The Daya Bay oscillation analysis results

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On behalf of Daya Bay Collaboration

Neutrino Oscillation

$$\nu_\alpha = \sum_i U_{\alpha i} \nu_i \qquad \begin{array}{ll} \alpha = e, \mu, \tau & \text{Flavor eigenstates} \\ i = 1, 2, 3 & \text{Mass eigenstates} \end{array}$$

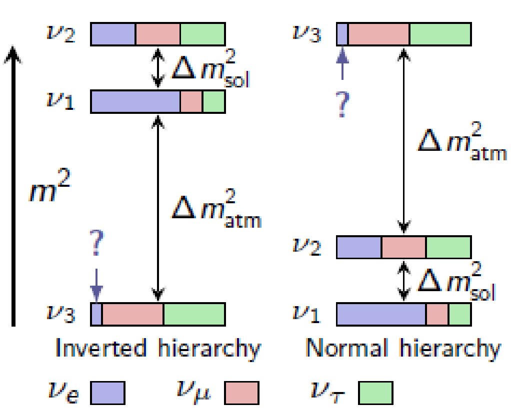
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta_{CP}} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix}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

$\theta_{23} \sim 5°$ Atmospheric ν
Accelerator ν

$\theta_{13} < 10°$
Short-Baseline Reactor ν
Accelerator ν

$\theta_{12} \sim 35°$
Solar ν
Long-Baseline Reactor ν

Remaining unknowns: 1) mass hierarchy 2) CP phase



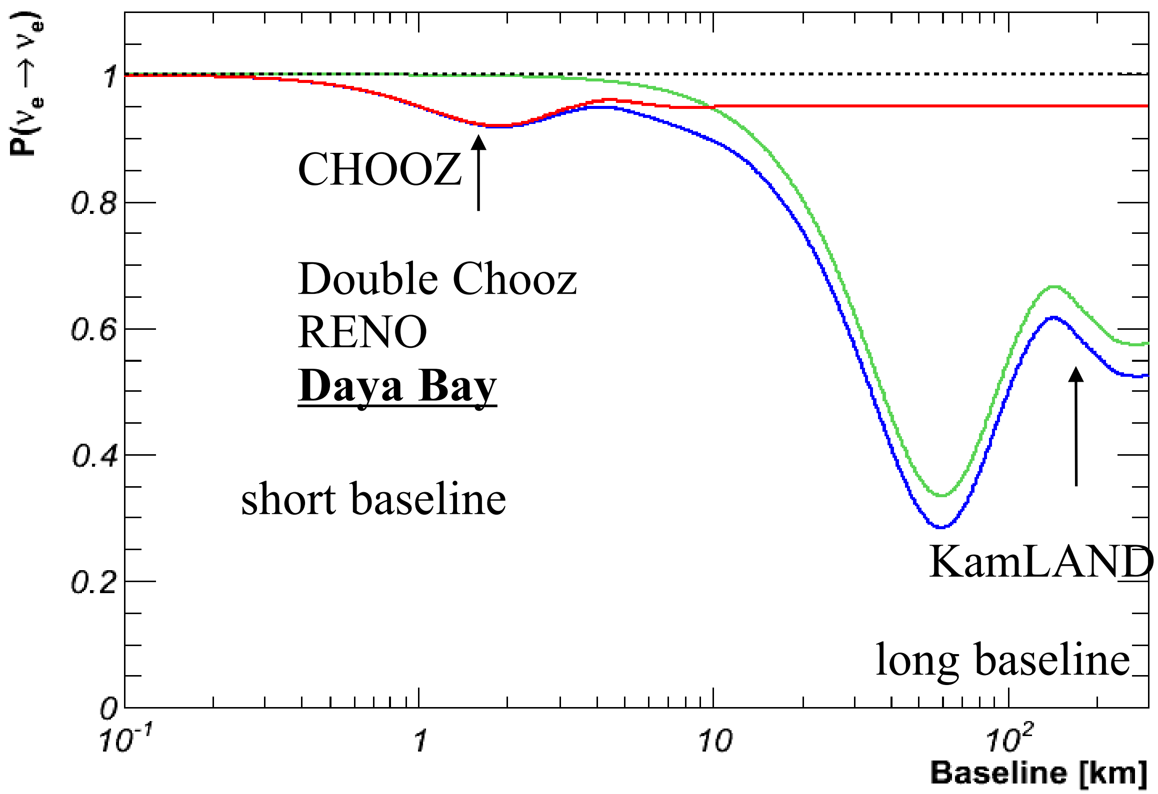
Magnitude of θ13 is the signpost to the determination of these unknowns!

θ_{13} measurement with reactor

Reactor anti-neutrino survival probability

$$P_{\bar{\nu}_e\to\bar{\nu}_e}(L) = 1 - \cos^4\theta_{13}\underbrace{\sin^2 2\theta_{12}\sin^2\Delta_{21}}_{\text{long baseline}} - \sin^2 2\theta_{13}\underbrace{(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32})}_{\sin^2\Delta_{ee}}$$

short baseline



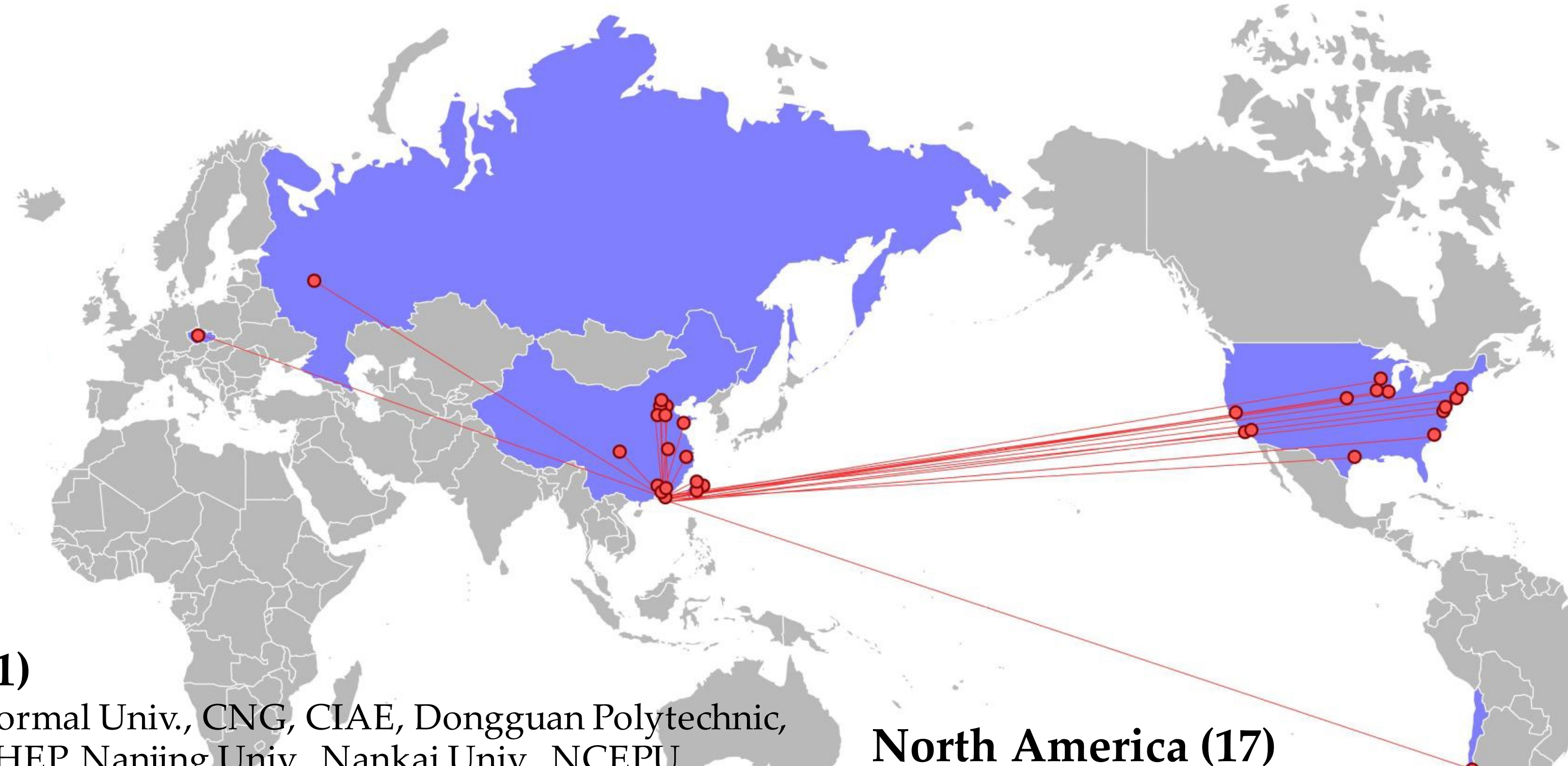
DayaBay: Relative measurement method:

$$\frac{N_\mathrm{f}}{N_\mathrm{n}} = \left(\frac{N_\mathrm{p,f}}{N_\mathrm{p,n}}\right)\left(\frac{L_\mathrm{n}}{L_\mathrm{f}}\right)^2\left(\frac{\epsilon_\mathrm{f}}{\epsilon_\mathrm{n}}\right)\left[\frac{P_\mathrm{sur}(E_\nu, L_\mathrm{f})}{P_\mathrm{sur}(E_\nu, L_\mathrm{n})}\right].$$

To overcome the uncertainty from reactor

Daya Bay collaboration

~230 collaborators

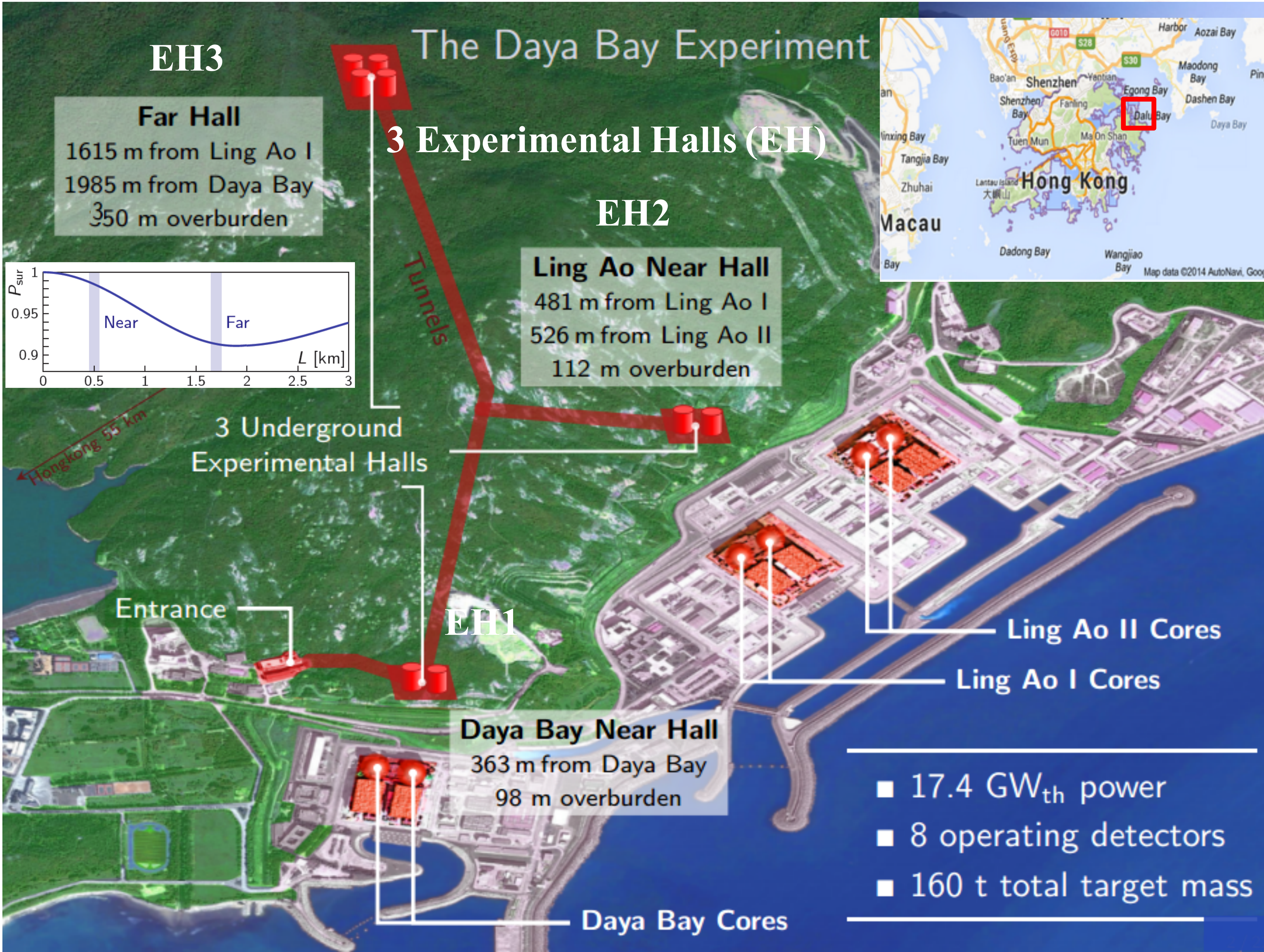


Asia (21)
Beijing Normal Univ., CNG, CIAE, Dongguan Polytechnic, ECUST, IHEP, Nanjing Univ., Nankai Univ., NCEPU, Shandong Univ., Shanghai Jiao Tong Univ., Shenzhen Univ., Tsinghua Univ., USTC, Xian Jiaotong Univ., Zhongshan Univ., Chinese Univ. of Hong Kong, Univ. of Hong Kong, National Chiao Tung Univ., National Taiwan Univ., National United Univ, CQU.

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



The Daya Bay Experiment
EH3
Far Hall
1615 m from Ling Ao I
1985 m from Daya Bay
350 m overburden
3 Experimental Halls (EH)
EH2
Ling Ao Near Hall
481 m from Ling Ao I
526 m from Ling Ao II
112 m overburden
Tunnels
P_{sur}
1
0.95
0.9
Near
Far
L [km]
0 0.5 1 1.5 2 2.5 3
3 Underground
Experimental Halls
Hongkong 55 km
Entrance
EH1
Ling Ao II Cores
Ling Ao I Cores
Daya Bay Near Hall
363 m from Daya Bay
98 m overburden
Daya Bay Cores
17.4 GW_{th} power
8 operating detectors
160 t total target mass
Shenzhen
Hong Kong
Macau
Map data ©2014 AutoNavi, Goo

Antineutrino Detector (AD)

- Inverse beta decay (IBD) reaction

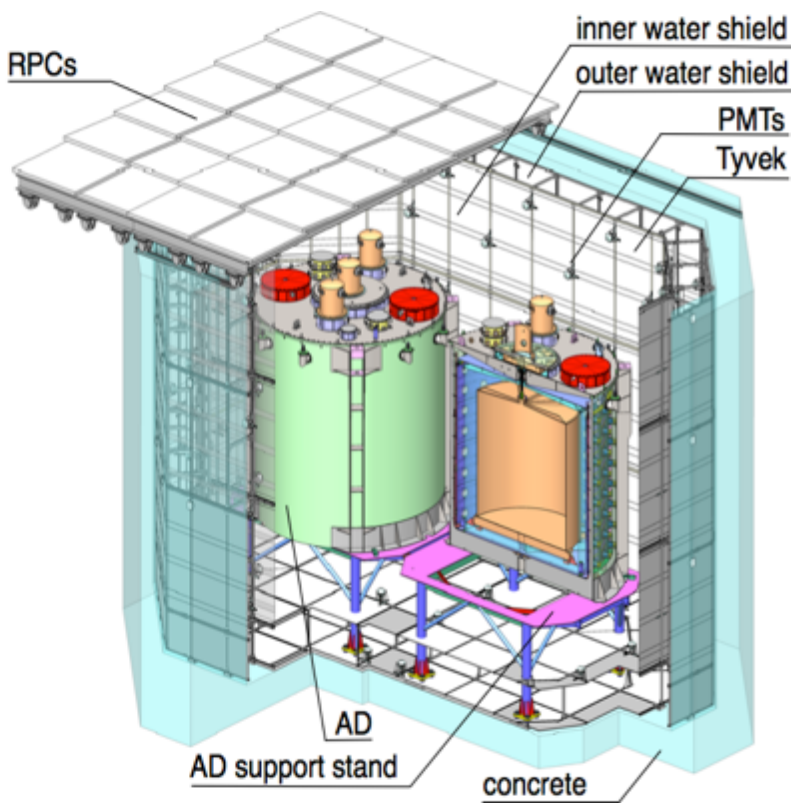
Prompt signal

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

Delayed Signal

$n + {}^{x}\mathrm{Gd} \rightarrow {}^{x+1}\mathrm{Gd} + \gamma' s$ ~30 μs 8MeV

$n + \mathrm{H} \rightarrow \mathrm{D} + \gamma$ ~200 μs 2.2MeV

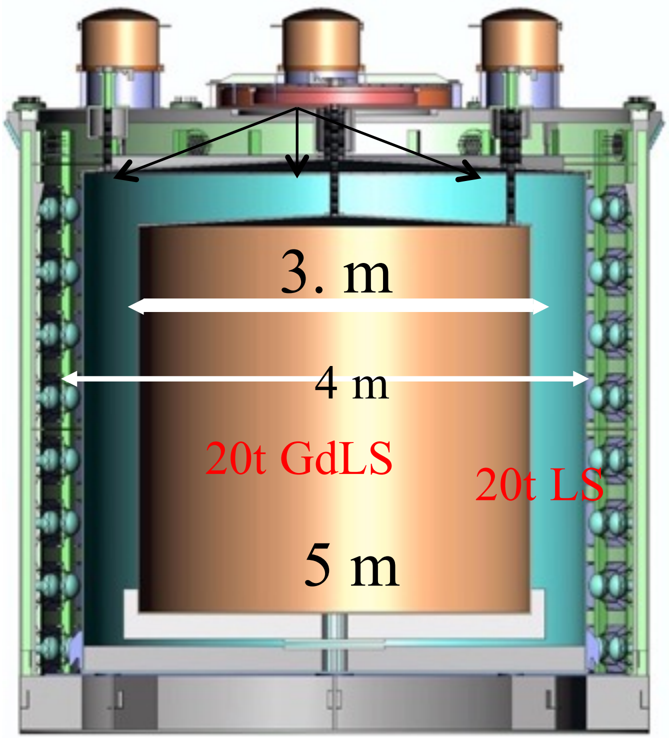


target: Gd-loaded Scintillator (GdLS), 20t

γ-catcher: normal Scintillator (LS), 22t

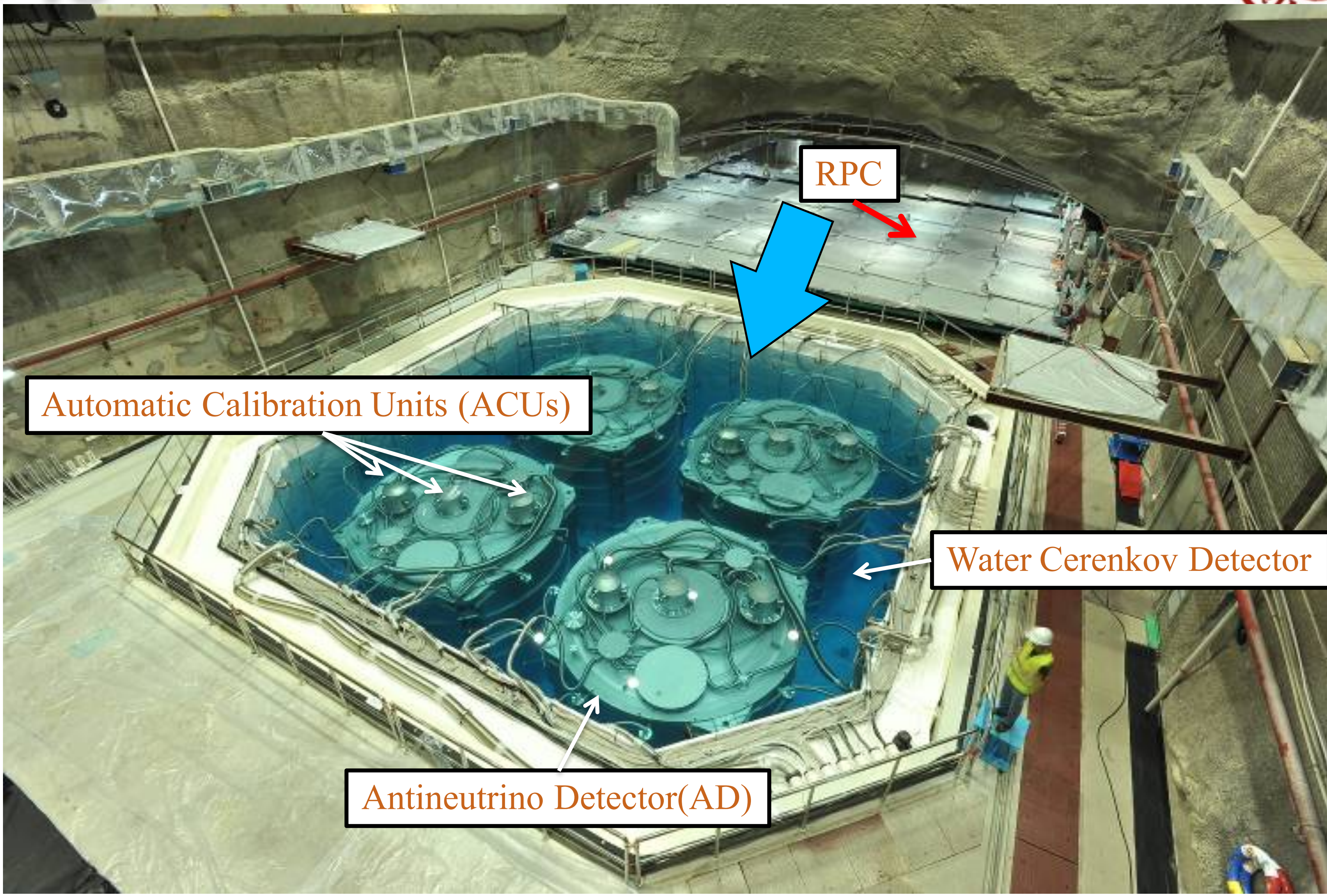
buffer shielding: mineral oil (MO), 36t

Automatic Calibration Units



- Water Cerenkov Detectors
  - 2.5 m of water from any direction
  - Two optically-isolated detectors at each hall
  - Tags cosmic muons
  - Shields against low energy radiation from surrounding material
- Resistive plate chambers (RPCs)
  - Covers water pool for further muon tagging

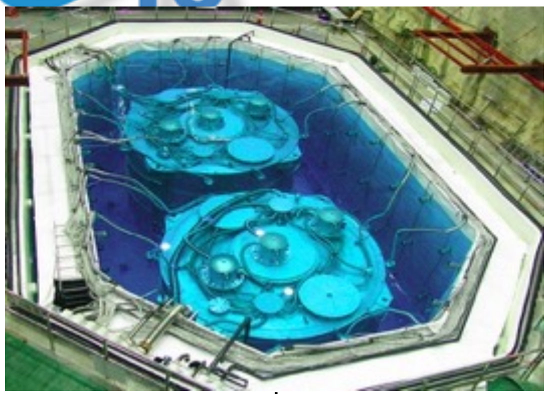
Far Hall (EH3)



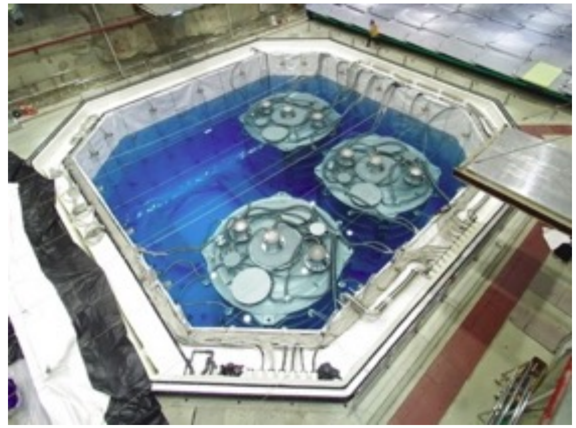
RPC
Automatic Calibration Units (ACUs)
Water Cerenkov Detector
Antineutrino Detector(AD)

Installation of ADs

Experimental Hall 1 (EH1)



EH3



EH3

217 days

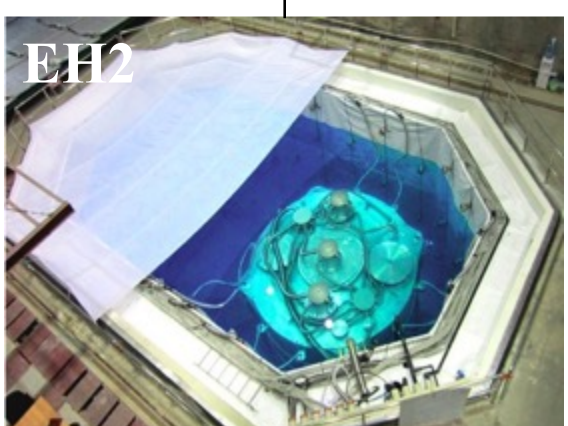
	6-AD		8-AD Data Taking

2012 2013 2014 2015 2016

AD = Antineutrino Detector

621-day data

1230-day data



<u>1230-day data of results will be presented in this talk.</u>

Energy Calibration

- PMT gain

  Single p.e. from PMT dark noise

  Weekly deployment of LED

- Energy reconstruction

  Calibration sources

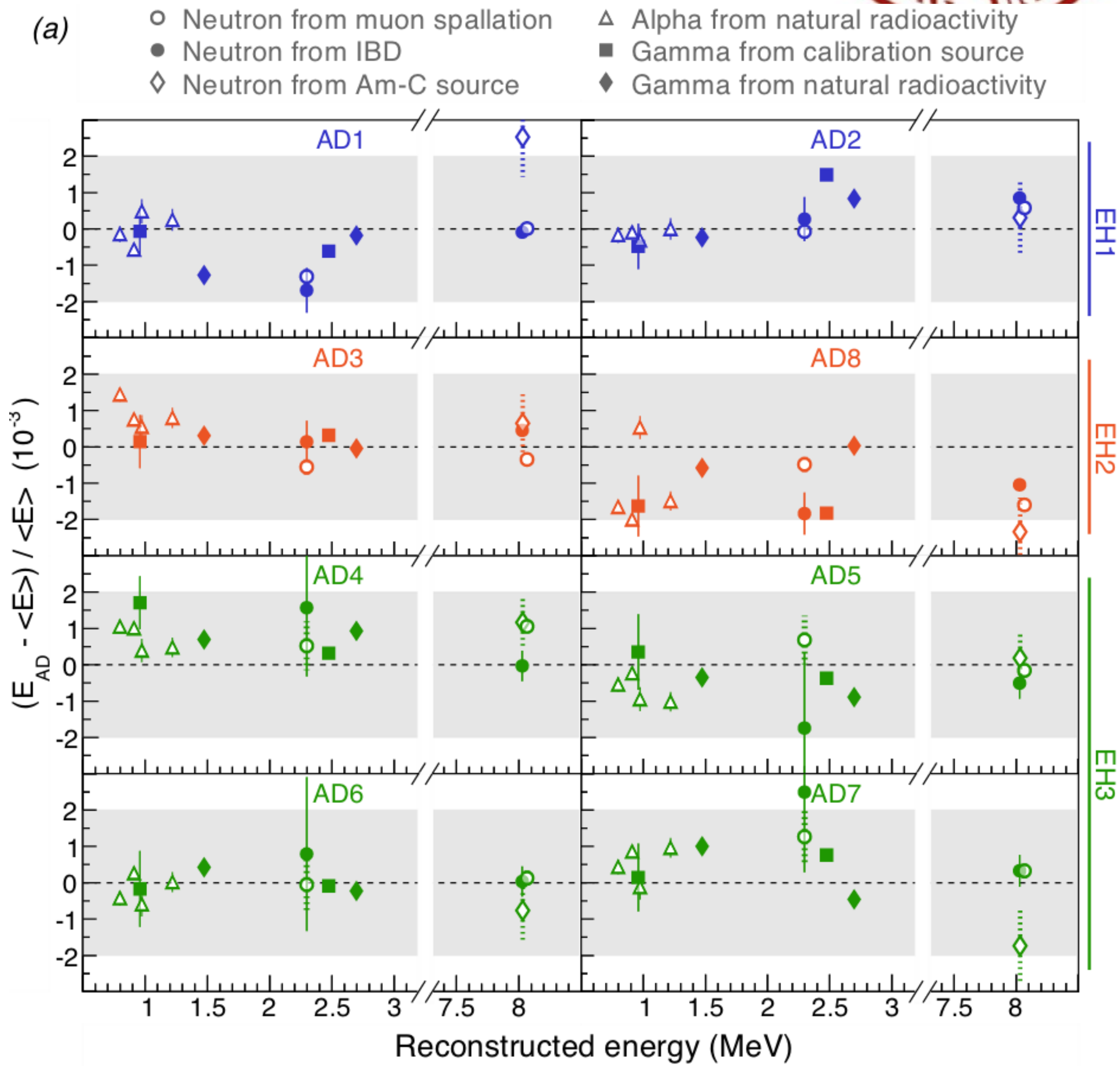
  Spallation neutrons

- Relative energy scale

  ^{68}Ge, ^{60}Co, ^{241}Am-^{13}C

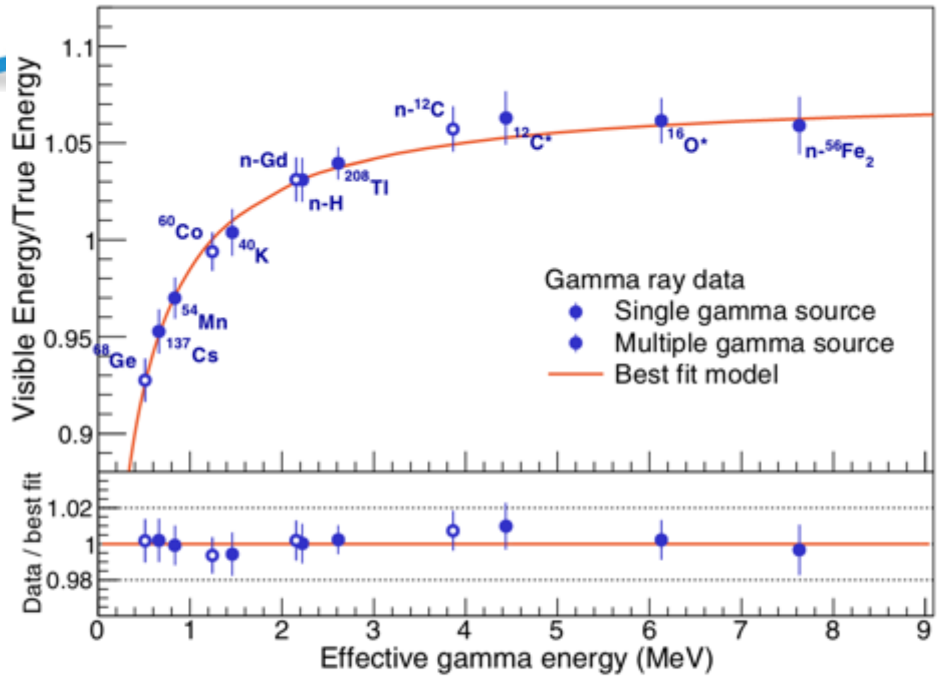
  Spallation neutrons

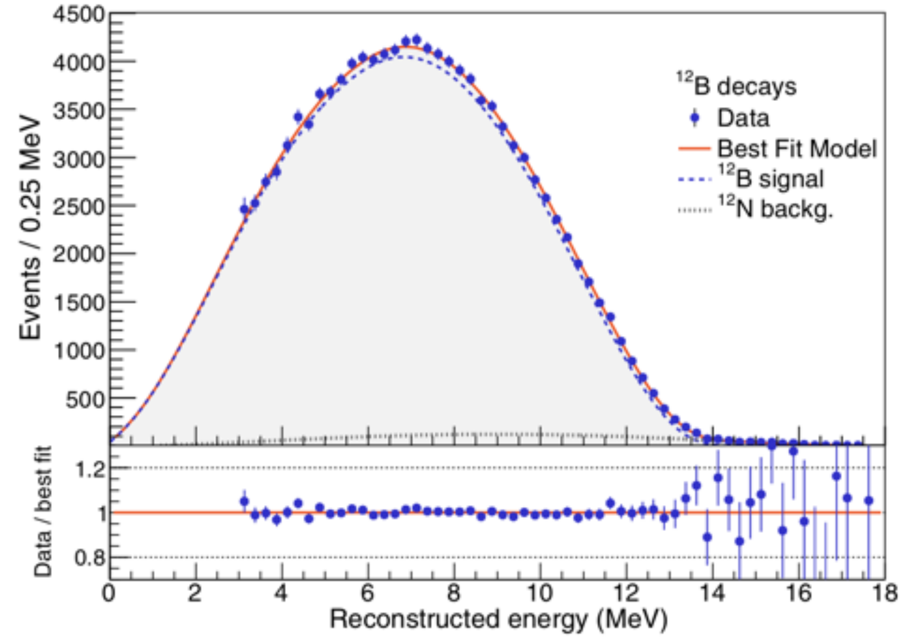
  Natural radioactivity

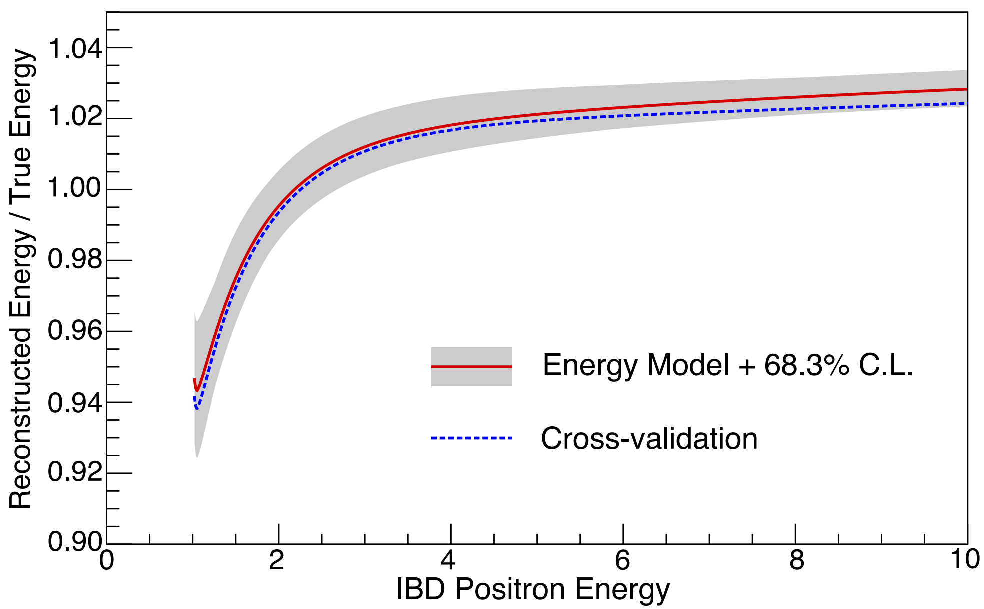


The relative energy scale uncertainty is less than 0.2%.

Energy model







- **Energy model**

  Includes the non-linearity from LS and readout electronics

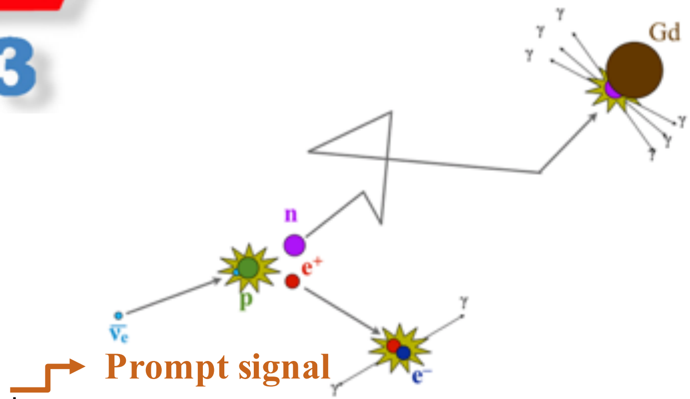
  Built based on various γ peaks and continuous ^{12}B β spectrum

- **Validated with**

  Michel electron; β+γ continuous spectra from $^{212/214}$Bi and ^{208}Tl

  Bench tests of Compton scattering electrons in LS

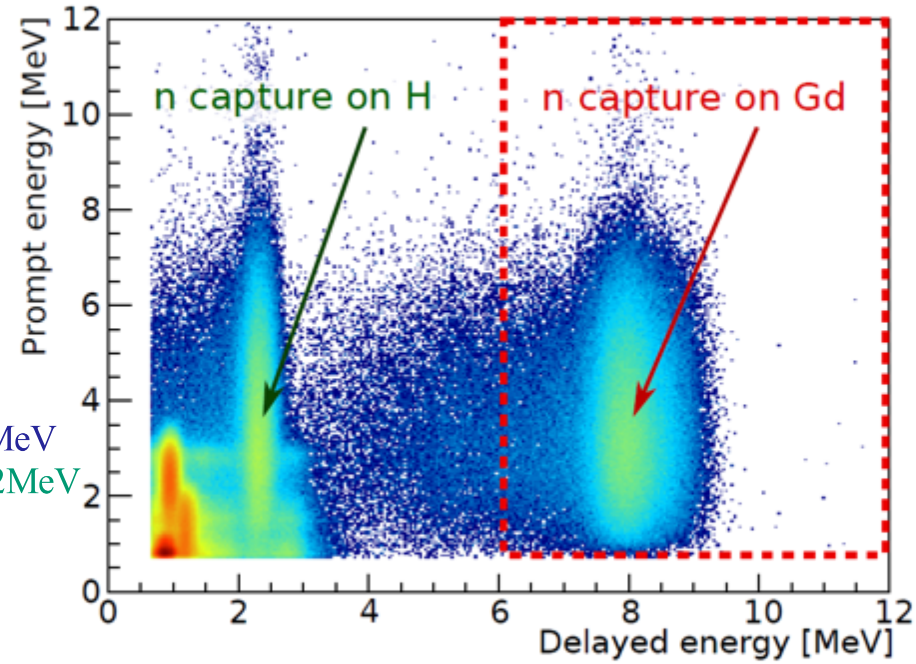
Antineutrino candidates selection



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

Delayed Signal $n + {}^{x}\mathrm{Gd} \to {}^{x+1}\mathrm{Gd} + \gamma' s$ ~30 μs 8MeV

$n + \mathrm{H} \to \mathrm{D} + \gamma$ ~200 μs 2.2MeV



- 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

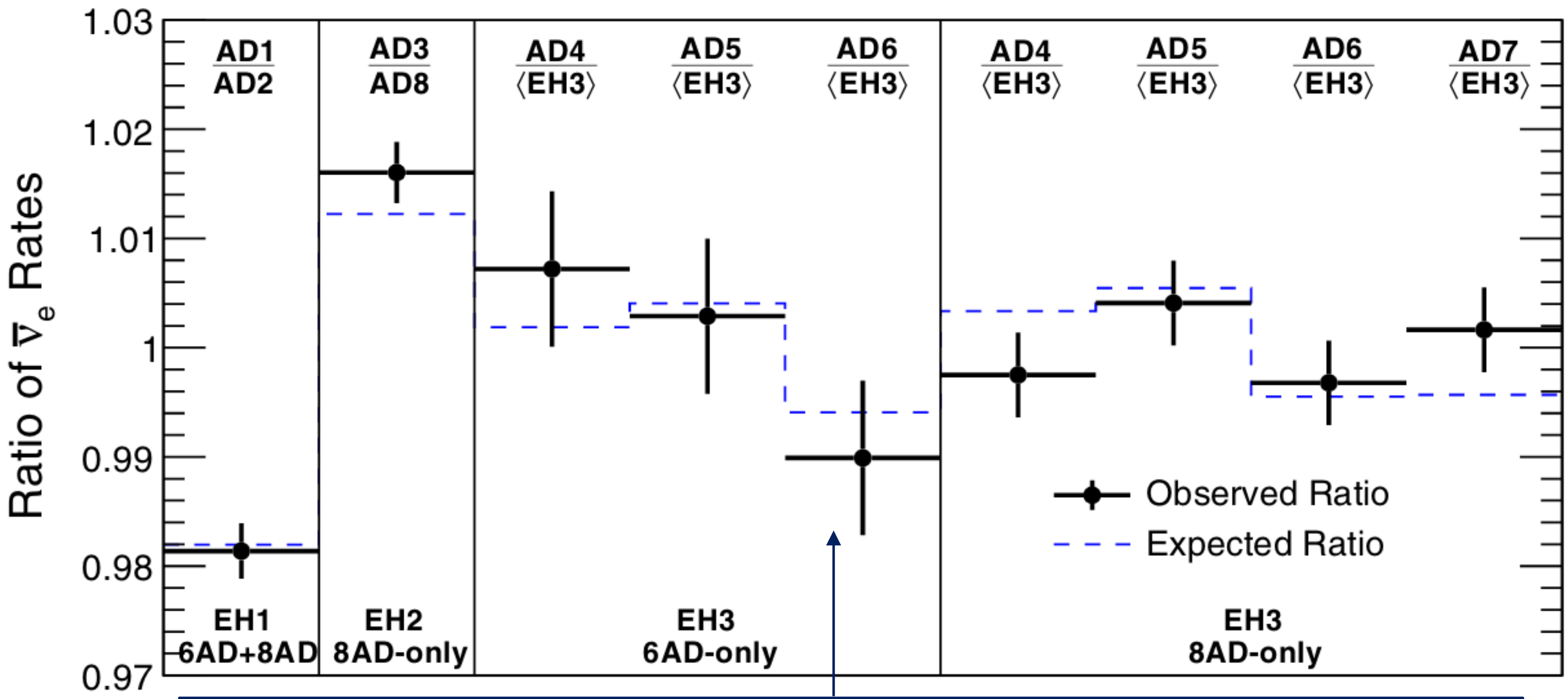
  Water pool muon: reject 0.6 ms
  - AD muon (>20 MeV): reject 1 ms
  - AD shower muon (>2.5 GeV): reject 1 s

1230days

	Efficiency	Correlated	Uncorrelated
Target protons	-	0.92%	0.03%
Flasher cut	99.98%	0.01%	0.01%
Delayed energy cut	92.7%	0.97%	0.08%
Prompt energy cut	99.8%	0.10%	0.01%
Multiplicity cut		0.02%	0.01%
Capture time cut	98.7%	0.12%	0.01%
Gd capture fraction	84.2%	0.95%	0.10%
Spill-in	104.9%	1.00%	0.02%
Livetime	-	0.002%	0.01%
Combined	80.6%	1.93%	0.13%

Side by side comparison

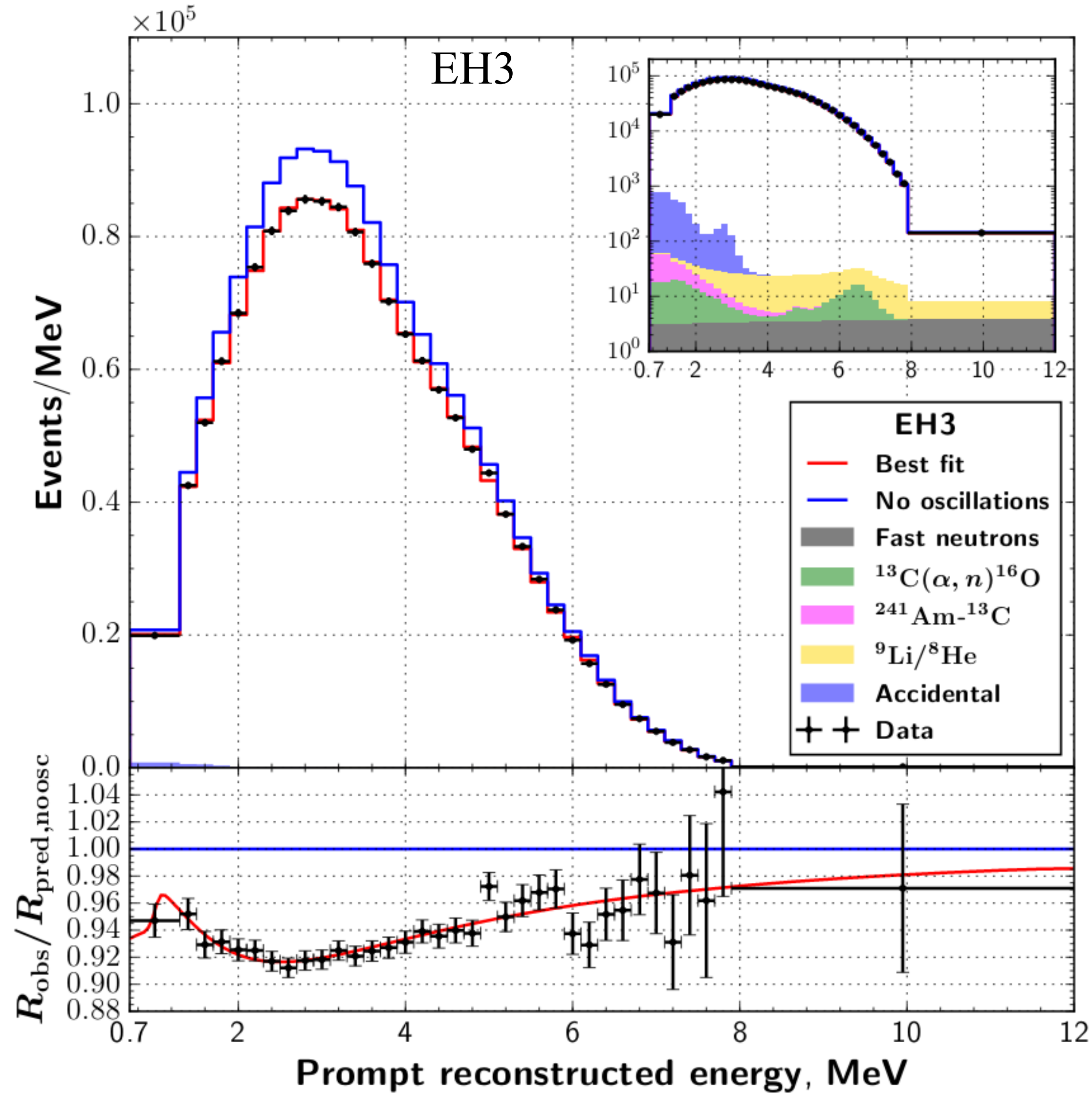
- Multiple detectors in the same hall
  - Allow examination of the uncorrelated uncertainty
  - The observed ratios of IBD rates are consistent with expectations
  - Confirm the systematic uncertainty



*Uncertainty dominated by statistics and the **0.13%** uncorrelated error.*
Most of the background uncertainty has been cancelled.

Backgrounds

1230 days data



- Accidentals:

  Uncertainty less than 0.02%

- Fast neutron:

  Uncertainty less than 0.05%

- $^{9}Li/^{8}He$

  Uncertainty 0.1%~0.15%

- From the ^{241}Am-^{13}C calibration source

  Uncertainty 0.05%~0.1%

- $^{13}C(\alpha,n)^{16}O$

  Uncertainty less than 0.05%

Sites	B/S ratio	Background error
Daya Bay（EH1）	1.8%	0.2%
Ling Ao（EH2）	1.5%	0.15%
Far（EH3）	2.0%	0.2%

Data summary

1230 days data

- Over 2.5M (300K) IBD candidates in total (the far site).
- Double the statistics of Phys. Rev. Lett. 115, 111802 (2015)

	EH1		EH2		EH3			
	AD1	AD2	AD3	AD8	AD4	AD5	AD6	AD7
ΔN_{p} [%]	0.00 ± 0.03	0.13 ± 0.03	-0.25 ± 0.03	0.02 ± 0.03	-0.12 ± 0.03	0.24 ± 0.03	-0.25 ± 0.03	-0.05 ± 0.03
	Selection A							
$\overline{\nu}_e$ candidates	597618	606351	567196	466013	80479	80742	80067	66862
DAQ live time [days]	1117.178	1117.178	1114.337	924.933	1106.915	1106.915	1106.915	917.417
ϵ_μ	0.8255	0.8221	0.8573	0.8571	0.9824	0.9823	0.9821	0.9826
ϵ_{m}	0.9744	0.9747	0.9757	0.9757	0.9759	0.9758	0.9756	0.9758
Accidentals [day^{-1}]	8.46 ± 0.09	8.46 ± 0.09	6.29 ± 0.06	6.18 ± 0.06	1.27 ± 0.01	1.19 ± 0.01	1.20 ± 0.01	0.98 ± 0.01
Fast neutron [AD^{-1} day^{-1}]	0.79 ± 0.10		0.57 ± 0.07		0.05 ± 0.01			
^{9}Li,^{8}He [AD^{-1} day^{-1}]	2.46 ± 1.06		1.72 ± 0.77		0.15 ± 0.06			
^{241}Am-^{13}C, 6-AD [day^{-1}]	0.27 ± 0.12	0.25 ± 0.11	0.28 ± 0.13		0.22 ± 0.10	0.21 ± 0.10	0.21 ± 0.10	
^{241}Am-^{13}C, 8-AD [day^{-1}]	0.15 ± 0.07	0.16 ± 0.07	0.13 ± 0.06	0.15 ± 0.07	0.04 ± 0.02	0.03 ± 0.02	0.03 ± 0.02	0.05 ± 0.02
^{13}C$(\alpha, \mathrm{n})^{16}$O [day^{-1}]	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
$\overline{\nu}_e$ rate [day^{-1}]	653.03 ± 1.37	665.42 ± 1.38	599.71 ± 1.12	593.82 ± 1.18	74.25 ± 0.28	74.60 ± 0.28	73.98 ± 0.28	74.73 ± 0.30

Oscillation Results

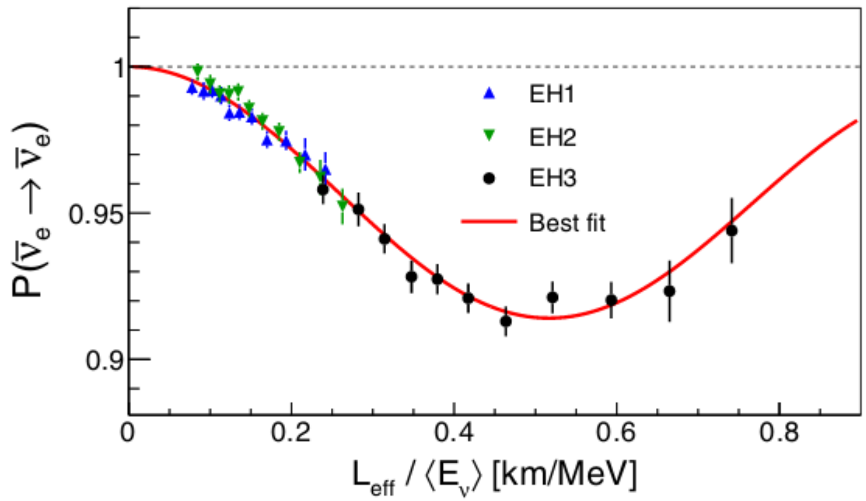
1230 days data

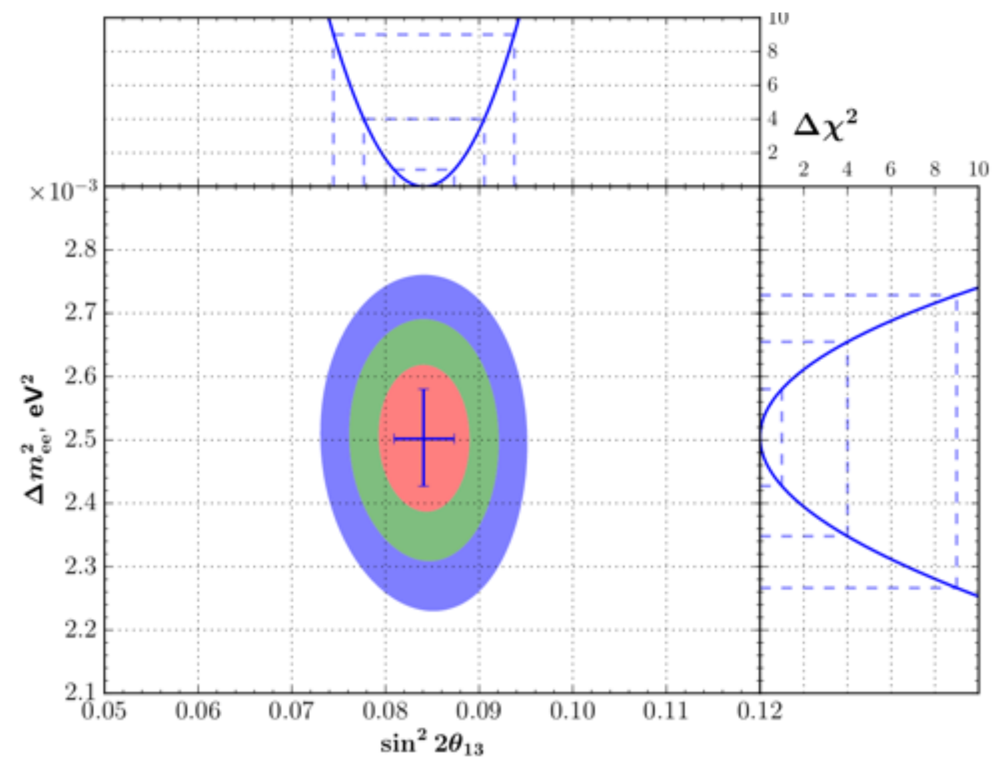
$\sin^2 2\theta_{13} = [8.41 \pm 0.27(\text{stat.}) \pm 0.19(\text{syst.})] \times 10^{-2}$

$|\Delta m^2_{ee}| = [2.50 \pm 0.06(\text{stat.}) \pm 0.06(\text{syst.})] \times 10^{-3}\text{eV}^2$

$\chi^2/\text{NDF} = 232.6/263$

$$P = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\frac{1.267\Delta m^2_{21}L}{E} - \sin^2 2\theta_{13}\sin^2\frac{1.267\Delta m^2_{ee}L}{E}.$$





Oscillation results

1230 days data

- Most precise

  $\sin^2 2\theta_{13}$ and $|\Delta m^2_{32}|$

- Consistent results among

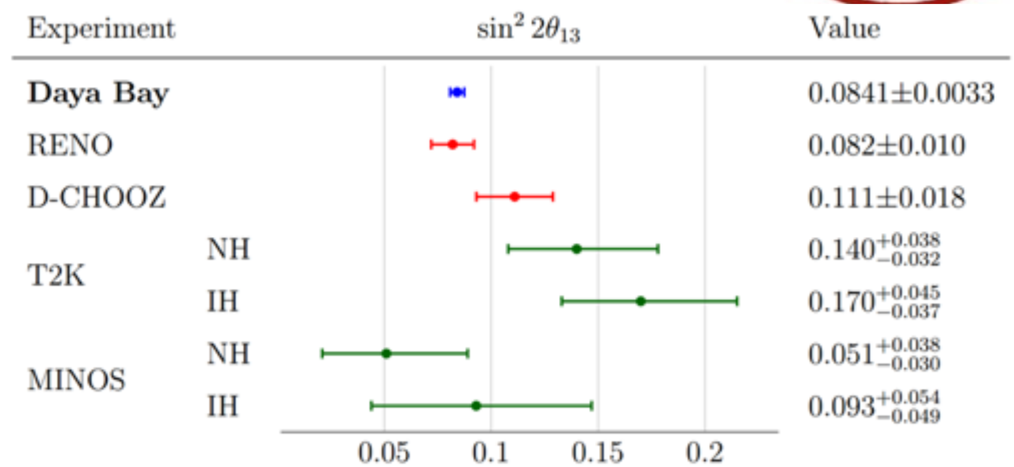
  The MeV-scale reactor

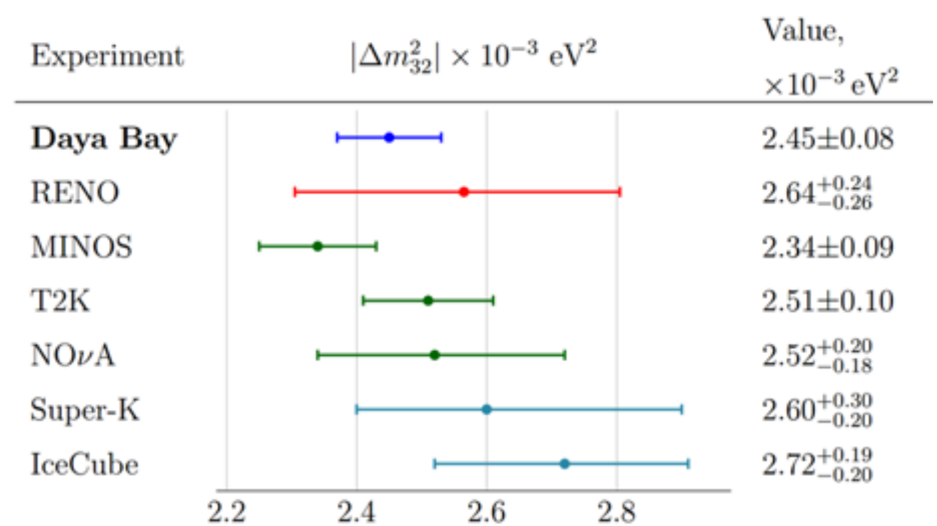
  The GeV-scale accelerator and

  atmospheric experiments

Δm^2_{32} (NH)=$[2.45\pm0.08]\times10^{-3}$eV^2

Δm^2_{32} (IH) =$[-2.55\pm0.08]\times10^{-3}$eV^2

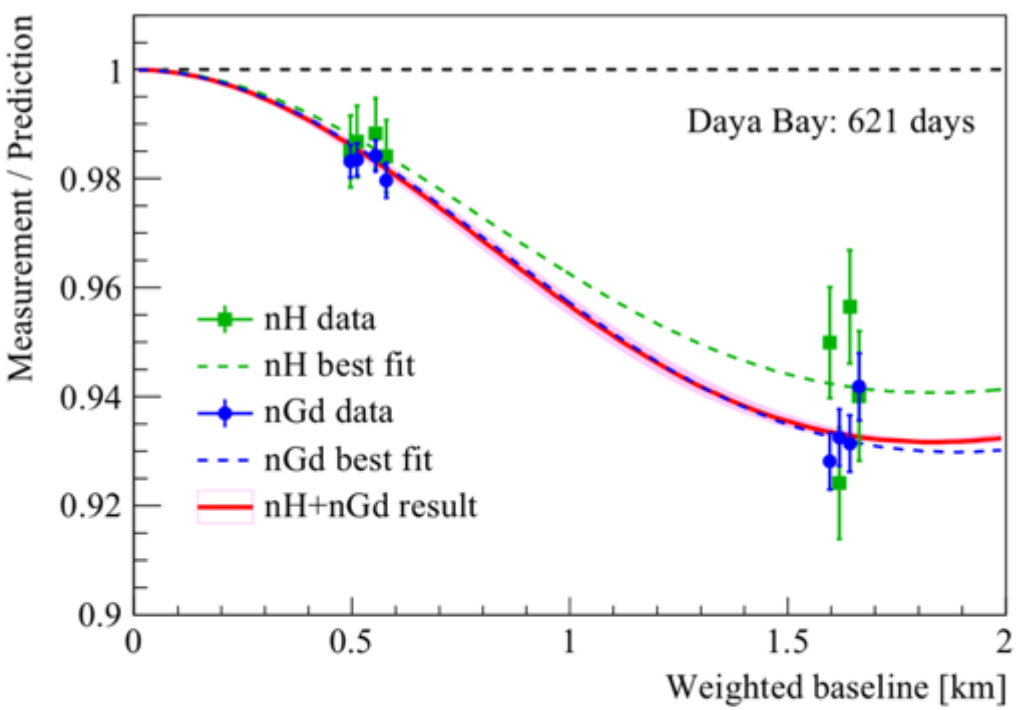


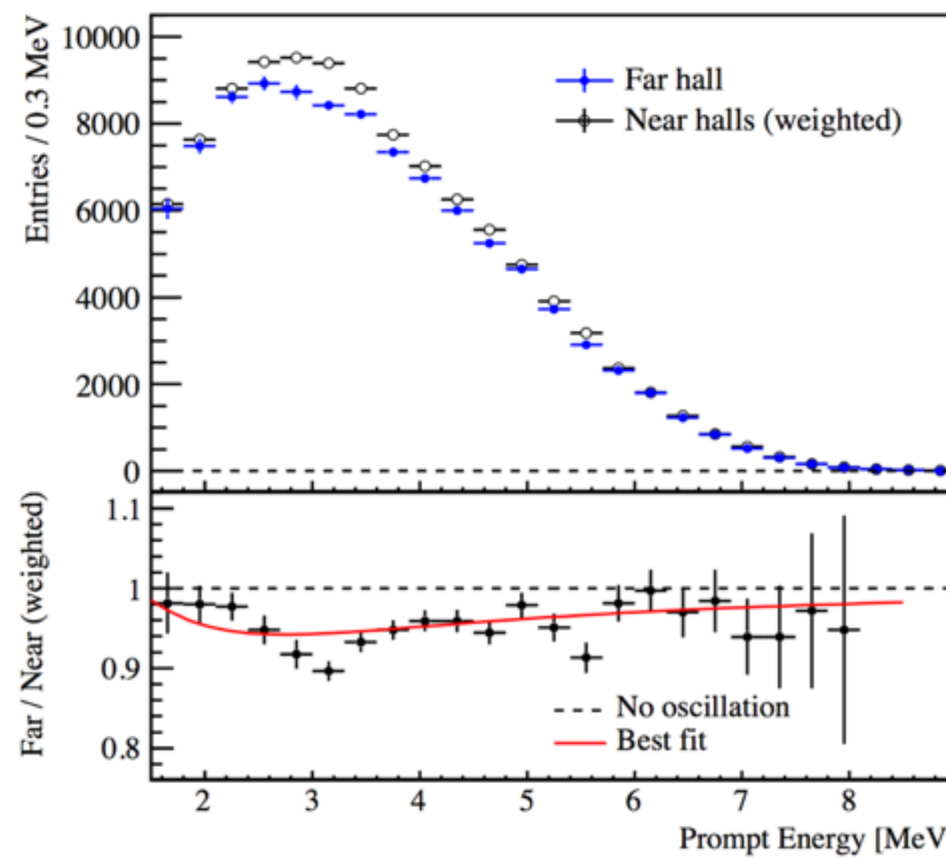


Fit with full 3-flavor oscillation formula assuming normal mass hierarchy.

Independent Measurement of θ_{13} using nH

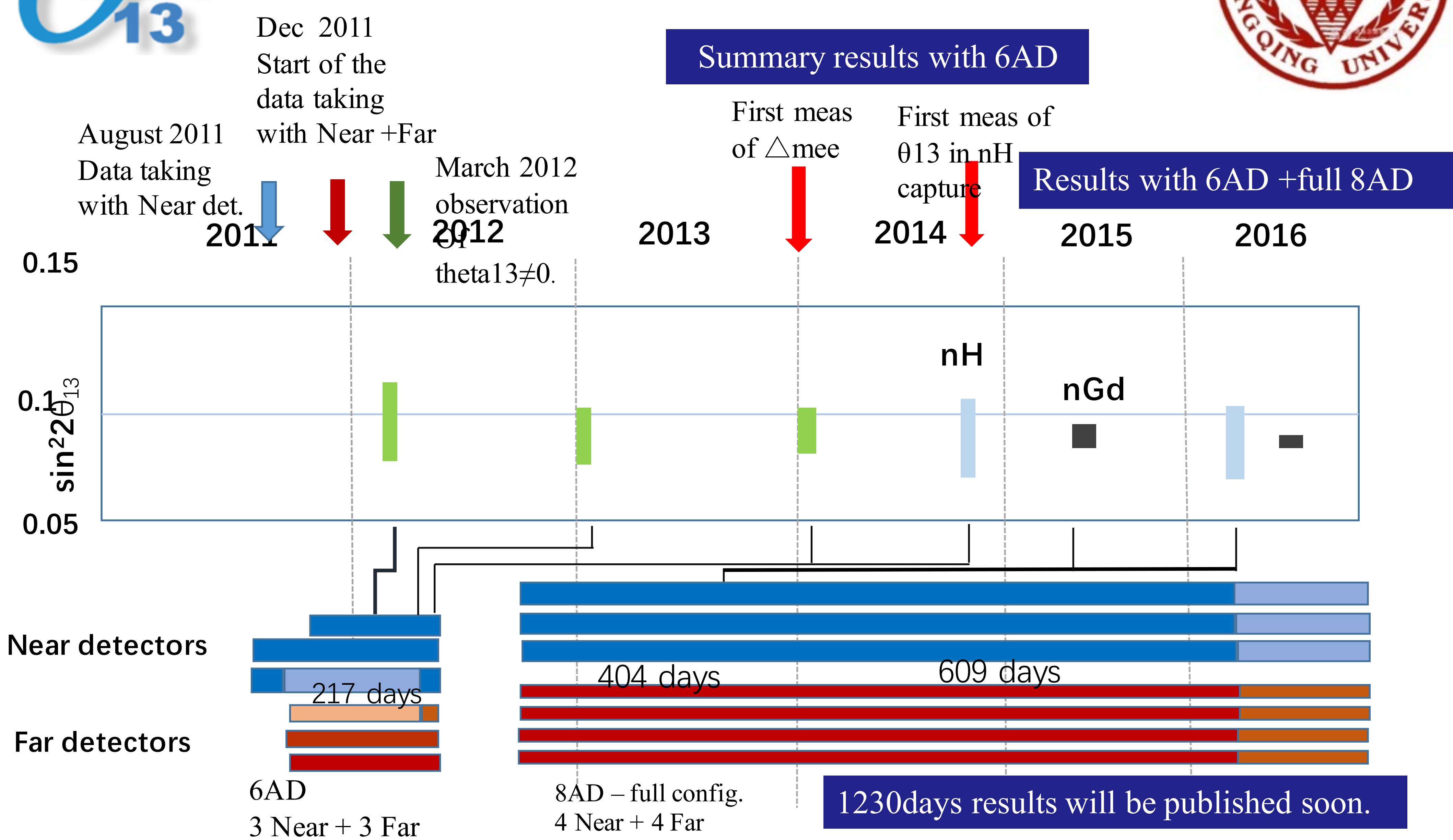
621 days data





- Rate analysis: $\sin^2 2\theta_{13} = 0.071 \pm 0.011$ $\chi^2/NDF = 6.3/6$
- Consistent results with those of the n-Gd analysis
- Spectrum distortion consistent with the oscillation hypothesis

Major milestones of the Daya Bay experiment



Summary

- Most precise measurement of $\sin^2 2\theta_{13}$ and $|\Delta m^2_{ee}|$ with 1230days of data are presented:

$$\sin^2 2\theta_{13} = [8.41 \pm 0.33] \times 10^{-2}$$
$$|\Delta m^2_{ee}| = [2.50 \pm 0.08] \times 10^{-3} eV^2$$
$$\Delta m^2_{32}(NH) = [2.45 \pm 0.08] \times 10^{-3} eV^2$$
$$\Delta m^2_{32}(IH) = [-2.55 \pm 0.08] \times 10^{-3} eV^2$$

- Independent measurement $\sin^2 2\theta_{13}$ using neutron captured on hydrogen with 631-day of data is also presented.

$$\sin^2 2\theta_{13} = 0.071 \pm 0.011$$


Thanks !