Results from the Daya Bay Reactor Neutrino Experiment

J. Pedro Ochoa*

Berkeley Lab

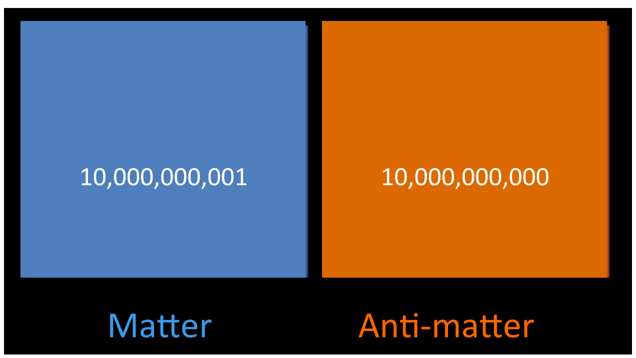
**for the Daya Bay Collaboration*

IX Latin-American Symposium of High-Energy Physics

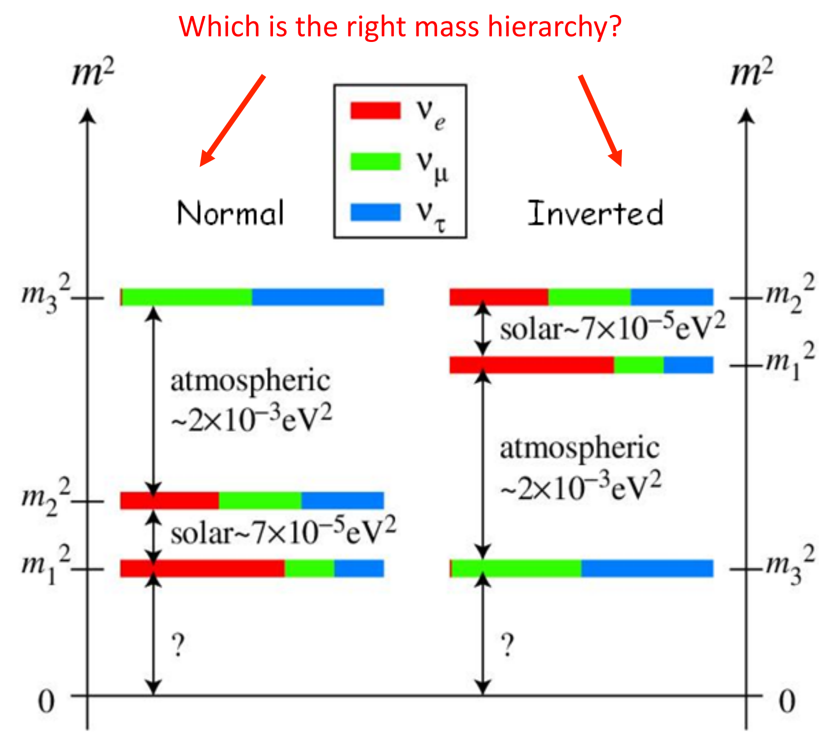
Sao Paulo, Brazil – Dec. 2012

The search for θ_{13}

- The study of neutrino oscillations has now entered a precision era:
  - In particular, the neutrino mass differences are now known to a few percent
- Until recently however, one piece of the puzzle was missing: the θ_{13} mixing angle
  - Important parameter in Standard Model, key input to future extensions
  - A non-zero θ_{13} could also open the door to answering many other questions:
    - Is there CP violation in the lepton sector?
    - Why is there more matter than anti-matter in our universe?



    - What is the mass hierarchy of the neutrino sector?



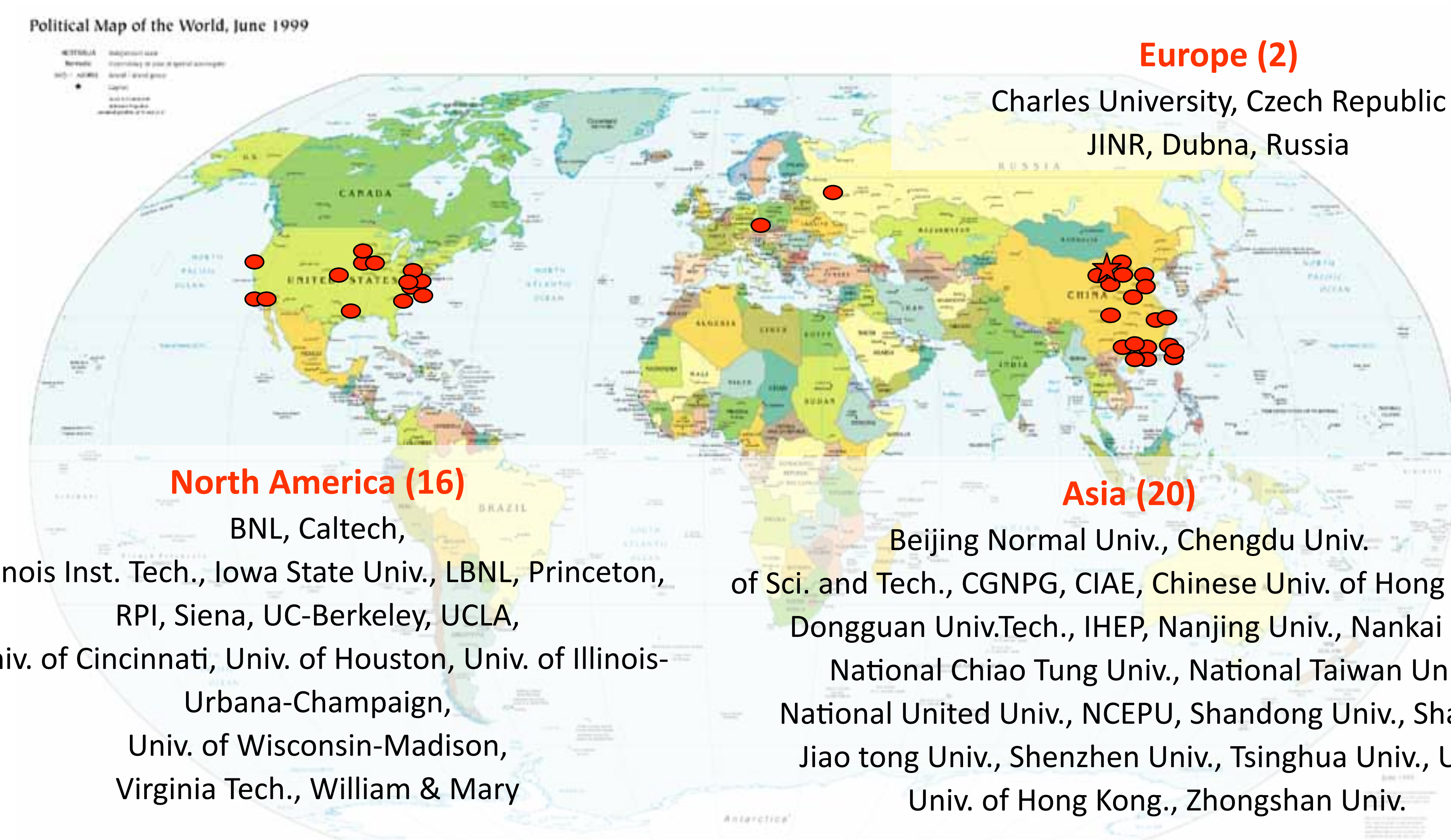
- Until less than a year ago ago we had some indications that θ_{13} might be non-zero:

$$\sin^2(2\theta_{13}) < 0.15 \text{ (90 C.L.)}$$ ← from PDG 2011

  - The Daya Bay Experiment was designed to make a precise measurement of θ_{13}

The Daya Bay Reactor Neutrino Experiment

❖ **The Daya Bay Collaboration:**



Europe (2)

Charles University, Czech Republic
JINR, Dubna, Russia

North America (16)

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

Asia (20)

Beijing Normal Univ., Chengdu Univ. of Sci. and Tech., CGNPG, CIAE, Chinese Univ. of Hong Kong, Dongguan Univ.Tech., IHEP, Nanjing Univ., Nankai Univ., National Chiao Tung Univ., National Taiwan Univ., National United Univ., NCEPU, Shandong Univ., Shanghai Jiao tong Univ., Shenzhen Univ., Tsinghua Univ., USTC, Univ. of Hong Kong., Zhongshan Univ.

~230 Collaborators

Daya Bay Experimental Layout

- Electron anti-neutrinos are produced in copious amounts in nuclear reactors.

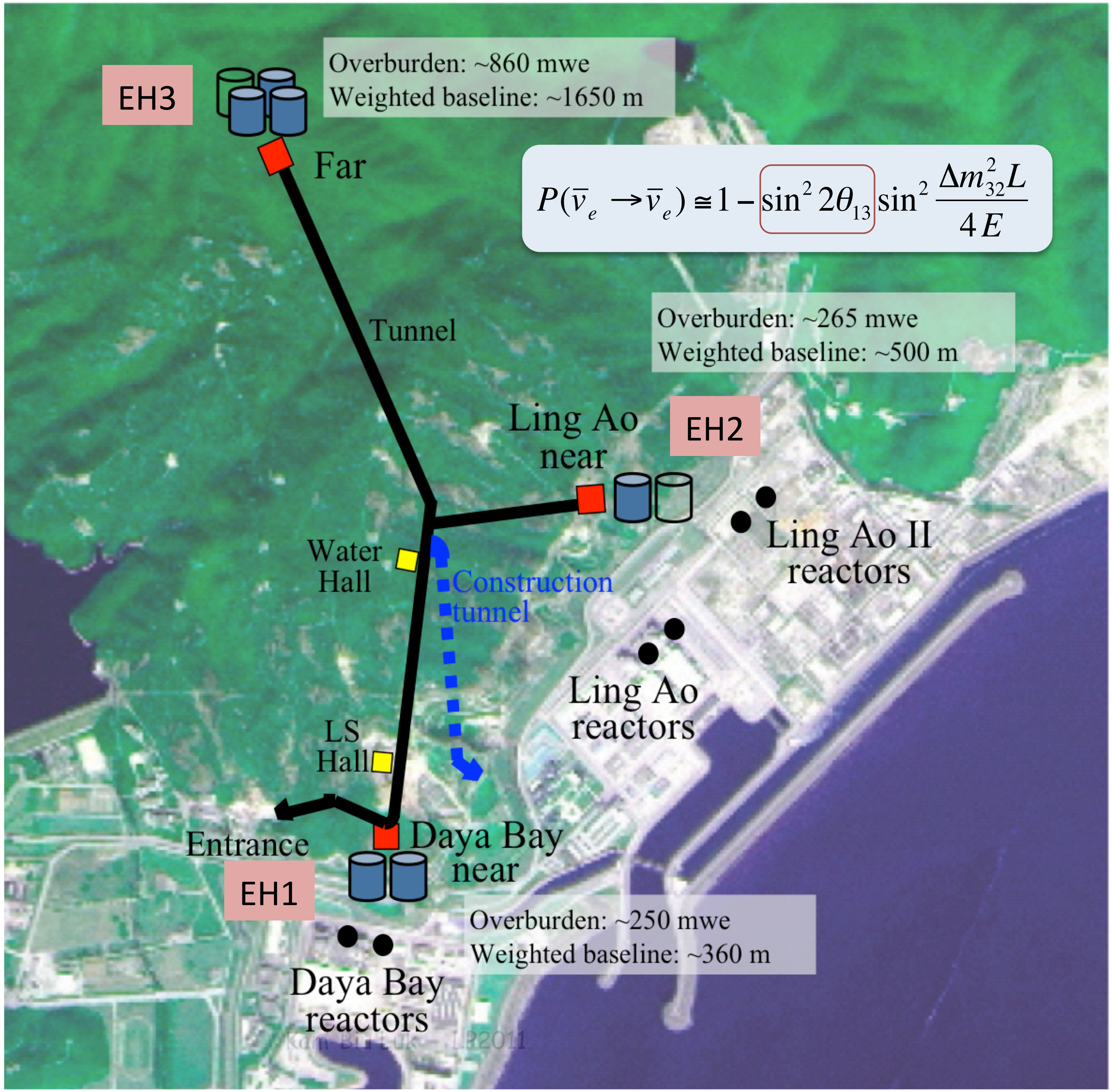
  We position our detectors around the Daya Bay Power Plant in China, among the most powerful in the world.

- **Main principle:**

  (i) sample the reactor anti-neutrino flux in the near and far locations, and

  (ii) look for evidence of disappearance

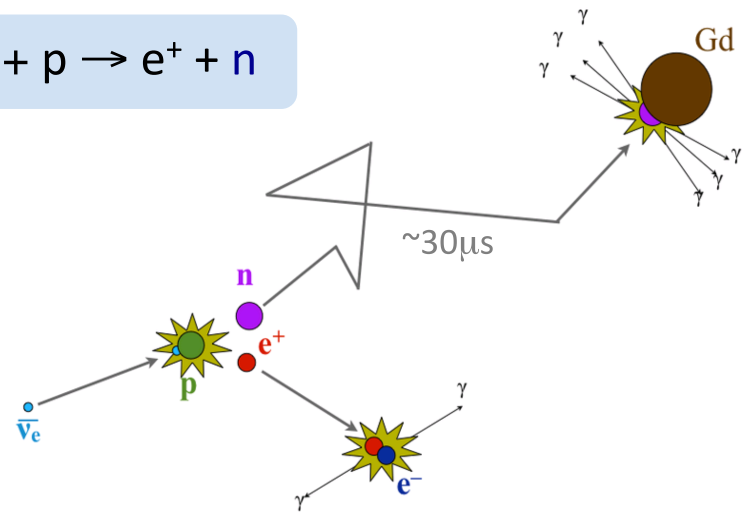
  Note: 6 / 8 detectors started taking physics data since Dec. 2011



The Detectors

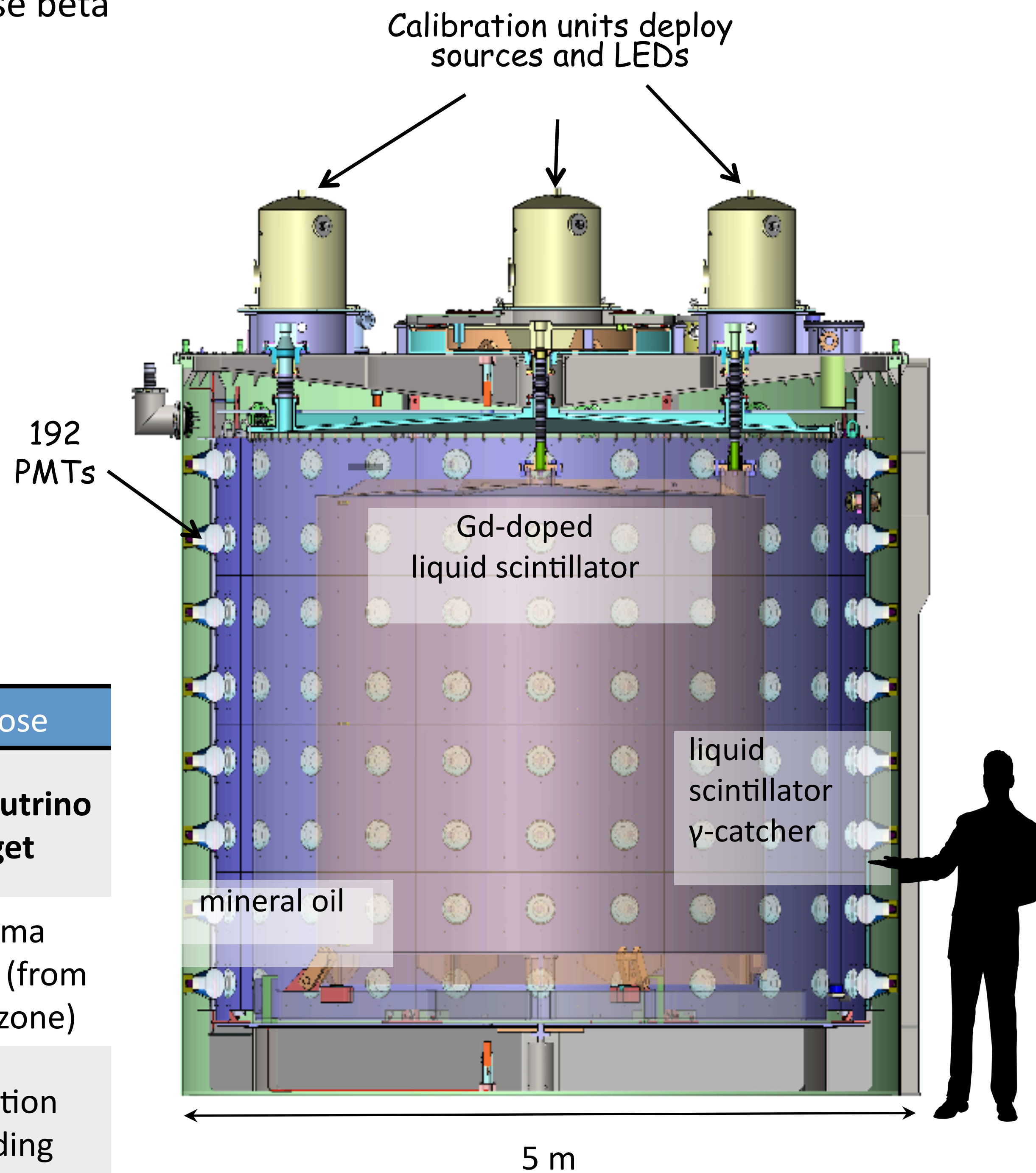
- Anti-neutrinos are detected via the inverse beta decay (IBD) reaction:

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



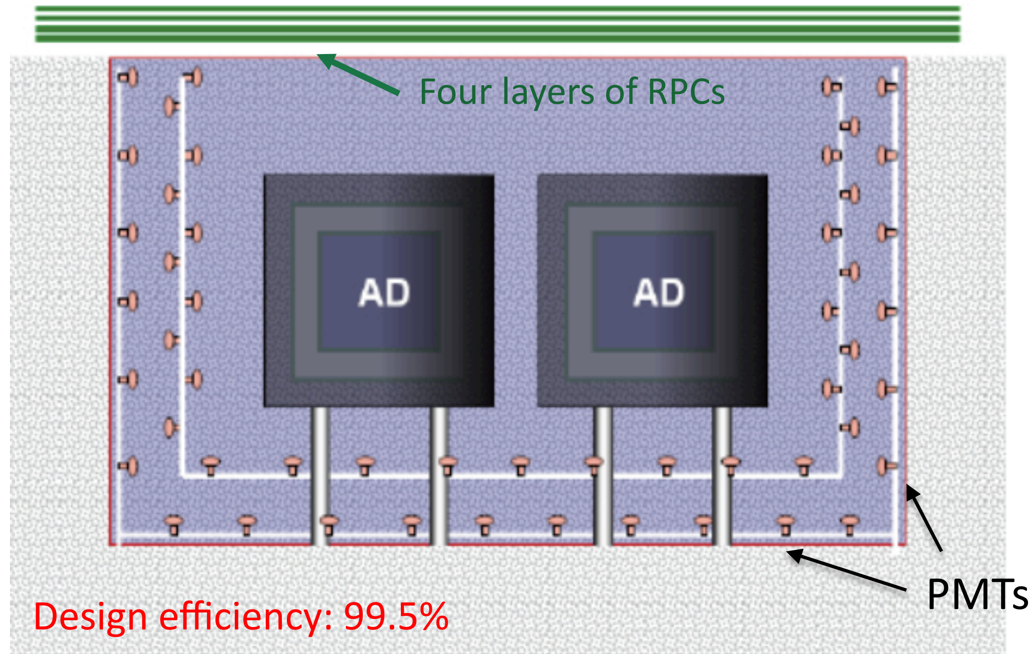
- The detectors are ~100ton three-zone cylindrical modules:

Zone	Mass	Liquid	Purpose
Inner acrylic vessel	20 t	Gd-doped liquid scintillator	**Anti-neutrino target**
Outer acrylic vessel	20 t	Liquid scintillator	Gamma catcher (from target zone)
Stainless steel vessel	40 t	Mineral Oil	Radiation shielding

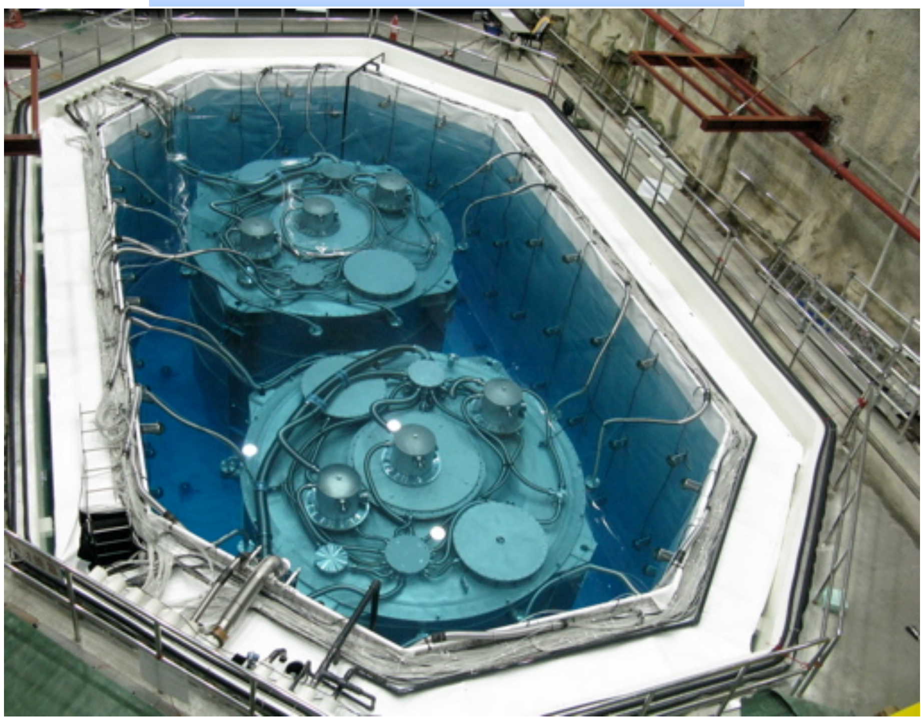


The Water Pool

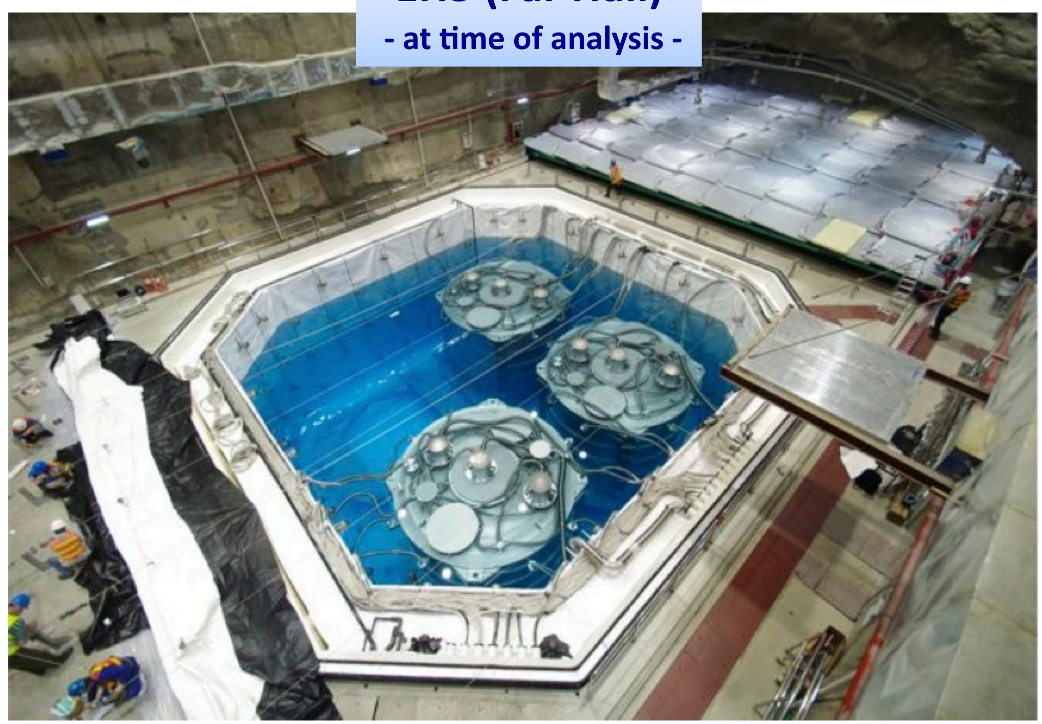
- The detectors are immersed in an instrumented water pool:
  - Double purpose:
    - ✓ Attenuates gammas from ambient radioactivity as well as neutrons produced by cosmic rays
    - ✓ Serves as a Cerenkov detector to tag cosmic ray muons (thus reducing backgrounds)



EH1 (Daya Bay Near Hall)



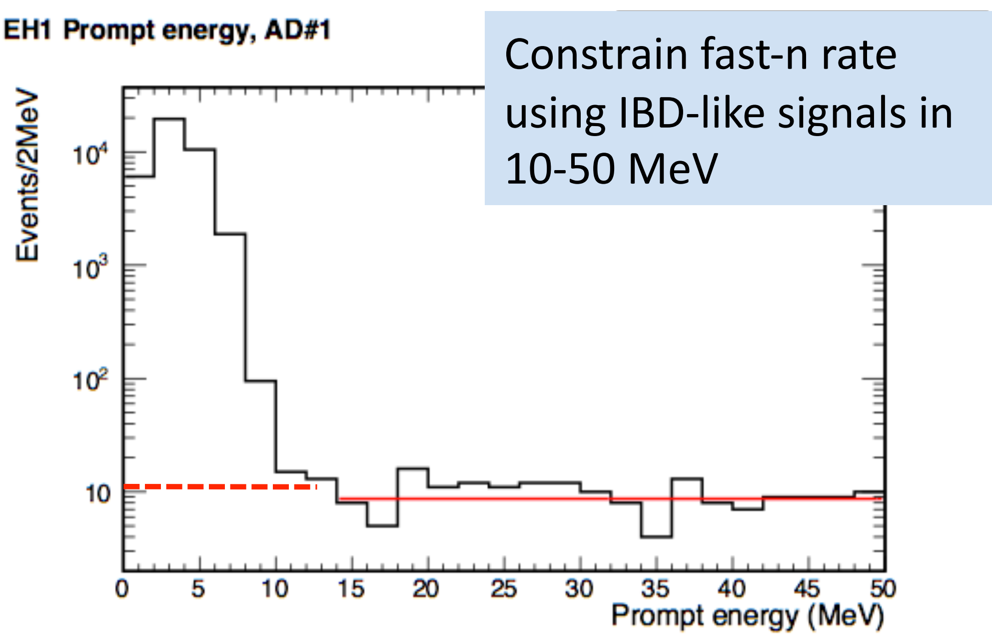
EH3 (Far Hall)
- at time of analysis -

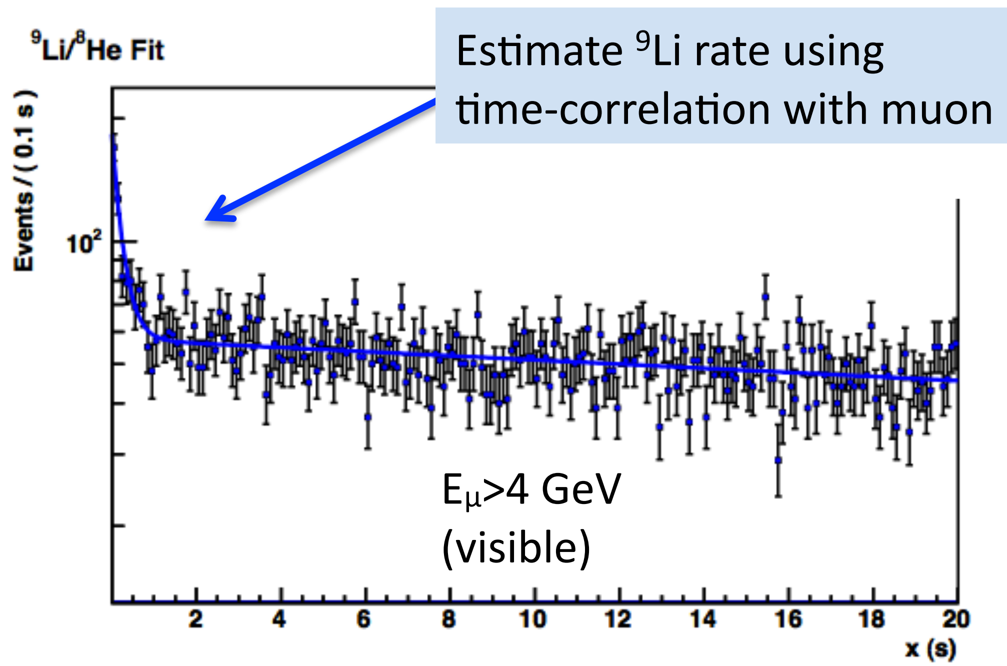


Backgrounds

- Not quite a background free experiment, but close:
  - Total backgrounds are **5% (2%)** in far(near) halls
  - Background uncertainties are **0.3% (0.2%)** in far (near) halls
- The backgrounds are all estimated using data-driven methods:
  - The largest source of background (accidental coincidences) can be measured to ~1%

	Near Halls		Far Hall	
	B/S %	$\sigma_{B/S}$ %	B/S %	$\sigma_{B/S}$ %
Accidentals	1.5	0.02	4.0	0.05
Fast neutrons	0.12	0.05	0.07	0.03
^{9}Li/^{8}He	0.4	0.2	0.3	0.2
^{241}Am-^{13}C	0.03	0.03	0.3	0.3
^{13}C(α, n)^{16}O	0.01	0.006	0.05	0.03





Dataset for oscillation analysis

- Dataset:
  - ✓ December 24th 2011 to May 11th 2012 ⟵ less than six months!
- Have accumulated **more than 200k** antineutrino interactions:

	AD1	AD2	AD3	AD4	AD5	AD6
Antineutrino candidates	69121	69714	66473	9788	9669	9452
DAQ live time (day)	127.5470		127.3763	126.2646		
Efficiency	0.8015	0.7986	0.8364	0.9555	0.9552	0.9547
Accidentals (/day)	9.73±0.10	9.61±0.10	7.55±0.08	3.05±0.04	3.04±0.04	2.93±0.03
Fast neutron (/day)	0.77±0.24	0.77±0.24	0.58±0.33	0.05±0.02	0.05±0.02	0.05±0.02
^{8}He/^{9}Li (/day)	2.9±1.5		2.0±1.1	0.22±0.12		
Am-C corr. (/day)	0.2±0.2					
^{13}C(α, n)^{16}O (/day)	0.08±0.04	0.07±0.04	0.05±0.03	0.04±0.02	0.04±0.02	0.04±0.02
Antineutrino rate (/day)	**662.47 ±3.00**	**670.87 ±3.01**	**613.53 ±2.69**	**77.57 ±0.85**	**76.62 ±0.85**	**74.97 ±0.84**

Consistent rates for side-by-side detectors

Uncertainty currently dominated by statistics

Summary of 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%

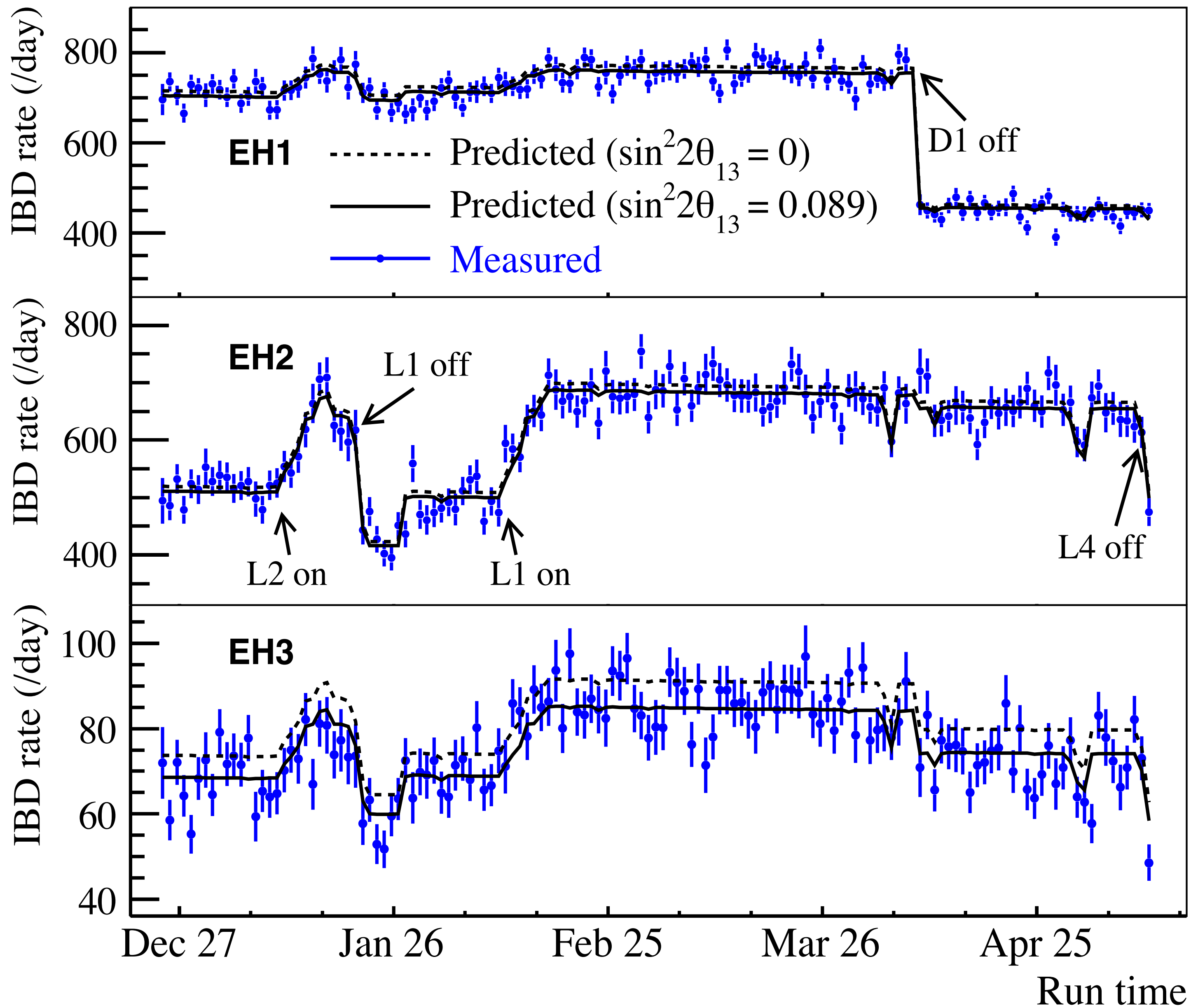
For near/far oscillation, only uncorrelated uncertainties are used.

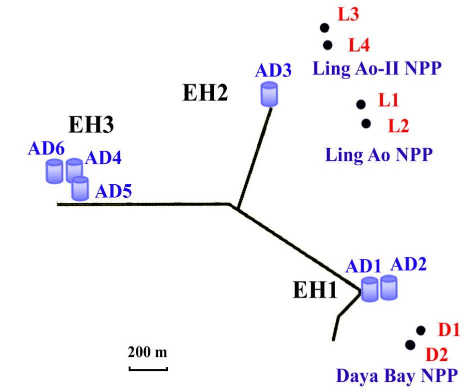
Largest systematics are smaller than far site statistics (~1%)

Influence of uncorrelated reactor systematics reduced by far vs. near measurement.

Latest Results

❖ Measured anti-neutrino event rates vs. time:





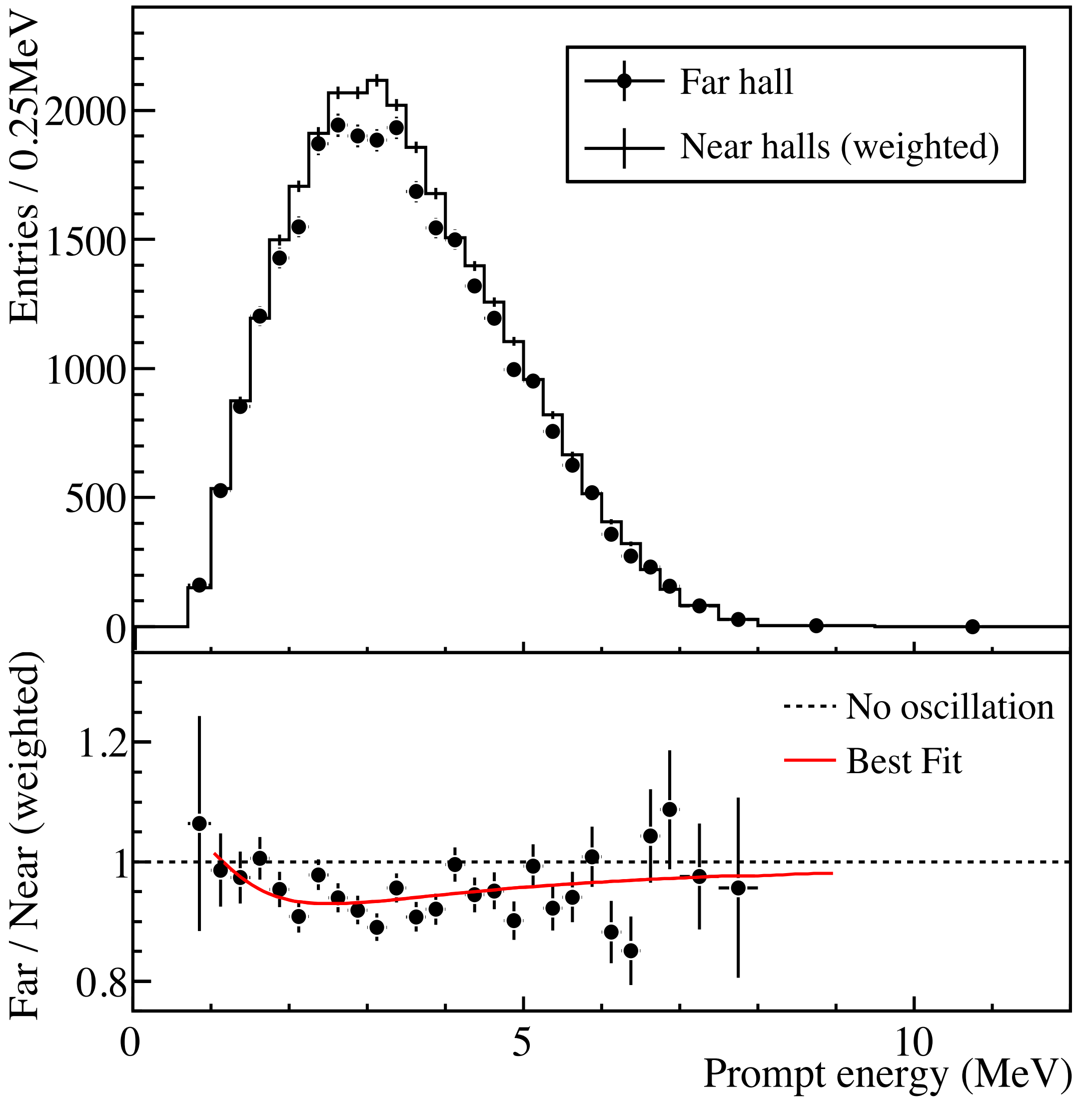
- DX and LX denote the DayaBay and LingAo reactors respectively
- The reactors come on and off due to refueling.
- Detector rates strongly correlated with reactor flux expectations.

Notes:

- Normalization is determined by fit to near-hall data.
- Absolute normalization is within a few percent of expectations.

Near/Far Comparison

Compare the far/near measured rates and spectra



$$R = \frac{Far_{measured}}{Far_{expected}} = \frac{M_4 + M_5 + M_6}{\sum_{i=4}^{6}(\alpha_i(M_1 + M_2) + \beta_i M_3)}$$

M_n are the measured rates in each detector. Weights α_i,β_i are determined from baselines and reactor fluxes.

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

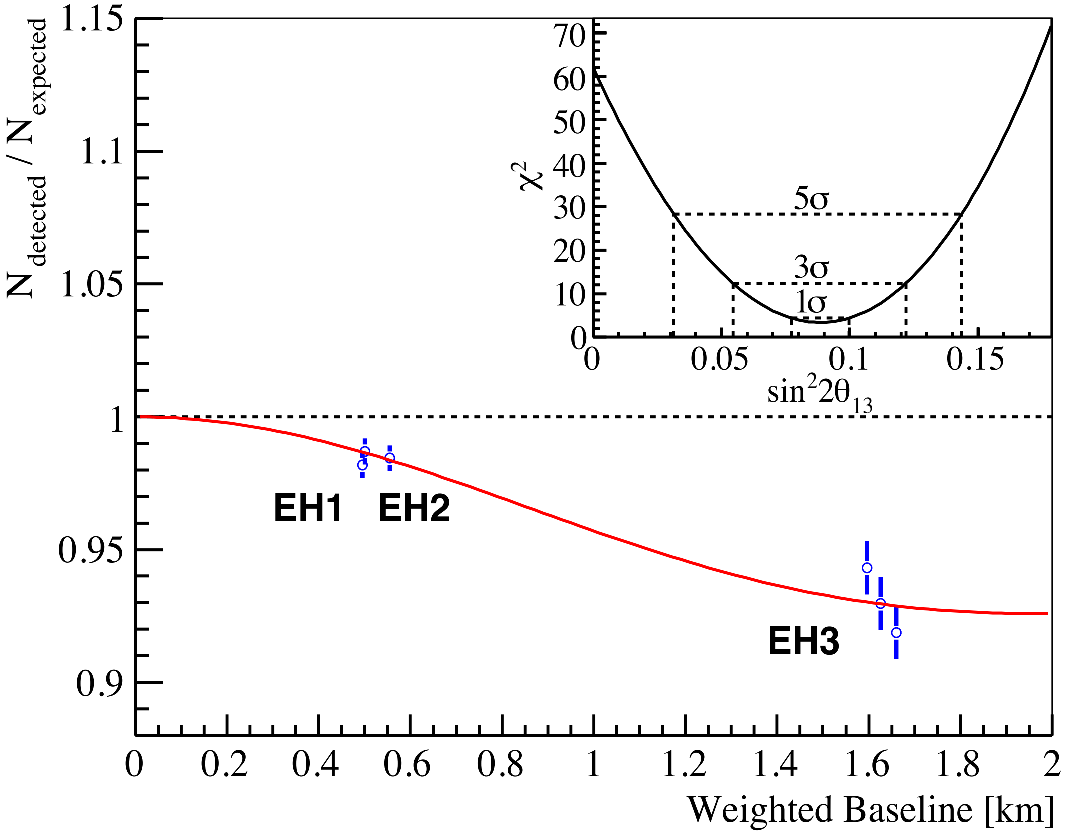
Clear observation of far site deficit.

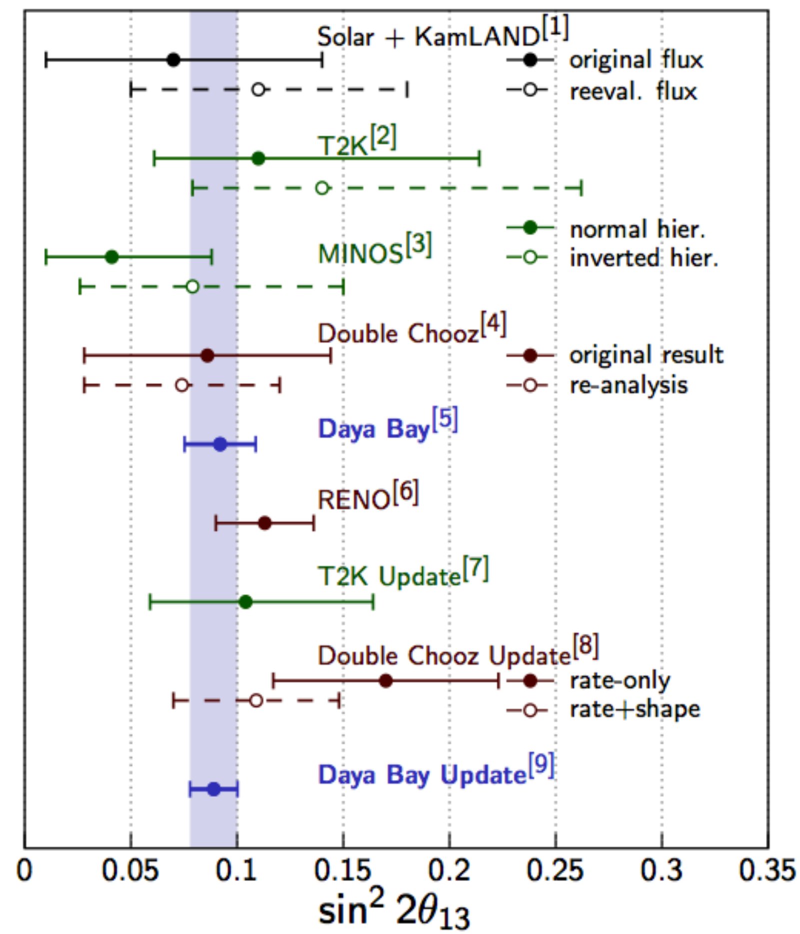
Spectral distortion consistent with oscillation.*

* Caveat: Spectral systematics not fully studied; θ_{13} value from shape analysis is not recommended.

Oscillation Analysis

Estimate θ_{13} using measured rates in each detector.





Uses standard χ^2 approach.

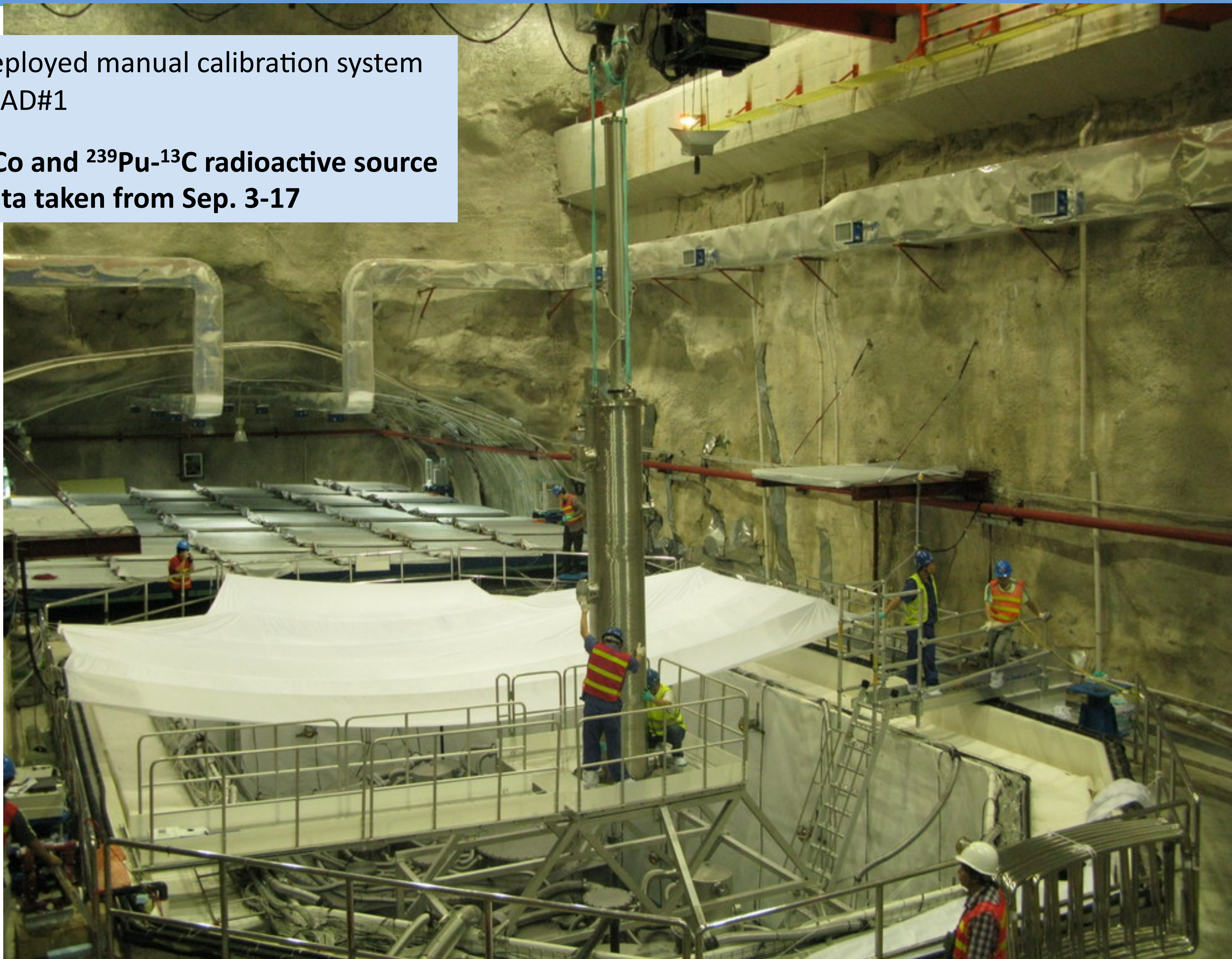
Far vs. near relative measurement (Absolute rate is not constrained)

Consistent results obtained by independent analyses, different reactor flux models.

Most precise measurement of $\sin^2 2\theta_{13}$ to date.

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

Recent Progress



Deployed manual calibration system in AD#1

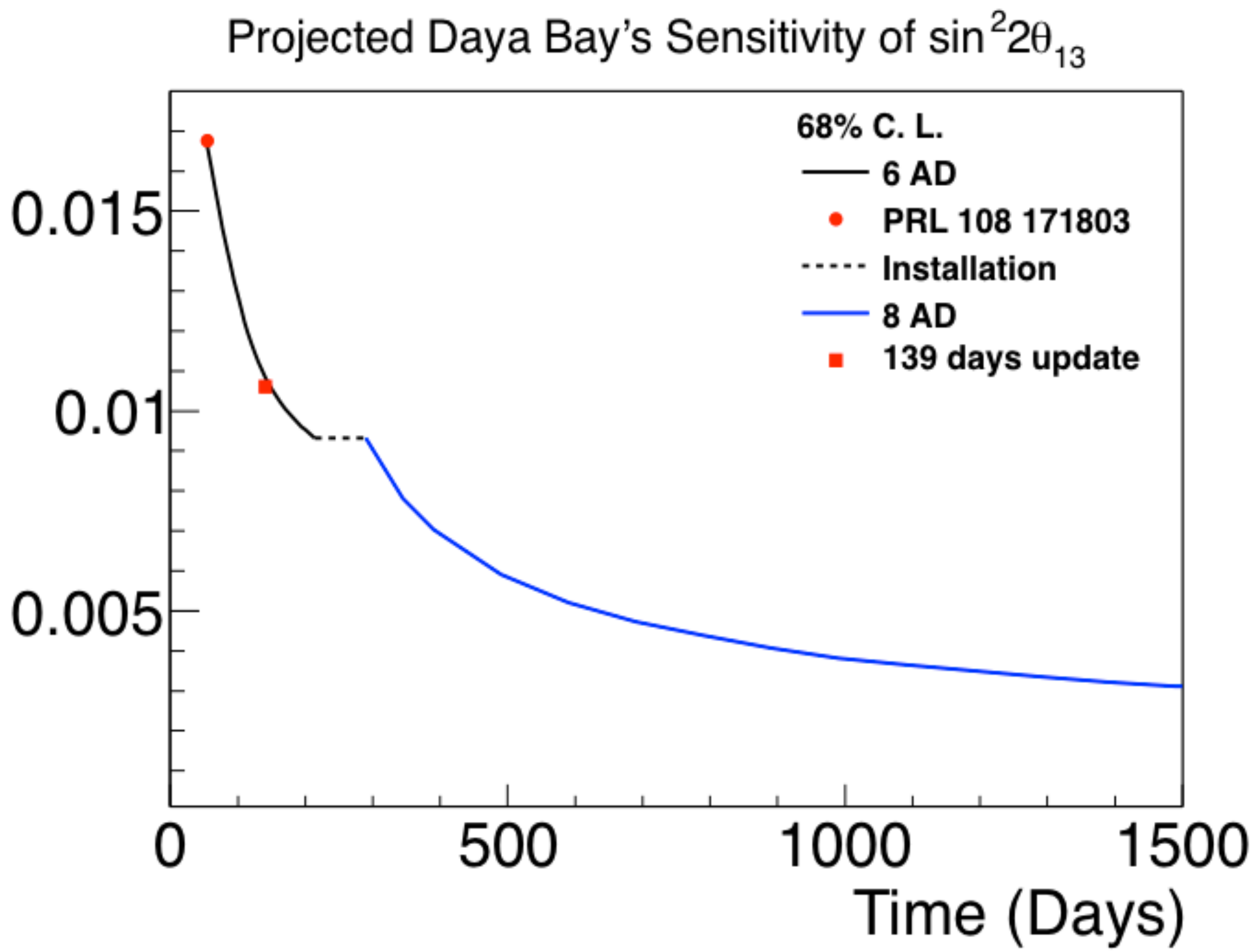
^{60}Co and ^{239}Pu-^{13}C radioactive source data taken from Sep. 3-17

Current Status

All eight detectors have been taking data since October 2012

Prospects

- Prospects for θ_{13} are very encouraging:
  - Current θ_{13} uncertainty is still largely dominated by statistics
  - **Expect a ~5% measurement of $\sin^2(2\theta_{13})$ in less than 3 years**



- Daya Bay will also make significant contributions in other areas:
  - Location of oscillation "dip" in energy spectrum constraints Δm^2_{ee} (i.e. combination of Δm^2_{31} and $\Delta^2 m_{32}$)
  - High-statistics IBD samples from Daya Bay can yield most precise measurement of reactor anti-neutrino spectrum

→ in progress!

Summary & Conclusions

- We observe an unambiguous observation of electron antineutrino disappearance at a distance of ~2km from the source:

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

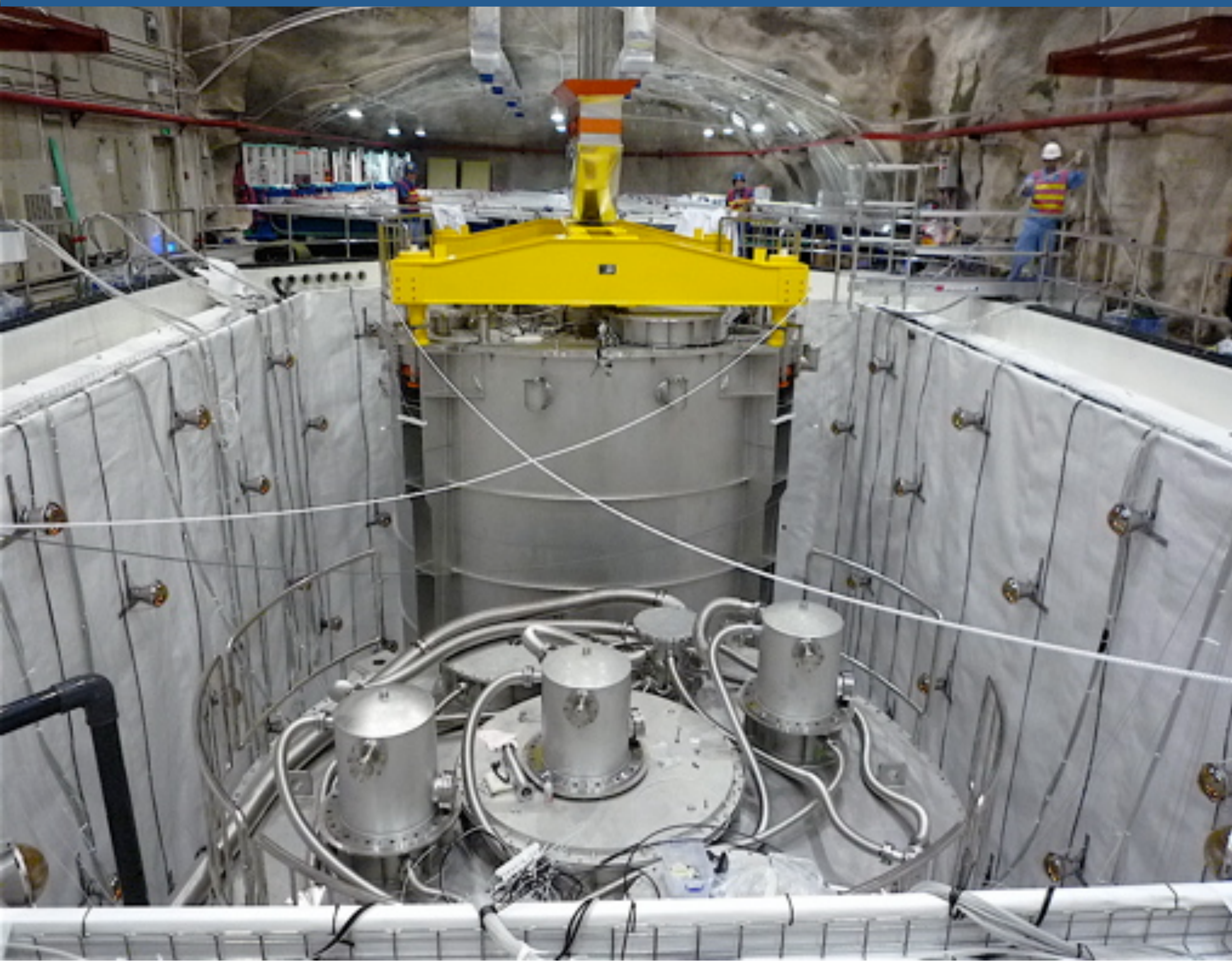
  - The interpretation in terms of neutrino oscillations rules out $\theta_{13}=0$ at more than 7σ:

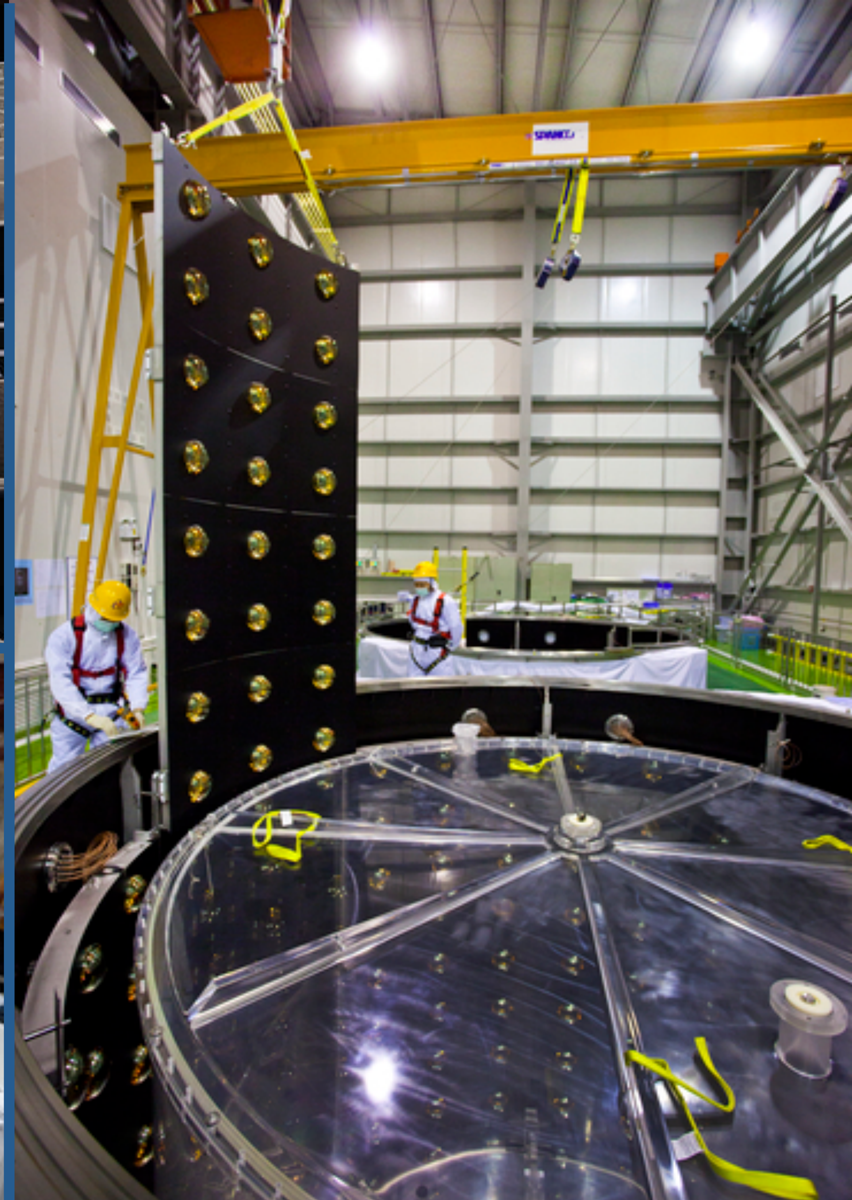
$$\sin^2 2\theta_{13} = 0.089 \pm 0.010\ (\mathrm{stat}) \pm 0.005\ (\mathrm{syst})$$

  - The result has important consequences for particle physics and cosmology

- Future looks very positive for Daya Bay:

  - Last two detectors already installed and commissioned
  - Daya Bay will continue to have the best sensitivity to θ_{13} among all the other experiments in operation or in construction.
  - Other results expected soon, such as precise reactor flux and spectra measurements, Δm^2_{ee} measurement, and others.





Thank you for your attention!