Recent Results From The Daya Bay Experiment

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On behalf of the Daya Bay Collaboration

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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

Neutrino Mixing

Neutrino **flavour eigenstates** ≠ **Mass eigenstates**

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$\mathbf{U_{PMNS}}$ is a 3×3 unitary matrix described by three mixing angles θ_{23}, θ_{13}, θ_{12}, and CP phase δ + 2 Majorana phases.

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

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

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

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

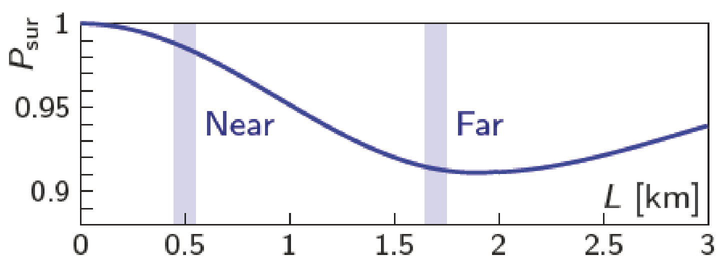
The Daya Bay Experiment is a well designed short baseline reactor neutrino experiment to precisely determine θ_{13}.

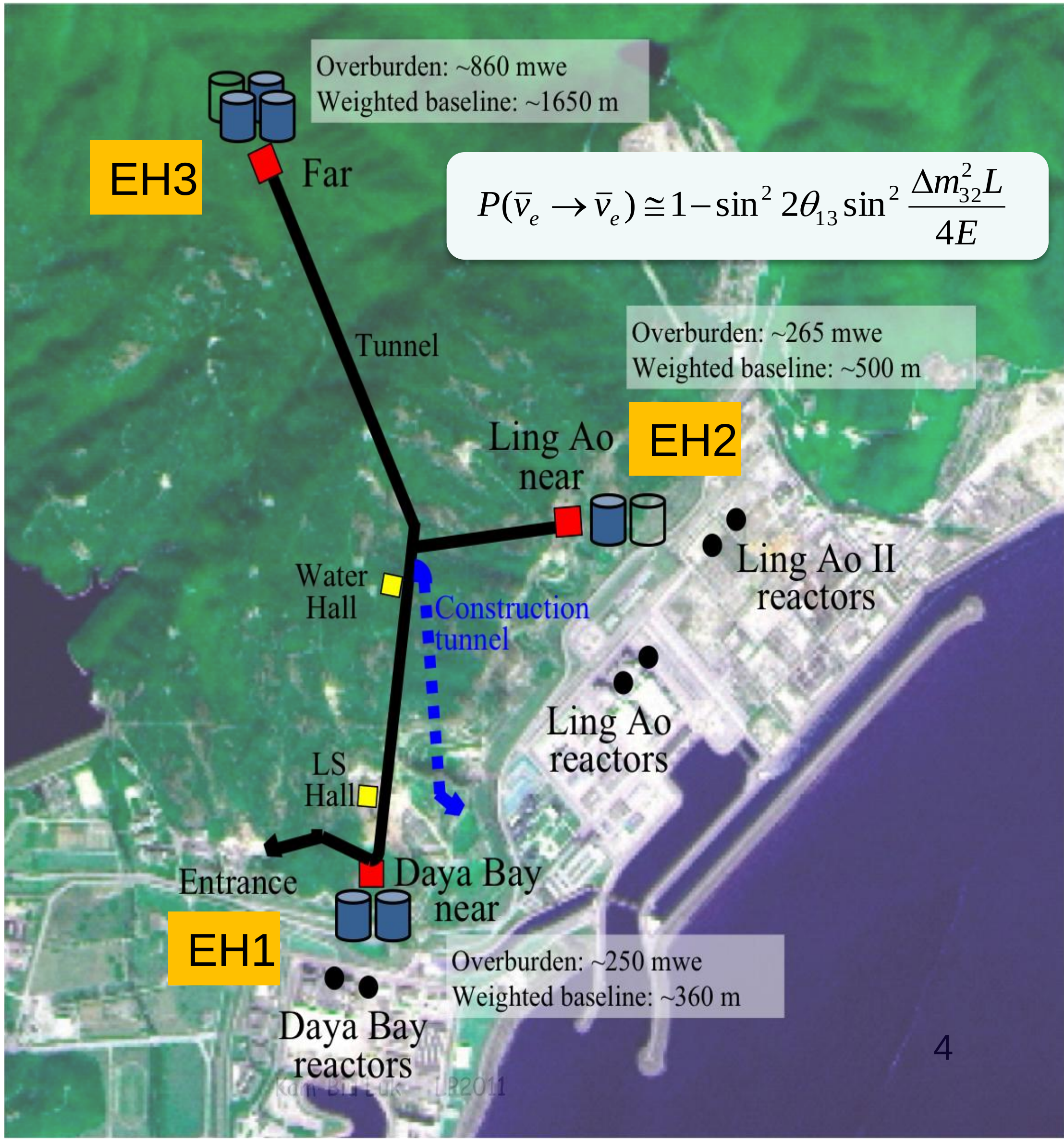
Daya Bay Experiment Layout

- 6 reactor cores, 17.6GW$_{th}$ total power
- Relative measurement
  - 2 near sites, 1 far site
- Multiple detector modules
- Good cosmic ray shielding

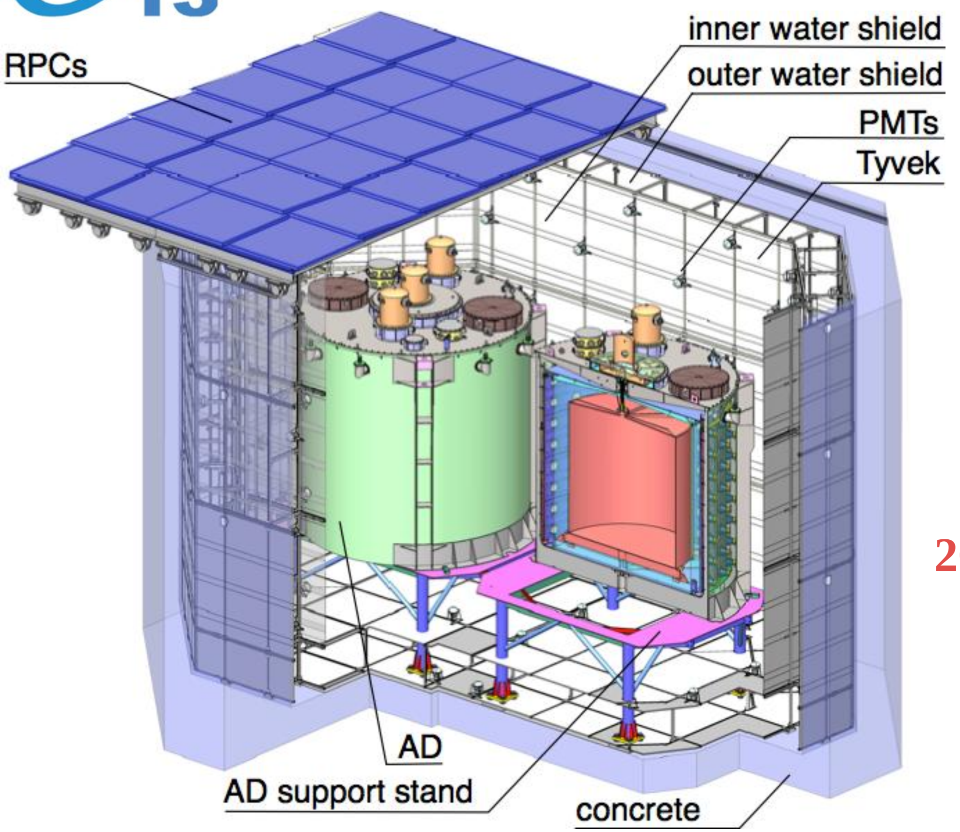
TABLE I. Vertical overburden (m.w.e.), muon rate R_μ (Hz/m^2), and average muon energy E_μ (GeV) of the three EHs, and the distances (m) to the reactor pairs.

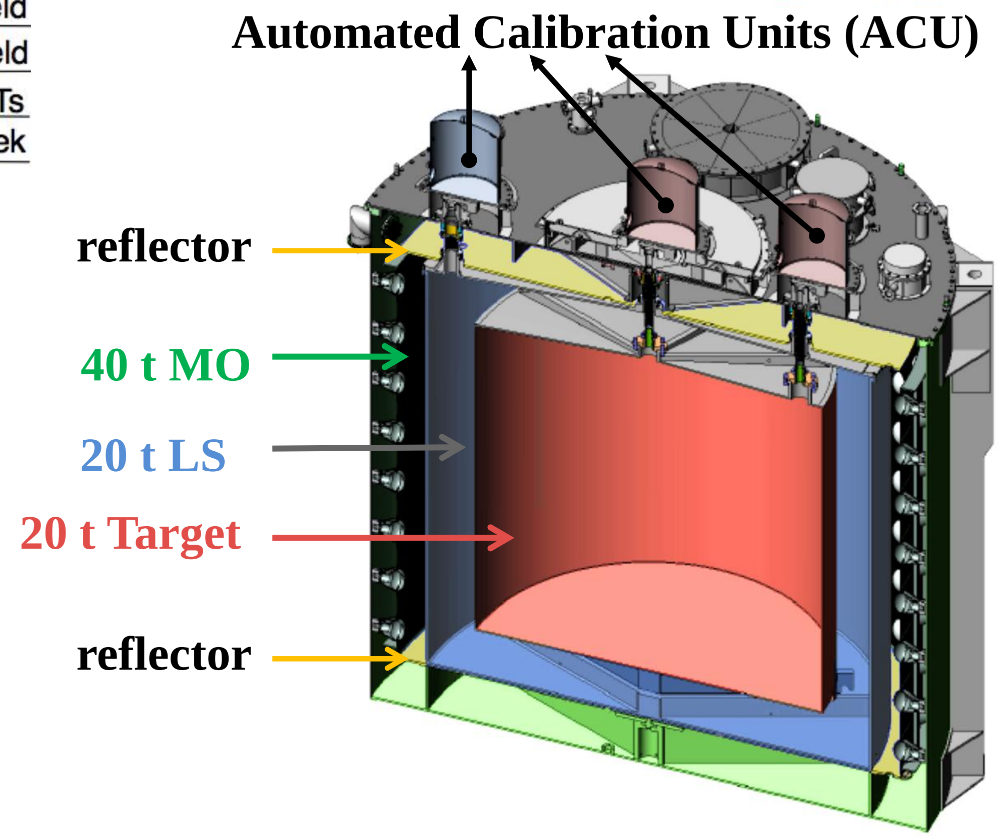
	Overburden	R_μ	E_μ	D1,2	L1,2	L3,4
EH1	250	1.27	57	364	857	1307
EH2	265	0.95	58	1348	480	528
EH3	860	0.056	137	1912	1540	1548





The Daya Bay Detectors



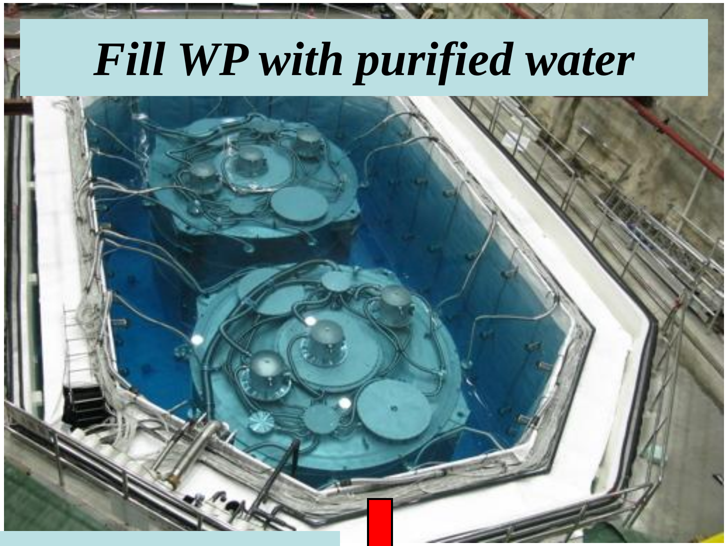


- Multiple Anti-neutrino Detector (AD) modules to check Uncorr. Syst. Err.
  - Far: 4 modules， near: 2 modules

- Multiple muon detectors to reduce veto eff. uncertainties
  - Water Cherenkov： 2 layers, efficiency > 97%
  - RPC： 4 layers at the top + telescopes, efficiency > 88%

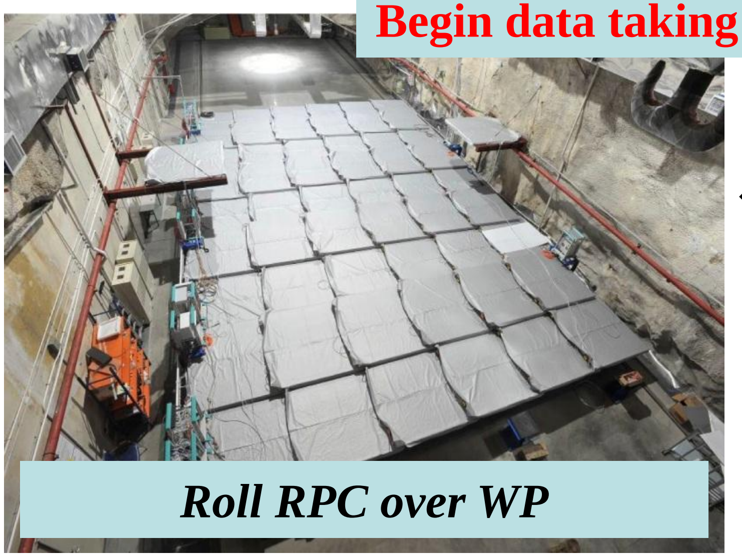
Daya Bay Near Hall (EH1)

Install filled AD to water pool



Fill WP with purified water

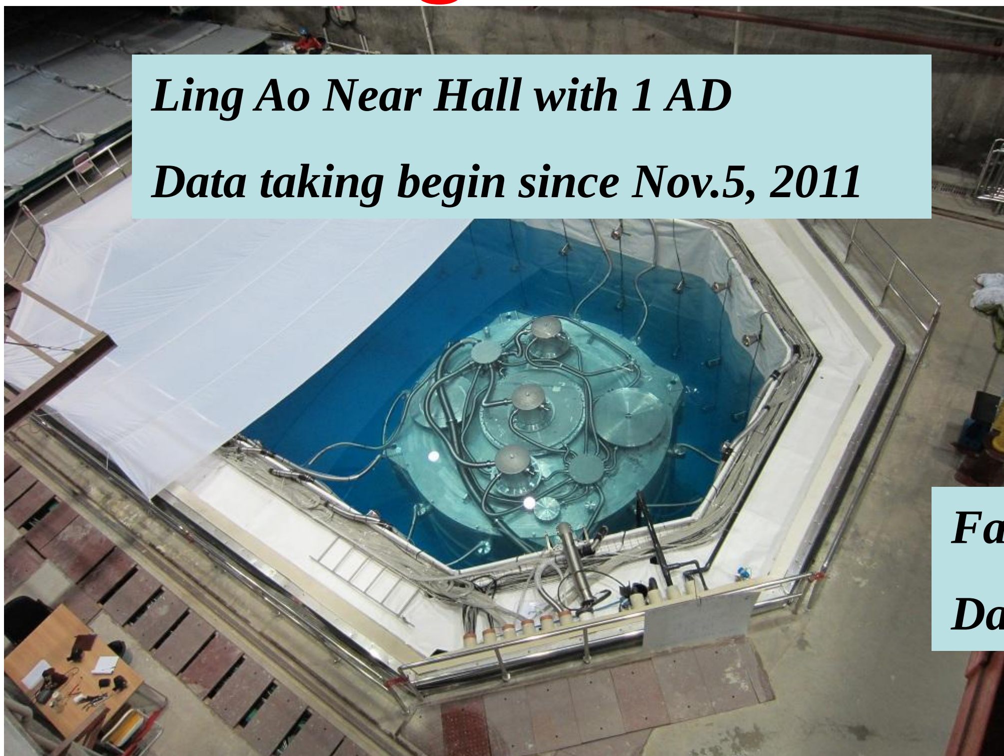
Begin data taking since Aug.15, 2011.

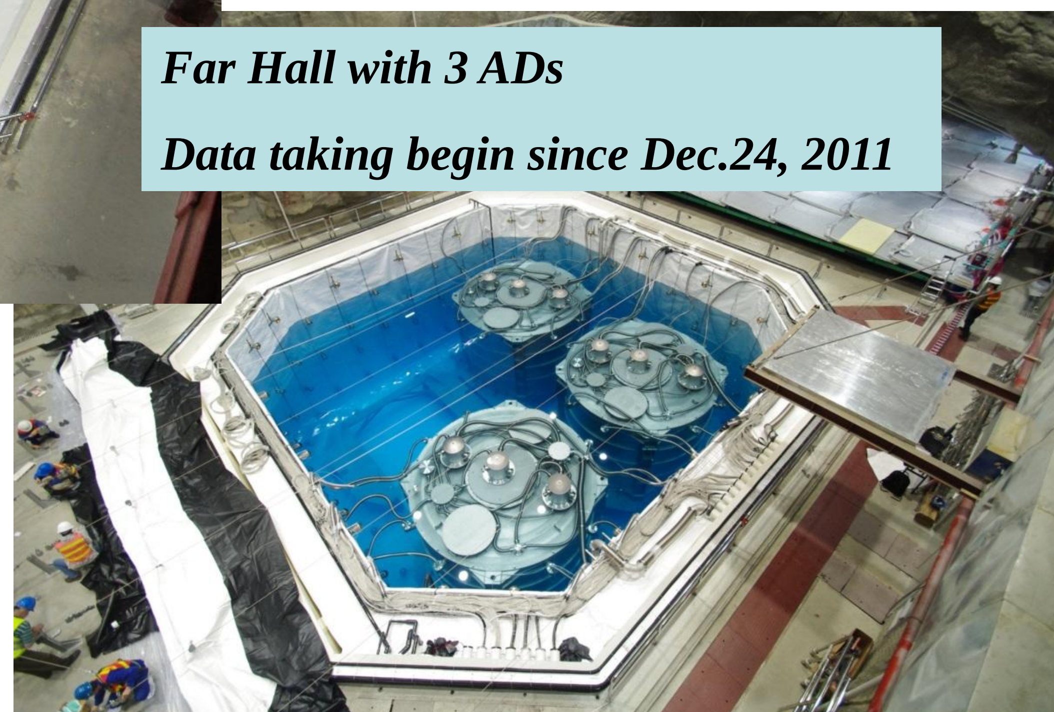


Roll RPC over WP

Cover the water pool

Ling Ao Near Hall & Far Hall





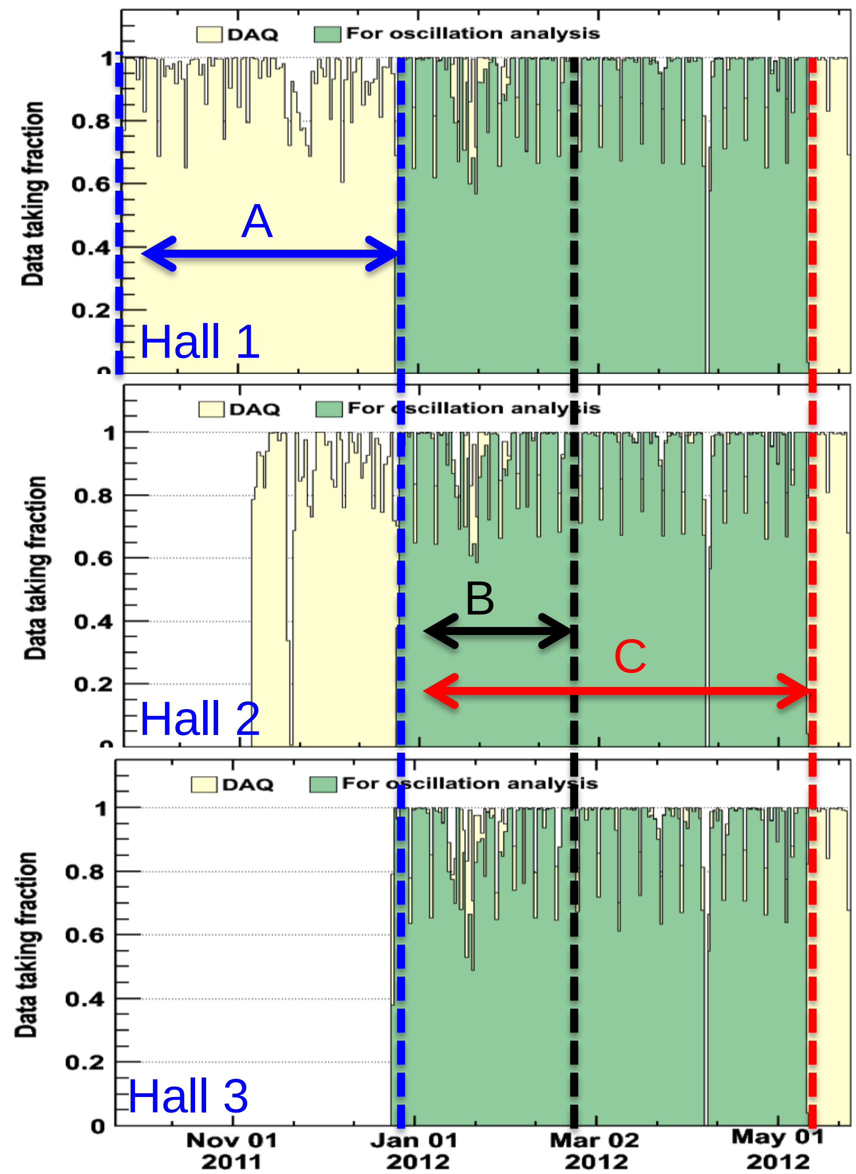
Data Period

- **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)

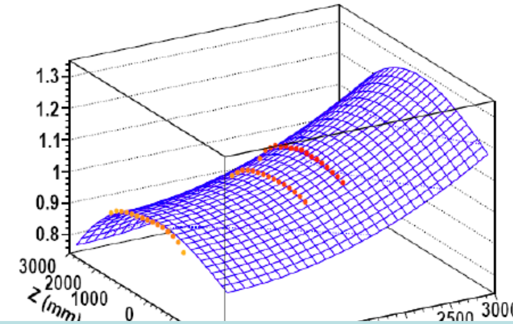
- **C: Updated oscillation analysis: Dec. 24, 2011 – May 11, 2012**
  Chinese Phys. C 37, (2013) 011001

  - **Data volume: 40TB**
  - **DAQ eff. ~ 96%**
  - **Eff. for physics: ~ 94%**

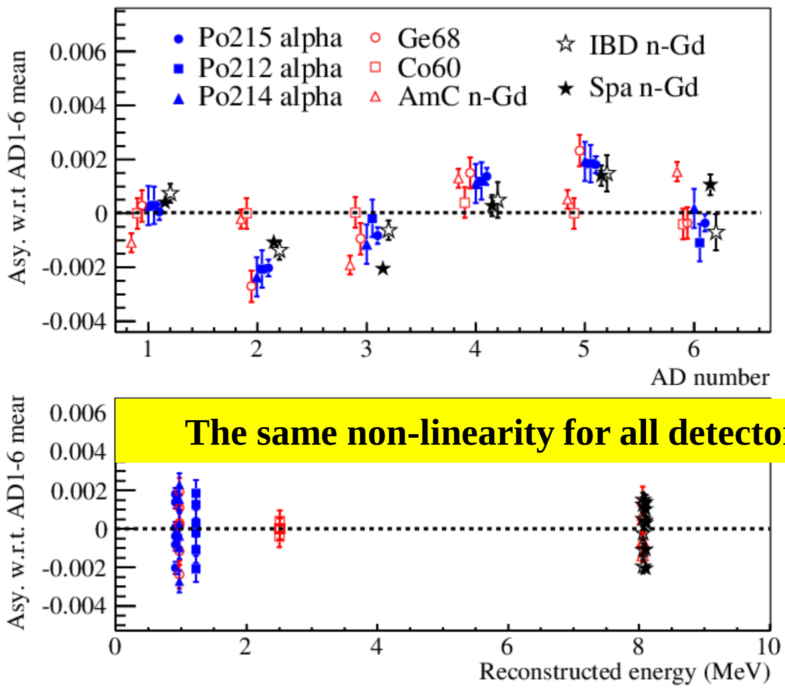


Calibration & reconstruction

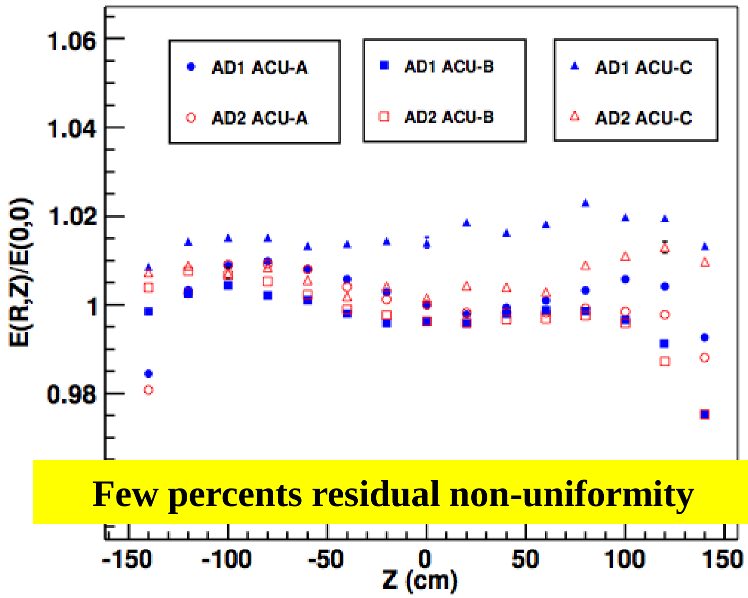
- Low intensity LED for PMT gain.
- ^{60}Co at detector center for energy scale.
- ^{60}Co at different positions to correct spatial dependence (non-uniformity).
- Calibrate energy scale using neutron capture peak.



Non-uniformity correction function



The same non-linearity for all detectors



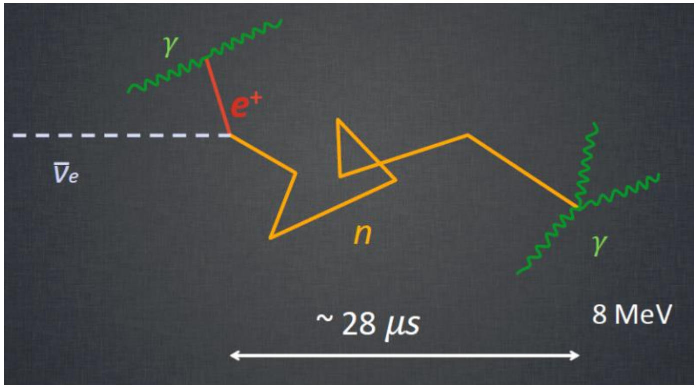
Few percents residual non-uniformity

0.5% relative energy scale uncertainty:

0.12% efficiency uncertainty among detectors

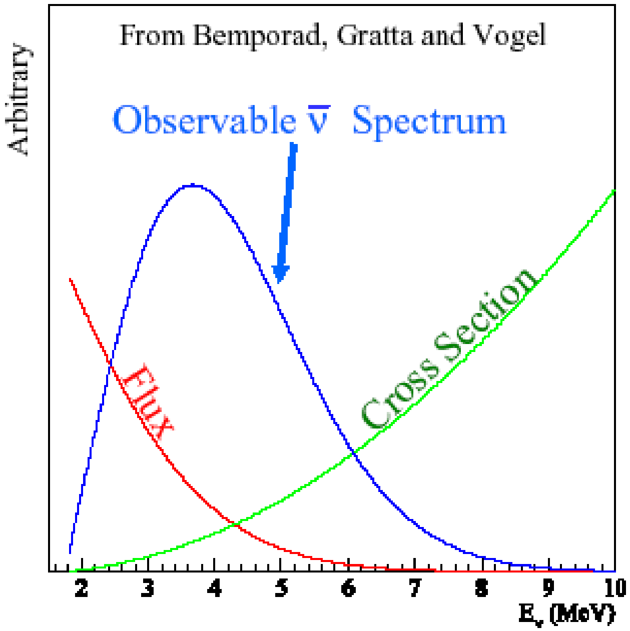
Neutrino Event Signature in Gd-LS

Signature: $\bar{\nu}_e + p \rightarrow e^+ + n$ (IBD)



- **Prompt: e+, E: 1-10 MeV**
- **Delayed: n, E: 2.2 MeV@H, 8 MeV @ Gd**
- **Capture time: 28 μs in 0.1% Gd-LS**

Neutrino Event: coincidence in time, space and energy

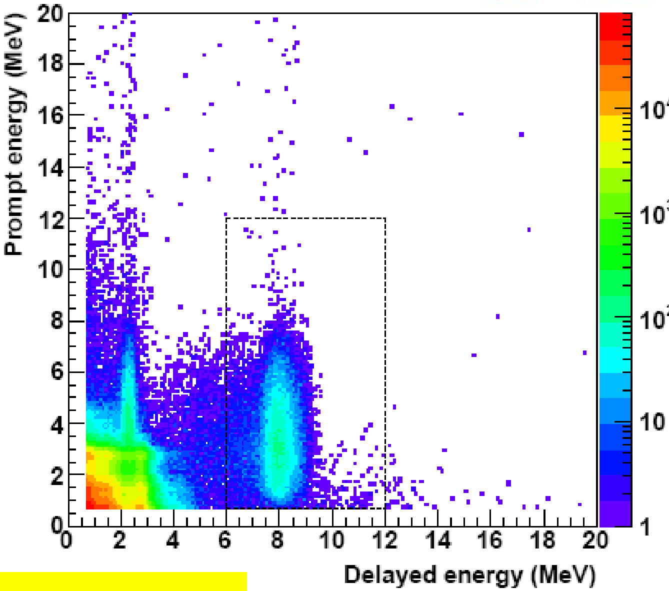


Neutrino energy:

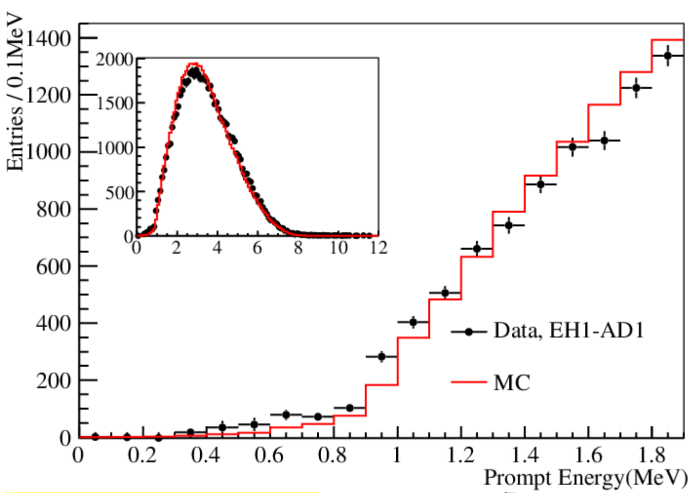
$$E_{\bar{\nu}} \cong T_{e^+} + \underbrace{T_n}_{\text{10-40 keV}} + \underbrace{(M_n - M_p) + m_{e^+}}_{\text{1.8 MeV: Threshold}}$$

Anti-neutrino Events Selection

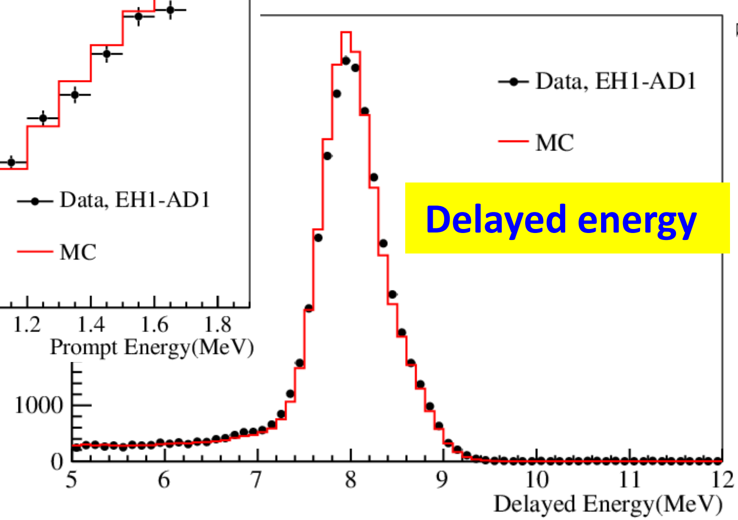
- **Anti-neutrino event selection**
  - **0.7 MeV < E_p < 12.0 MeV**
  - **6.0 MeV < E_d < 12.0 MeV**
  - **1 μs < $\Delta t_{p\text{-}d}$ < 200 μs**
  - **Muon Veto: 0.6 ms after a Pool muon (reject fast neutron), 1 ms after an AD muon (reject double neutron), 1 s after an AD shower muon (reject $^{9}Li/^{8}He$)**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



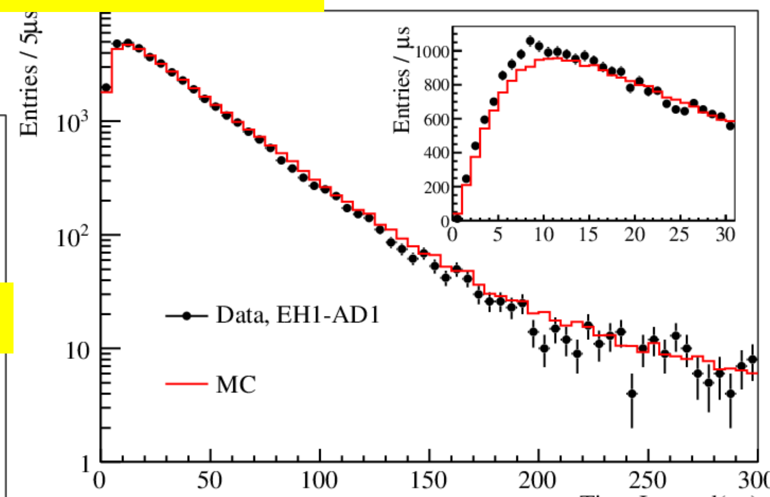
Good Agreement with MC



Prompt energy



Delayed energy

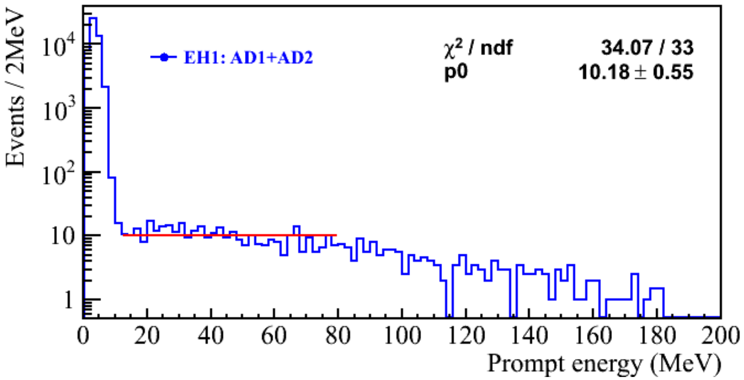


Time between prompt-delayed

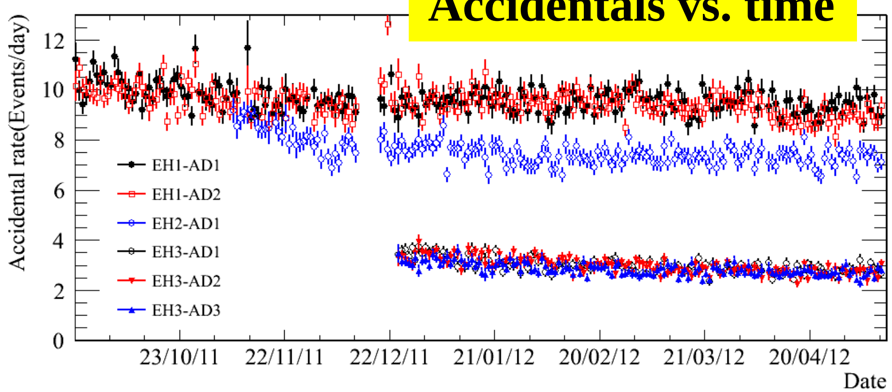
Backgrounds

- **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(α,n)^{16}O**

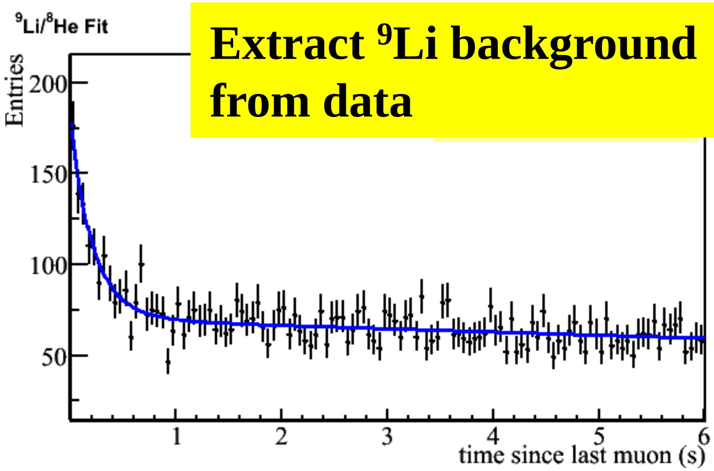
Extract fast neutron background from data



Accidentals vs. time



Extract ^{9}Li background from data



Backgrounds summary

	Near Halls		Far Hall		
	B/S %	$\sigma_{B/S}$ %	B/S %	$\sigma_{B/S}$ %	$\Delta B/B$
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%
$^{13}C(\alpha, n)^{16}O$	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
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Flasher cut	99.98%	0.01%	0.01%
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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

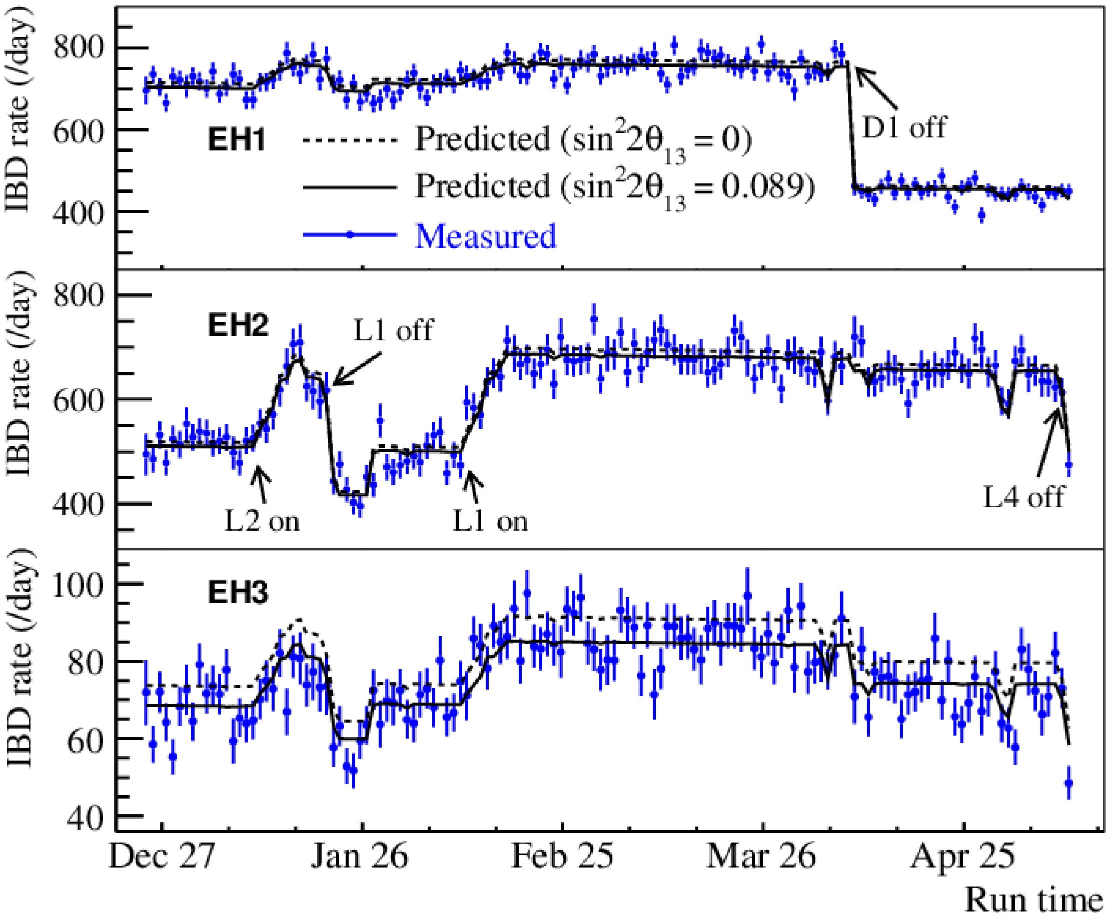
Baseline: 0.38%

Goal: 0.18%

Reactor uncorrelated uncertainty:

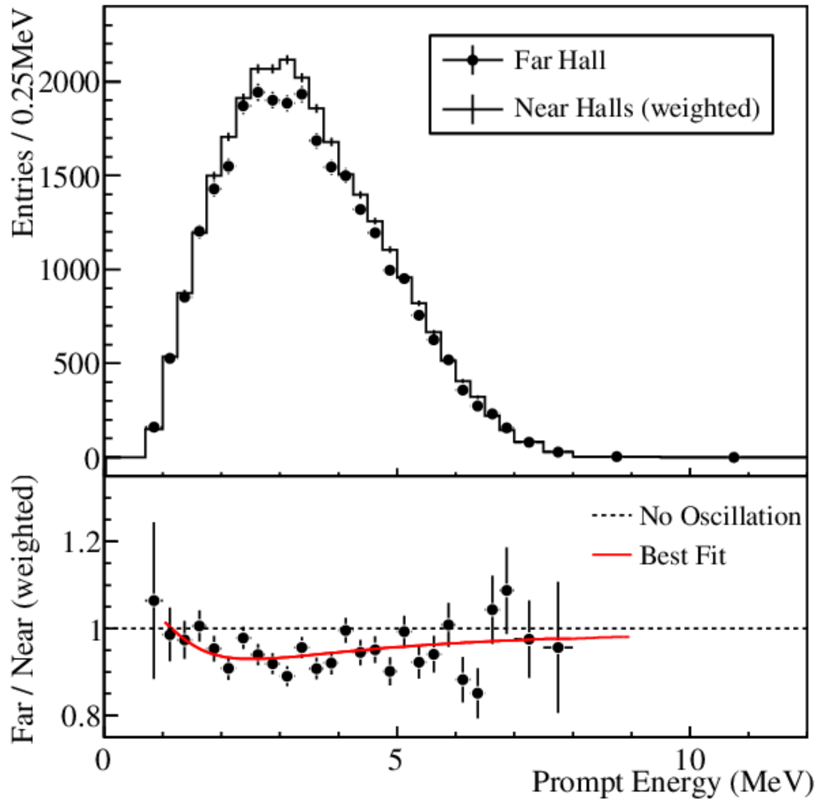
Reduced by a 1/20 factor in the near/far measurement

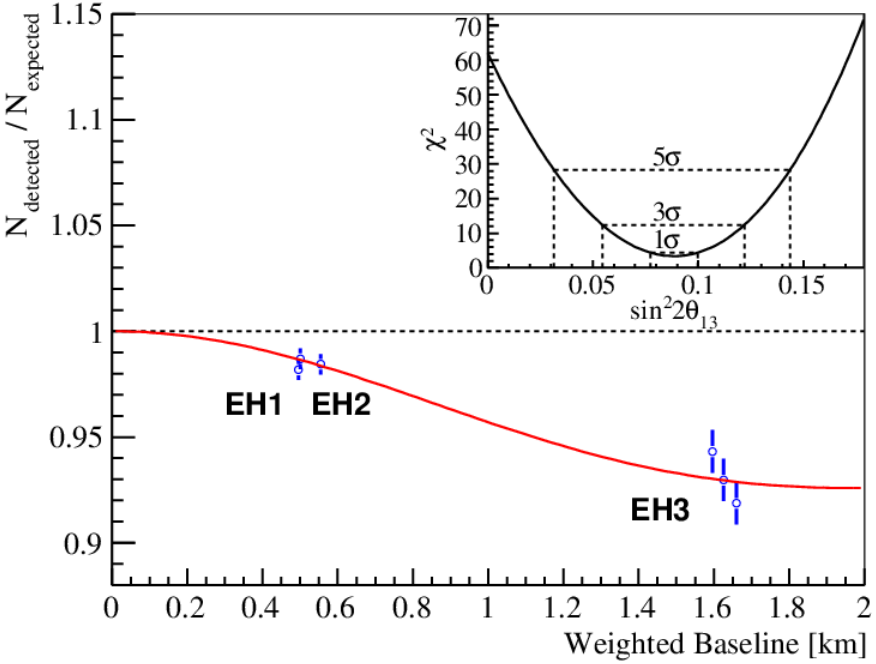
Anti-neutrino rate vs. time



- **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



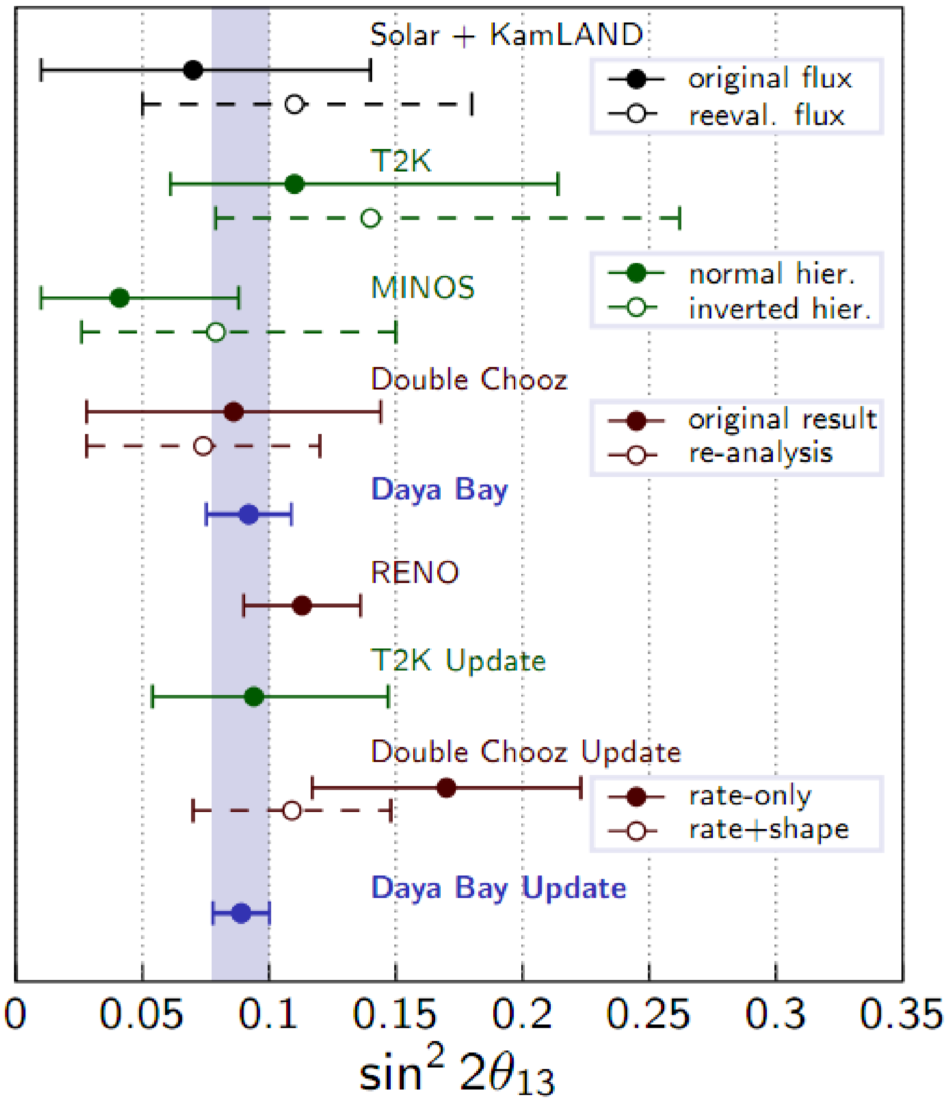


R = 0.944 ± 0.007 (stat) ± 0.003 (syst)

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

With 2.5x more statistics, an improved measured of θ_{13}

Global landscape of $\sin^2 2\theta_{13}$



Summary

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

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

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

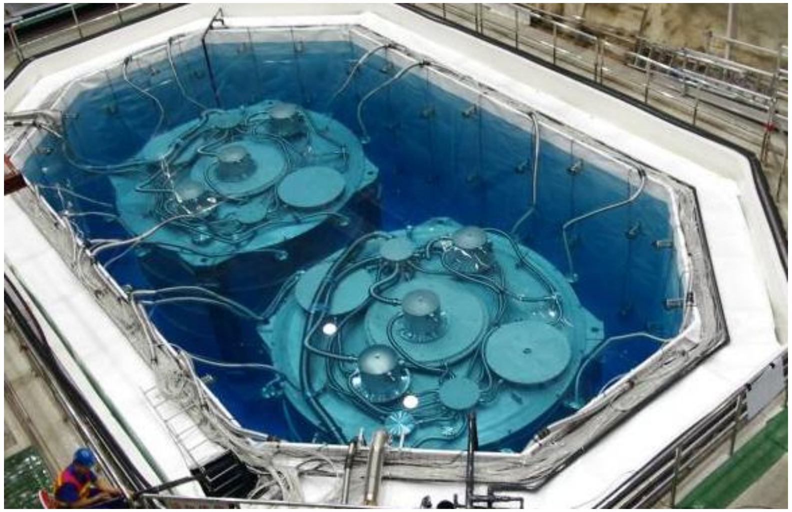
$\sin^2 2\theta_{13} = 0.089 \pm 0.010(\mathrm{stat}) \pm 0.005(\mathrm{syst})$

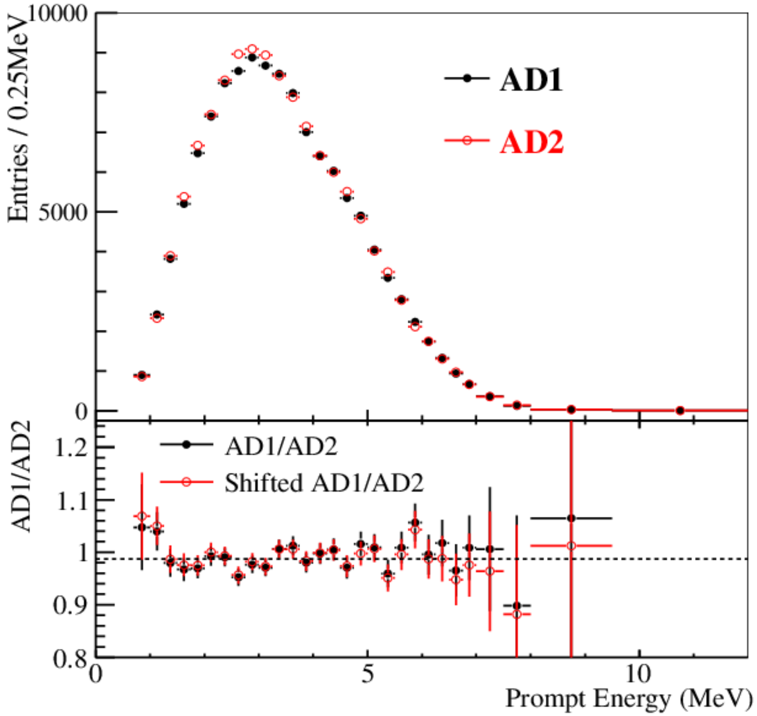
- Data taking with all eight detectors have began since Oct.19, 2012.
- Daya Bay will continue to provide the most precise measurement of θ_{13} over the world.
- Shape analysis results will come soon.
- More physics expected: reactor flux and spectrum, etc.

Backup

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)**



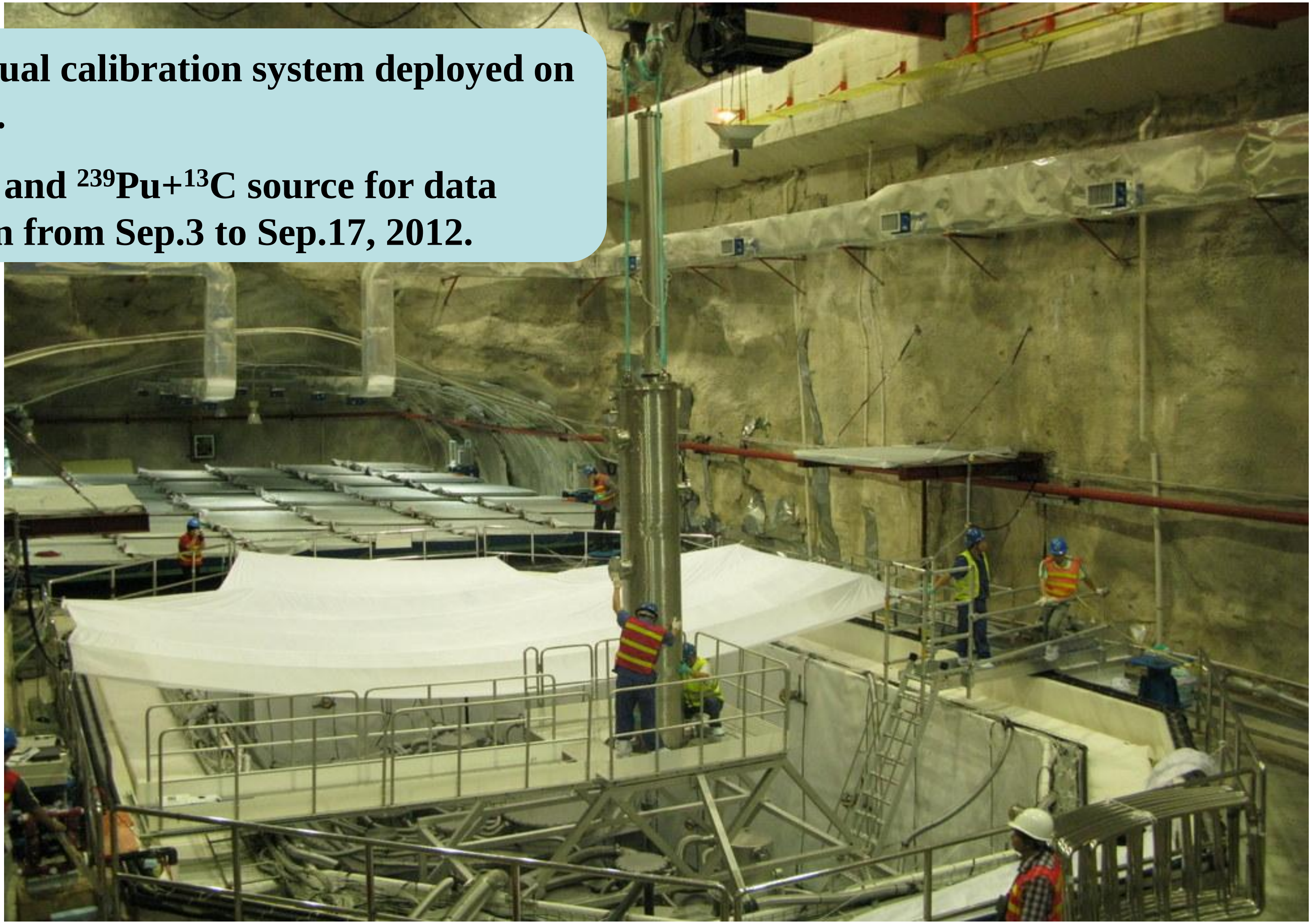


Nucl. Inst. and Meth. A 685 (2012), pp. 78-97

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.



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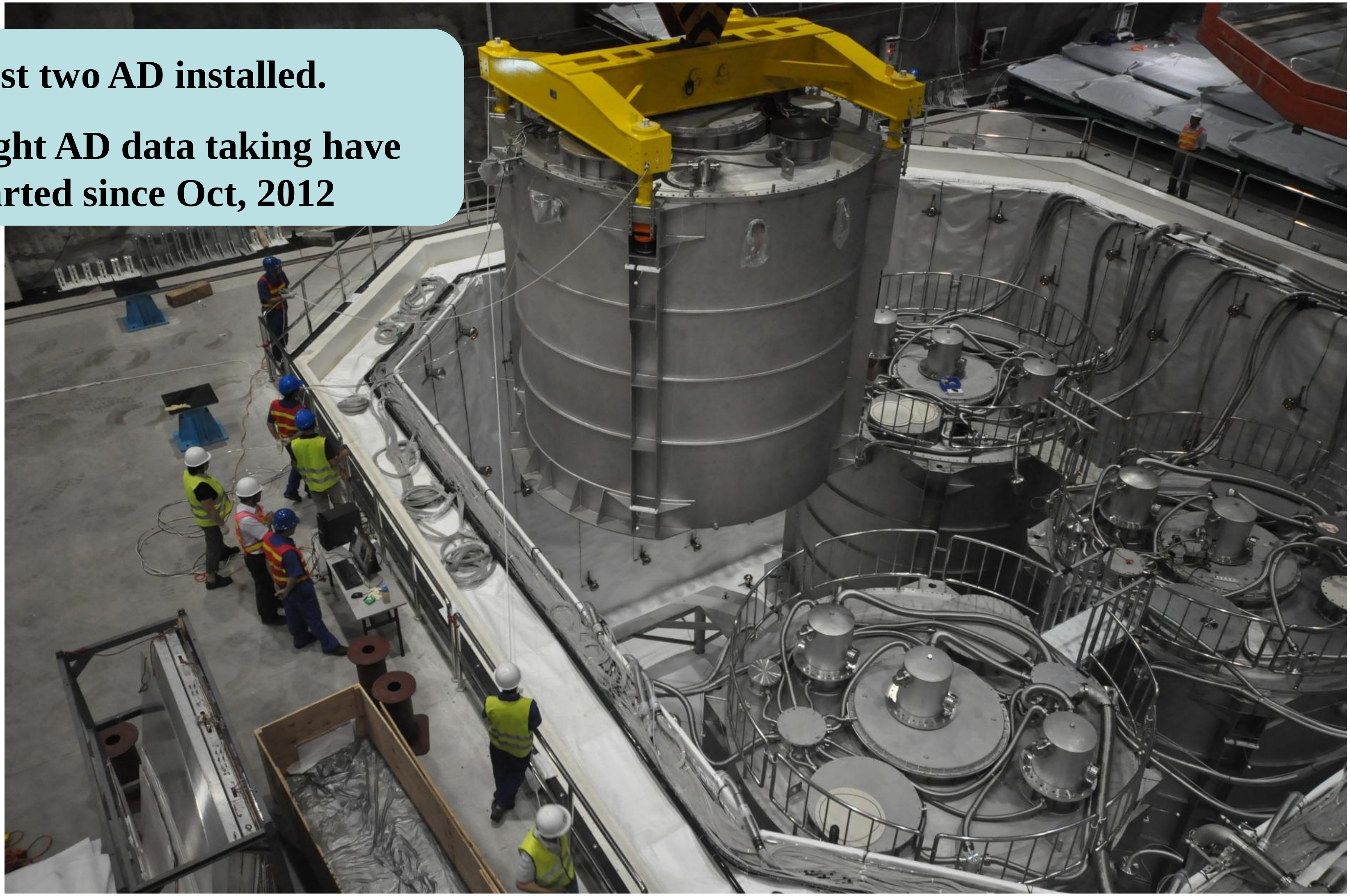

Last two AD installed.

Eight AD data taking have started since Oct, 2012