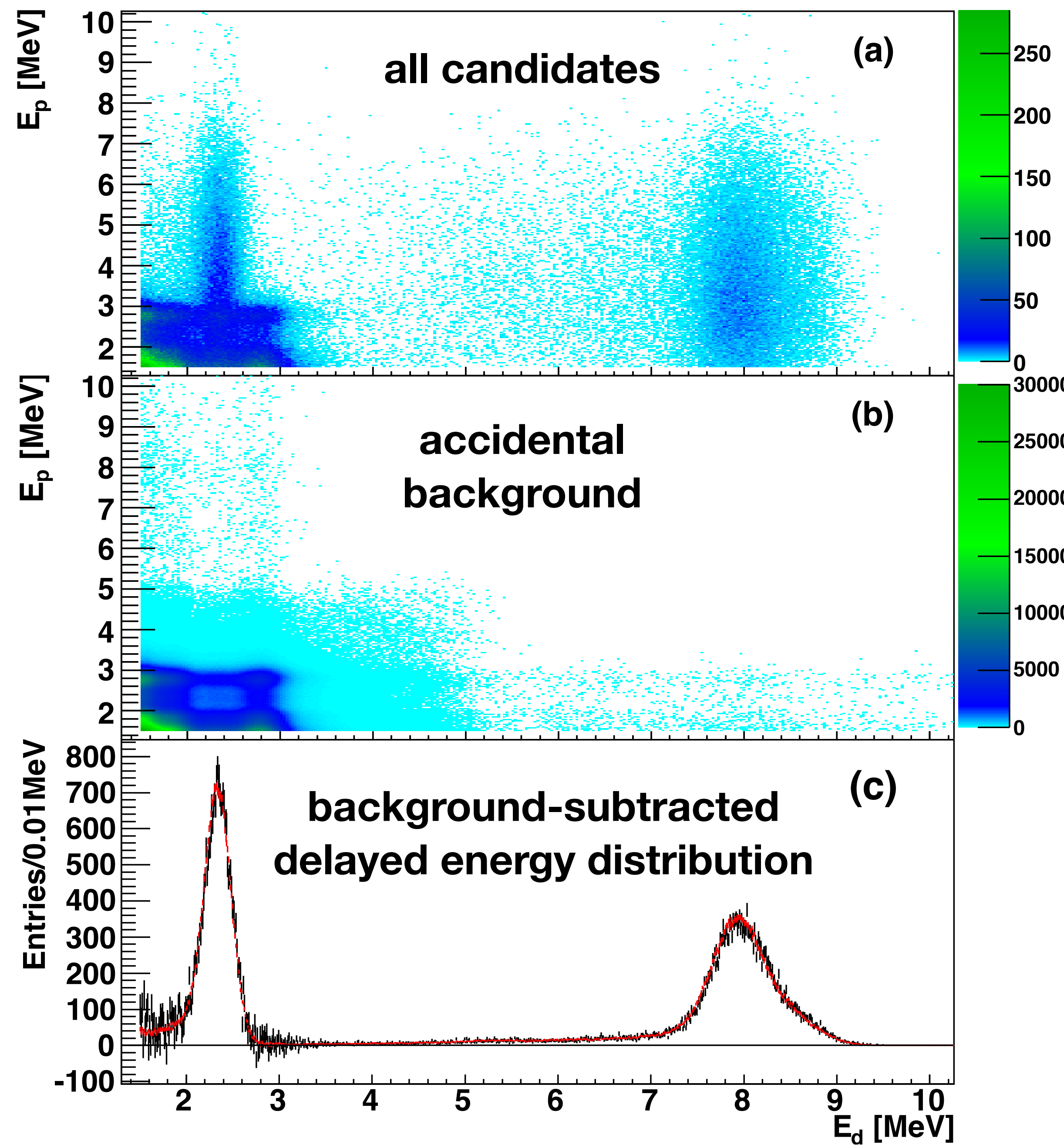


Independent $\sin^2 2\theta_{13}$ measurement through nH

- Advantage
  - High statistics (15% capture in the 20-ton Gd-LS region and 100% in the 20-ton LS region)
  - Different systematic uncertainties from nGd analysis
- Challenge
  - High accidental background
    - longer capture time
    - lower delayed energy
- Strategy
  - Raise prompt energy cut Ep > 1.5 MeV
  - Require prompt to delayed distance ΔR < 0.5 m
  - Relative measurement to reduce systematics

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

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

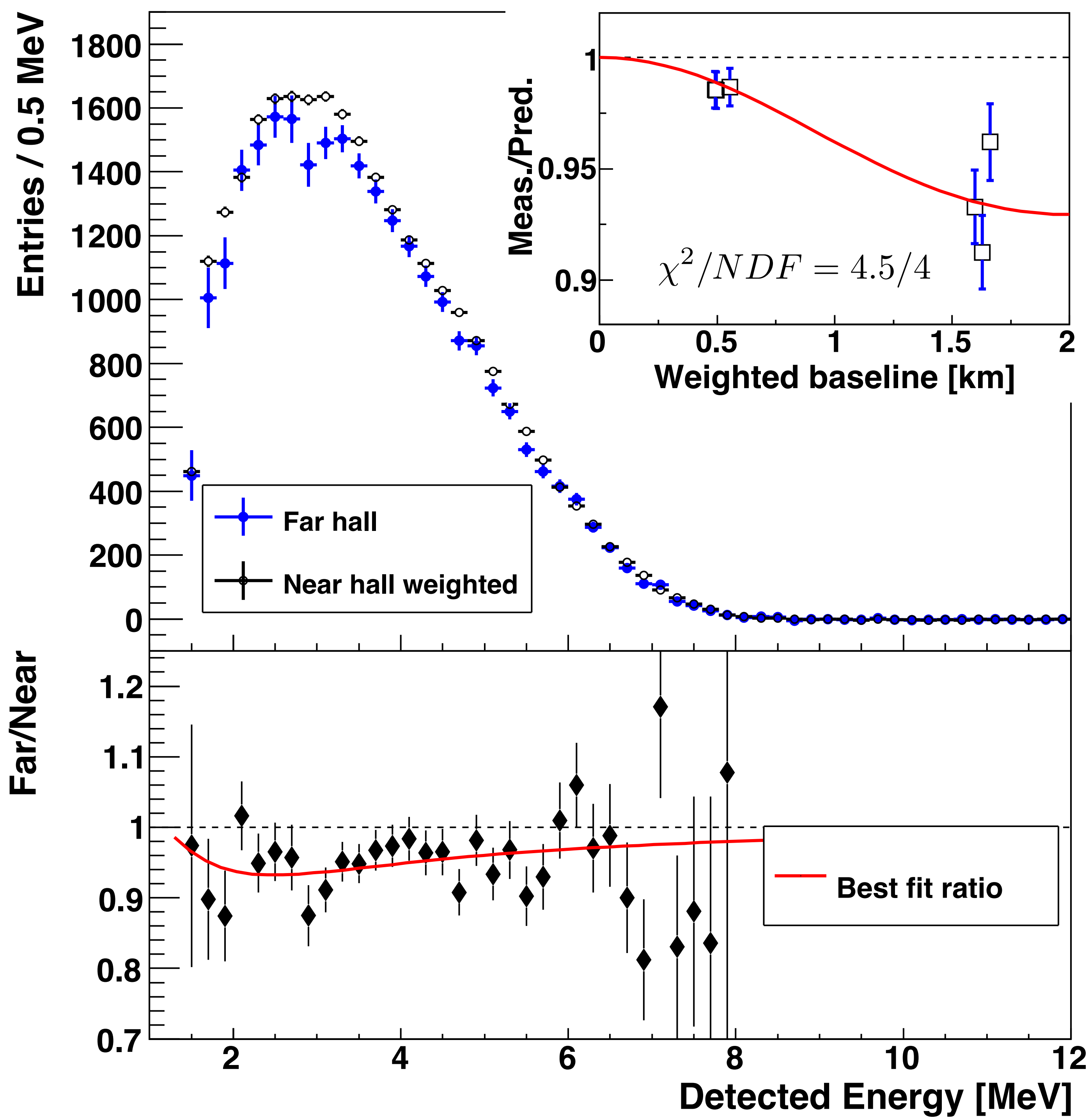


nH Analysis Results

- All 217 days of 6-AD period
- Observed significant rate deficit at far site, 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 analysis in progress

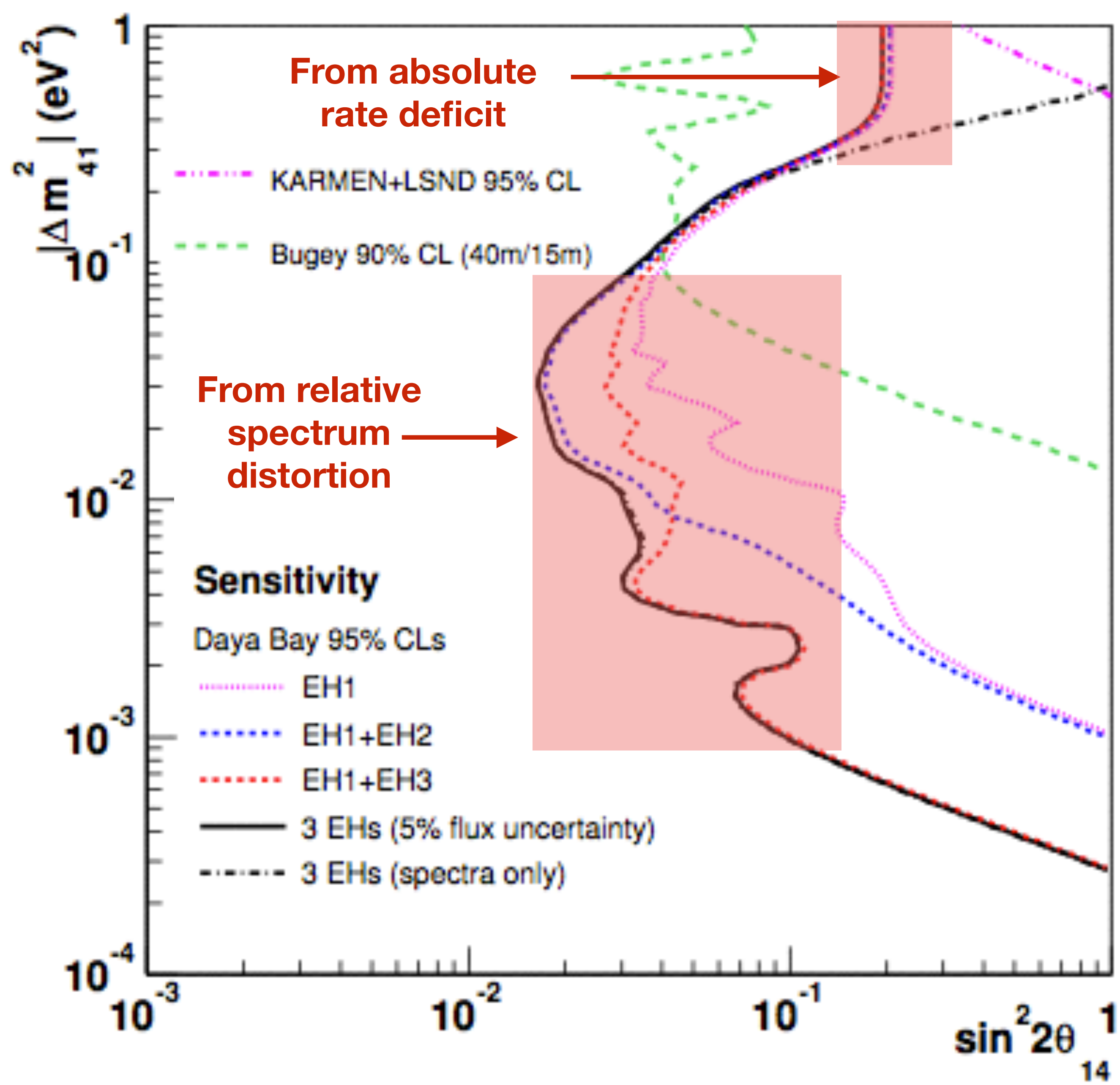
Light Sterile Neutrino Search

- Daya Bay has a unique combination of multiple baselines: EH1 (~350m), EH2 (~500m), EH3 (~1600m)
  - Sterile neutrinos will cause additional spectrum difference between different sites

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

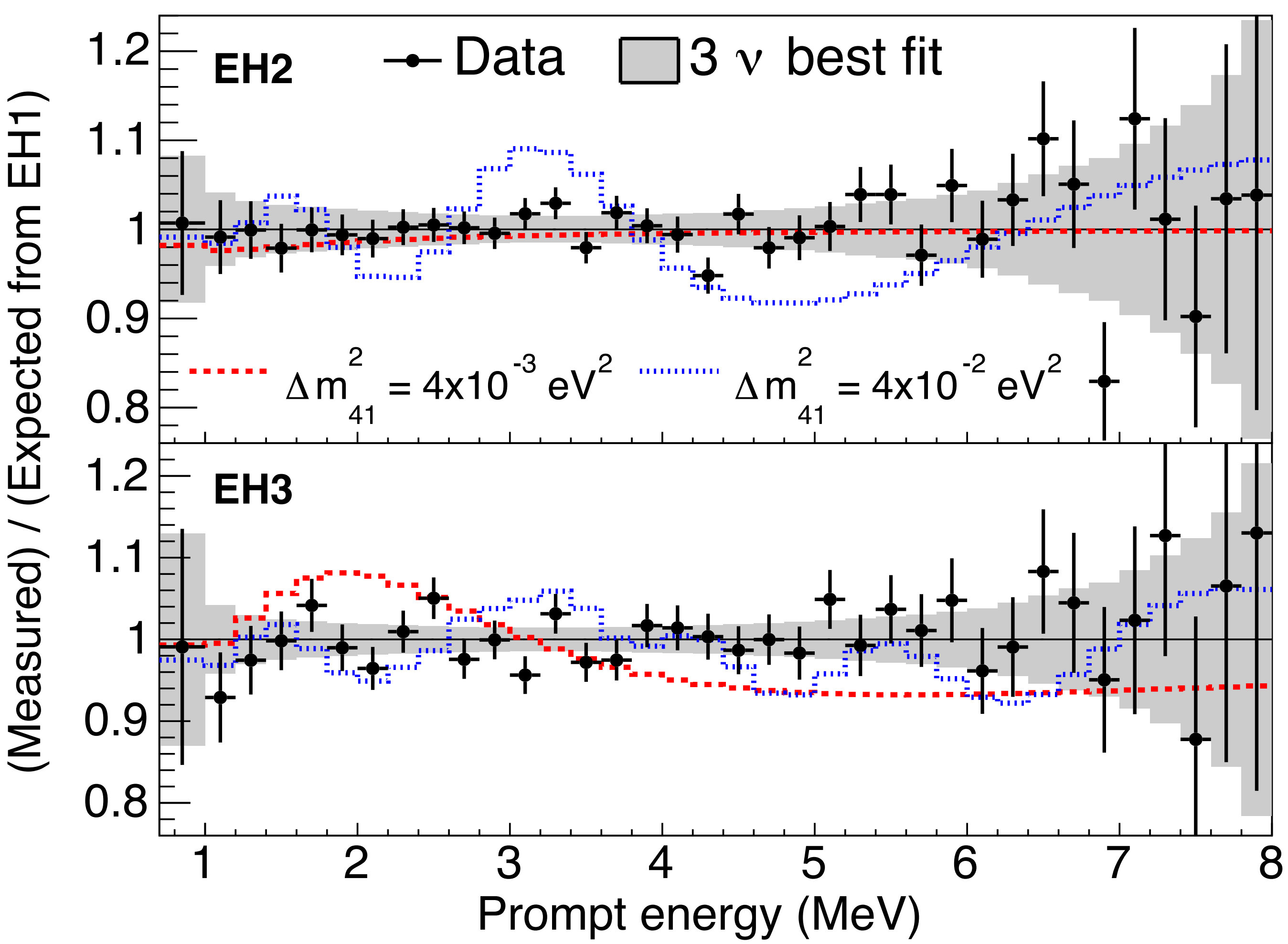
  - High sensitivity in the largely unexplored region $\Delta m^2_{41} < 0.1$ eV^2
  - A robust relative measurement independent of reactor related uncertainties

Expected Sensitivity

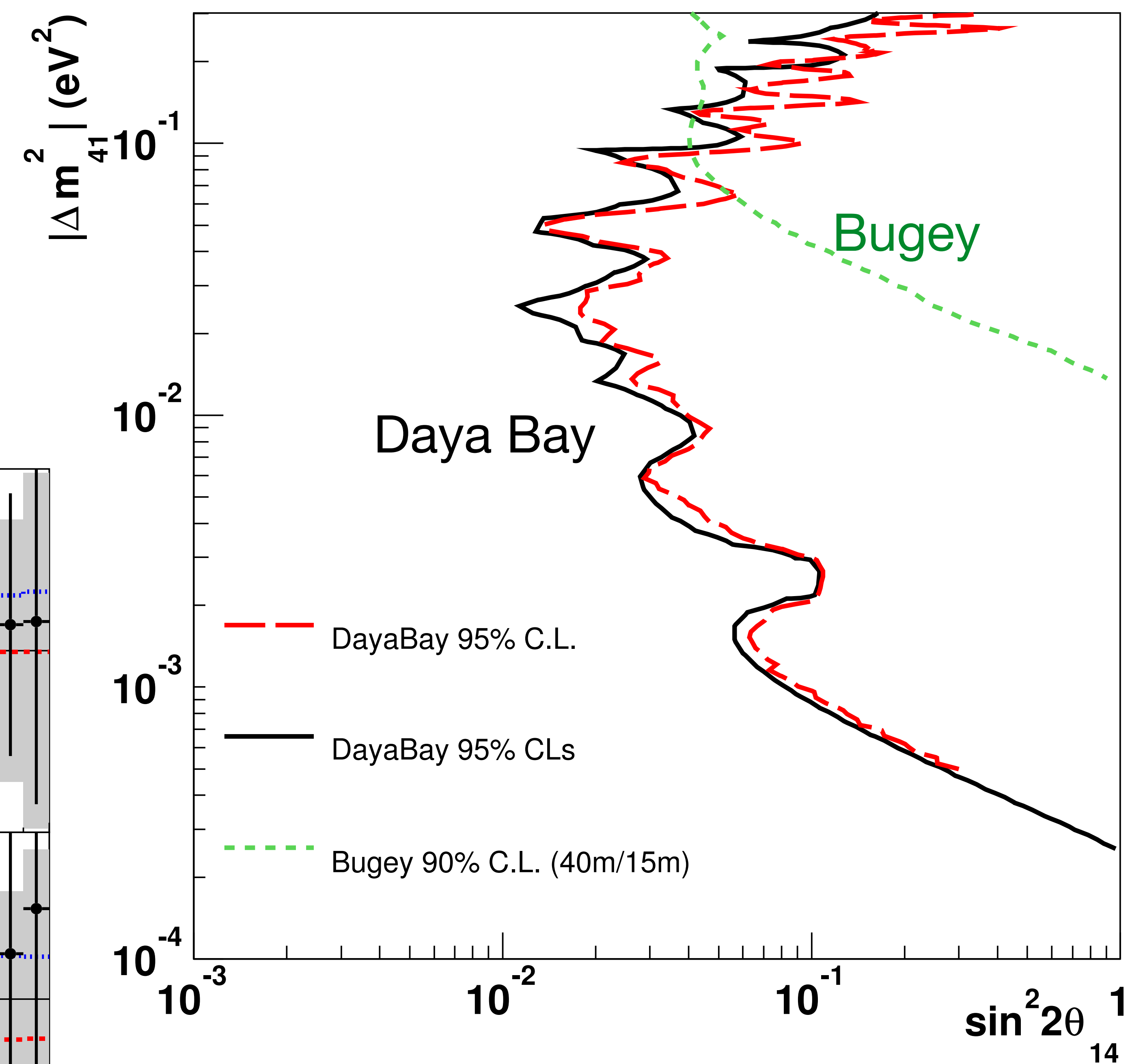


Light Sterile Neutrino Search Results

- All 217 days of 6-AD period
- Consistent with standard 3-flavor neutrino oscillation model
- Able to set stringent limits in the region $10^{-3}\ \mathrm{eV}^2 < \Delta m^2_{41} < 0.1\ \mathrm{eV}^2$



dashed curves assumes $\sin^2 2\theta_{14} = 0.1$



Summary

- Daya Bay has measured

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

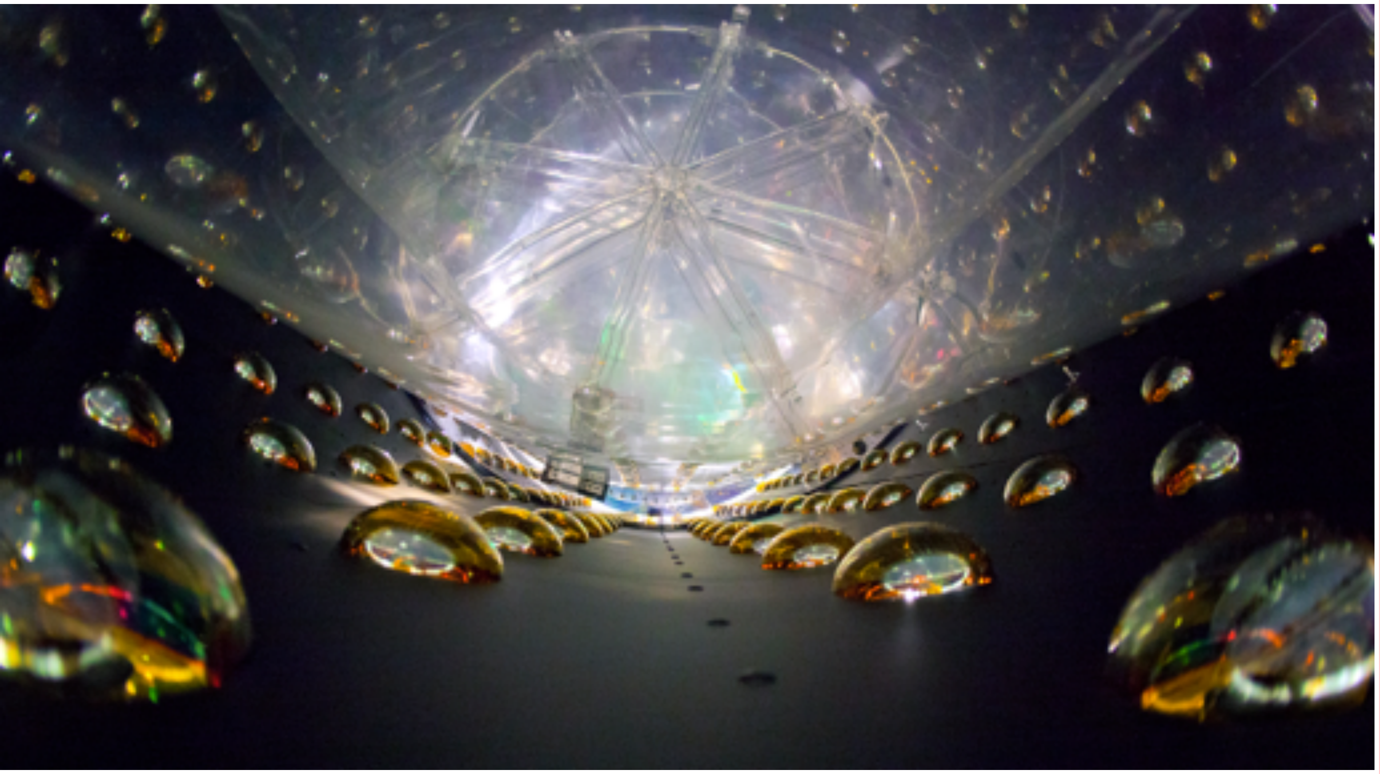
  with 621 days of data. The precision measurement of θ_{13} opens the door for future experiments to study neutrino mass hierarchy and leptonic CP violation.

- Precision will be further improved in the coming years. By the end of 2017, we expect to measure both $\sin^2 2\theta_{13}$ and Δm^2_{ee} to precision below 3%.

- Meanwhile, Daya Bay has many parallel on-going analysis:
  - Absolute reactor antineutrino flux measurement is consistent with previous short-baseline experiments
  - Independent nH rate analysis has measured $\sin^2 2\theta_{13} = 0.083 \pm 0.018$
  - We set stringent limits for sterile neutrinos in the region $10^{-3}\ \mathrm{eV}^2 < \Delta m^2_{41} < 0.1\ \mathrm{eV}^2$

Stayed tuned for more exciting news from Daya Bay!

A Lot More Daya Bay Details in Poster Sessions



1. Calibration of Antineutrino Detectors at Daya Bay *(Patrick Tsang)*
2. Characterizing the Energy Response of the Daya Bay Antineutrino Detectors *(Soeren Jetter)*
3. The AmC calibration source induced background at Daya Bay Experiment *(Gaosong Li)*
4. Natural radioactivity and related background in Daya Bay experiment *(Zeyuan Yu)*
5. Improvements on Monte Carlo Simulation and Studies of Absolute Detection Efficiency at Daya Bay *(Guofu Cao)*
6. A Relative Rate and Shape Measurement of Neutrino Oscillation at the Daya Bay Experiment *(Henoch Wong)*
7. Prediction of the Reactor Antineutrino Flux and Spectrum for the Daya Bay experiment *(Xubo Ma)*
8. Measurement Of The Absolute Reactor Flux And Spectrum At Daya Bay *(Bryce Littlejohn)*
9. Spectrum Unfolding and Generic Reactor Antineutrino Spectrum Study at Daya Bay *(Qingwang Zhao)*
10. An independent measurement of theta_13 using Hydrogen neutron capture at Daya Bay *(Bei-zhen Hu)*
11. Search for sterile neutrino mixing at Daya Bay *(Yasuhiro Nakajima)*
12. Underground Muon Flux in Daya Bay and JUNO experiment *(Jilei Xu)*
13. Production of muon-induced radioactive isotopes at Daya Bay *(Sishuo Liu)*
14. Supernova Early Warning in the Daya Bay Reactor Neutrino Experiment *(Hanyu Wei)*