西安交通大學
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Results from Daya Bay Neutrino Experiment

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for Daya Bay Collaboration

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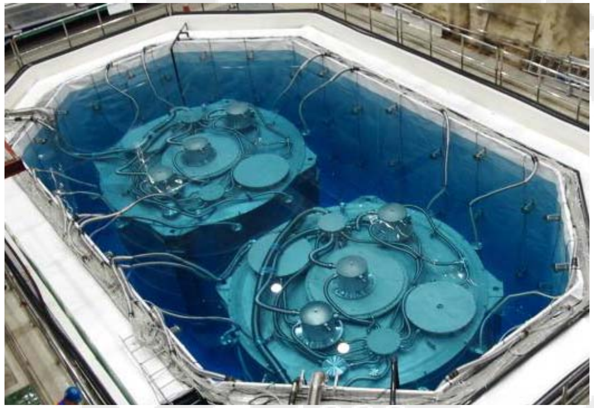


1. Motivation

- Fundamental building blocks of matter:

$$\begin{pmatrix} e & \mu & \tau \\ \nu_e & \nu_\mu & \nu_\tau \end{pmatrix} \qquad \begin{pmatrix} u & c & t \\ d & s & b \end{pmatrix}$$

- Neutrino mass: the central issue of neutrino physics
  - **Tiny mass but huge amount**
  - **Influence to Cosmology: evolution, large scale, structure, …**
  - **An evidence beyond the Standard Model**
- Neutrino oscillation: a great method to probe the mass

$\nu_e \rightarrow \nu_m \rightarrow \nu_e \rightarrow \nu_m \rightarrow$

$$P(\nu_e \text{->} \nu_m) = \sin^2(2\theta)\,\sin^2(1.27\,\Delta m^2 L/E)$$

Oscillation probability:

Oscillation amplitude (for $\sin^2(2\theta)$)

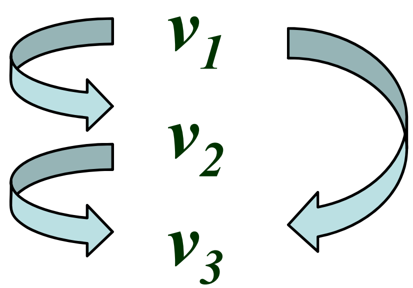
Oscillation frequency (for Δm^2)

θ_{13}:not exactly known before DYB

- Goal : measure θ_{13} precisely ?

θ_{12} solar neutrino oscillation

θ_{23}atmospheric neutrino oscillation



θ_{13} ?

- Neutrino mixing matrix:

Unknown : θ_{13}, δ + 2 Majorana phases

$$U_{PMNS}=\begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13}\end{pmatrix}\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}$$

"Atmospheric"

SK, K2K, T2K, MINOS,...

Short baseline reactor (DYB, RENO, DoubleChooz)

Long-baseline accelerator (T2K, MINOS...)

"Solar"

KamLAND, SNO, SK,...

Measuring θ_{13} with Short Baseline Exp.

$$P(\tilde{\nu}_e \rightarrow \tilde{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2[1.27\Delta m^2_{32} L/E] - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2[1.27\Delta m^2_{21} L/E]$$

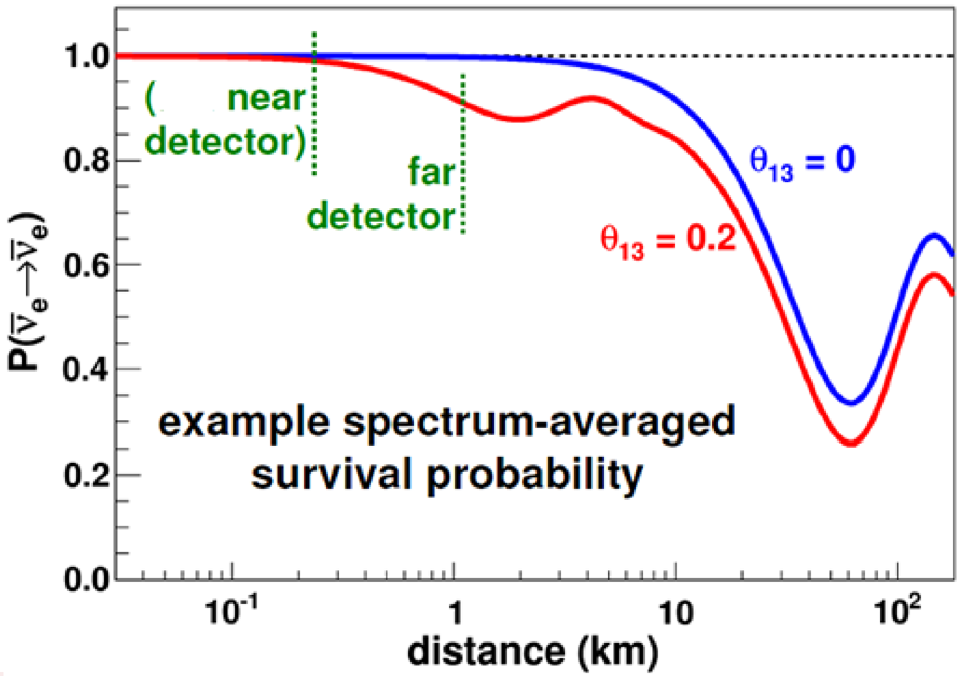
L is small (L < 5km)

$$P(\tilde{\nu}_e \rightarrow \tilde{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2[1.27\Delta m^2_{32} L/E]$$

Short-baseline reactor neutrino experiments

- Disappearance of electron antineutrinos from a reactor

- Daya Bay, RENO, Double Chooz



Near-Far Relative Measurement

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

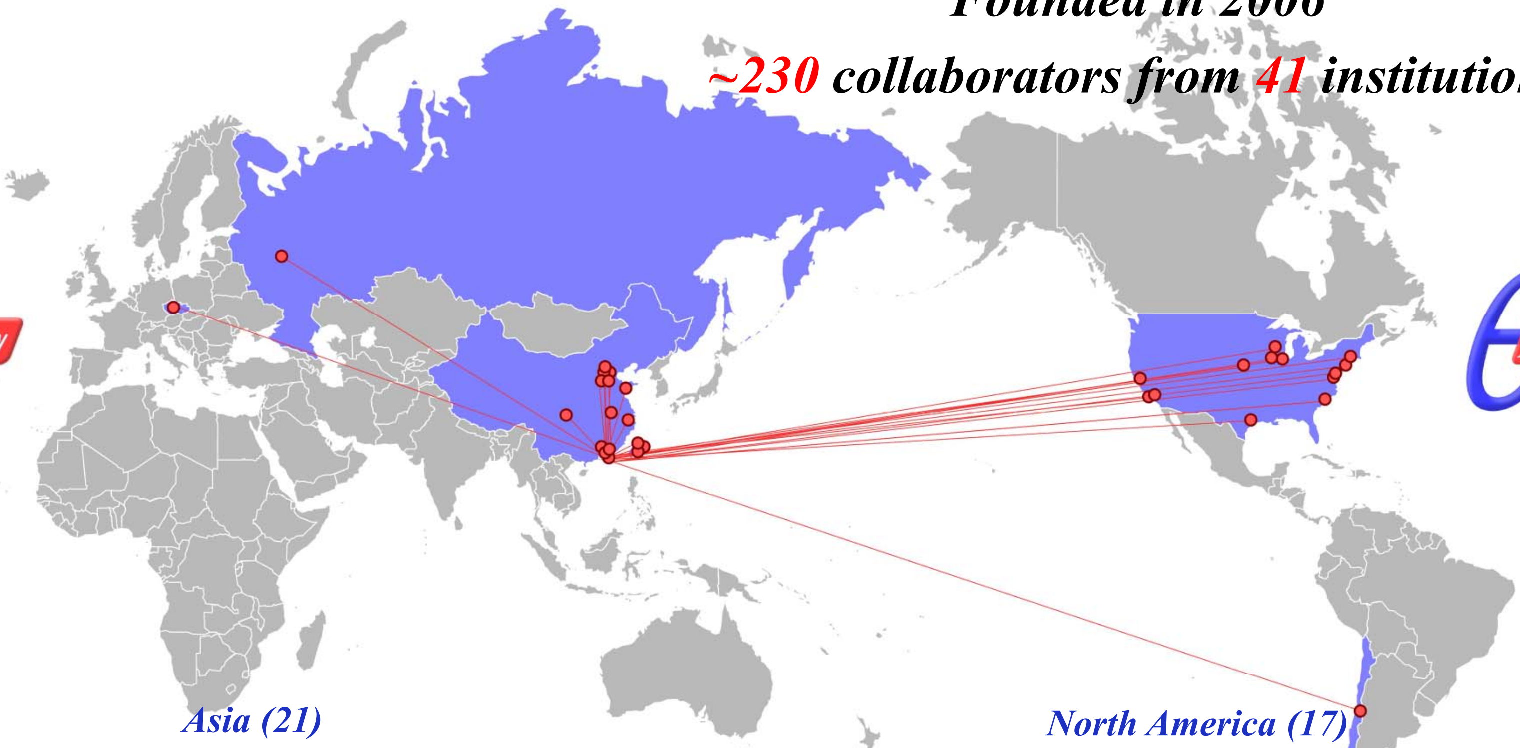
- *Measured far/near ratio of rates*
- *Target Mass ratio*
- *baseline ratio*
- *Detection efficiency ratio*
- *Survival probability* $\sin^2(2\theta_{13})$

- ***Relative far detector/near detector measurement – reactor flux uncertainties largely cancel***
- ***Identical detectors to cancel detector-related uncertainties***

2. The Daya Bay Collaboration

Founded in 2006

~230 collaborators from 41 institutions



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.

Europe (2)

Charles University, JINR Dubna

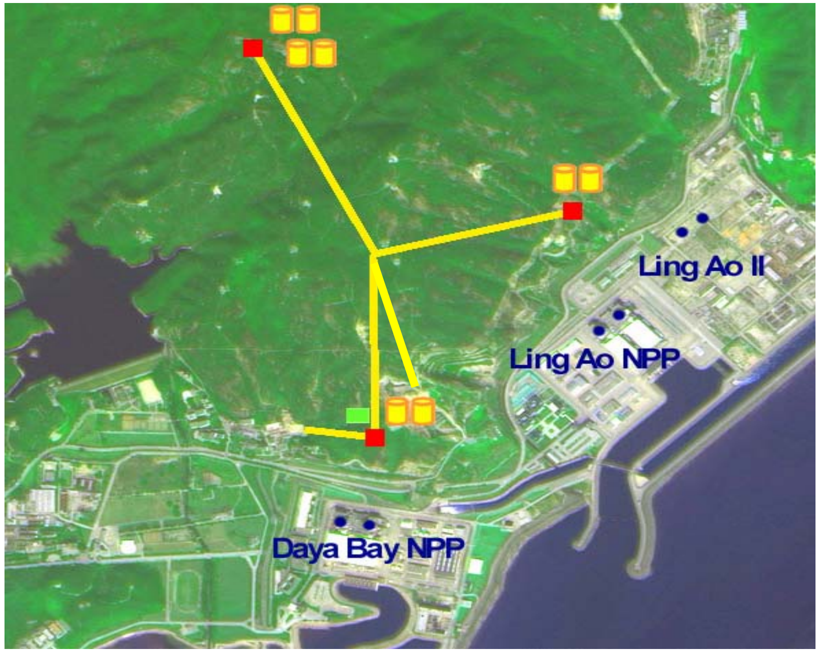
North America (17)

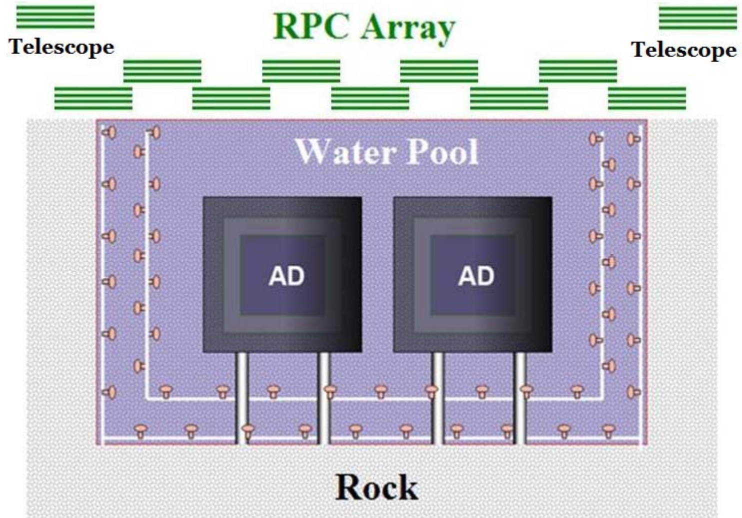
Brookhaven Natl Lab, CalTech, Illinois Institute of Technology, Iowa State, Lawrence Berkeley Natl Lab, Princeton, Rensselaer Polytechnic, Siena College, UC Berkeley, UCLA, Univ. of Cincinnati, Univ. of Houston, UIUC, Univ. of Wisconsin, Virginia Tech, William & Mary, Yale

South America (1)

Catholic Univ. of Chile

3. Experiment Layout and Detector Design

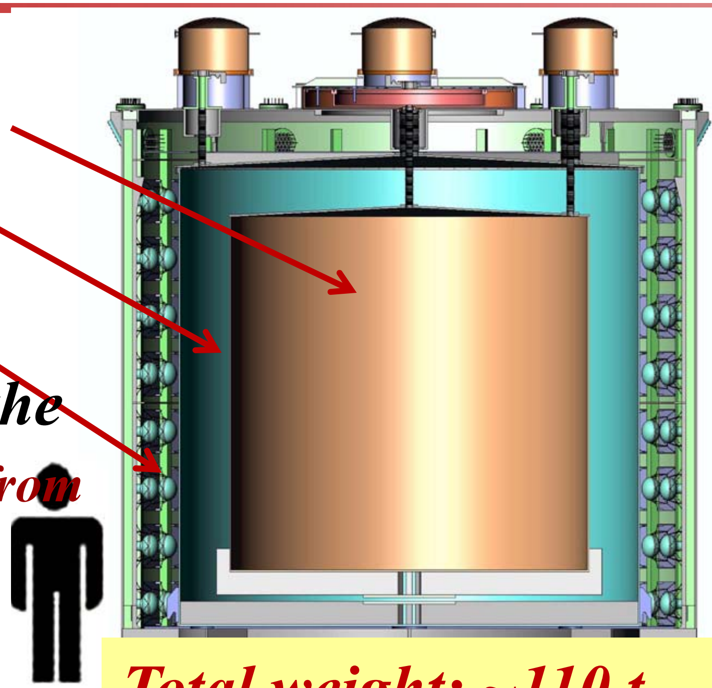




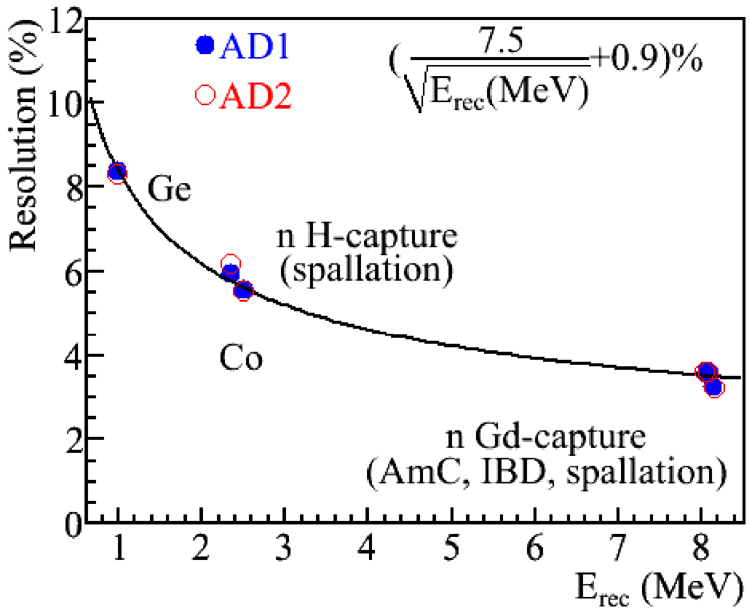
- 6 reactor cores (17.4 GW thermal power) to reduce Statistical Err.
- Relative measurement to cancel Correlated Syst. Err.
  - **2 near sites, 1 far site**
- Multiple AD modules at each site to reduce Uncorrelated Syst. Err.
  - **Far: 4 modules， near: 2 modules**
- Multiple muon detectors to reduce veto efficiency uncertainties
  - **Water Cherenkov： 2 layers**
  - **RPC： 4 layers at the top + telescopes**

Anti-neutrino Detector (AD)

- ***Three zones modular structure:***
  - *I. target: Gd-loaded scintillator, 1.6m,20t*
  - *II. γ -catcher: normal scintillator,45cm, 20t*
  - *III. buffer shielding: mineral oil ,45cm,40t*
- ***192 8" PMTs/module***
- ***Two optical reflectors at the top and the bottom,*** *Photocathode coverage increased from 5.6% to 12%*



Total weight: ~110 t



- ***Relative energy scale Unc. 0.4 %***
- ***Relative neutron energy selection 0.11 %***

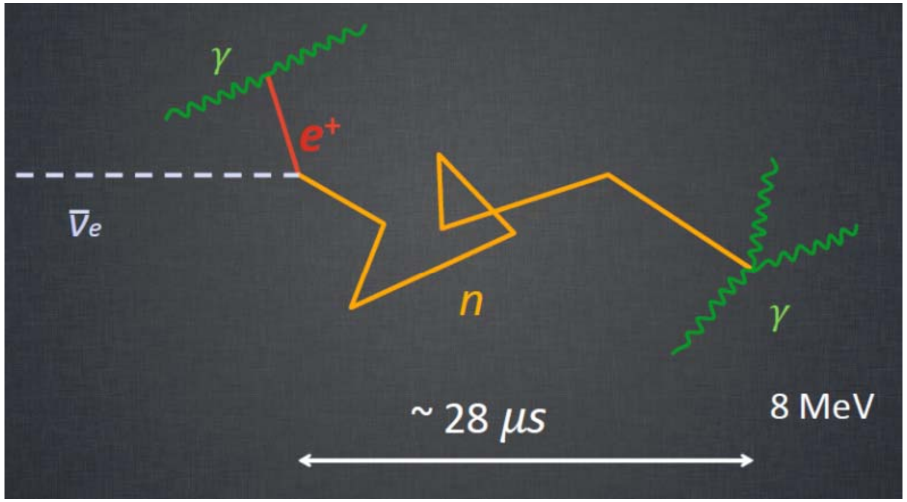
⇨

- ***Relative neutrino detection efficiency Unc. 0.2 %***

Neutrino Detection: Gd-loaded Liquid Scintillator

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

$t \approx 28$ ms(0.1% Gd)



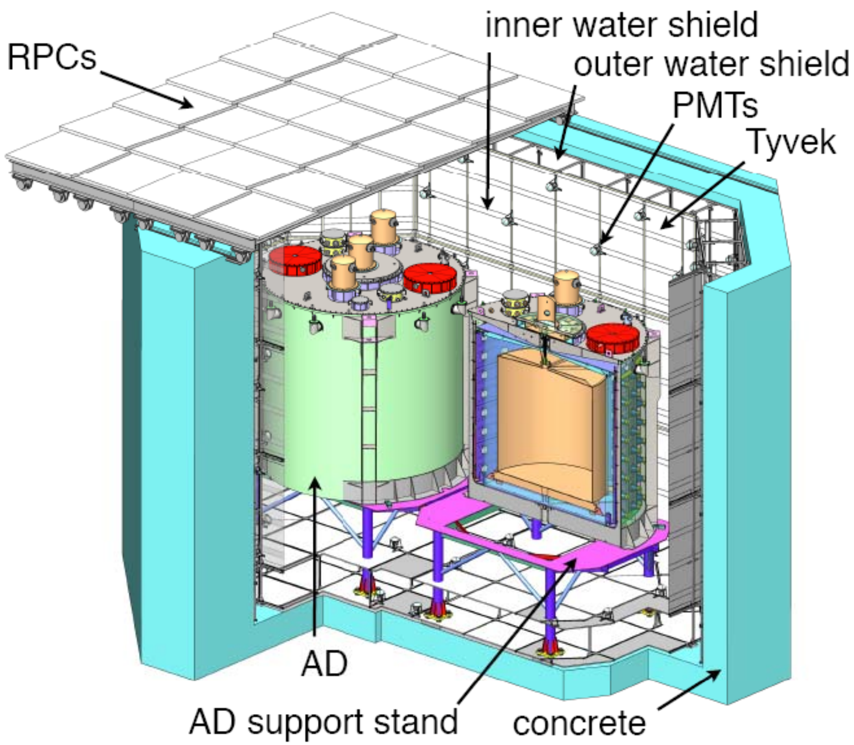
n + p → d + γ (2.2 MeV)

n + Gd → Gd* + γ(8MeV)

Neutrino Event Selection:

Coincidence in time, space and energy

Muon Veto Detector



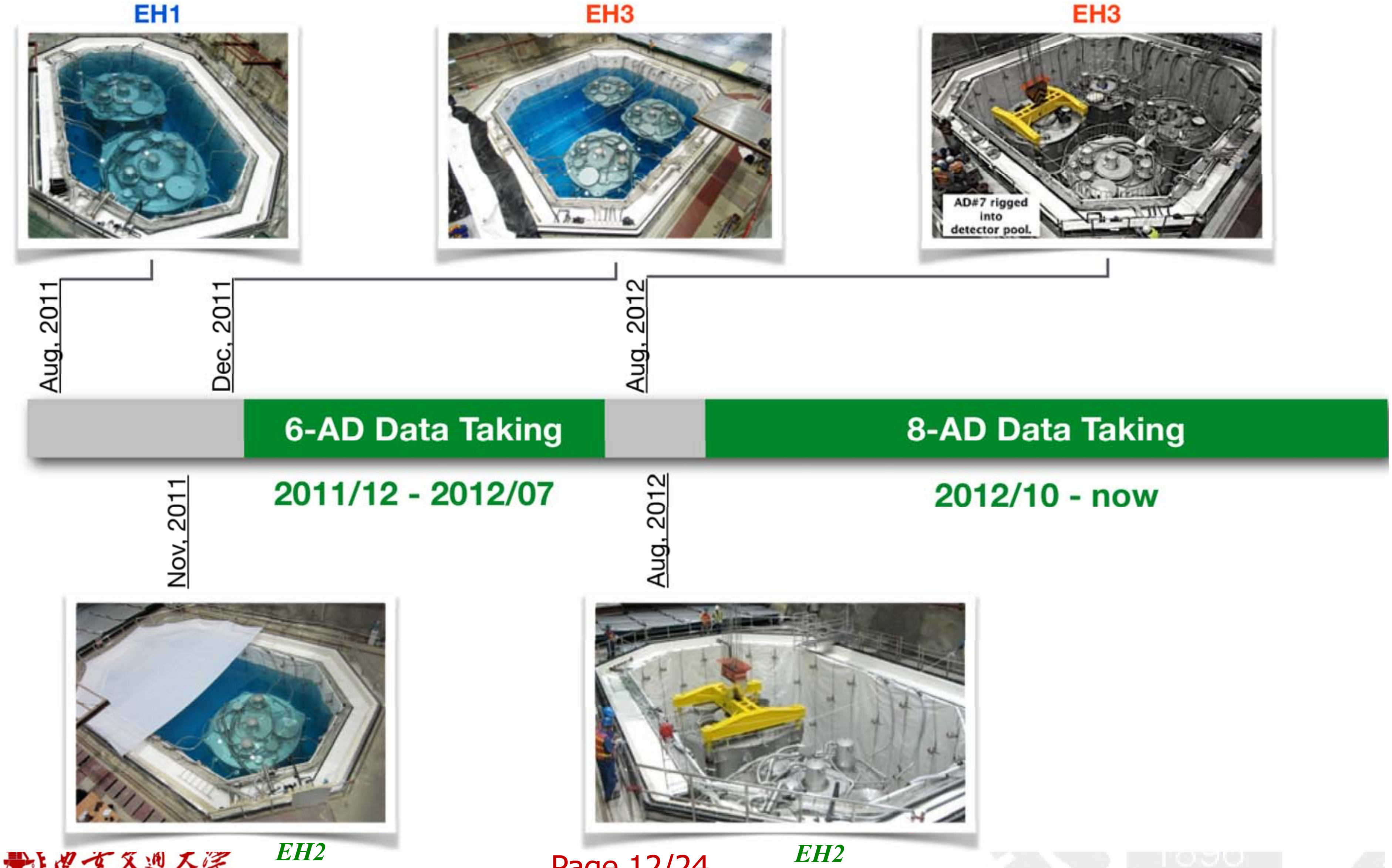
Two active cosmic-muon veto's

- ***Water Cerenkov: Eff.>97%***
- ***RPC Muon tracker: Eff. > 88%***

- Water Cerenkov detector
  - **Two layers, separated by Tyvek/PE/Tyvek film**
  - **288 8-inch PMTs for near halls 384 8-inch PMTs for the far hall**
- Water Cerenkov detector
  - **High purity de-ionized water in pools also for shielding**
  - **First stage water production in hall 4**
  - **Local water re-circulation & purification**

- RPCs
  - **4 layers/module**
  - **54 modules/near hall, 81 modules/far hall**
  - **2 telescope modules/hall**

4. Operation History



Two Detector Comparison:

- 90 days (9/23-12/23/2011)

- NIM A685 (2012) 78-97 arXiv:1202:6181

6-AD data taking

- 217 days (12/24/2011 – 7/28/2012)

- PRL 108 171803 (2012) arXiv:1203:1669 [55 days]

- CPC 37 011001 (2013) arXiv:1210.6327 [139 days]

- PRL 112 061801 (2014) arXiv:1310:6732 [217 days]

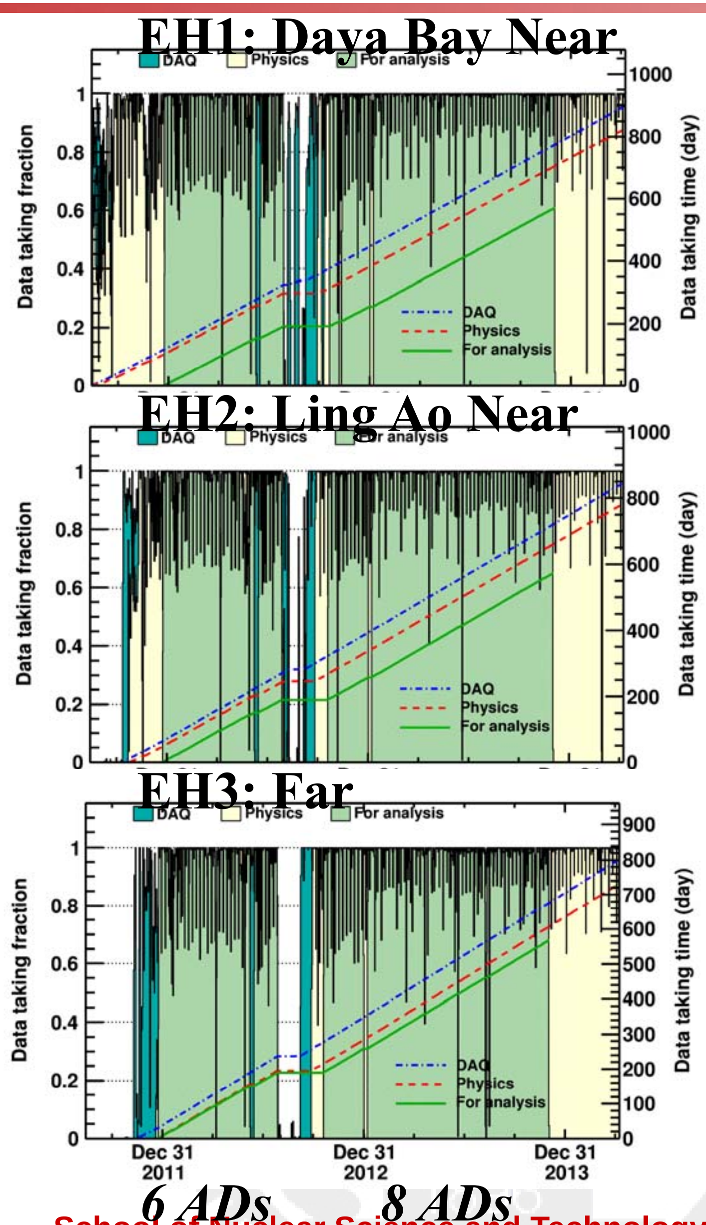
Shutdown: installed last 2 ADs, special calibrations

8-AD data taking

- since 10/19/2012

Most recent oscillation results: combined 6 AD

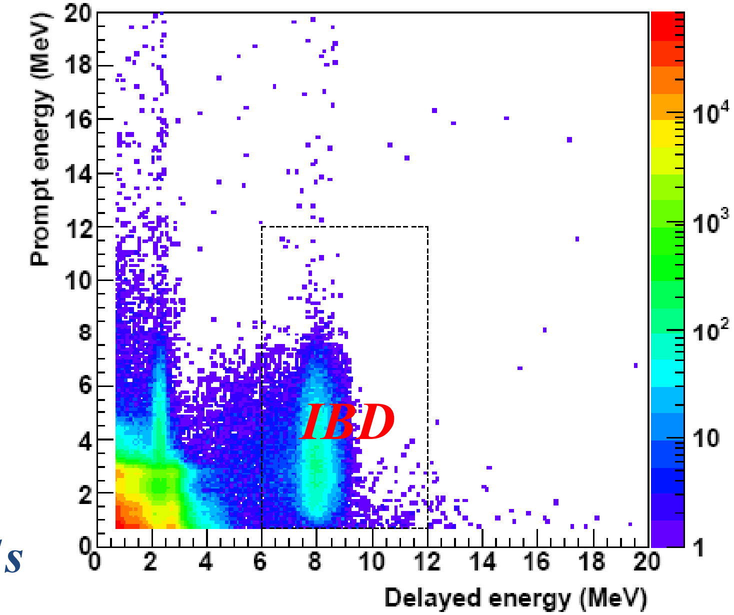
And 8 AD period: 621 days



5. Antineutrino (IBD) selection

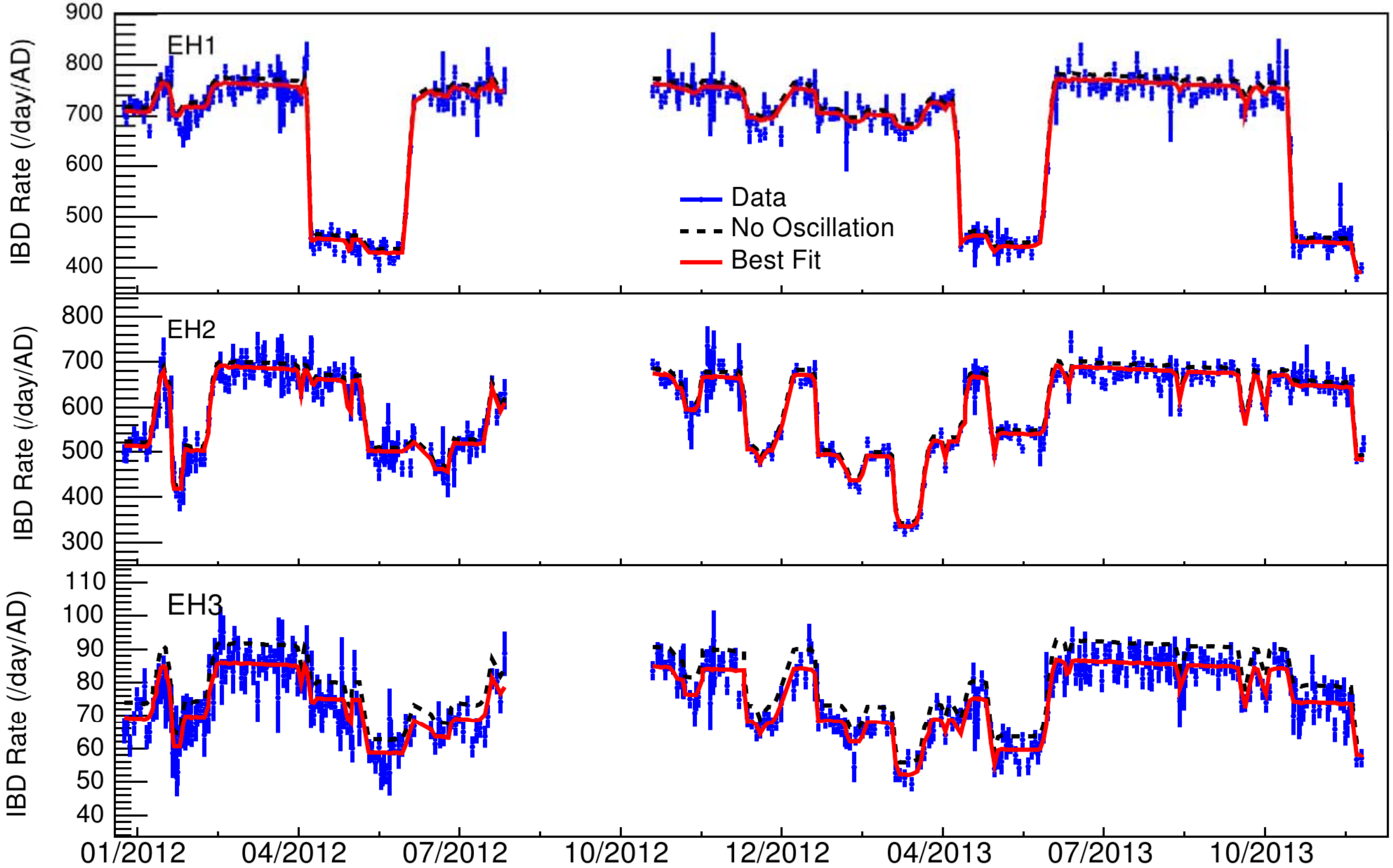
Selection:

- ***Reject PMT Flashers***
- ***Prompt Positron:*** *0.7 MeV < E^p < 12 MeV*
- ***Delayed Neutron:*** *6.0 MeV< E^d < 12 MeV*
- ***Capture time:*** *1 μs < Δt < 200 μs*
- ***Muon Veto:***
  - ***Pool Muon (>12 hit PMTs):*** *Reject 0.6 ms*
  - ***AD Muon (>3000 p.e.;>20 MeV):*** *Reject 1 ms*
  - ***AD Shower Muon (>3 × 10^5 p.e.; >2.5 GeV):*** *Reject 1s*
- ***Multiplicity:*** *only select isolated candidate pairs*



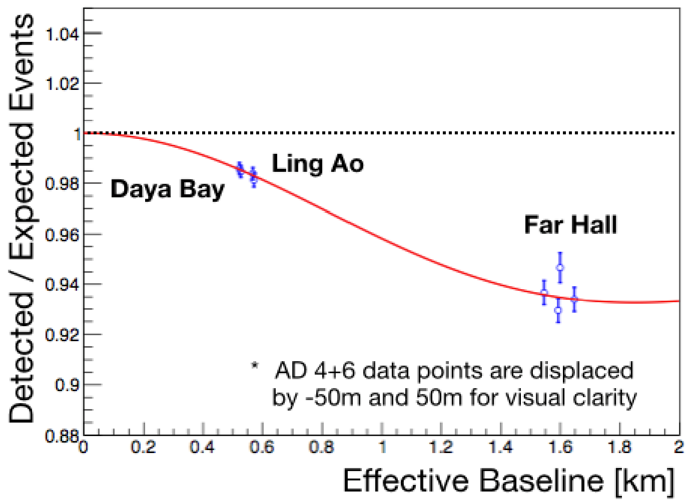
	Efficiency	Uncertainty Correlated	Uncertainty Uncorrelated
Target Protons		0.47%	0.03%
Flasher cut	99.98%	0.01%	0.01%
Delayed Energy cut	92.7%	0.97%	0.12%
Prompt Energy cut	99.81%	0.10%	0.01%
Capture time cut	98.70%	0.12%	0.01%
Gd capture ratio	84.2%	0.95%	0.10%
Spill-in correction	104.9%	1.50%	0.02%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

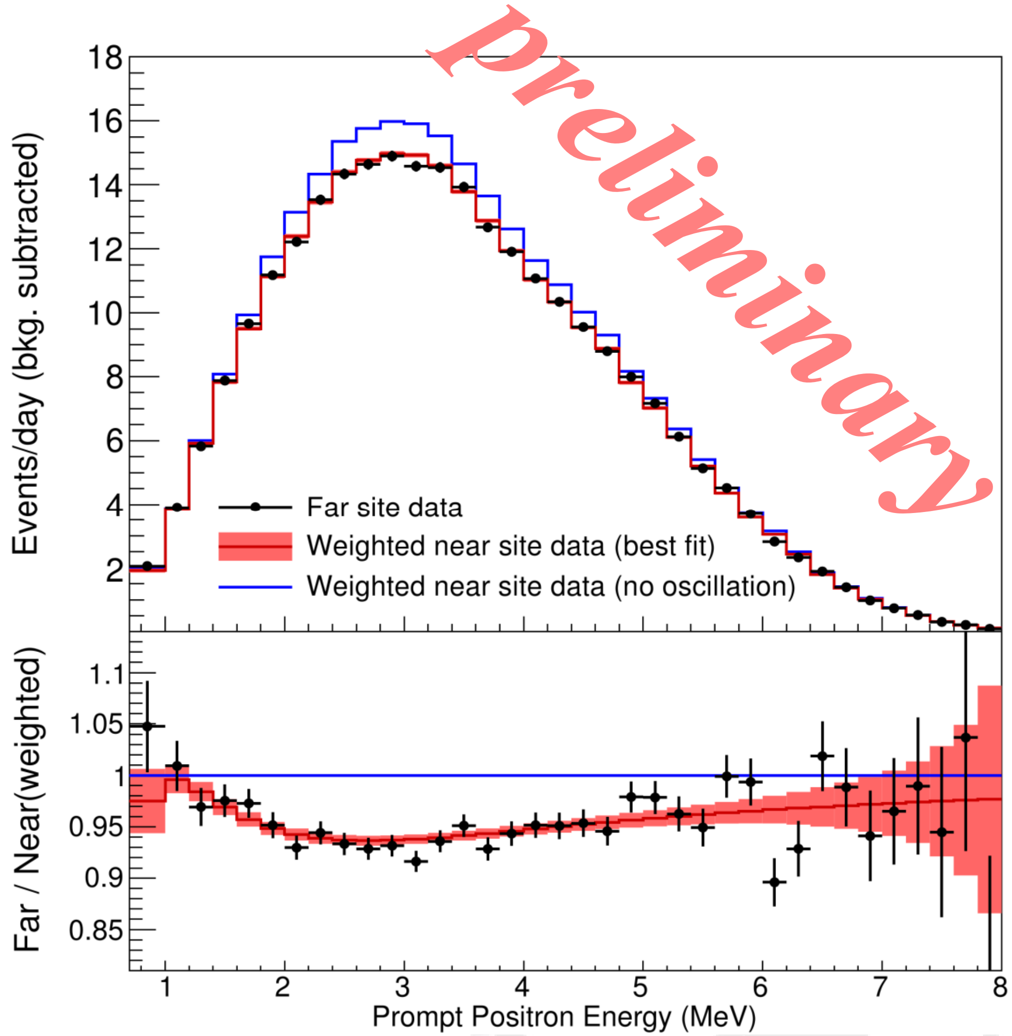
IBD Rate vs Time



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

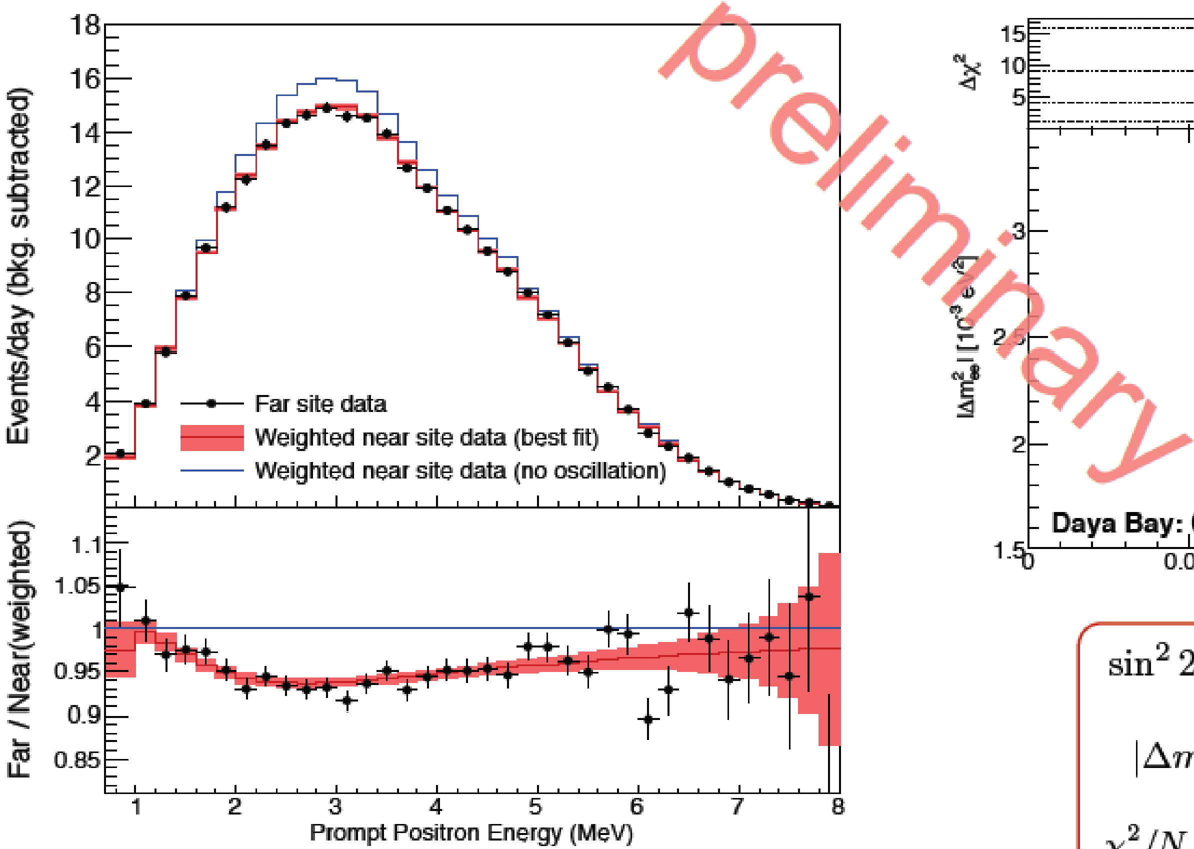
6. θ_{13} Measurement Results

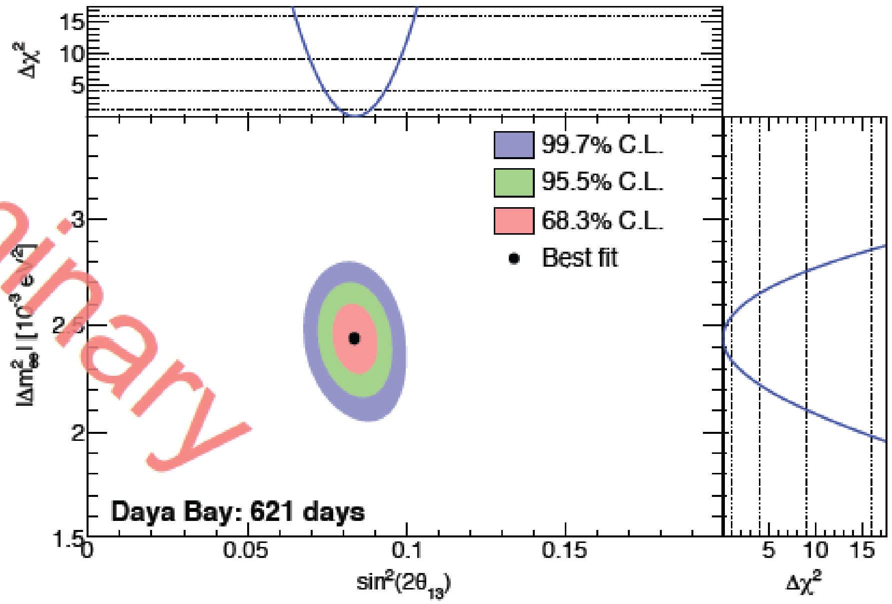




The observed relative rate deficit and relative spectrum distortion are highly consistent with oscillation interpretation

θ_{13} Oscillation Analysis using n-Captures on Gd





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

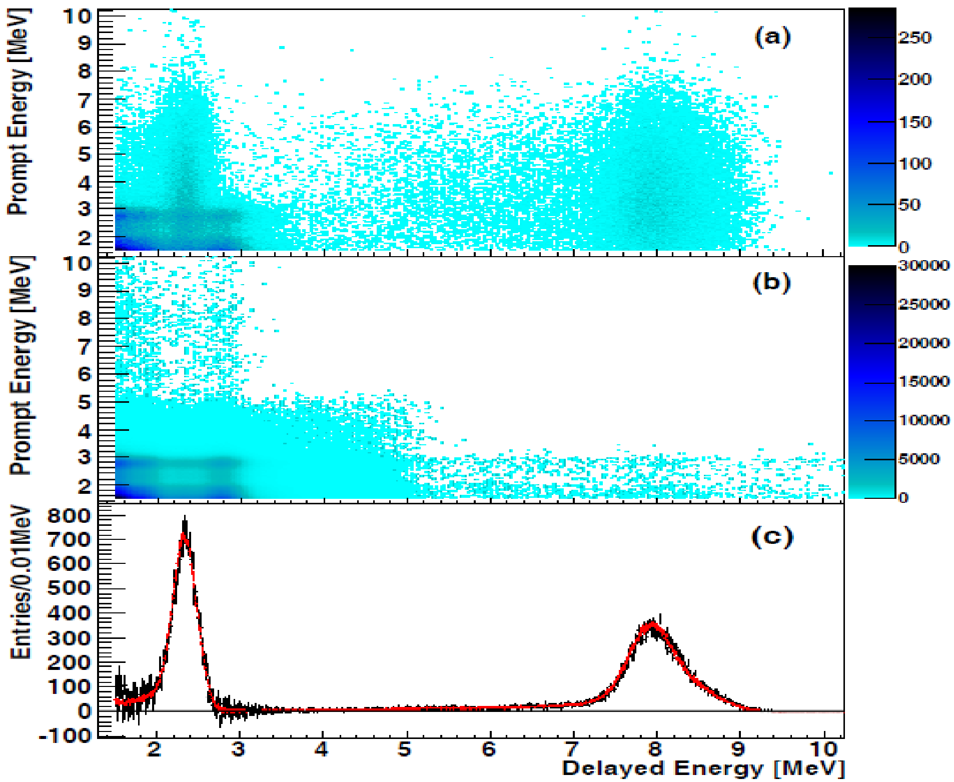
$$|\Delta m^2_{ee}| = 2.44^{+0.10}_{-0.11} \times 10^{-3}\mathrm{eV}^2$$

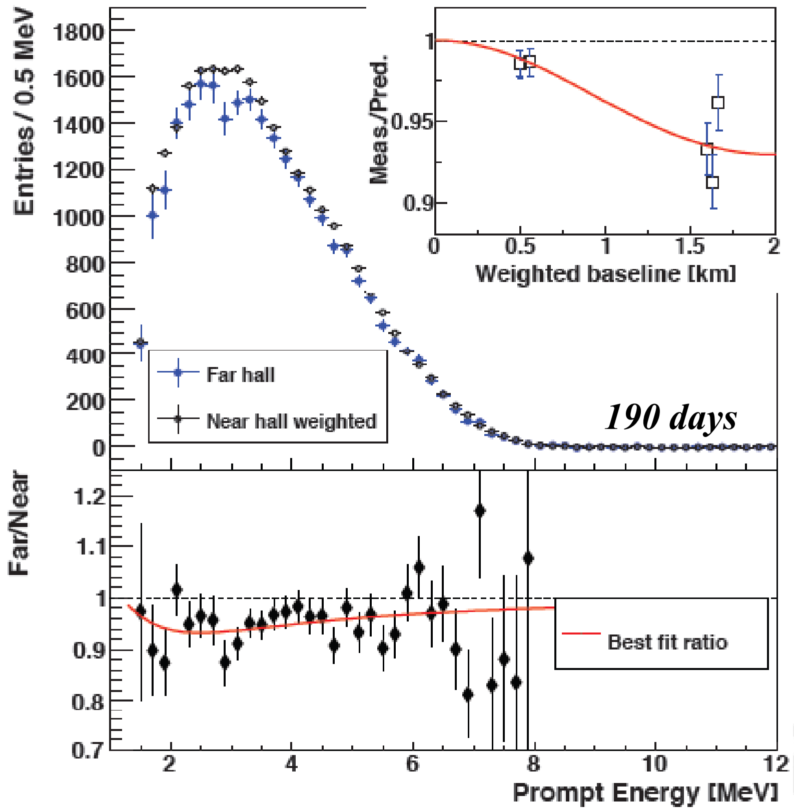
$$\chi^2/NDF = 134.7/146$$

- The far-site expected spectra are predicted based on the near-site observed spectra
- **The current analysis is designed to be (almost) independent of any reactor flux models**

- The most precise $\sin^2 2\theta_{13}$ measurement, ~6%
- The most precise Δm^2_{ee} measurement, comparable to long-baseline muon beam experiments

θ_{13} Oscillation Analysis using n-Captures on H





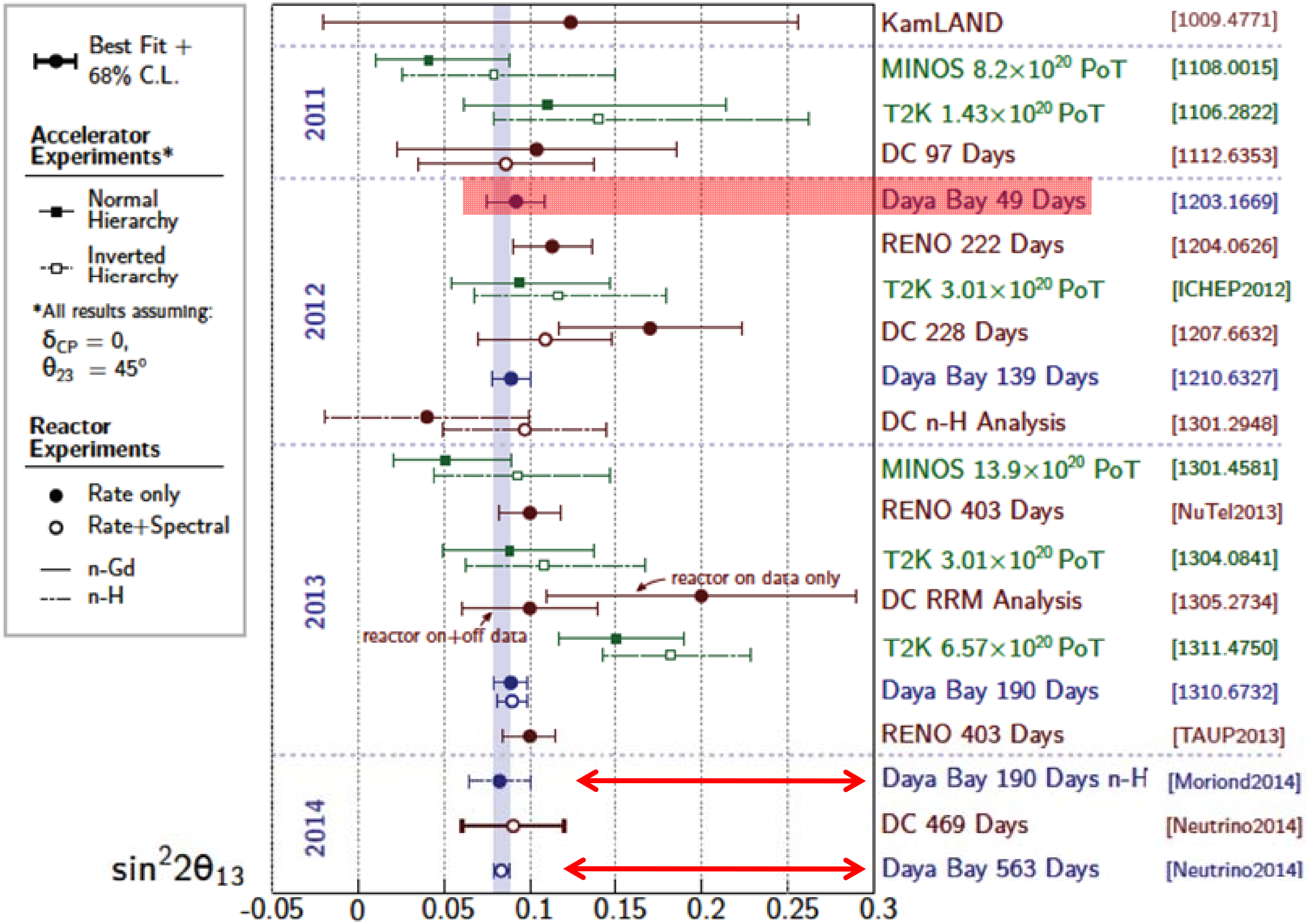
$\sin^2 2\theta_{13} = 0.083 \pm 0.018$

- nH IBD events have lower delayed energy and require longer correlation window thus the accidental rate is much higher, S/N~1 initially. Suppressed by
  - Higher prompt energy cut, >1.5MeV and prompt-delay distance cut <0.5m
  - Statistically subtracted by separation > 2m accidental event spectrum

➡ From the systematic perspective, nH samples are largely independent of nGd samples

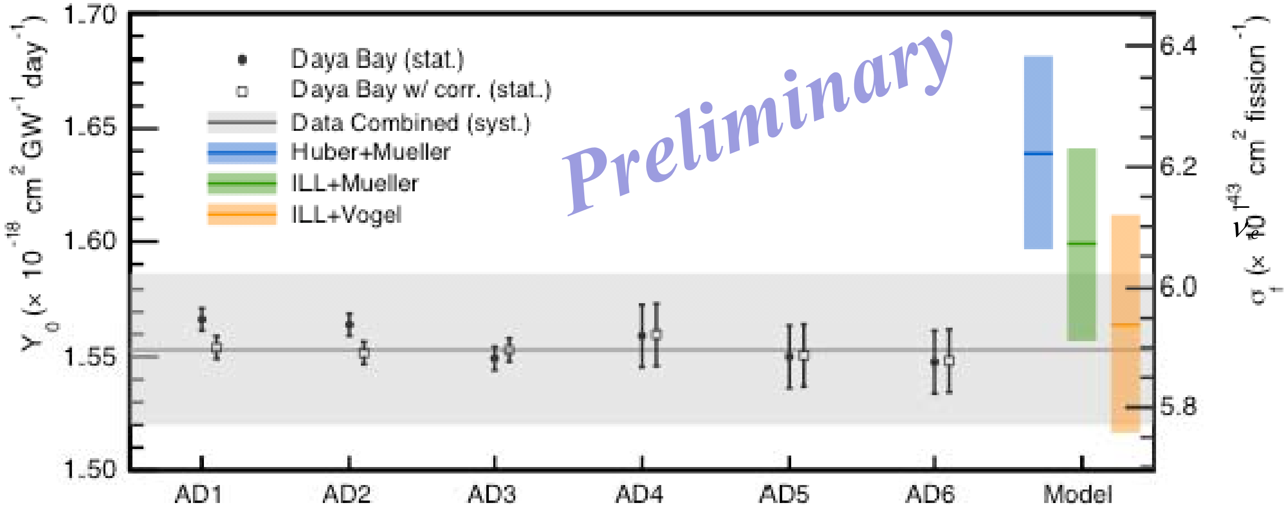
➡ nH based analysis shows independently convincing θ_{13} driven oscillation

$\sin^2 2\theta_{13}$ Measurement Timeline



7. Others: Absolute Reactor $\bar{\nu}_e$ Flux

- Measured IBD events (background subtracted) in each detector are normalized to *cm²/GW/day* (Y_0) and *cm²/fission* (σ_f).



3-AD (near sites) measurement:

$Y_0 = 1.553 \times 10^{-18}$

$\sigma_f = 5.934 \times 10^{-43}$

- Compare to reactor flux models: Measured / Predicted IBD ***candidates***

Data/Prediction (Huber+Mueller)

0.947 ± 0.022

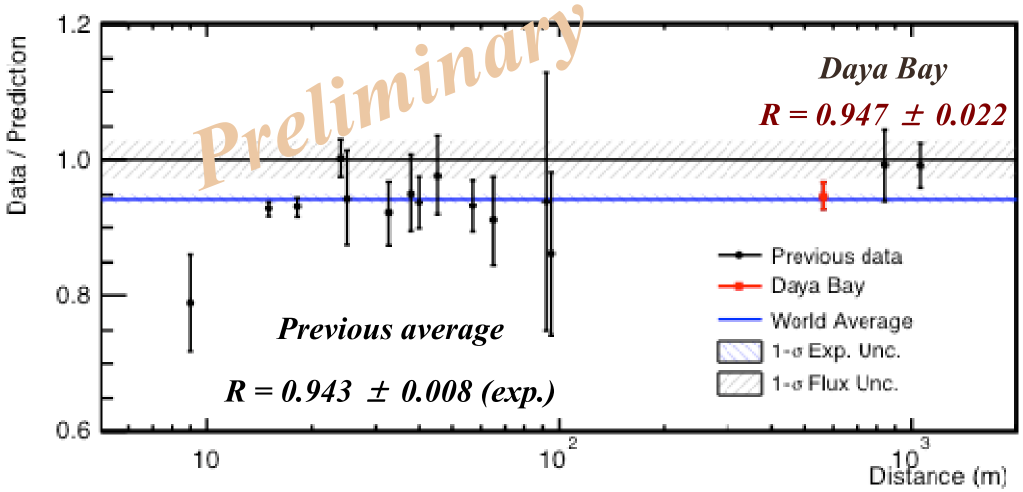
Data/Prediction (ILL+Vogel)

0.992 ± 0.023

	Uncertainty
statistics	0.2%
$\sin^2 2\theta_{13}$	0.2%
reactor	0.9%
detector efficiency	2.1%
combined	**2.3 %**

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

- **Global comparison of measurement and prediction (Huber+Mueller):**

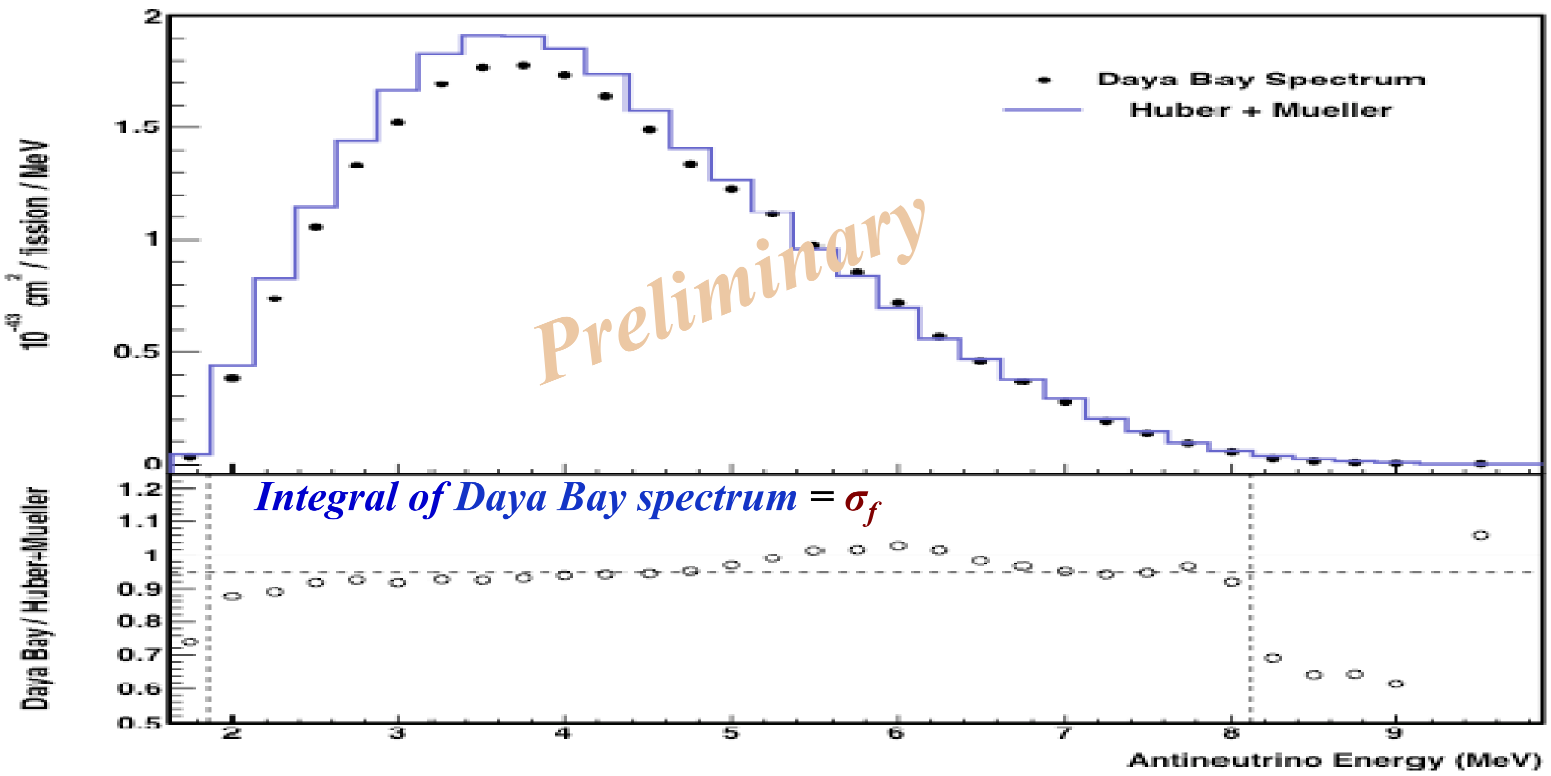


- Effective baseline of ***Daya Bay:*** $L_{eff} = 573m$
  - *Flux weighted detector-reactor distances of **3 ADs in near sites only.***
- Effective fission fractions α_k of ***Daya Bay*** $^{235}U: ^{238}U: ^{239}Pu: ^{241}Pu = 0.586: 0.076: 0.288: 0.050$
  - ***Mean fission fractions from 3 ADs in near sites only.***

7. Others: Observable $\bar{\nu}_e$ spectrum

✧Extract a generic observable reactor antineutrino spectrum $S_{obs\_\nu}(E_\nu)$:

●Supplies data outside [2, 8] MeV and could be used for flux and spectrum prediction.



✧ *Compare DYB spectrum and Huber+Mueller Prediction :* **Same rate deficit as flux measurement, and same shape deviation**

8. Summary

- **Daya Bay has measured:** $\sin^2 2\theta_{13} = 0.084^{+0.005}_{-0.005}$

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

  By the end of 2017, we expect the precision on both parameters to reach 3%.

- **We have an independent oscillation measurement using nH captures**

- **The absolute flux measurement is consistent with previous short baseline measurements.**

  $\sigma_f = (5.934 \pm 0.136) \times 10^{-43}$ **(cm^2/fission)**

  $^{235}U : ^{238}U : ^{239}Pu : ^{241}Pu = 0.586 : 0.076 : 0.288 : 0.050$

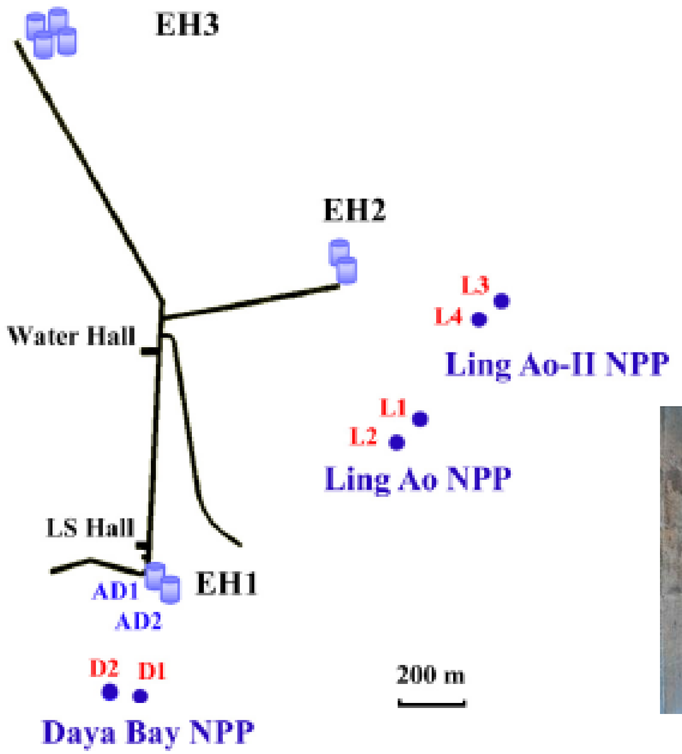
- **A generic observable reactor antineutrino spectrum (cm^2/fission/MeV) is extracted from the measured positron spectrum to be used for predictions.**

The End

Thanks for your attention！

Backup

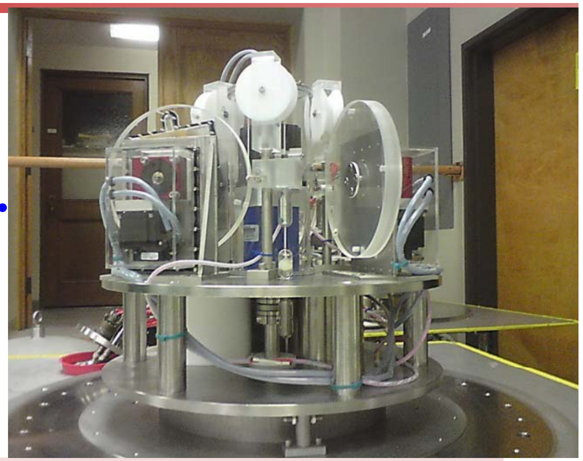
Underground Labs

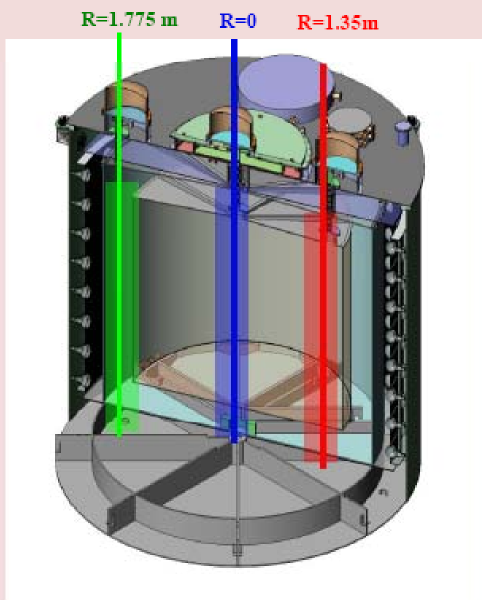


	n (MWE)	R_μ (Hz/m^2)	E_μ (GeV)	D1,2 (m)	L1,2 (m)	L3,4 (m)
EH1	250	1.27	57	364	857	1307
EH2	265	0.95	58	1348	480	528
EH3	860	0.056	137	1912	1540	1548

Automatic Calibration System

- Three Z axis:
  - **One at the center**
    - **For time evolution, energy scale, non-linearity.**
  - **One at the edge**
    - **For efficiency, space response**
  - **One in the g-catcher**
    - **For efficiency, space response**



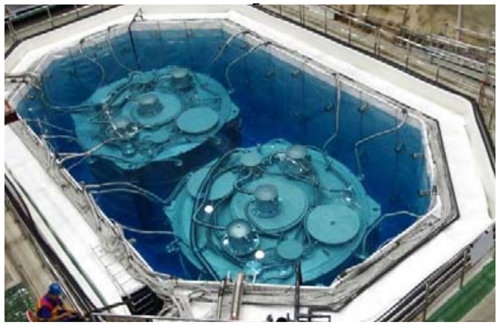


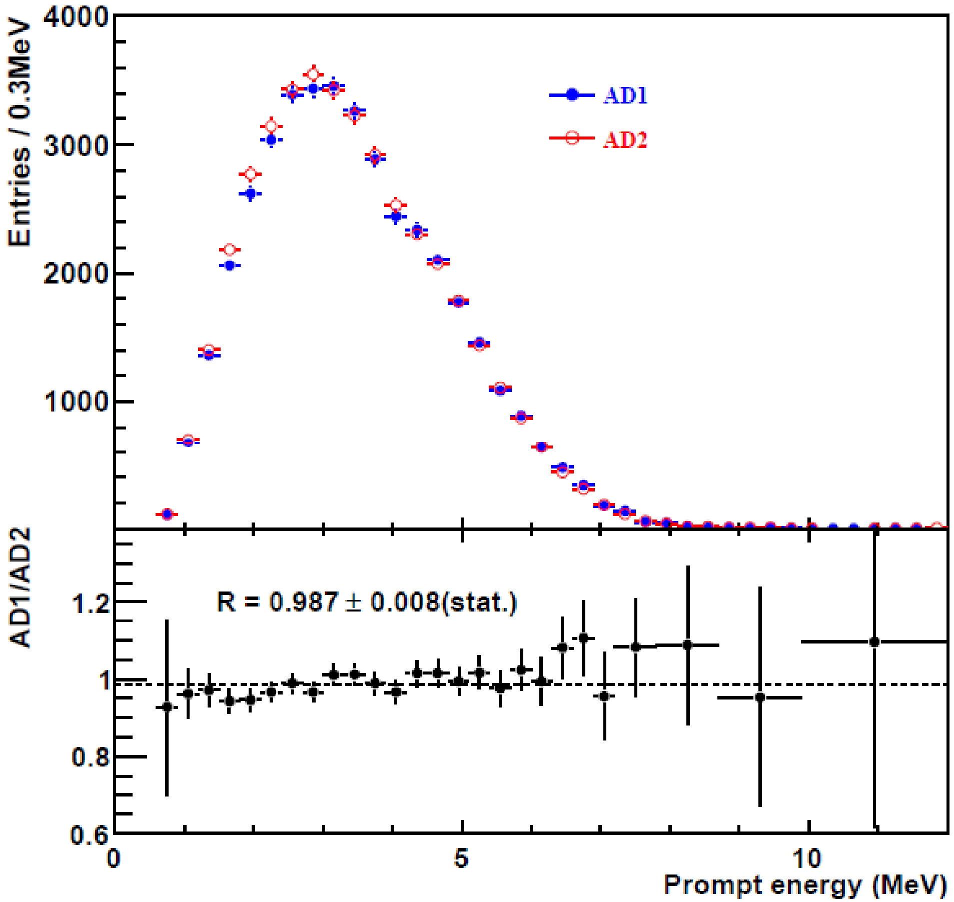
Automated Calibration

- 3 sources for each z axis:
  - **LED**
    - **for T_0, gain and relative QE**
  - **^{68}Ge (2×0.511 MeV γ's)**
    - **for positron threshold & non-linearity…**
  - **^{241}Am-^{13}C + ^{60}Co (1.17+1.33 MeV γ's)**
    - **For neutron capture time, …**
    - **For energy scale, response function, …**
- Once every **week:3 axis, 5 points in Z, 3 sources**

Side-by-side Comparison

- Expected ratio of neutrino events from AD1 and AD2: 0.981
- M 0.98





- *The ratio is not 1 because of target mass, baseline, etc.*
- *This final check shows that systematic errors are under control*