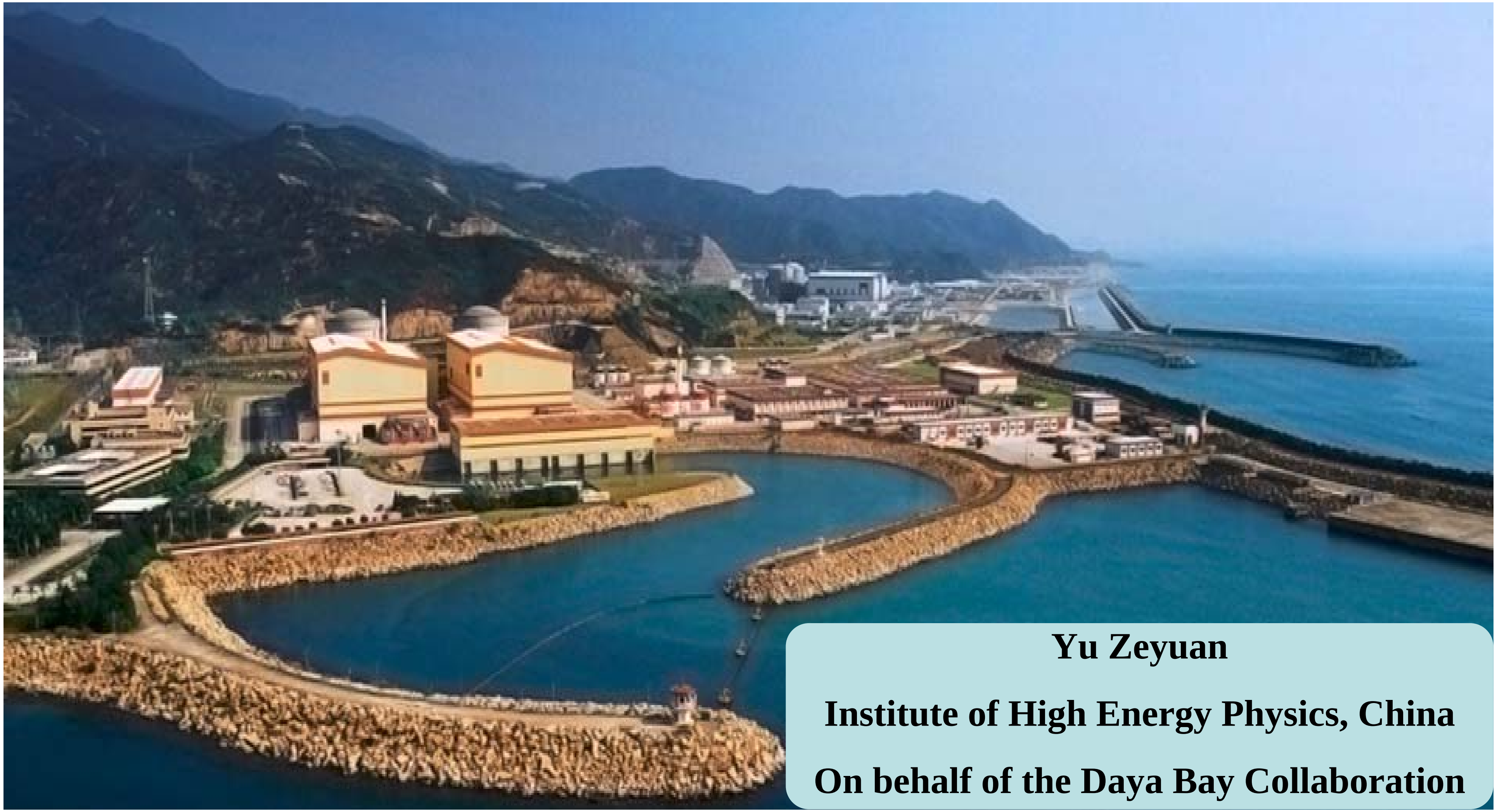
The Daya Bay Experiment



Yu Zeyuan

Institute of High Energy Physics, China

On behalf of the Daya Bay Collaboration

Neutrino Oscillation

PMNS matrix

$$U=\begin{pmatrix}1&0&0\\0&c_{23}&s_{23}\\0&-s_{23}&c_{23}\end{pmatrix}\begin{pmatrix}c_{13}&0&s_{13}\\0&e^{-i\delta}&0\\-s_{13}&0&c_{13}\end{pmatrix}\begin{pmatrix}c_{12}&s_{12}&0\\-s_{12}&c_{12}&0\\0&0&1\end{pmatrix}\begin{pmatrix}e^{i\rho}&0&0\\0&e^{i\sigma}&0\\0&0&1\end{pmatrix}$$

Last unknown mixing angle θ_{13} before 2011: $\sin^2(2\theta_{13}) < 0.15$ (90 C.L.)

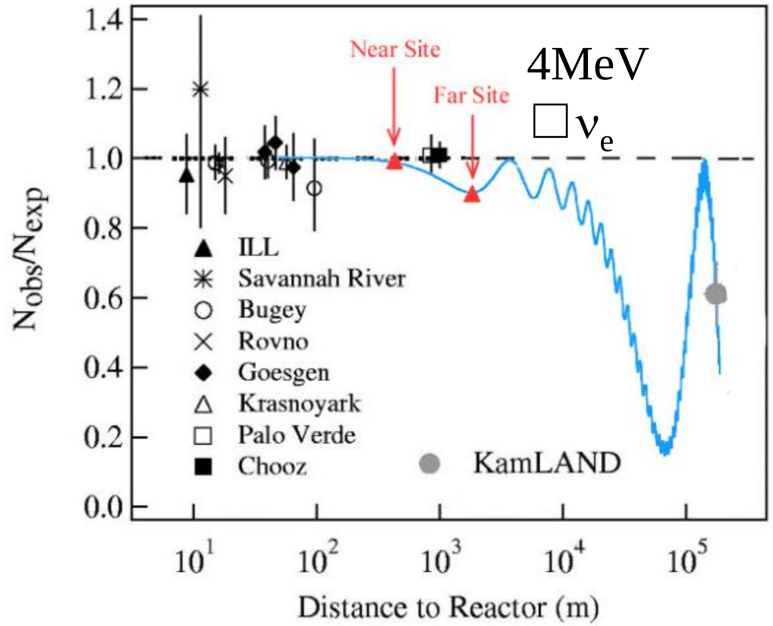
The Daya Bay Experiment is a well designed short baseline reactor neutrino experiment to precisely determine θ_{13}.

Reactor: disappearance: clean in physics

$$P_{\bar{\nu}_e\to\bar{\nu}_e}\approx 1-\sin^2 2\theta_{13}\sin^2\left(\Delta m^2_{31}L/4E\right)$$
$$-\cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\left(\Delta m^2_{21}L/4E\right)$$

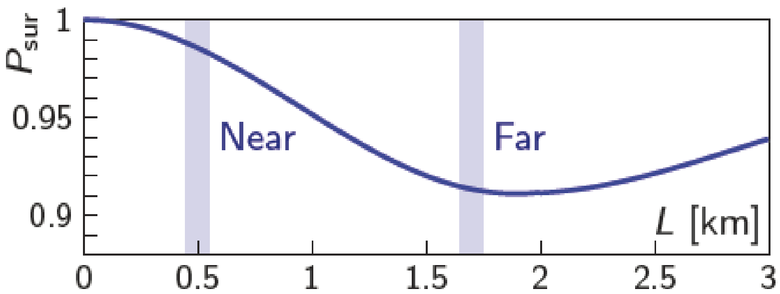
Accelerator: appearance, related to CPV, etc.

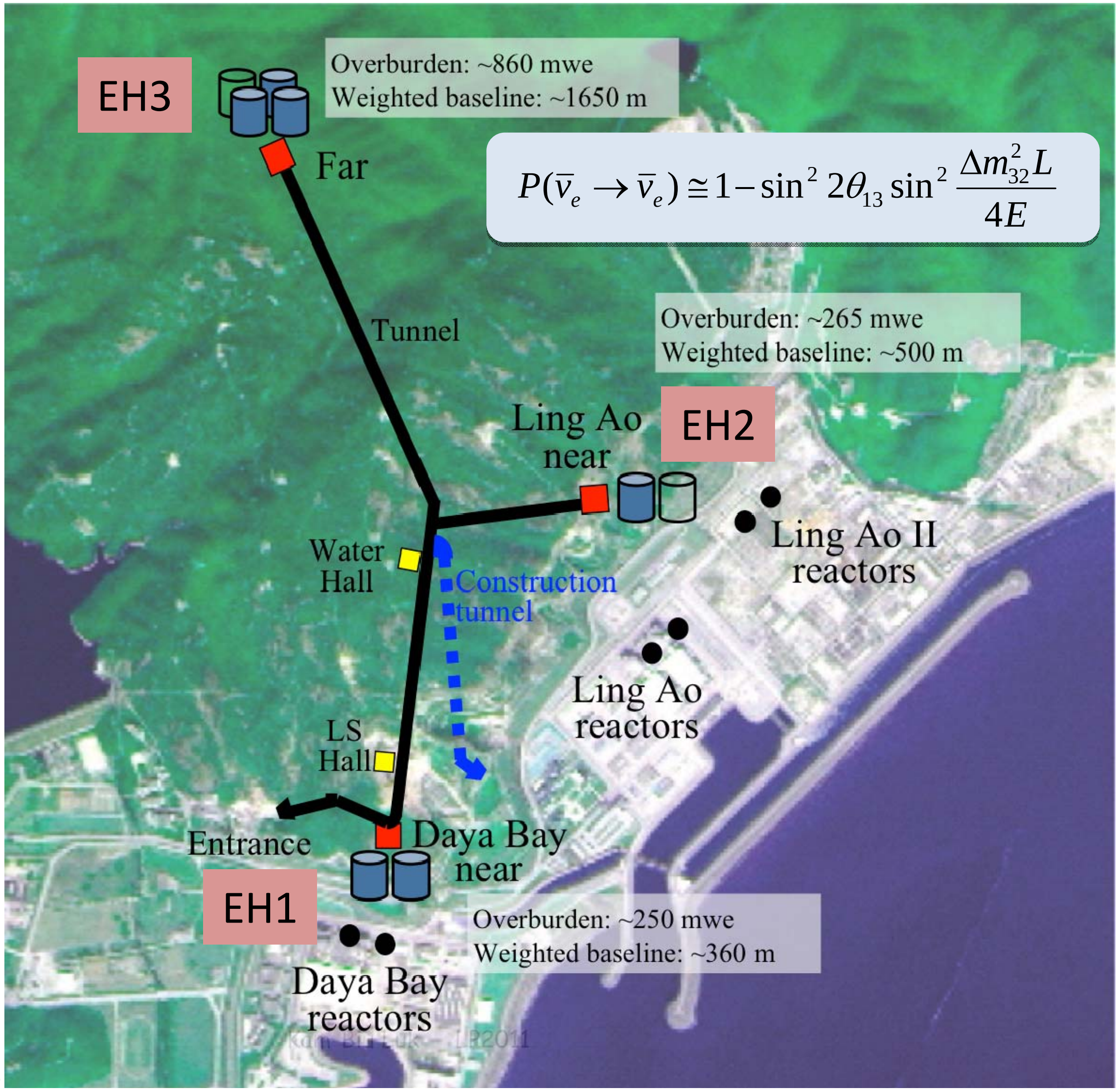
$$P_{\nu_\mu\to\nu_e}=\sin^2 2\theta_{13}\sin^2\theta_{23}\sin^2\left(\Delta m^2_{31}L/4E\right)$$
$$+\ (\text{CPV term}) + (\text{matter term})$$
$$+\ \cdots\cdots$$



Daya Bay Experiment Layout

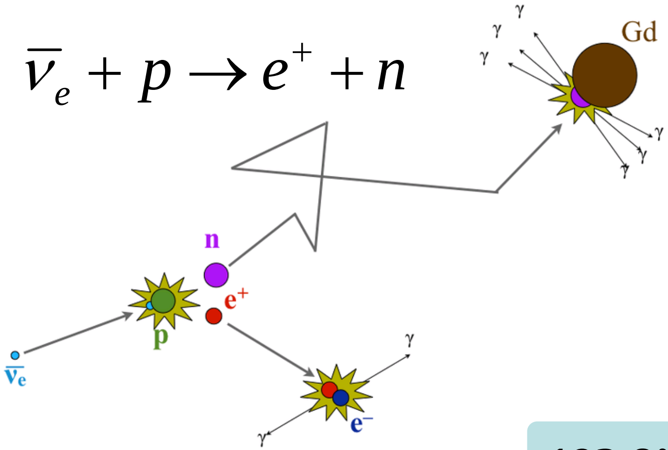
- **Keys to precise measurement:**
  - **(stat.) Powerful reactors (17.6GW) + Large target mass (80t).**
  - **(syst.) Reactor related: near/far measurement at optimized baselines.**
  - **(syst.) Detector related: eight functional "identical" detectors for near/far measurement**
  - **(syst.) Background related: large overburden to reduce muon + active/passive shielding**

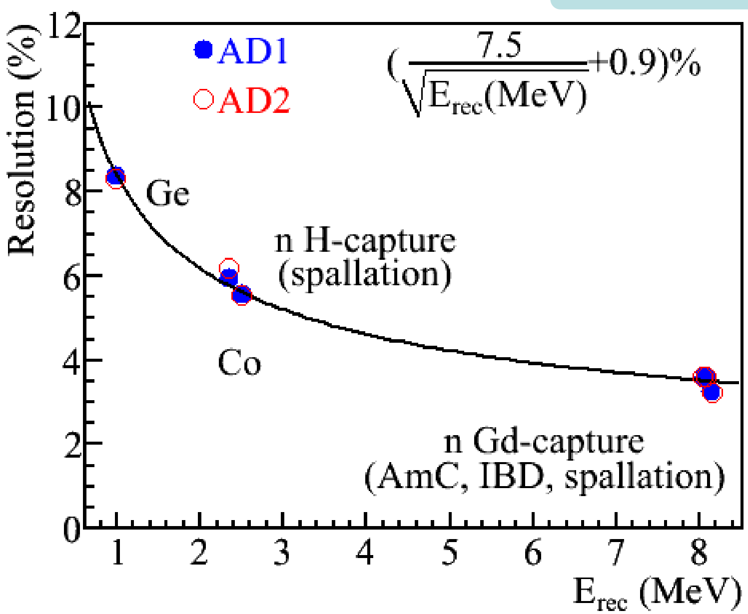


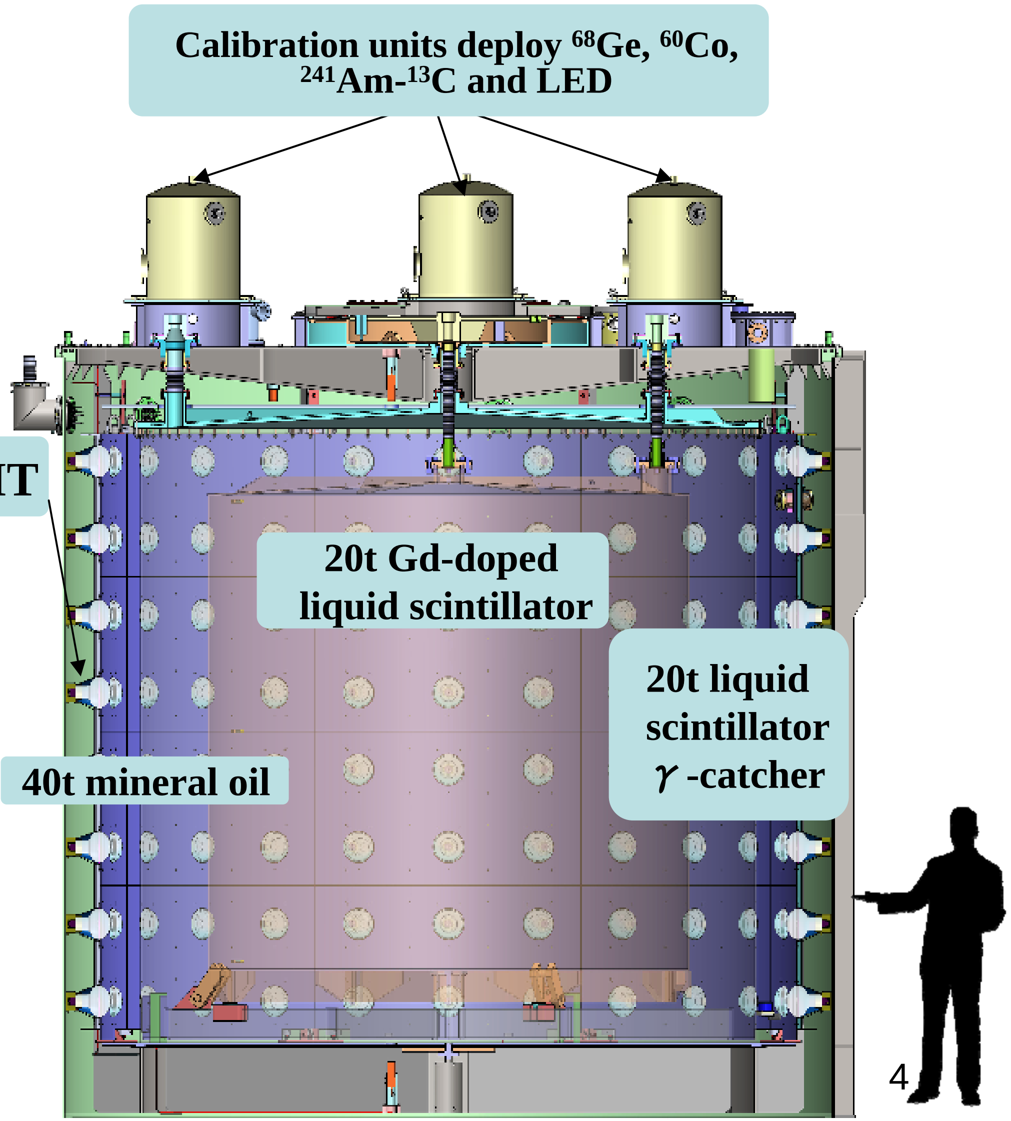


Anti-Neutrino Detector

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



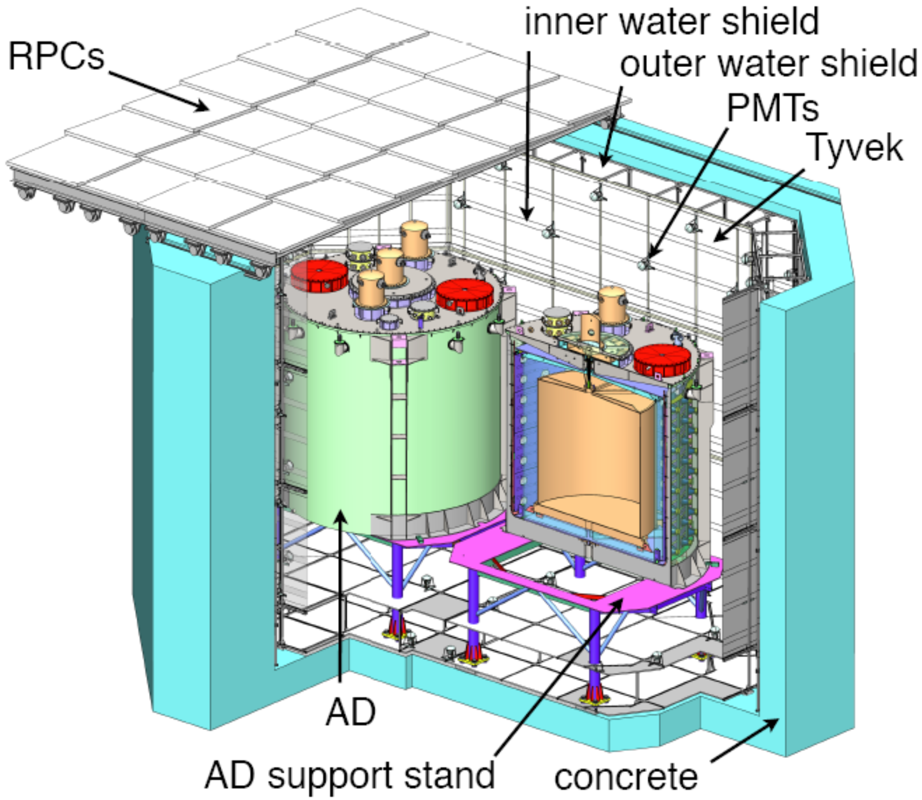




Muon Veto Detector

- **Water pool**
  - **Two layers separated by Tyvek.**
  - **Fill with purified water**
  - **Hundreds PMTs to collect Cherenkov lights from cosmic muon**
- **RPC**
  - **Four layers**

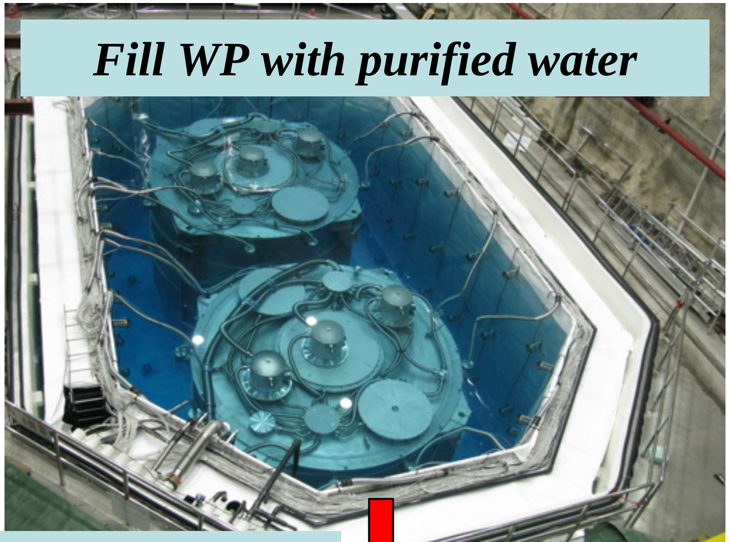
Multi detectors for efficiency crosscheck.



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

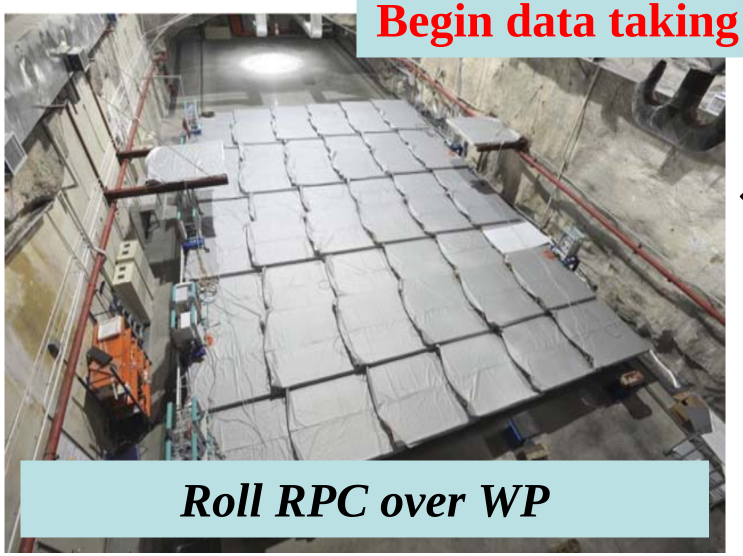
Daya Bay Near Hall (EH1)

Install filled AD to water pool



Fill WP with purified water

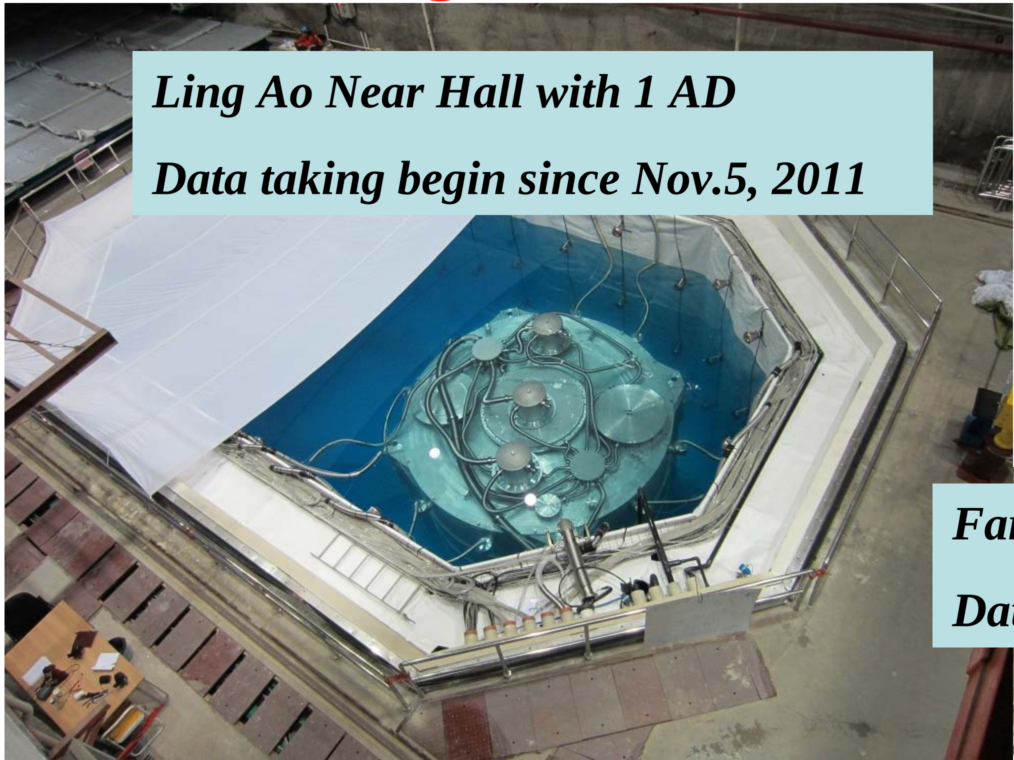
Begin data taking since Aug.15, 2011.



Roll RPC over WP

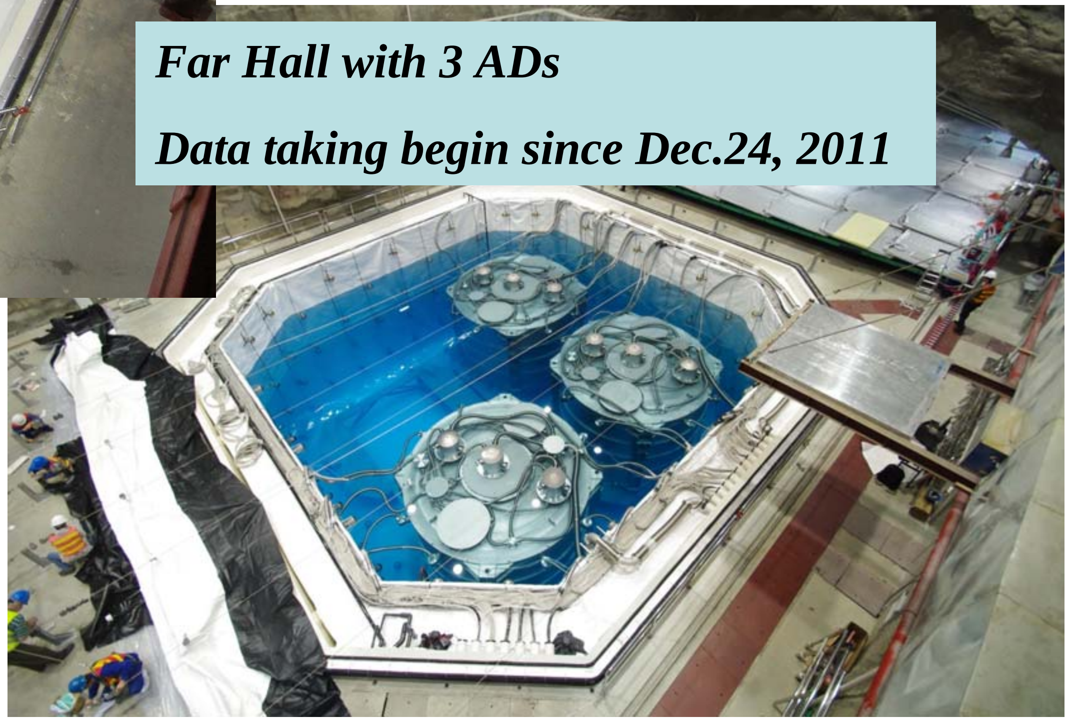
Cover the water pool

Ling Ao Near Hall & Far Hall



Ling Ao Near Hall with 1 AD

Data taking begin since Nov.5, 2011



Far Hall with 3 ADs

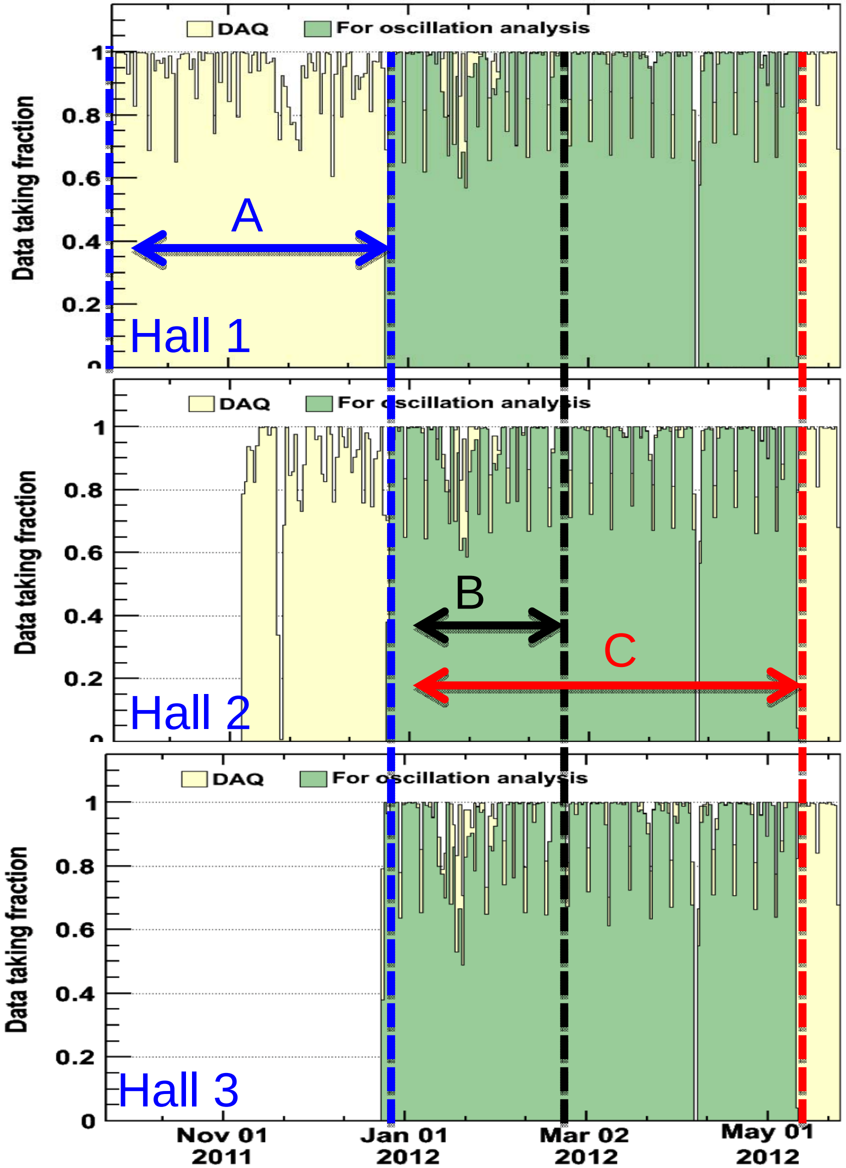
Data taking begin since Dec.24, 2011

Data Period

- **A : Two Detector Comparison: Sep. 23, 2011 – Dec. 23, 2011**
  Nucl. Inst. and Meth. A 685 (2012), pp. 78-97

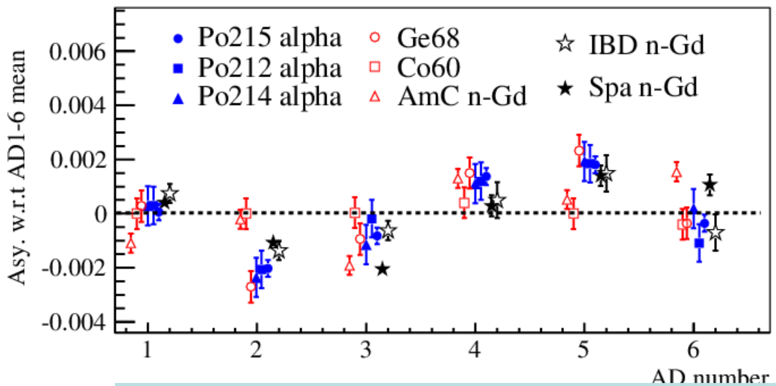
- **B: First Oscillation Result: Dec. 24, 2011 – Feb. 17, 2012**
  Phys. Rev. Lett. 108, 171803 (2012)

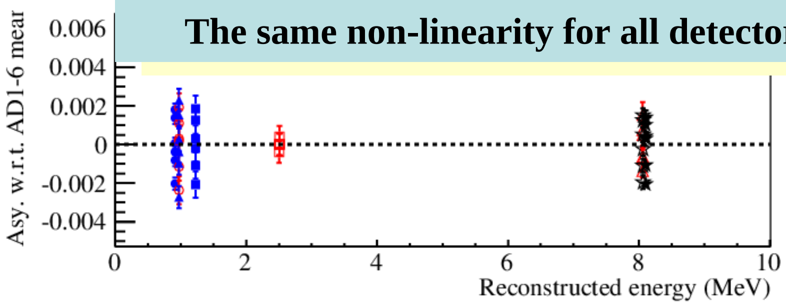
- **C: Updated oscillation analysis: Dec. 24, 2011 – May 11, 2012**
  Chinese Phys. C 37, (2013) 011001
  - **Data volume: 40TB**
  - **DAQ eff. ~ 96%**
  - **Eff. for physics: ~ 94%**



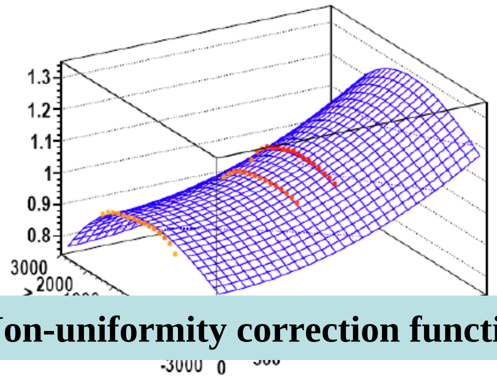
Calibration & reconstruction

- **Low intensity LED for PMT gain.**
- **^{60}Co at detector center for energy scale.**
- **^{60}Co at different positions to correct spatial dependence (non-uniformity).**
- **Calibrate energy scale using neutron capture peak.**

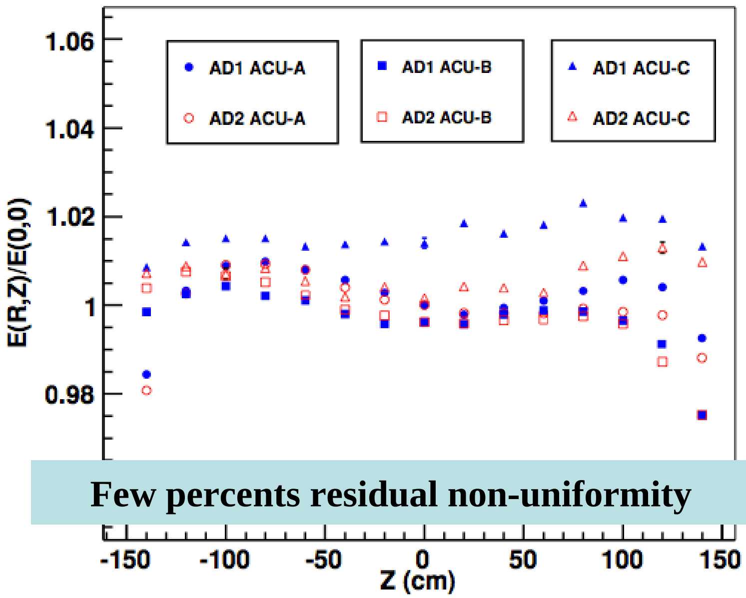




The same non-linearity for all detectors



Non-uniformity correction function



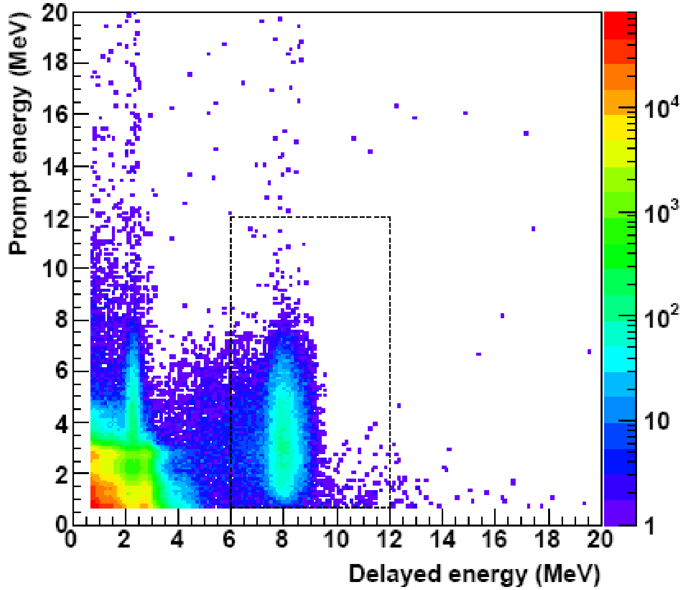
Few percents residual non-uniformity

0.5% relative energy scale uncertainty:

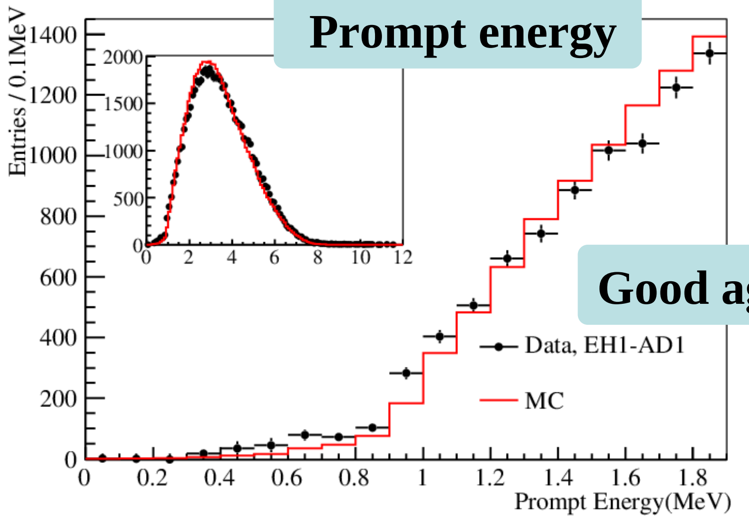
0.12% efficiency uncertainty among detectors

Anti-neutrino selection

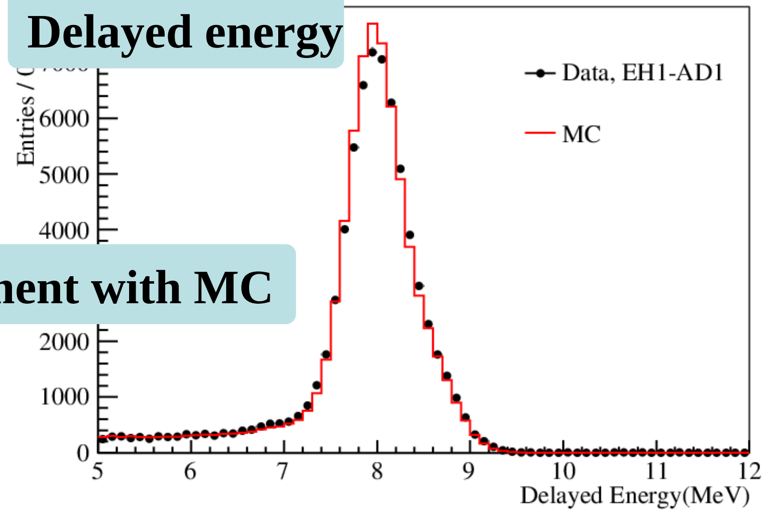
- **Anti-neutrino event selection**
  - – **0.7 MeV < E_p < 12.0 MeV**
  - – **6.0 MeV < E_d < 12.0 MeV**
  - – **1 μs < Δ$t_{p\text{-}d}$ < 200 μs**
  - – **Muon Veto: 0.6 ms after a Pool muon (reject fast neutron), 1 ms after an AD muon (reject double neutron), 1 s after an AD shower muon (reject $^{9}Li/^{8}He$)**
  - – **Multiplicity cut: No other >0.7 MeV trigger in (t_p-200 μs , t_d+200 μs)**



Prompt energy



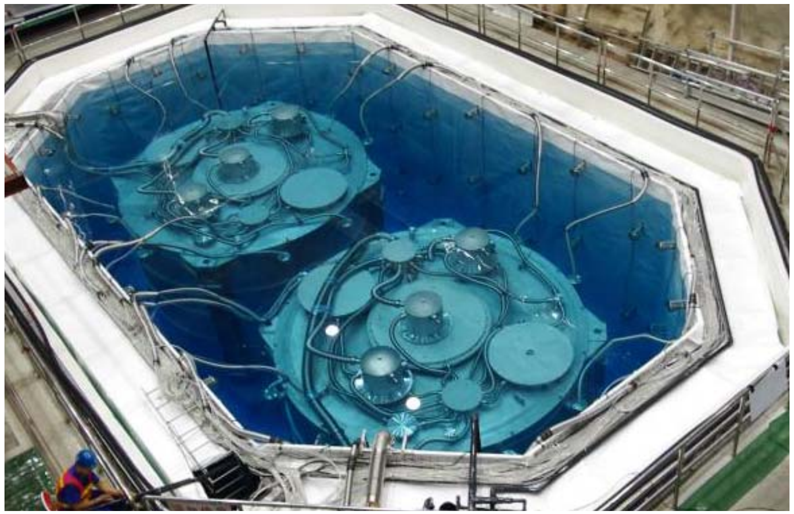
Delayed energy

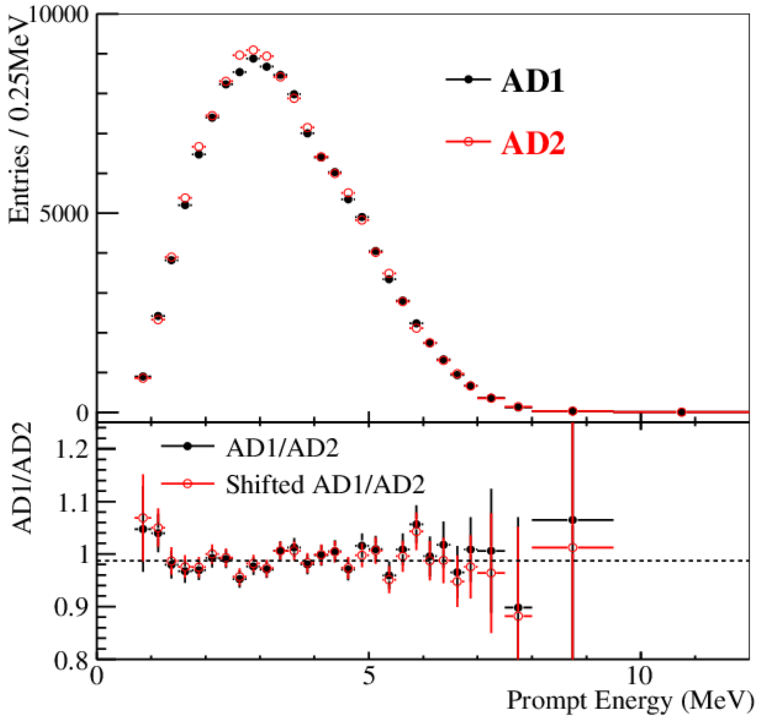


Good agreement with MC

Side by side comparison

- **Multi detectors in one site**
  - **Compare detector response, signals, backgrounds**
  - **Systematics well under control**
- **Expected neutrino ratio: R(AD1/AD2) = 0.982**
  - **Not one due to a little different baselines, target masses.**
- **Measured ratio: R(AD1/AD2) = 0.987 ± 0.004(stat) ± 0.003(syst)**

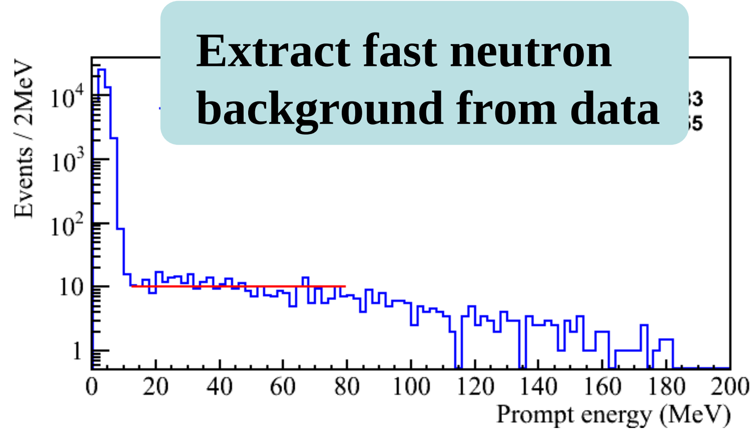


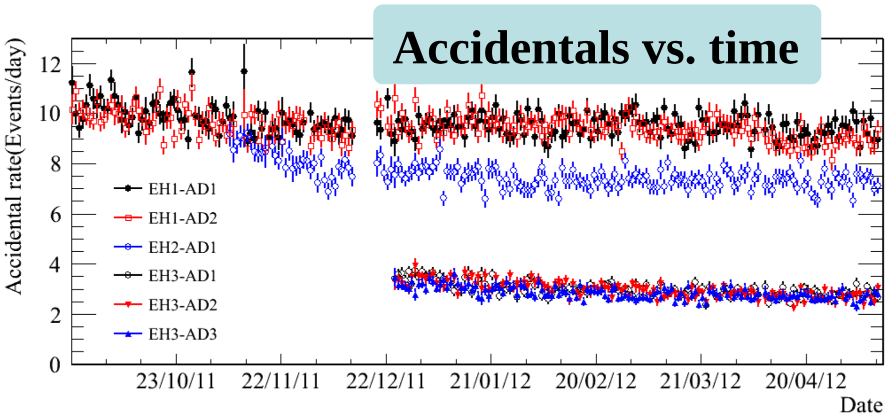


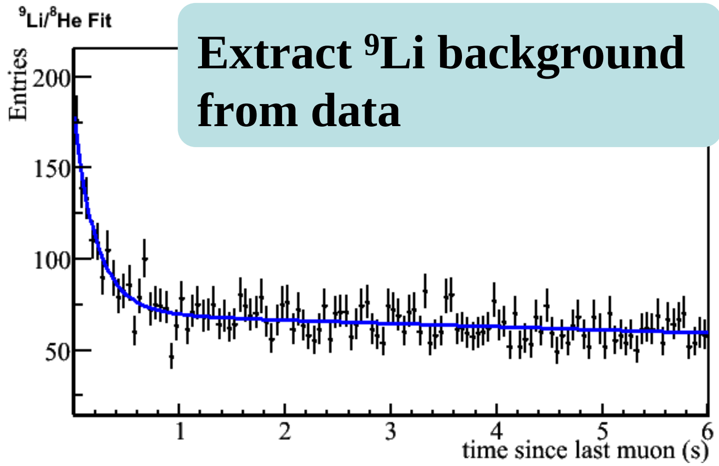
Nucl. Inst. and Meth. A 685 (2012), pp. 78-97

Backgrounds

- **Uncorrelated background**
  - **Accidentals: two uncorrelated events pass selection and mimic neutrino event.**
- **Correlated background**
  - **Muon spallation**
    - **$^{9}Li/^{8}He$**
    - **Fast neutrons**
  - **From ^{241}Am-^{13}C calibration source**
  - **$^{13}C(\alpha,n)^{16}O$**







Backgrounds

	Near Halls		Far Hall		
	B/S %	$\sigma_{B/S}$ %	B/S %	$\sigma_{B/S}$ %	ΔB/B
Accidentals	1.5	0.02	4.0	0.05	~1%
Fast neutrons	0.12	0.05	0.07	0.03	~40%
^{9}Li/^{8}He	0.4	0.2	0.3	0.2	~50%
^{241}Am-^{13}C	0.03	0.03	0.3	0.3	~100%
^{13}C(α, n)^{16}O	0.01	0.006	0.05	0.03	~50%
Sum	2.1	0.21	4.7	0.37	~10%

- **Total backgrounds are 5% (2%) at far (near) halls.**
- **Background uncertainties are 0.4% (0.2%) at far (near) halls.**

Systematics

Detector			
	Efficiency	Correlated	Uncorrelated
Target Protons		0.47%	0.03%
Flasher cut	99.98%	0.01%	0.01%
Delayed energy cut	90.9%	0.6%	0.12%
Prompt energy cut	99.88%	0.10%	0.01%
Multiplicity cut		0.02%	<0.01%
Capture time cut	98.6%	0.12%	0.01%
Gd capture ratio	83.8%	0.8%	<0.1%
Spill-in	105.0%	1.5%	0.02%
Livetime	100.0%	0.002%	<0.01%
Combined	78.8%	1.9%	0.2%

Reactor			
Correlated		Uncorrelated	
Energy/fission	0.2%	Power	0.5%
$\overline{\nu}_e$/fission	3%	Fission fraction	0.6%
		Spent fuel	0.3%
Combined	3%	Combined	0.8%

Correlated uncertainty fully canceled in near/far measurement

Efficiencies & uncertainties

Detector			
	Efficiency	Correlated	Uncorrelated
Target Protons		0.47%	0.03%
Flasher cut	99.98%	0.01%	0.01%
Delayed energy cut	90.9%	0.6%	0.12%
Prompt energy cut	99.88%	0.10%	0.01%
Multiplicity cut		0.02%	$<$0.01%
Capture time cut	98.6%	0.12%	0.01%
Gd capture ratio	83.8%	0.8%	$<$0.1%
Spill-in	105.0%	1.5%	0.02%
Livetime	100.0%	0.002%	$<$0.01%
Combined	78.8%	1.9%	0.2%

Reactor			
Correlated		Uncorrelated	
Energy/fission	0.2%	Power	0.5%
$\overline{\nu}_e$/fission	3%	Fission fraction	0.6%
		Spent fuel	0.3%
Combined	3%	Combined	0.8%

Correlated uncertainty fully canceled in near/far measurement

Detector uncorrelated uncertainty:

Designed value:
Baseline: 0.38%
Goal: 0.18%

Efficiencies & uncertainties

Detector			
	Efficiency	Correlated	Uncorrelated
Target Protons		0.47%	0.03%
Flasher cut	99.98%	0.01%	0.01%
Delayed energy cut	90.9%	0.6%	0.12%
Prompt energy cut	99.88%	0.10%	0.01%
Multiplicity cut		0.02%	<0.01%
Capture time cut	98.6%	0.12%	0.01%
Gd capture ratio	83.8%	0.8%	<0.1%
Spill-in	105.0%	1.5%	0.02%
Livetime	100.0%	0.002%	<0.01%
Combined	78.8%	1.9%	0.2%

Reactor			
Correlated		Uncorrelated	
Energy/fission	0.2%	Power	0.5%
$\overline{\nu}_e$/fission	3%	Fission fraction	0.6%
		Spent fuel	0.3%
Combined	3%	Combined	0.8%

Correlated uncertainty fully canceled in near/far measurement

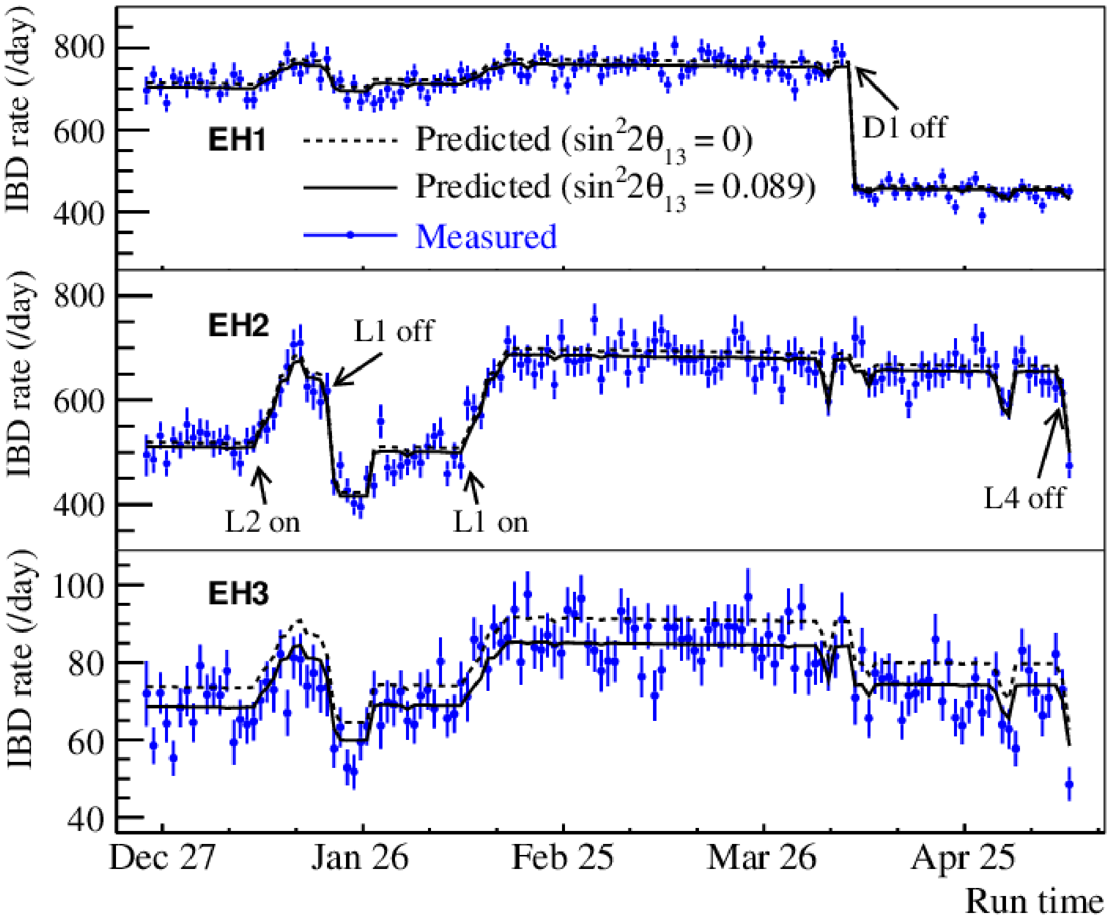
Detector uncorrelated uncertainty:

Designed value:
Baseline: 0.38%
Goal: 0.18%

Reactor uncorrelated uncertainty:

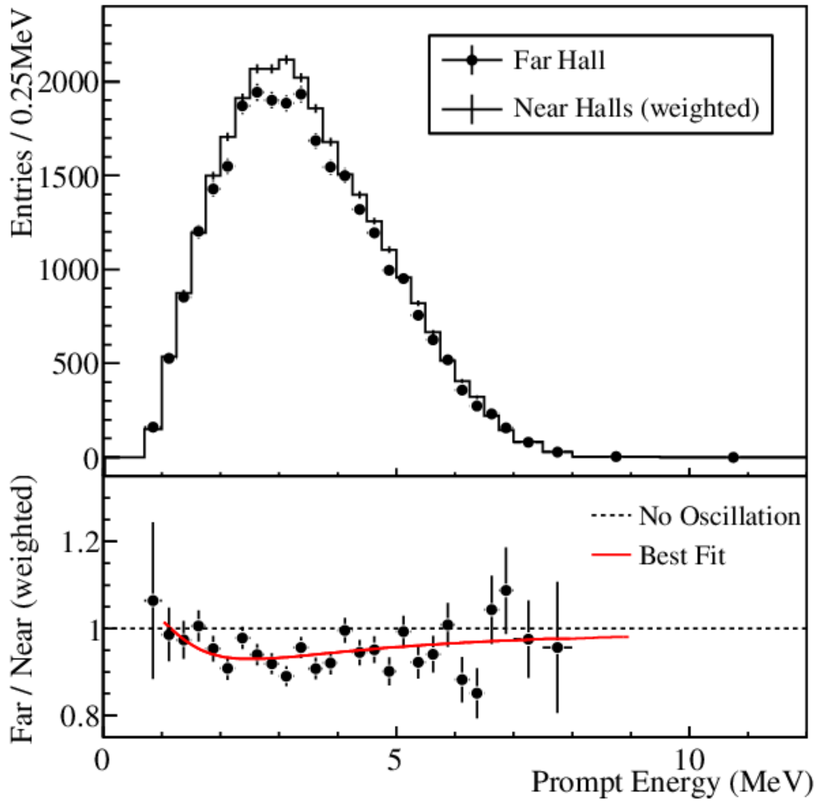
Reduced by a 1/20 factor in the near/far measurement

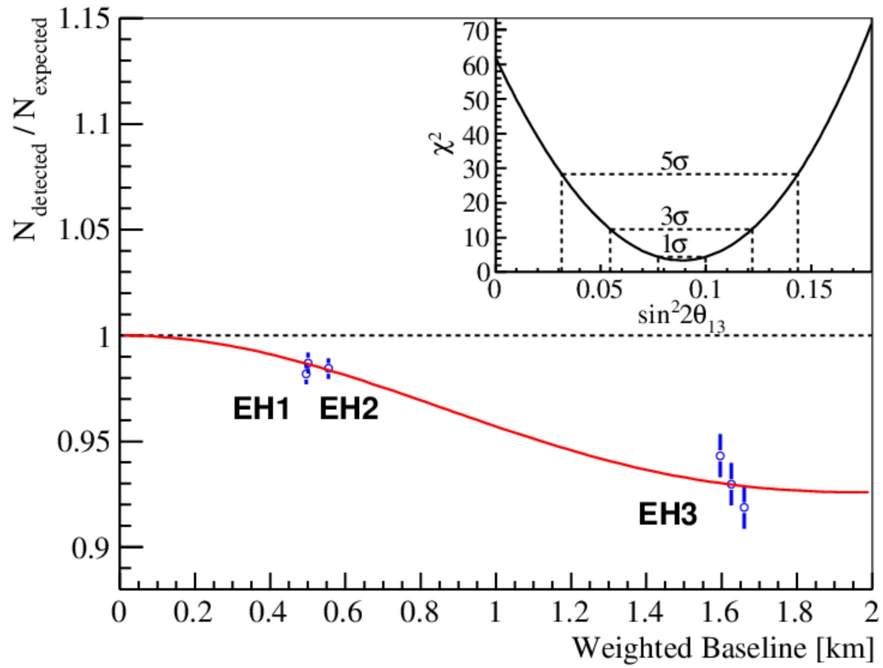
Anti-neutrino rate vs. time



- **Detected neutrino rates strongly correlated with reactor flux expectations.**
- **Predicted rate**
  - **Normalization is determined by fit to near/far data.**
  - **Absolute normalization is within a few percent of expectations.**

Anti-neutrino disappearance





R = 0.944 ± 0.007 (stat) ± 0.003 (syst)

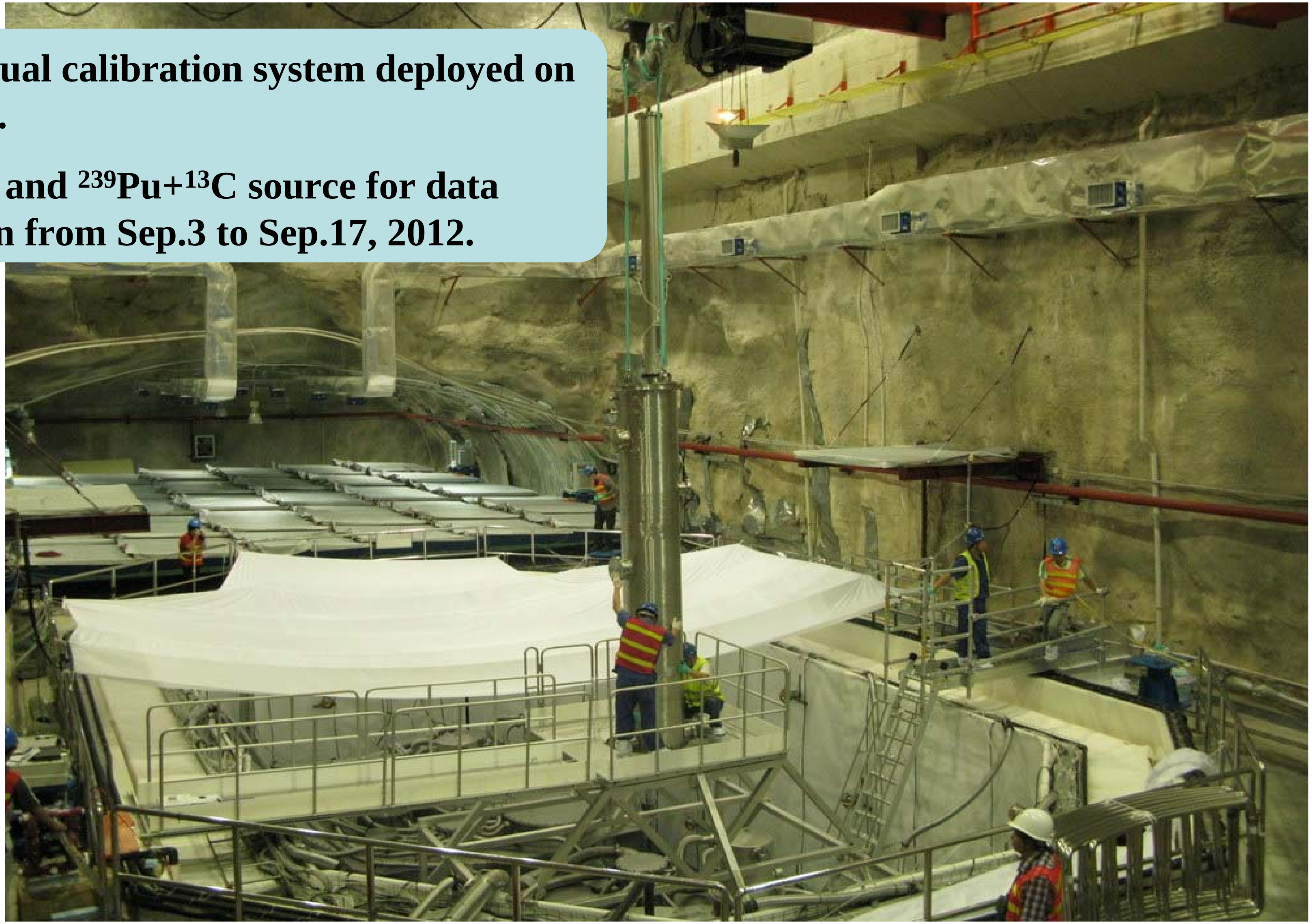
$\sin^2 2\theta_{13} = 0.089 \pm 0.010(stat) \pm 0.005(syst)$

A clear observation of far site deficit with 139 days data.
Spectral distortion consistent with oscillation.

Recent progress

Manual calibration system deployed on AD1.

^{60}Co and ^{239}Pu+^{13}C source for data taken from Sep.3 to Sep.17, 2012.



Recent progress

Last two AD installed.

Eight AD data taking have started since Oct, 2012

Summary

- Unambiguous observation of reactor electron anti-neutrino disappearance at ~2km baseline:

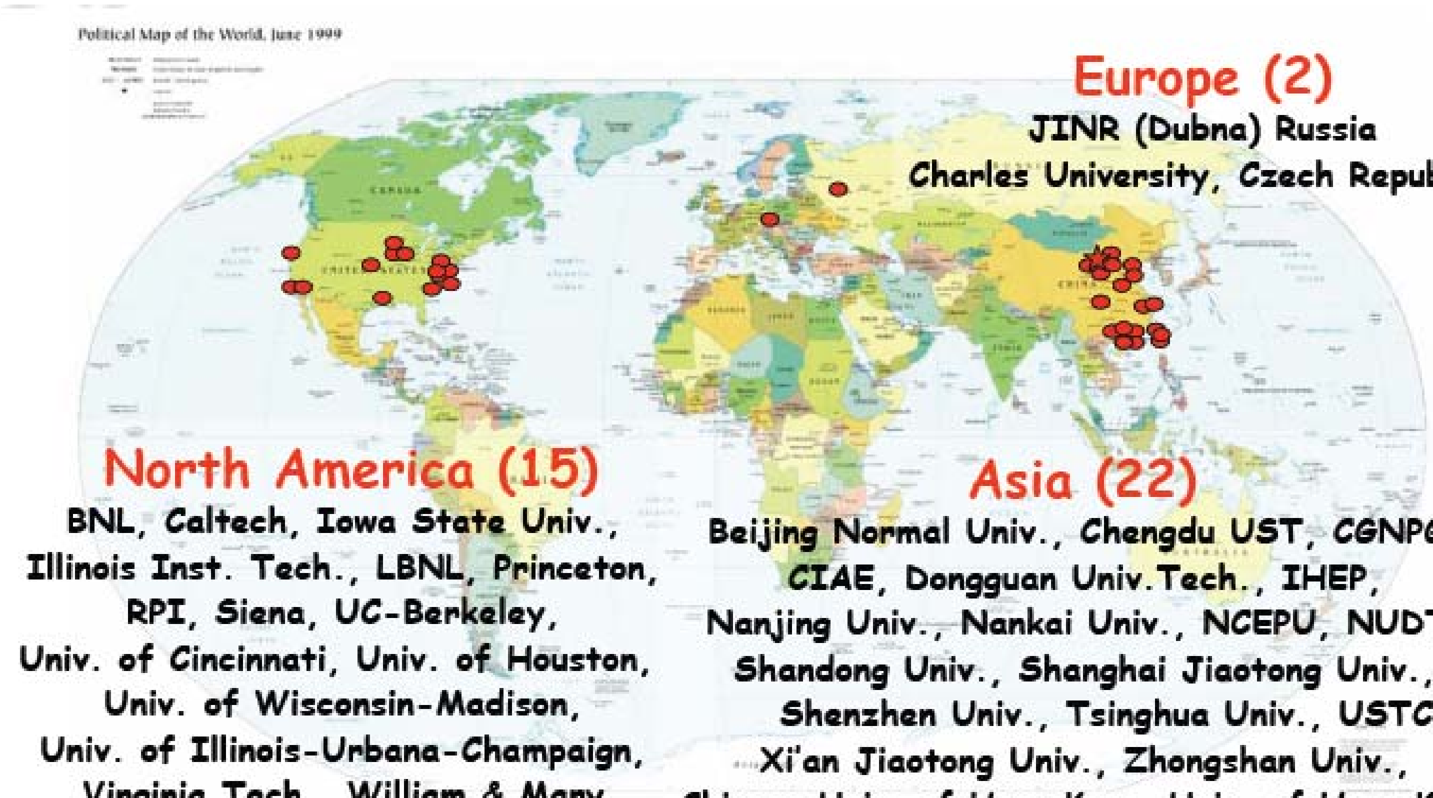
$R = 0.944 \pm 0.007\,(\text{stat}) \pm 0.003\,(\text{syst})$

- Interpreting the disappearance as neutrino oscillation yields the most precise measurement of θ_{13}

$\sin^2 2\theta_{13} = 0.089 \pm 0.010(\text{stat}) \pm 0.005(\text{syst})$

- Data taking with all eight detectors have began since Oct.19, 2012.
- Daya Bay will continue to provide the most precise measurement of θ_{13} over the world.
- Shape analysis results will come soon.
- More physics expected: reactor flux and spectrum, etc.

The Daya Bay Collaboration



Europe (2)

JINR (Dubna) Russia
Charles University, Czech Republic

North America (15)

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

Asia (22)

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

~230 Collaborators