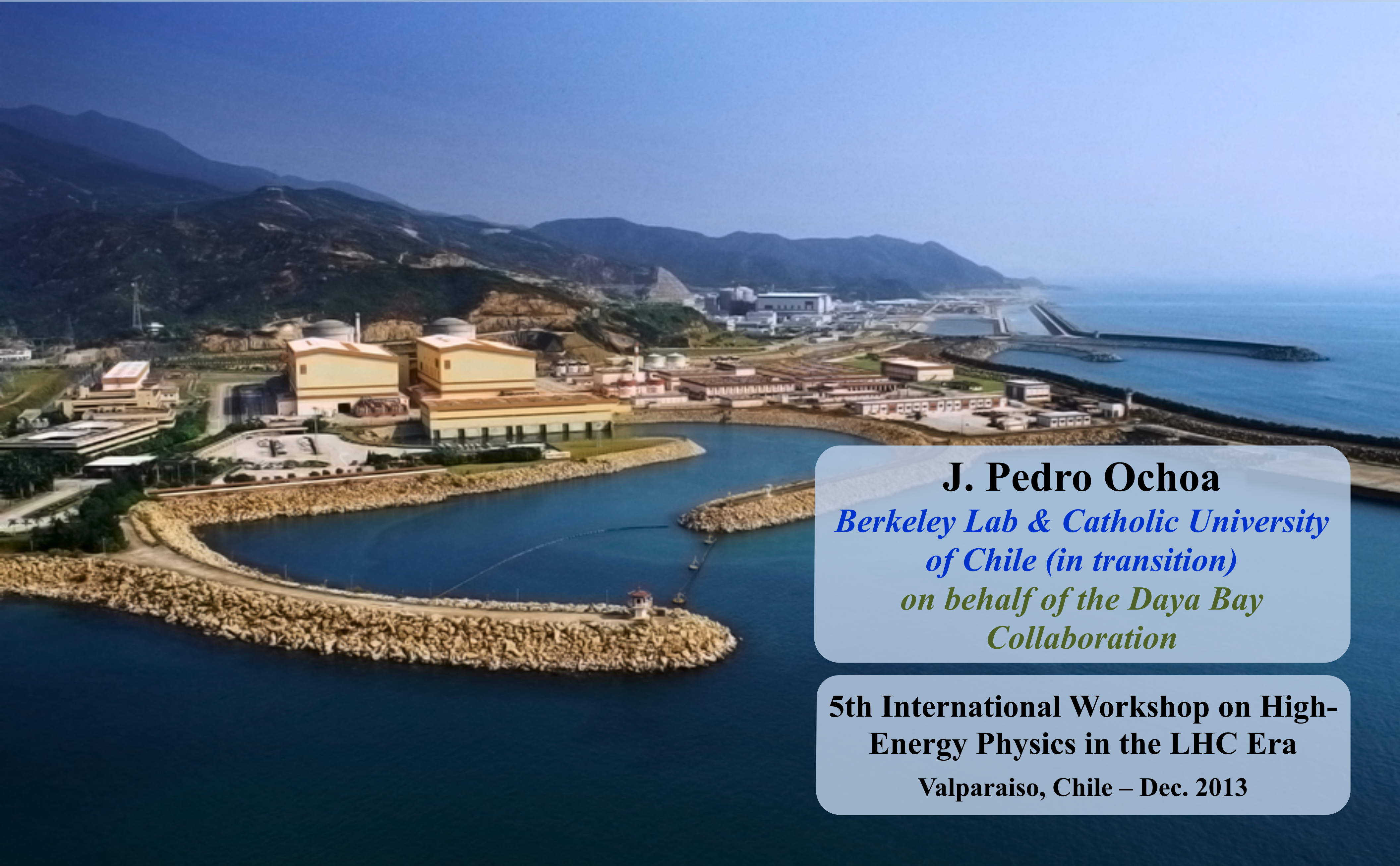
Latest Results from the Daya Bay Reactor Neutrino Experiment



J. Pedro Ochoa
Berkeley Lab & Catholic University of Chile (in transition)
on behalf of the Daya Bay Collaboration

5th International Workshop on High-Energy Physics in the LHC Era
Valparaiso, Chile – Dec. 2013

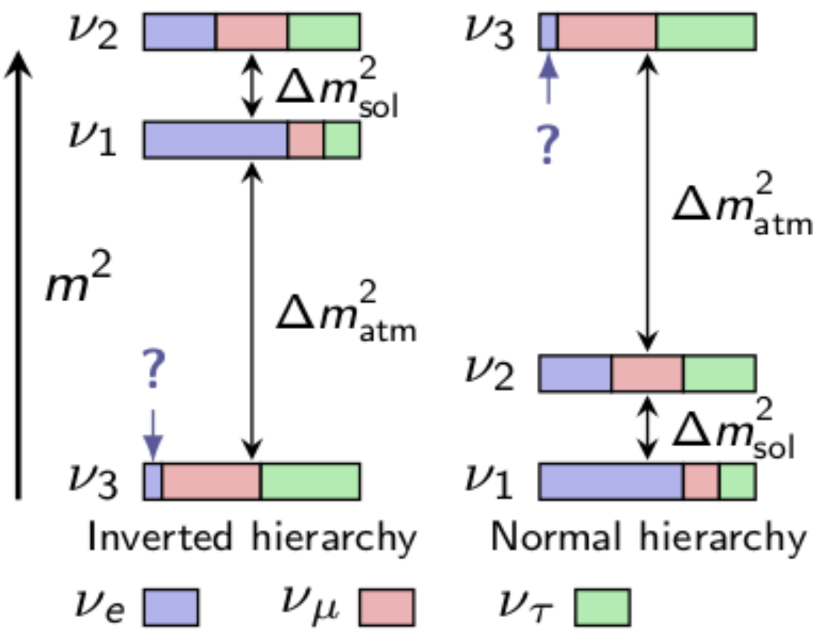
Three-Neutrino Framework: Current Status

- Neutrino weak eigenstates are mixtures of mass eigenstates:

$$\left|\nu_\alpha\right\rangle = \sum_i U^*_{\alpha i}\left|\nu_i\right\rangle$$

How they interact

How they propagate



θ_{13} only recently well established by Daya Bay

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

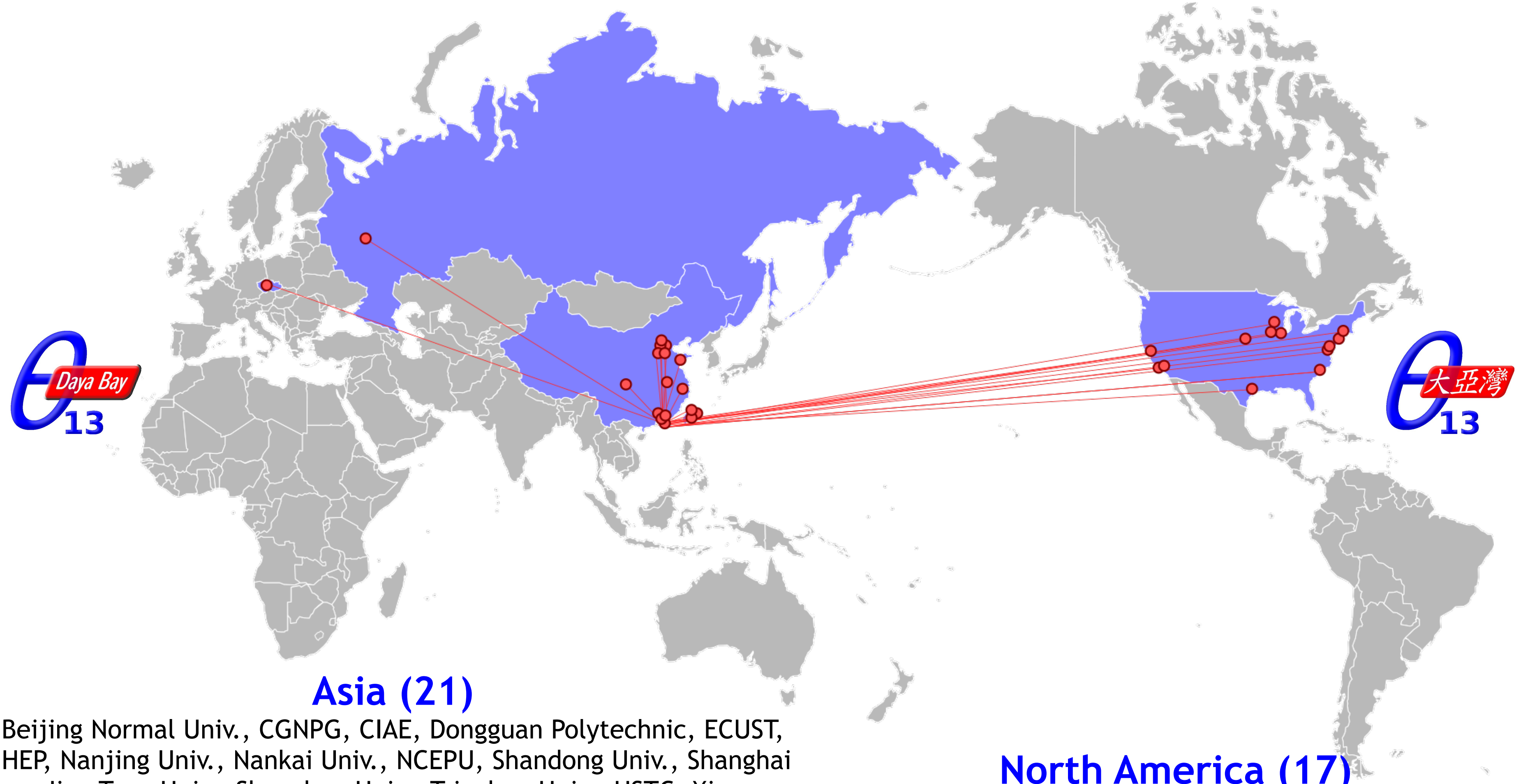
θ_{23} ~ 45° established through atmospheric and accelerator experiments: possibly maximal

Gateway to CP violation and mass hierarchy

θ_{12} ~ 34° established through solar experiments and KamLAND: large but not maximal

The Daya Bay Reactor Neutrino Experiment

❖ The Daya Bay Collaboration:



Asia (21)

Beijing Normal Univ., CGNPG, 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

~230 Collaborators

Daya Bay Experimental Layout

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

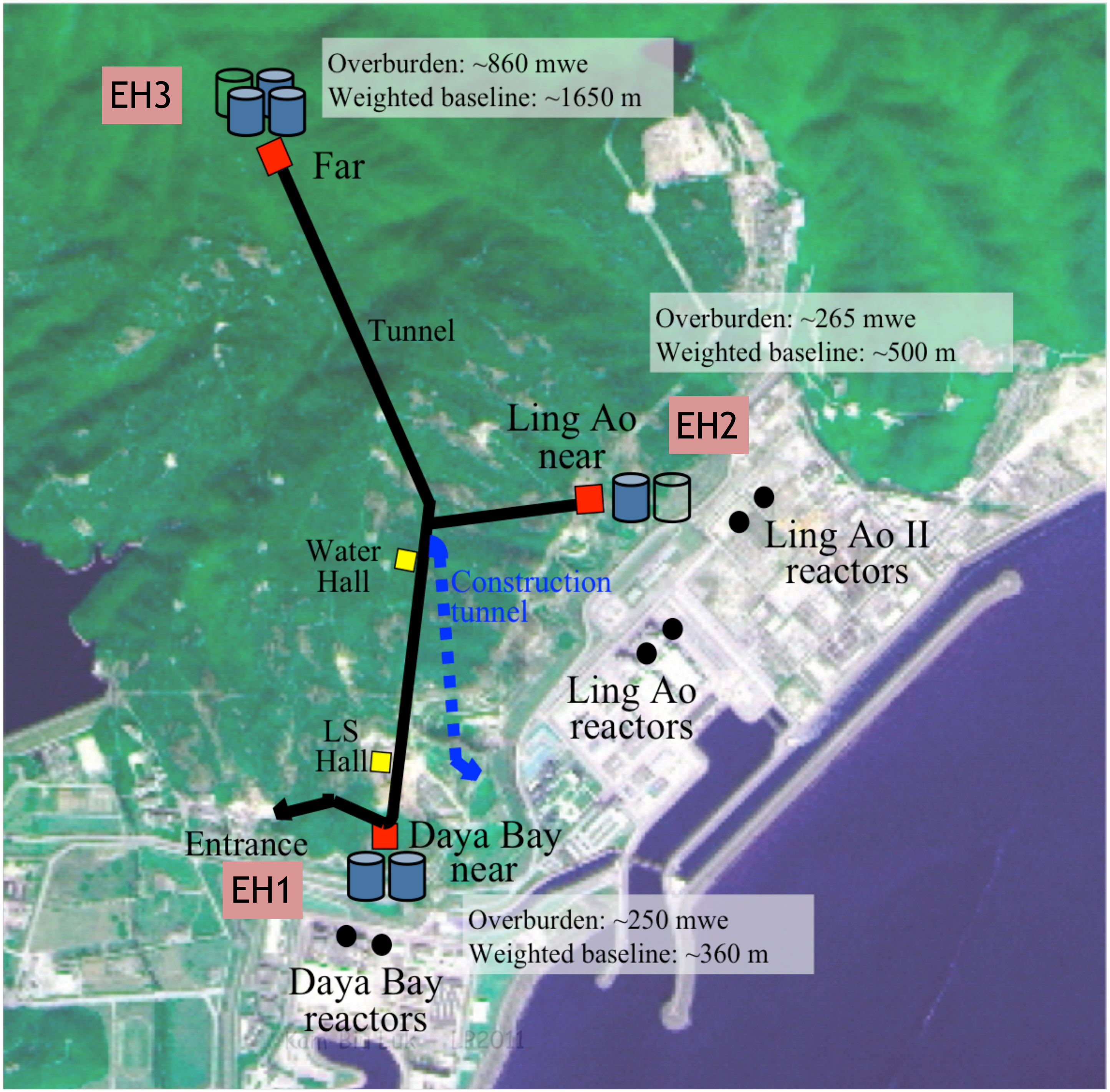
  We position 8 detectors around the Daya Bay Power Plant in China, among the most powerful in the world.

- **Main principle:**

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

  (ii) look for evidence of disappearance

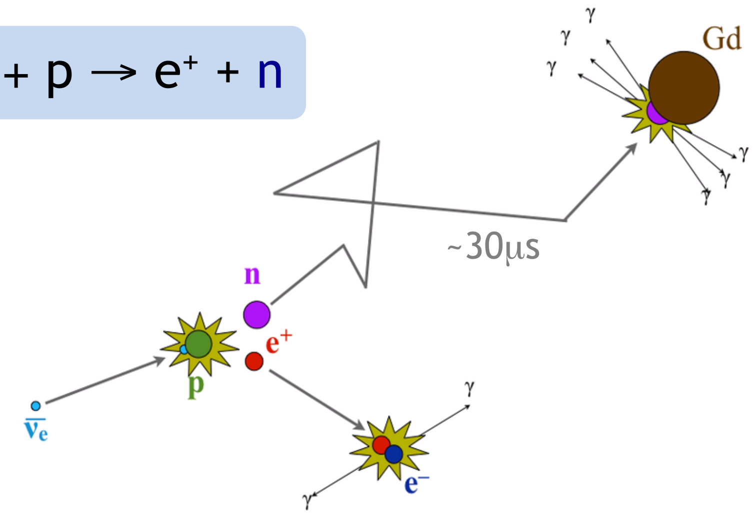
  Note: results shown here use data collected with 6 / 8 detectors



The Detectors

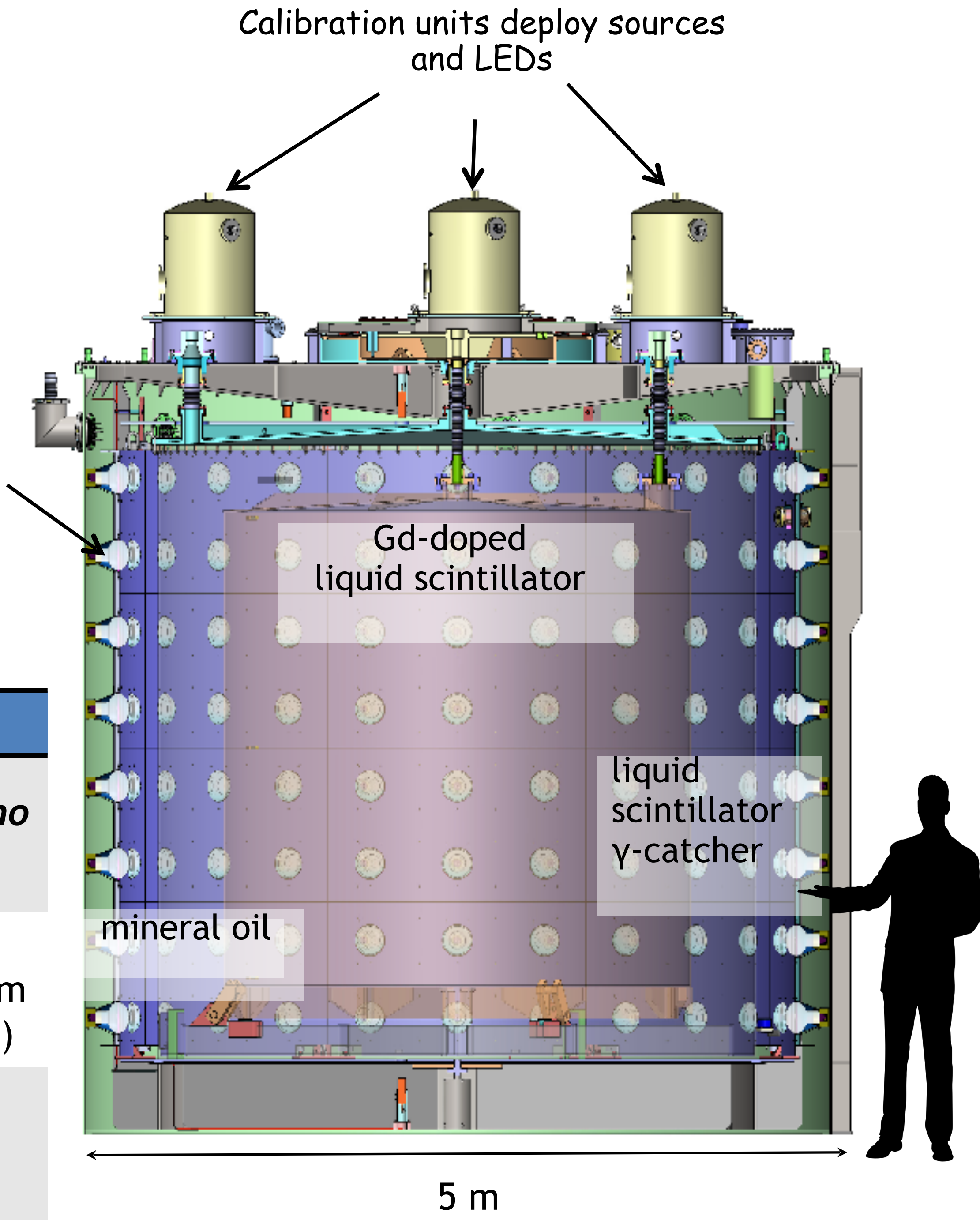
- Anti-neutrinos are detected via the inverse beta decay (IBD) reaction:

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



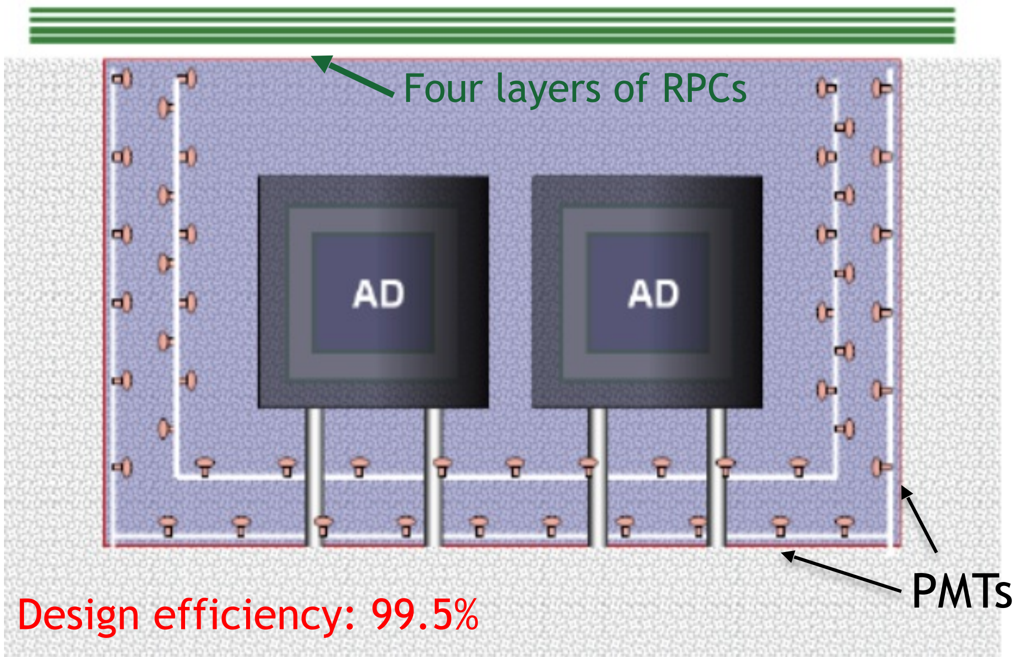
- The detectors are ~100ton three-zone cylindrical modules:

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*



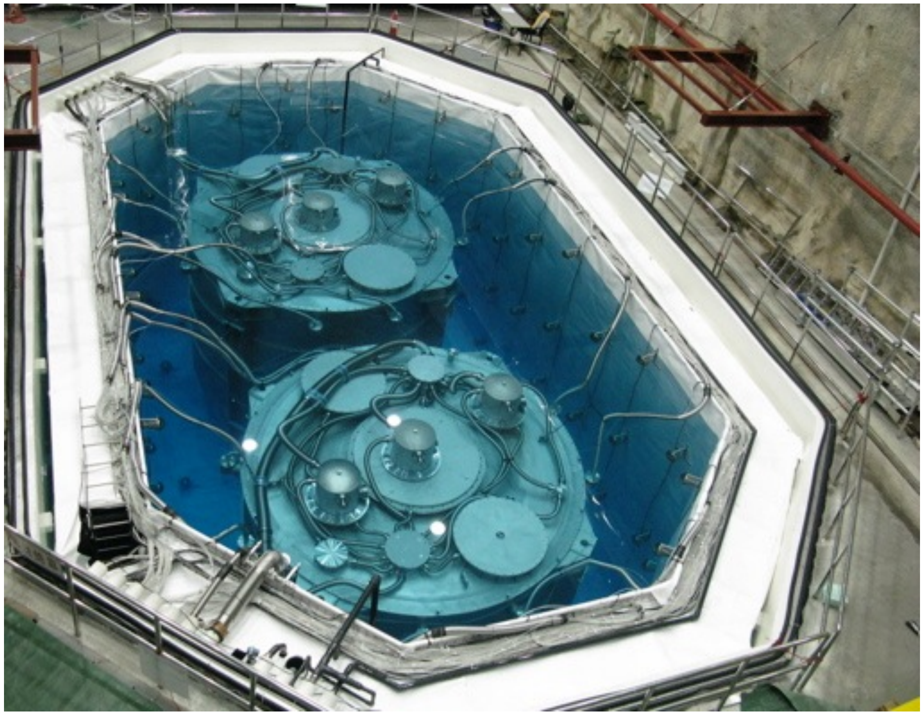
Muon Veto System

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

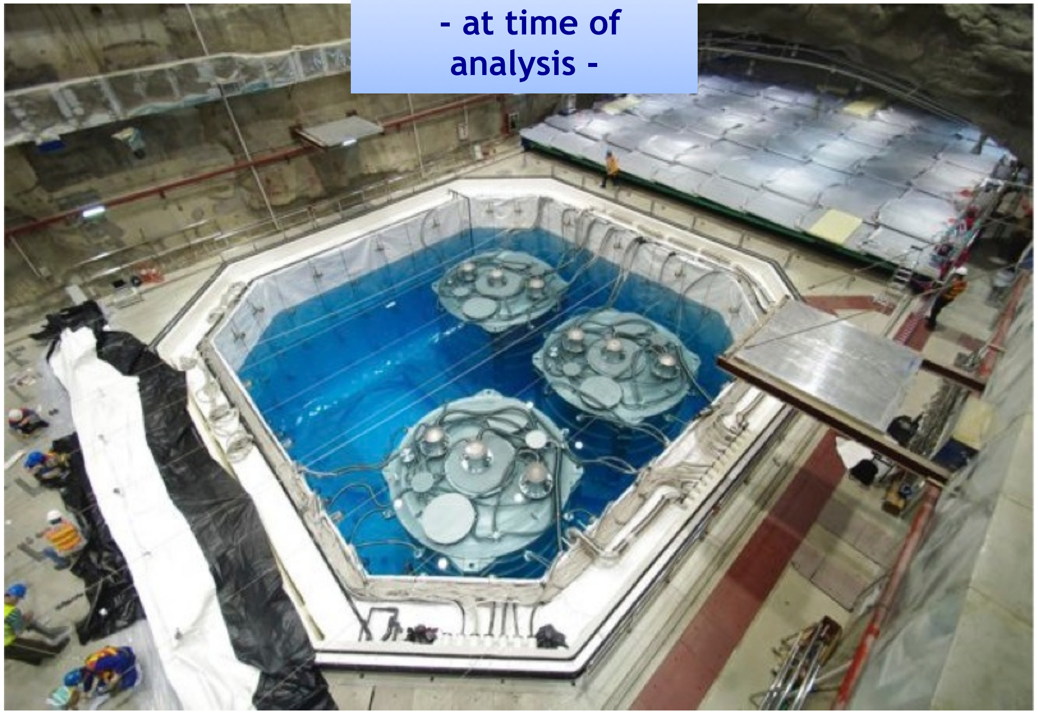


Design efficiency: 99.5%

EH1 (Daya Bay Near Hall)



EH3 (Far Hall)
- at time of analysis -



Analyzed Datasets

Two detector comparison [1202.6181]

- 90 days of data, Daya Bay near only
- NIM A **685** (2012), 78-97

First oscillation analysis [1203:1669]

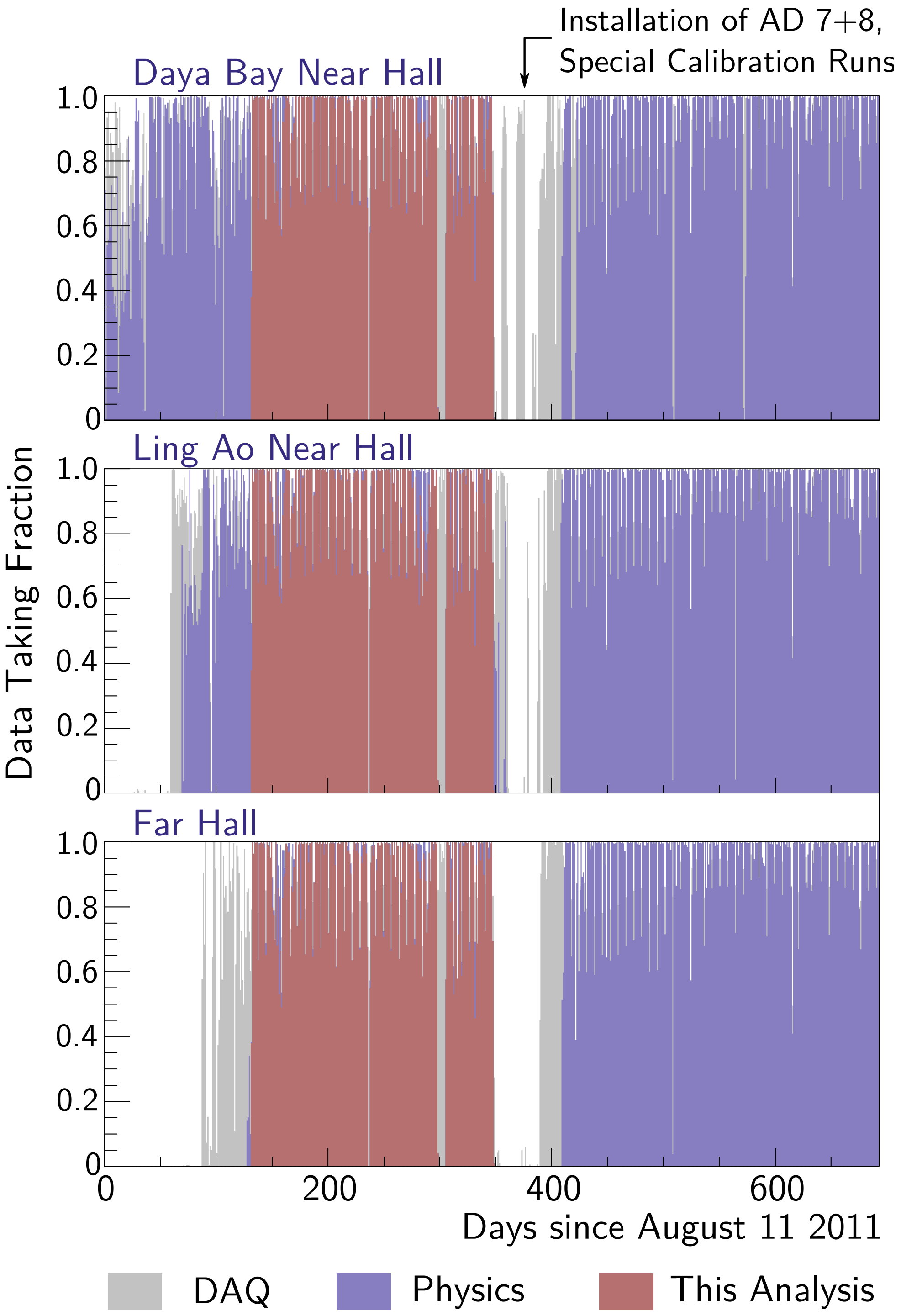
- 55 days of data, 6 ADs near+far
- PRL **108** (2012), 171803
- Top 10 breakthrough of 2012 by Science Magazine

Improved oscillation analysis [1210.6327]

- 139 days of data, 6 ADs near+far
- CP C **37** (2013), 011001

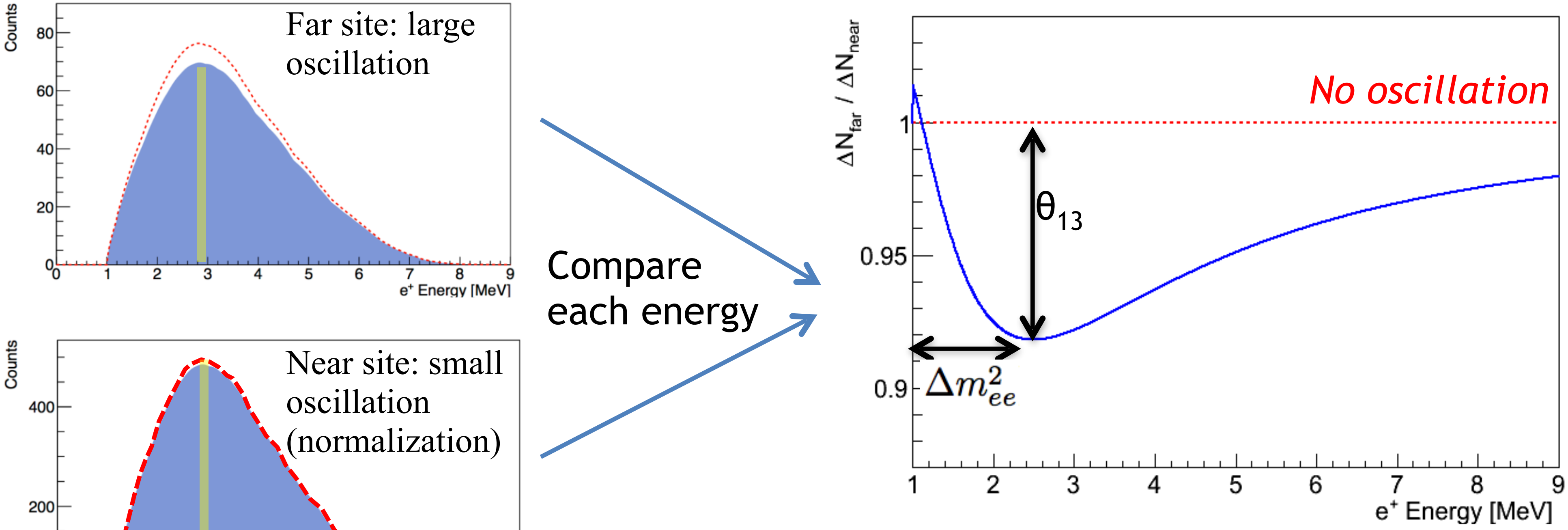
Spectral Analysis [1310.6732]

- 217 days complete 6 AD period
- 55% more statistics than CPC result



Doing a Spectral Measurement

- With a spectral measurement can measure the mass splitting:



Compare each energy

But require good understanding of the detectors' energy response!

- Which mass splitting do we measure? Define an effective mass splitting Δm^2_{ee}:

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

$$\sin^2(\Delta m^2_{ee}\tfrac{L}{4E}) \equiv \cos^2\theta_{12}\sin^2(\Delta m^2_{31}\tfrac{L}{4E}) + \sin^2\theta_{12}\sin^2(\Delta m^2_{32}\tfrac{L}{4E})$$

so that: $\left|\Delta m^2_{ee}\right| \simeq \left|\Delta m^2_{32}\right| \pm 5.21\times10^{-5}\mathrm{eV}^2$

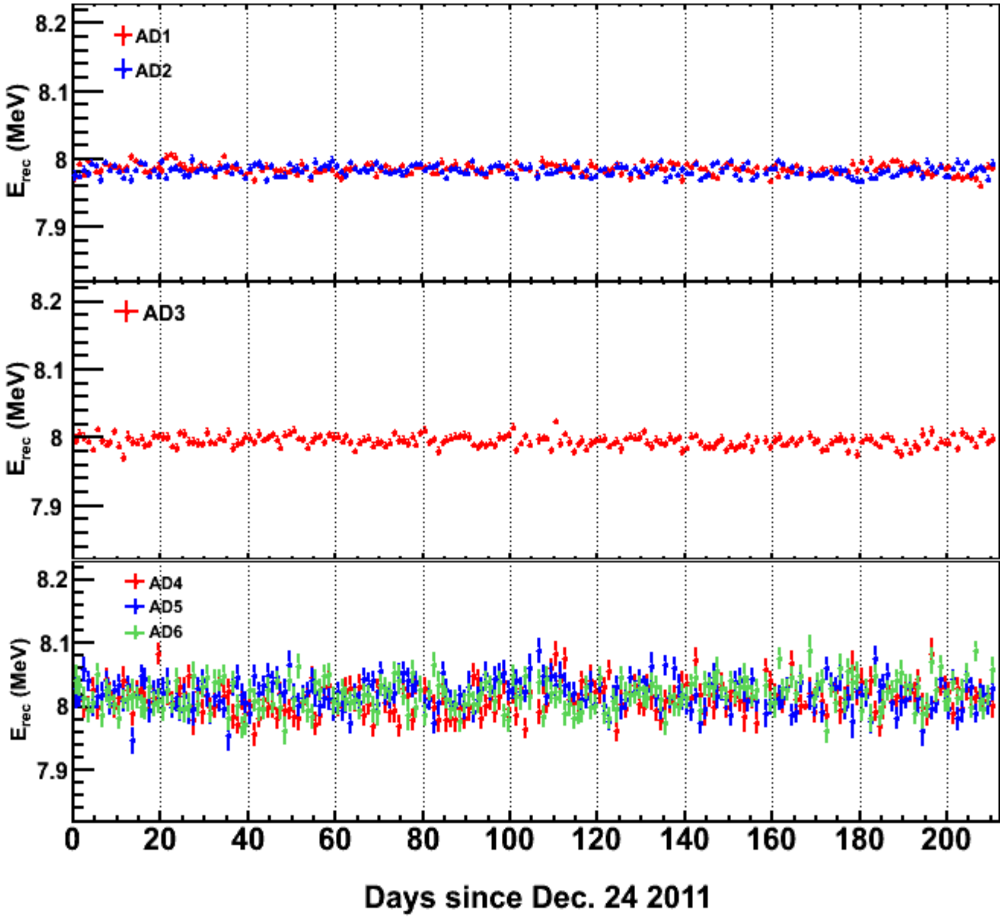
+: Normal Hierarchy
–: Inverted Hierarchy

Ingredient #1: Calibration

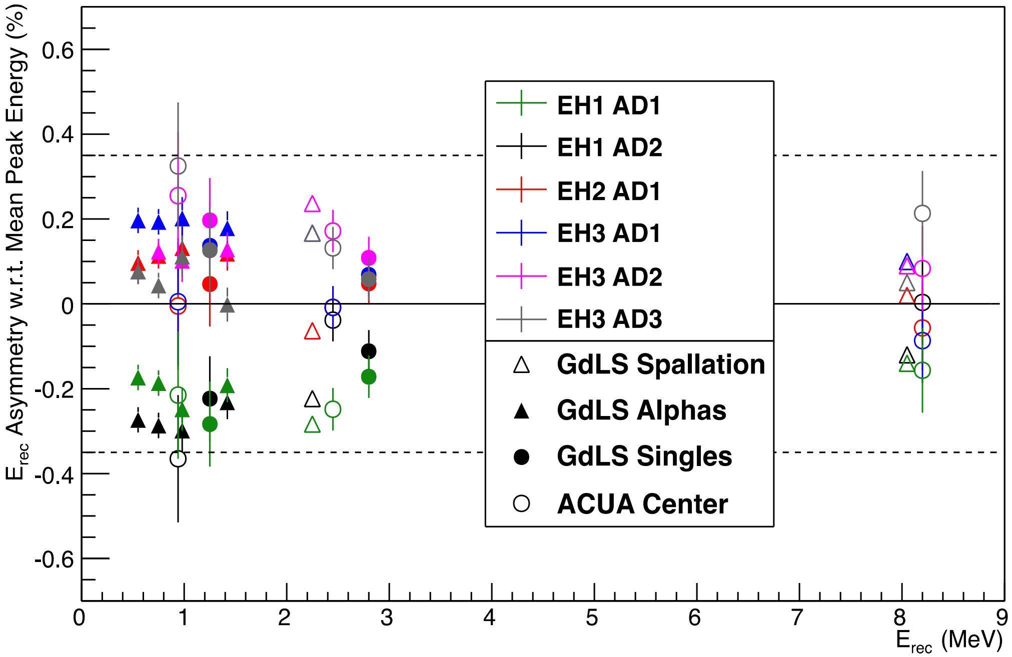
- One key is achieving a stable and consistent energy response between detectors:

After calibration, achieve energy response that is **stable to ~0.1%** in all detectors, with a **total relative uncertainty of 0.35%** between detectors.

Spallation *n*Gd capture peak vs. time (after calibration)



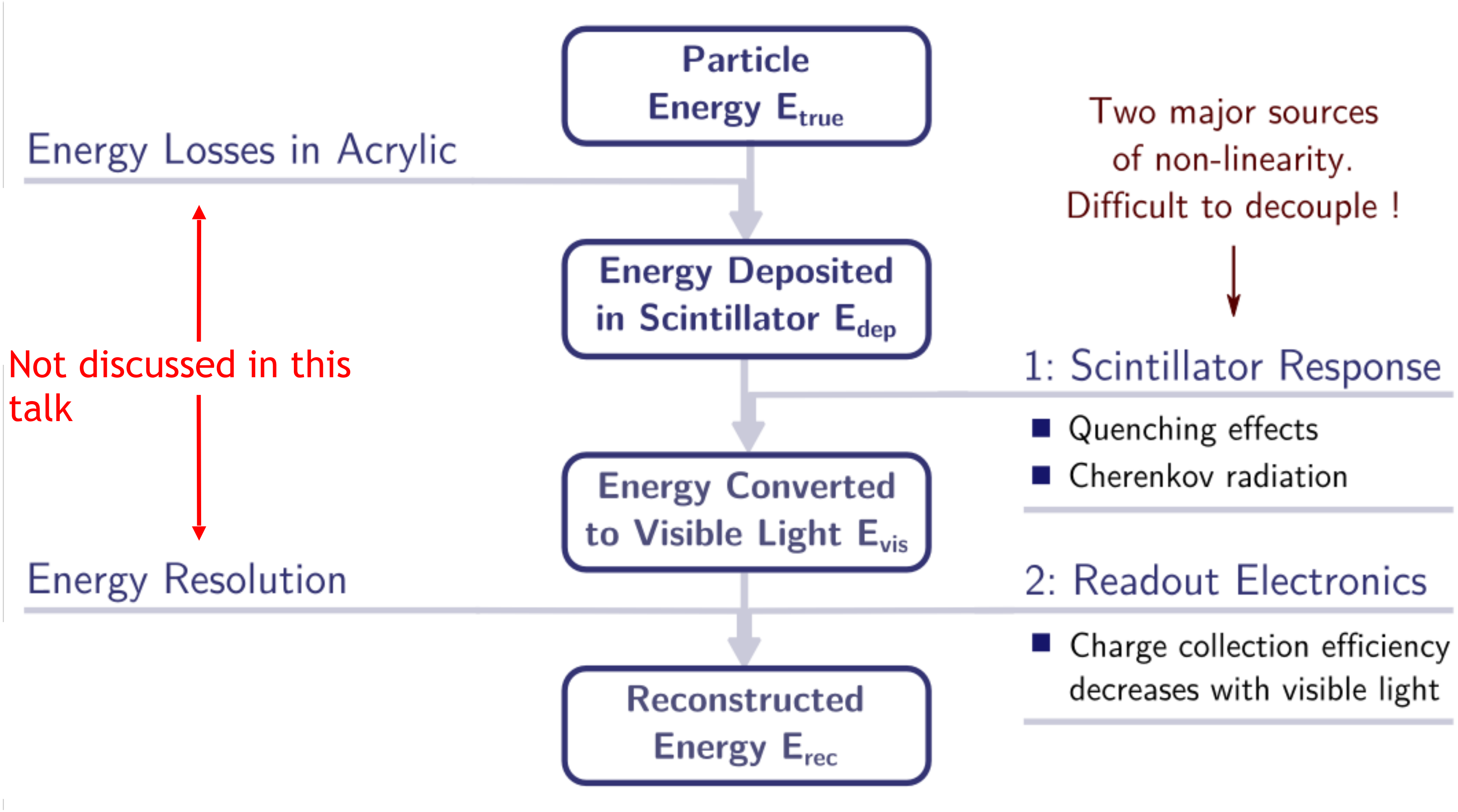
Relative energy peaks in all detectors (after calibration)



After initial reconstruction, position non-uniformity is also corrected for

Ingredient #2: Energy Response Model

- Also need to relate reconstructed kinetic energy E_{rec} to true energy E_{true}:



Particle Energy E_{true}

Energy Losses in Acrylic

Two major sources of non-linearity. Difficult to decouple !

Energy Deposited in Scintillator E_{dep}

Not discussed in this talk

1: Scintillator Response

- Quenching effects
- Cherenkov radiation

Energy Converted to Visible Light E_{vis}

2: Readout Electronics

- Charge collection efficiency decreases with visible light

Energy Resolution

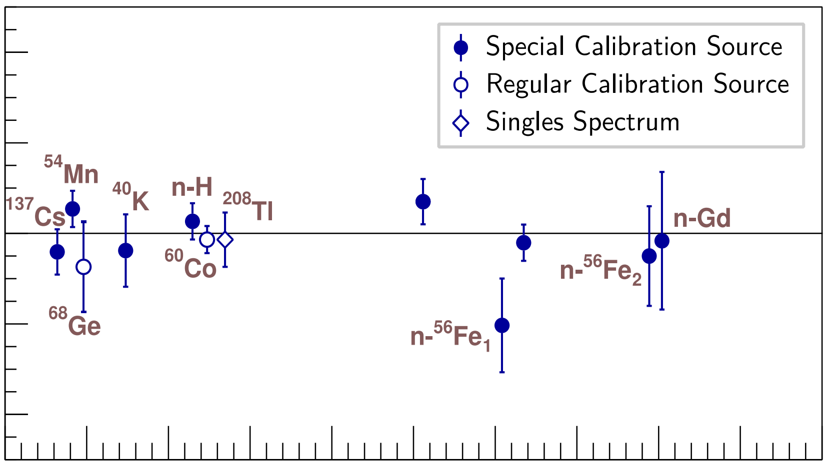
Reconstructed Energy E_{rec}

✓ **Minimal impact on oscillation measurement**

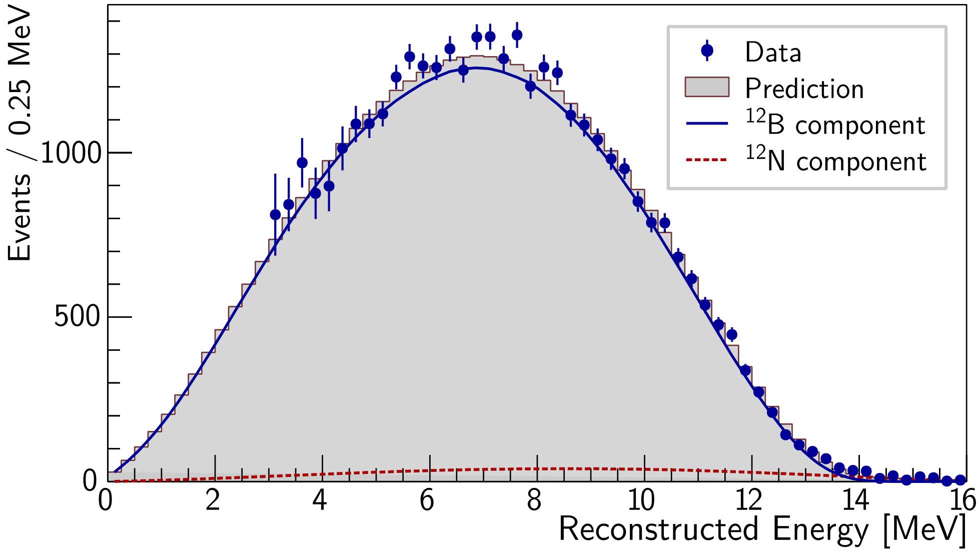
✓ **Crucial for measurement of reactor spectra (in progress)**

Ingredient #2: Non-Linearity Response Model

- Model is constrained using monoenergetic gamma lines from various sources and continuous spectrum from ^{12}B produced by muon spallation inside the scintillator:

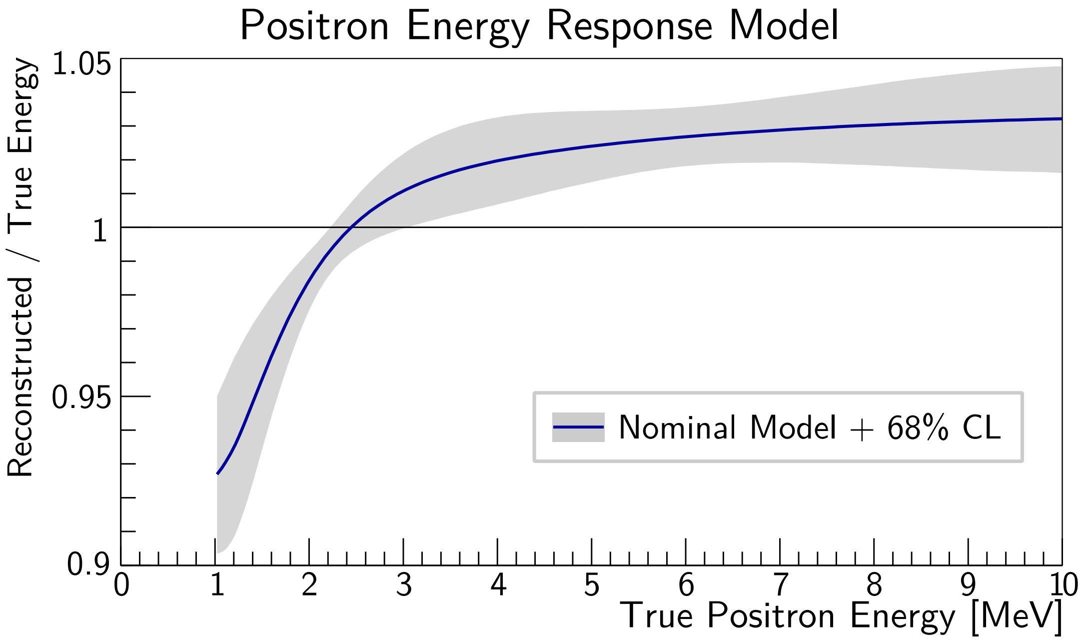


Gamma Ray Energy Peaks



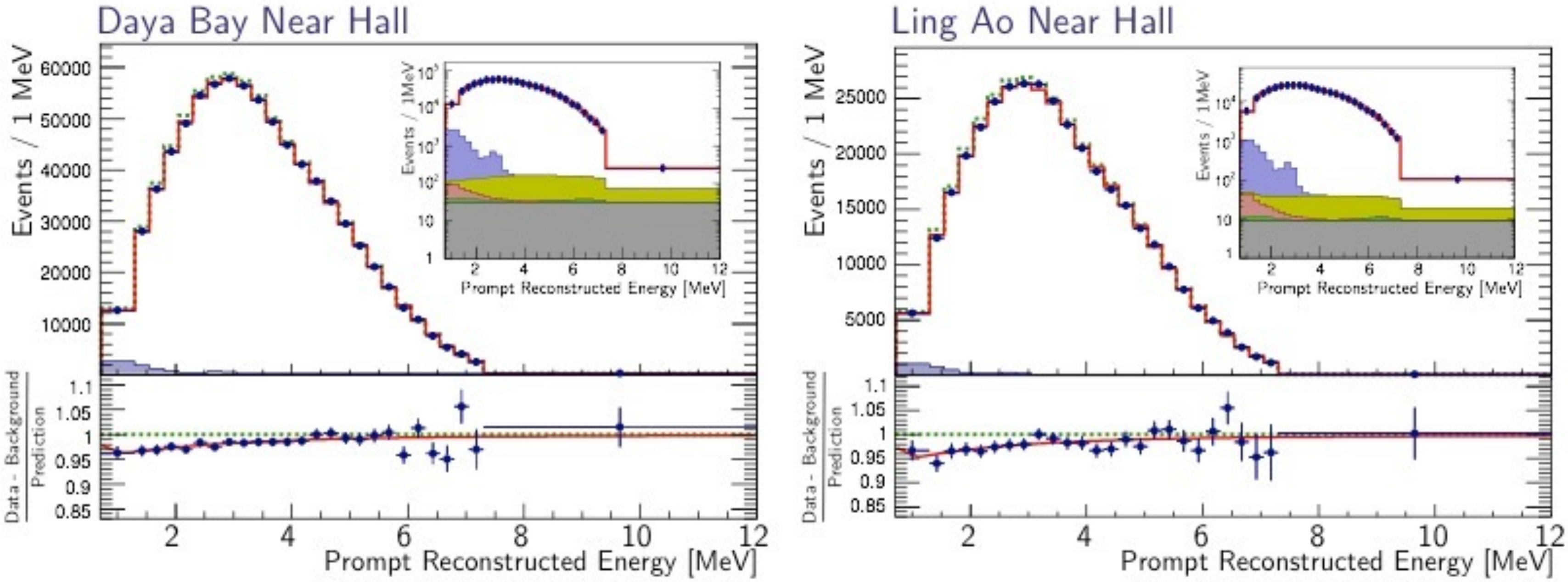
^{12}B Beta-Decay Spectrum

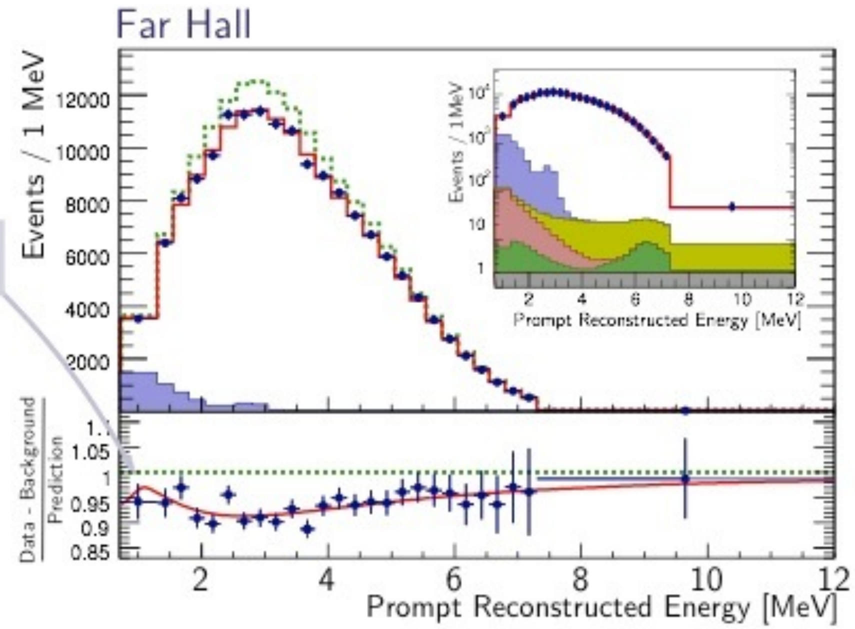
Final positron energy non-linearity response



Positron Energy Response Model

Dataset for Oscillation Analysis





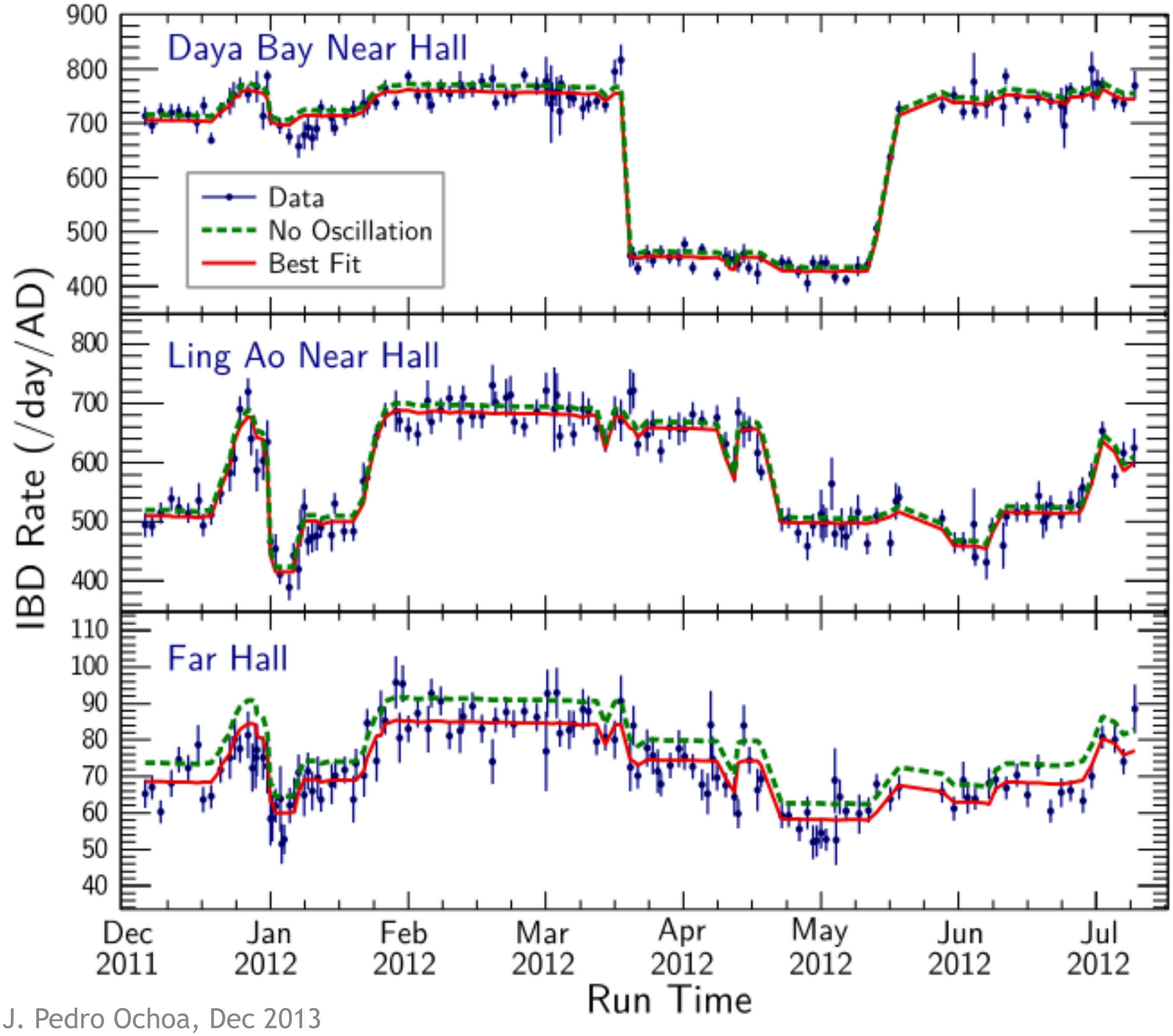
Shape distortion from energy losses in acrylic

- Backgrounds represent only 5% (2%) in far (near) sites
- Spectral Distortion is consistent with oscillations

This analysis uses more than 300k antineutrino interactions

Antineutrino Rates vs. Time

- For main analysis we simultaneously fit all detectors using reactor model, with the absolute normalization as a free parameter:

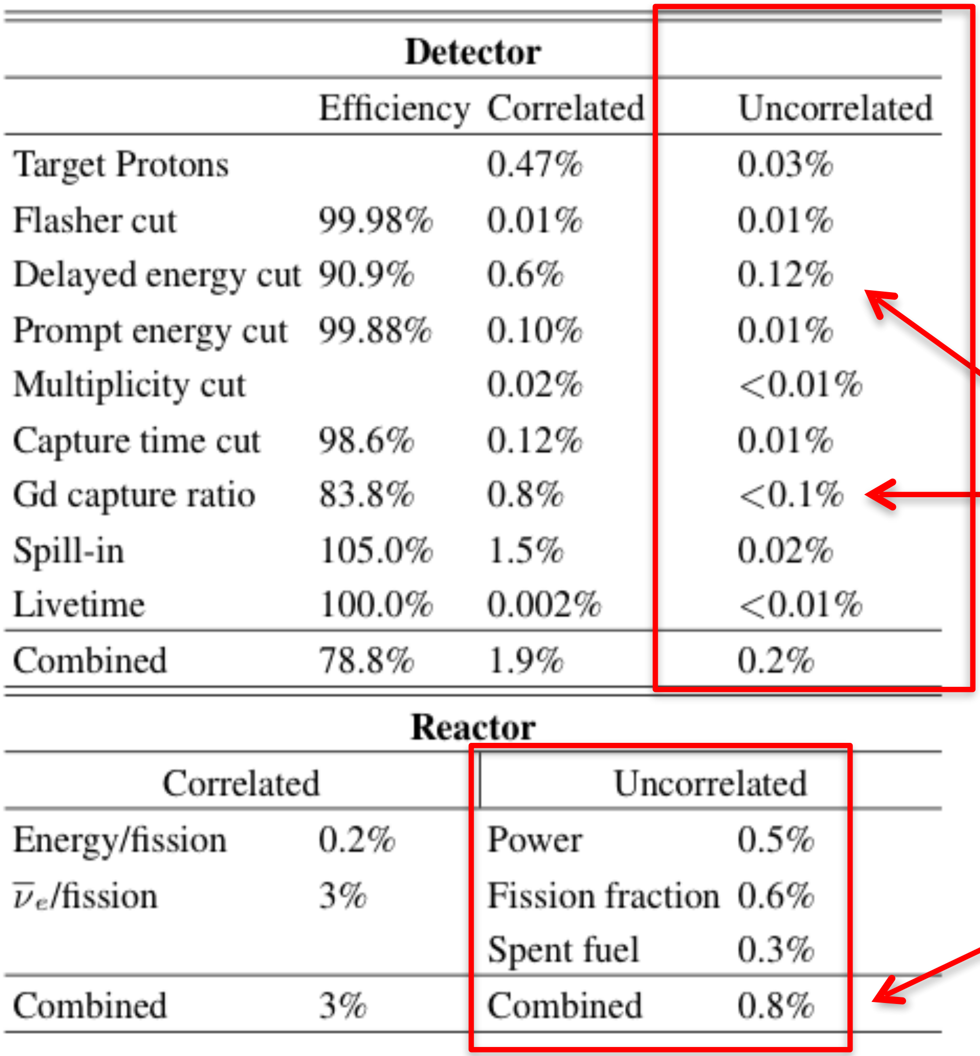


Note:

- Normalization is determined by fit to data. It is within a few percent of expectations.
- Paper on absolute reactor neutrino flux and shape is in preparation

Detected rate strongly correlated with reactor flux expectations

Systematic 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 play a significant role

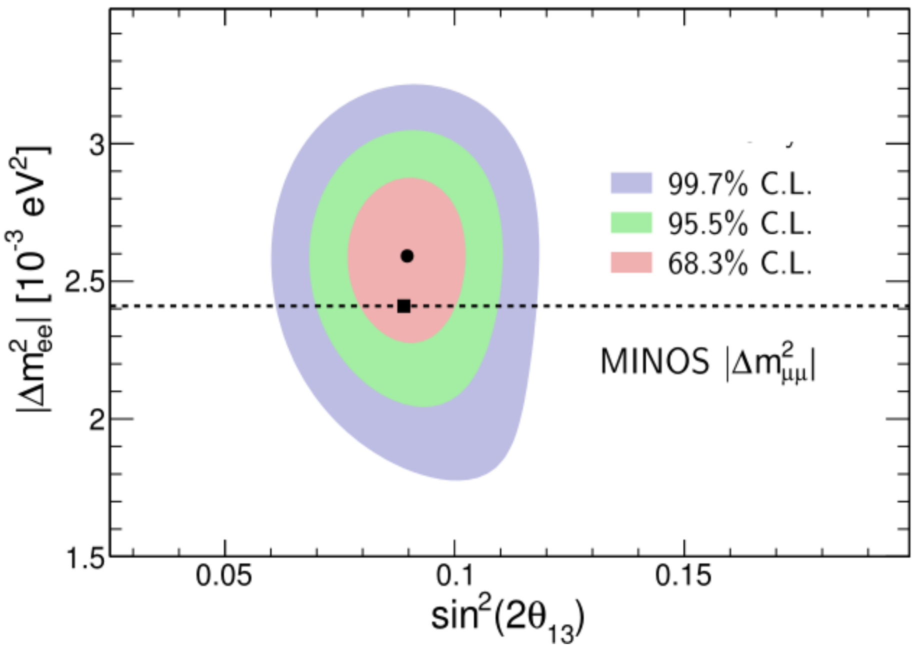
Largest systematics are smaller than far site statistics (~0.5%)

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

- Statistics contribute 73% (65%) to total uncertainty in $\sin^2 2\theta_{13}$ ($|\Delta m^2_{ee}|$)
- Major systematics:
  - θ_{13}: Reactor model, relative + absolute energy, and relative efficiencies
  - $|\Delta m^2_{ee}|$: Relative energy model, relative efficiencies, and backgrounds

Results

- Rate + shape results are consistent with previous results:



$$\sin^2 2\theta_{13} = 0.090^{+0.008}_{-0.009}$$

$$|\Delta m^2_{ee}| = 2.59^{+0.19}_{-0.20} \cdot 10^{-3}\text{eV}^2$$

$$\chi^2/N_{\text{DoF}} = 162.7/153$$

World's first measurement in this channel!

Strong confirmation of oscillation-interpretation of observed $\bar{\nu}_e$ deficit

	Normal MH Δm^2_{32} [10^{-3}eV^2]	Inverted MH Δm^2_{32} [10^{-3}eV^2]
From Daya Bay Δm^2_{ee}	$2.54^{+0.19}_{-0.20}$	$-2.64^{+0.19}_{-0.20}$
From MINOS $\Delta m^2_{\mu\mu}$	$2.37^{+0.09}_{-0.09}$	$-2.41^{+0.11}_{-0.09}$

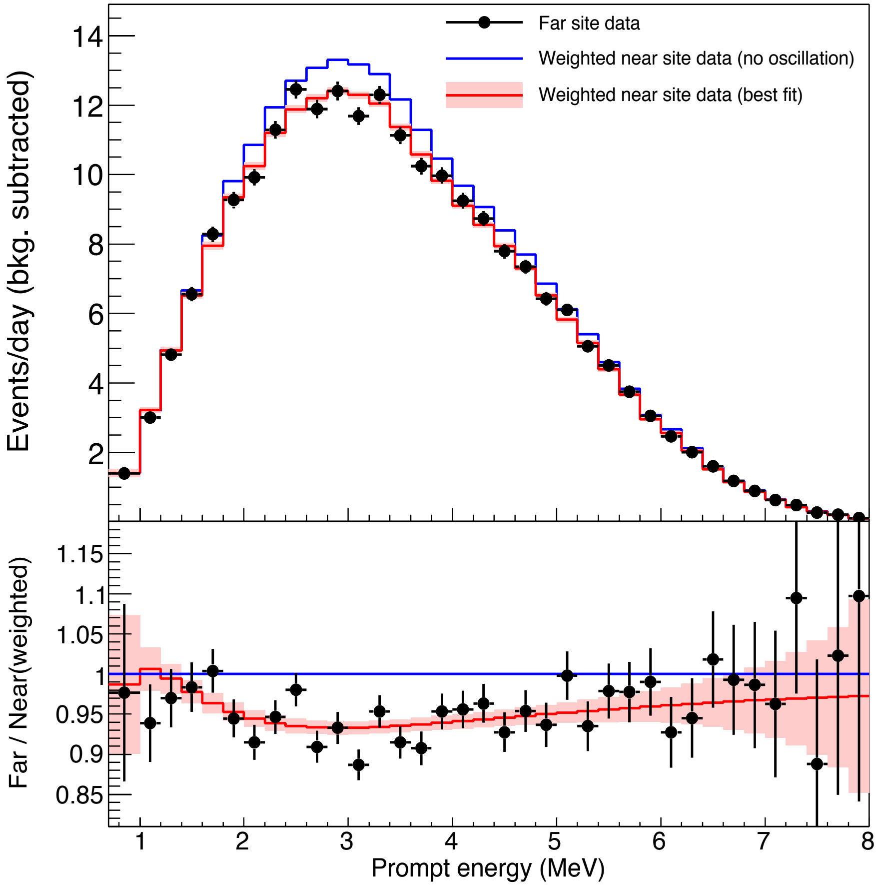
A. Radovic, DPF2013

Independent Cross-Check

Independent crosscheck with minimal reactor assumptions

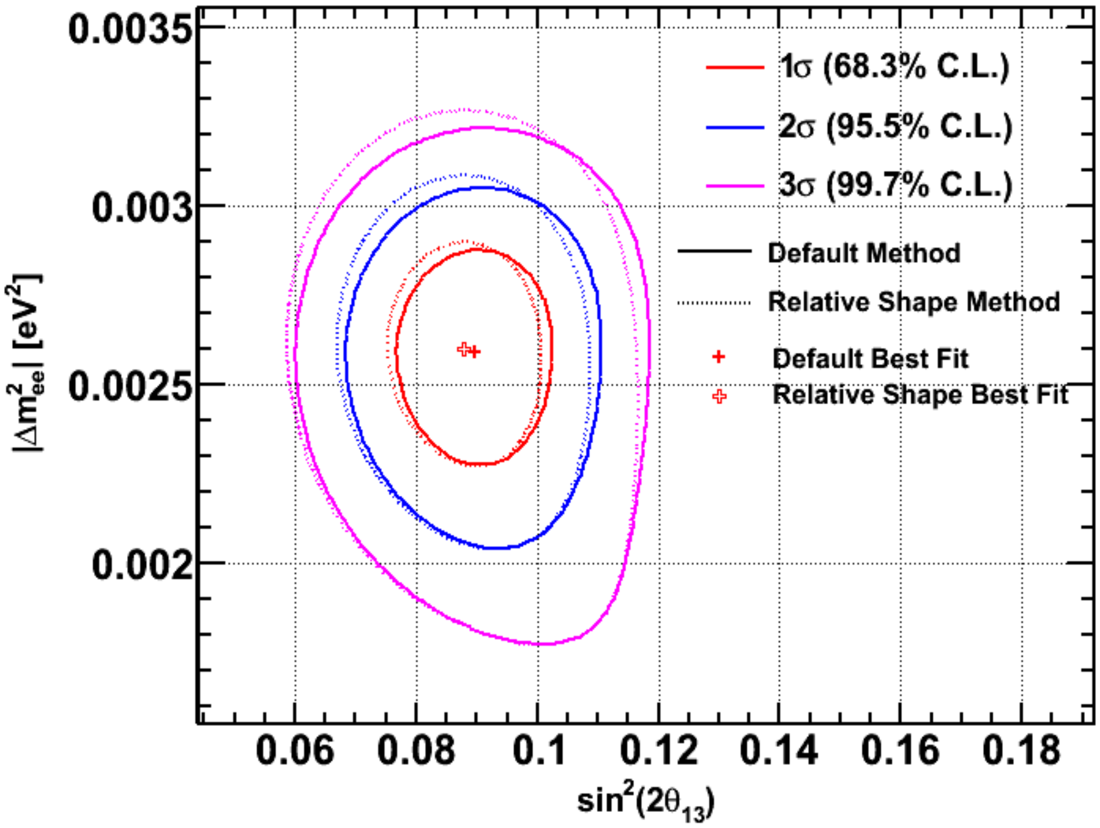
Predict far spectra directly from measured near site spectra

→ Minimizes impact of absolute flux and spectra prediction.

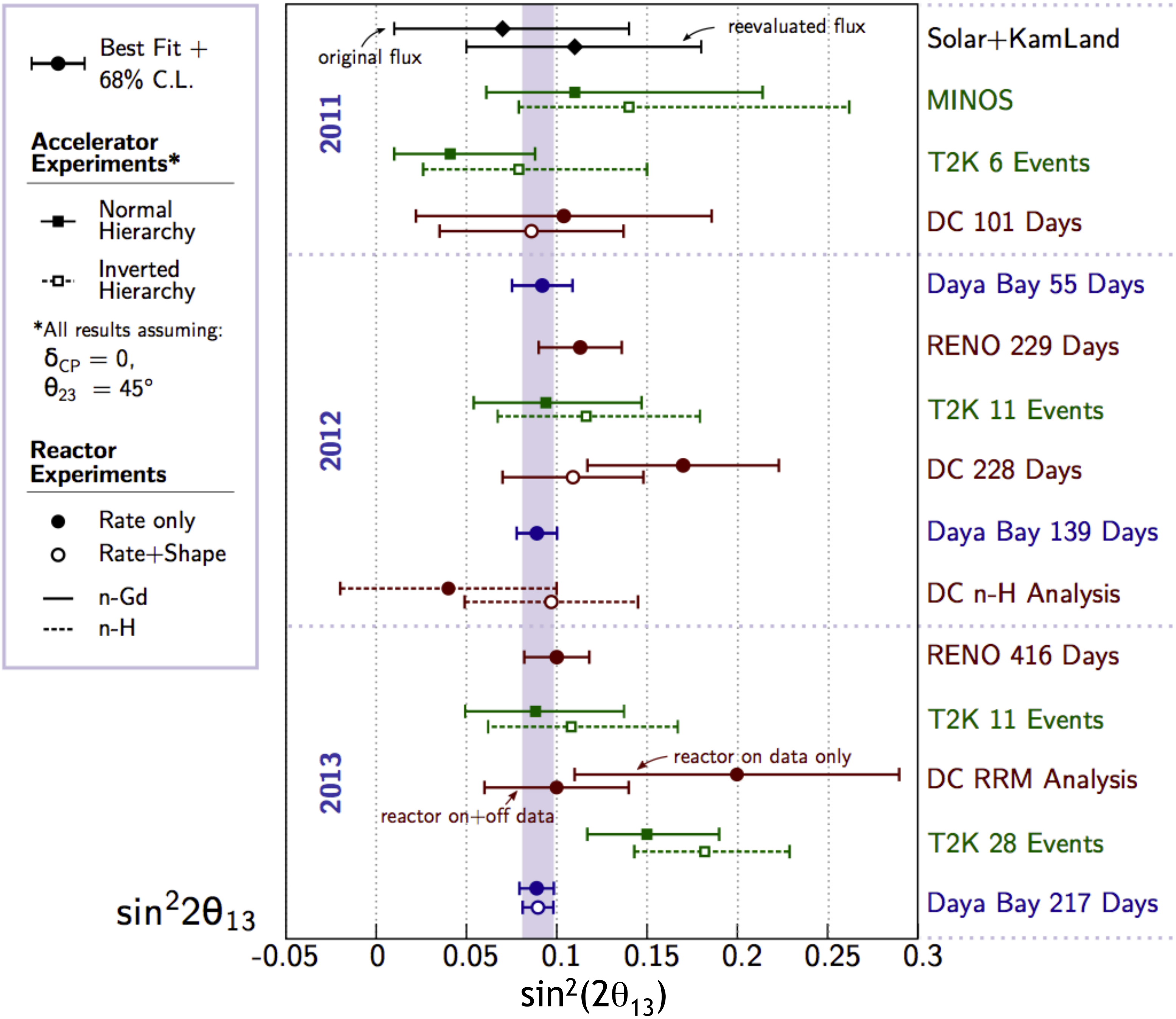


Use covariance matrices to account for systematic errors

→ Alternate method finds consistent uncertainties for neutrino parameters.



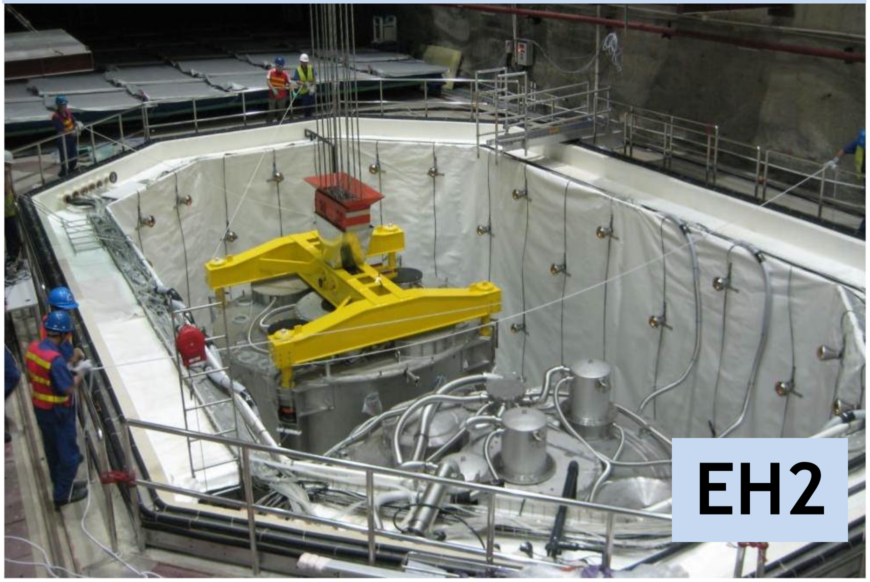
Global Landscape of θ_{13} Measurements

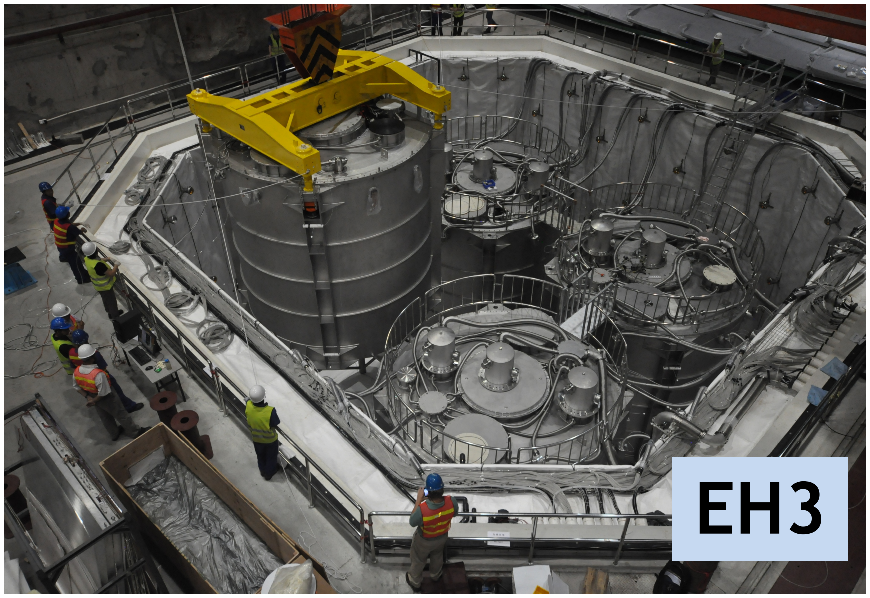


World's most precise measurement of θ_{13} to date.

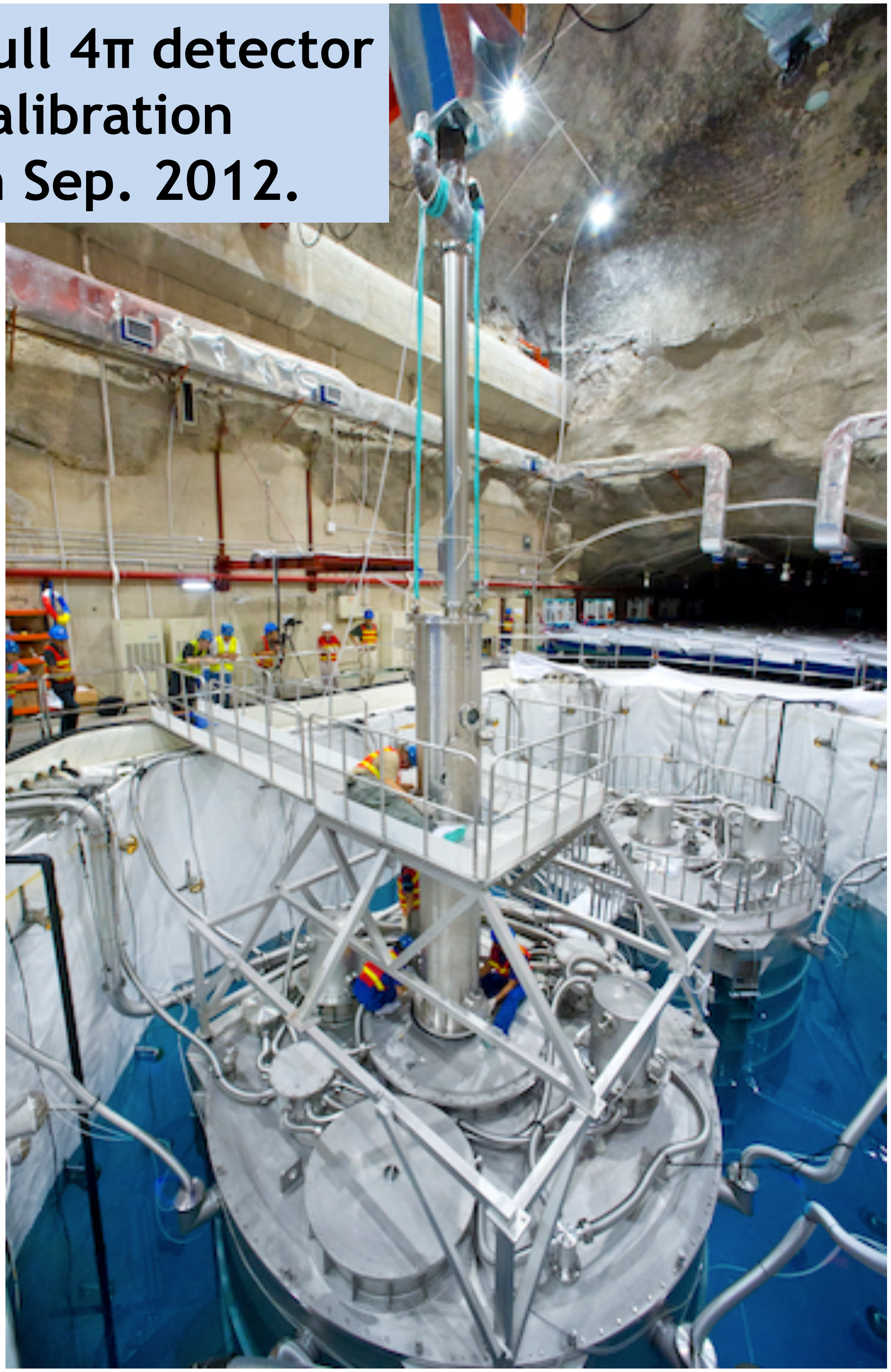
Daya Bay Onsite Progress

Final two detectors installed, operating since Oct. 2012.



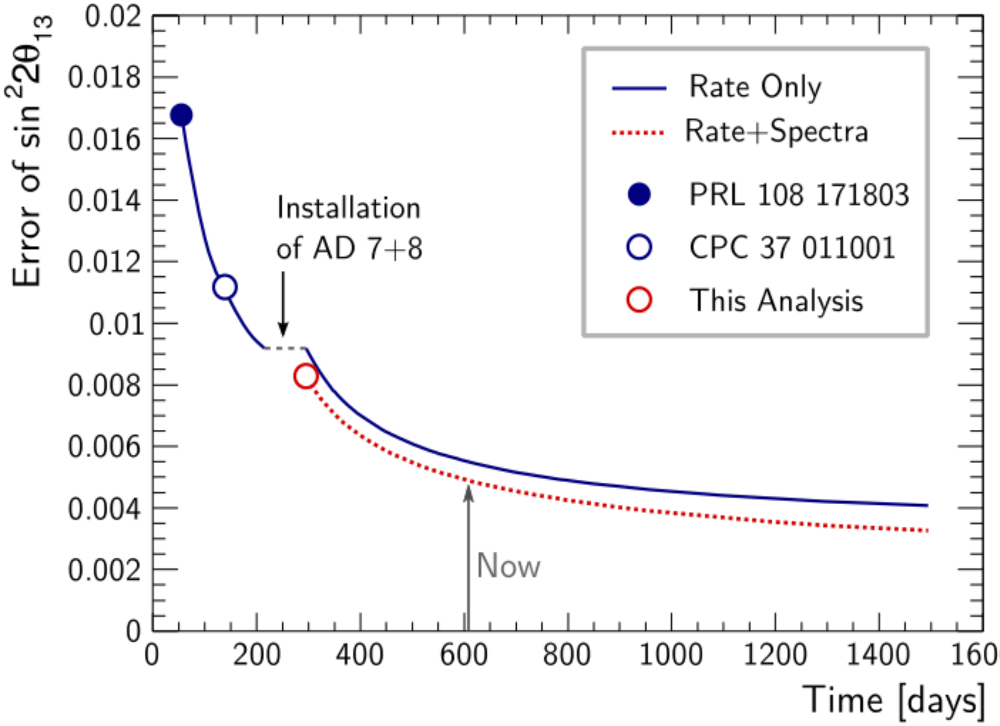


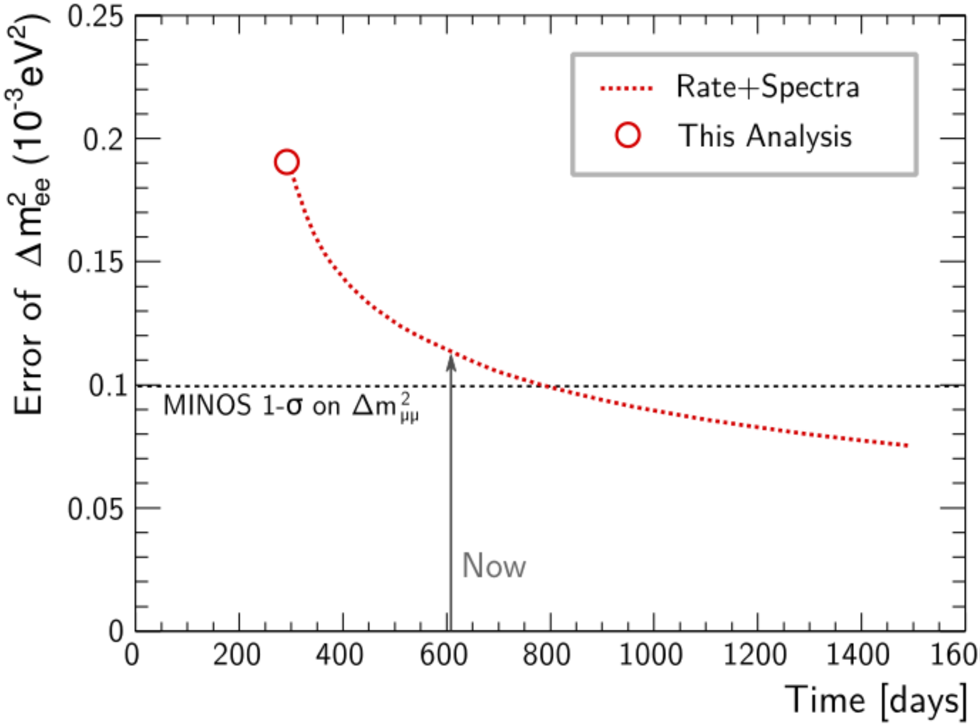
Full 4π detector calibration in Sep. 2012.



Daya Bay’s Future

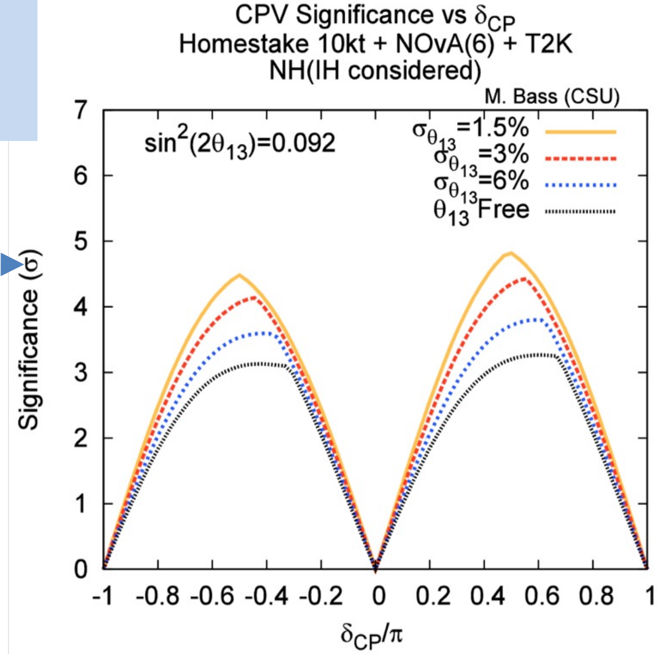
- ❖ Increased precision in oscillation parameters:





World’s most precise measurement of θ_{13} for a long time to come, and very precise estimate of Δm^2

- ✓ Constrains non-standard oscillation models
- ✓ Improves reach of next-generation experiments



- ❖ Absolute reactor neutrino spectrum flux and shape measurement:
  - ✓ Probe reactor models and explore reactor antineutrino ‘anomaly’
- ❖ Others (cosmogenic production, supernovae… etc)

Summary & Conclusions

- First direct measurement of the short-distance electron antineutrino oscillation frequency:

$$|\Delta m^2_{ee}| = 2.59^{+0.19}_{-0.20} \times 10^{-3}\, eV^2$$

- Most precise estimate of the θ_{13} mixing angle:

$$\sin^2(2\theta_{13}) = 0.090^{+0.008}_{-0.009}$$

- Stay tuned for more exciting results from Daya Bay!

Thank you for your attention!