Recent Results from the Daya Bay Experiment

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BNL

Outline

Inside the Daya Bay Detector

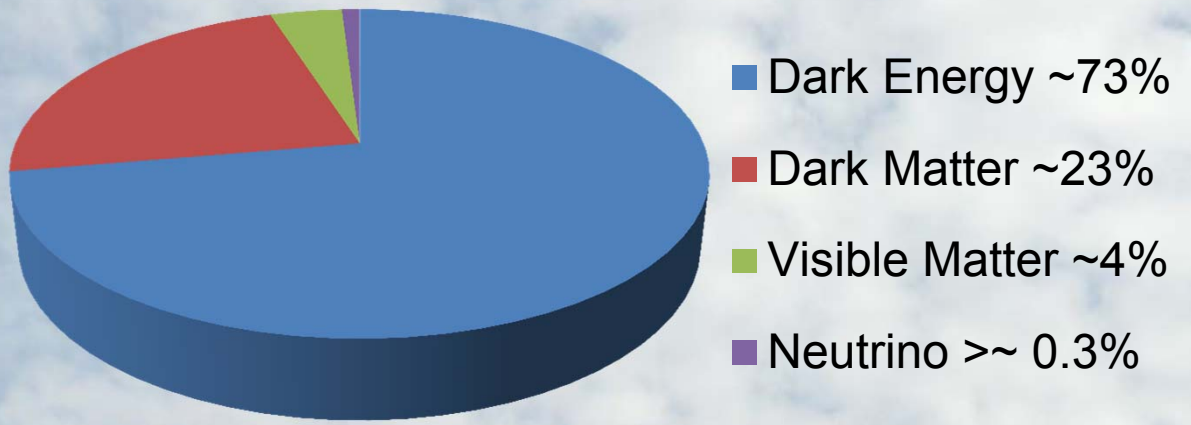
- Neutrino Oscillation
- Daya Bay Experiment
- Precision Measurements of θ_{13} and Δm^2_{ee}
- Search for a light sterile neutrino
- Reactor flux and spectrum

Basics about the Neutrino

- Neutrinos interact through weak interaction
  - **It takes a wall thicker than our galaxy to stop a neutrino**
- Neutrinos have non-zero mass
  - **Physics beyond the standard model**

2015

Energy Budget of the Universe



- The smallness of neutrino mass also suggests a new mechanism of the mass generation

Neutrino Oscillation

Neutrino Flavor Eigenstate $\neq$ Neutrino Mass Eigenstate

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} \quad \begin{matrix} m_1 \\ m_2 \end{matrix}$$

Neutrino are produced and detected by weak interaction, but propagate as mass eigenstates

$$|\nu_\alpha(t)\rangle = \cos\theta \cdot e^{-i(P_1 \cdot r - Et)} |\nu_1(0)\rangle + \sin\theta \cdot e^{-i(P_2 \cdot r - Et)} |\nu_2(0)\rangle$$

Appearance $\quad P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2\left(1.27 \Delta m_{21}^2 \left[eV^2\right] \frac{L\left[km\right]}{E\left[GeV\right]}\right)$

Survival $\quad P(\nu_\alpha \to \nu_\alpha) = 1 - P(\nu_\alpha \to \nu_\beta) \quad \left(\Delta m_{ij}^2 = m_i^2 - m_j^2\right)$

Pontecorvo-Maki-Nakagawa-Sakata Matrix

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\delta_1} & 0 & 0 \\ 0 & e^{i\delta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric + Accelerator

(Anti)-ν_μ survival

Reactor

Anti-ν_e survival

+

Accelerator

ν_e appearance

Solar+Reactor

(Anti)-ν_e survival

$0\nu\beta\beta$

$\Delta m^2_{32} \sim 2.4\times10^{-3} eV^2$	$\Delta m^2_{32} \sim 2.4\times10^{-3} eV^2$	$\Delta m^2_{21} \sim 7.5\times10^{-5} eV^2$
$\theta_{23} \sim 45^\circ$	**$\theta_{13} \sim 8.4^\circ$** δ = ???	$\theta_{12} \sim 34^\circ$

Appearance

$$P(\nu_\alpha \to \nu_\beta)$$

Survival

$$P(\nu_\alpha \to \nu_\alpha)$$

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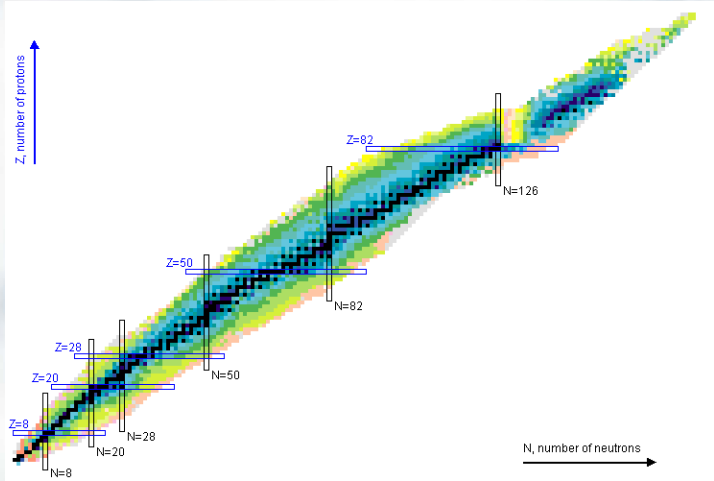
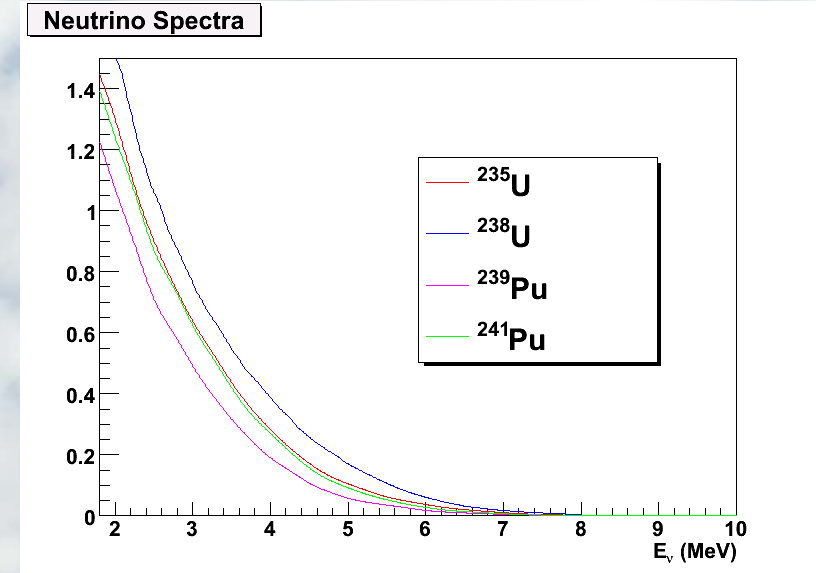
Reactor Neutrinos

- Pure anti-ν_e source *
- ~ 200 MeV per fission
- ~ 6 anti-ν_e per fission
- ~ 2 x 10^{20} anti-ν_e/GW_{th}/sec





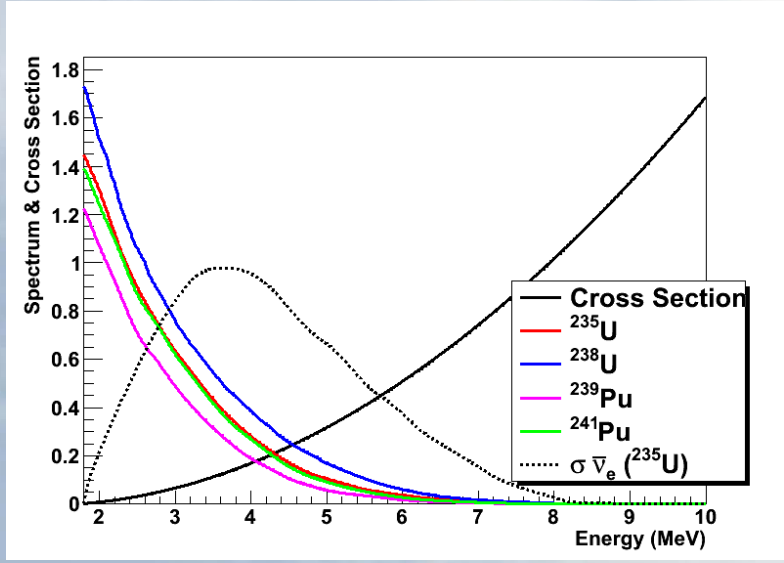
U-235, Pu-239, Pu-241 from β spectrum measurement
U-238 from calculations

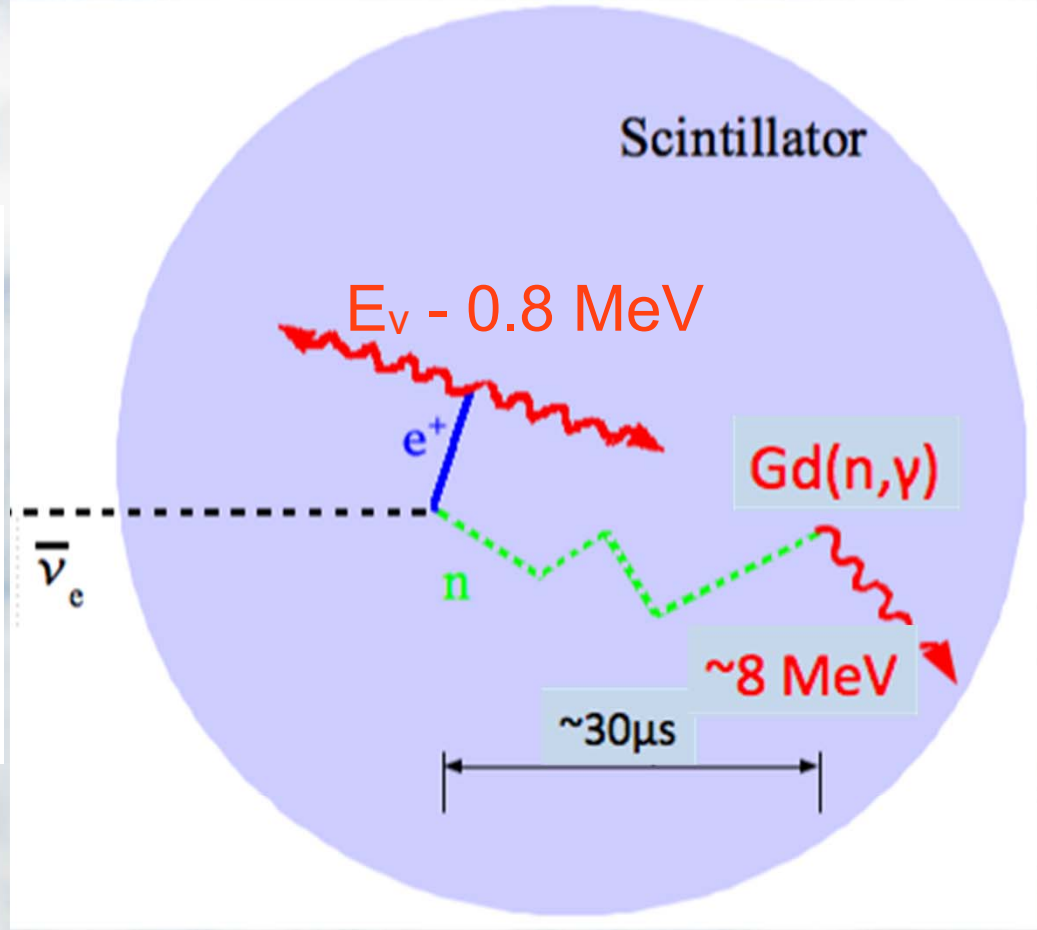
*: a small component of ν_e at ~0.1 MeV

Anti-ν_e Detection

- Inverse Beta Decay:threshold @ 1.8 MeV

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





Coincidence signal:

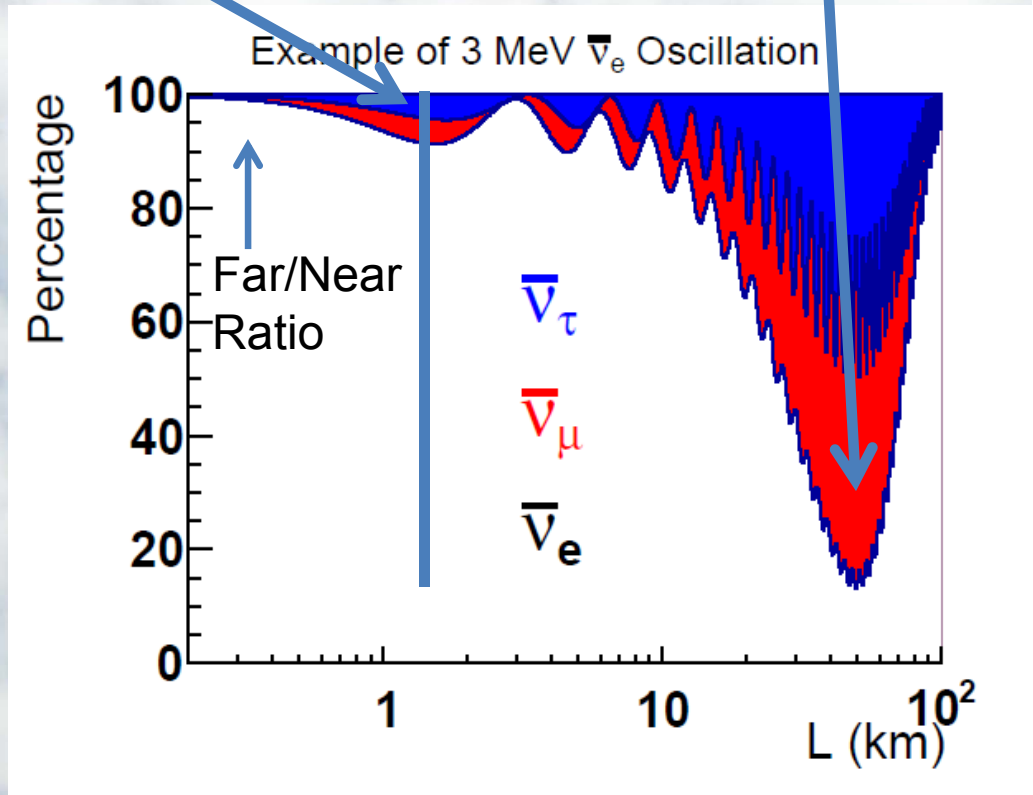
Prompt: e^+ & annihilation → $E_{prompt} \approx E_\nu - E_n - 0.78 MeV$

Delayed: n + Gd → 8 MeV with 30 us capture time

Daya Bay: Anti-ν_e Disappearance

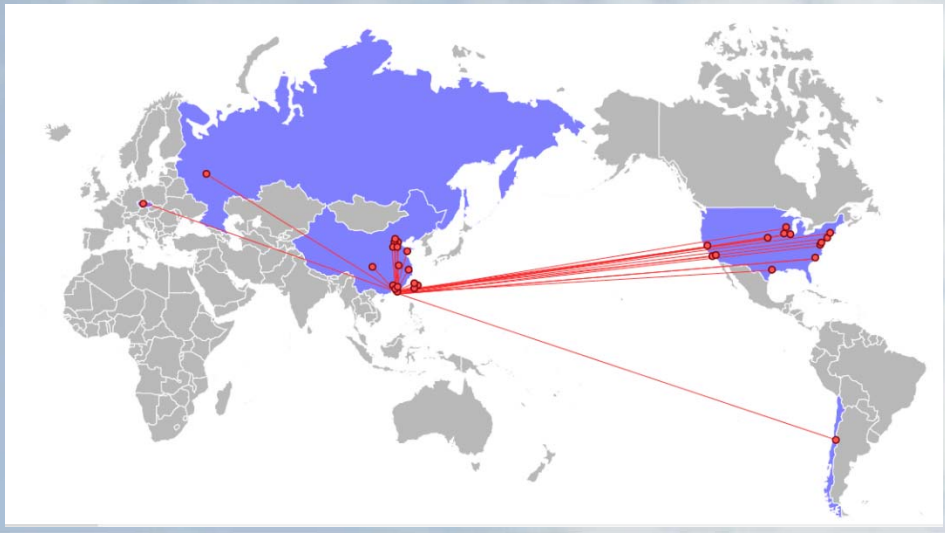
$$P(\overline{\nu_e} \to \overline{\nu_e}) \approx 1 - \sin^2 2\theta_{13} \cdot \sin^2\left(\Delta m^2_{ee} \cdot \frac{L}{E}\right) - \cos^4\theta_{13} \cdot \sin^2 2\theta_{12} \cdot \sin^2\left(\Delta m^2_{21} \cdot \frac{L}{E}\right)$$

- Very clean measurement of θ_{13} at L ~ 2km
  - Not sensitive to mass hierarchy
  - Free to CP phase δ in PMNS
  - Ratio to cancel uncertainty in reactor flux

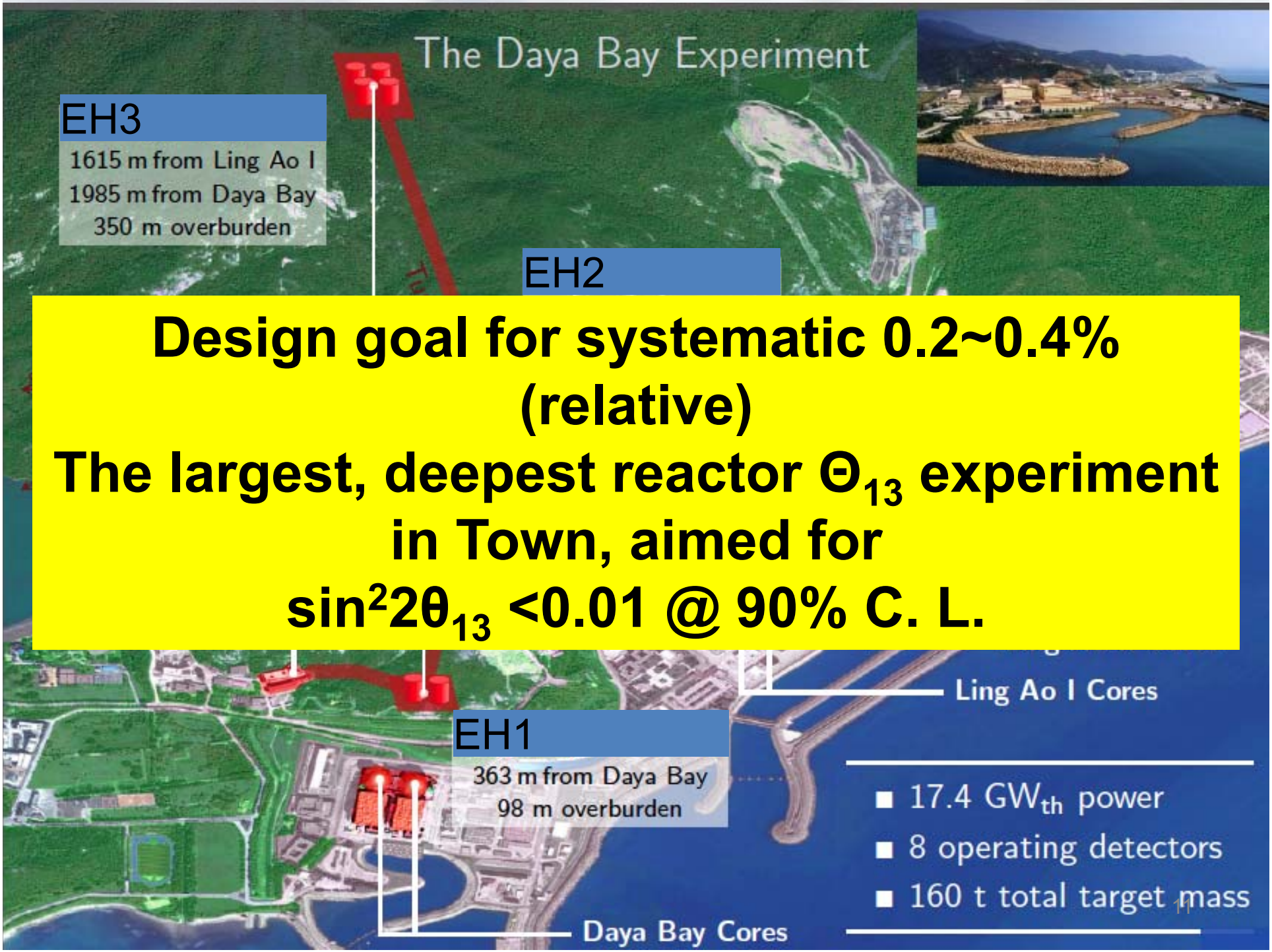


$$|\Delta m^2_{ee}| \sim |\Delta m^2_{32}| \approx |\Delta m^2_{31}| >> |\Delta m^2_{21}|$$

The Daya Bay Collaboration



Asia: 22 institutions
North America: 17 institutions
Europe: 2 institutions
South America: 1 institution
42 institutions
~ 230 collaborators



Design goal for systematic 0.2~0.4% (relative)

The largest, deepest reactor Θ_{13} experiment in Town, aimed for $\sin^2 2\theta_{13}$ <0.01 @ 90% C. L.

Key to reach 0.01

- (Stat) Powerful reactors (17.6 GW) +Large Mass (80 ton)

Far/Near ν_e Ratio

Distances from reactor

Oscillation deficit

$$\frac{N_{\rm f}}{N_{\rm n}} = \left(\frac{N_{\rm p,f}}{N_{\rm p,n}}\right)\left(\frac{L_{\rm n}}{L_{\rm f}}\right)^2\left(\frac{\epsilon_{\rm f}}{\epsilon_{\rm n}}\right)\left[\frac{P_{\rm sur}(E,L_{\rm f})}{P_{\rm sur}(E,L_{\rm n})}\right]$$

Detector Target Mass

Detector efficiency

- (Sys) Reactor related: using near/far to form ratio + baseline (near ~0.4 km, far ~1.7 km)
- (Sys) Detector related: “identical detectors” + “precise detector calibration”
- (Sys) Background related: deep underground to reduce cosmic + active/passive shielding

Daya Bay Anti-ν_e Detector

Automated calibration system

Reflectors at top/bottom of cylinder
Effective photo-cathode coverage ~12%

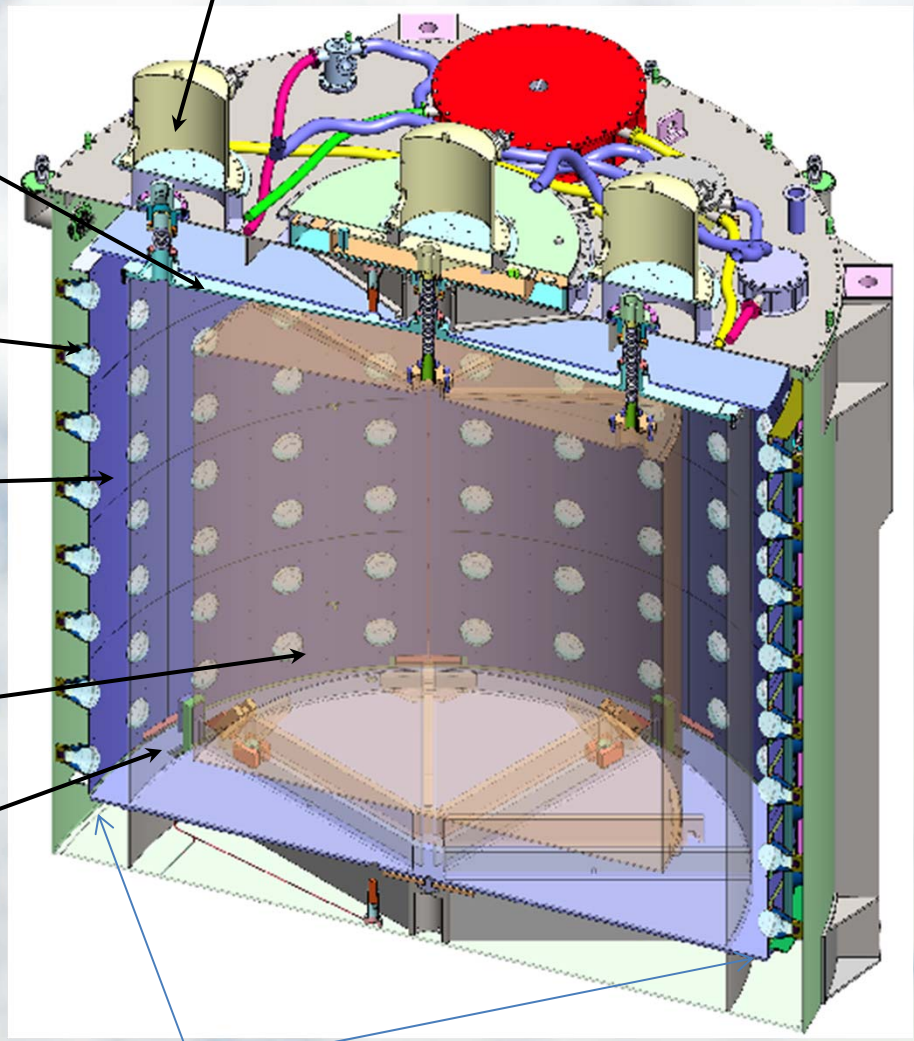
$$\frac{\delta E}{E} = \left(\frac{7.5}{\sqrt{E(MeV)}} + 0.9\right)\%$$

192 Photomultipliers on the surrounding wall

Steel tank
40 ton mineral oil
(Shielding)

Inner acrylic tank
20 ton Gd-loaded liquid scintillator
(Target)

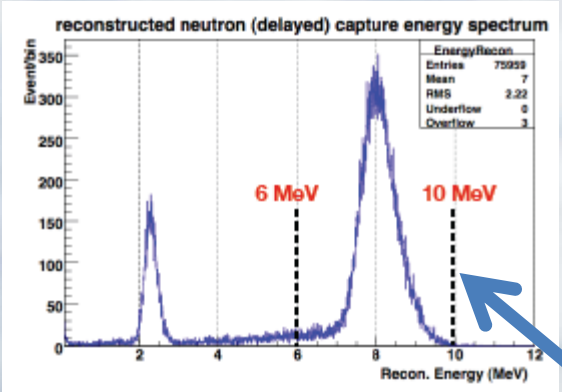
Outer acrylic tank
20 ton liquid scintillator
(gamma catching)



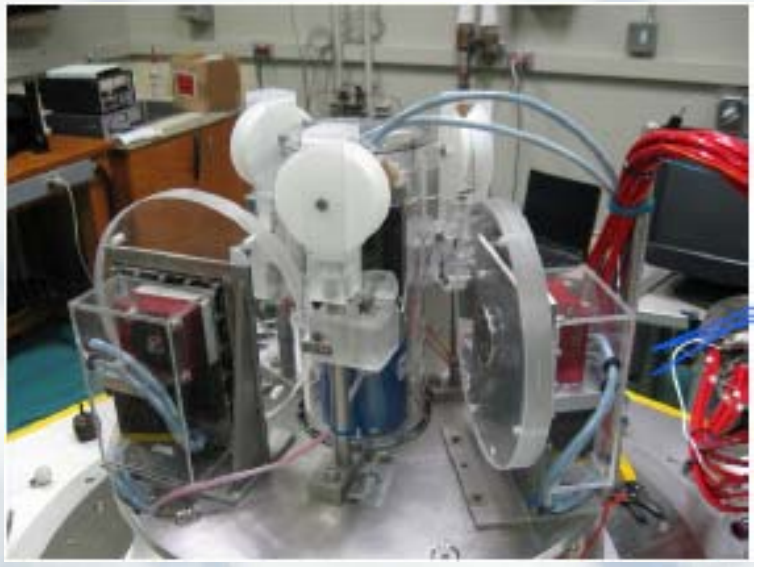
5 m diameter

Calibration System

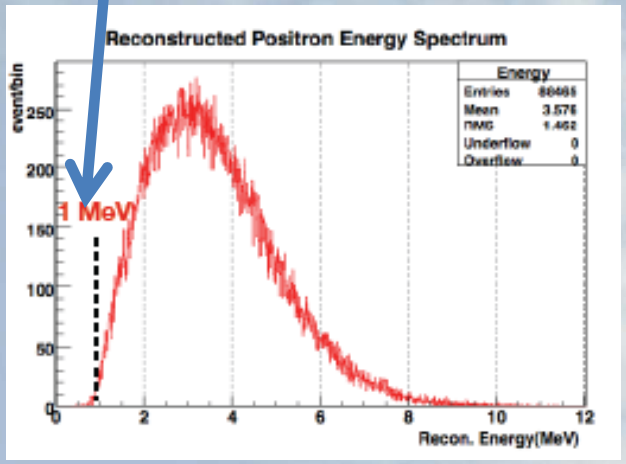
- Automated: weekly calibration



> 6 MeV in DYB



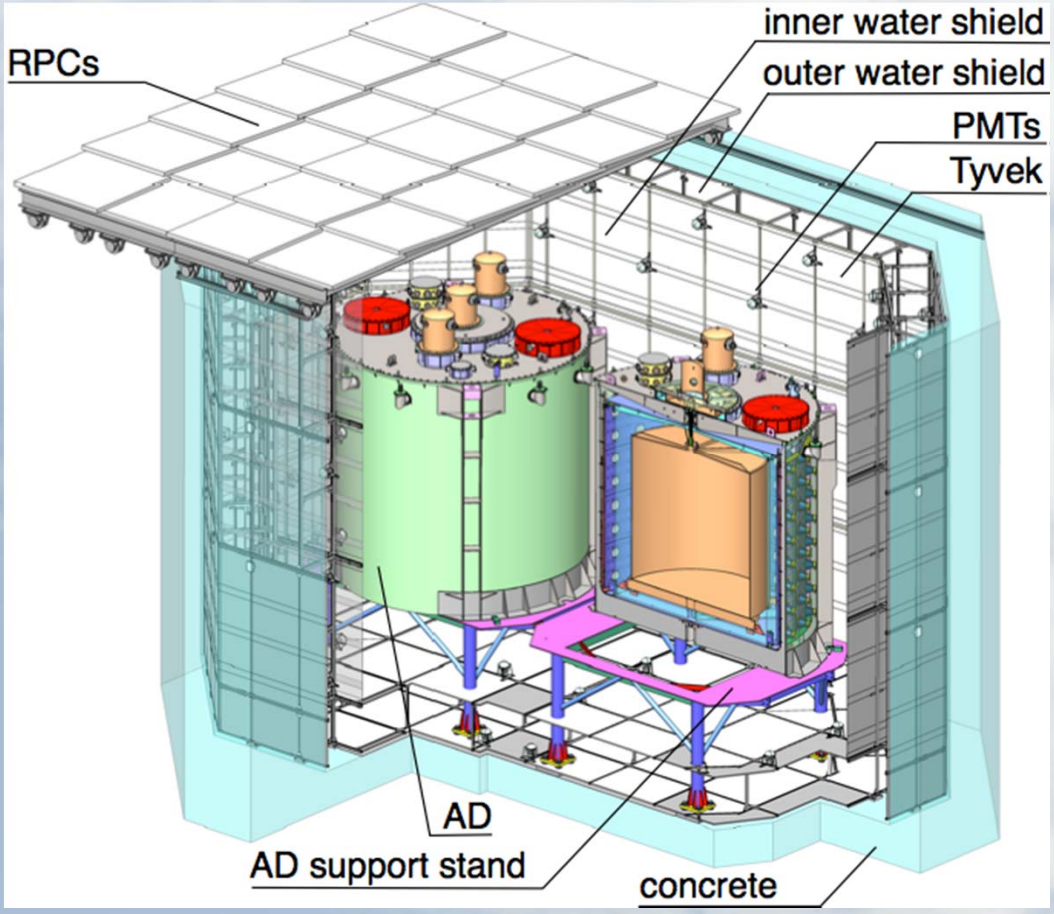
- Ge68, LED, Co60, Am-C



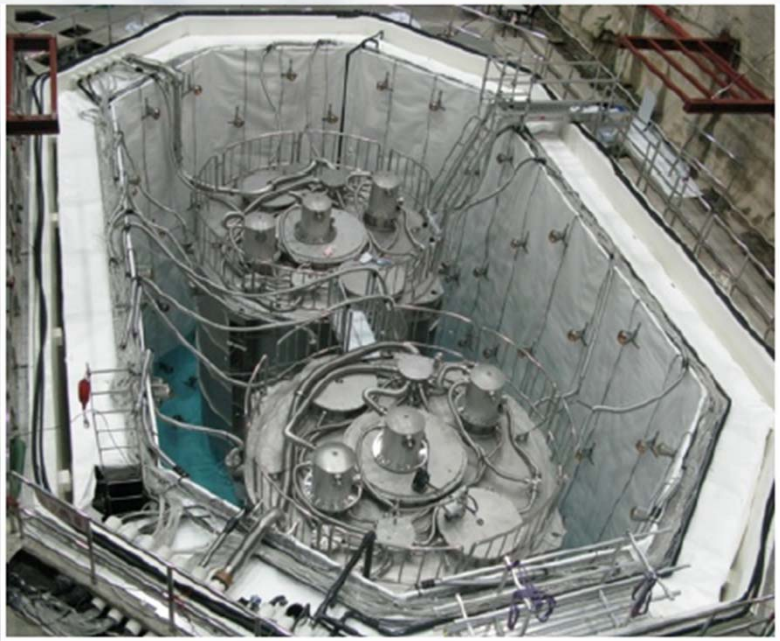
0.7→12 MeV in DYB

Muon Veto System

Dual tagging systems: 2.5 meter thick two-section water shield and Resistance Plate Chambers (RPC)

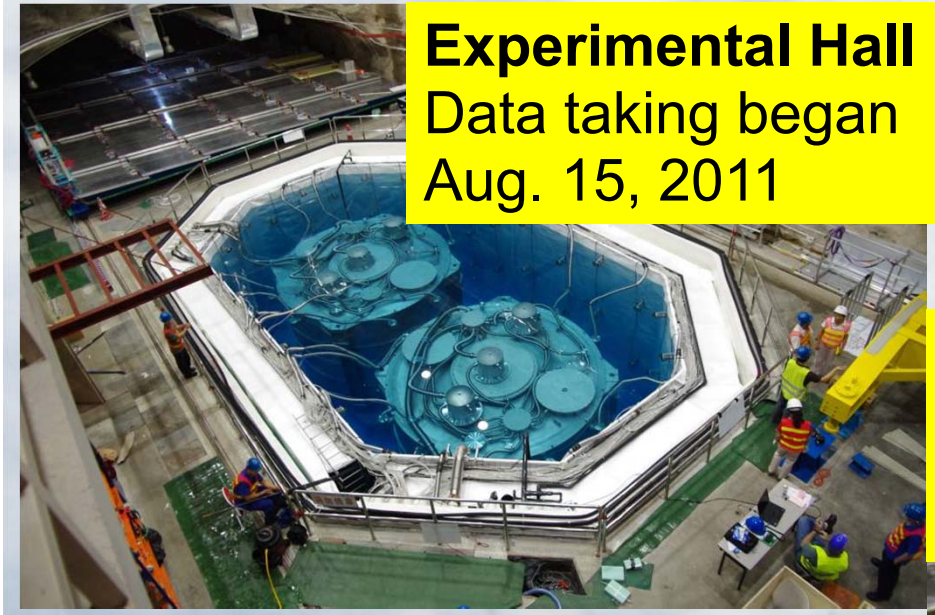


Two Zone ultrapure water Cherenkov detector



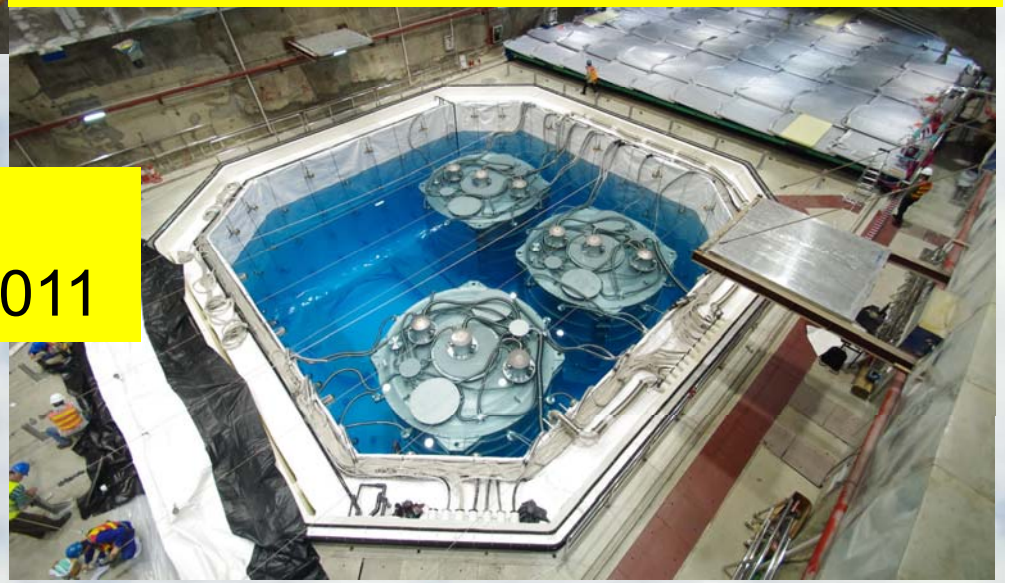
AD: Anti-neutrino Detector

Detectors in 3 Sites

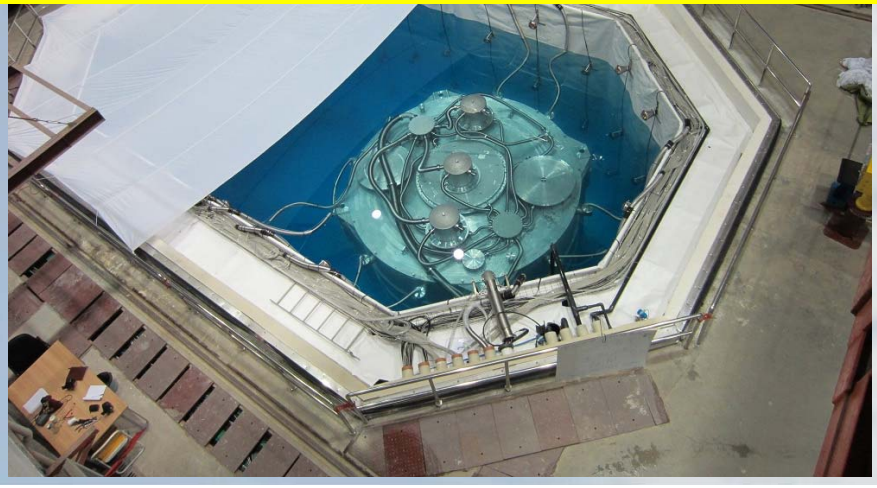


Experimental Hall 1
Data taking began
Aug. 15, 2011

Experimental Hall 3: Began 3 detectors operation on
Dec. 24, 2011



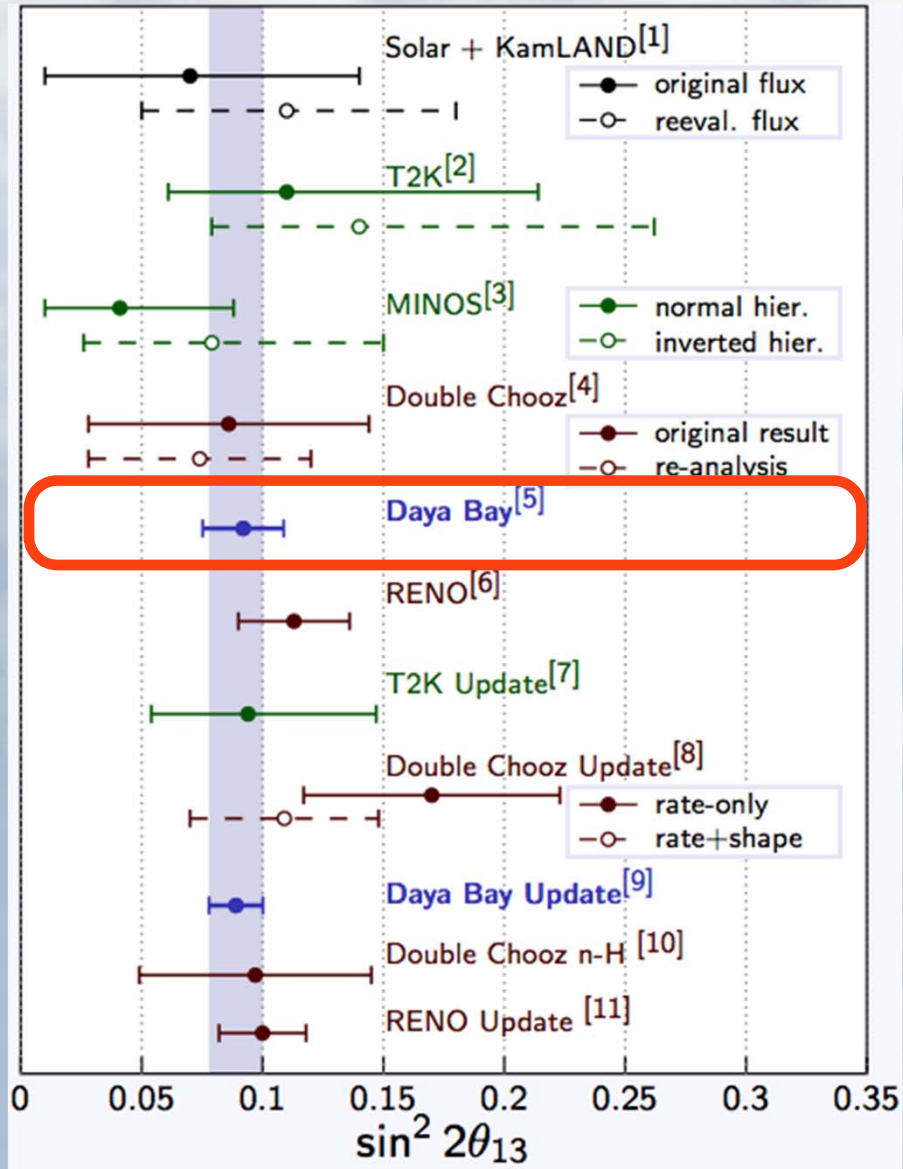
Experimental Hall 2: Began 1 detector operation on Nov. 5, 2011

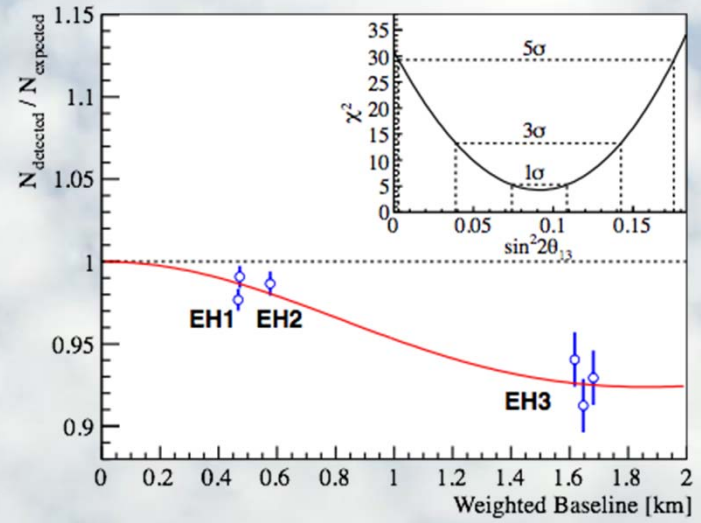


The Hunting Race for θ_{13} Since 2011

2011

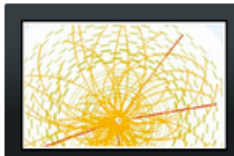
2013





March 2012, Daya Bay reported the discovery of non-zero value of θ_{13} with a statistical significance > 5σ

A Top-10 Scientific Breakthrough of 2012



FREE ACCESS

The Discovery of the Higgs Boson

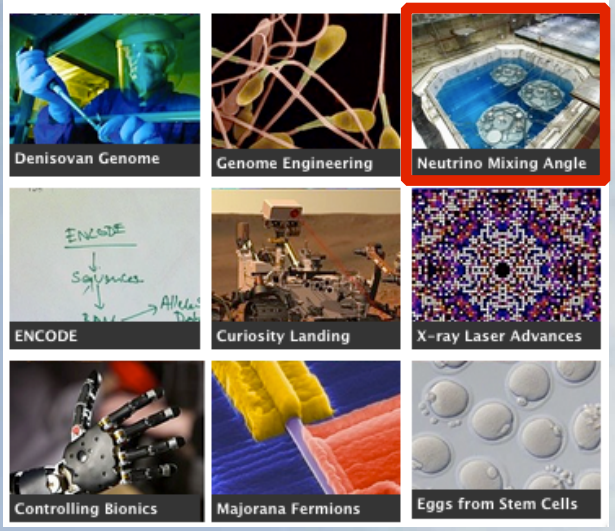
A. Cho

Exotic particles made headlines again and again in 2012, making it no surprise that the breakthrough of the year is a big physics finding: confirmation of the existence of the Higgs boson. Hypothesized more than 40 years ago, the elusive particle completes the standard model of physics, and is arguably the key to the explanation of how other fundamental particles obtain mass. The only mystery that remains is whether its discovery marks a new dawn for particle physics or the final stretch of a field that has run its course.

Read more about the Higgs boson from the research teams at CERN.

Runners-Up FREE WITH REGISTRATION

This year's runners-up for Breakthrough of the Year underscore feats in engineering, genetics, and other fields that promise to change the course of science.



TALENs, and another genome-editing tool called meganucleases is that they must be reengineered for each new DNA target. These proteins have two parts: the DNA targeting section and the DNA-cutting section. The new technology substitutes RNA—which is simpler to make than a piece of a protein—for the DNA targeting section. It also makes use of a bacterial protein called Cas9, which is part of a natural bacterial defense system called CRISPR, to do the cutting.

Researchers have shown in a test-tube that they can combine these two RNAs into a single one that both matches the DNA target and holds Cas9 in place. Using this system, they were able to cut specific target DNA, demonstrating the potential of Cas9 to work like TALENs. Now, those researchers are trying this approach in organisms other than bacteria, and other genome engineers are quite excited about their prospects, suggesting that it may one day challenge zinc finger nucleases and TALENs as the core genome engineering technology.

CRASH PROJECT OPENS A DOOR IN NEUTRINO PHYSICS

Sometimes it's not the result itself so much as the promise it holds that matters most. This year, physicists measured the last parameter describing how elusive particles called neutrinos morph into one another as they zip along at near-light speed. And the result suggests that in the coming decades neutrino physics will be every bit as rich as physicists had hoped—and may even help explain how the universe evolved to contain so much matter and so little antimatter.

RUNNER-UP

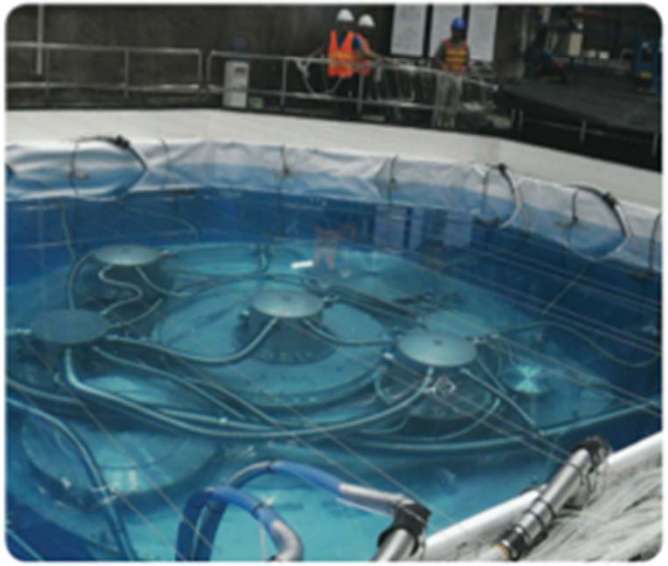
Born in certain nuclear interactions, neutrinos come in three types or flavors that change into one another in so-called neutrino oscillations. The rates and extents to which the flavors mix depend on six parameters: the three differences between the neutrinos' masses, and three "mixing angles." In March, the 250 researchers with the Daya Bay Reactor Neutrino Experiment in China reported that last unknown parameter, the mixing angle known as θ_{13} (pronounced "theta one three"), equals 8.8°, give or take 0.8°.

The result itself is remarkable, as it's not every year that physicists measure a new fundamental parameter. The real excitement, however, stems from the result's broader implications. The measurement proves that all three mixing angles are greater than zero. That fact, in turn, implies that the oscillations of antineutrinos might differ from those of neutrinos, something that would not be possible had θ_{13} equaled zero.

That's a big deal. Such a difference would analogous to the effect that created the matter-antimatter imbalance in the universe.

In fact, researchers in the United States, Japan, and Europe are engaged in experiments in which they use particle accelerators to fire neutrinos hundreds of kilometers through Earth to huge particle detectors. Current efforts seek to pin down, for example, the neutrinos emanating from the reactors at the Daya Bay Nuclear Power Plant and two neighboring plants in Shenzhen. In making a definitive measurement, they beat out teams working at reactors in France and South Korea and accelerator-based experiments in Japan and the United States.

The measurement of θ_{13} wasn't the only result in particle physics this year. Researchers working with the world's largest atom smasher, the Large Hadron Collider (LHC) in Switzerland, discovered the Higgs boson, the



That was fast! Construction of China's Daya Bay Reactor Neutrino Experiment began in 2007. With 2 months' worth of data, it scooped competitors in Japan, France, Korea, and the United States.

Science **338**, 1527

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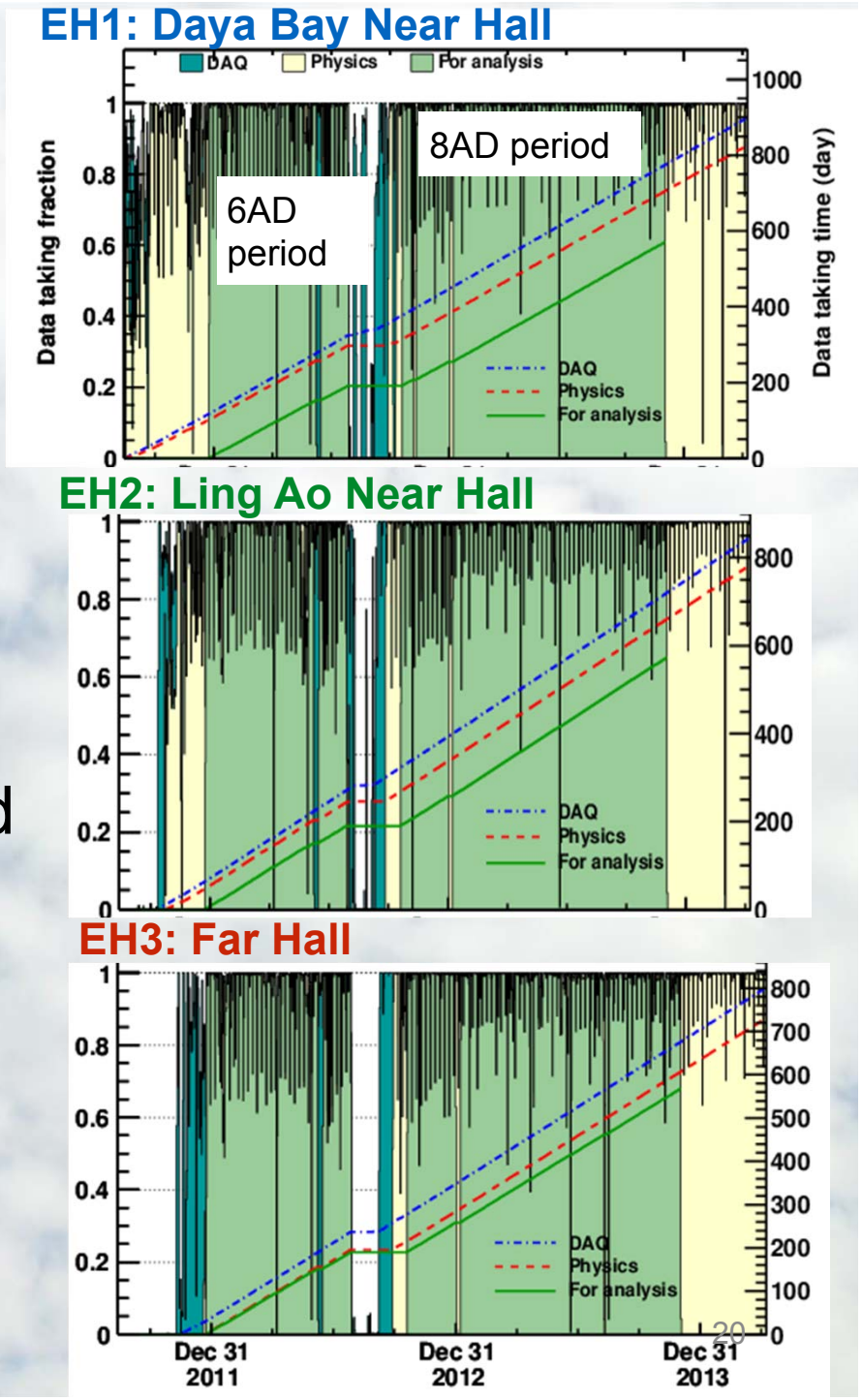
Oscillation Analysis

- Using 6-AD period (217 days):
  - Independent $\sin^2 2\theta_{13}$ measurement with neutron capture on hydrogen (nH)
  - **PRD 90, 071101R (2014).**

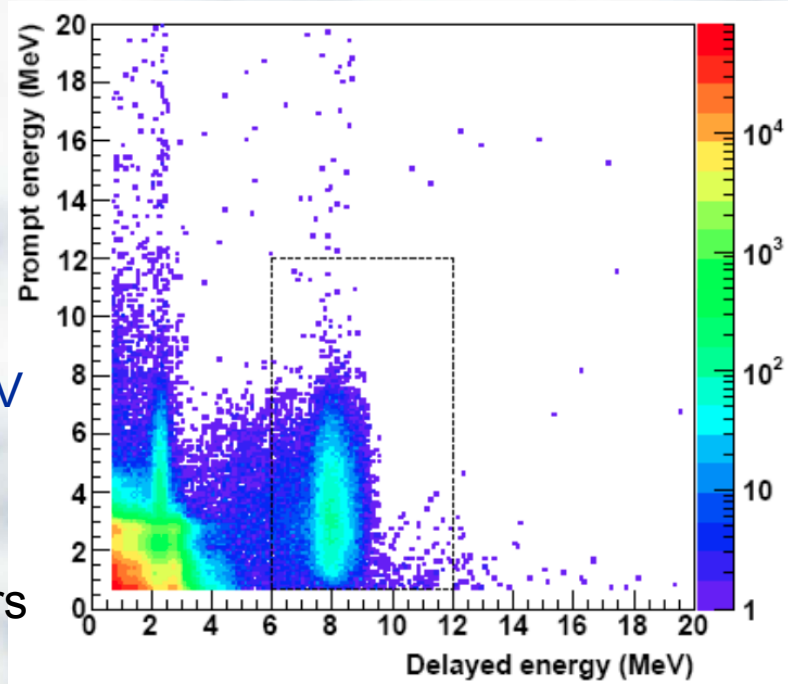
- Using combined 6+8 AD period (621 days)
  - Precision measurements of $\sin^2 2\theta_{13}$ and Δm^2_{ee}
  - **PRL 115, 11802 (2015),** 4 times more statistics than previous release



Anti-Neutrino Candidate Selection

Reject PMT flashers

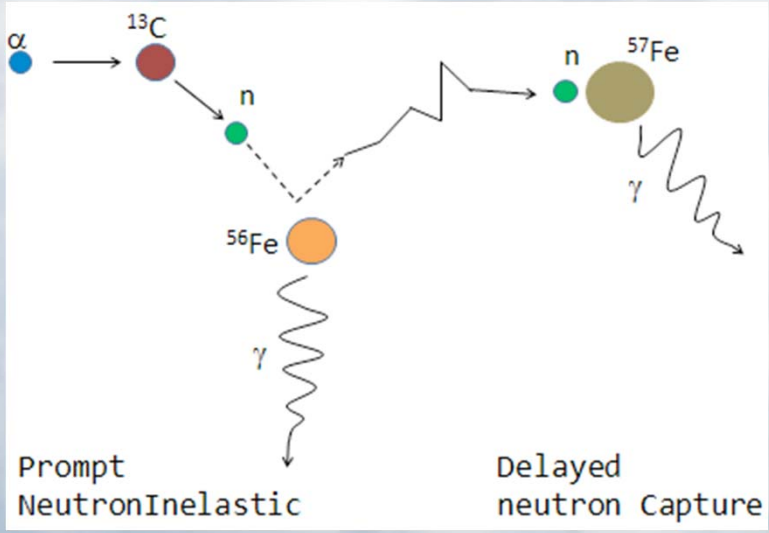
- Muon veto:
  - Water pool Muon: reject 0.6ms
  - AD Muon (>20 MeV): reject 1 ms
  - AD Shower Muon (>2.5 GeV): reject 1s
- Prompt positron Energy: 0.7 MeV < Ep < 12 MeV
- Delayed neutron Energy: 6 MeV < Ed < 12 MeV
- Neutron Capture time: 1 us < Δt < 200 us
- Multiplicity cut: only select isolated candidate pairs

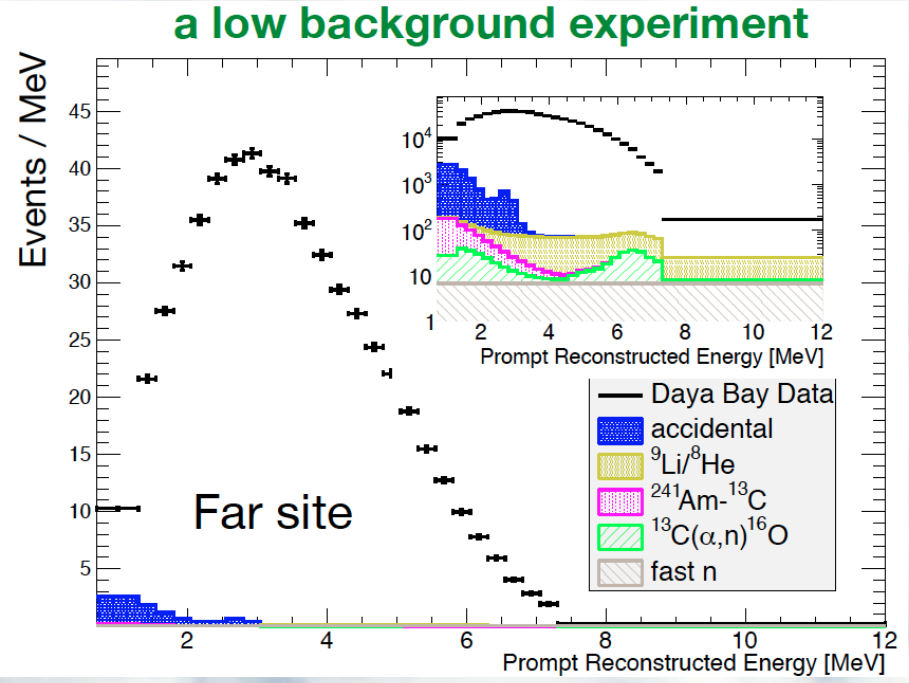


	Efficiency	Uncertainty	
		Correlated	Uncorrelated
Target Protons		0.47%	0.03%
Flasher cut	99.98%	0.01%	0.01%
Delayed Energy cut	92.7%	0.97%	0.12%
Prompt Energy cut	99.81%	0.10%	0.01%
Capture time cut	98.70%	0.12%	0.01%
Gd capture ratio	84.2%	0.95%	0.10%
Spill-in correction	104.9%	1.50%	0.02%
Combined	80.6%	2.1%	0.2%

Oscillation Analysis

Background

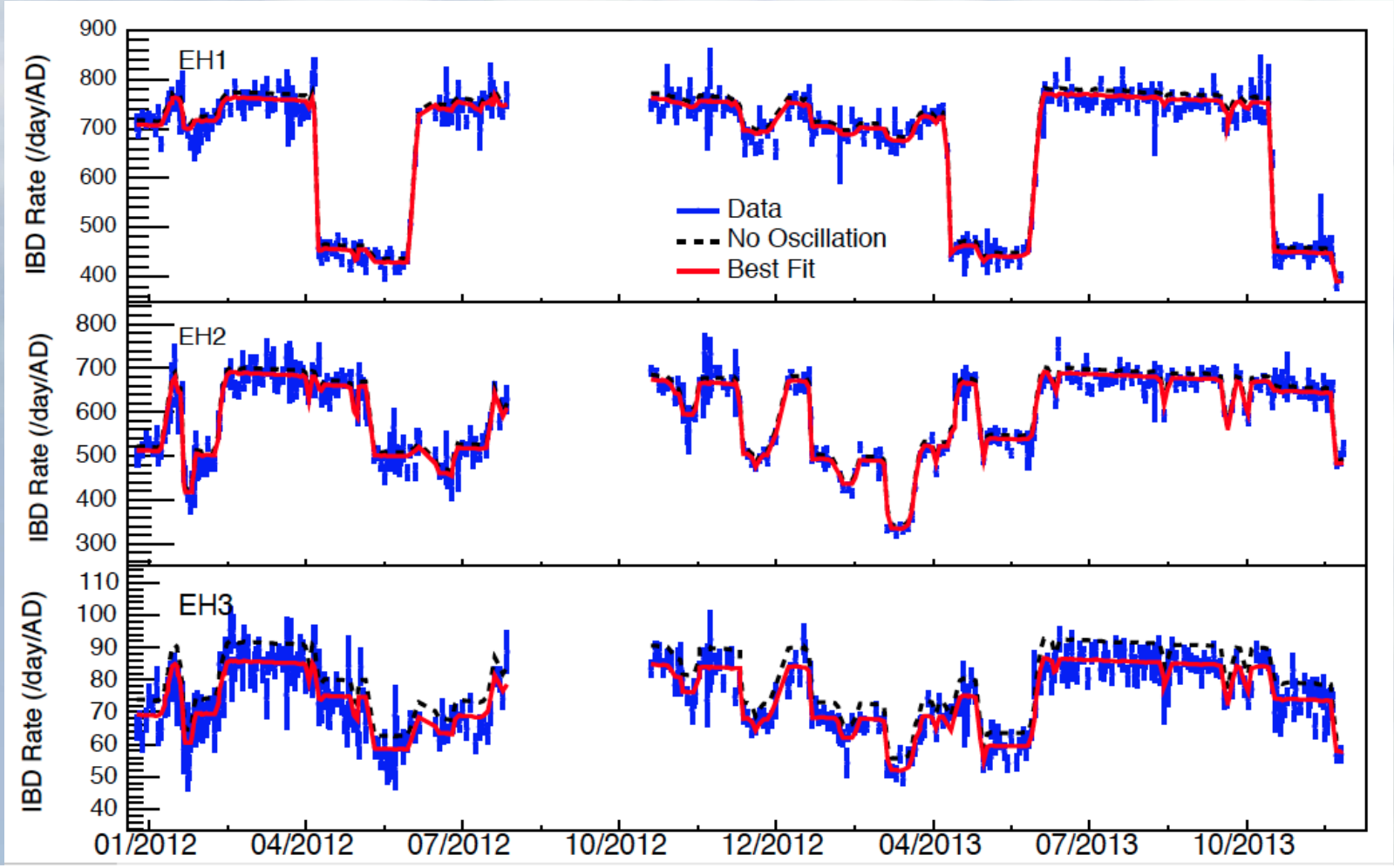




Background	Near	Far	Uncertainty	Method
Accidentals	1.4%	2.3%	Negligible	Statistically calculated from uncorrelated singles
$^{241}Am^{13}C$ source	0.03%	0.2%	~50%	MC benchmarked with single gamma and strong $^{241}Am^{13}C$ source
$^{9}Li/^{8}He$	0.4%	0.4%	~50%	Measured with after-muon events
Fast Neutron	0.1%	0.1%	~30%	Measured from AD/Water/RPC tagged muon events
$^{13}C(\alpha,n)^{16}O$	0.01%	0.1%	~50%	Calculated from measured radioactivity

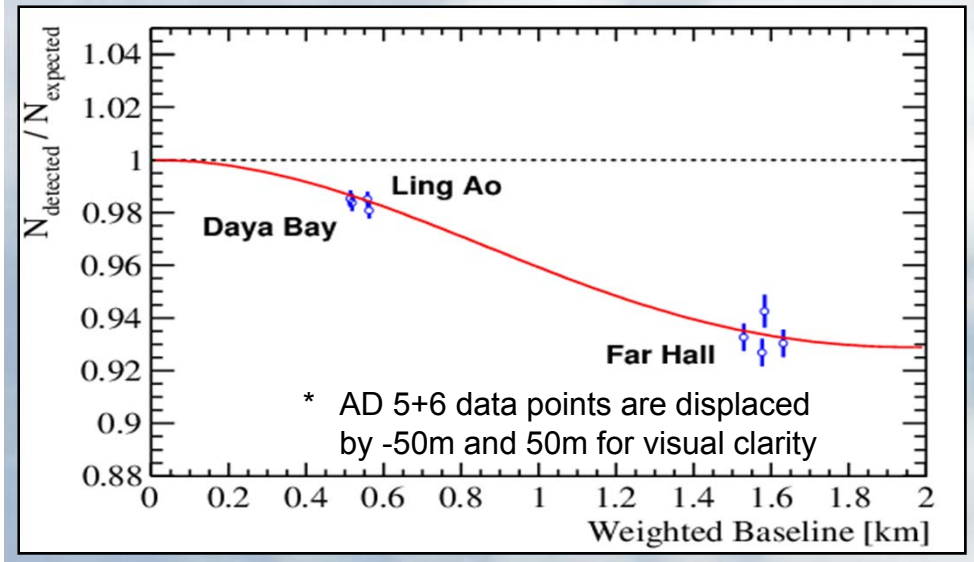
IBD Rate VS. Time

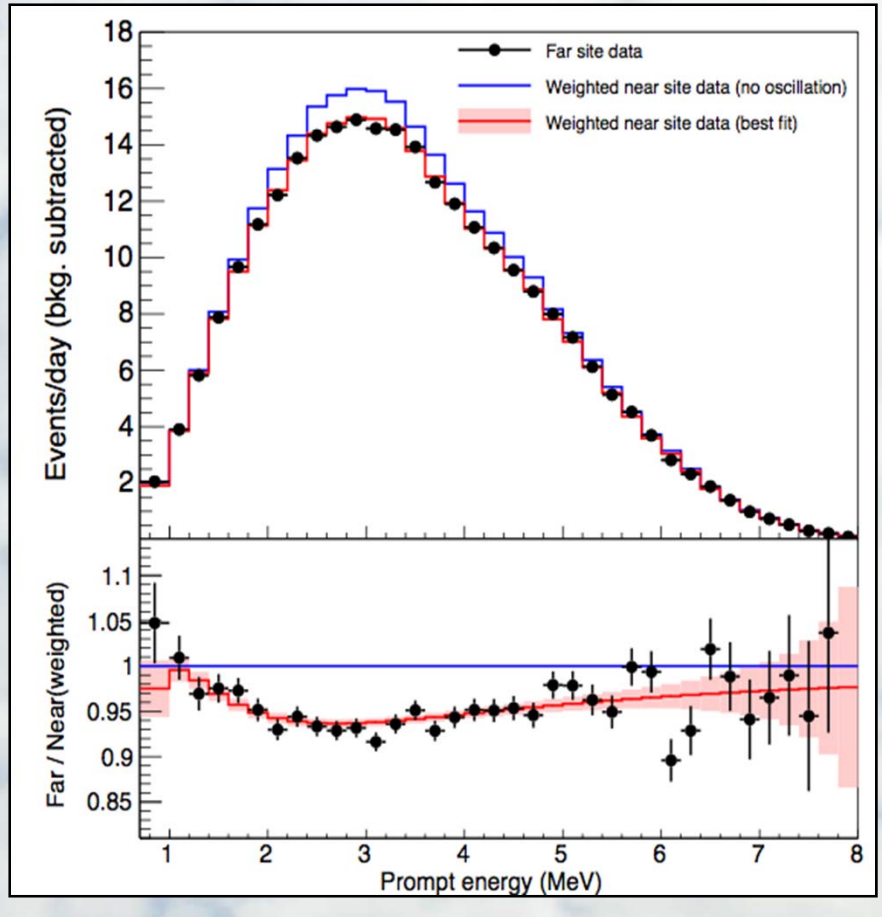
- 621 days of data, including more than one year in full 8-AD configuration. Collected more than 1 M antineutrino events, 150 K at far site.
- Detected rate strongly correlated with reactor flux expectation



Far vs. Near Comparison (nGd)

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



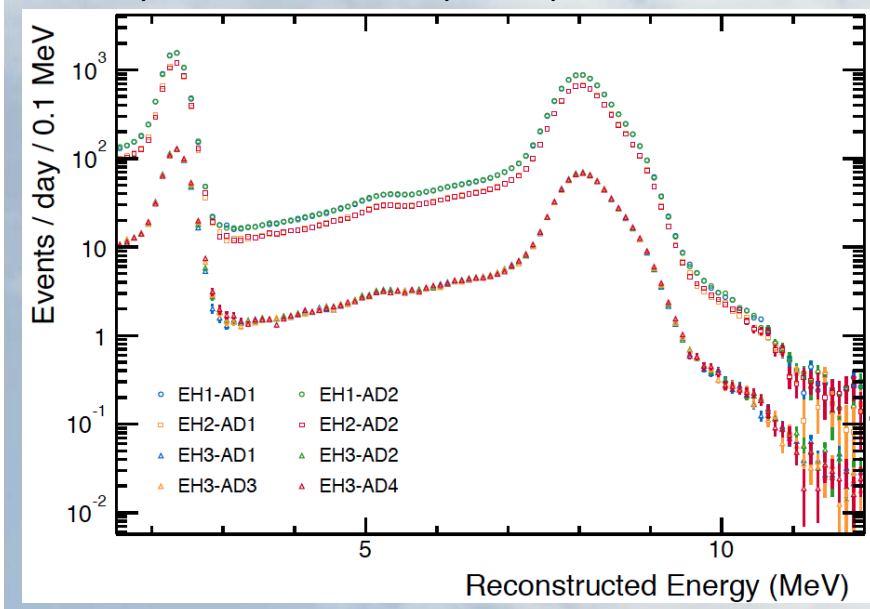


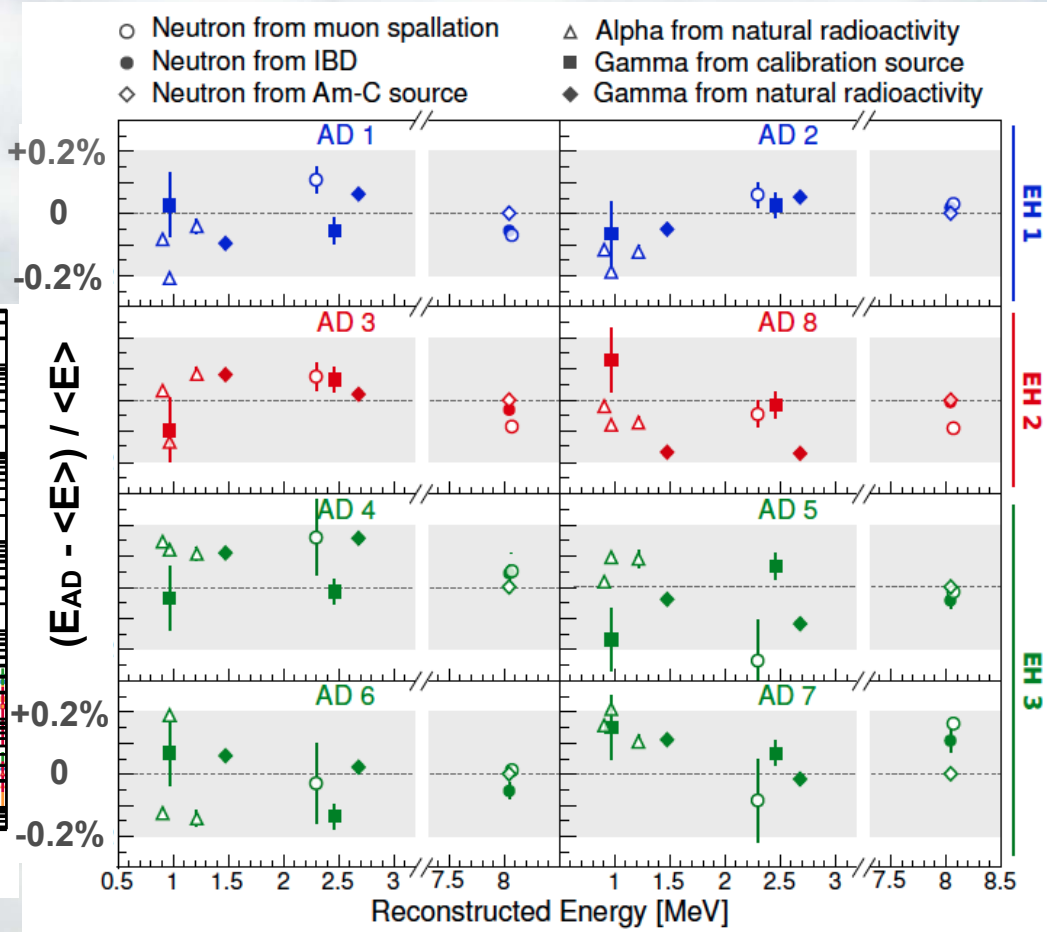
The observed relative rate deficit and relative spectrum distortion are highly consistent with oscillation interpretation

Relative Energy Scale

ACU: ^{60}Co, ^{68}Ge, $^{241}Am^{13}C$
Spallation: nGd, nH
Gamma: ^{40}K, ^{208}Ti
Alpha: ^{212}Po, ^{214}Po, ^{215}Po

Spallation neutron capture spectrum

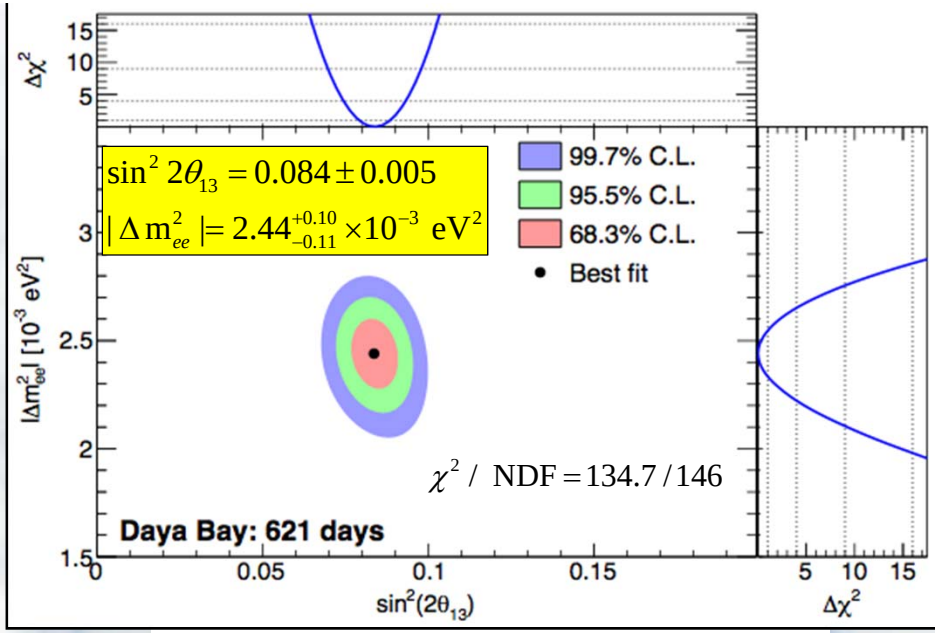


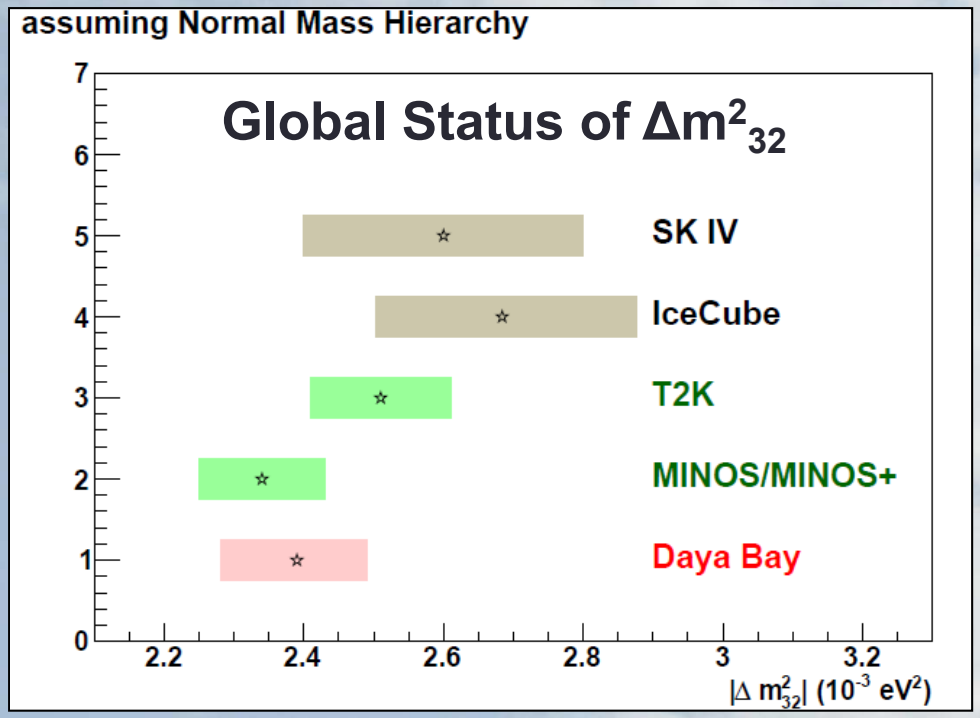


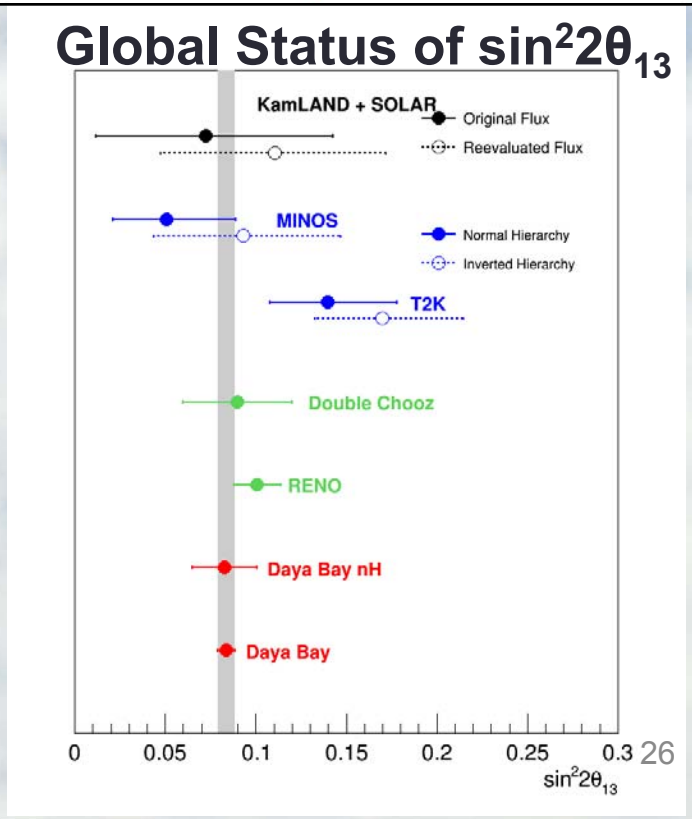
Less than 0.2% variation in reconstructed energy between ADs

Oscillation Results

- **Most precise measurement of $\sin^2 2\theta_{13}$**
- **Most precise measurement of Δm^2_{ee} in the electron neutrino disappearance channel**
  - consistent with the muon neutrino disappearance experiments

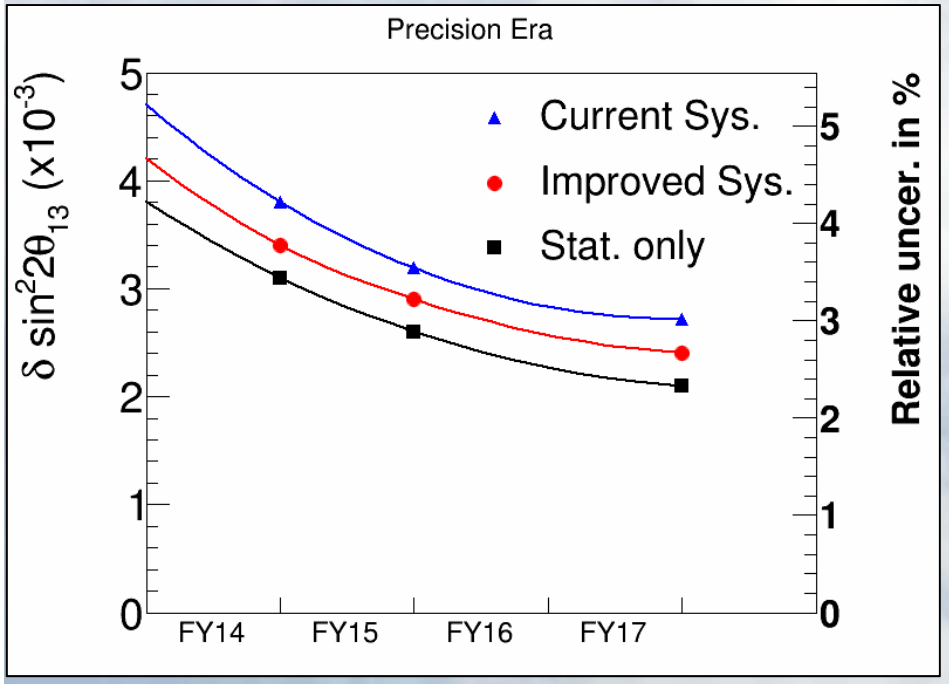




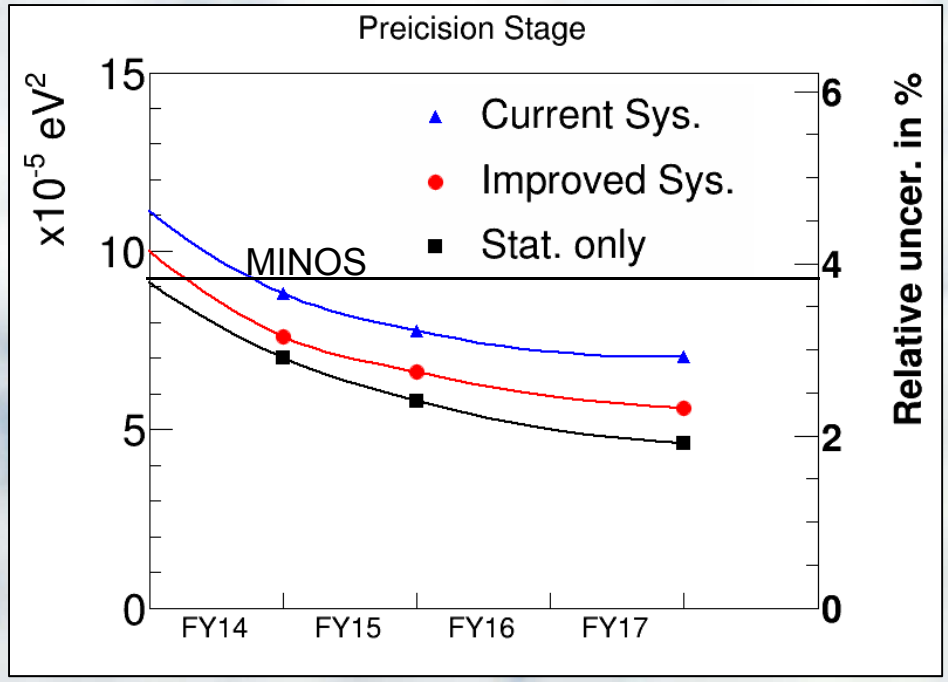


Precision Measurement Phase

$\sin^2 2\theta_{13}$



Δm^2_{ee}



Combination of n-Gd and n-H with anticipated systematics improvements

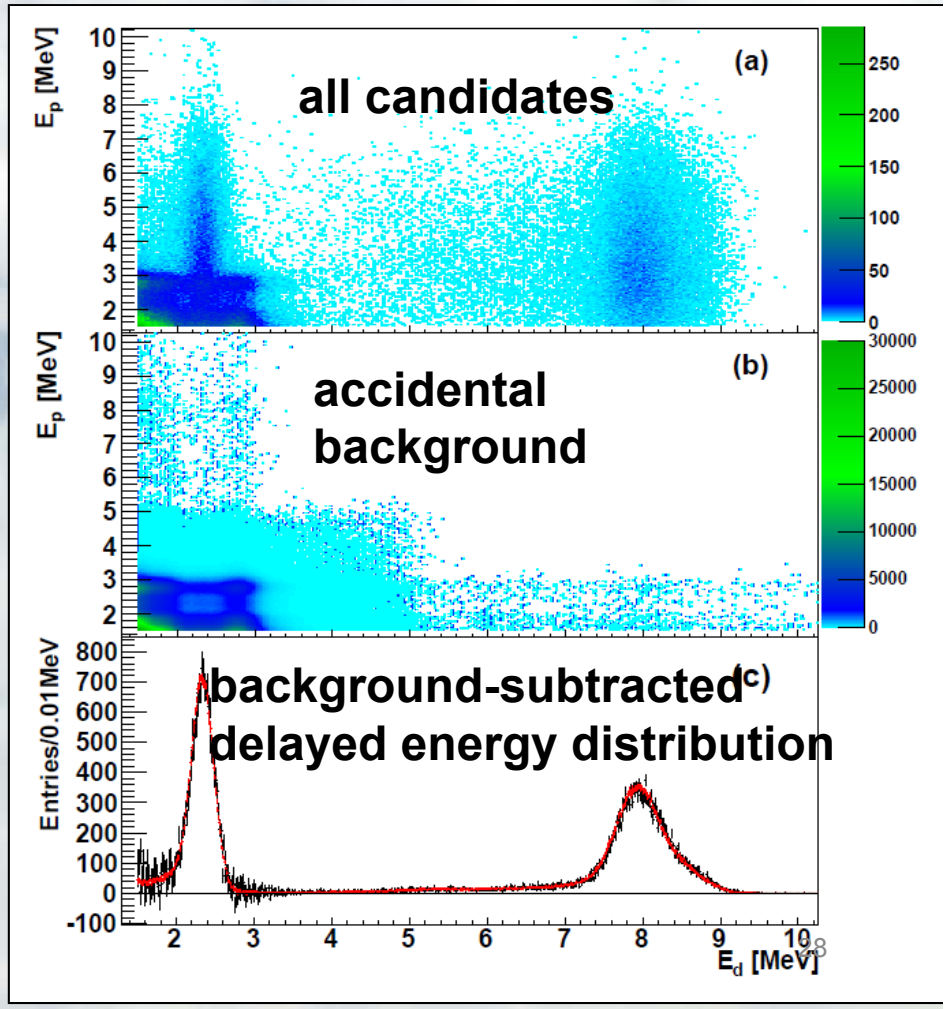
The most precise measurement of $\sin^2 2\theta_{13}$ for the foreseeable future

Independent $\sin^2 2\theta_{13}$ through nH

- Advantage
  - High statistics (15% capture in the 20-ton Gd-LS and 100% in the 20-ton LS)
  - Different systematic uncertainties from nGd analysis
- Challenge
  - High accidental background
    - longer capture time
    - lower delayed energy
- Strategy
  - Prompt energy cut Ep > 1.5 MeV
  - Require prompt to delayed distance ΔR < 0.5 m
  - Relative measurement to reduce systematics

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

$+H \rightarrow D + \gamma$	2.2 MeV	200 μs
$+Gd \rightarrow Gd^* \rightarrow Gd + \gamma's$	8MeV	30 μs



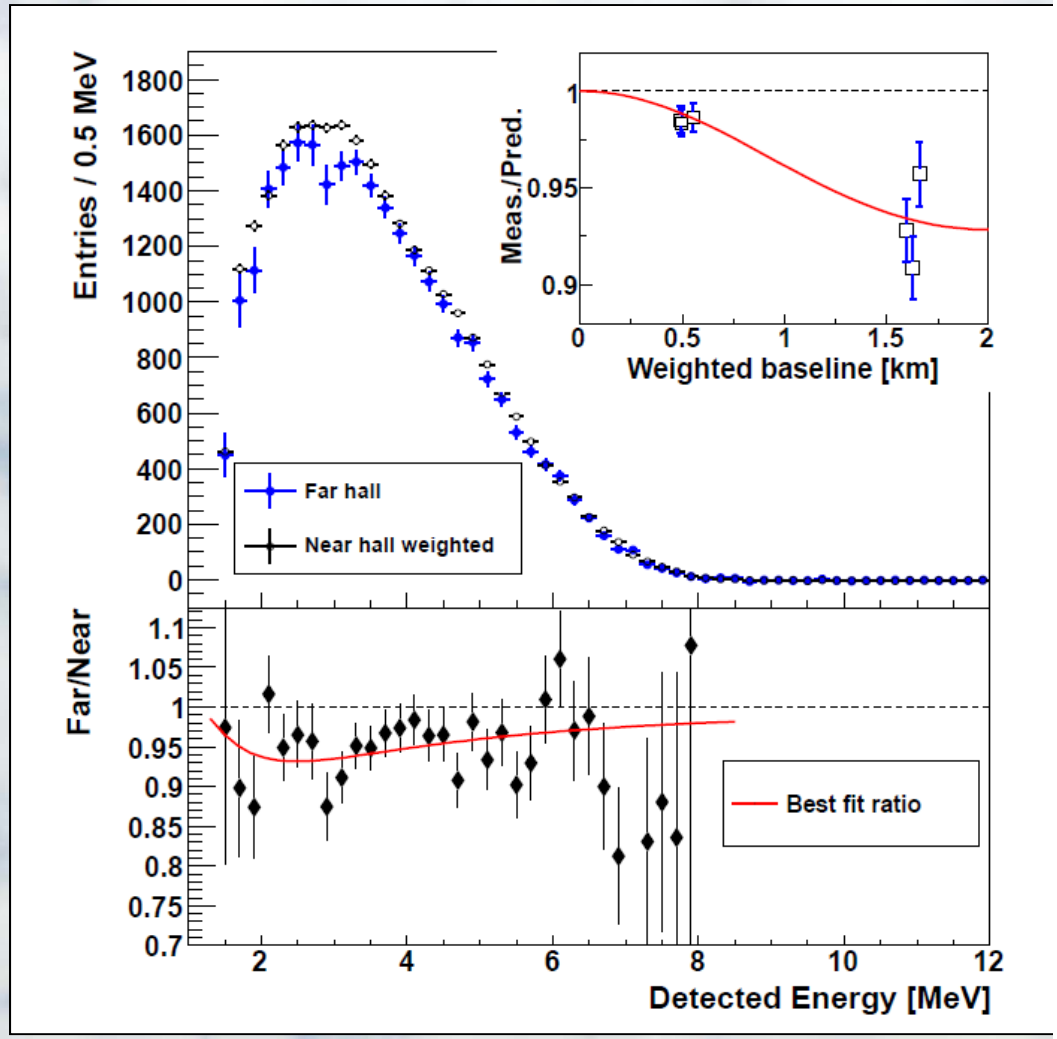
nH Analysis Results

- All 217 days of 6-AD period
- Observed significant rate deficit at far site, rate analysis measures:

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

  - an independent and consistent result with nGd analysis
  - another precise measurement of $\sin^2 2\theta_{13}$

- Spectrum distortion is consistent with oscillation explanation
  - spectral analysis in progress



Where are we?

$$\sin^2\theta_{12} = 0.306^{+0.018}_{-0.015} \qquad \sin^2\theta_{23} = 0.42^{+0.08}_{-0.03}$$

(PDG)

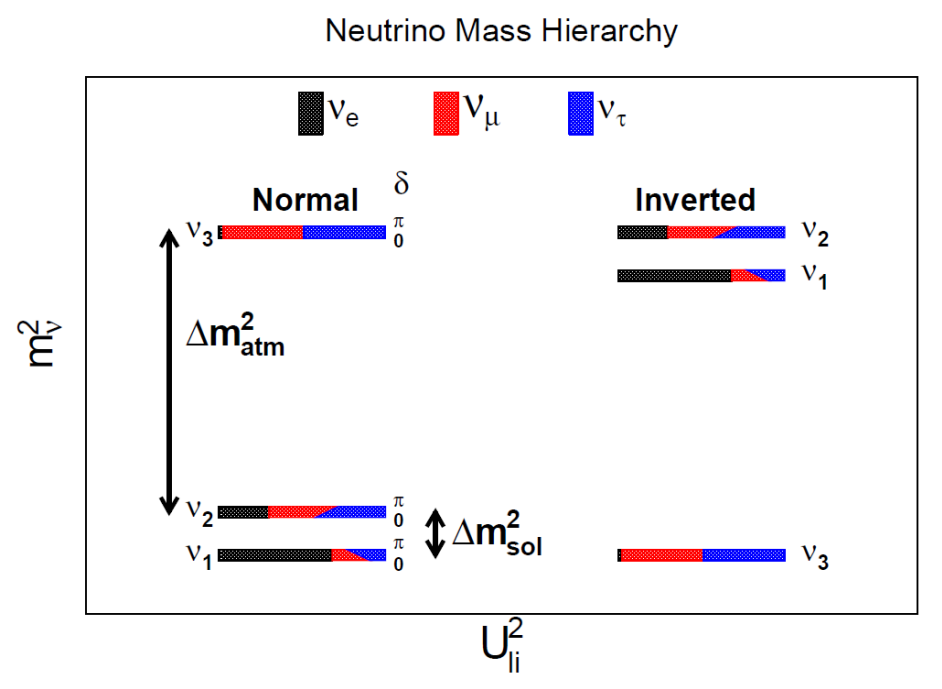
$$\Delta m^2_{sol} = \Delta m^2_{21} = 7.58^{+0.22}_{-0.26}\times 10^{-5} eV^2 \qquad \left|\Delta m^2_{atm}\right| = \left|\Delta m^2_{32}\right| = 2.35^{+0.12}_{-0.09}\times 10^{-3} eV^2$$

Daya Bay:

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

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

- How large is the CP phase δ?
- Normal or Inverted Hierarchy?
- Precision Measurements

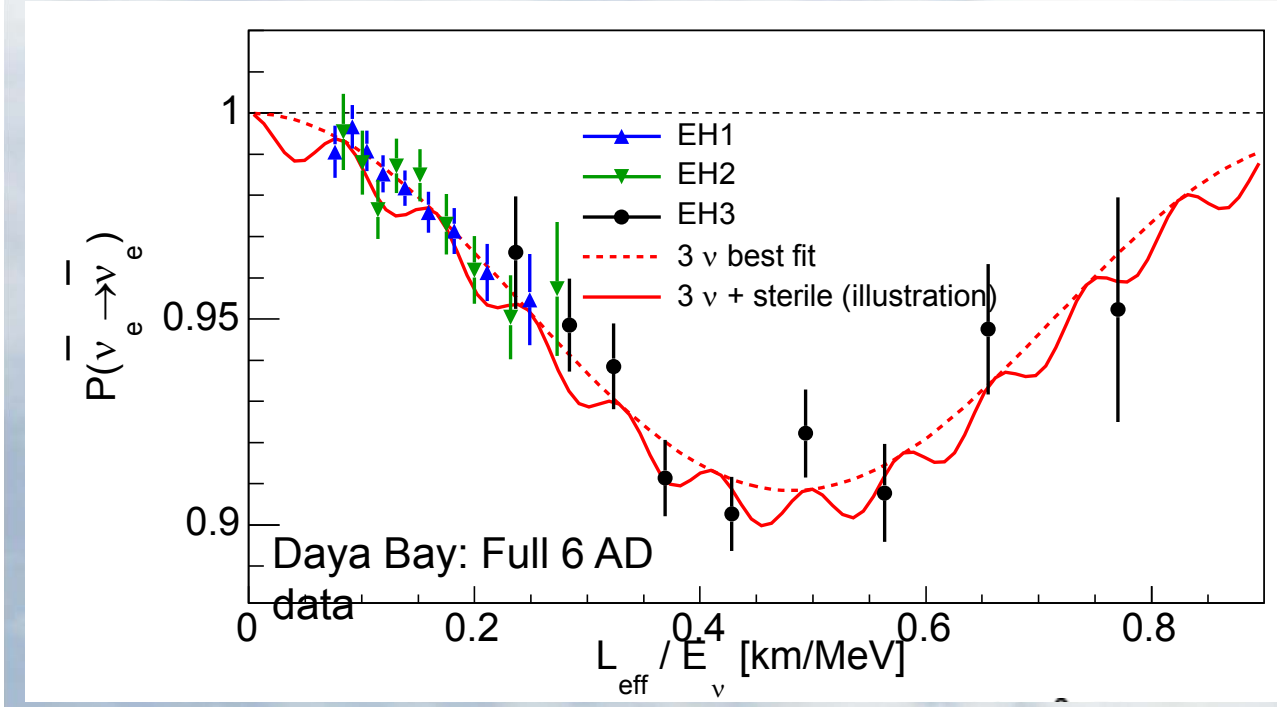


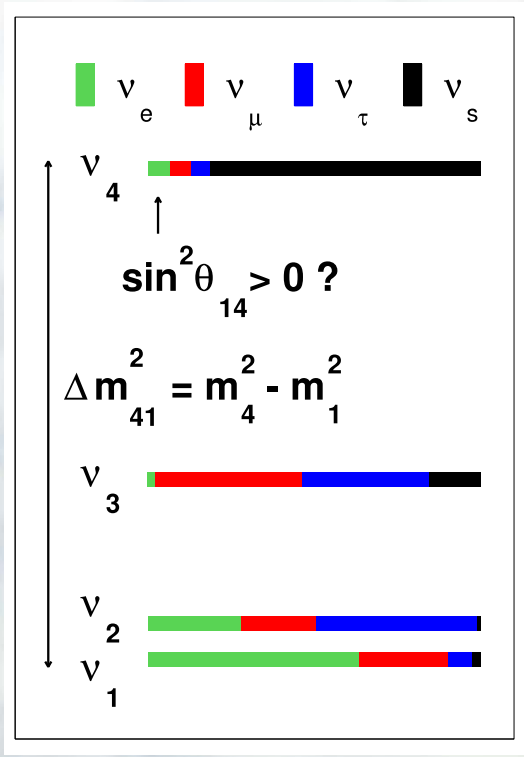
Outline

Inside the Daya Bay Detector

- Neutrino Oscillation
- Daya Bay Experiment
- Precision Measurements of θ_{13} and Δm^2_{ee}
- Search for a light sterile neutrino
- Reactor flux and spectrum

Possible light sterile neutrino oscillation

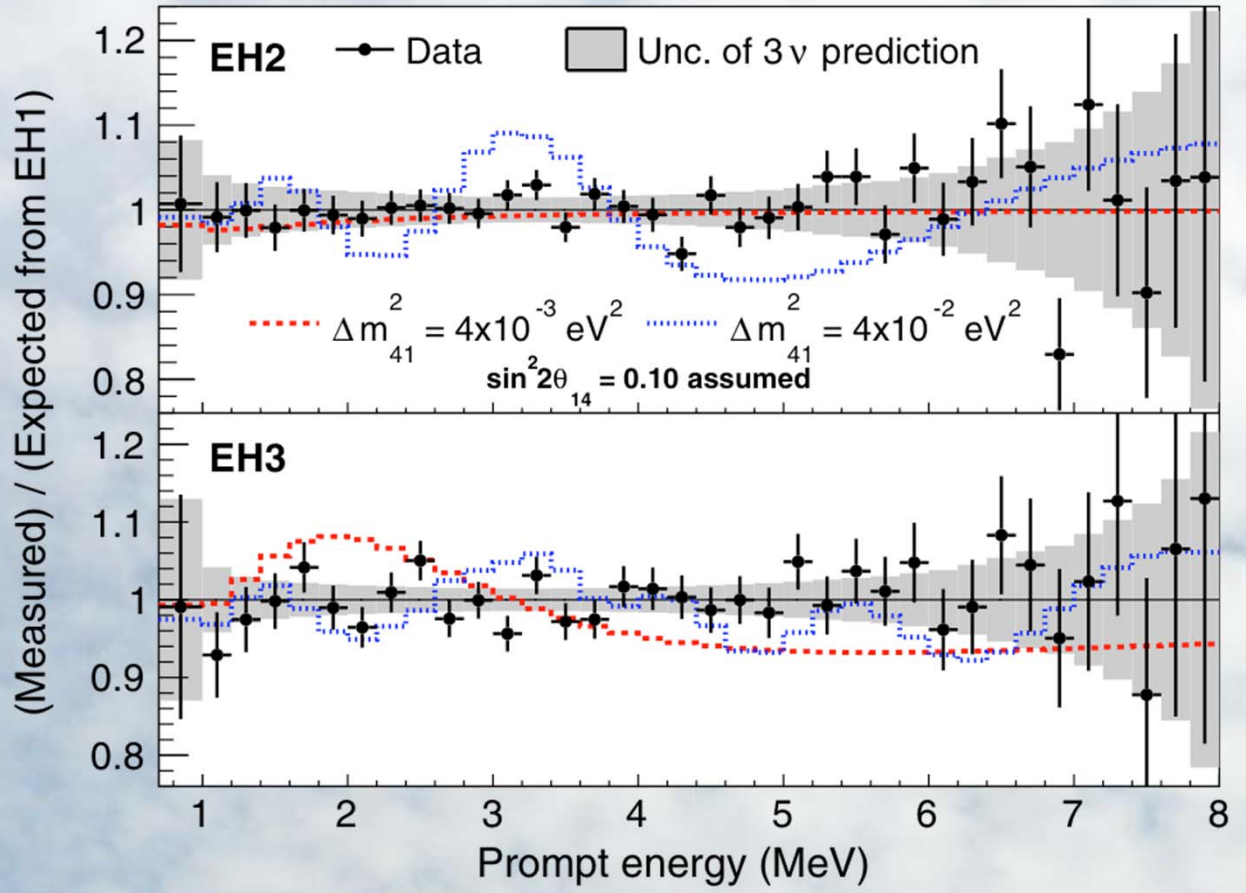




$$P(\bar{\nu}_e \to \bar{\nu}_e) \cong 1 - \cos^4\theta_{14}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{ee} L}{4E_\nu}\right) - \sin^2 2\theta_{14}\sin^2\left(\frac{\Delta m^2_{41} E}{4E_\nu}\right)$$

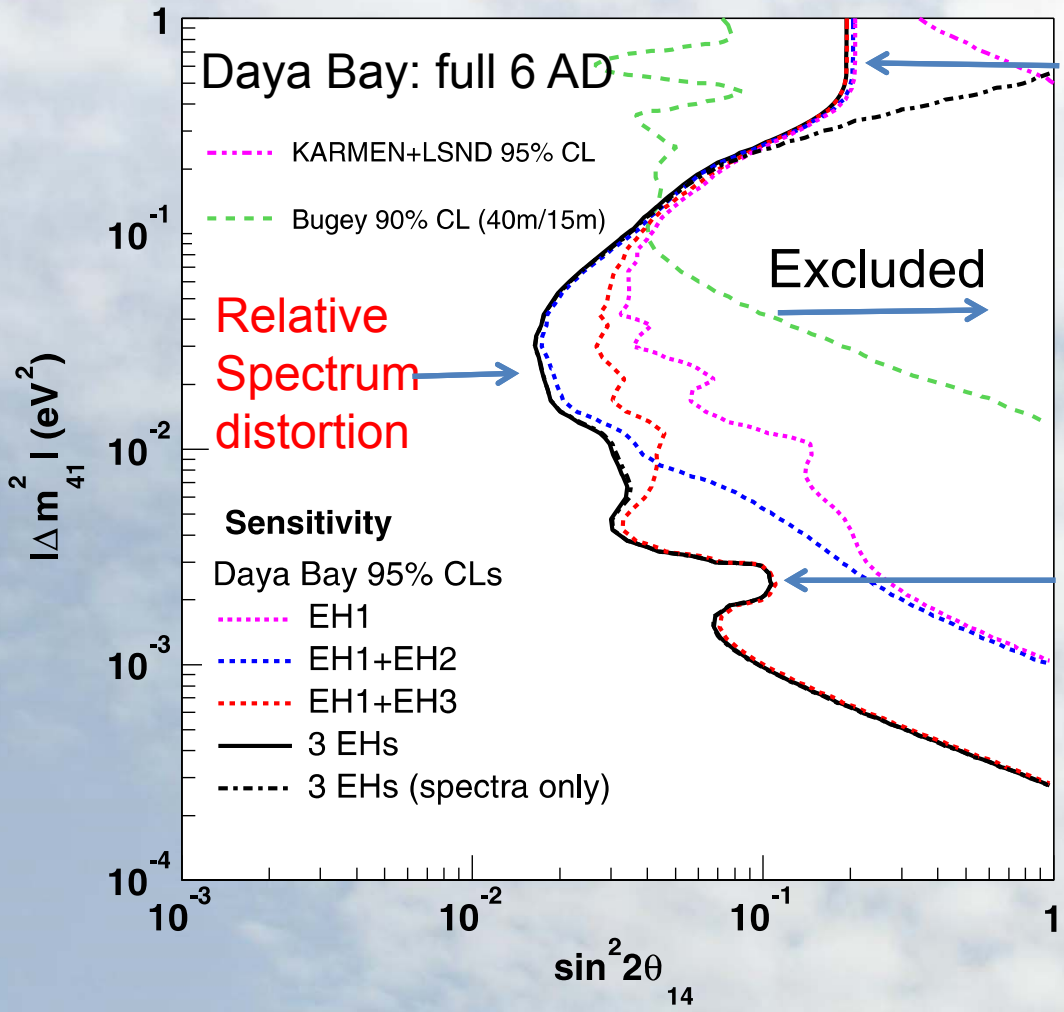
- A minimum extension of the 3-ν model: 3(active) + 1(sterile)-ν model
- Search for a higher frequency oscillation pattern besides $|\Delta m^2_{ee}|$

“Extra”-Spectrum Distortion to EH1



Three experimental halls are sensitive to different mass ranges of sterile neutrinos due to different baselines. Combining them is more powerful!

Light Sterile Neutrino Sensitivity

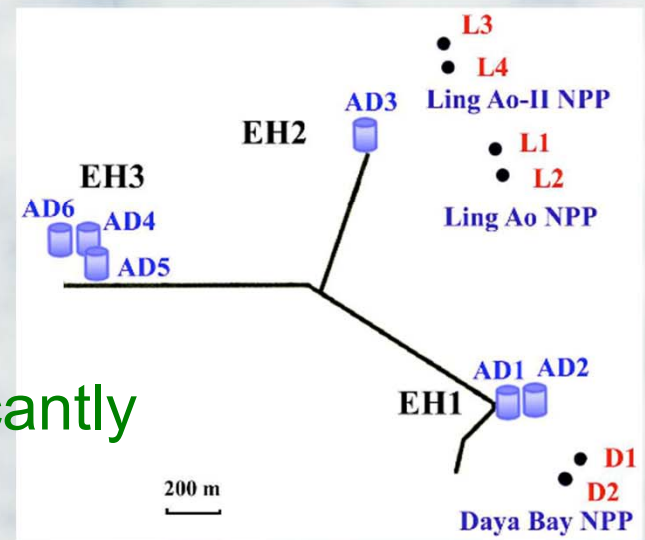


Fast oscillation smeared out

Absolute rate deficit

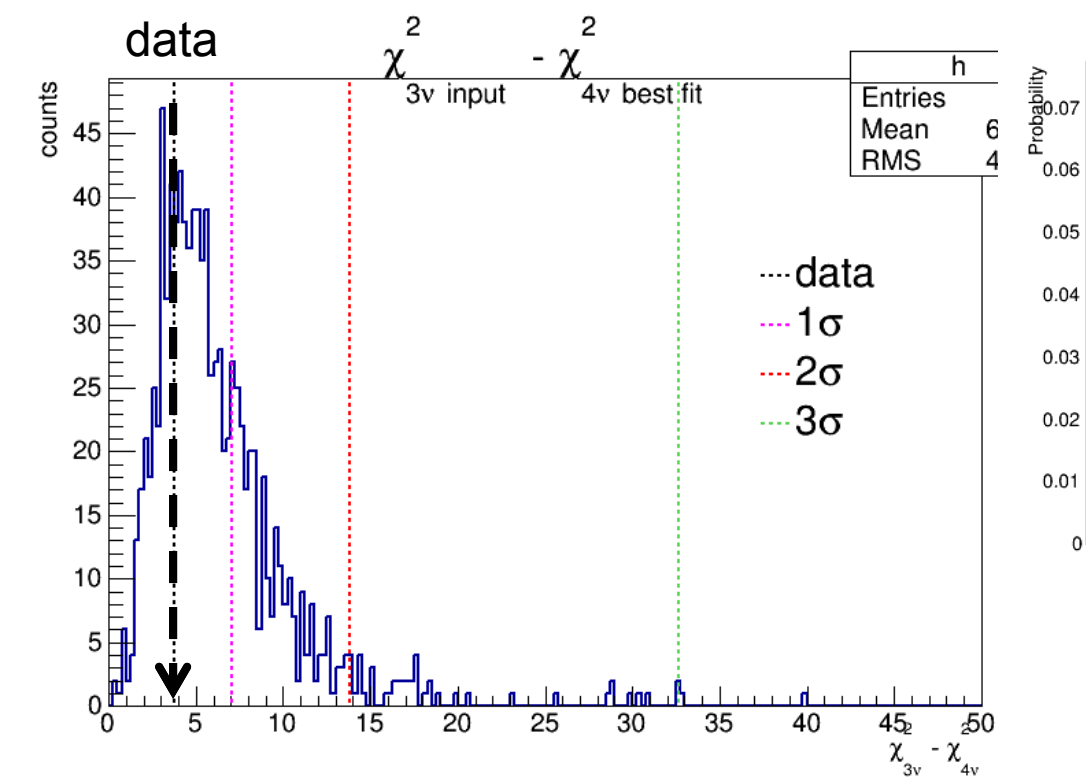
Can probe largely unexplored region at $|\Delta m^2_{41}| < 0.1$ eV^2

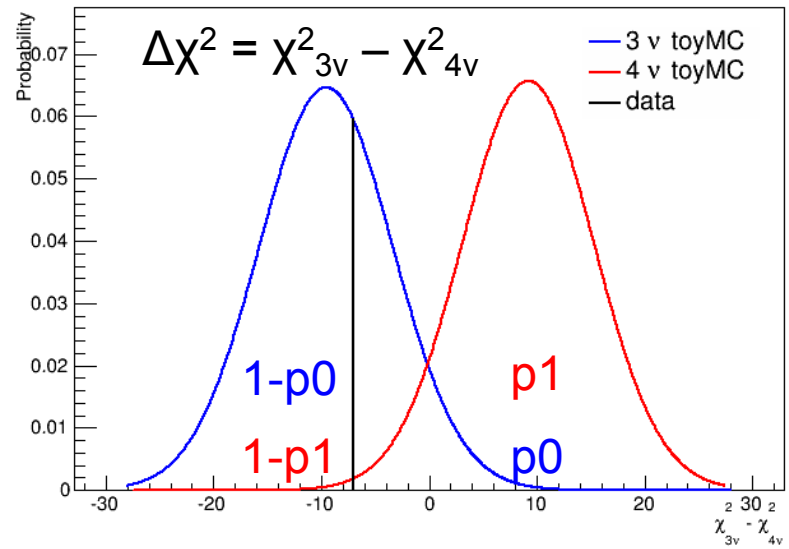
$|\Delta m^2_{41}|=|\Delta m^2_{31}|$. Degeneracy region of $\sin^2 2\theta_{14}$ and $\sin^2 2\theta_{13}$



Multiple baselines of Daya Bay significantly enhance the search sensitivity.

Statistical tests: 3-ν or 4-ν ?





$$CL_s = \frac{1-p_1}{1-p_0}$$

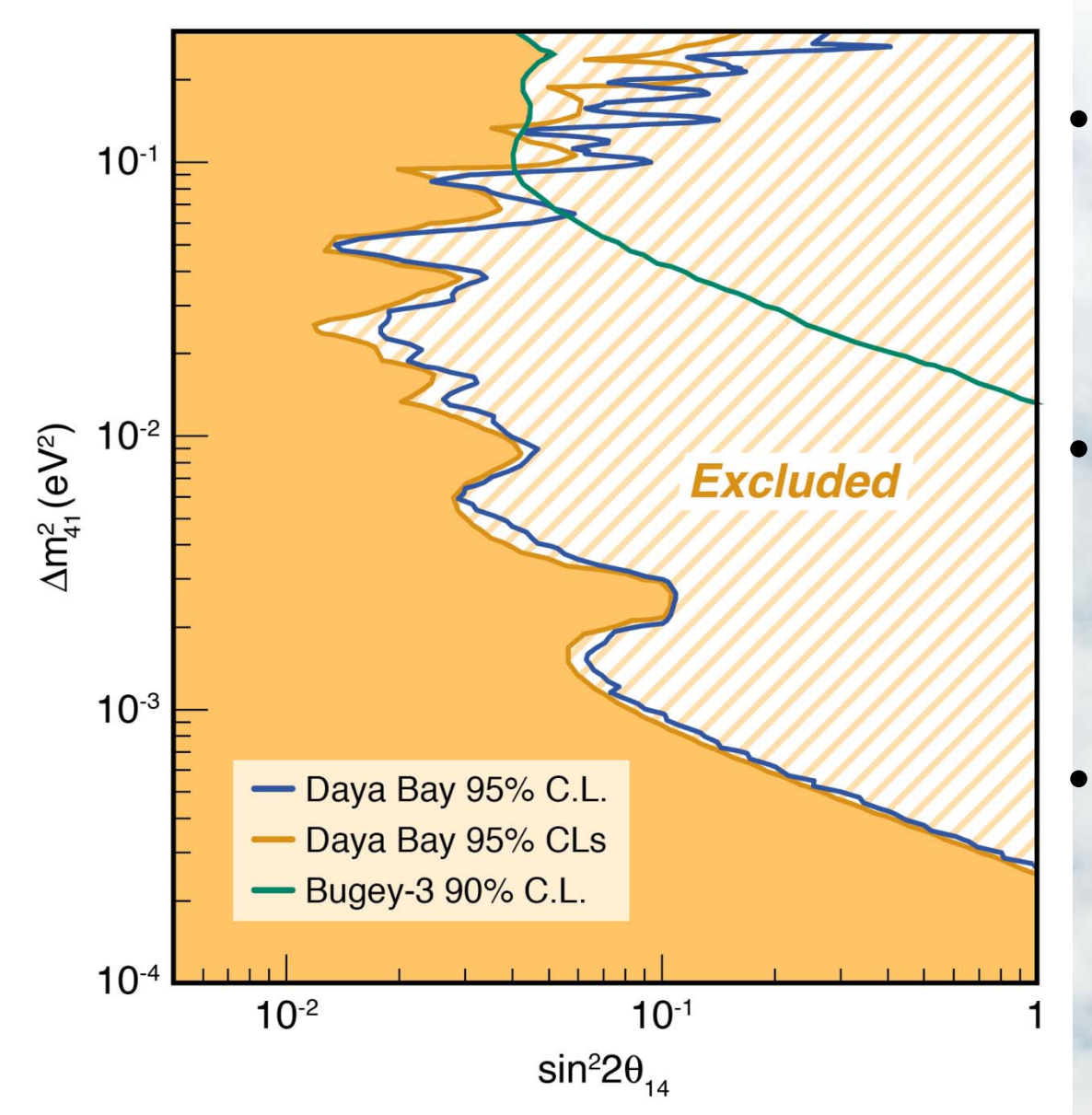
A.L. Read J. Phys. G28, 2693
T. Junk NIMA434, 435

$$CLs = \frac{\left(1+Erf\left(\frac{\overline{\Delta\chi^2_{4\nu}} - \Delta\chi^2_{data}}{\sqrt{8\overline{\Delta\chi^2_{4\nu}}}}\right)\right)}{\left(1+Erf\left(\frac{\overline{\Delta\chi^2_{3\nu}} - \Delta\chi^2_{data}}{\sqrt{8\overline{\Delta\chi^2_{3\nu}}}}\right)\right)}$$

arXiv:1407.5052

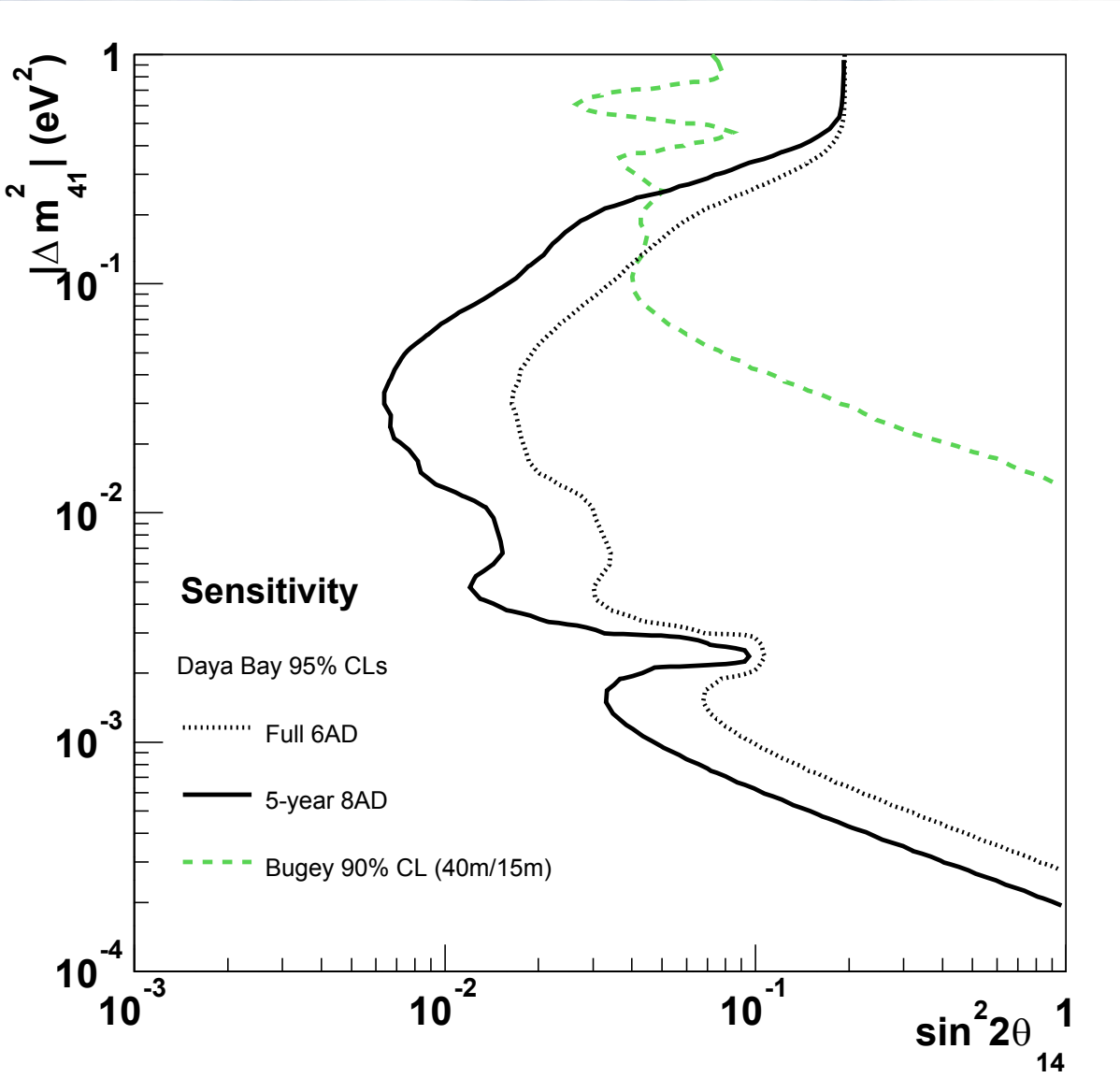
- **Data is consistent with 3-ν hypothesis with FC test**
  No evidence for sterile neutrino
  - $\Delta\chi^2_{data}$ = 3.8; p-value is 0.74 (~0.11σ)

Final Data Contours (full 6 AD)



- Consistent results for various analyses
- Set the best upper limit in the $|\Delta m^2_{41}| < 0.1 eV^2$ region
- Insensitive to various combination of mass hierarchies

Future Sensitivities



- Current results are limited by statistics.
- Expect large improvement with the full 5-year data set till FY-17
- Work in progress to combine with MINOS and Bugey

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Absolute Reactor Anti-Neutrino Flux

- 217 days of 6-AD period data
- Effective fission fraction

^{235}U	^{238}U	^{239}Pu	^{241}Pu
58.6%	7.6%	28.8%	5.0%

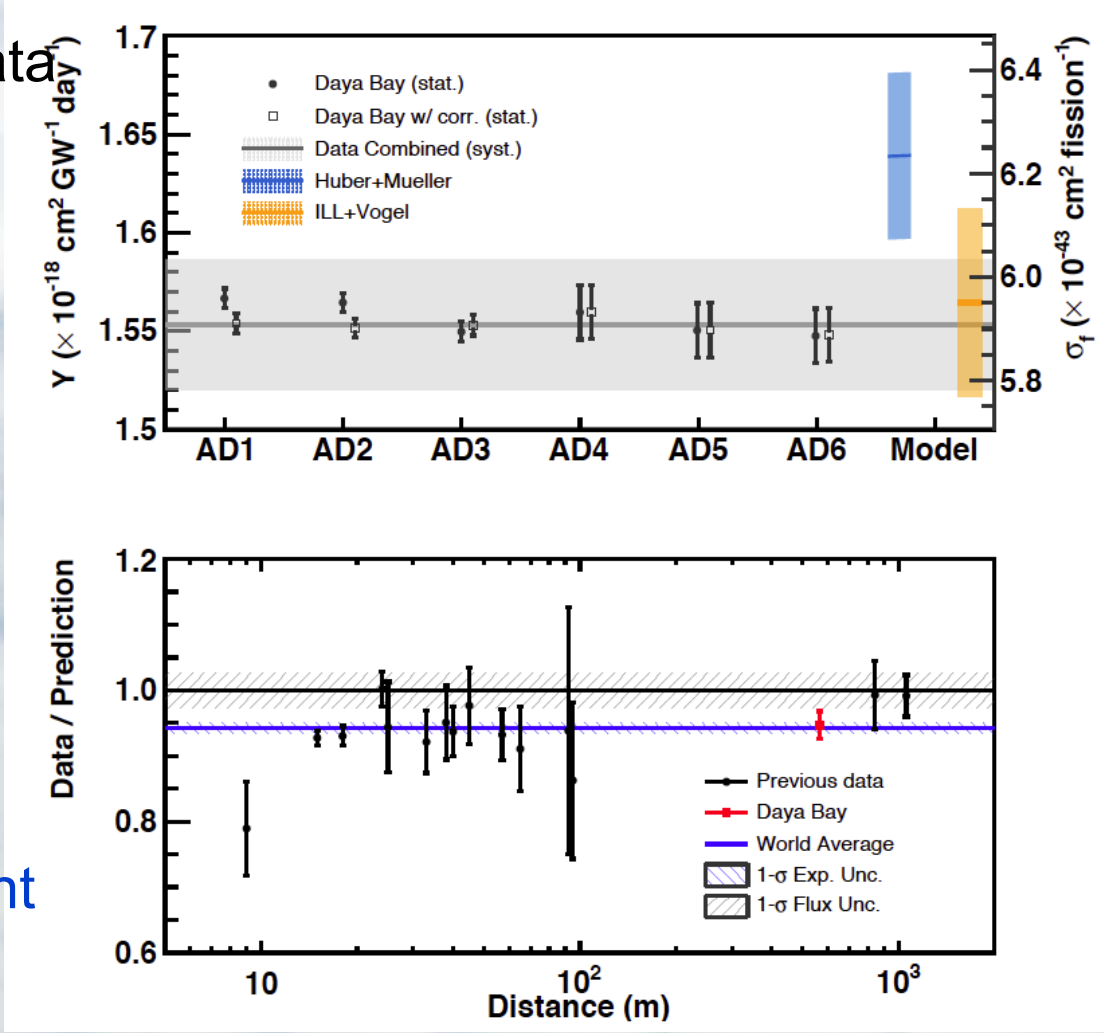
- Daya Bay result:

$R_{dyb} = 0.946 \pm 0.022$

- The World Average:

$R_{globe} = 0.942 \pm 0.009$

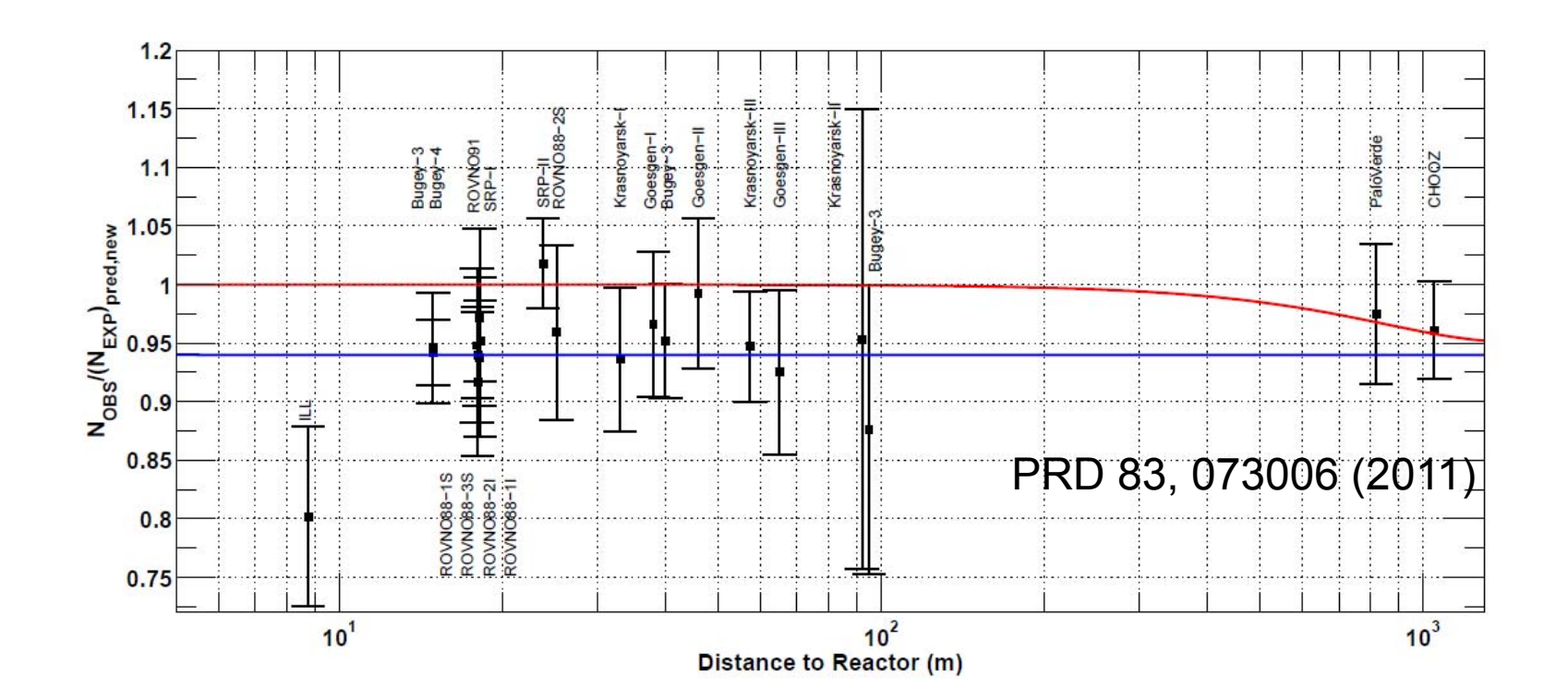
Daya Bay's absolute reactor flux measurement is consistent with previous short baseline experiments



arXiv:1508.04233

One Note About Global Average

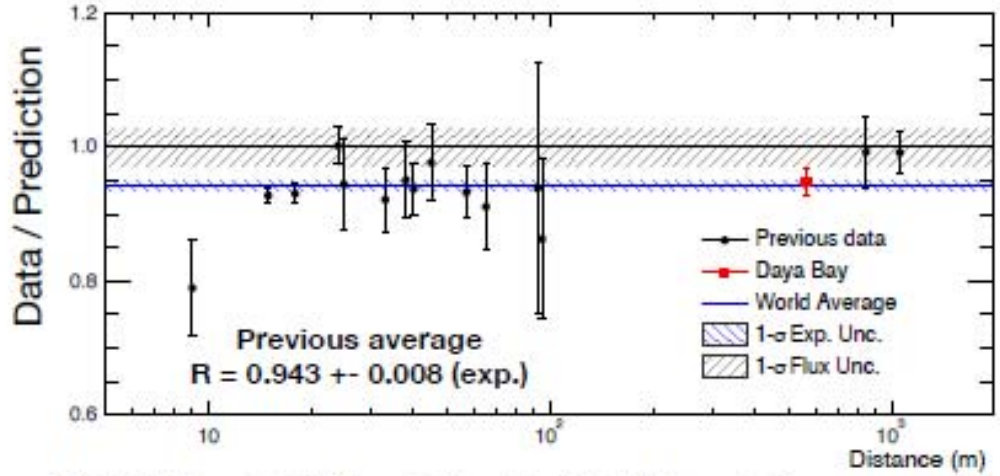
- We reported 0.946 +- 0.008 (exp.)
- Many literatures reported 0.928 (~ 1.5% lower)
- What's going on?



- We carried out a re-evaluation, and obtained a higher value C. Zhang, X. Qian and P. Vogel, PRD 87, 073018 (2013)

One Note About Global Average

- We obtained R = 0.943 +- 0.008 (exp.)
- Many literatures report this number to be 0.928 (1.5% lower).
  - A tricky statistical mistake. They used the measured values to build the theoretical covariance matrix.



$$\chi^2(R_g^{\rm past}) = (R_g^{\rm past} - R_i)\cdot V_{ij}^{-1}(R_g^{\rm past} - R_j),$$

$$V = V^{\rm exp} + V^{\rm theory}$$

$$V_{ij}^{\rm theory} = R_i^{\rm obs} R_j^{\rm obs} (\sigma^{\rm theory})^2$$

which should be

$R^{\rm theory}$ $R^{\rm theory}$

Otherwise could lead to an interesting puzzle that the average is smaller than any of measurements

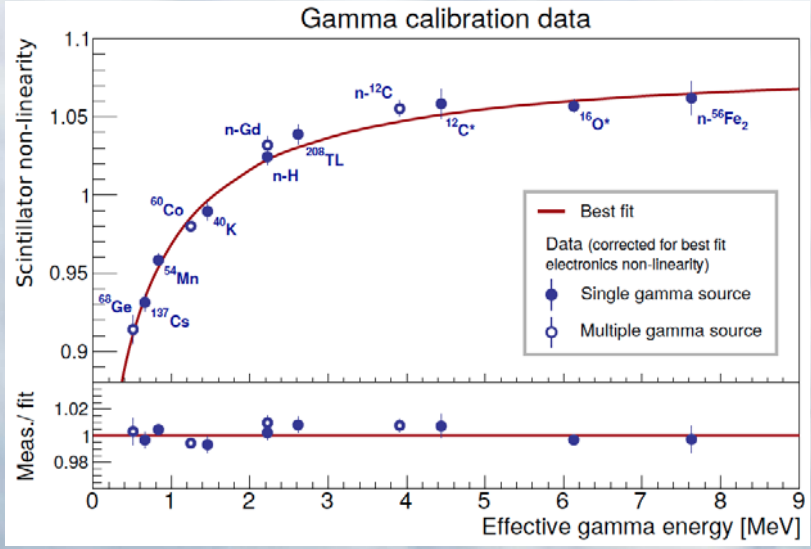
a well known statistics problem originally described in
G. D'Agostini, NIMA 346 (1994) 306

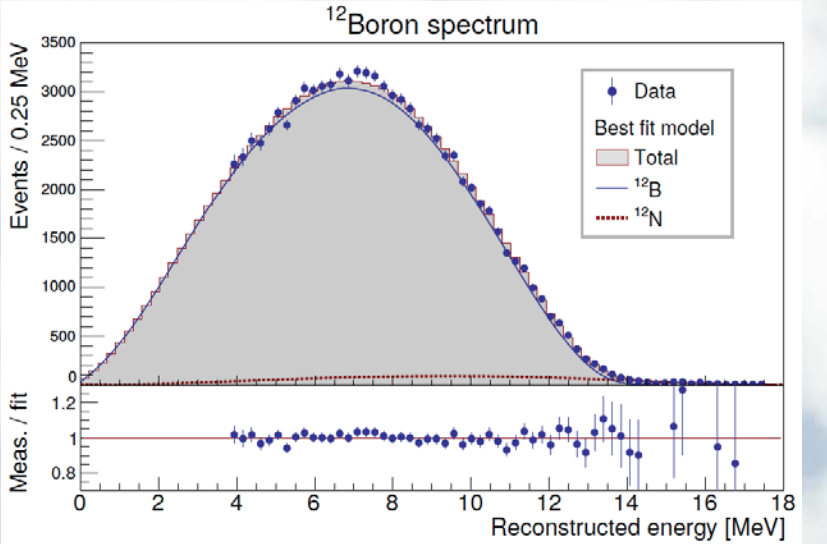
see also

V. Blobel, "Some Comments on χ^2 Minimisation Applications,"SLAC-R-0703, pp.101–105.

B. Roe arXiv:1506.09077

Energy Nonlinearity Calibration

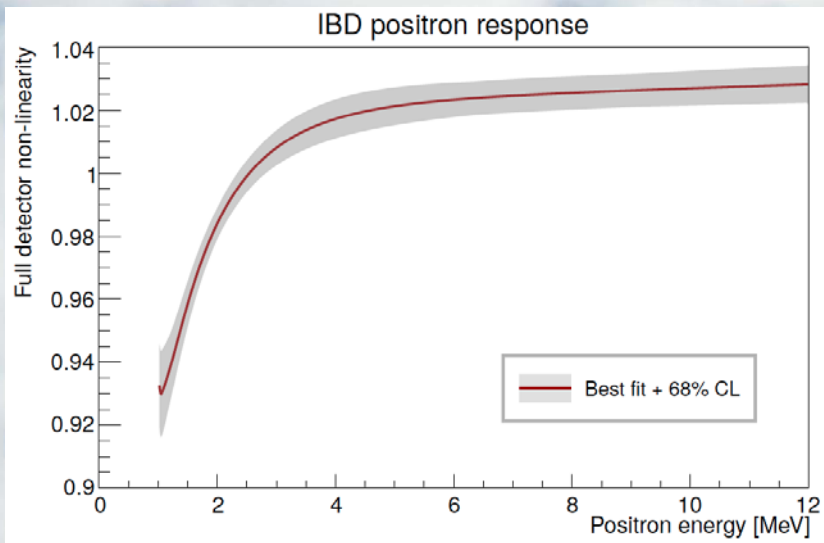




Sources of detector energy nonlinearity

- Scintillator quenching (Birks Law)
- Cherenkov light
- PMT readout electronics
    - Modeled with MC and single channel FADC measurement

Energy model is constrained with gamma and electron sources.



~1% uncertainty (correlated among detectors)

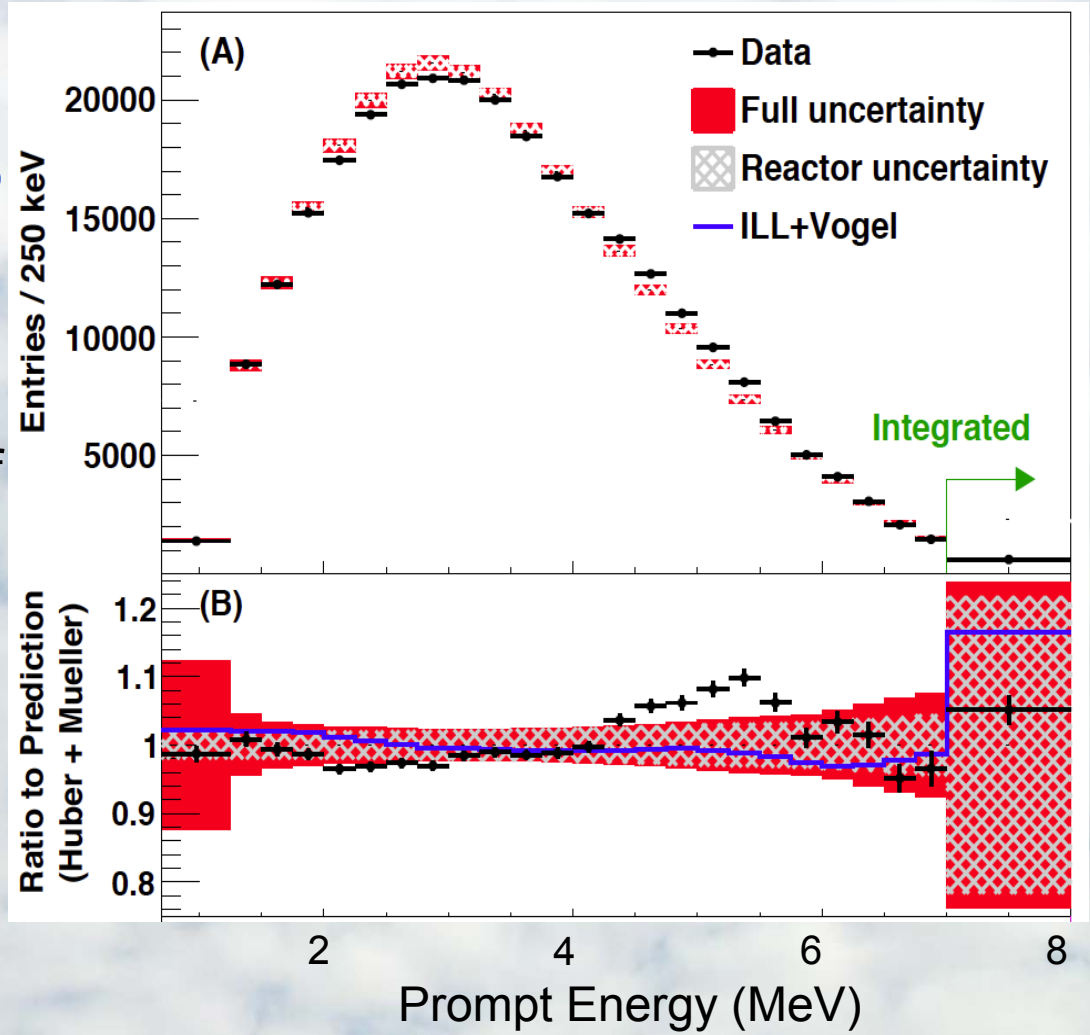
Absolute Reactor Anti-Neutrino spectrum

- 217 days of 6-AD period data

- Measured reactor anti-neutrino spectrum not consistent with prediction

- Absolute shape comparison of data and prediction
  - 2.6σ (global) discrepancy
  - 4σ (local) discrepancy

No impact on the $\sin^2 2\theta_{13}$ and Δm^2_{ee} measurement result



arXiv:1508.04233

Summary

- Many exciting discoveries in neutrino oscillation physics in the last decade
- We now determined θ_{13}

$$\text{Daya Bay:} \quad \sin^2 2\theta_{13} = 0.084^{+0.005}_{-0.005}$$

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

- Large value of θ_{13} opens doors to study mass hierarchy, leptonic CP phase …
- We enter the precision era of neutrino physics
  - Exciting decades to come!

About Flux Measurement Result

- Interpretation one: Daya Bay saw 5.7% deficit with respect to the Huber+Muller model, so there must be a sterile neutrino.
  - **Wrong!** The reactor flux models could have large uncertainties. The theoretical flux could be over-estimated.
- Interpretation two: The Daya Bay result is consistent with all previous short-baseline measurements, so there is no "anomaly" from experimental point of view.
  - **Correct!** Our "modern" experiment has validated the results from experiments in 80-90s.
- Question: So is the "reactor antineutrino anomaly" real or not?
  - **We don't know yet**. To definitively answer that question, one has to observe the spectral "oscillation" feature in the data (like the Daya Bay L/E plot). We need the future ~5m baseline reactor/source experiments to tell us.

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