Precision measurement of $\sin^2 2\theta_{13}$ and $|\Delta m^2_{ee}|$ from Daya Bay

Jiajie Ling

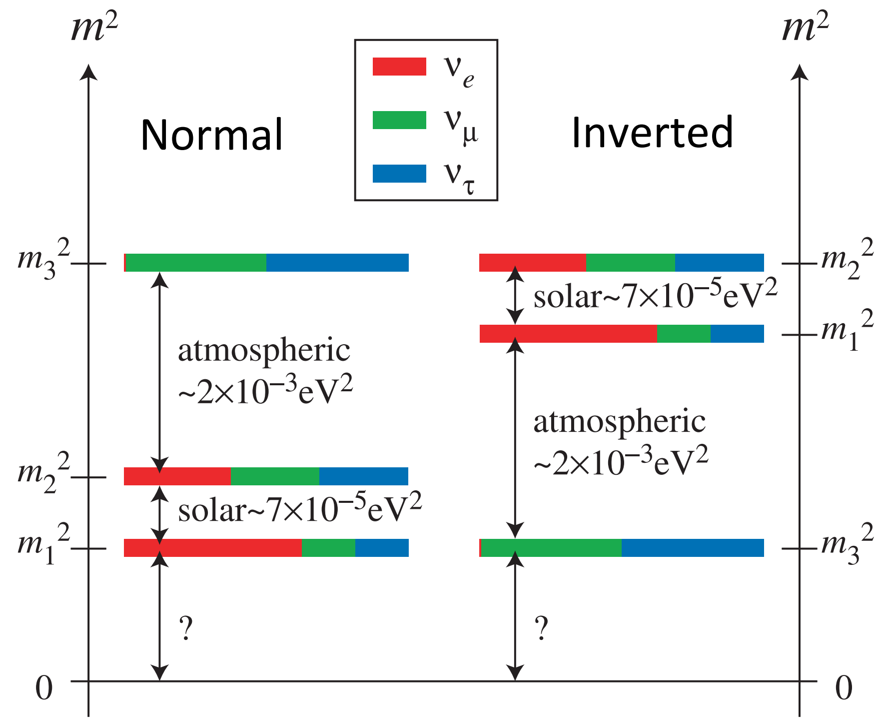
On behalf of the Daya Bay Collaboration

Daya Bay θ_{13}

中山大學 SUN YAT-SEN UNIVERSITY

ICHEP2016CHICAGO

Neutrino Mixing



Pontecorvo-Maki-Nakagawa-Sakata Matrix

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U_{\alpha i}^{*} |\nu_i\rangle$$

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{-i\alpha_1/2} & 0 & 0 \\ 0 & e^{-i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$c_{ij} \equiv \cos\theta_{ij}$

$s_{ij} \equiv \sin\theta_{ij}$

Atmospheric — $\theta_{23} \approx 45°$

"CP" sector — $\theta_{13} = 9°$

Solar — $\theta_{12} \approx 34°$

Majorana

$|\Delta m^2_{32}| \approx |\Delta m^2_{31}| \approx 2.4 \times 10^{-3}$ eV^2

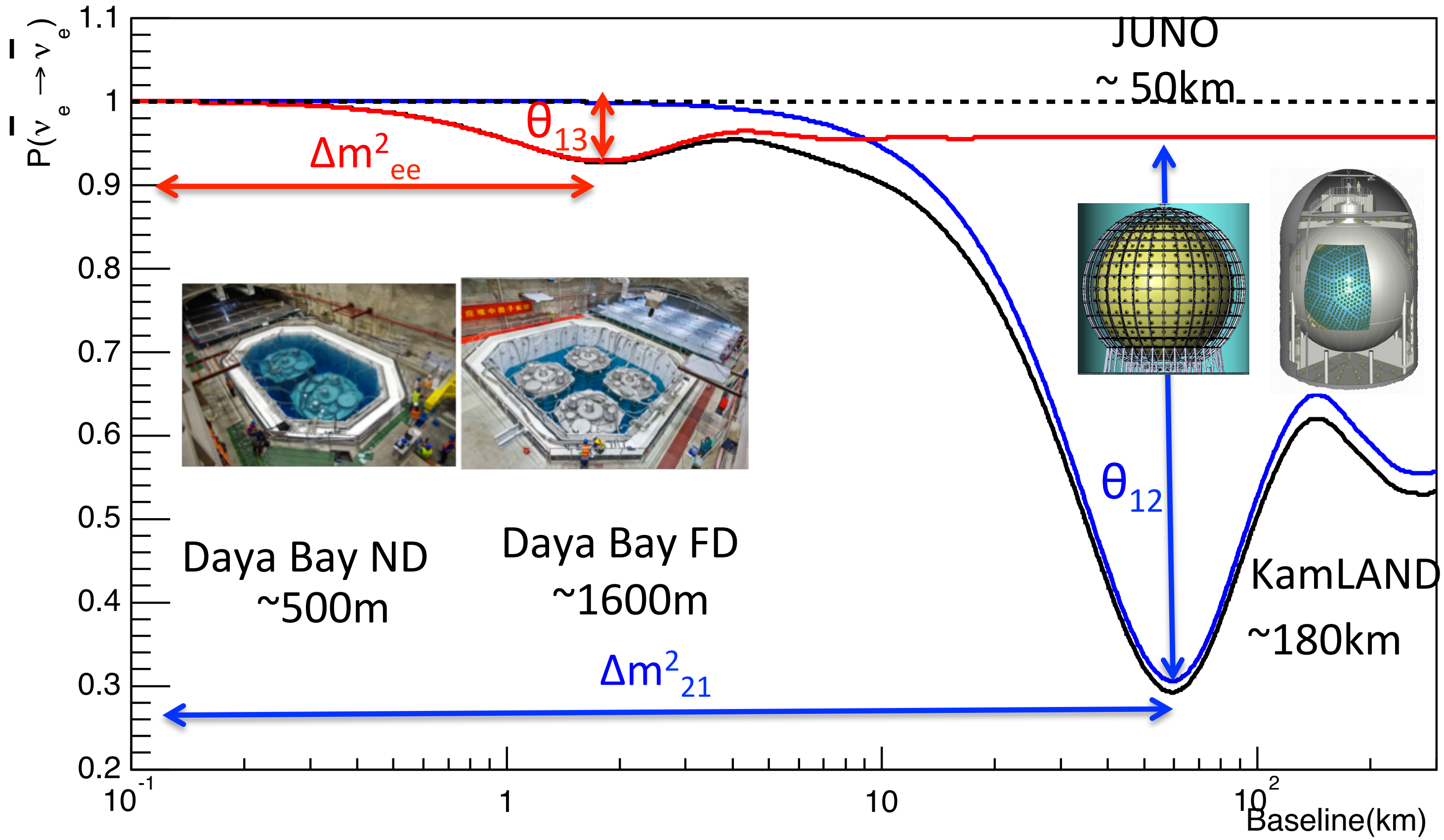
$\Delta m^2_{21} \approx 7.6 \times 10^{-5}$ eV^2

Reactor Antineutrino Oscillation

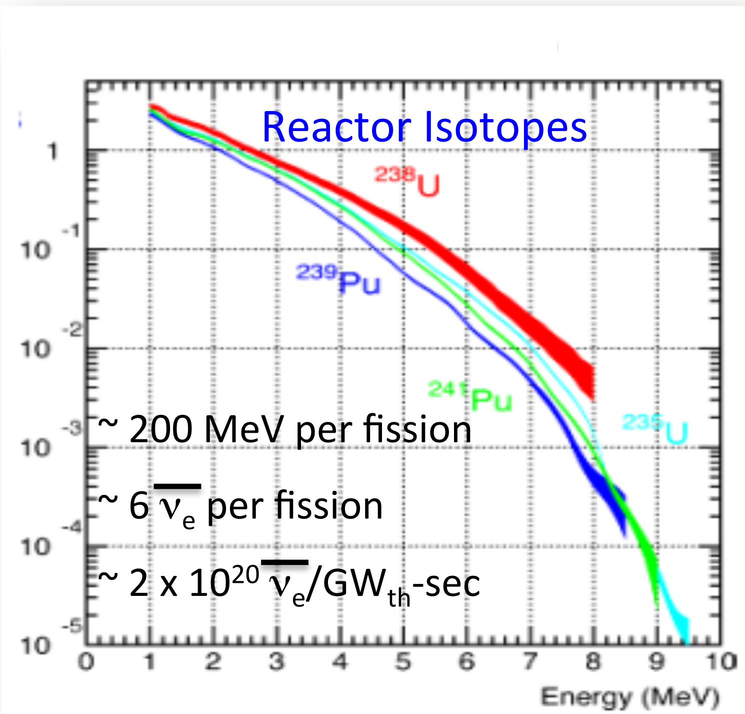
$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{13}\left(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}\right) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$

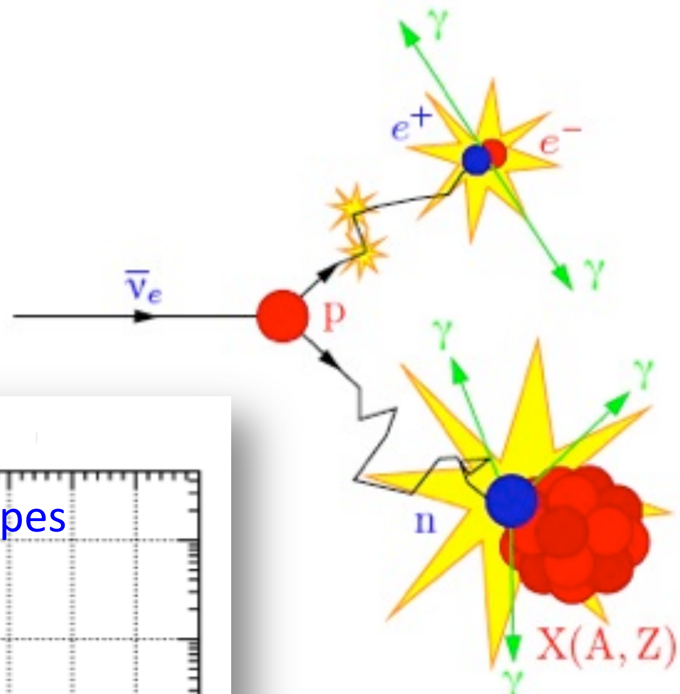
$$\approx 1 - \sin^2 2\theta_{13}\sin^2\Delta_{ee} - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$

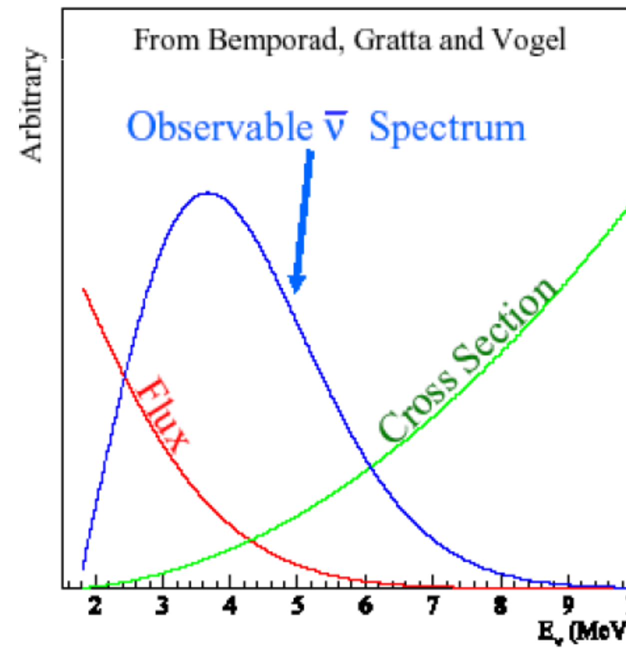
$$\Delta_{ij} = \Delta m^2_{ij}\frac{L}{4E}$$



Reactor Antineutrino and Detection







- Source: Clean $\overline{\nu}_e$ signal
- Detection: Inverse beta decay (IBD)

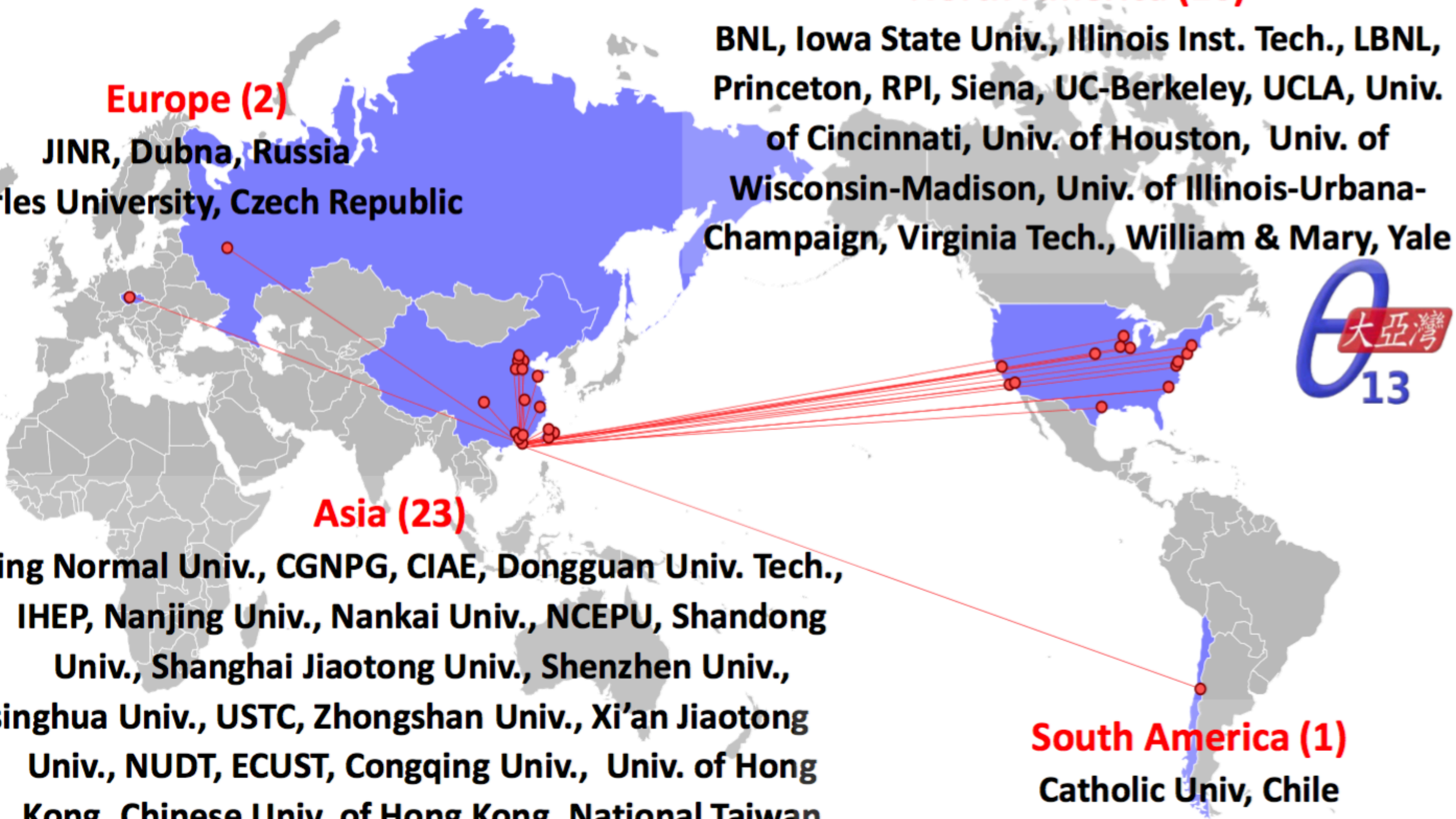
Coincidence signals:

Prompt: e^+ $E_p \approx E_\nu - 0.8$ MeV

Delayed: nH (2.2MeV) or nGd (8MeV) capture

The Daya Bay Collaboration

203 collaborators from 42 institutions:



Europe (2)

JINR, Dubna, Russia
Charles University, Czech Republic

North America (16)

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

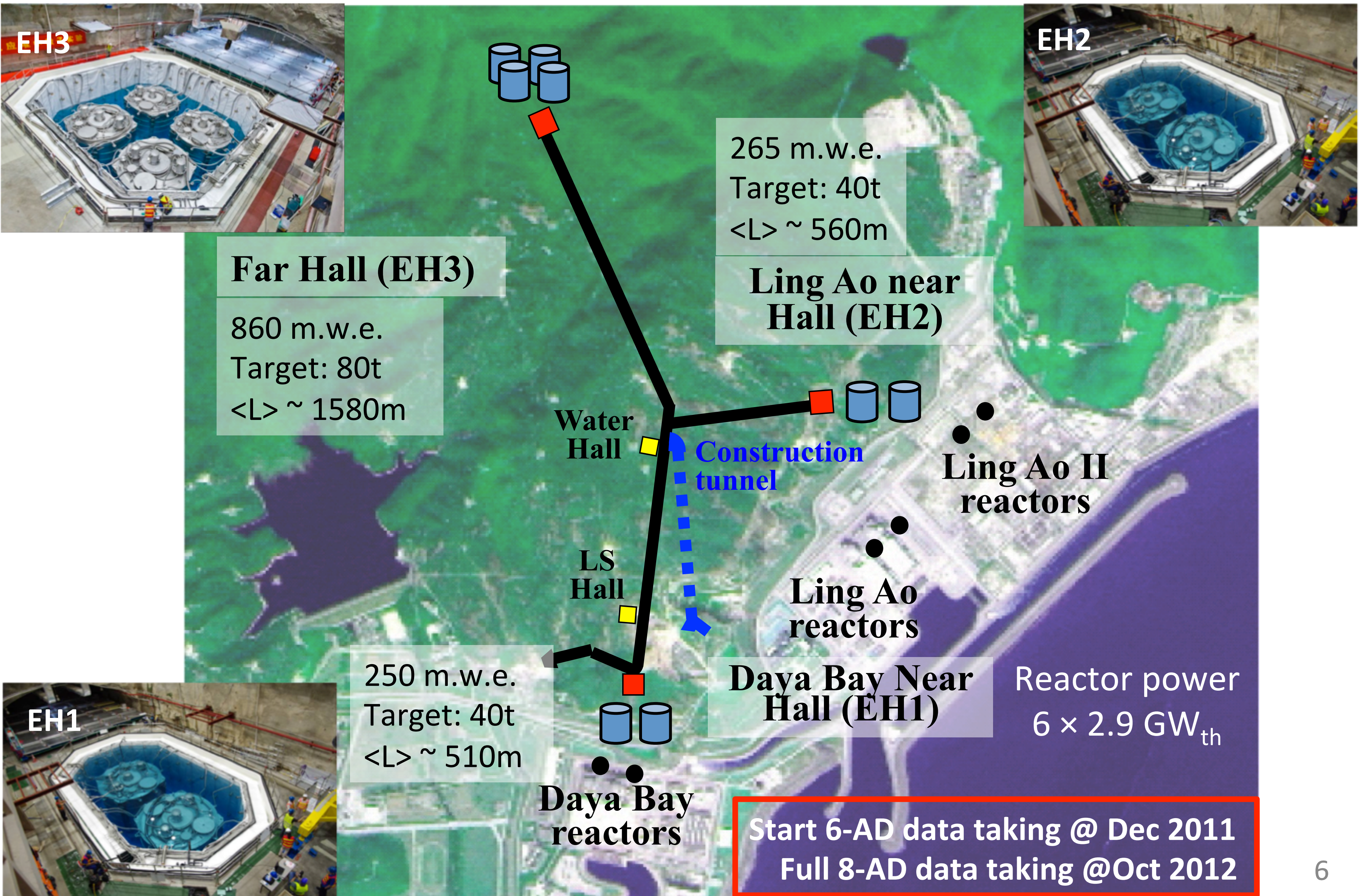
Asia (23)

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

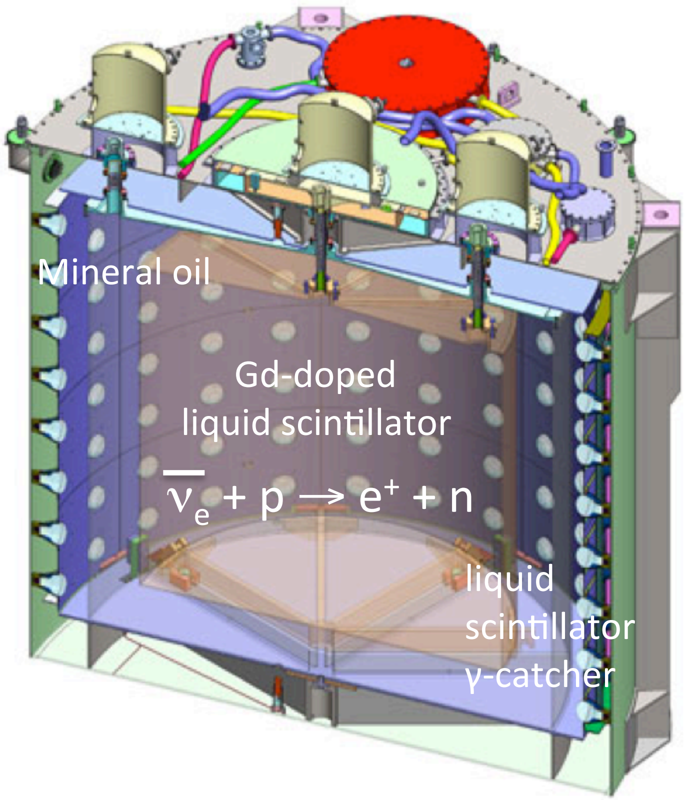
South America (1)

Catholic Univ, Chile

Daya Bay Experimental Setup



3-Zone Antineutrino Detectors

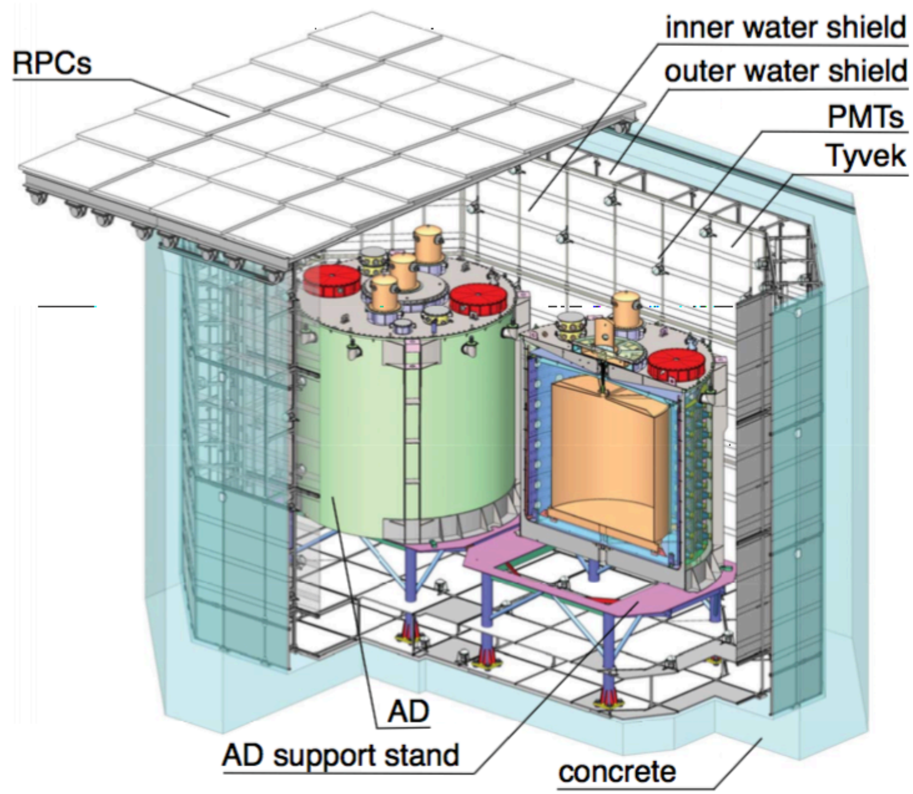


target mass: 20t Gd-LS
other mass: 20t LS + 40t MO
photo sensors: 192 8" PMTs

Relative Measurement:

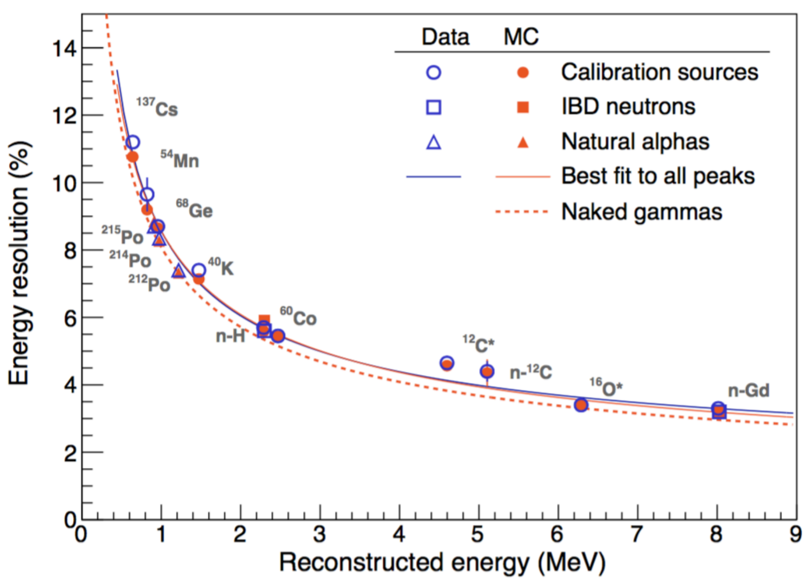
- 8 "identical", 3-zone detectors

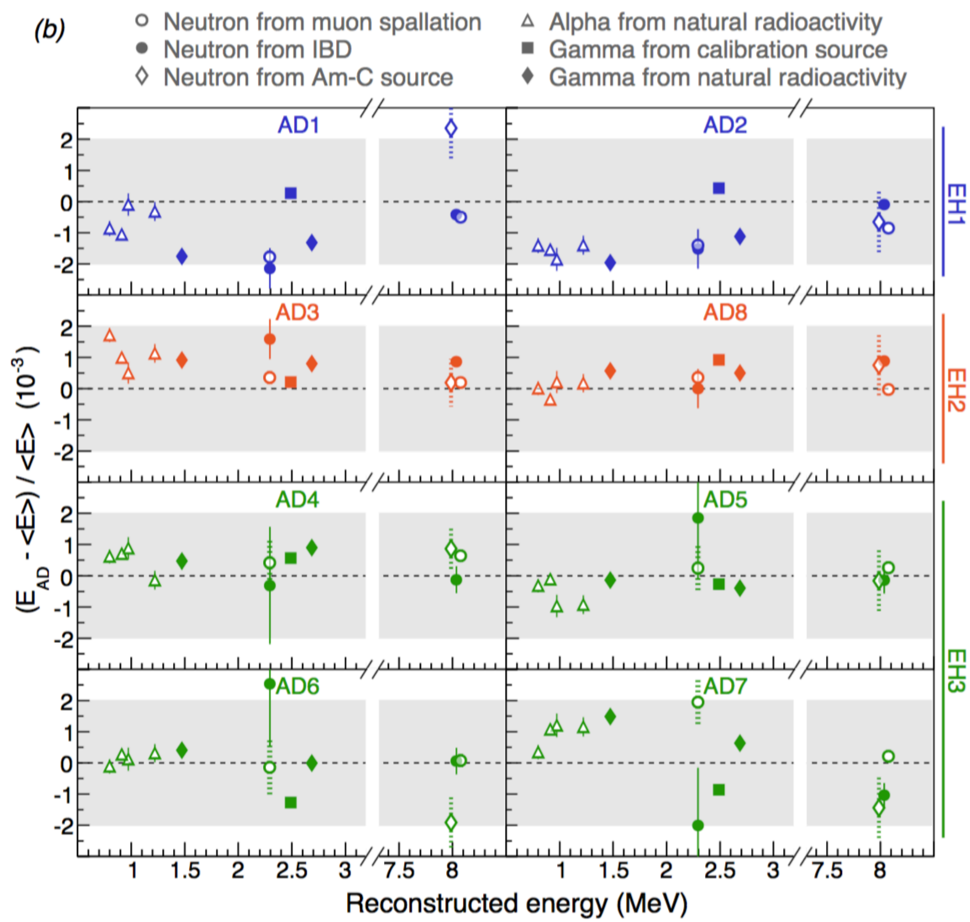
$$\frac{N_f}{N_n} = \left(\frac{N_{p,f}}{N_{p,n}}\right)\left(\frac{L_n}{L_f}\right)^2\left(\frac{\epsilon_f}{\epsilon_n}\right)\left[\frac{P_{sur}(E_\nu, L_f)}{P_{sur}(E_\nu, L_n)}\right]$$



Detector Energy Calibration

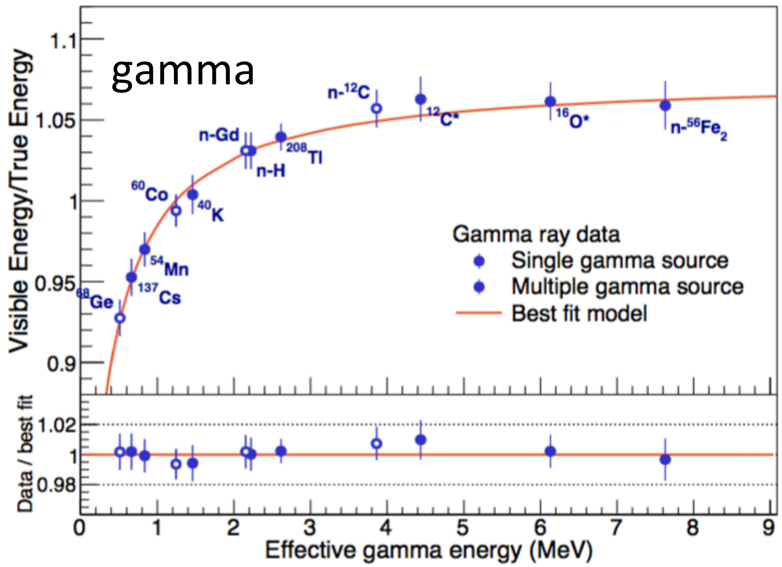
- Weekly calibration
  - ^{68}Ge, $^{241}Am^{13}C$, ^{60}Co
  - LED diffuser ball
- Special calibration campaign
  - ^{137}Cs, ^{54}Mn, $^{241}Am^{9}Be$, $^{239}Pu^{13}C$
- Spallation neutrons
- Natural radioactivity
- Manual 4π calibration

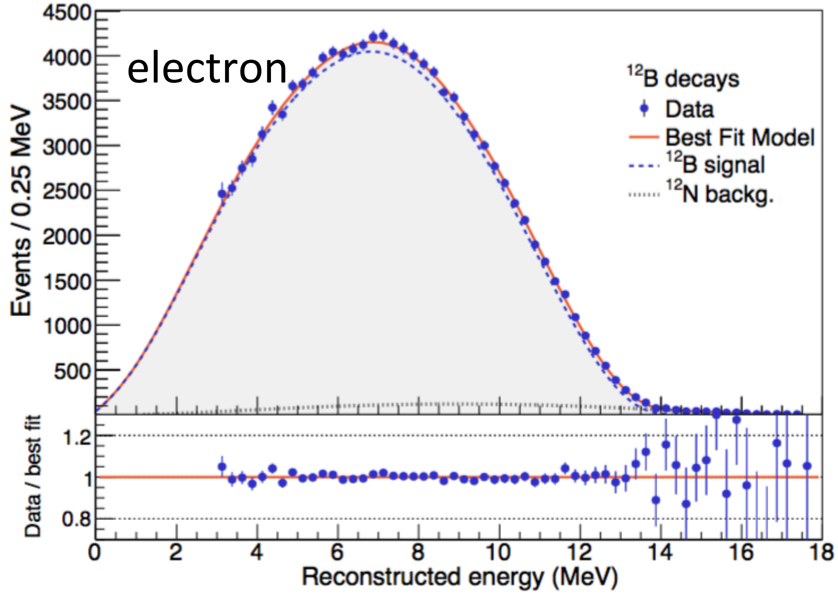


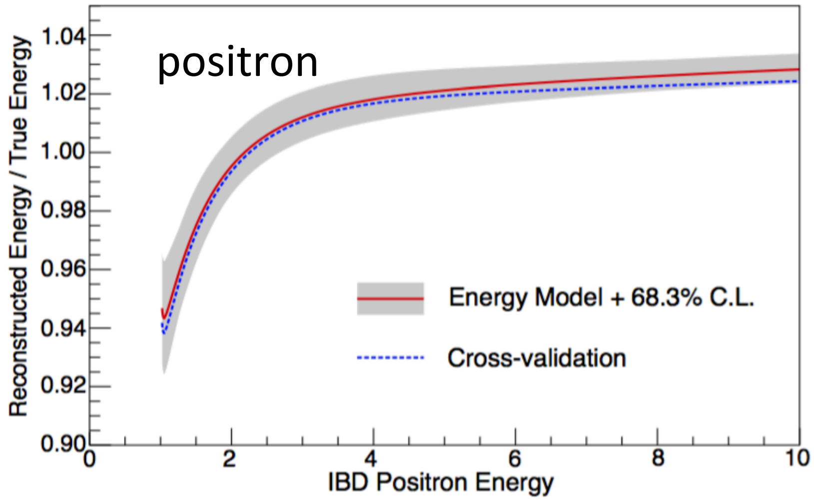


Relative detector energy scale < 0.2%

Energy Non-linearity Calibration



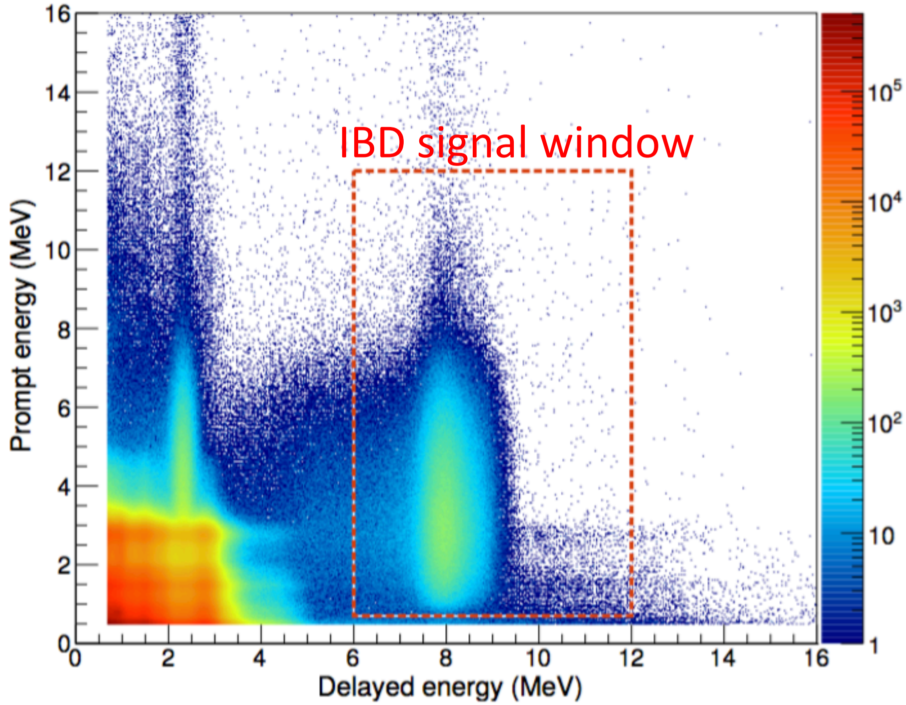


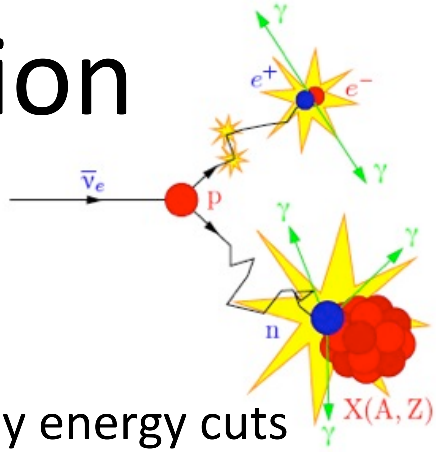


- Two major sources of non-linearity:
  - Scintillator response
  - Readout electronics
- Energy model for positron is derived from measured gamma and electron responses using simulation.

~1% uncertainty (correlated among detectors)

Coincidence IBD selection

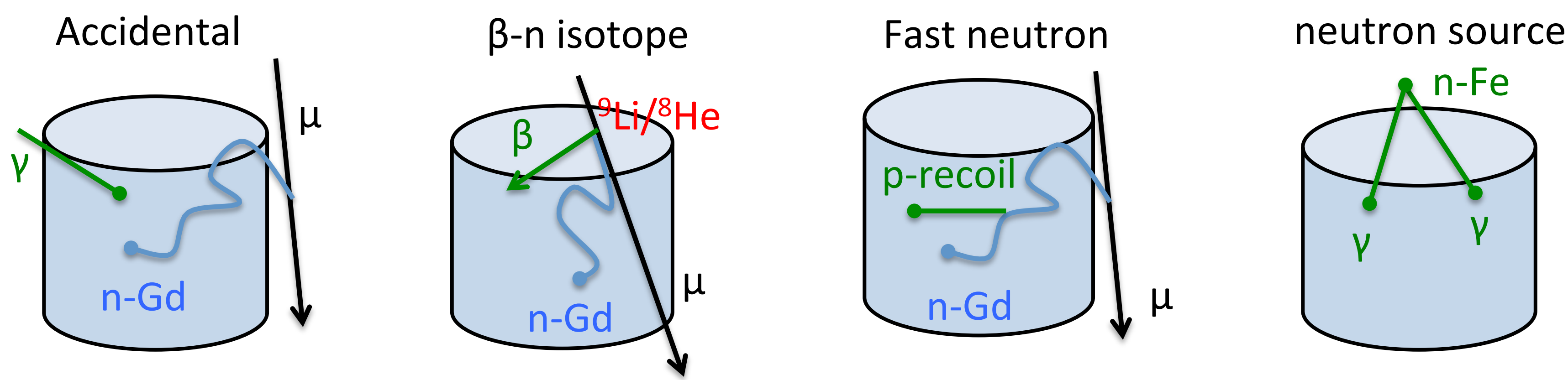




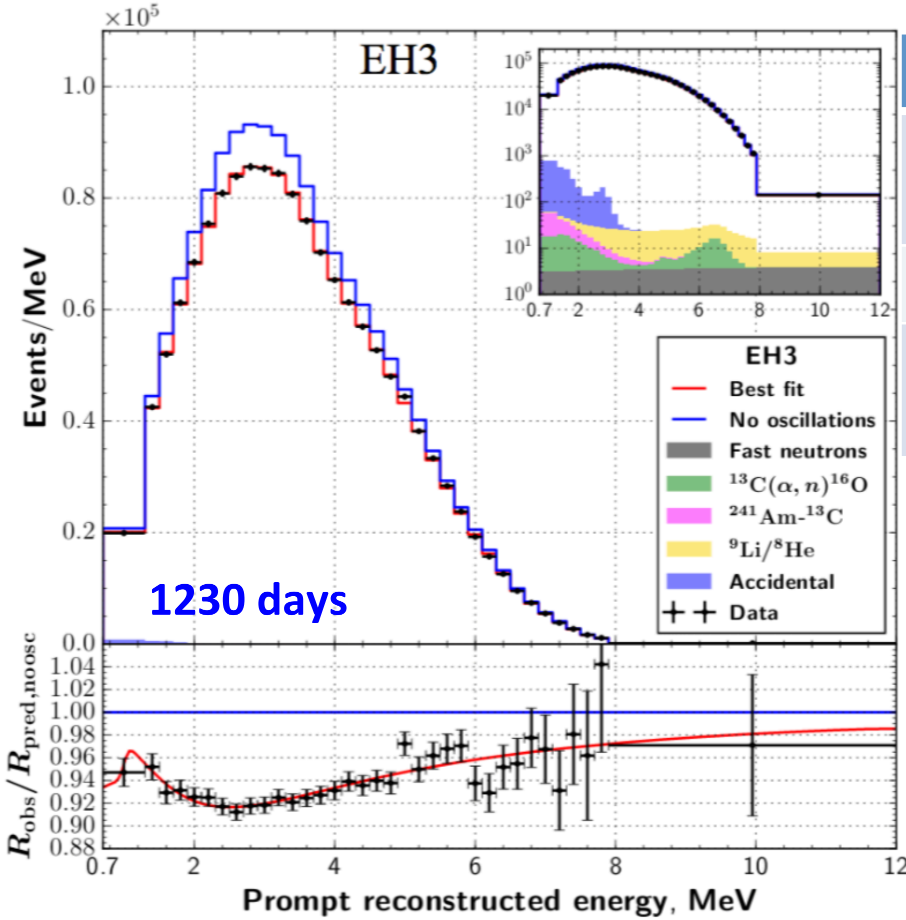
IBD selection cuts

- PMT Flasher cut
- Muon veto cut
- Prompt and delay energy cuts
- Neutron capture time cut
- Multiplicity cut

Main Backgrounds:



Summary of IBD candidates

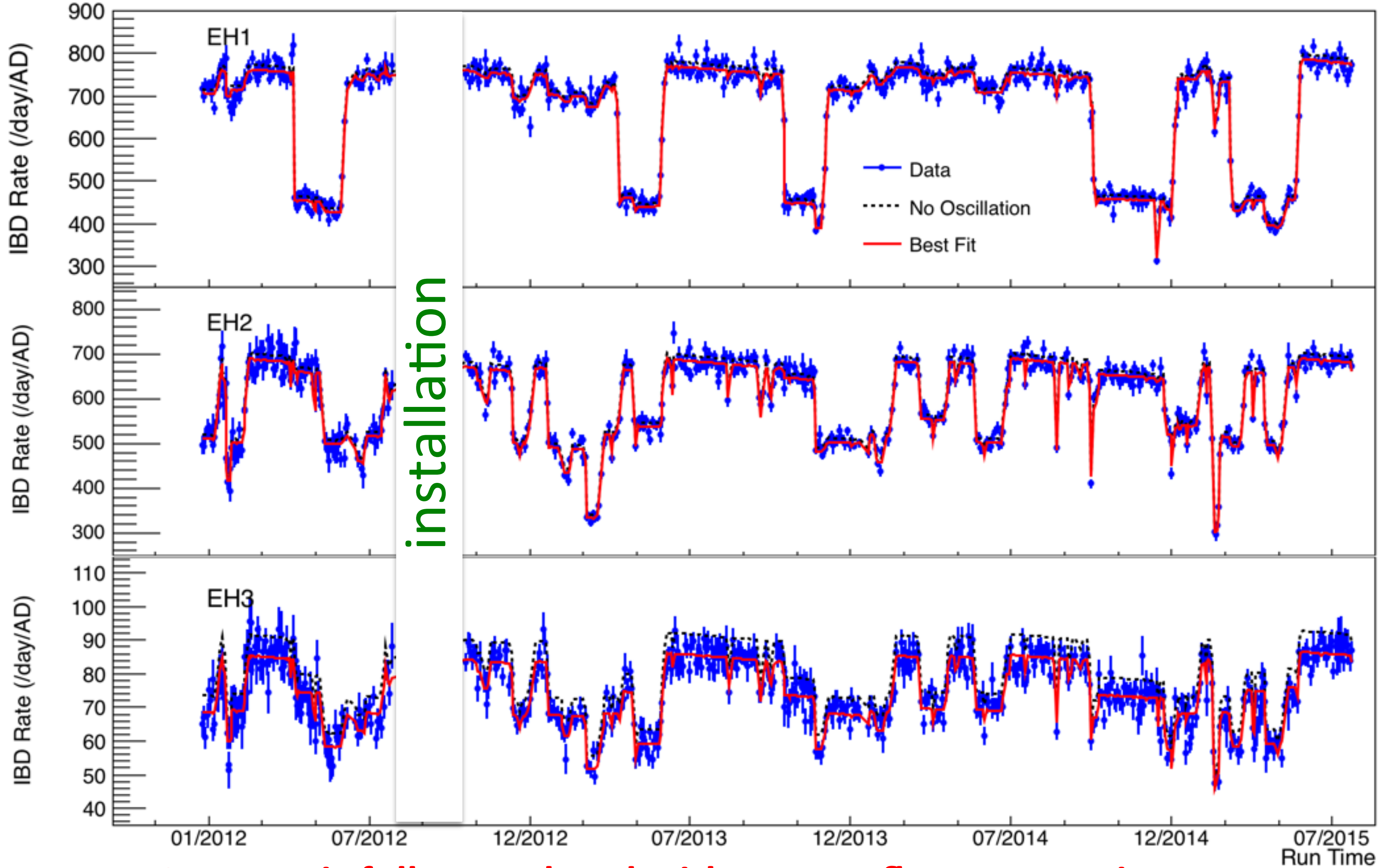


	EH1	EH2	EH3
IBD candidates	1,203,969	1,033,209	308,150
B/S ratio	1.8±0.2%	1.5±0.2%	2.0±0.2%
IBD rate (day^{-1})	1058.5	998.2	285.2

- **Over 2.5M (300K) IBD candidates in total (the far site)!**
- **≤ 2% backgrounds**
- ^{9}Li/^{8}He has the largest uncertainty on B/S ratio: 0.1% ~ 0.15%

6-AD: 217 days (Dec/2011 – Jul/2012)
8-AD: 1013 days (Oct/2012 – Jul/2015)

IBD Rate vs. Time

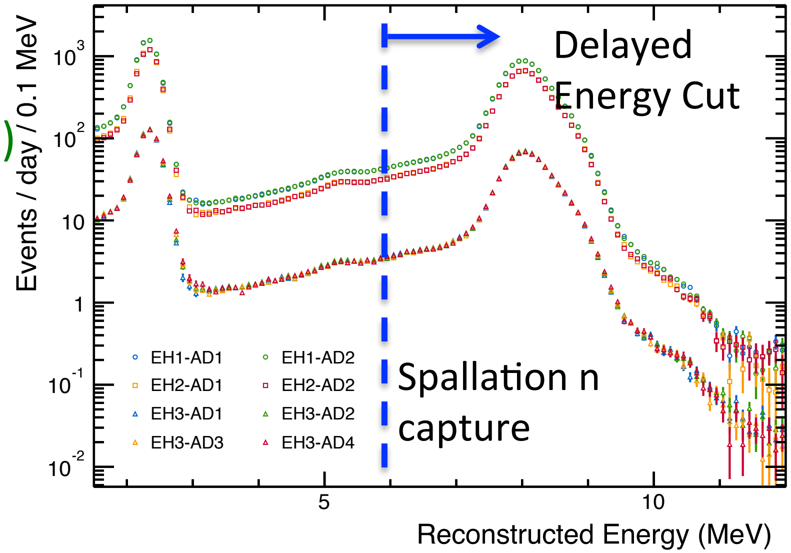


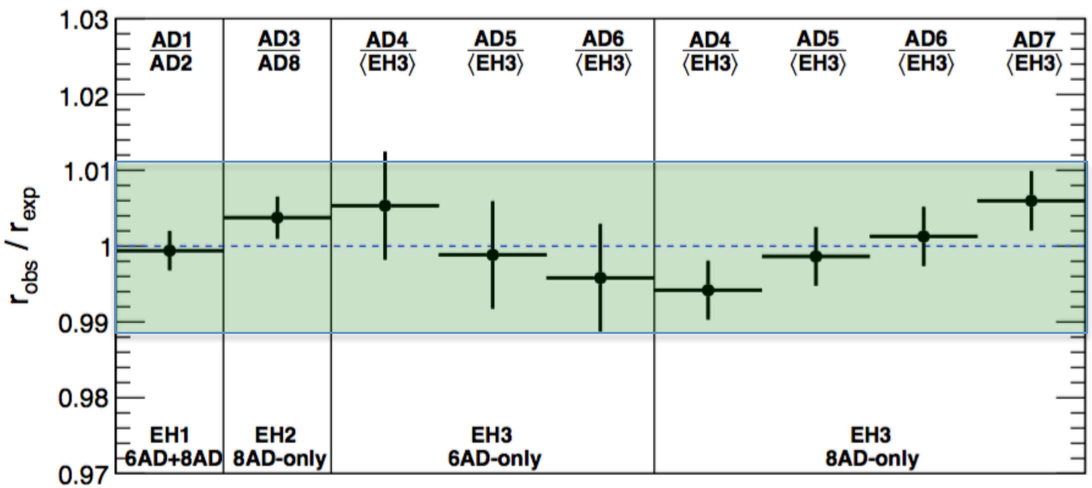
IBD rate is fully correlated with reactor flux expectations

Summary of systematics

Detector efficiency

	Efficiency	Correlated	Uncorrelated	Previous
Target protons	-	0.92%	0.03%	
Flasher cut	99.98%	0.01%	0.01%	
Delayed energy cut	92.7%	0.97%	0.08%	(0.12%)
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%	(0.2%)

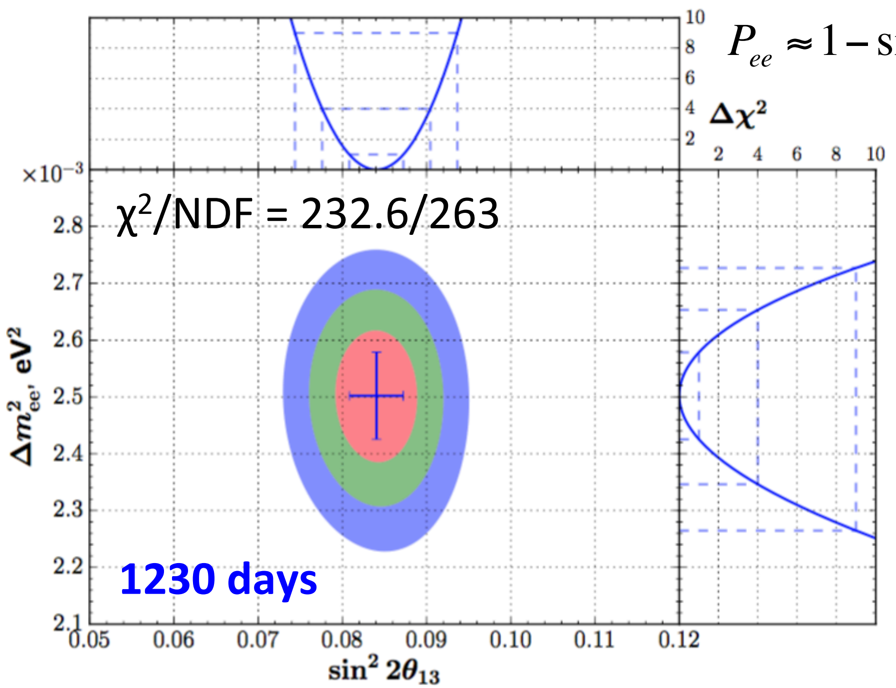


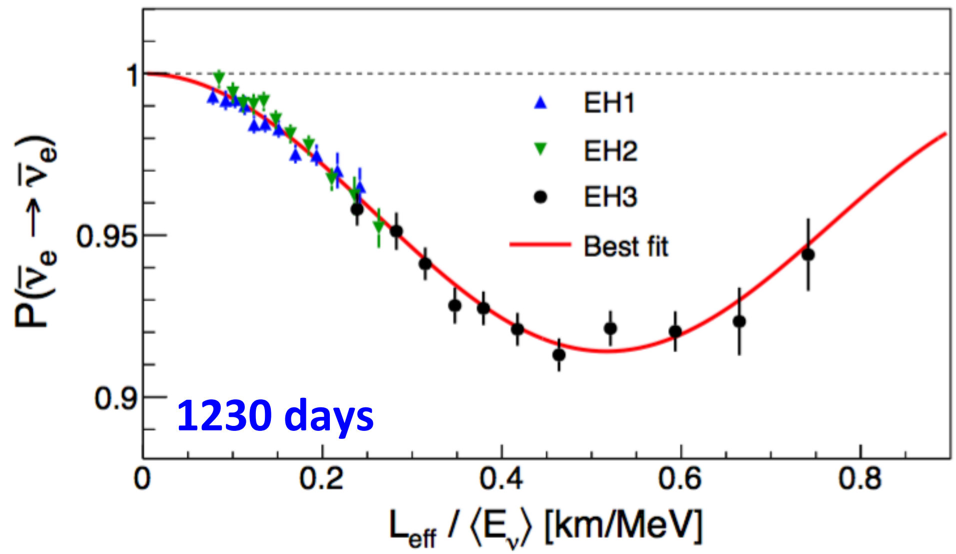


Multiple detectors in the same experimental hall enables cross-check of the uncorrelated uncertainty

Oscillation Analysis Result

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





$$\sin^2 2\theta_{13} = 0.0841 \pm 0.0027(stat.) \pm 0.0019(syst.)$$

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

- **Consistent with 3-neutrino oscillation framework**
- **Multiple analyses yield consistent results**

Global comparison

1230 days

Most precise measurement

- **$\sin^2 2\theta_{13}$ uncertainty: 3.9%**
- **$|\Delta m^2_{32}|$ uncertainty: 3.4%**

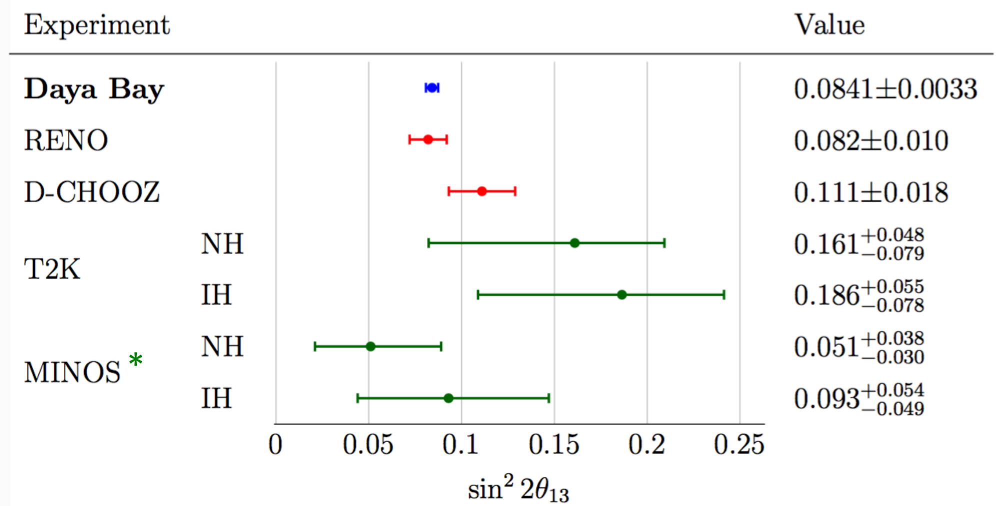
Consistent results with reactor and accelerator experiments.

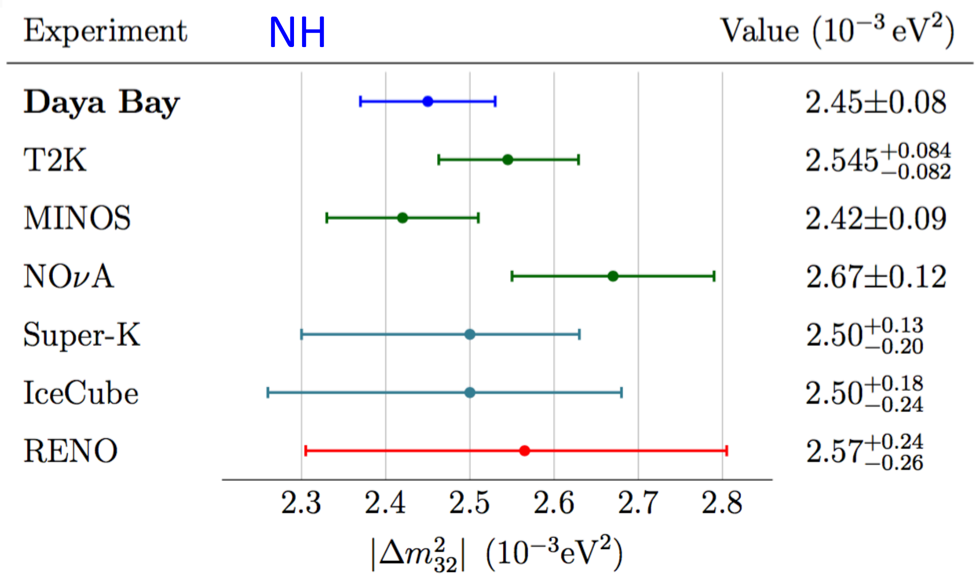
At Daya Bay:

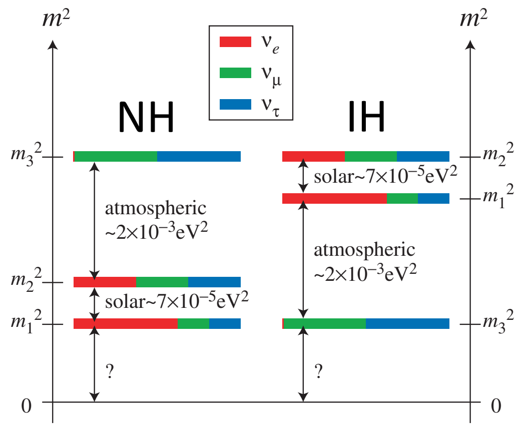
$|\Delta m^2_{ee}| \approx |\Delta m^2_{32}| \pm 0.05 \times 10^{-3}\ eV^2$

NH: $\Delta m^2_{32} = [2.45 \pm 0.08] \times 10^{-3}\ eV^2$

IH: $\Delta m^2_{32} = [-2.55 \pm 0.08] \times 10^{-3}\ eV^2$

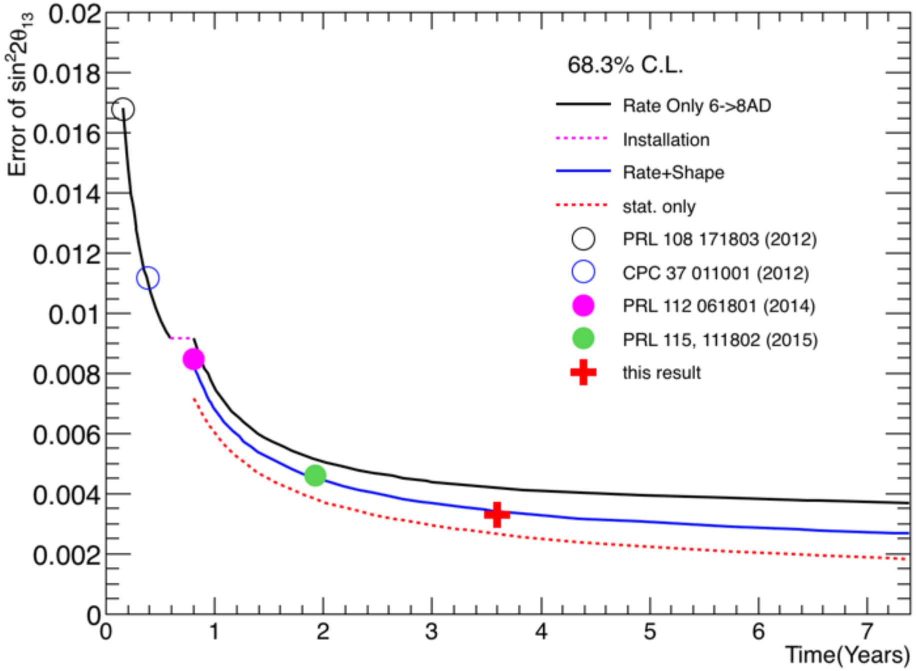


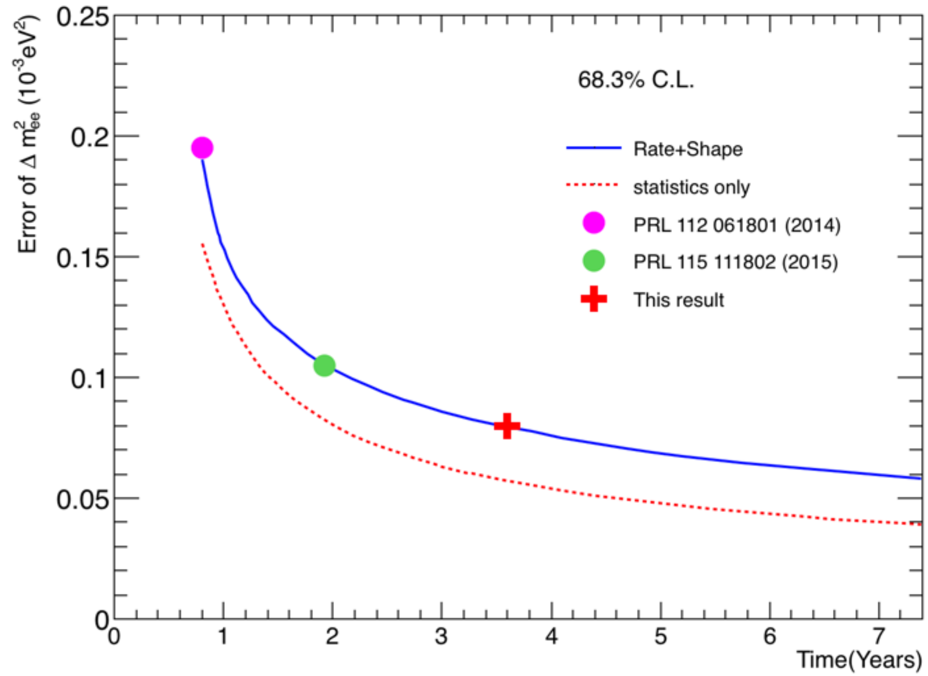




** Combined fit results for $2\sin^2\vartheta_{23}\sin^2 2\vartheta_{13}$*

$\sin^2 2\theta_{13}$ and $|\Delta m^2_{ee}|$ Error Projection



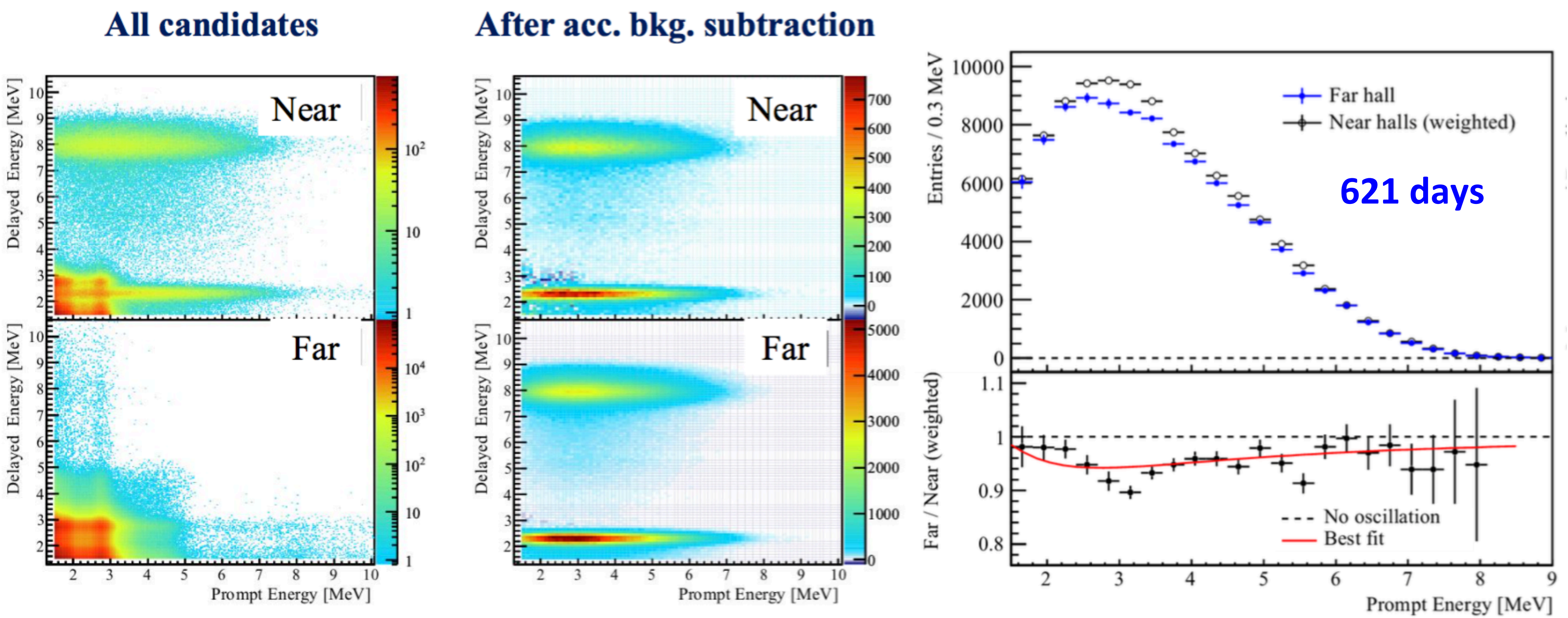


Daya Bay experiment is expected to run until 2020

The errors of $\sin^2 2\theta_{13}$ and $|\Delta m^2_{ee}|$ are expected to ≤ 3%

Poster: Hanyu Wei

$\sin^2 2\theta_{13}$ from nH Analysis



- Independent $\sin^2 2\theta_{13}$ measurement
- Challenging analysis:
  - 12% (54%) accidental background at near (far) site

Phys. Rev. D 93, 072011 (2016)

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

Poster Advertisement

- **Hanyu Wei,** **Independent measurement of θ_{13} via neutron capture on hydrogen analysis at Daya Bay**
- **Patrick, K.V. Tsang,** **Measurement of reactor antineutrino flux and spectrum at Daya Bay**
- **Henoch Wong,** **Search for a Light Sterile Neutrino at Daya Bay**
- **Aaron Higuera and Ming-Chu Chu,** **Search for Time-Varying Neutrino Oscillation and Lorentz-CPT Violation at Daya Bay**
- **Maria Dolgareva,** **Study of decoherence effects in neutrino oscillations at Daya Bay**

Summary

- The most precise measurements

  $\sin^2 2\theta_{13} = [8.41 \pm 0.33] \times 10^{-2}$

  $|\Delta m^2_{ee}| = [2.50 \pm 0.08] \times 10^{-3}\ \mathrm{eV}^2$

  (insensitive to mass hierarchy and error on $\sin^2 2\vartheta_{12}$*)*

  NH: $\Delta m^2_{32} = [2.45 \pm 0.08] \times 10^{-3}\ \mathrm{eV}^2$

  IH: $\Delta m^2_{32} = [-2.55 \pm 0.08] \times 10^{-3}\ \mathrm{eV}^2$
- Independent $\sin^2 2\theta_{13}$ measurement from nH
- Plan to run until 2020 and achieve ≤3% uncertainties