The Latest Daya Bay Results in Neutrino Oscillation and Reactor Flux Studies

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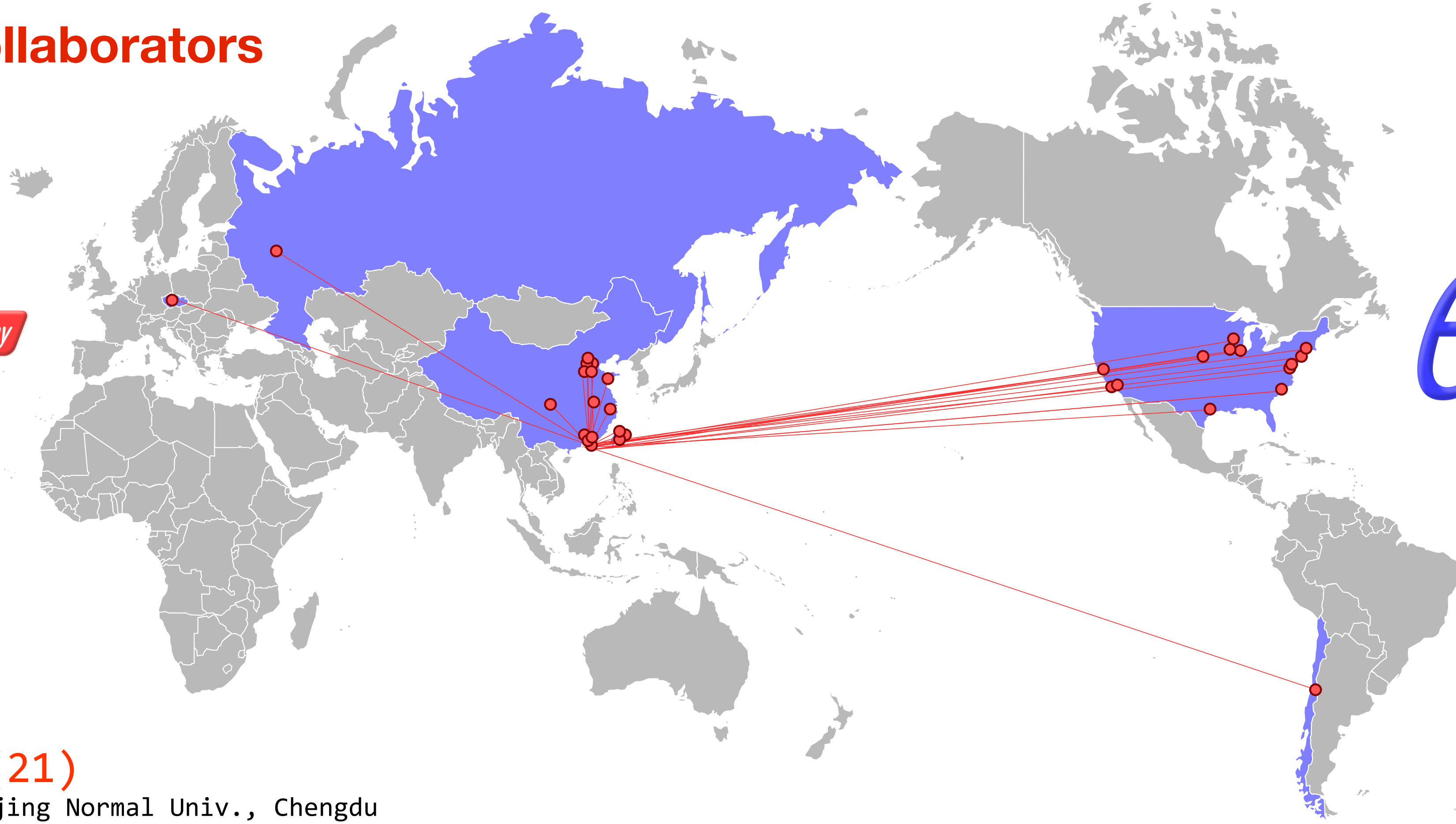
2nd International Workshop on Particle Physics and Cosmology after Higgs and Planck, Hsinchu, Oct 9, 2014

- *A review of the Daya Bay experiment*
- *The first oscillation results of the complete Daya Bay*
- θ_{13} *measurement using neutron capture on hydrogen events*
- *Oscillation searches at* $\Delta m^2 \sim 0.01\text{-}0.1\ eV^2$ *scales*
- *Reactor flux and spectrum results*
- *Summary & conclusion*

The Daya Bay Collaboration

~230 collaborators



Asia (21)

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

North America (17)

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

Europe (2)

JINR, Dubna, Russia; Charles University, Czech Republic

South America (1)

Catholic Univ. of Chile

Neutrino Oscillation Physics using Reactors

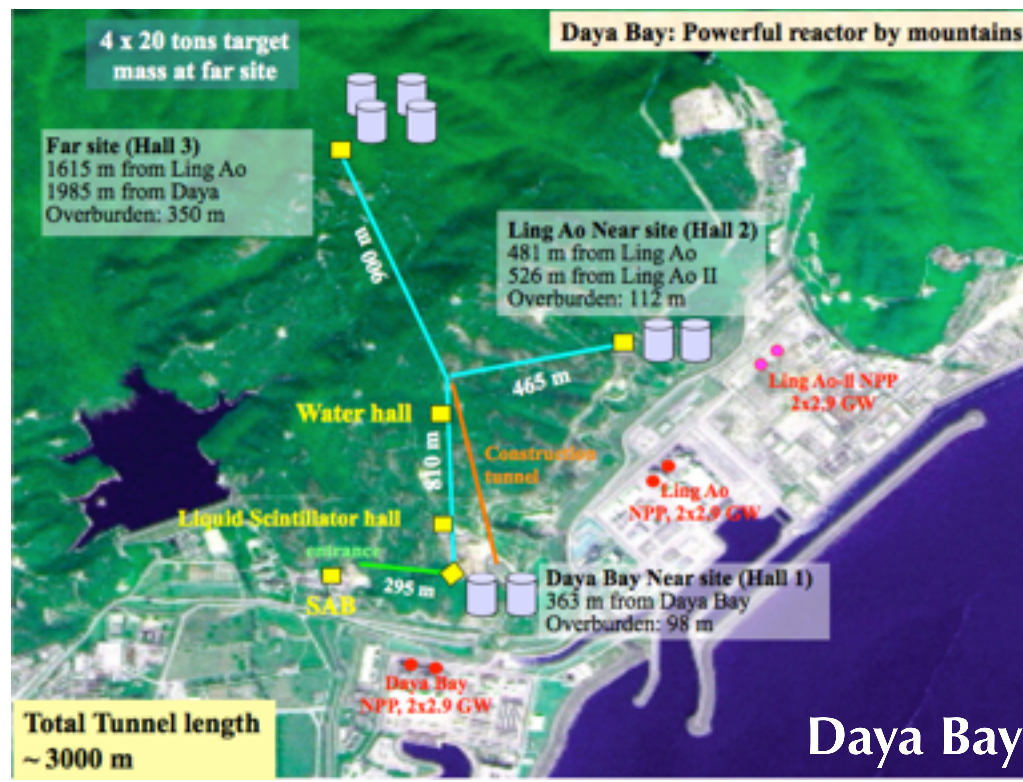
$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix}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

Atmospheric Sector:	The Lastly Known:	Solar Sector:
SK, K2K/T2K/MINOS, **DYB**, etc	Short-baseline Reactor, T2K	SNO,KamLAND, SK etc

- Two practical ways to measure θ_{13}

$$P_{\nu_\alpha \to \nu_\beta} = 1 - 4 \sum_{i<j} |V_{\alpha j}|^2 |V_{\beta i}|^2 \sin^2 \frac{\Delta m^2_{ji} L}{4E}$$

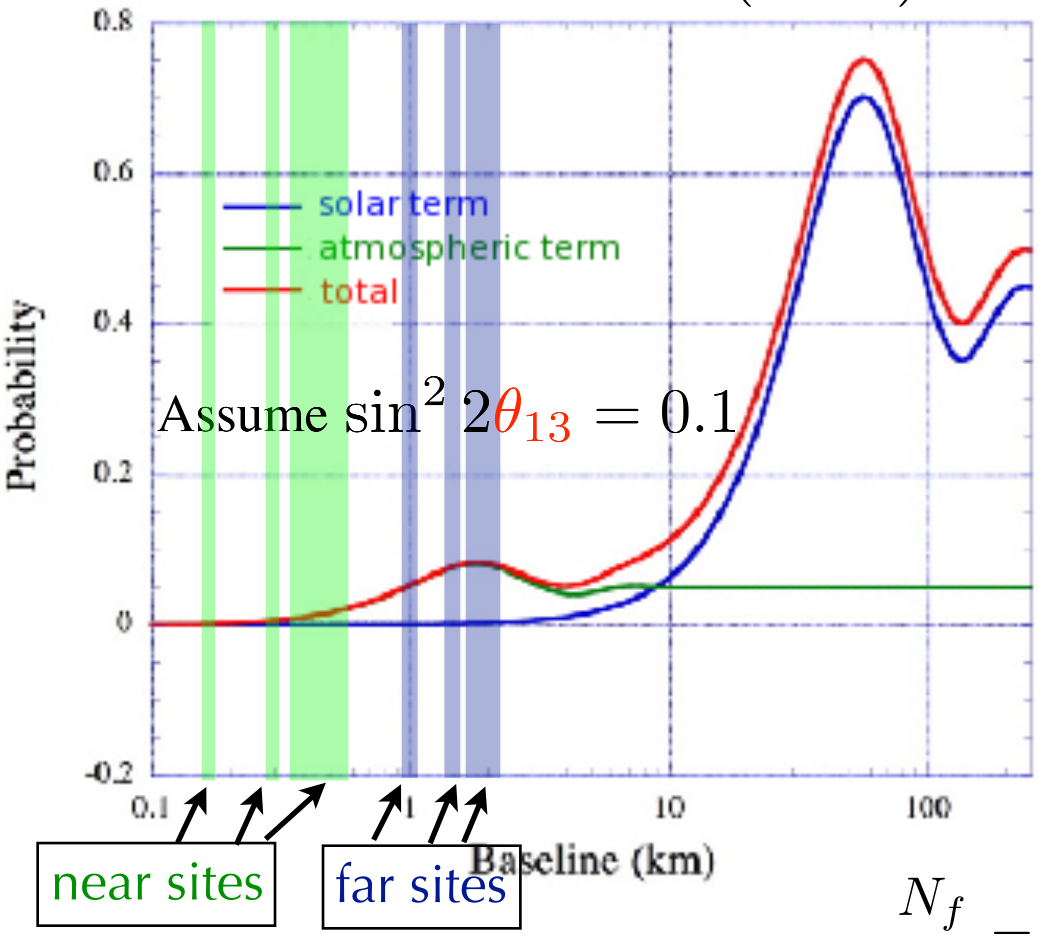
  - **Appearance experiments $\nu_\mu \to \nu_e$** depend on 3 unknown parameters θ_{13}, δ_{CP} and mass hierarchy
  - **Short-baseline reactor experiments $\nu_e \to \nu_e$** depend on 2 unknown parameters θ_{13} and mass hierarchy, with mass hierarchy has little effect



Design of the Daya Bay Experiment

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

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



Important lessons learned from past reactor experiments:

- Near-far reactor flux uncertainty **cancellation.** (First proposed for Kr2Det in 2000)
- 2 versus many: functionally **"identical"** detectors
  - ✦ And 8 is the lucky number of Daya Bay due to the layout

$$\frac{N_f}{N_n} = \frac{N_{\text{proton},f}}{N_{\text{proton},n}} \frac{\epsilon_f}{\epsilon_n} \left(\frac{L_n}{L_f} \right)^2 \frac{P_{sur}(\sin^2 2\theta_{13}, L_f, E)}{P_{sur}(\sin^2 2\theta_{13}, L_n, E)}$$

Time Correlation Detection of Reactor Antineutrinos

Detection Principle: Inverse Beta Decay (IBD)

0.1% Gd doped liquid scintillator (LS) as target

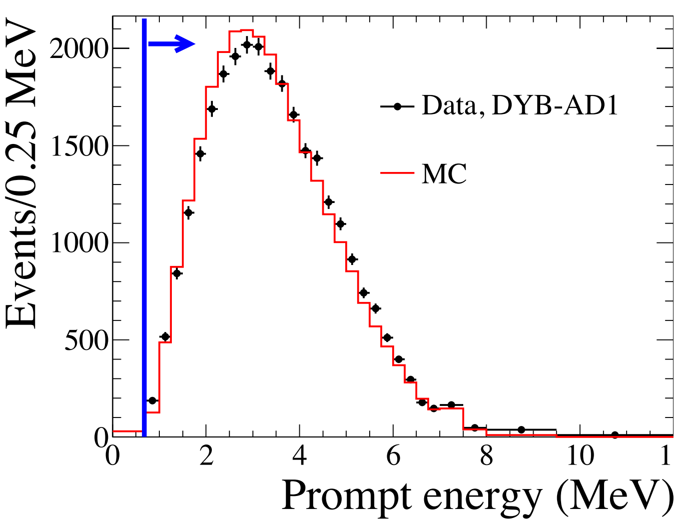
$$\bar{\nu}_e + p \rightarrow e^+ + n \xrightarrow{0.3\text{b}} n + p \rightarrow D + \gamma(2.2\,\text{MeV})$$

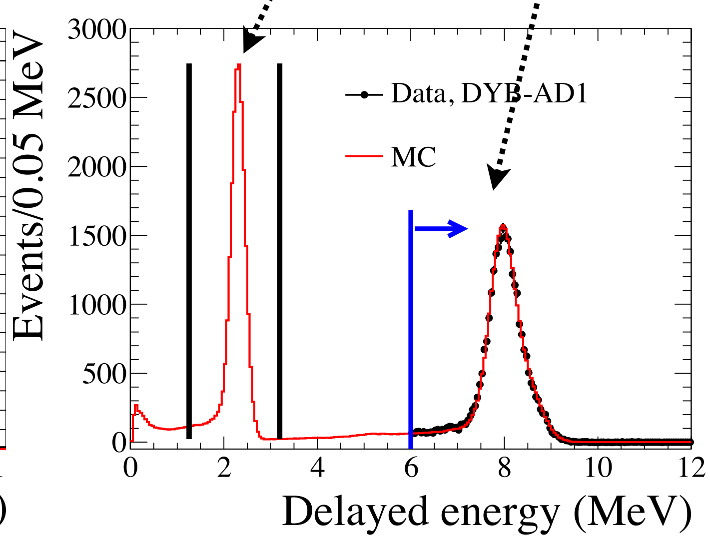
$$E_{\bar{\nu}_e} \approx E_{e^+} + m_n - m_p$$

~49,000b

$$n + Gd \rightarrow Gd^* \rightarrow Gd + \gamma(\sim 8\,\text{MeV})$$

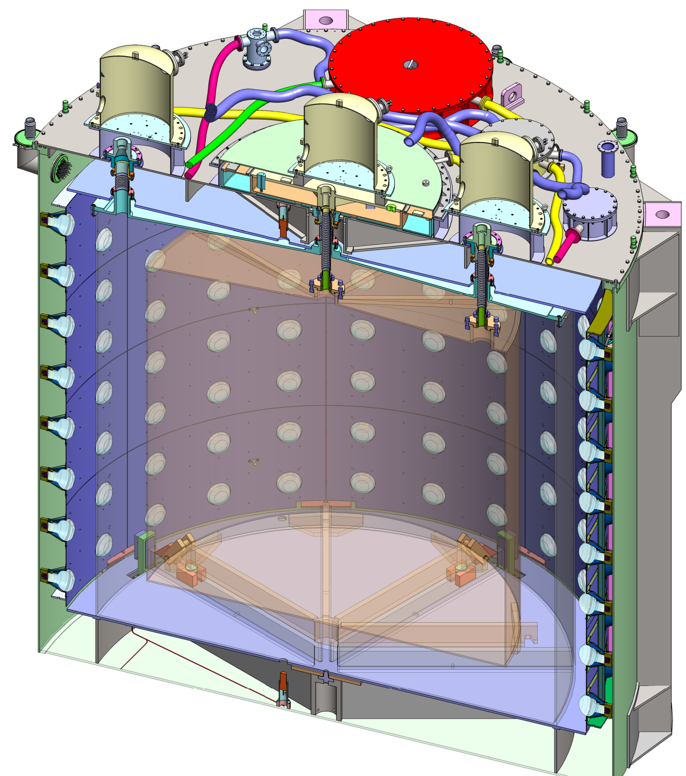
Prompt-delayed correlation is the key!





Correlated Signals

- Powerful background suppression
- Well-defined targets: captures generate lights in LS zones and 8MeV delayed signals only from the Gd zone



Daya Bay Progresses since Summer 2011

A. Two-detector data taking checking "identical" detectors, 9/23/11 – 12/23/11, [90 days]

- Side-by-side comparison of 2 detectors, *NIM A **685**, 78-97 (2012)*

B. Partial Daya Bay six-detector data taking 12/24/11 – 7/28/12, [217 days]

- θ_{13}, *PRL. **108**, 171803 (2012)*, [55 days]
- θ_{13}, *CPC **37**, 011001 (2013)* , [139 days]
- θ_{13} & Δm^2_{ee}, *PRL. **112**, 061801 (2014)*, [217 days]
- **NEW: Daya Bay reactor antineutrino flux analysis (tomorrow)**
- **NEW: θ_{13} using neutron captures on H [217 days]**
- **NEW: sterile neutrino searches [217 days]**

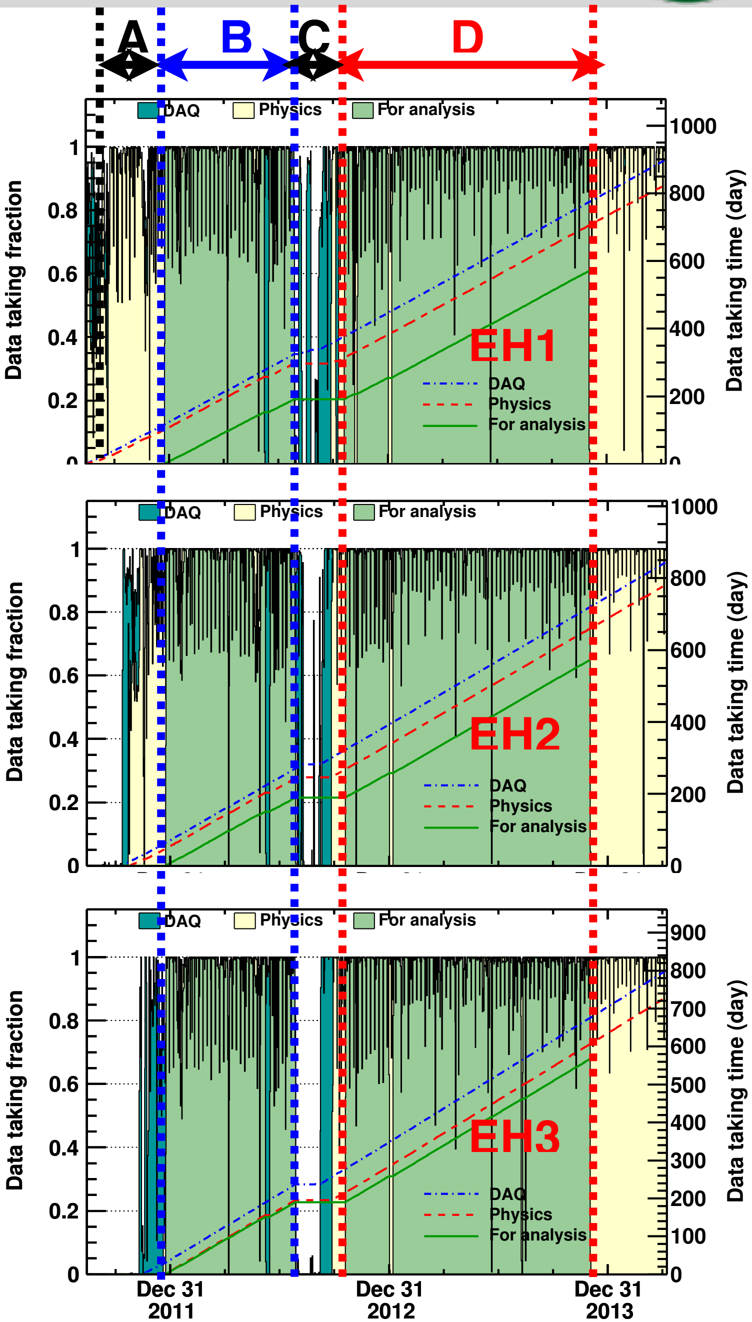
C. Shutdown, 8-detector completion and special calibrations

- Calibration with the manual calibration system, special sources, and reconfiguration of Am-C sources in far site detectors

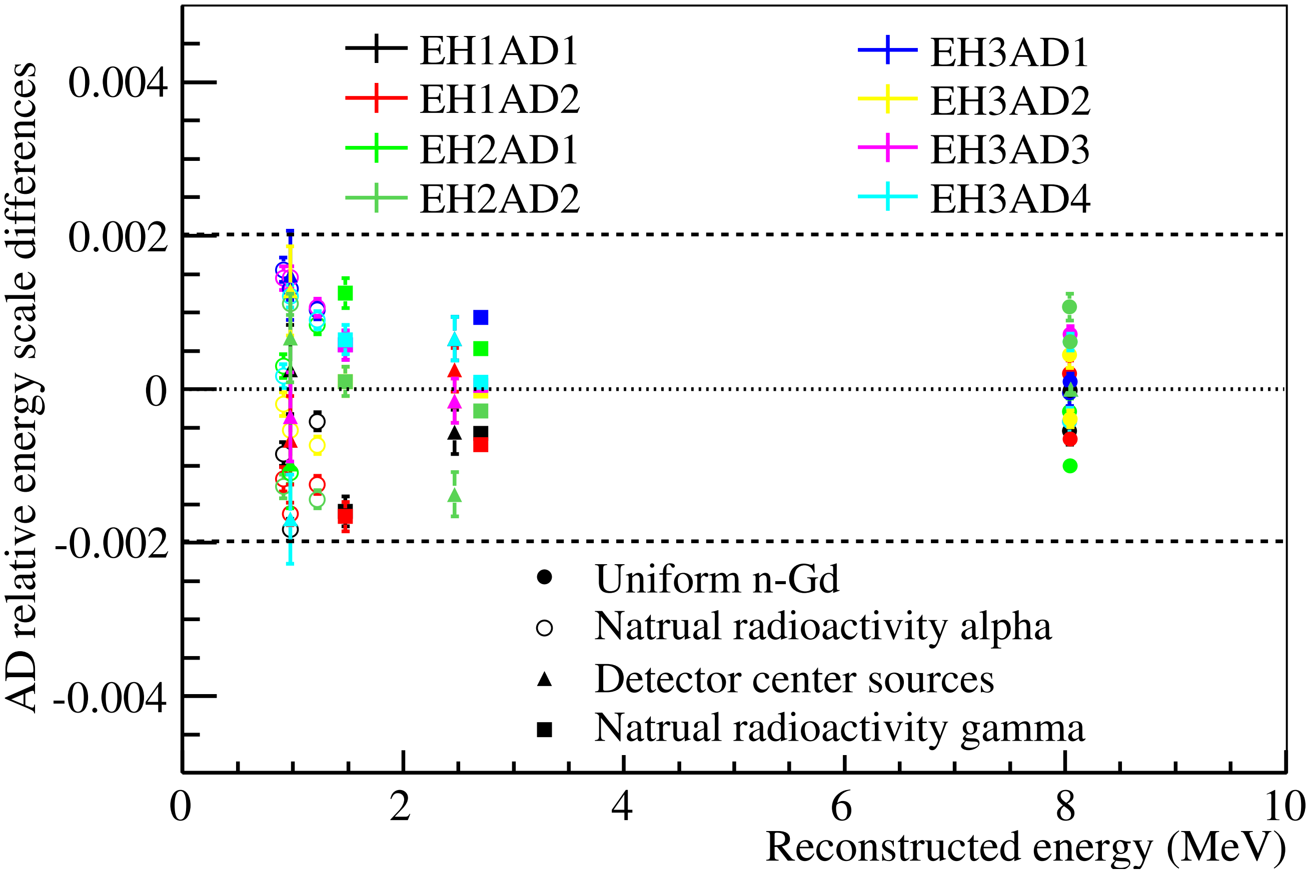
D. Complete Daya Bay 8-detector data taking since 10/19/12

This NEW oscillation analysis combines both 6-AD and 8-AD till Nov 28, 2013, Periods B and D, 621 days of data taking

- **A NEW energy model, ~1% uncertainty**
- **NEW: the most precise θ_{13} and the most precise Δm^2_{ee}**



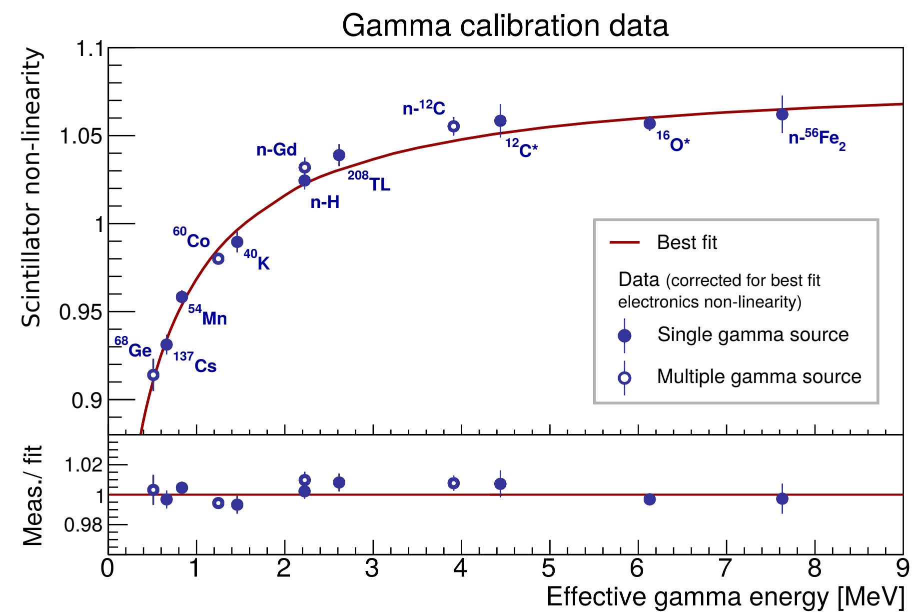
Improvements in Relative Energy Responses

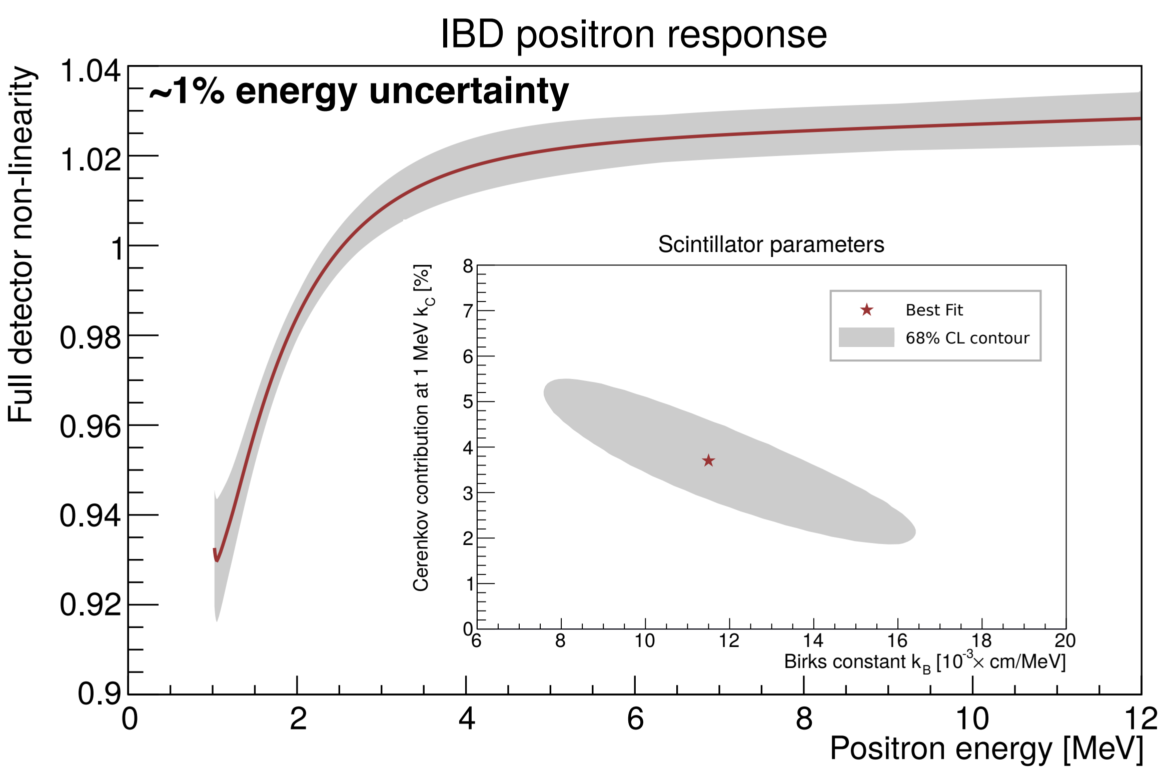


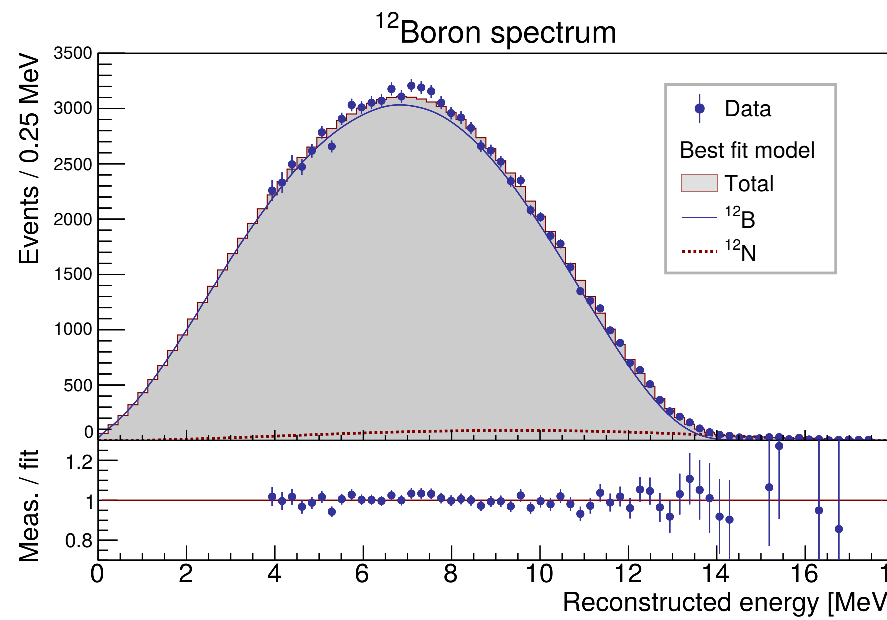
- We have improved our energy reconstruction by more careful controls of channel quality and corresponding corrections
- The relative energy scale uncertainty between 8 detectors is now within 0.2%, improved from 0.35% in 2013 which was between 6 detectors

Improved Energy Non-linearity Model

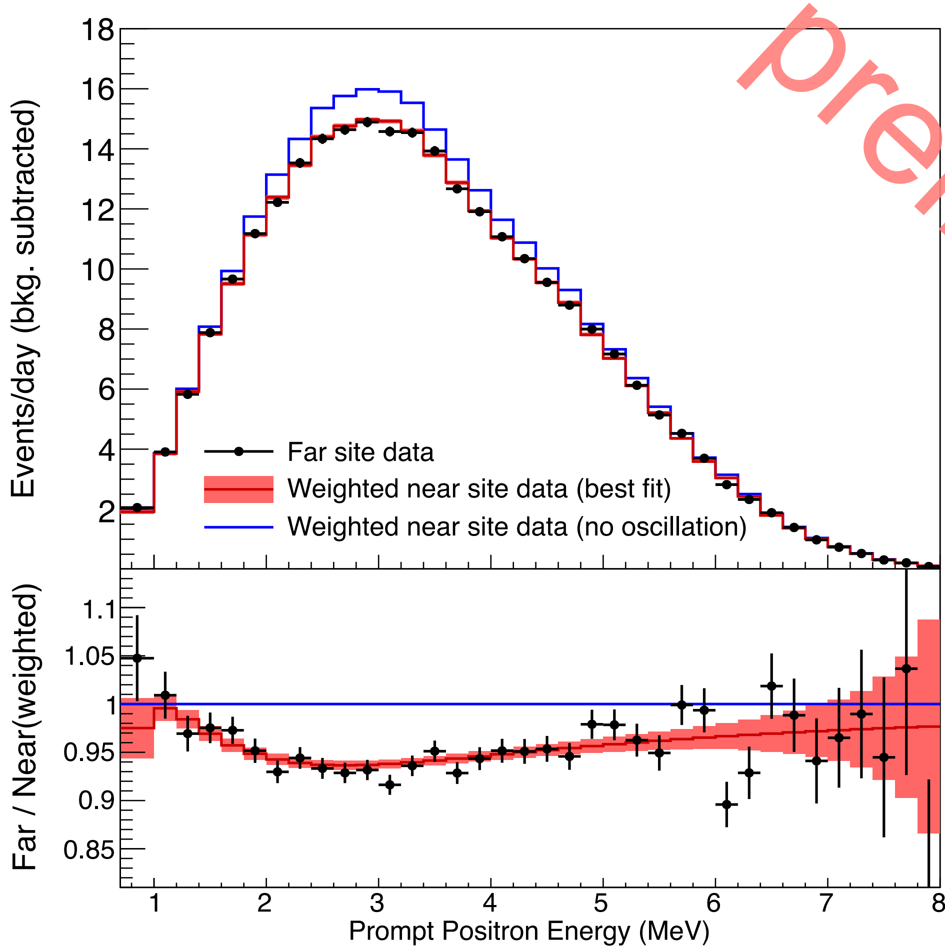
- Daya Bay absolute energy scale uncertainty consists of two components: the electronic non-linearity and the liquid scintillator non-linearity
- Electronic non-linearity checked by FADC
- (Almost) all mono-energetic gammas and ^{12}B beta data in the right energy range constrain the LS non-linearity

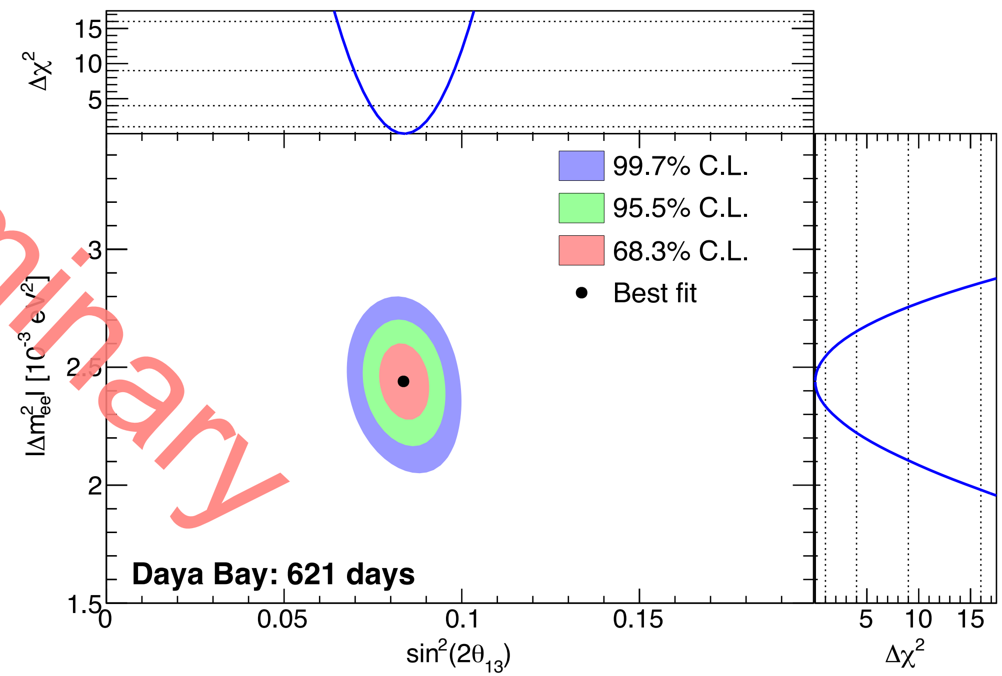






The Latest Daya Bay Oscillation Analysis





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

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

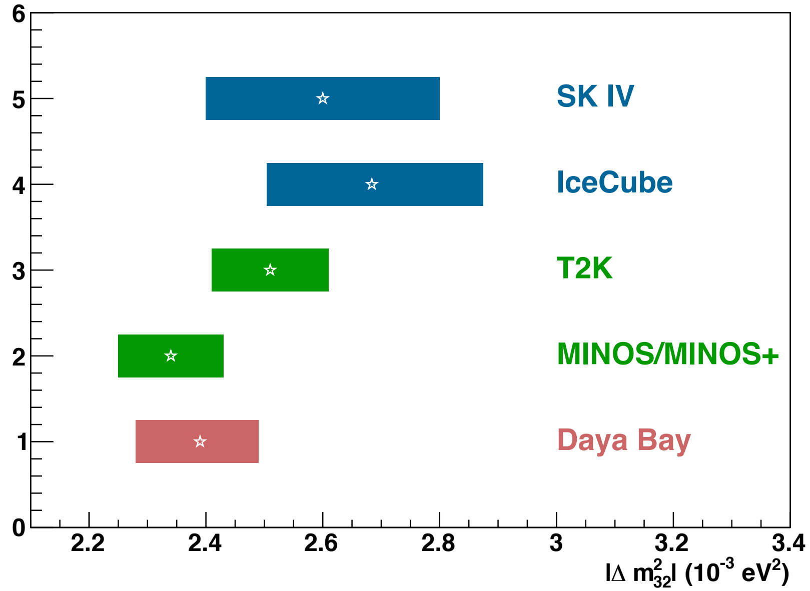
$$\chi^2/NDF = 134.7/146$$

- 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**

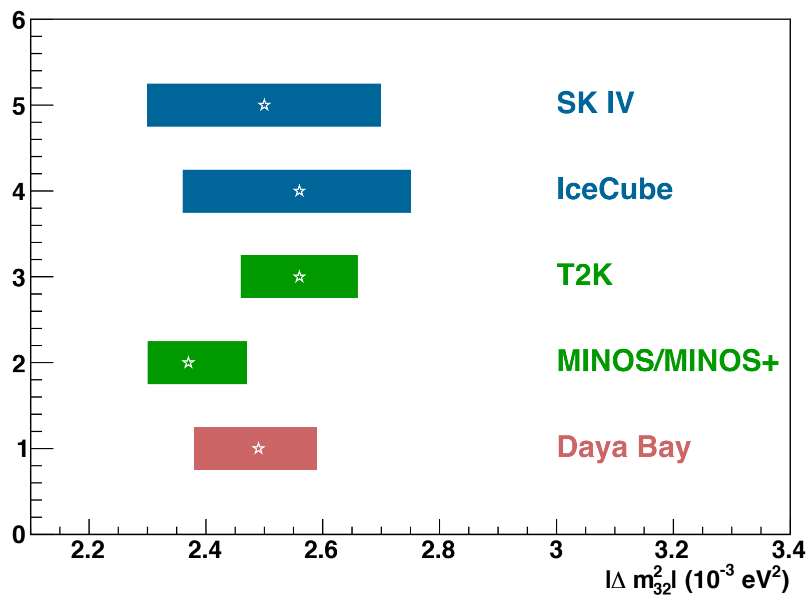
- The most precise $\sin^2 2\theta_{13}$ measurement, ~6%
- The most precise Δm^2_{ee} measurement, comparable to long-baseline muon beam experiments

The Significance of Δm^2_{ee}

assuming Normal Mass Hierarchy



assuming Inverted Mass Hierarchy



Δm^2_{32} measurements from five experiments

All Results are from Neutrino 2014

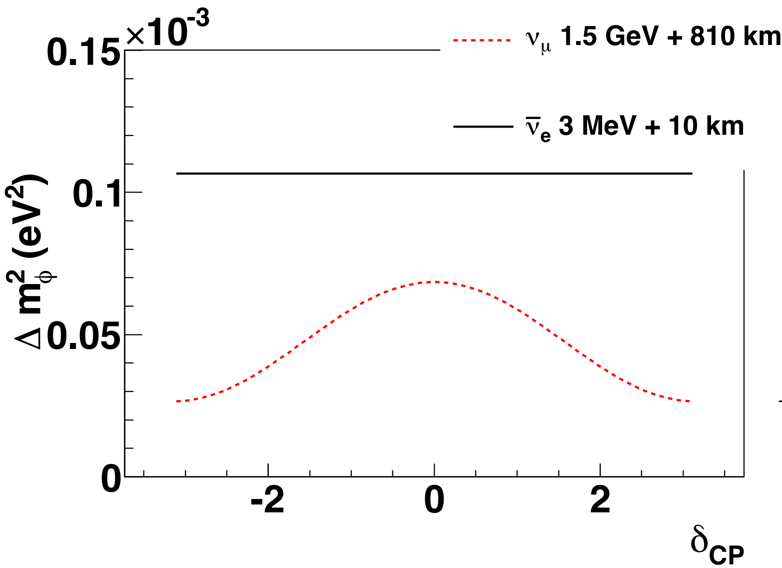
Atmospheric Neutrinos

Accelerator Neutrinos

Reactor Neutrinos

(Global Δm^2_{32} measurements slightly favors inverted mass hierarchy)

Why is the e-type Δm^2 Measurement Interesting?

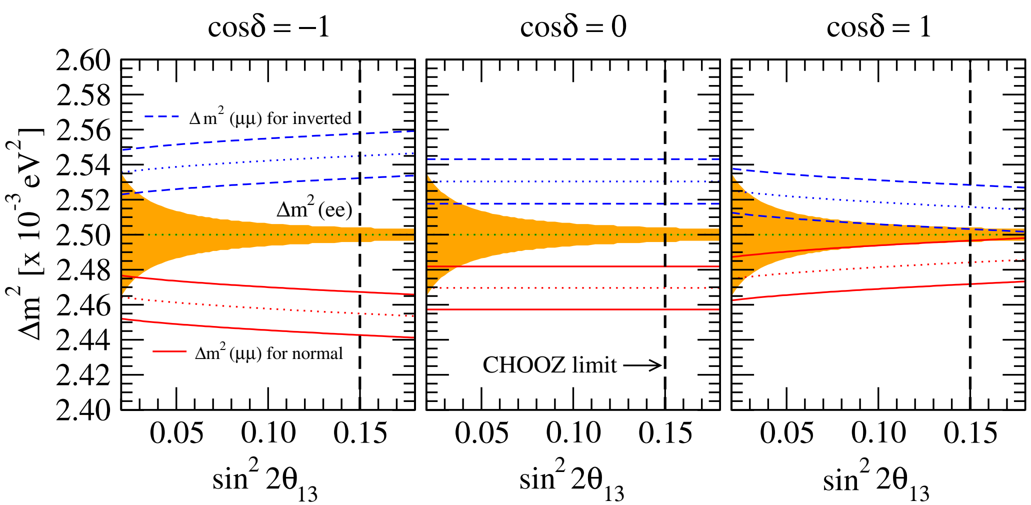


$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$
$$= 1 - 2s_{13}^2c_{13}^2 - 4c_{13}^4 s_{12}^2 c_{12}^2\sin^2\Delta_{21} + 2s_{13}^2c_{13}^2\sqrt{1-4s_{12}^2c_{12}^2\sin^2\Delta_{21}}\cos(2\Delta_{32}\pm\phi)$$

$$P_{\nu_\mu\to\nu_\mu} = 1 - P_{21}^{\mu} - \cos^2\theta_{13}\sin^2 2\theta_{23}\sin^2\frac{(\Delta m_{32}^2 \pm \phi)L}{4E}$$

Qian et al, PRD87(2013)3, 033005

FIG. 6: The dependence of effective mass-squared difference $\Delta m^2_{ee\phi}$ (solid line) and $\Delta m^2_{\mu\mu\phi}$ (dotted line) w.r.t. the value of δ_{CP} for $\bar{\nu}_e$ and ν_μ disappearance measurements, respectively.



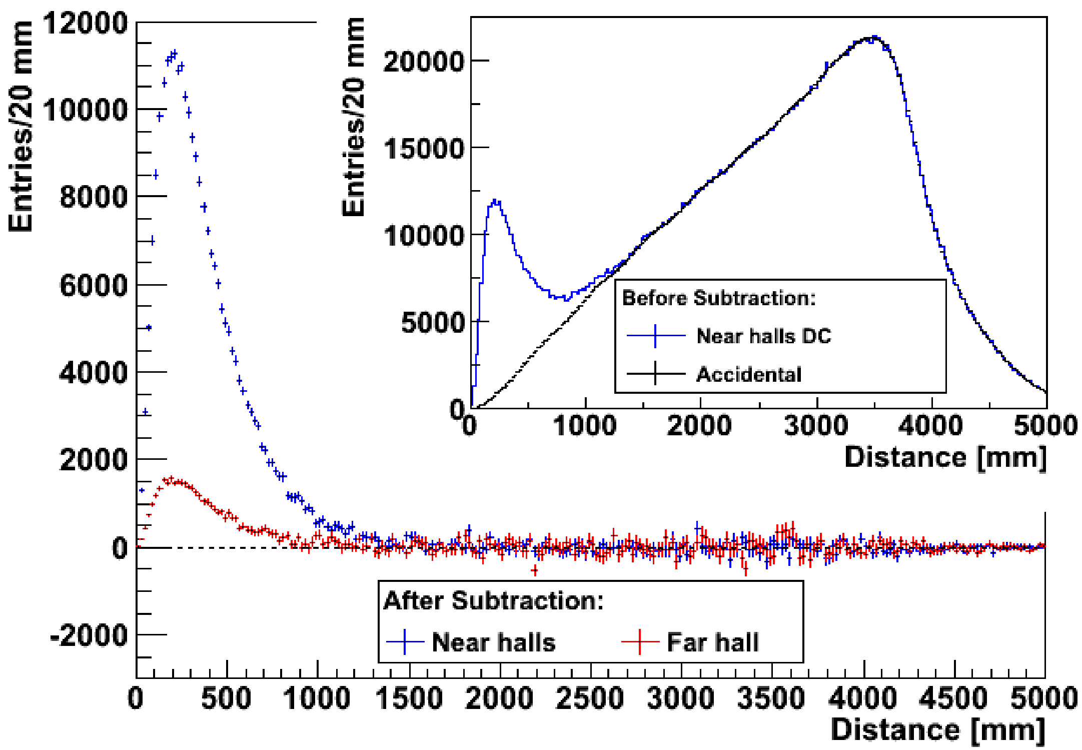
Minakata et al PRD74(2006), 053008

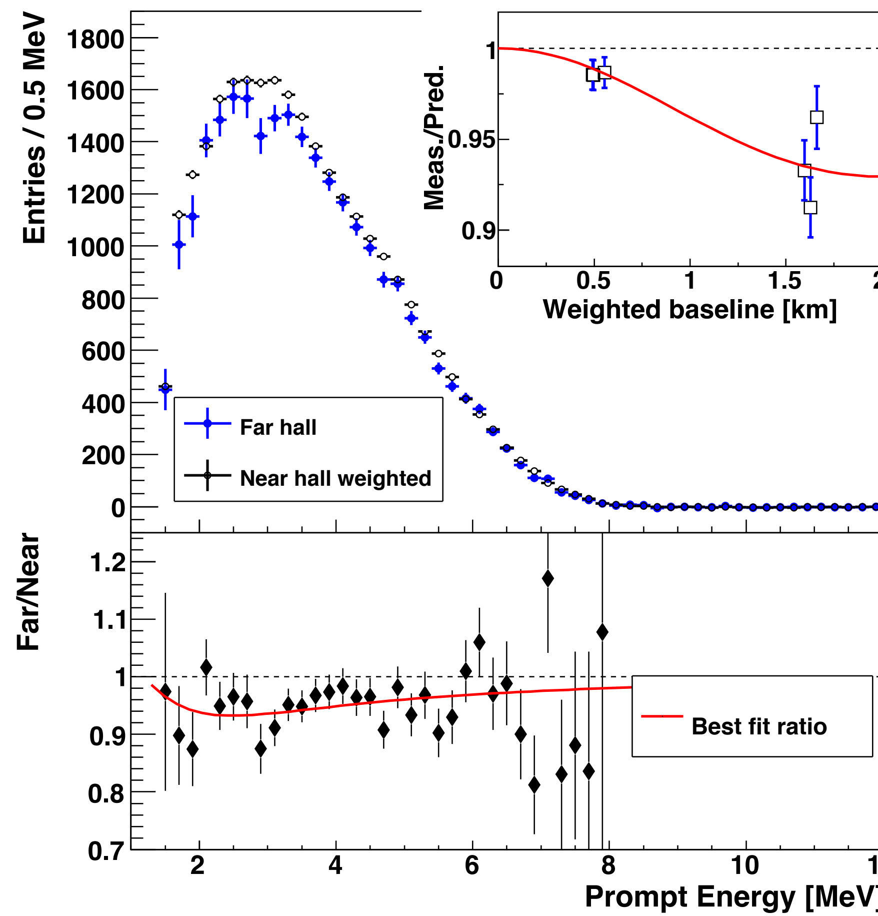
TABLE II: Simple fitting for mass splitting Δm^2_{32} and Δm^2_{31} using Eqs. (11), (12), (16), and (19) in NH (or (20) in IH) as constraints. The corresponding 2-tailed p-values increase from that in Table I. Here the slight preference for normal hierarchy remains.

	Fit in normal hierarchy	Fit in inverted hierarchy
Δm^2_{32}	$(2.46 \pm 0.07) \times 10^{-3}$ eV^2	$-(2.51 \pm 0.07) \times 10^{-3}$ eV^2
Δm^2_{31}	$(2.53 \pm 0.07) \times 10^{-3}$ eV^2	$-(2.44 \pm 0.07) \times 10^{-3}$ eV^2
χ^2/DoF	0.96/2	1.21/2
p-value	62%	55%

Zhang&Ma, arXiv:1310.4443

θ_{13} Oscillation Analysis using Captures on H





- Daya Bay detectors are effectively 2-zone detectors for IBD detection like KamLAND — additional ~65% IBDs.
- 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 accidental bkg spectrum

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

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

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

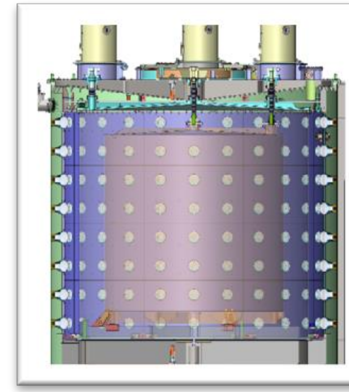
The Daya Bay Detection Efficiency

Reactor

Antineutrino detection (IBD positron)

$$S(E_{e^+}) = S(E_{\bar{\nu}_e})\sigma_{IBD}(E_{\bar{\nu}_e})N_p \cdot t_{live} \cdot \varepsilon_{m\cdot\mu} \cdot \varepsilon \cdot \text{Detector Response}$$

AD



Detection efficiency ε, and its uncertainty

	Efficiency	Correlated Uncertainty	Uncorrelated Uncertainty
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%

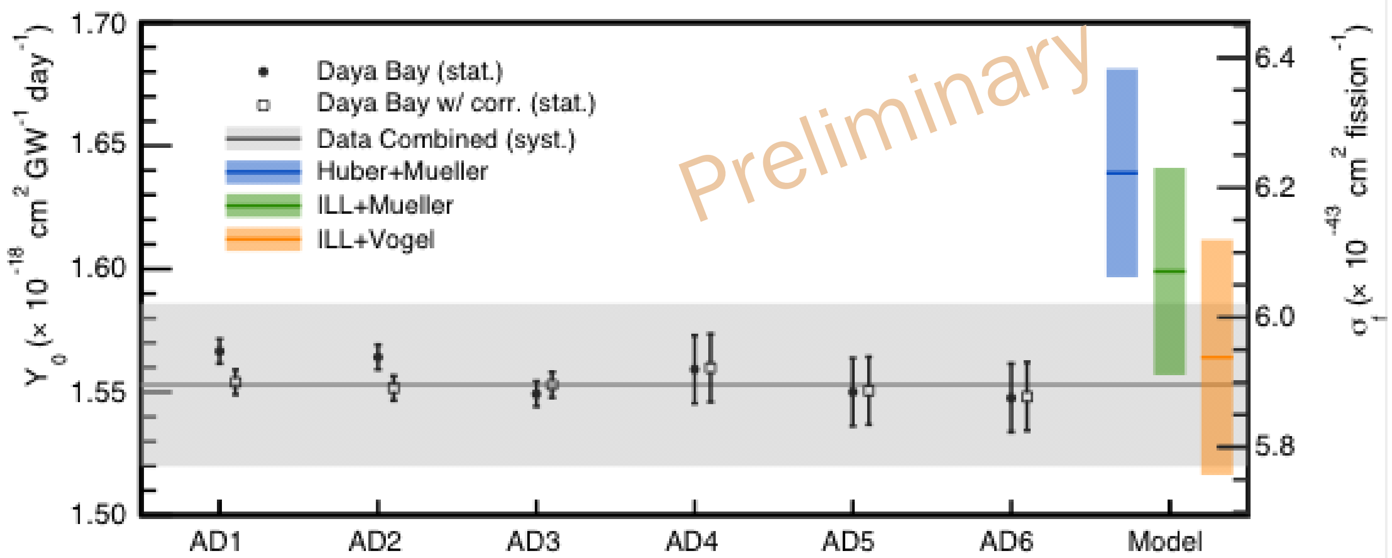
Detector efficiency is obtained from Full Detector MC simulation which is tuned with various data. Correlated uncertainties are obtained by comparison of MC and data.

An improved evaluation of the detection efficiency regarding Gd capture ratio, delay energy cut and spill-in effect, has been performed.

Detector Response is developed for spectral measurement.

The Daya Bay Flux Normalization Measurement

- Measured IBD events (background subtracted) in each detector are normalized to *cm²/GW/day* (***Y₀***) and *cm²/fission* (***σ_f***).



3-AD (near sites) measurement:

$Y_0 = 1.553\times10^{-18}$

$\sigma_f = 5.934\times10^{-43}$

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

Data/Prediction (Huber+Mueller)
0.947 ± 0.022

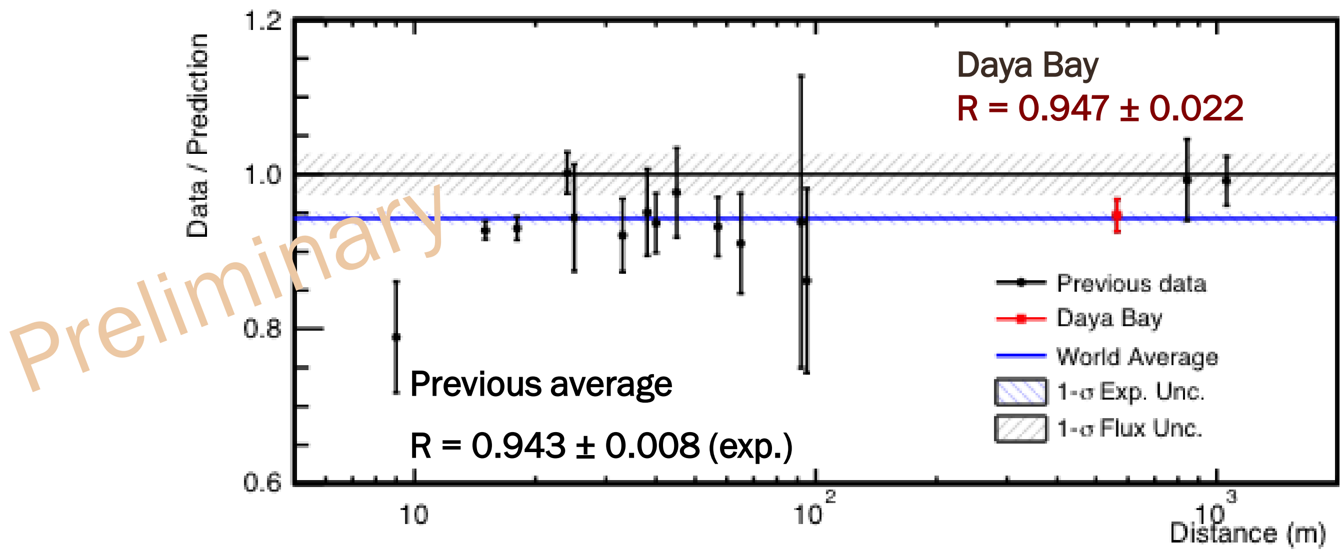
Data/Prediction (ILL+Vogel)
0.992 ± 0.023

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

Daya Bay Absolute Flux Measurement and Others

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

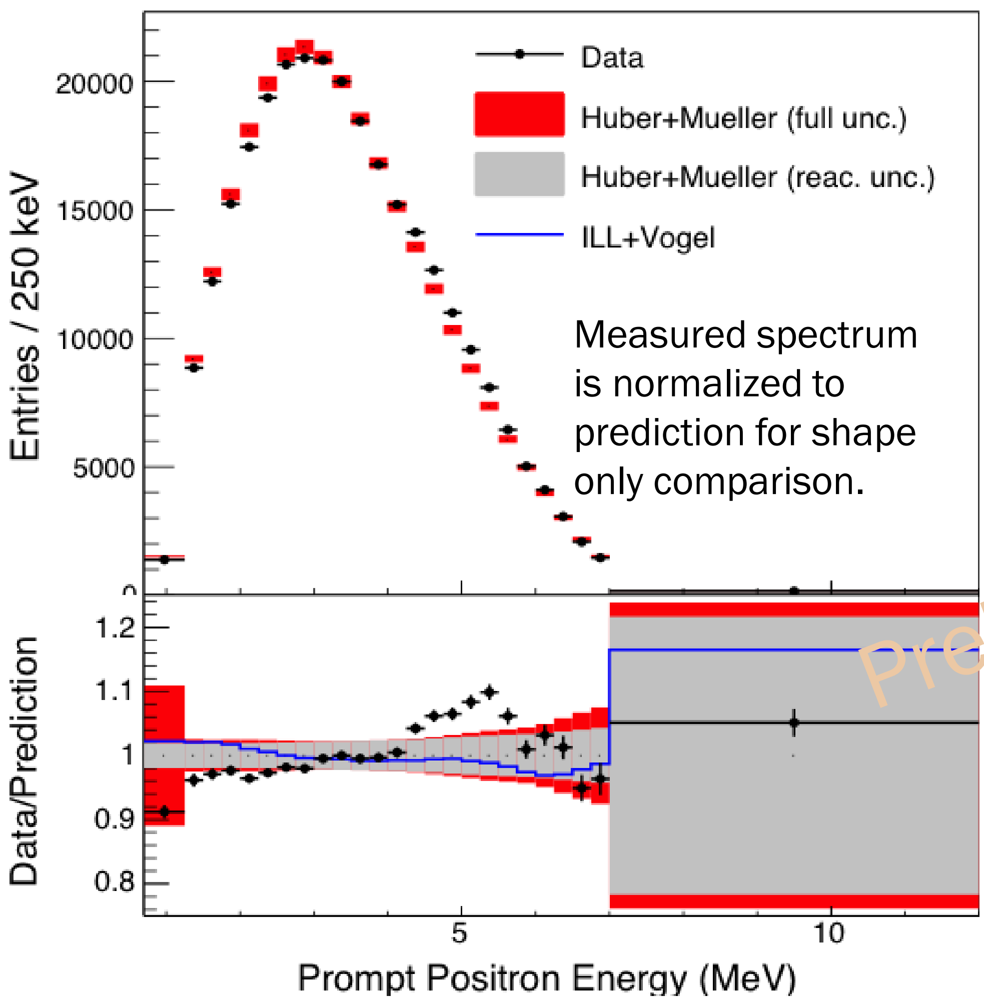
- Global comparison of measurement and prediction (Huber+Mueller):



- 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.

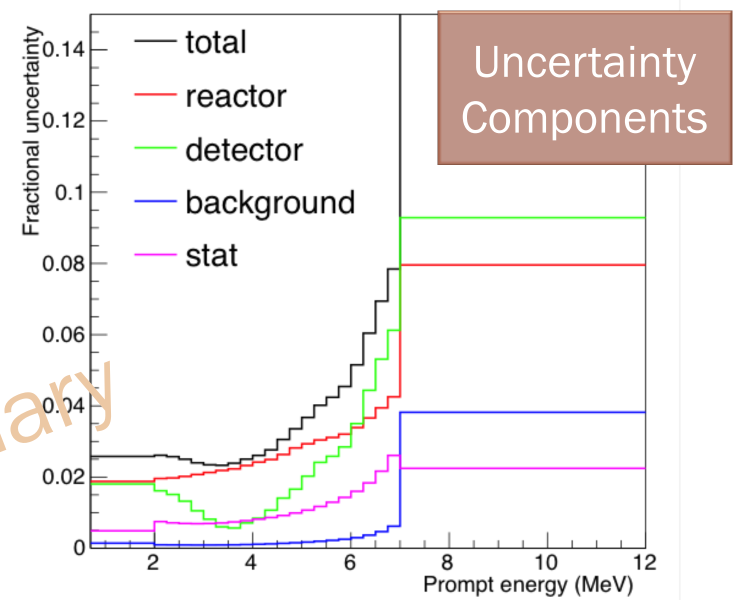
How Consistent between Calculation and Daya Bay Observation

- We would like to check whether the observation of Daya Bay is consistent with flux spectrum calculation
- Considering all the correlations and the best-fit theta13



$$\chi^2 = (N_i^{obs} - N_i^{pred})V_{ij}^{-1}(N_j^{obs} - N_j^{pred})$$

$$V = V_{stat} + V_{reactor} + V_{detector} + V_{bkgs}$$

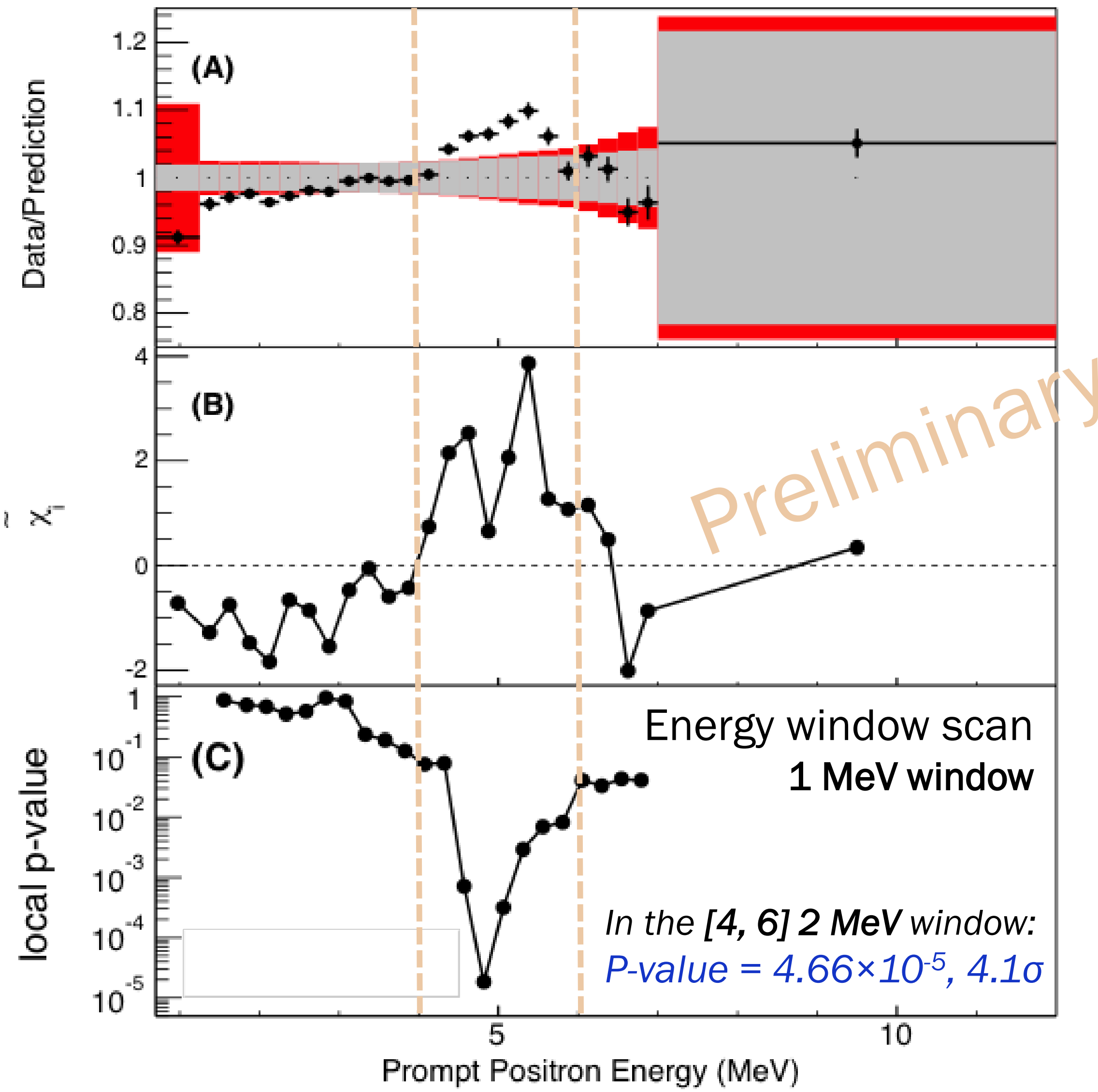


X^2/ndf (0.7 < E < 12 MeV)

41.4/24

P-value = 0.015, 2.4σ

What is Responsible for the Discrepancy?



(A) Spectral comparison of data and prediction (Huber +Mueller) (P-value=0.015, 2.4σ)

(B) χ^2 contribution of each bin, evaluated by:

$$\tilde{\chi}_i = \frac{N_i^{obs} - N_i^{pred}}{|N_i^{obs} - N_i^{pred}|}\sqrt{\frac{1}{2}\sum_j(\chi_{ij}^2 + \chi_{ji}^2)}$$

$$where\ \chi_{ij}^2 = (N_i^{obs} - N_i^{pred})(V^{-1})_{ij}(N_j^{obs} - N_j^{pred})$$

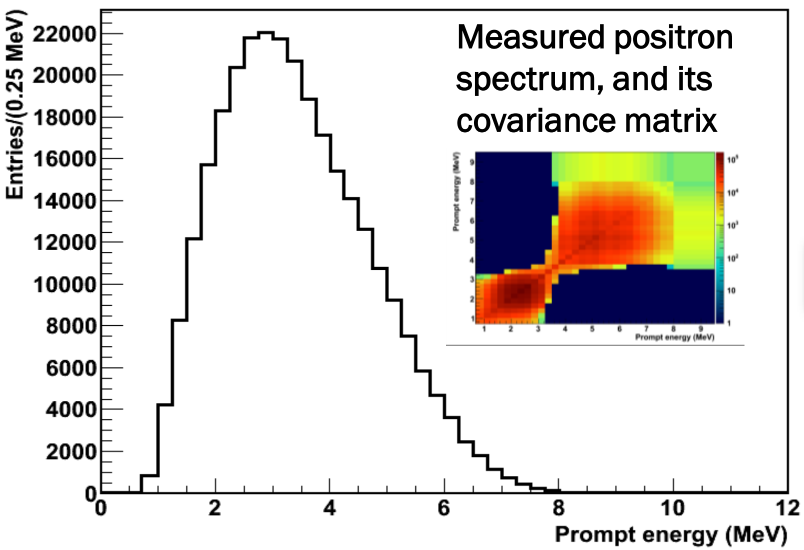
(C) P-value of $\Delta\chi^2$/ndf in a certain energy window (e.g. 1 MeV)

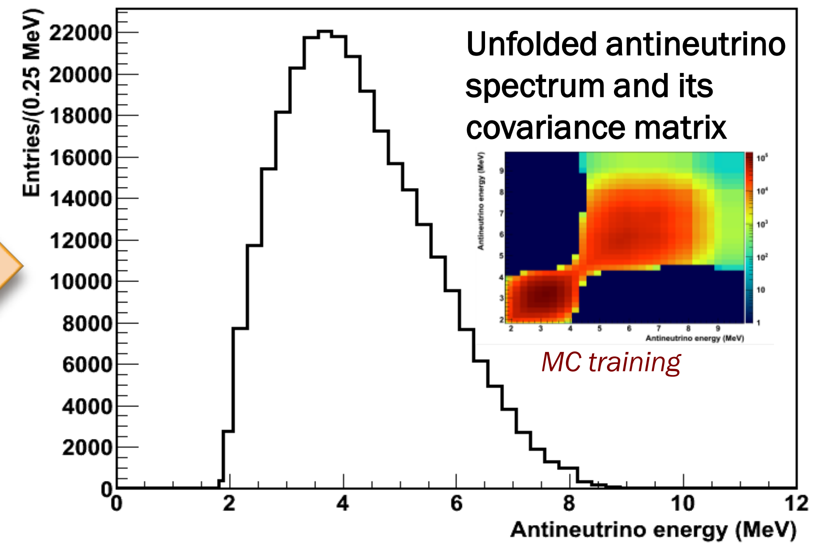
Introduce N (# of bins) nuisance parameters with no pull terms to oscillation fitter.

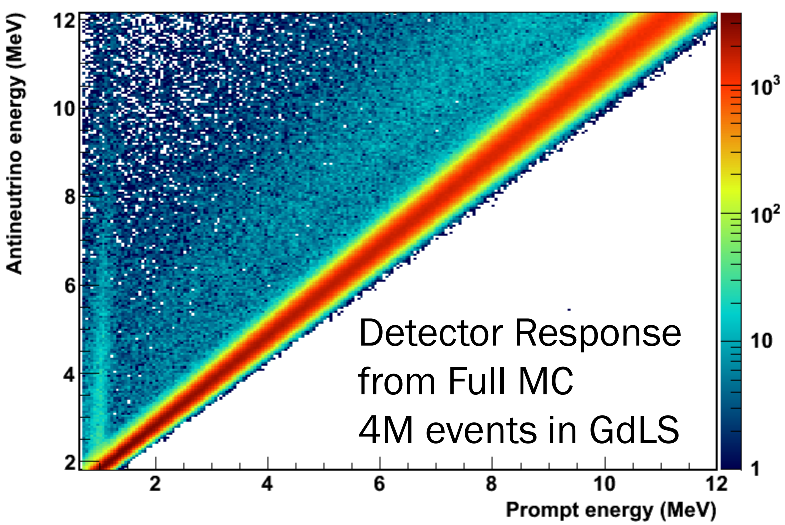
Expect the χ^2 difference after introducing the N nuisance parameters follows a χ^2 distribution with N-1 dof.

Spectrum Unfolding

- Antineutrino spectrum from measurement
  - Unfold the measured positron spectrum of 3 ADs in near Halls







Input of unfolding:

1. Measured positron spectrum, covariance matrix
2. Detector response matrix

Unfolding methods:

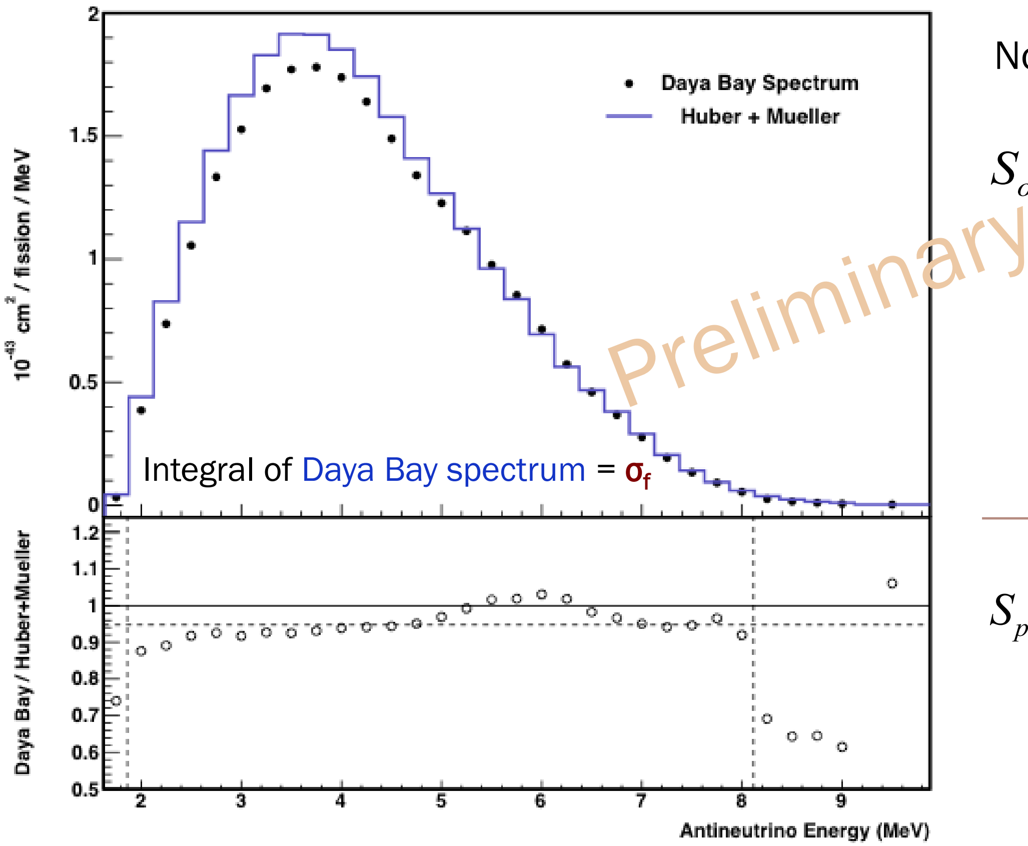
Bayesian iterative and SVD

Output of unfolding:

Antineutrino spectrum, covariance matrix

The Daya Bay Unfolded Flux Spectrum

- Extract a generic observable reactor antineutrino spectrum $S_{obs\_\nu}(E_\nu)$:
  - It supplies data outside [2, 8] MeV and could be used for flux and spectrum prediction.



Normalize the unfolded spectrum to *cm²/fission/MeV*.

$$S_{obs\_\bar{\nu}_e}(E_{\bar{\nu}_e}) = \frac{S_{unfolded}(E_{\bar{\nu}_e})}{P_{eff}(E_{\bar{\nu}_e}, L) \cdot N_p \cdot F_{total}}$$

where

N_p is proton number per unit target mass;

$P_{eff}(E_{\bar{\nu}_e}, L)$ is suvival probability of $\bar{\nu}_e$ weighted by flux;

F_{total} is total number of fissions of all reactors.

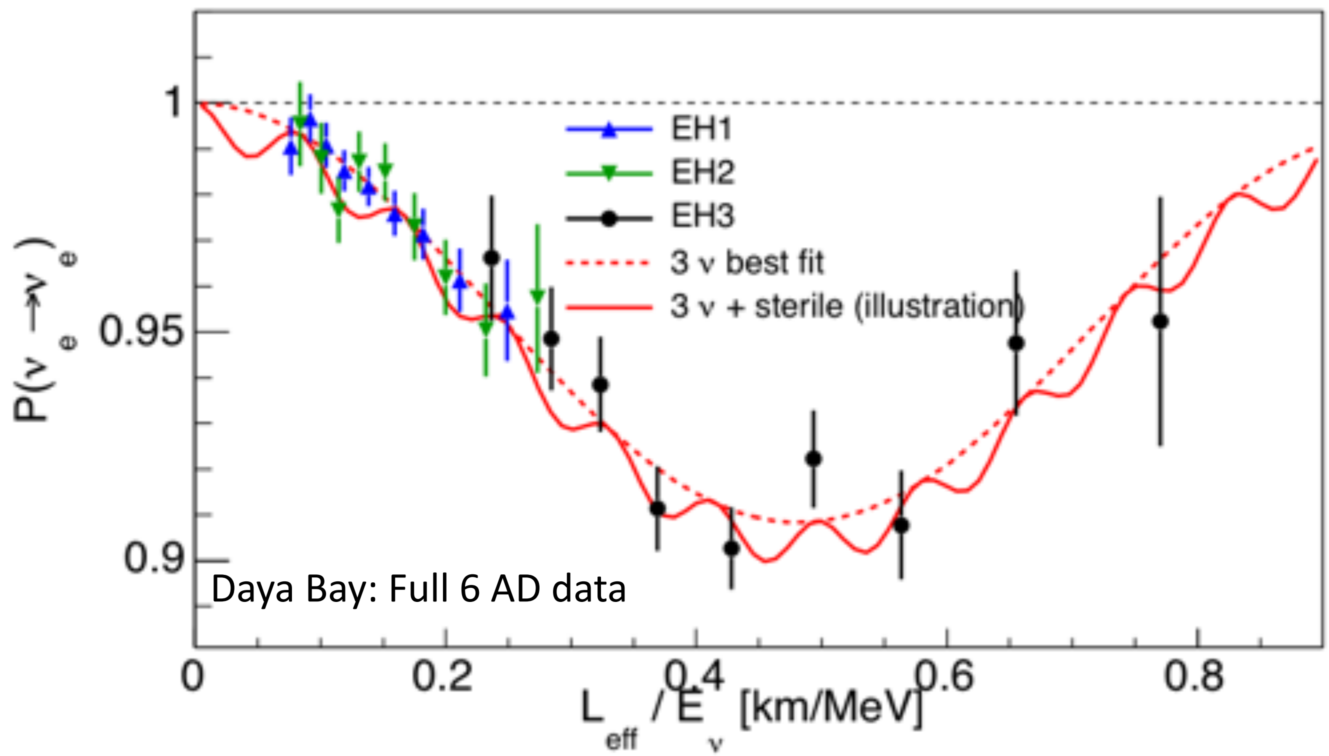
$$S_{pred\_\bar{\nu}_e}(E) = (\sum_k \alpha_k S_k(E) + c^{ne}(E) + SNF(E)) \cdot \sigma_{IBD}(E)$$

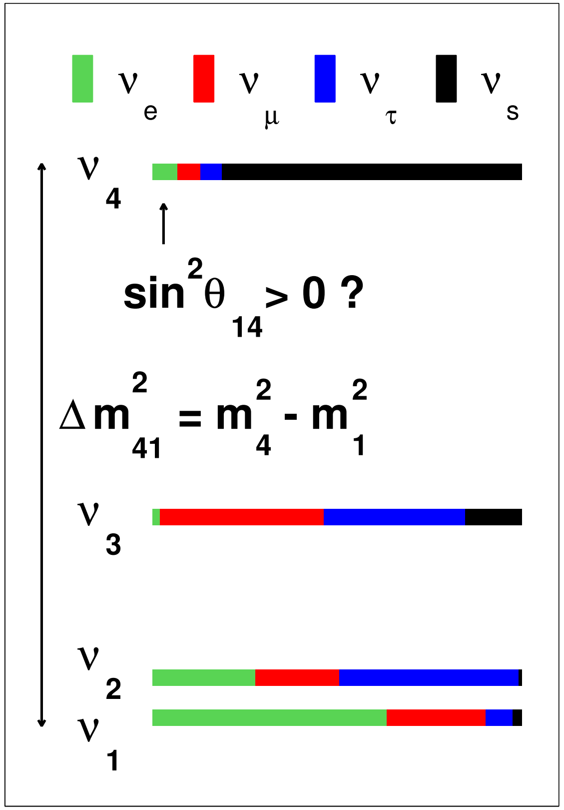
where

α_k are the effective fission fractions of Daya Bay

- Compare Daya Bay spectrum $S_{obs\_\nu}(E_\nu)$ and Huber+Mueller Prediction $S_{pred\_\nu}(E_\nu)$:
  - Same rate deficit as flux measurement, and same shape deviation structure as in comparison of positron spectrum.

Sterile Neutrino Signal in Daya Bay





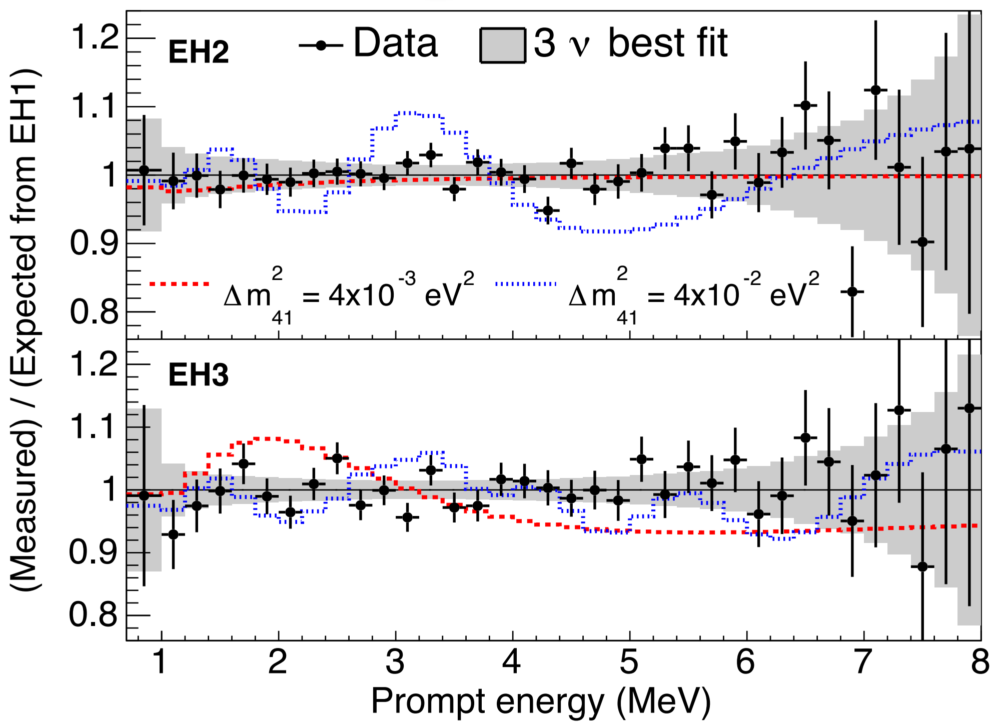
$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \cong 1 - \cos^4\theta_{14} \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{ee} L}{4E_\nu}\right) - \sin^2 2\theta_{14} \sin^2\left(\frac{\Delta m^2_{41} E}{4E_\nu}\right)$$

- A minimum extension of the 3-ν model: 3(active) + 1(sterile)-ν model
- Search for a higher frequency oscillation pattern besides $|\Delta m^2_{ee}|$

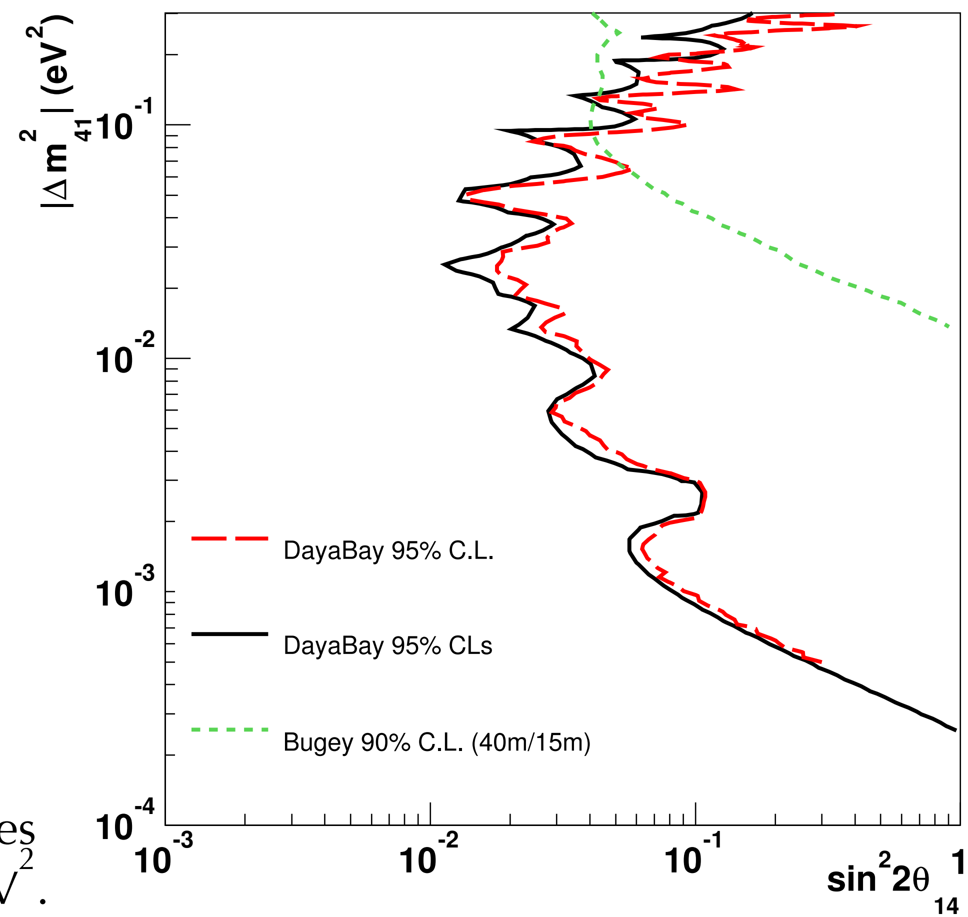
A Unique Opportunity for Sterile Neutrino Searches

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \simeq 1 - \cos^4\theta_{14}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{ee} L}{4E_\nu}\right) - \sin^2 2\theta_{14}\sin^2\left(\frac{\Delta m^2_{41} L}{4E_\nu}\right)$$

- Daya Bay baselines >350m ⇒ not as sensitive to mass-squared splittings greater than or around 1eV^2

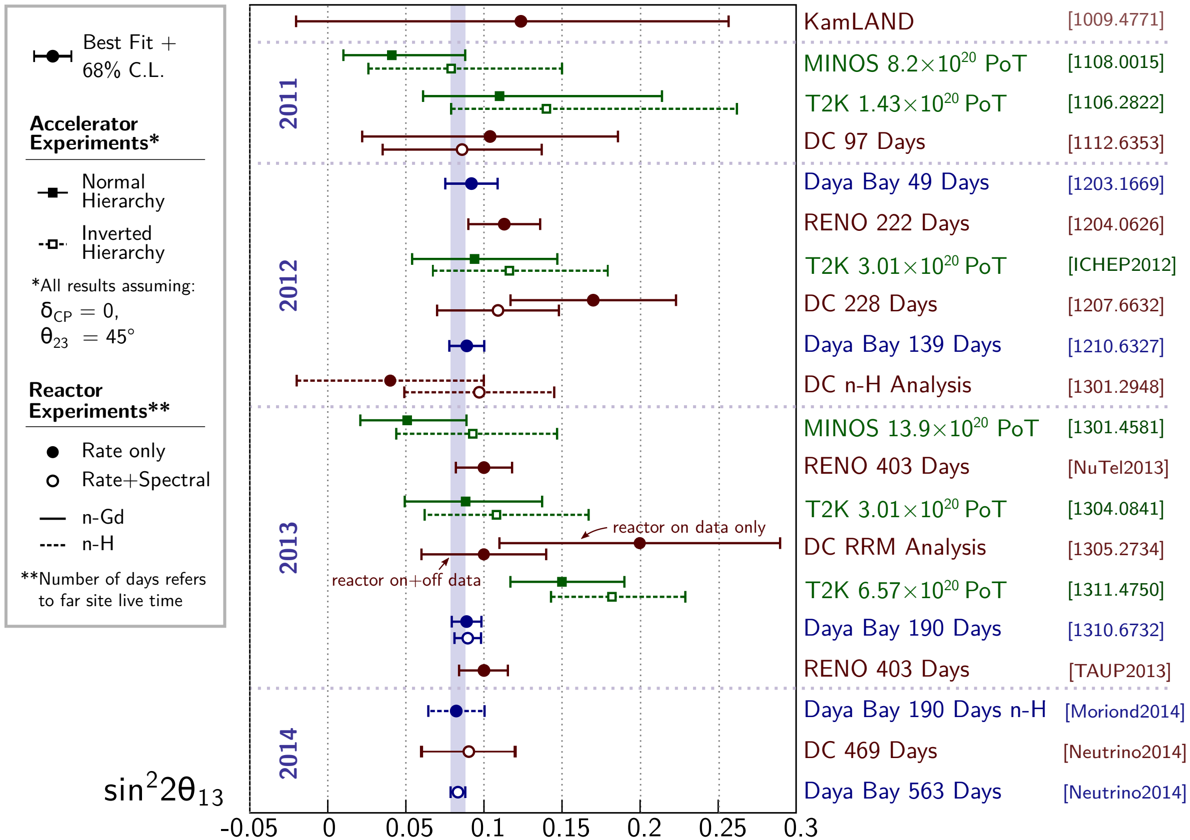


dashed curves assumes $\sin^2 2\theta_{14} = 0.1$



- Daya Bay has multiple baselines whose differences enabled searches in the range of $\Delta m^2 \sim 0.01$-0.1eV^2. Independent of reactor flux models

Summary and Conclusion

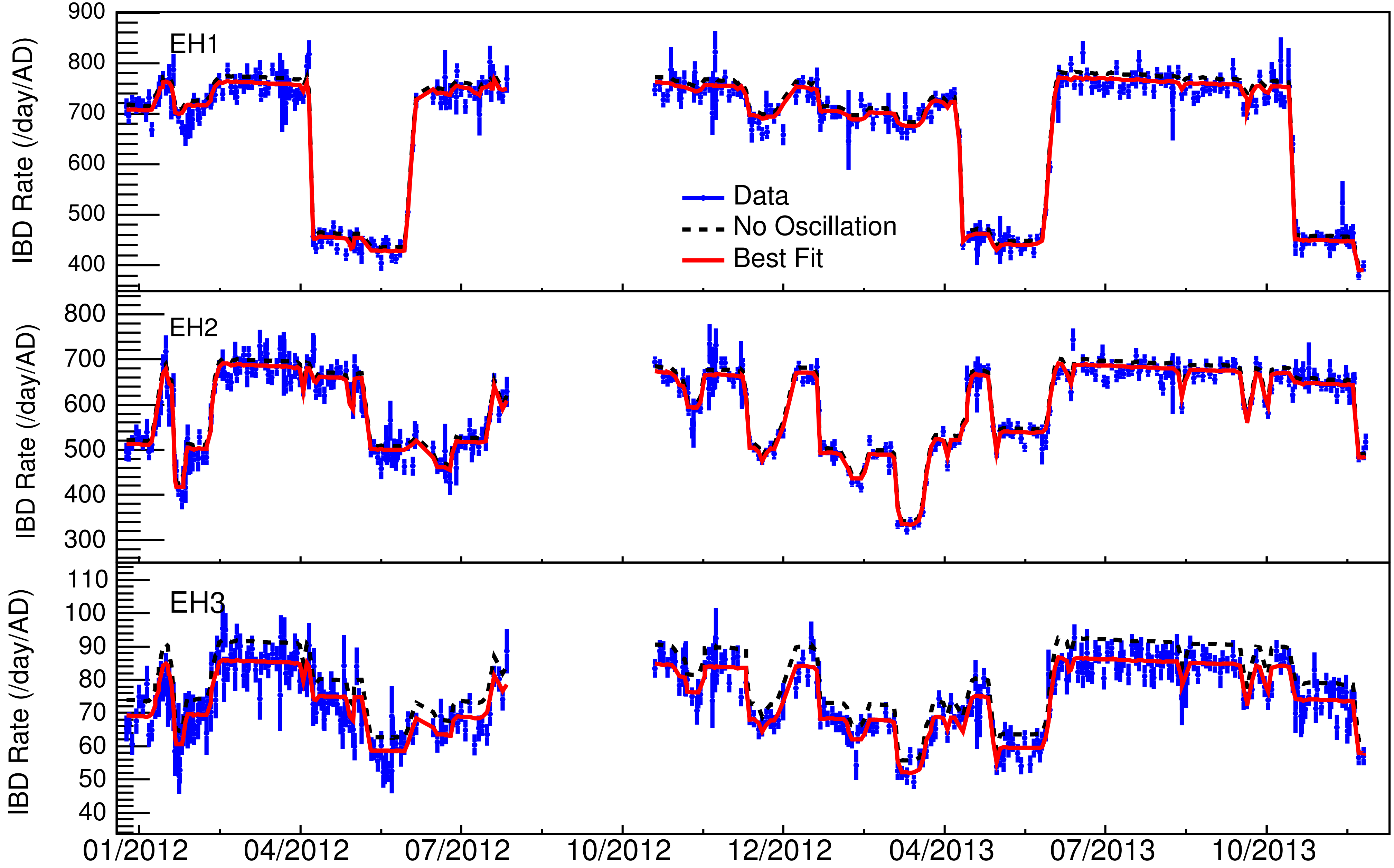


- ➡ **Most precise $\sin^2 2\theta_{13}$, ~6%; most precise Δm^2_{ee}, ~4%**
  - ➡ An independent oscillation analysis using n-captures on H carried out

- ➡ A search of light sterile neutrino states carried out utilizing Daya Bay's unique multi-baselines, independent of reactor flux models
- ➡ The Daya Bay detector energy non-linearity ~1%, a very meaningful precision for future experiments
- ➡ Daya Bay reactor flux normalization measurement is consistent with previous data.
  - ➡ Spectrum inconsistent with calculation.

SYSU-IHEP School of HEP

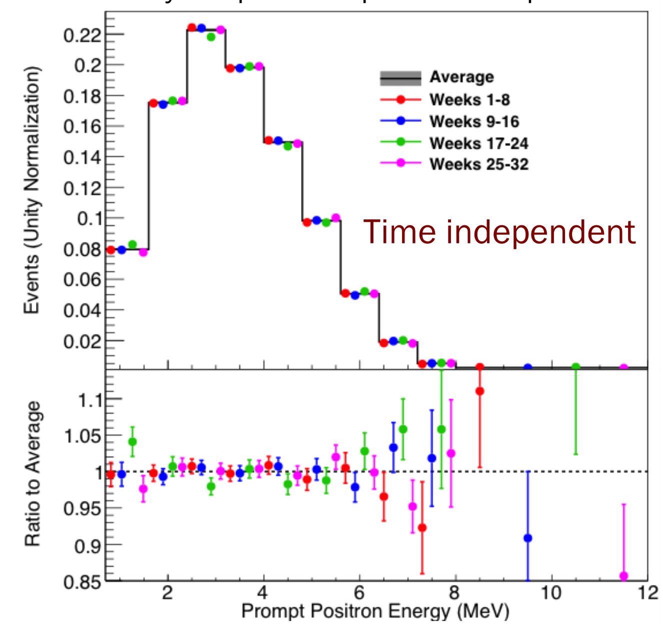
Daya Bay Measurement of IBD Rates



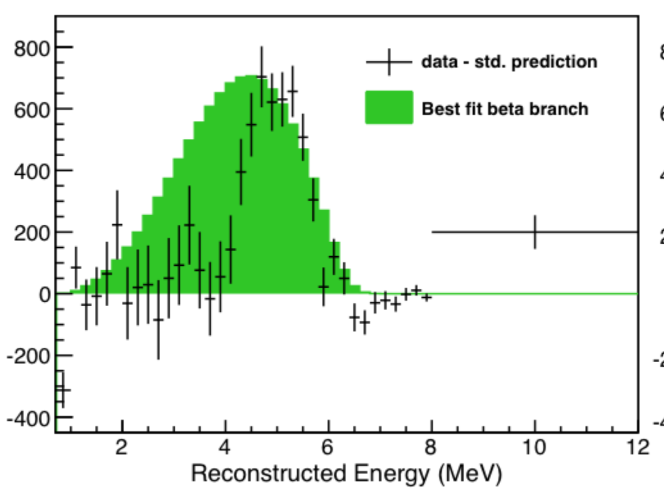
What the Discrepancy is or is Not

- The events are reactor power correlated & time independent.
- The events match all IBD event characteristics:
  - Neutron capture time and distance distributions, prompt event position distribution, etc.
  - Disfavors unexpected backgrounds
- ^{12}B spectrum does not have local structure at [4, 6] MeV.
  - Disfavors electronics and nonlinear energy model distortion
- Extending the reactor model by adding a single β-branch or mono-energetic line cannot remove the local discrepancy.

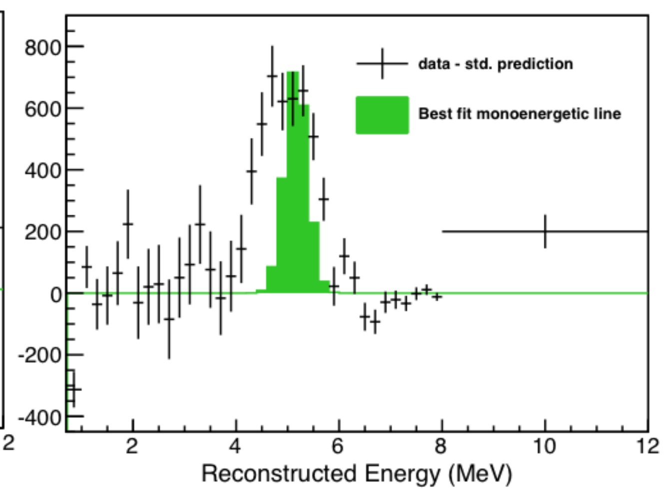
Weekly IBD positron spectrum comparison



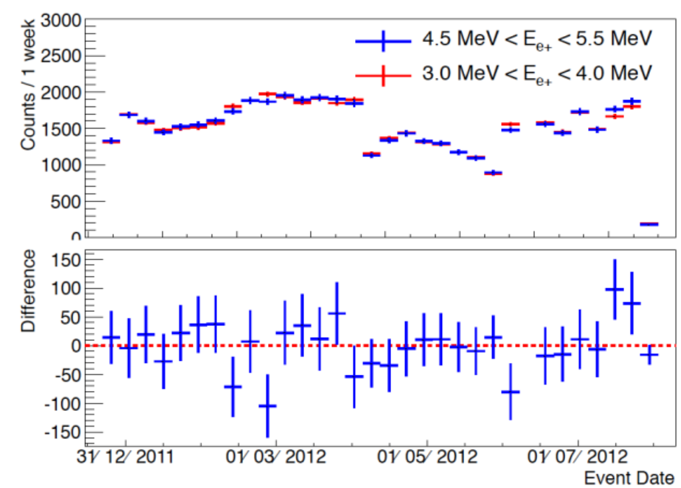
Add a β-branch (Q = 7 MeV) in reactor model



Add a gamma line (5 MeV) in reactor model



Time distributions of events in [4.5, 5.5] MeV and IBD events in [3, 4] MeV.



The 6AD and 8AD Combined Data

Data Summary

preliminary

6-AD Period

	AD1	AD2	AD3	AD4	AD5	AD6
IBD candidates	101998	103137	93742	13889	13814	13645
DAQ live time(day)	190.989		189.623	189.766		
ε_μ	0.8234	0.8207	0.8576	0.9811	0.9811	0.9808
ε_m	0.9741	0.9745	0.9757	0.9744	0.9742	0.974
Accidentals(/day)	9.53 ± 0.10	9.29 ± 0.10	7.40 ± 0.08	2.93 ± 0.03	2.87 ± 0.03	2.81 ± 0.03
Fast neutron(/day)	0.78 ± 0.12		0.54 ± 0.19	0.05 ± 0.01		
9Li/8He(/day)	2.8 ± 1.5		1.7 ± 0.9	0.27 ± 0.14		
AmC correlated(/day)	0.27 ± 0.12	0.25 ± 0.11	0.27 ± 0.12	0.22 ± 0.1	0.21 ± 0.1	0.21 ± 0.09
$^{13}C(\alpha,n)^{16}O$(/day)	0.08 ± 0.04	0.07 ± 0.04	0.05 ± 0.03	0.05 ± 0.03	0.05 ± 0.03	0.05 ± 0.03
IBD rate(/day)	652.38 ± 2.58	662.02 ± 2.59	580.84 ± 2.14	73.04 ± 0.67	72.71 ± 0.67	71.88 ± 0.67
side-by-side ibd rate ratio	0.985 ± 0.005					

8-AD Period

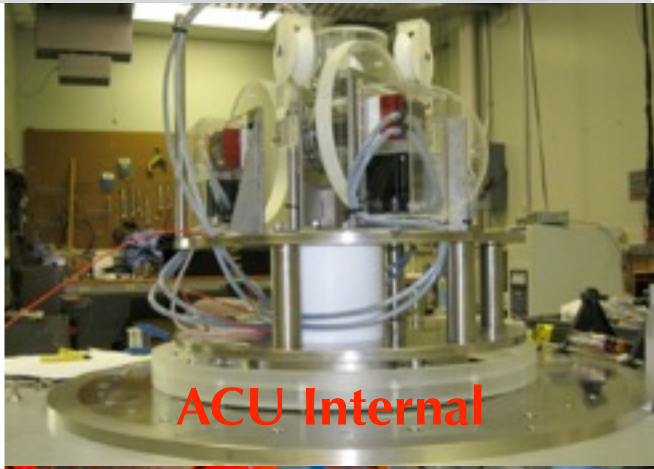
	AD1	AD2	AD3	AD8	AD4	AD5	AD6	AD7
IBD candidates	202461	206217	193356	190046	27067	27389	27032	27419
DAQ live time(day)	374.447		378.407		372.685			
ε_μ	0.8255	0.8223	0.8574	0.8577	0.9811	0.9811	0.9808	0.9811
ε_m	0.9746	0.9749	0.9759	0.9756	0.9762	0.976	0.9757	0.9758
Accidentals(/day)	8.62 ± 0.09	8.76 ± 0.09	6.43 ± 0.07	6.86 ± 0.07	1.07 ± 0.01	0.94 ± 0.01	0.94 ± 0.01	1.26 ± 0.01
Fast neutron(/day)	0.78 ± 0.12		0.54 ± 0.19		0.05 ± 0.01			
9Li/8He(/day)	2.8 ± 1.5		1.7 ± 0.9		0.27 ± 0.14			
AmC correlated(/day)	0.20 ± 0.09	0.21 ± 0.10	0.18 ± 0.08	0.22 ± 0.10	0.06 ± 0.03	0.04 ± 0.02	0.04 ± 0.02	0.07 ± 0.02
$^{13}C(\alpha,n)^{16}O$(/day)	0.08 ± 0.04	0.07 ± 0.04	0.05 ± 0.03	0.07 ± 0.04	0.05 ± 0.03	0.05 ± 0.03	0.05 ± 0.03	0.05 ± 0.03
IBD rate(/day)	659.58 ± 2.12	674.36 ± 2.14	601.77 ± 1.67	590.81 ± 1.66	74.33 ± 0.48	75.40 ± 0.49	74.44 ± 0.48	75.15 ± 0.49
side-by-side ibd rate ratio	0.978 ± 0.004		1.019 ± 0.004					

Expected: AD1/AD2 = 0.982; AD3/AD8 = 1.012

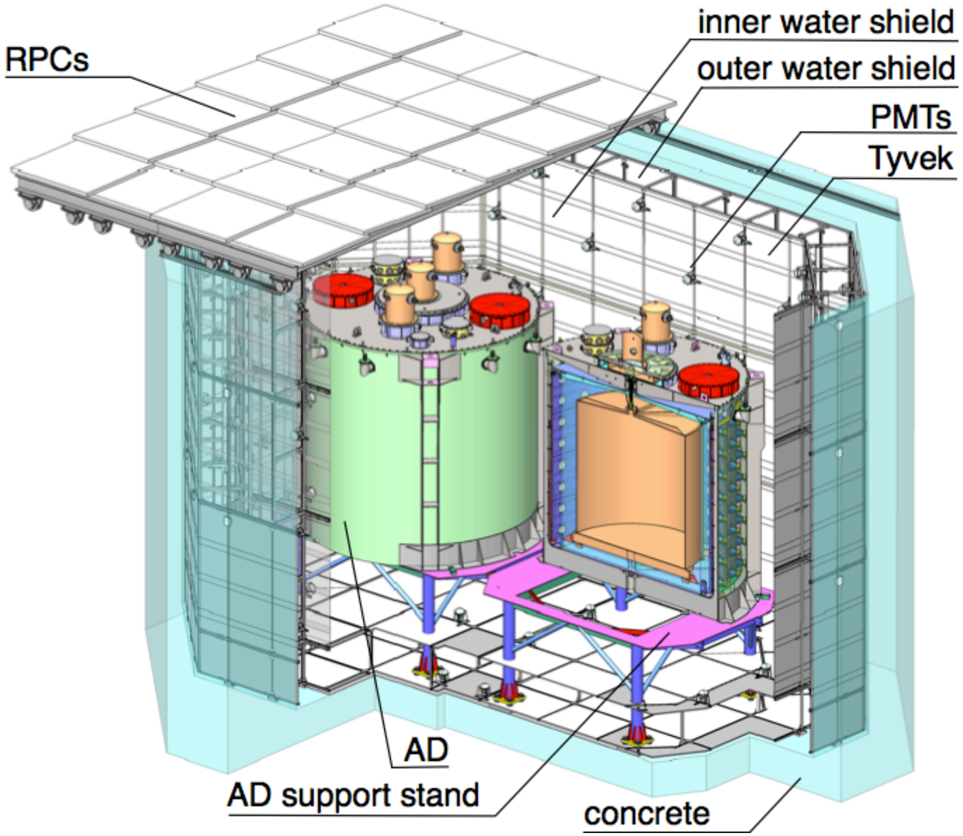
Daya Bay Detector Calibrations

- Three automated calibration units (ACU) on each detector, 2 for the Gd-LS volume and 1 for the LS one, carry out weekly calibrations (vertical scans)
  - Sources: ~100Hz ^{68}Ge(e^+), ~20Hz ^{60}Co, ~0.7Hz ^{241}Am-^{13}C(n), and a LED diffuser ball
- Special calibration efforts in Summer 2012
  - Manual calibration system (MCS) with 4π scan was installed to further understand detector energy responses using Pu-C and Co sources
  - One detector's ACUs were loaded with ^{137}Cs, ^{54}Mo, ^{40}K, Pu-C, and ^{241}Am-Be sources and thorough scanned vertically
  - A stronger ^{241}Am-^{13}C is placed on a detector to understand the induced background better

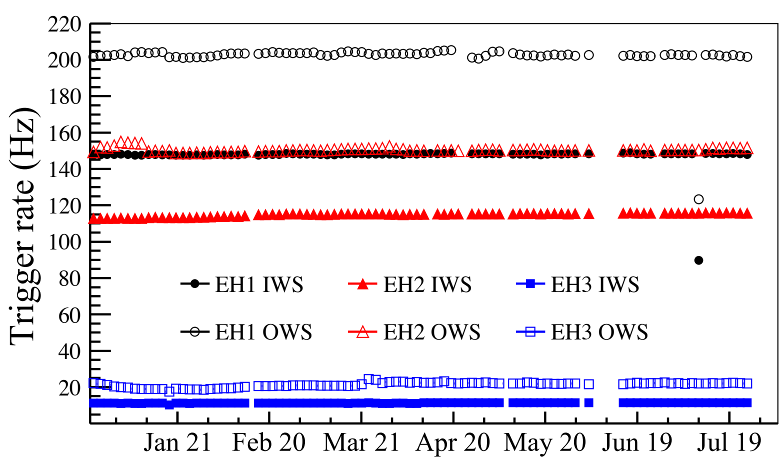
✓**The Daya Bay absolute energy scale uncertainty has reached ~1% after a thorough analysis of the collected calibration data**

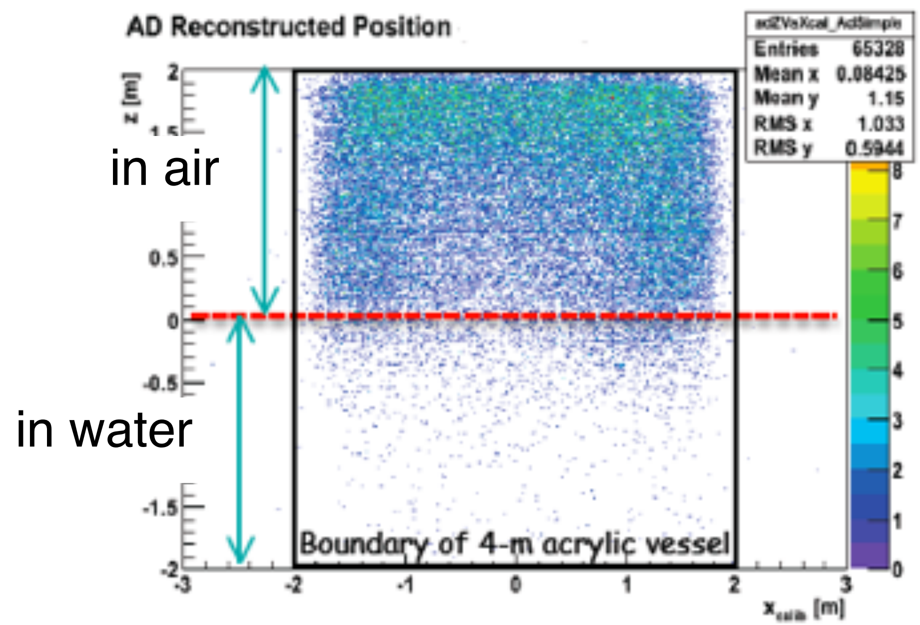


Veto/Reduce Cosmic/Environmental Backgrounds

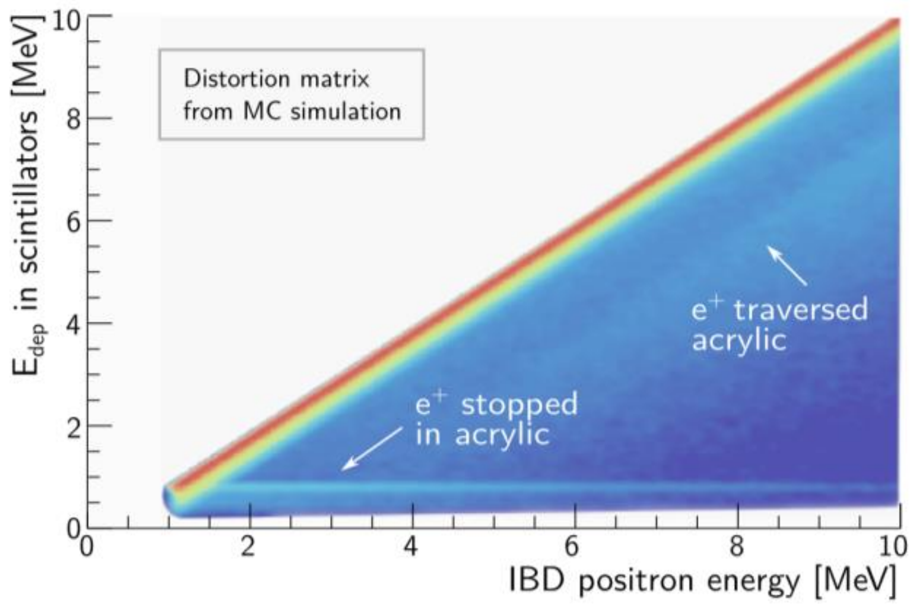


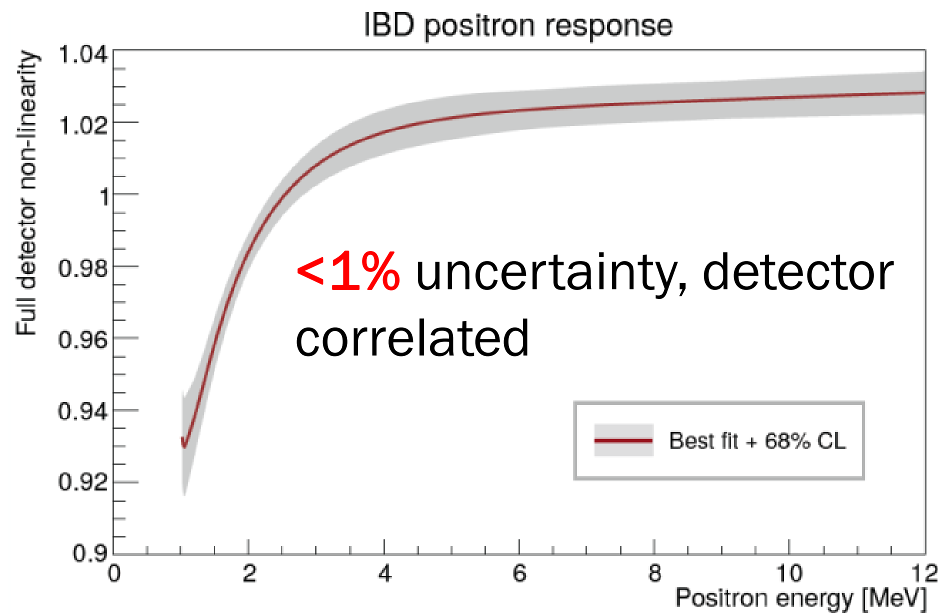
- ~100m-350m overburdens for 3 sites
- Two independent active muon veto systems: RPC; Water Cherenkov is separated into inner (IWS) and outer (OWS) ones to improve the muon efficiency
- Water Cherenkov detectors also shields the environmental gamma radiations
  - >2.5 m thick water in each direction



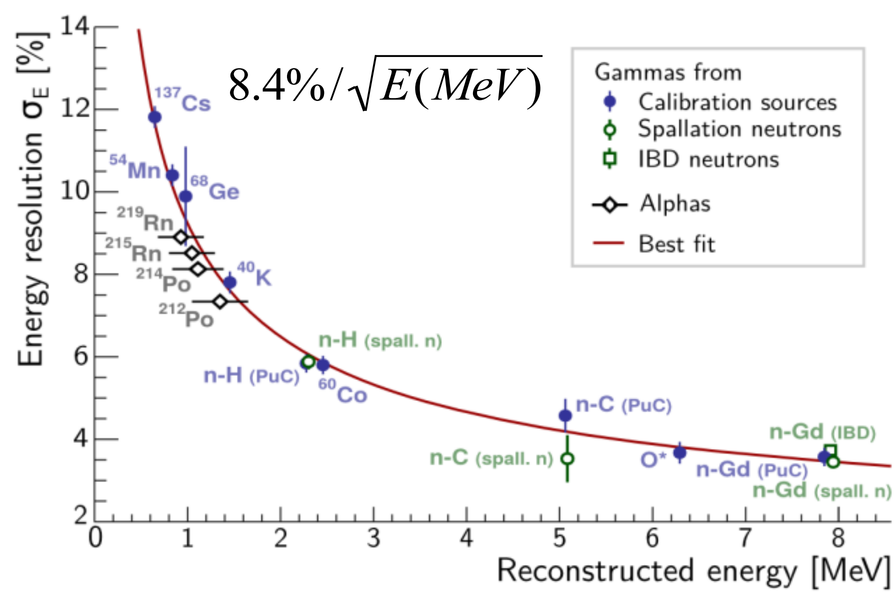


Reactor Flux Spectrum Comparison



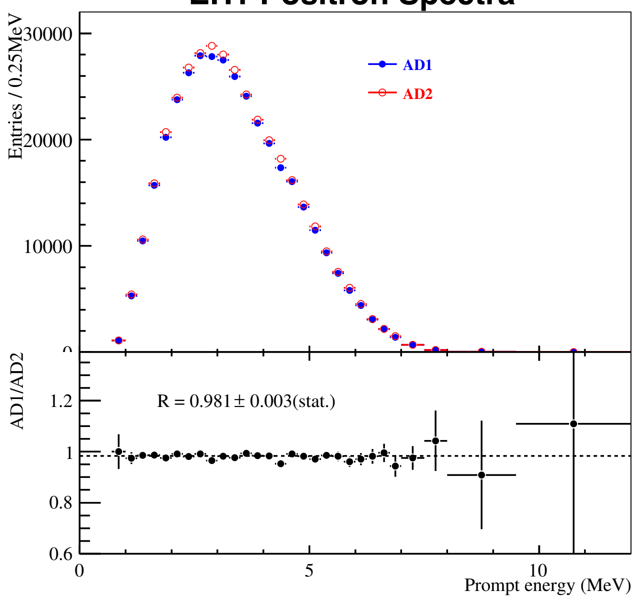


1. MC predict the deposit energy
2. Apply non-linearity model
3. Apply the energy resolution model

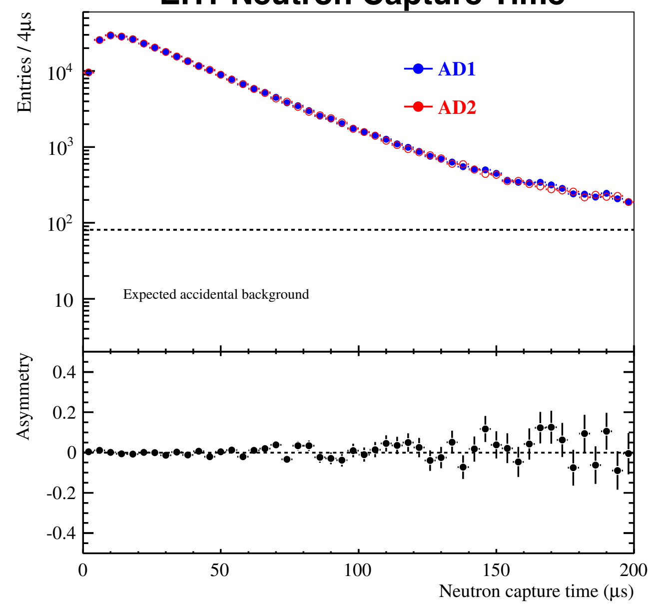


How Identical Are Daya Bay "Identical" Detectors?

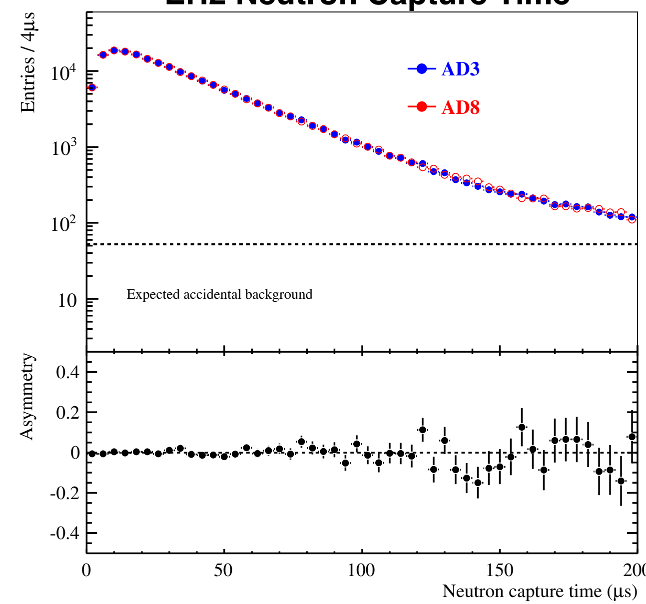
EH1 Positron Spectra



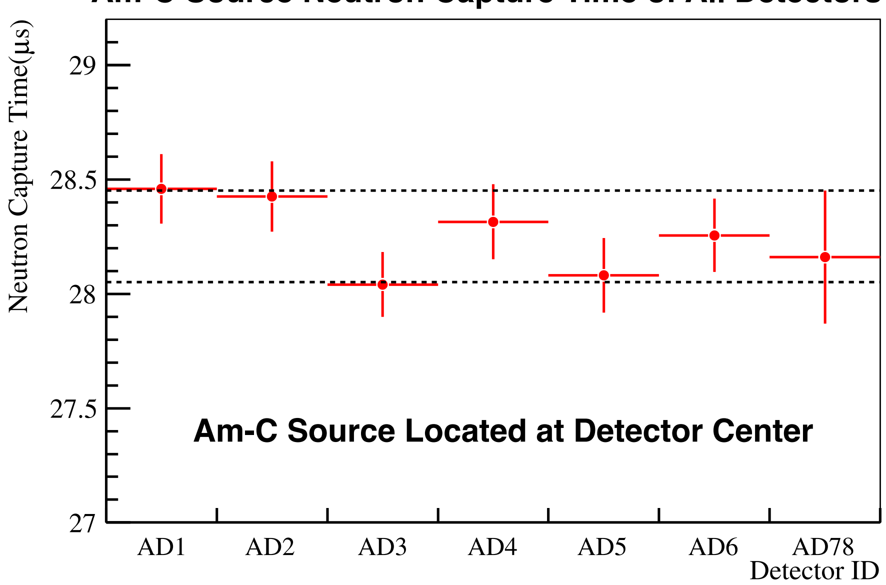
EH1 Neutron Capture Time



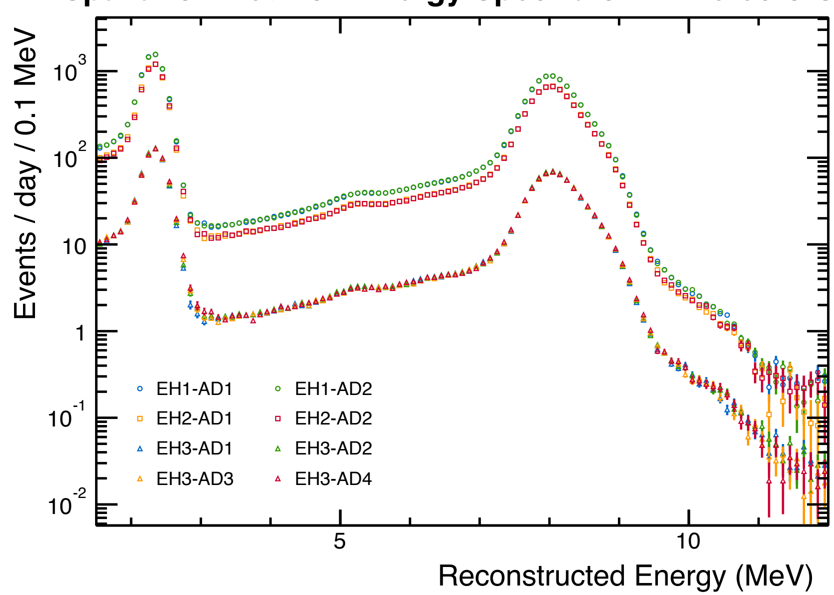
EH2 Neutron Capture Time



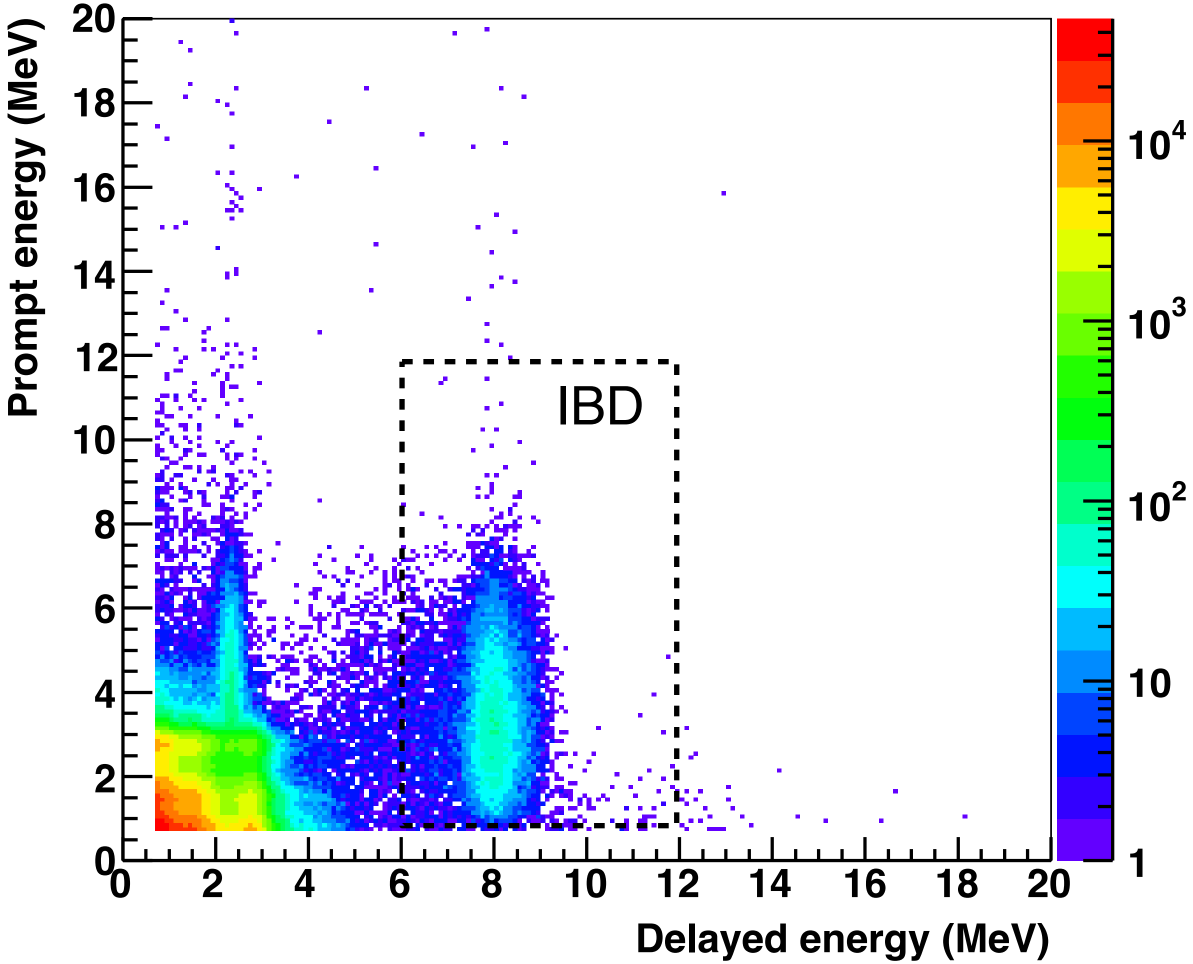
Am-C Source Neutron Capture Time of All Detectors



Spallation Neutron Energy Spectra of All Detectors



IBD Candidates and Backgrounds



- First apply flasher cuts to clean up data
- Muon veto cuts get rid of cosmogenic products
- IBD energy&time cuts
  - Prompt energy cut; delayed energy cut
  - **Time correlation** cut to pick out IBD pairs
- Background events contain accidental ones and three other correlated types: cosmogenic, calibration source Am-C and $^{13}C(\alpha, n)^{16}O$ backgrounds

Flux Model Independent Near-Far Prediction

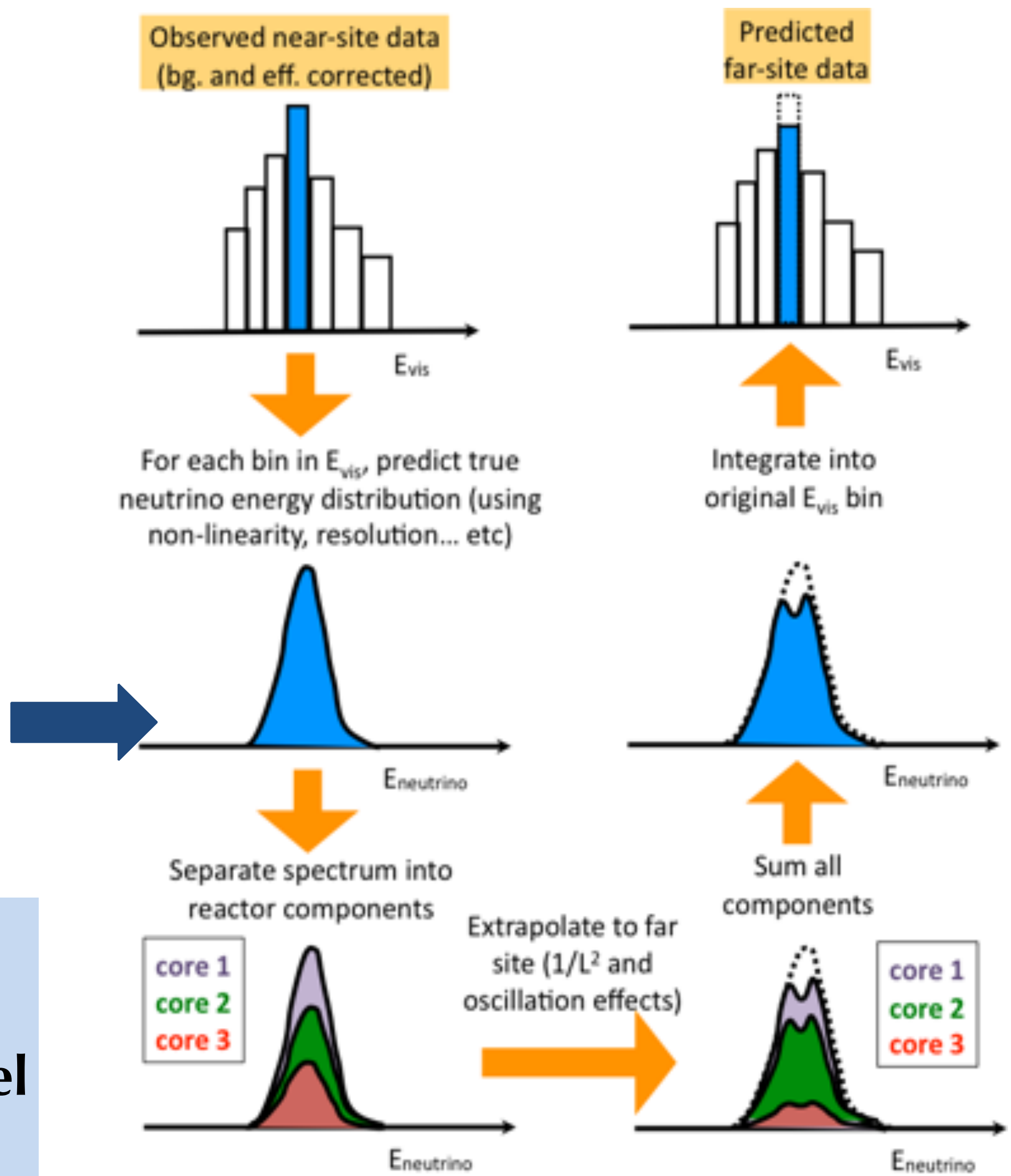
From the

- relative reactor core power info
- experimental layout geometry

it is possible to determine what fraction of events in each near detector at each true energy bin originate from each core.

Each of these components is then individually extrapolated to the far site

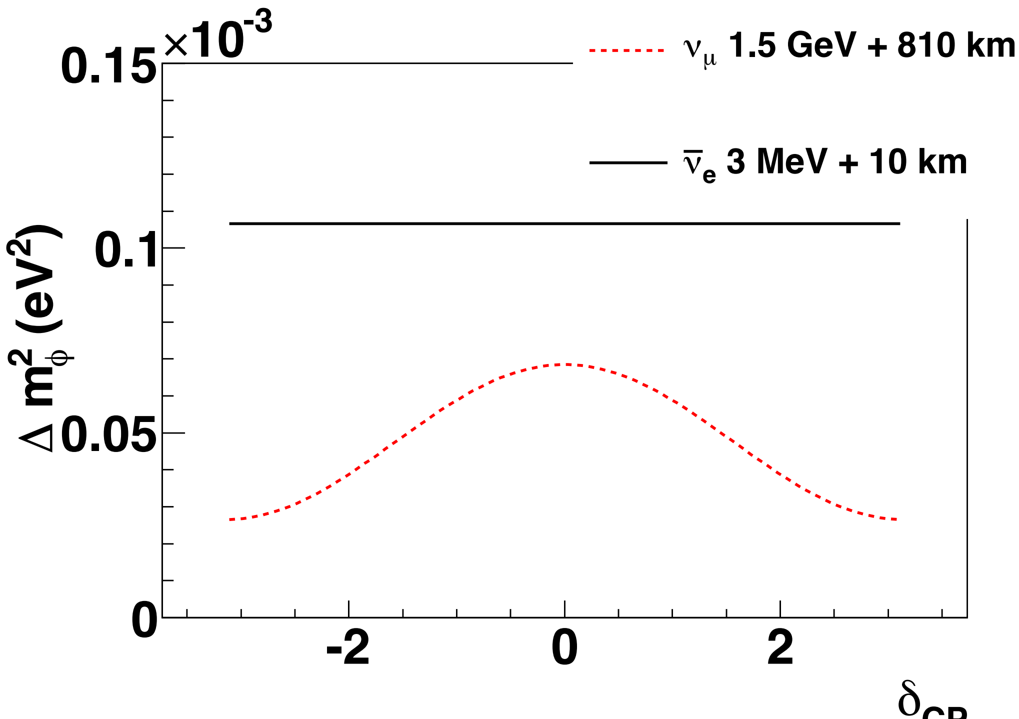
All reactor and detector correlated systematics, including the absolute flux and shape uncertainties, **cancel to first order.**



One Way to Reach Neutrino Mass Hierarchy

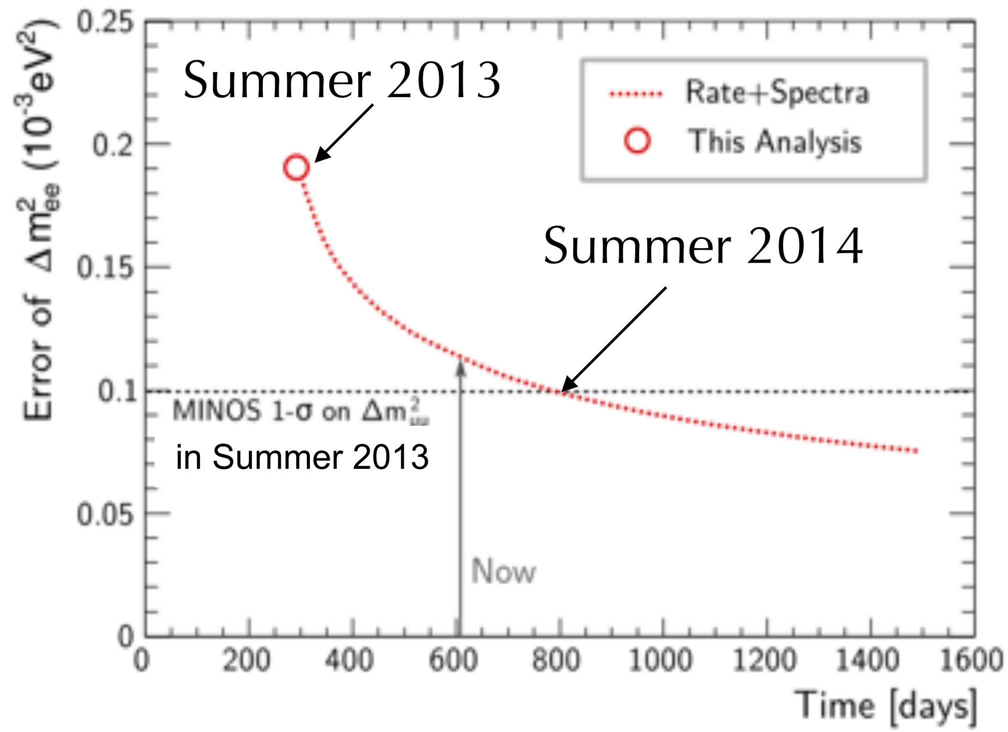
$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - 2s_{13}^2c_{13}^2 - 4c_{13}^4 s_{12}^2 c_{12}^2 \sin^2 \Delta_{21} + 2s_{13}^2c_{13}^2\sqrt{1 - 4s_{12}^2c_{12}^2\sin^2\Delta_{21}}\cos(2\Delta_{32} \pm \phi)$$

$$P_{\nu_\mu \to \nu_\mu} = 1 - P_{21}^{\mu} - \cos^2\theta_{13}\sin^2 2\theta_{23}\sin^2\frac{(\Delta m_{32}^2 \pm \phi)L}{4E}$$



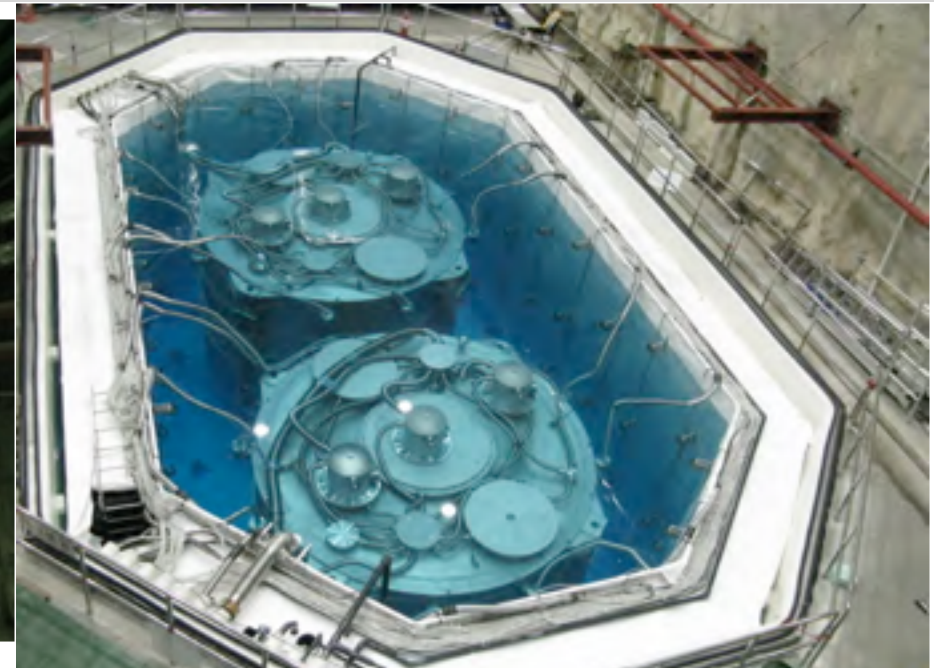
X. Qian et al, PRD87(2013)3, 033005

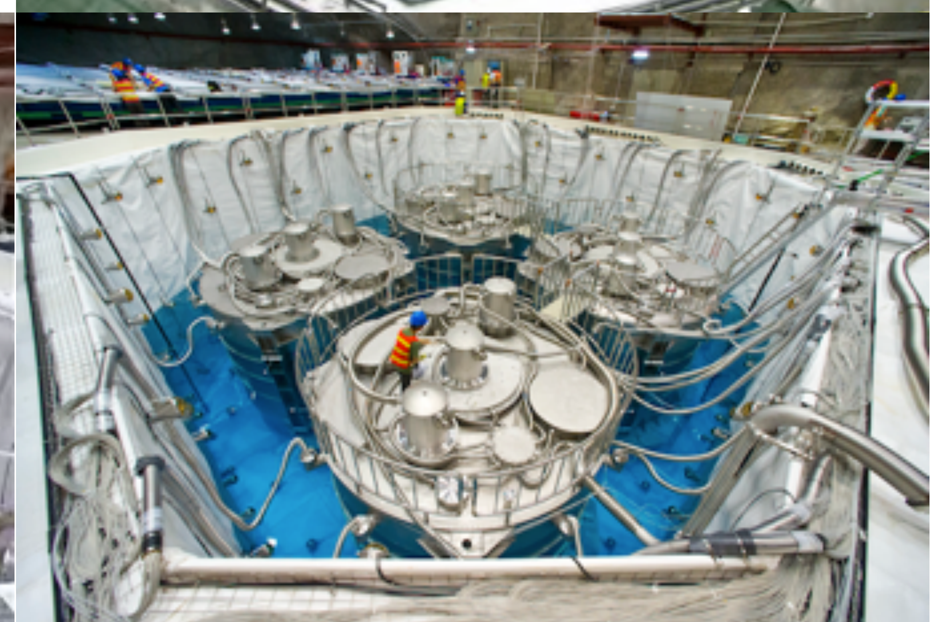
FIG. 6: The dependence of effective mass-squared difference $\Delta m^2_{ee\phi}$ (solid line) and $\Delta m^2_{\mu\mu\phi}$ (dotted line) w.r.t. the value of δ_{CP} for $\bar{\nu}_e$ and ν_μ disappearance measurements, respectively.



The Δm^2_{ee} precision projection of Daya Bay

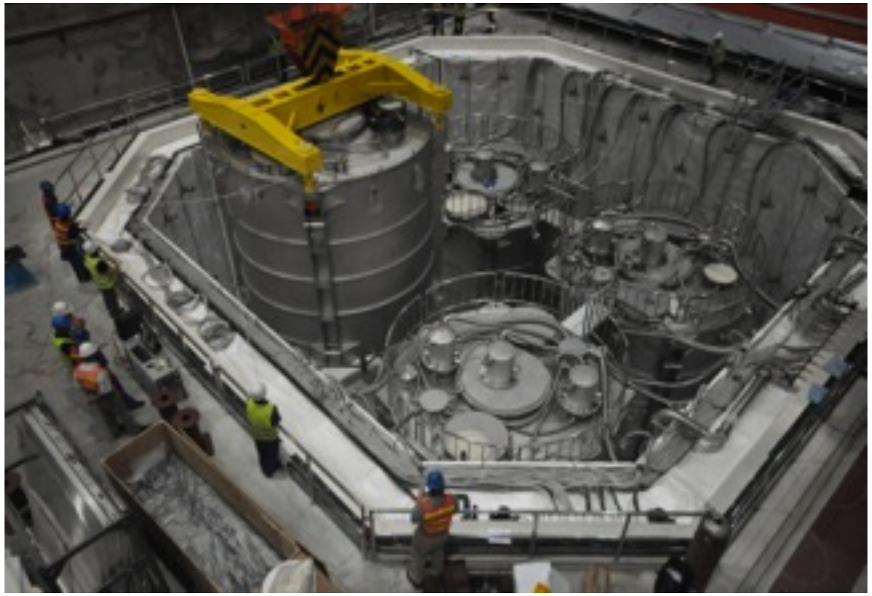
Completed Daya Bay



Nice Pictures on Various Activities

Final two detectors installed, operating since Oct. 2012.



4π detector calibration in Sep. 2012.