
on behalf of the Daya Bay Collaboration

Recent Results From Daya Bay

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BROOKHAVEN NATIONAL LABORATORY

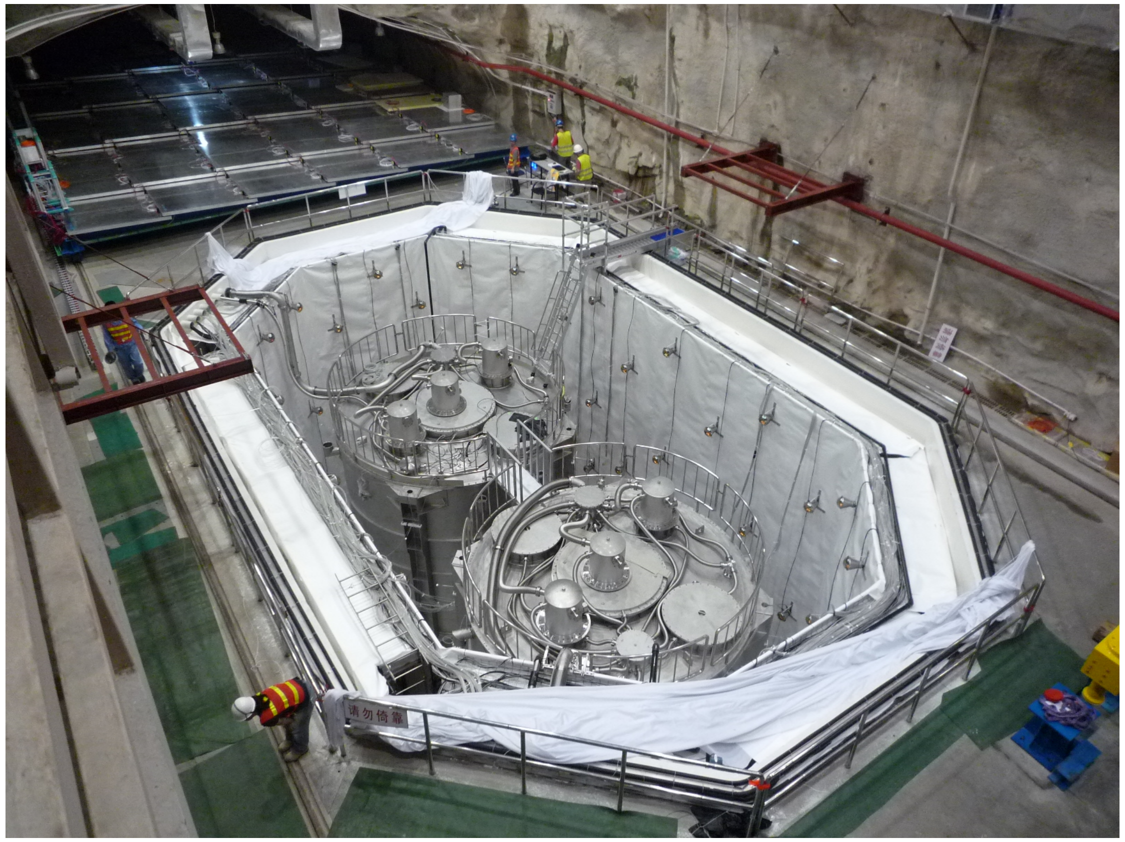
INFO 2015, Santa Fe, 7/14/2014

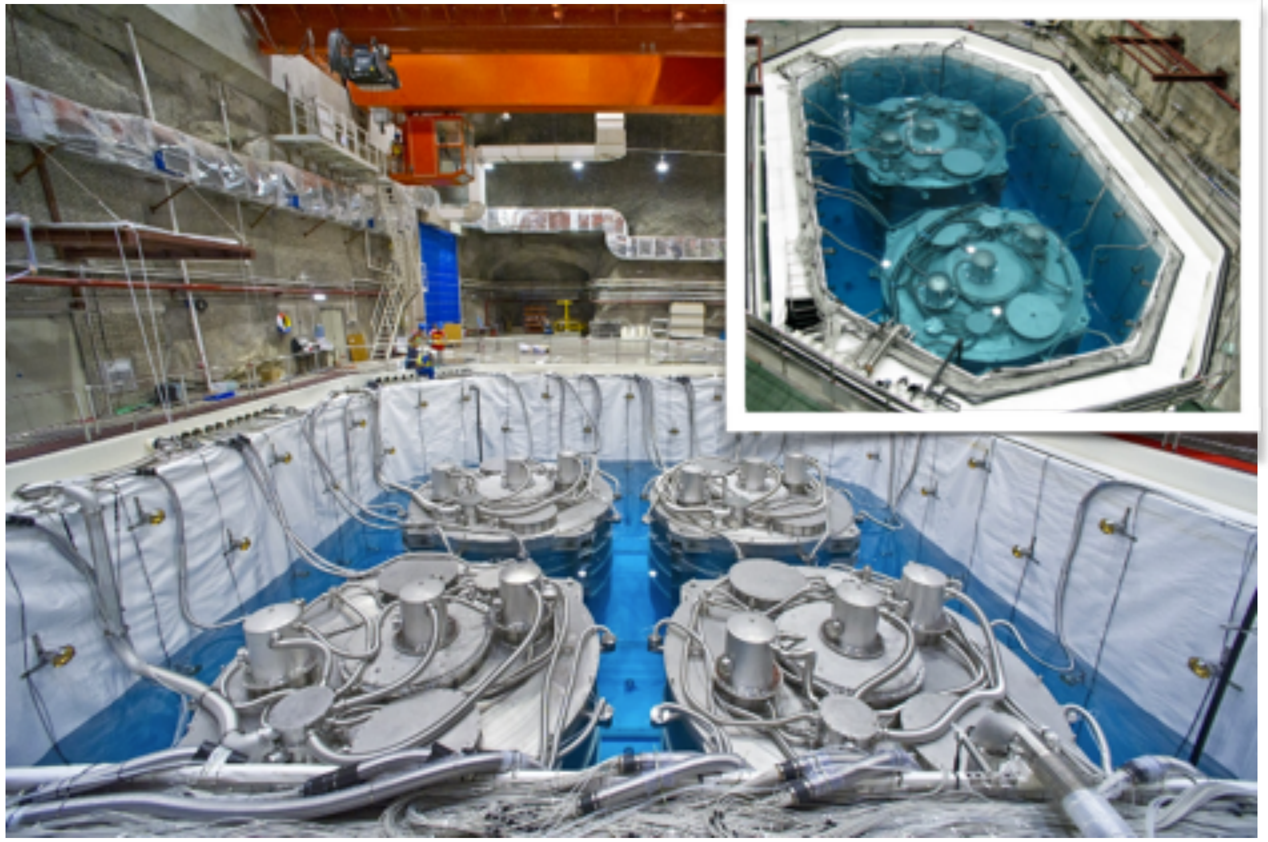
INFO 11 (Jul 18)

- Smooth progress
  - Two ADs in Daya Bay Near Hall installed
  - Dry-run test completed
  - Muon system for Daya Bay Near Hall completed. Water pool fill in August
  - Hall 1 physics data taking soon

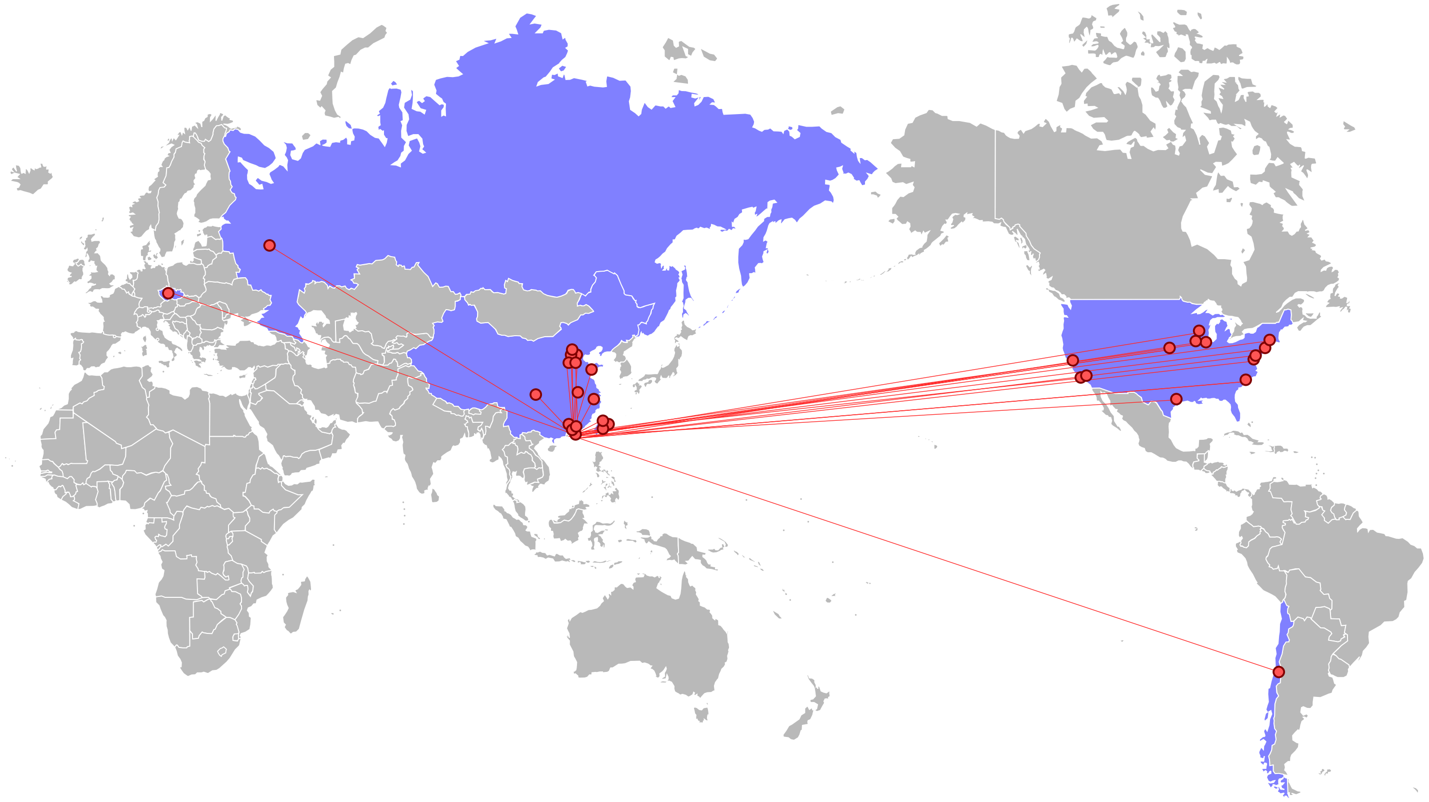
INFO 15 (today)

- Many important results
  - Most precise measurement of $\sin^2 2\theta_{13}$ with 621 days of data
  - Comparable precision of Δm^2_{32} with accelerator experiments
  - Light sterile neutrino search
  - Precise measurements of reactor antineutrino spectrum





The Daya Bay Collaboration



Asia (22)

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. Chongqing 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

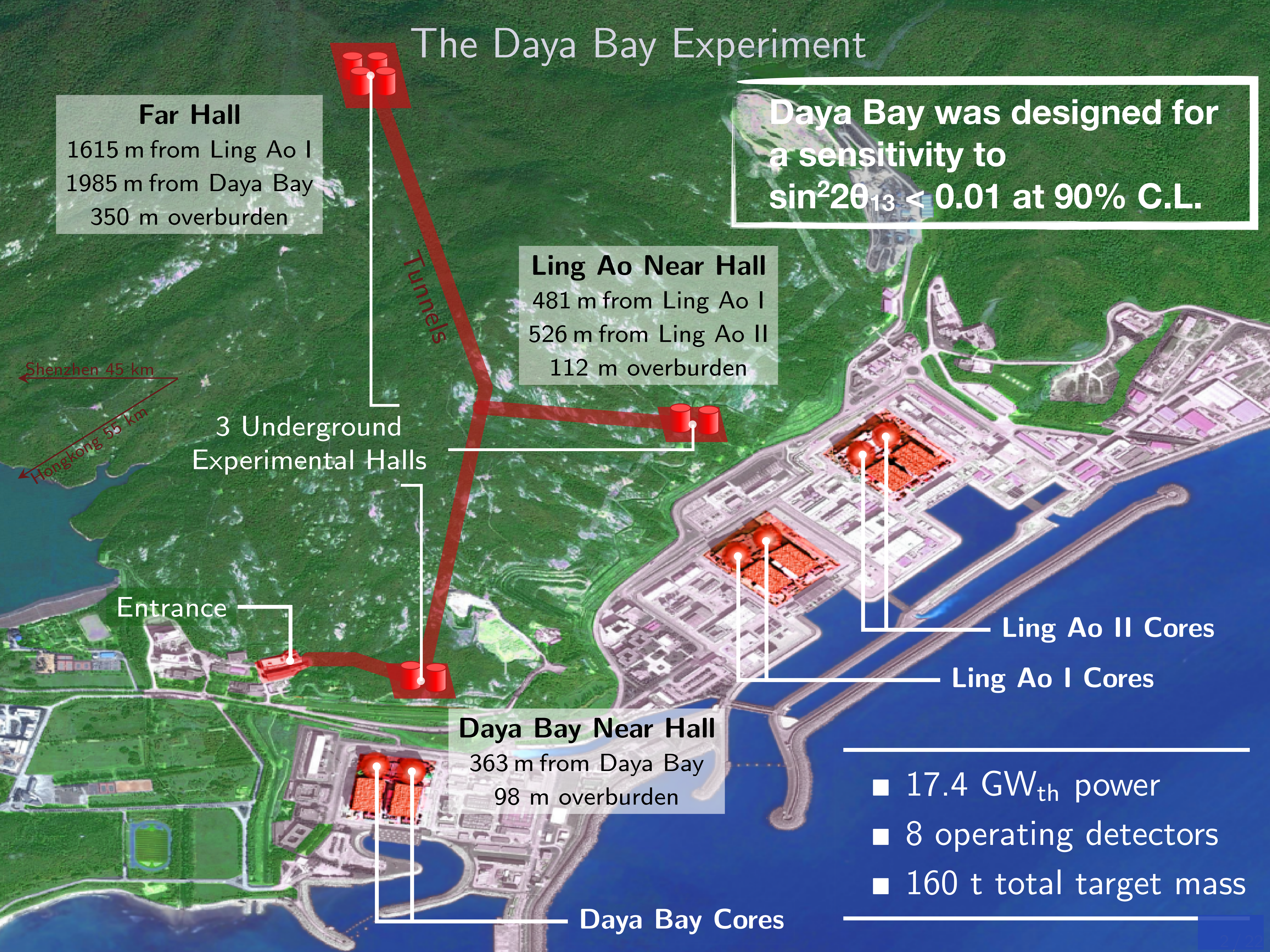
~230 collaborators

70 km

Series AR/18/IRS
Edition 7 2002

Survey and Mapping Office, Lands Department

The Daya Bay Experiment



Far Hall
1615 m from Ling Ao I
1985 m from Daya Bay
350 m overburden

Ling Ao Near Hall
481 m from Ling Ao I
526 m from Ling Ao II
112 m overburden

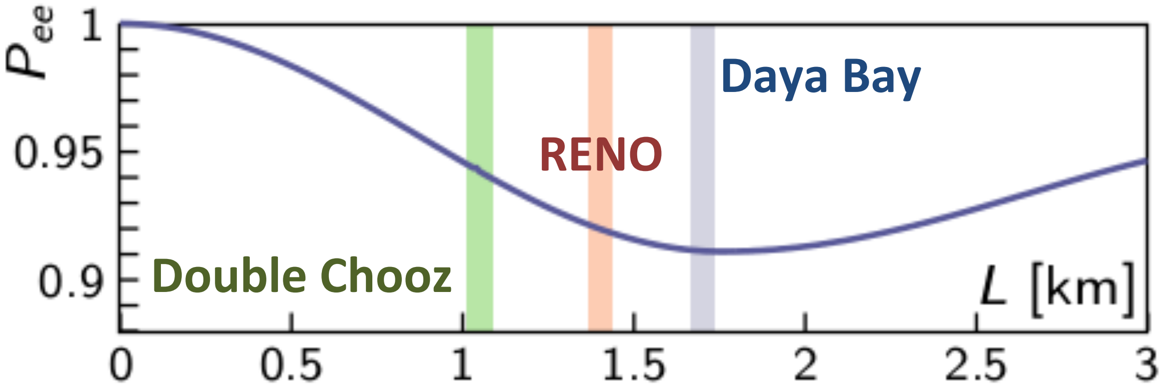
Daya Bay Near Hall
363 m from Daya Bay
98 m overburden

Daya Bay was designed for a sensitivity to $\sin^2 2\theta_{13} < 0.01$ at 90% C.L.

- 17.4 $\mathrm{GW_{th}}$ power
- 8 operating detectors
- 160 t total target mass

Baseline Optimization

- Detector locations optimized to known parameter space of $|\Delta m^2_{ee}|$
- Far site maximizes term dependent on $\sin^2 2\theta_{13}$



Go strong, big and deep!

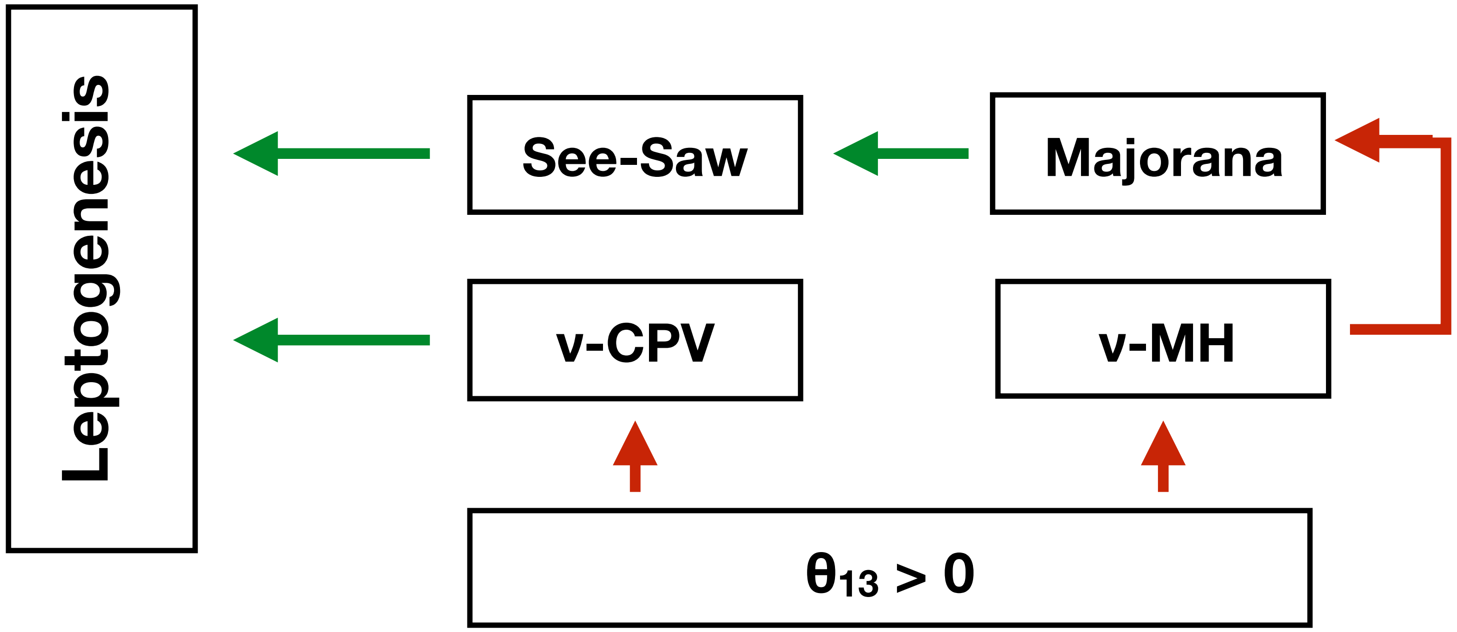
	Reactor [GW_{th}]	**Target [tons]**	**Depth [m.w.e]**
Double Chooz	8.6	16 (2 × 8)	300, 120 (far, near)
RENO	16.5	32 (2 × 16)	450, 120
Daya Bay	17.4	160 (8 × 20)	860, 250
	Large Signal		Low Background

How Small is θ13?

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

$$\downarrow$$

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


Leptogenesis

See-Saw

Majorana

ν-CPV

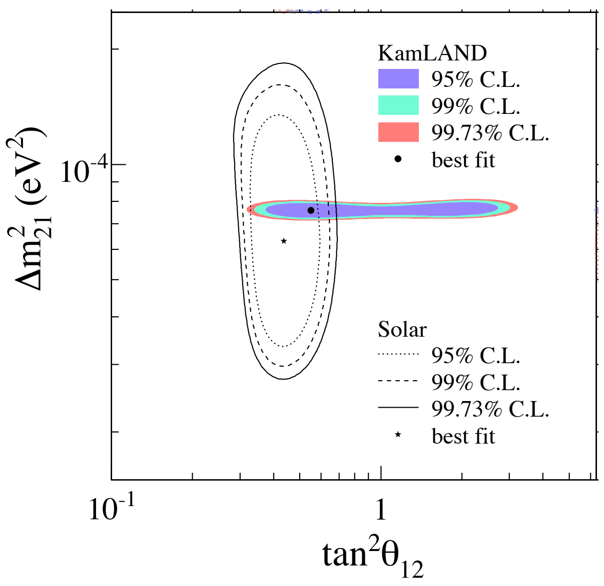
ν-MH

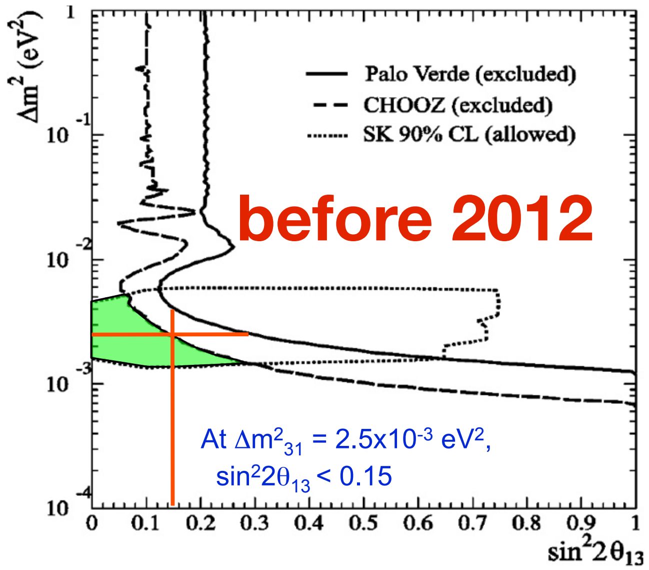
$\theta_{13} > 0$

$\theta_{12} \sim 35°$
Solar ν
Long-Baseline Reactor ν

$\theta_{13} < 10°$
Short-Baseline Reactor ν
Accelerator ν

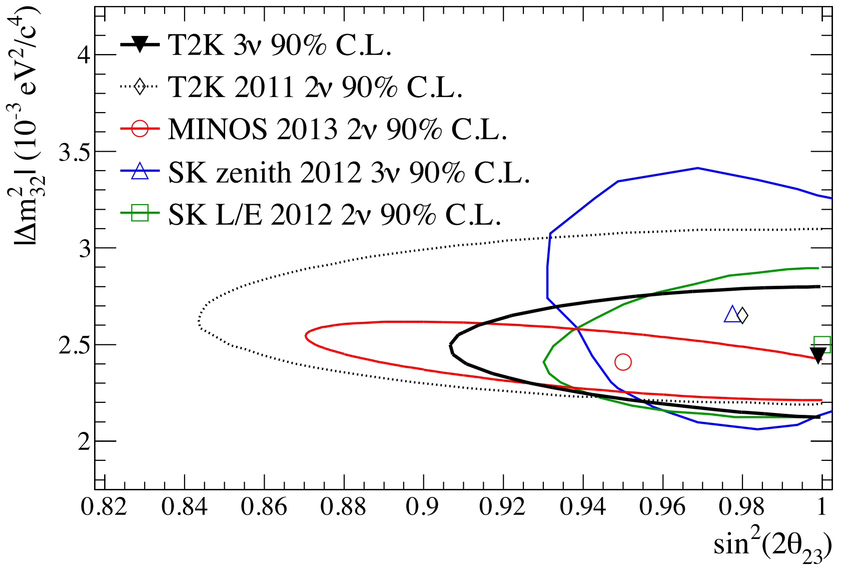
$\theta_{23} \sim 45°$
Atmospheric ν
Accelerator ν





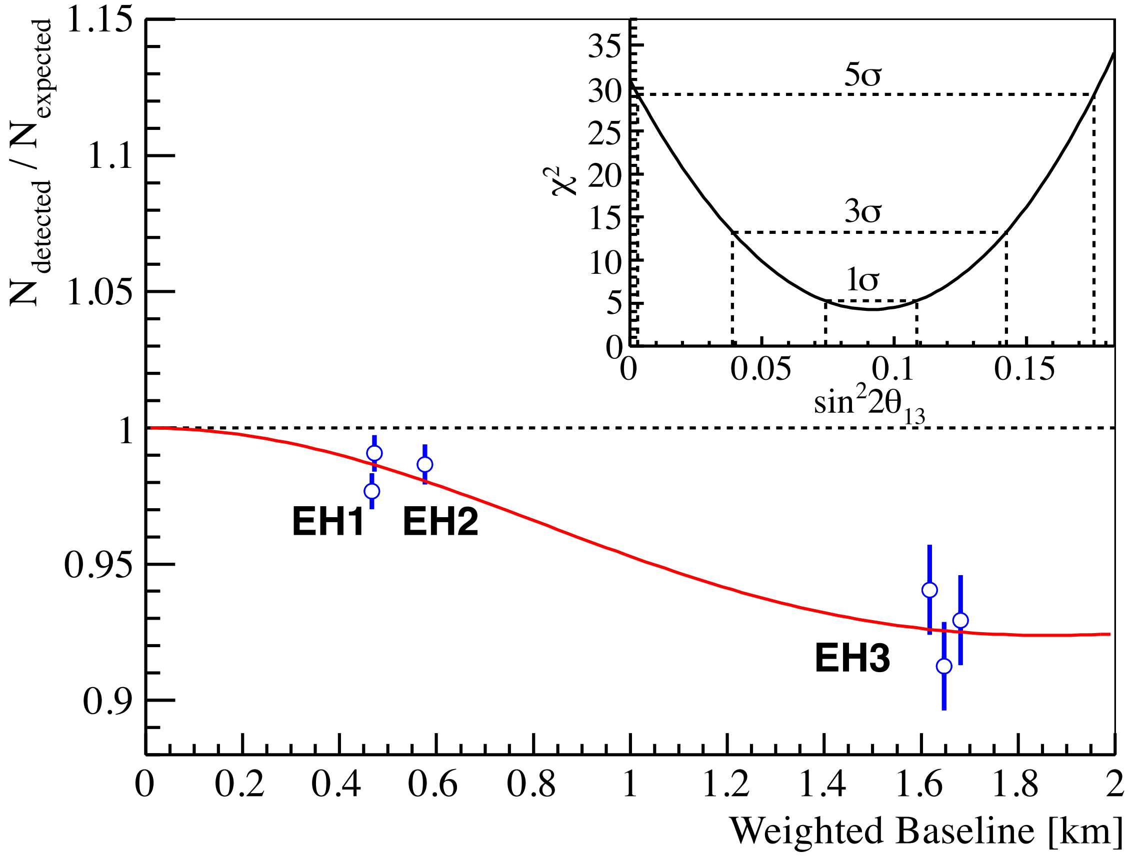
before 2012

At $\Delta m^2_{31} = 2.5\times10^{-3}$ eV^2,
$\sin^2 2\theta_{13} < 0.15$



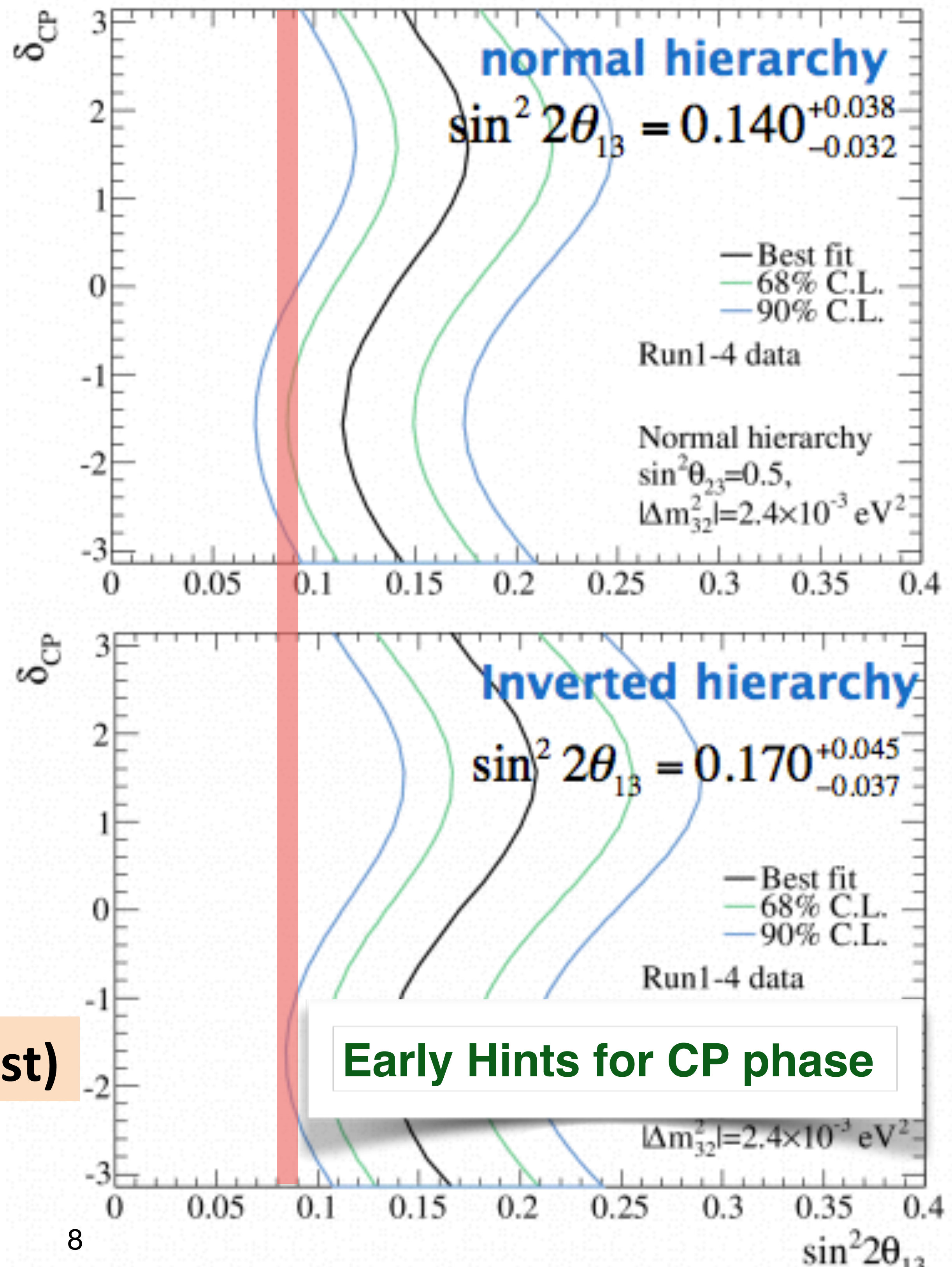
Discovery of non-zero θ13

Daya Bay 55 days



Daya Bay Measurement

T2K Measurement



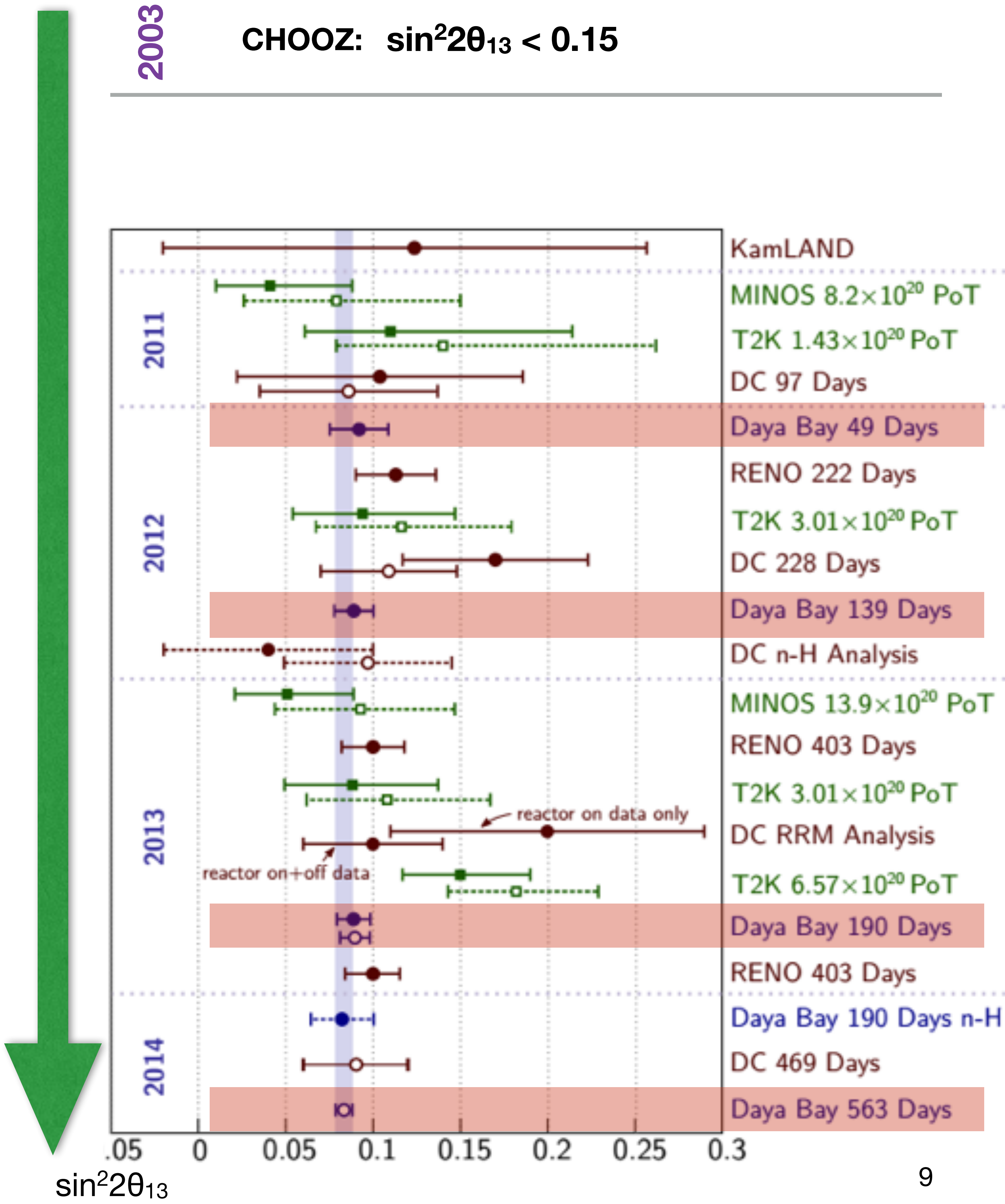
Early Hints for CP phase

- First 5σ discovery of non-zero θ_{13}
  PRL 108 (2012),171803

$\sin^2 2\theta_{13} = 0.092 \pm 0.016$ (stat) ± 0.005 (syst)

Scientific Goals After 2012

- Precision measurement of $\sin^2 2\theta_{13}$
  - aim to determine $\sin^2 2\theta_{13}$ to better than 3% by the end of 2017
- Precision measurement of atmospheric mass splitting $|\Delta m^2_{32}|$ (to better than 3%)
- Search for new neutrino physics such as a light sterile neutrino
- Precision measurement of reactor antineutrino flux and spectrum



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Relative measurement

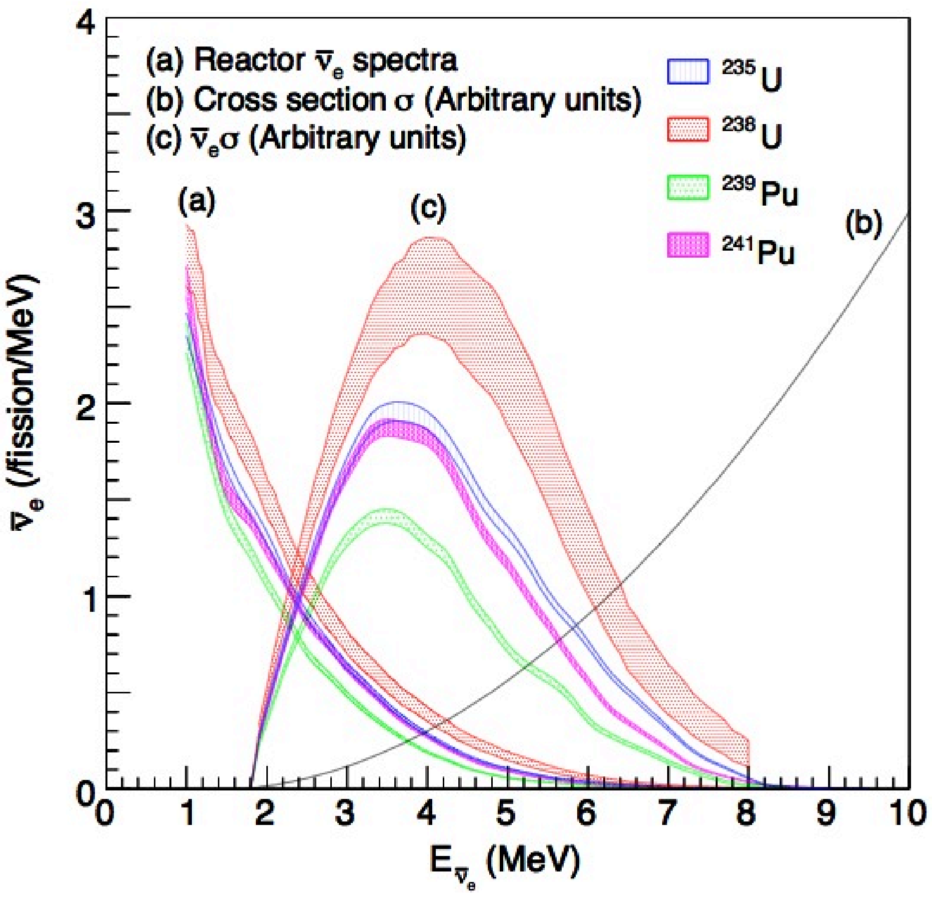
- **Reactor-related systematics**: Far/Near relative measurement
- **Detector-related systematics**: multiple functionally identical detectors (4 Near + 4 Far)

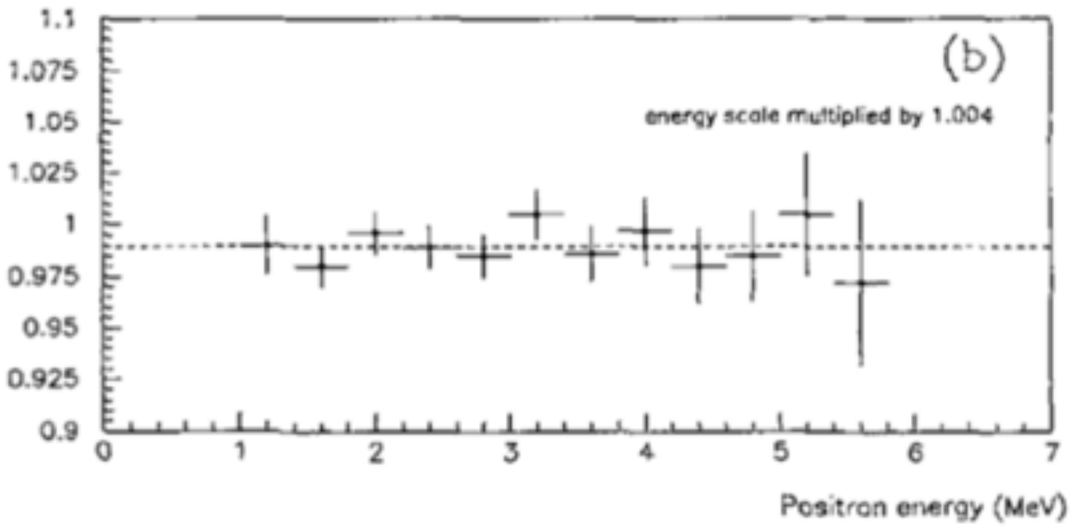
- Precision measurement of reactor antineutrino flux and spectrum

Absolute measurement

- Extensive calibration and Data / MC comparison

Reactor Antineutrinos





Comparison of Bugey 3 spectrum relative to ILL+Vogel model.
Phys. Lett. B 374, 243 (1996)

Nuclear Reactor

- pure $\bar{\nu}_e$ source (Free!)
- 6 $\bar{\nu}_e$/ fission
- 6 x 10^{20} $\bar{\nu}_e$ / sec / $3GW_{th}$

ILL+Vogel Model

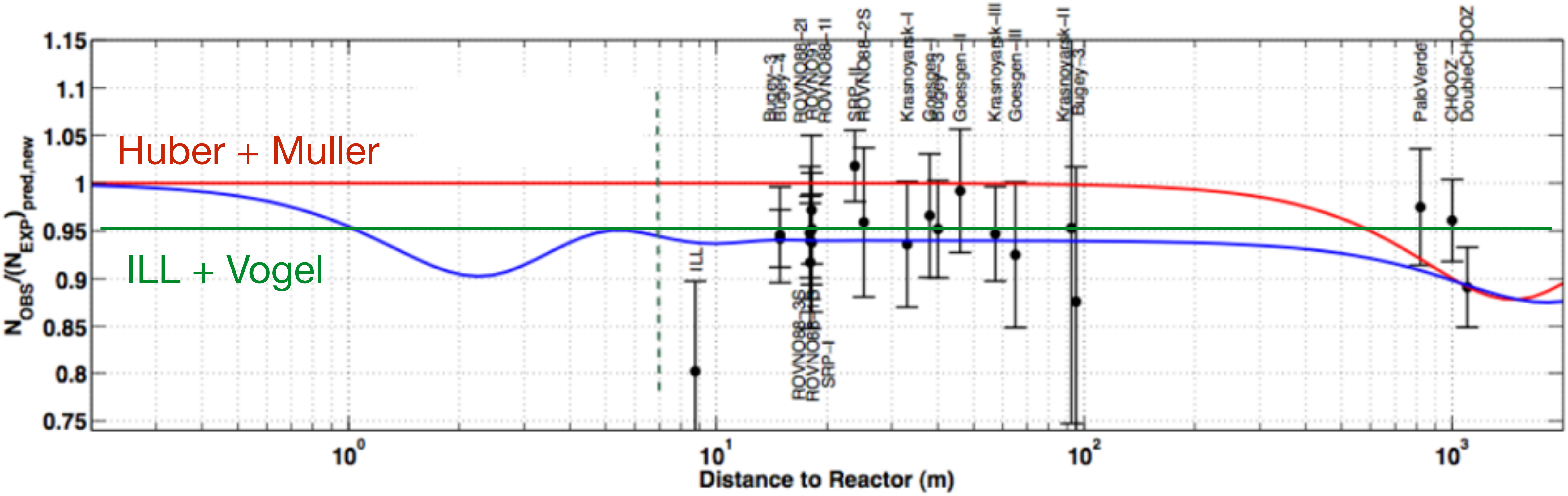
- ^{235}U, ^{239}Pu, ^{241}Pu neutrino spectra converted from β-spectra measurements at ILL
  - ~ **2.7%** uncertainty (conversion from β-spectra to antineutrino spectra)

Phys. Lett. B160, 325 (1985),
Phys. Lett. B118, 162 (1982)
Phys. Lett. B218, 365 (1989),

- ^{238}U neutrino spectrum calculated theoretically
  - ~ 10% uncertainty (but only ~10% of the flux)

Reactor Antineutrino Anomaly

- Reanalysis of reactor antineutrino flux in 2011 improved the theoretical uncertainty (to **~2%**), but lead to a few % increase in flux prediction that doesn't agree with previous reactor antineutrino flux measurements.



G.Mention et. al, PRD 83, 073006 (2011)

P. Huber, PRC 84, 024617 (2011)

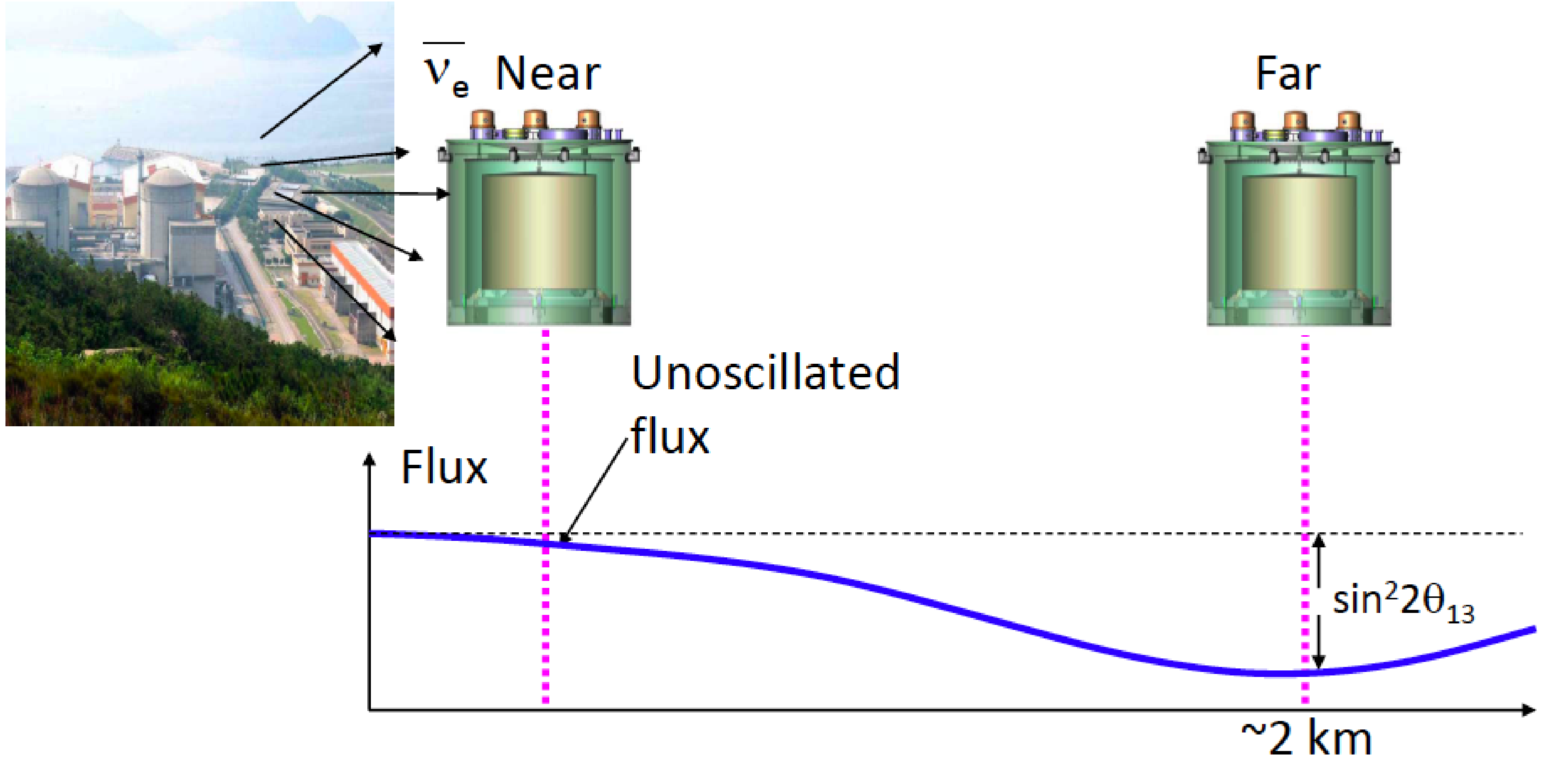
- However, recent re-evaluation of the systematics in the flux calculation suggests that the uncertainty should be **> 4%** due to forbidden beta decays.

A.C. Hayes et. al, PRL 112, 202501 (2014)

Far/Near Relative Measurement

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \simeq 1 - \sin^2 2\theta_{13} \sin^2(\Delta m^2_{ee} \frac{L}{4E}) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2(\Delta m^2_{21} \frac{L}{4E})$$

- **Far/Near measurement** to largely cancel reactor flux uncertainty (a factor of ~1/20)
- **“Functionally Identical detectors”** to cancel detector systematics



$$\frac{N_{far}}{N_{near}} = \left(\frac{N_{p,f}}{N_{p,n}}\right) \cdot \left(\frac{L_n}{L_f}\right)^2 \cdot \left(\frac{\varepsilon_f}{\varepsilon_n}\right) \cdot \left(\frac{P_{survival}(E, L_f)}{P_{survival}(E, L_n)}\right)$$

Far/Near Neutrino Ratio

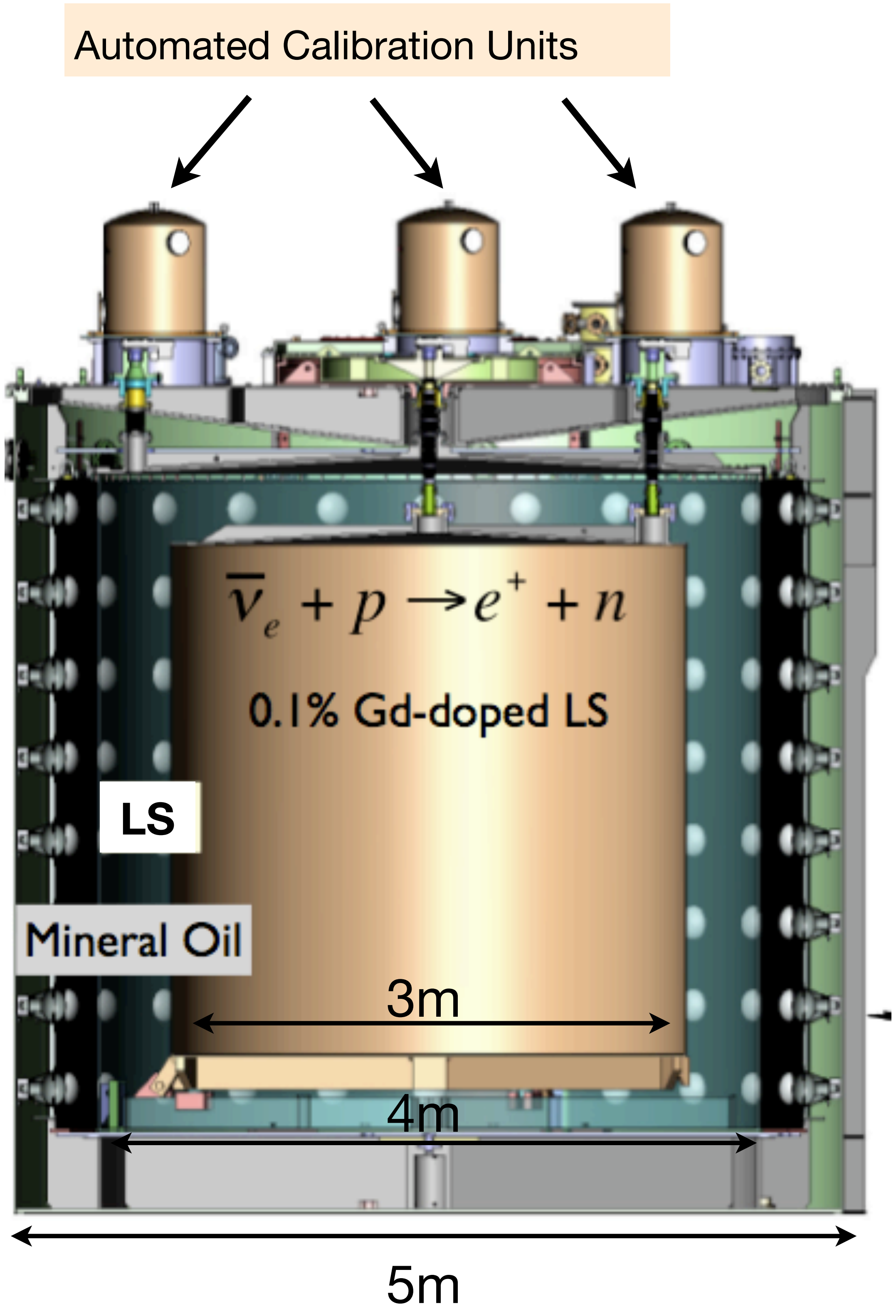
Detector Target Mass

Distance from Reactor

Detector Efficiency

Survival Probability (θ_{13})

Anti-neutrino Detector (AD)



8 functionally identical detectors

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

Each detector has 3 nested cylindrical zones separated by Acrylic Vessels:

Inner: 20 tons Gd-doped LS (target volume)
Mid: 20 tons LS (gamma catcher)
Outer: 40 tons mineral oil (buffer)

Each detector has:

192 8-inch Photomultipliers (PMTs)
Optical reflectors at top/bottom of cylinder
- effectively 12% photocoverage
~ 160 photoelectrons / MeV
~ 8%/√E (MeV) energy resolution

Anti-neutrino Detection Method

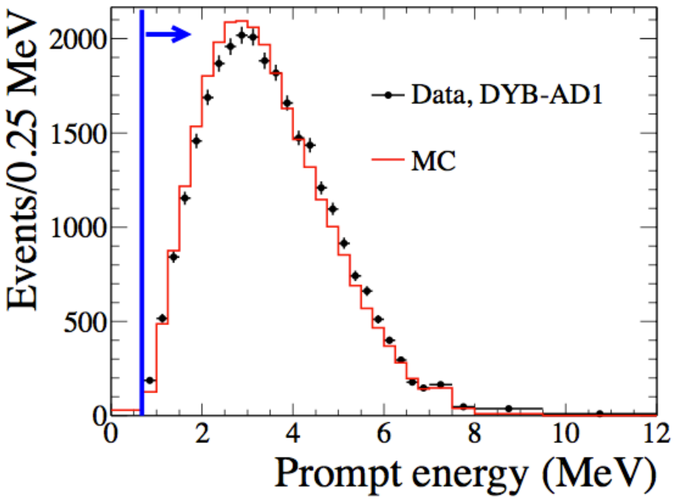
Inverse Beta Decay (IBD)

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

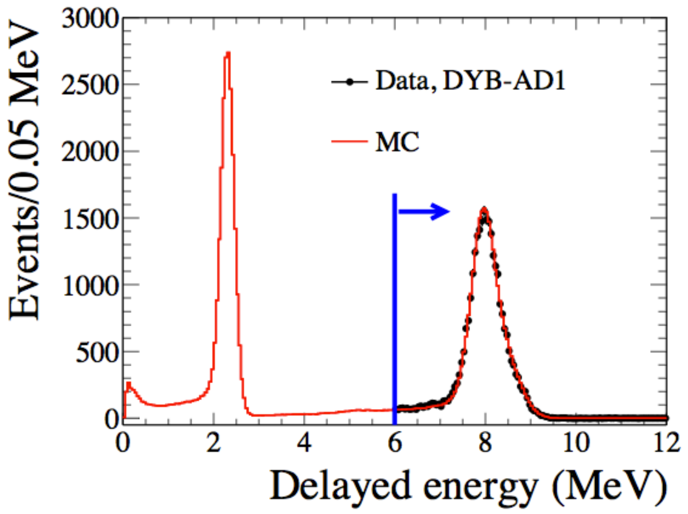
$$\mathrm{n} + {}^{A}\mathrm{Gd} \rightarrow {}^{A+1}\mathrm{Gd} + \boxed{\gamma' s}$$

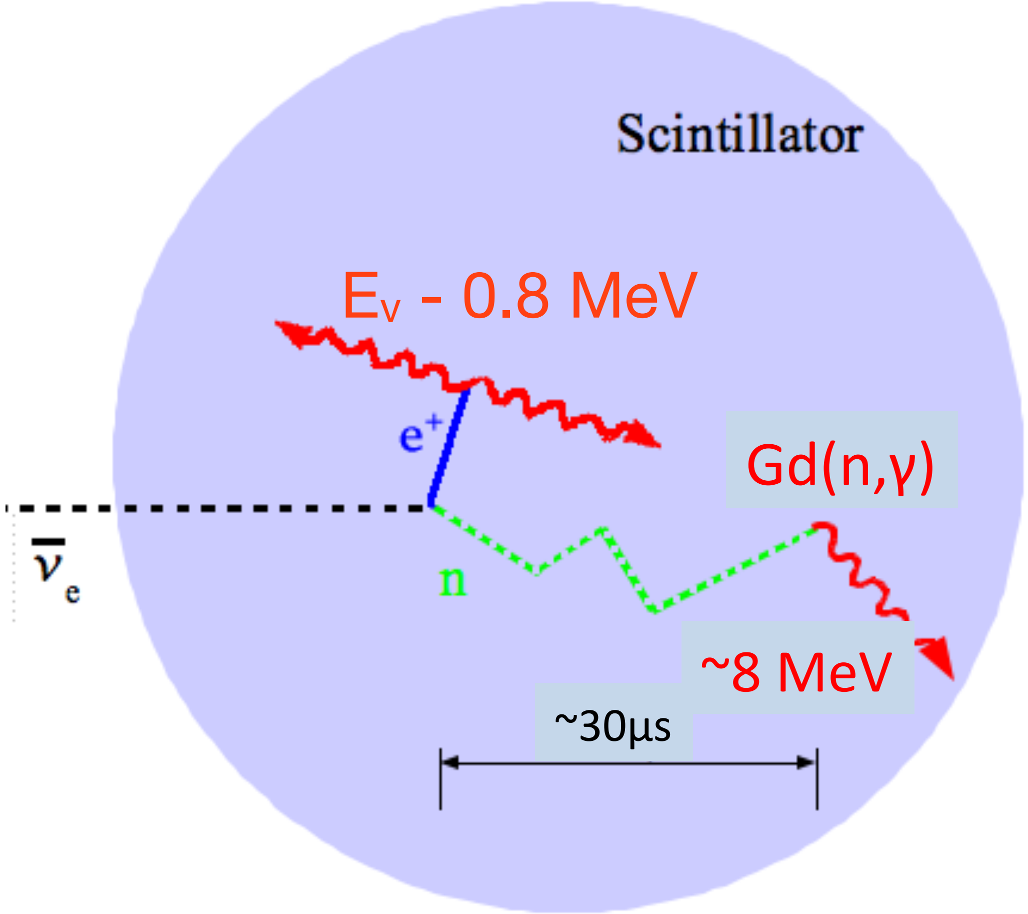
- $E_{\text{threshold}}$ = 1.8 MeV
- ‘Large’ cross section σ~10^{-42} cm^2
- Distinctive coincidence signature in a large liquid scintillator detector

Prompt Energy Signal



Delayed Energy Signal





Gd-LS defines the target volume.
Fiducial volume cut is not necessary.

Muon Veto System

Multiple muon veto detectors
>2.5m thick two-sector active water shield and RPC

Water Cherenkov

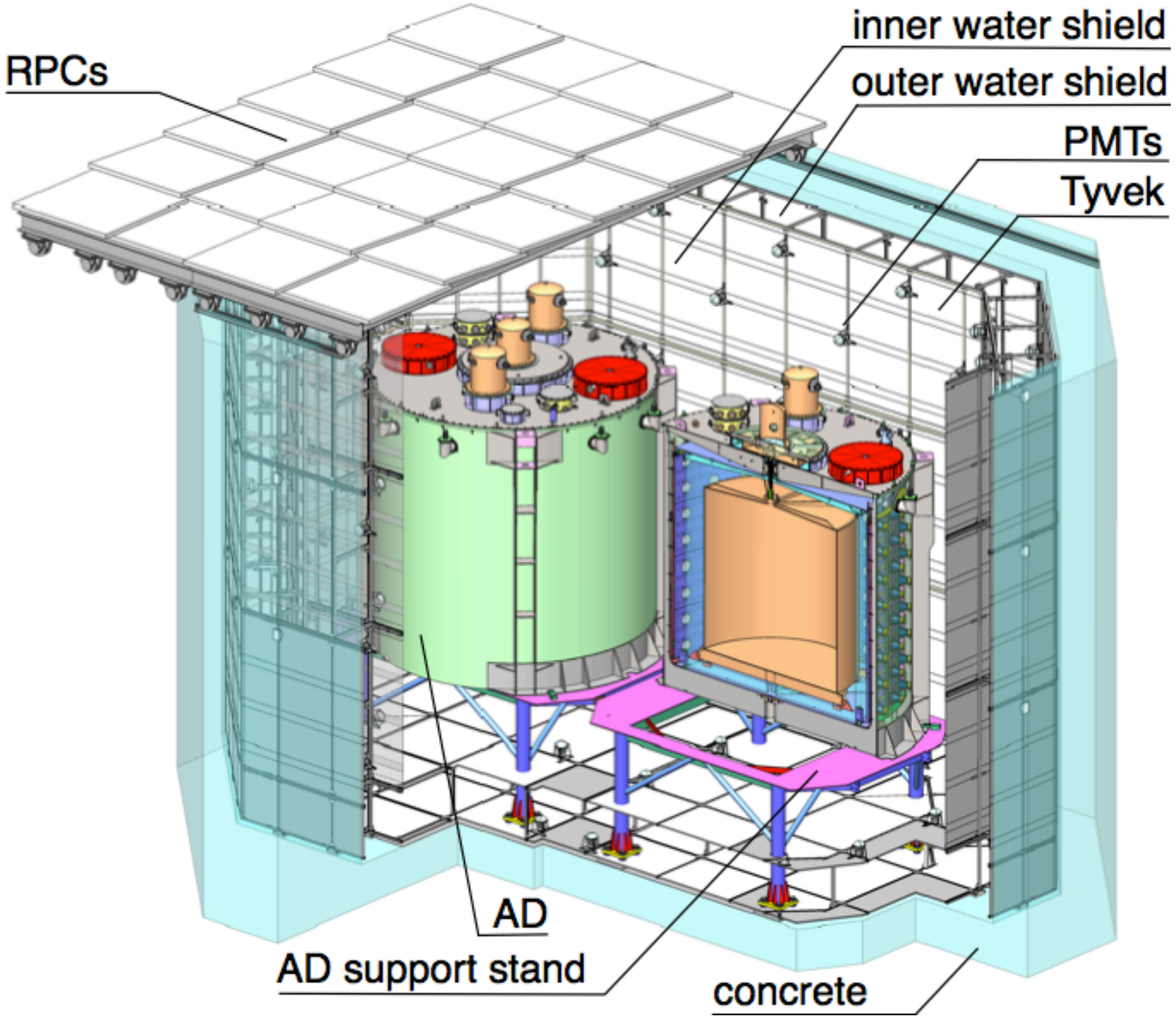
- Detectors submerged in water shielded against external neutrons and gammas

- Optically separated with Tyvek sheets into inner / outer region for better muon tracking

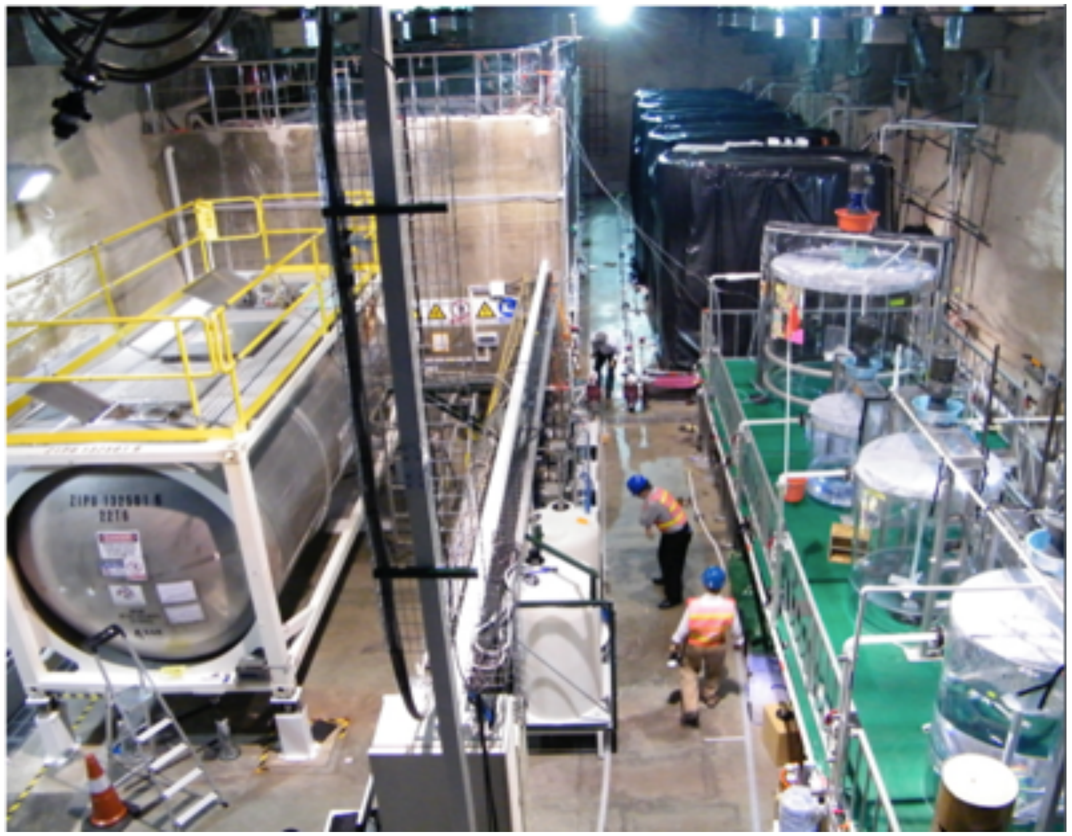
- 8-inch PMTs mounted on frames, 288 @Near, 384 @Far

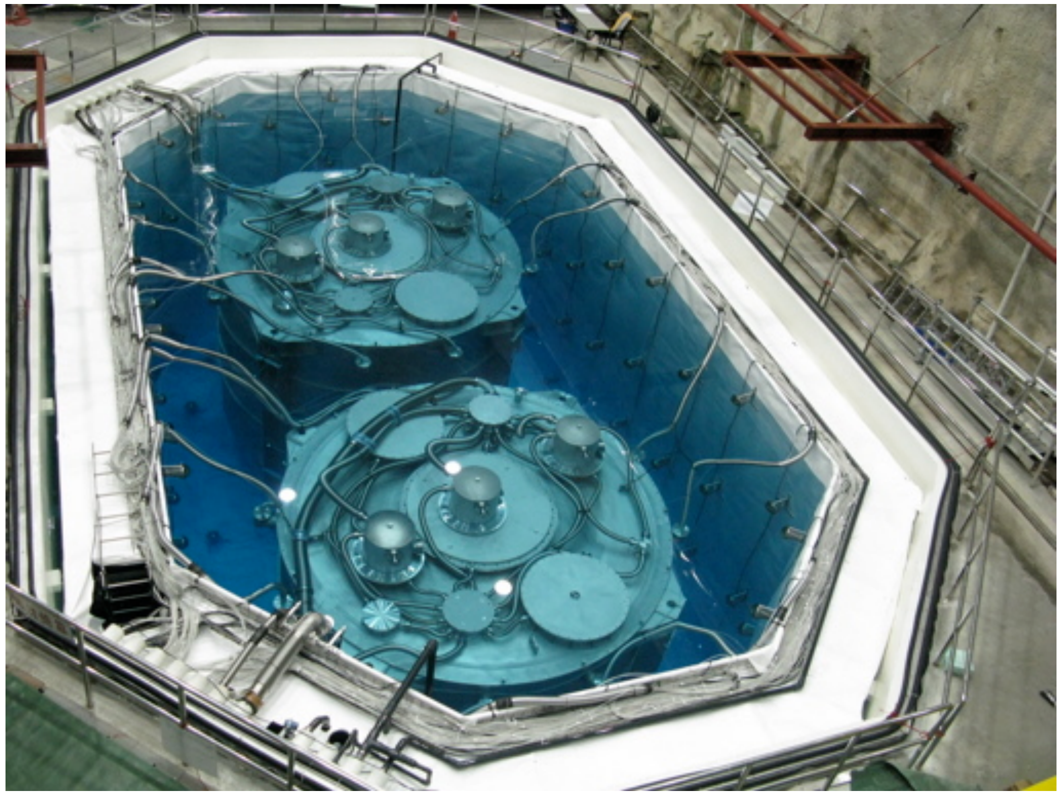
Resistive Plate Chamber (RPC)

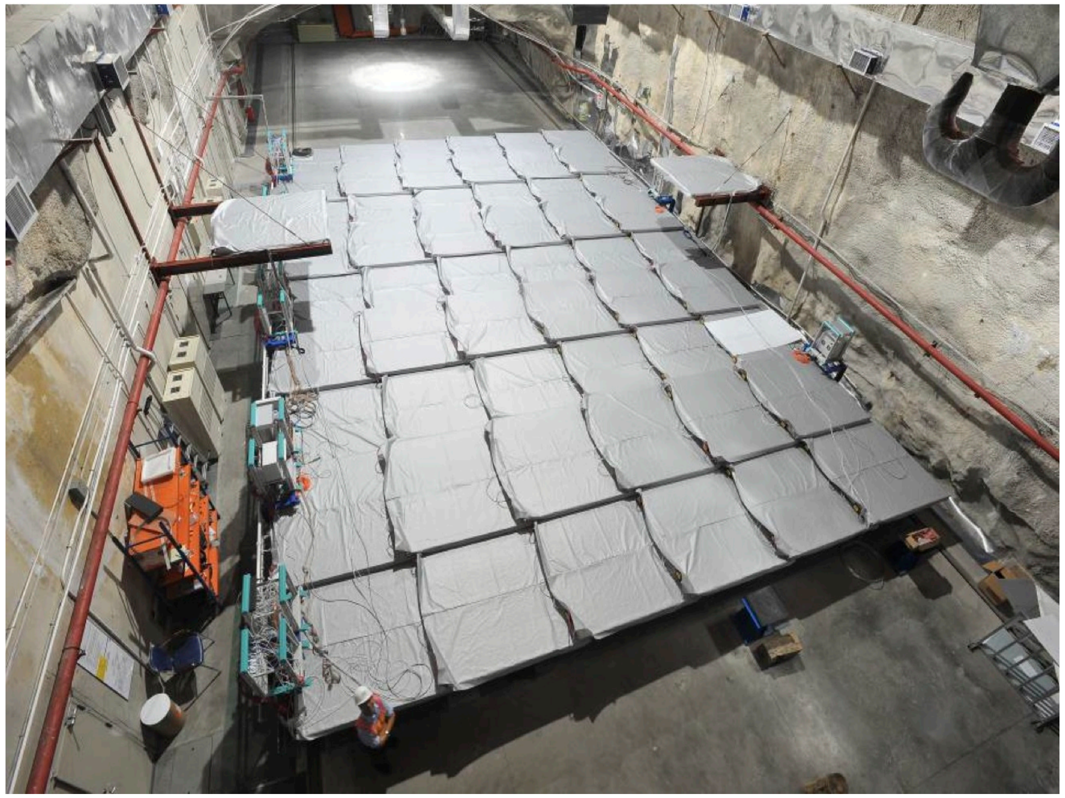
- Independent muon tagging
- Retractable roof above pool
- 54 modules @Near, 81 @Far



Antineutrino Detector Installation

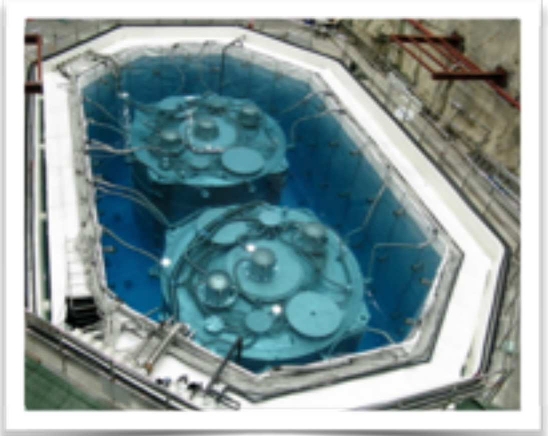




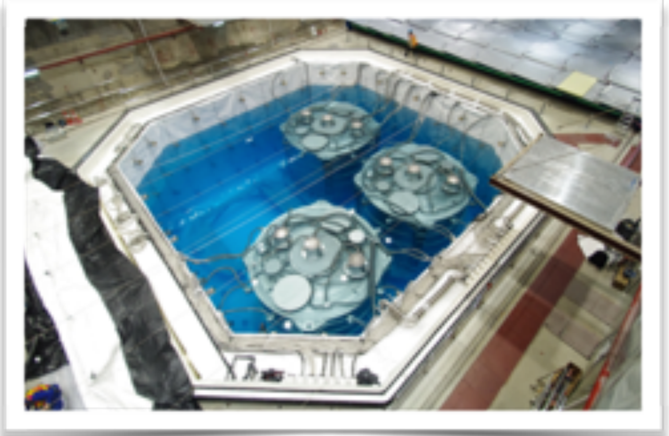


The Timeline of Detector Installation

EH1



EH3



EH3

Aug, 2011

Dec, 2011

Aug, 2012

6-AD Data Taking

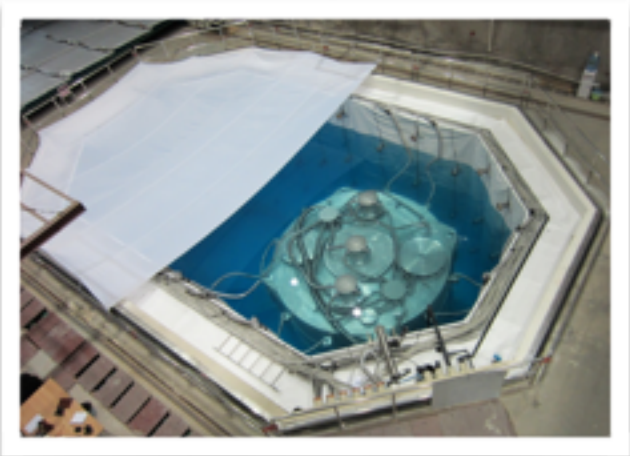
2011/12 - 2012/07

8-AD Data Taking

2012/10 - now

Nov, 2011

Aug, 2012



EH2

EH2

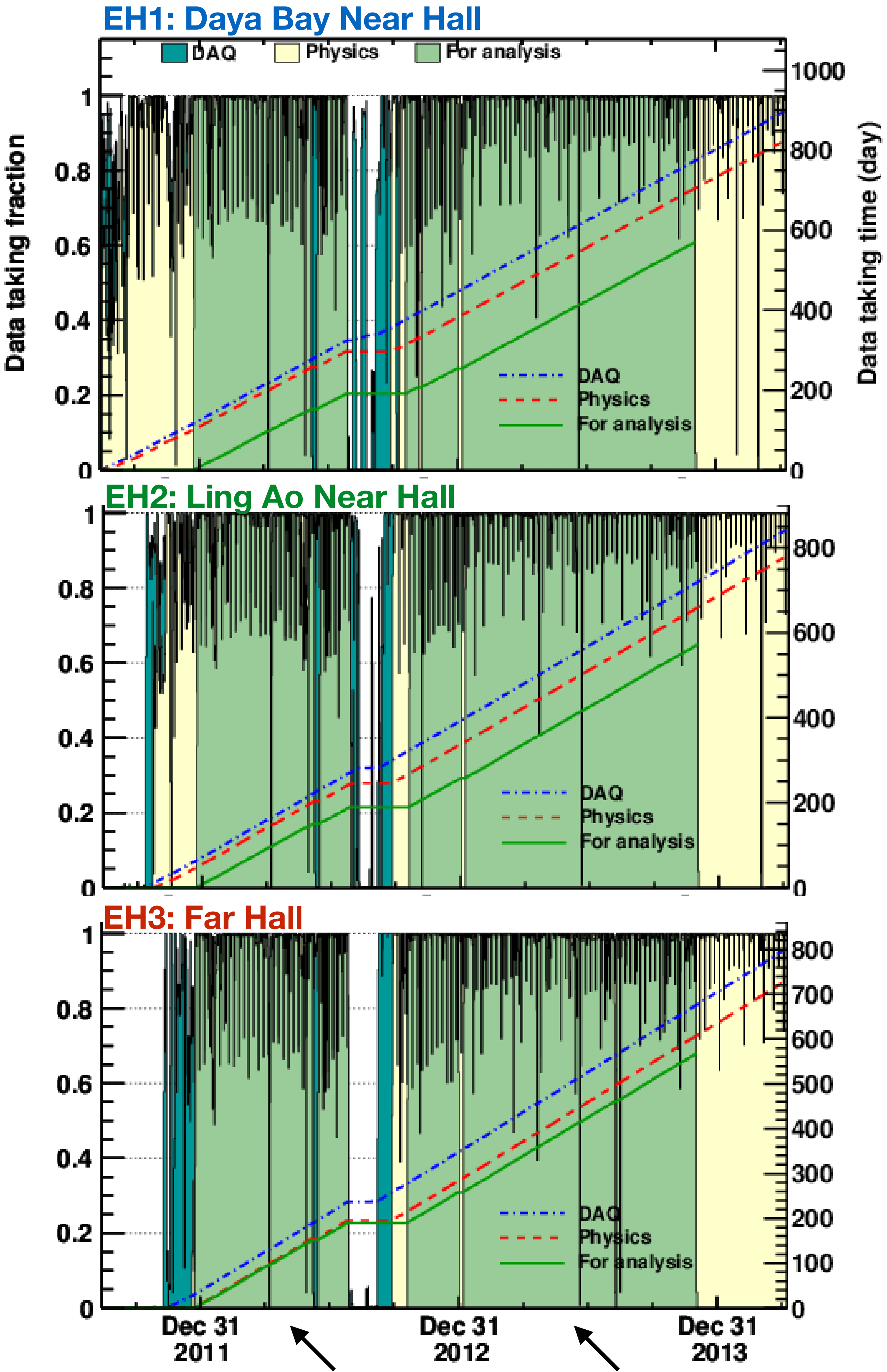
Analysis Results

Using Combined 6+8AD period (621 days):

- Oscillation analysis: $\sin^2 2\theta_{13}$ and Δm^2_{ee}
  - 4 times more statistics than our previously published results (*PRL 112, 061801 (2014)*)

Using 6-AD period (217 days):

- Independent measurement of $\sin^2 2\theta_{13}$ using neutron capture on hydrogen
- Light sterile neutrino search
- Measurement of reactor antineutrino flux and spectrum


EH1: Daya Bay Near Hall

EH2: Ling Ao Near Hall

EH3: Far Hall

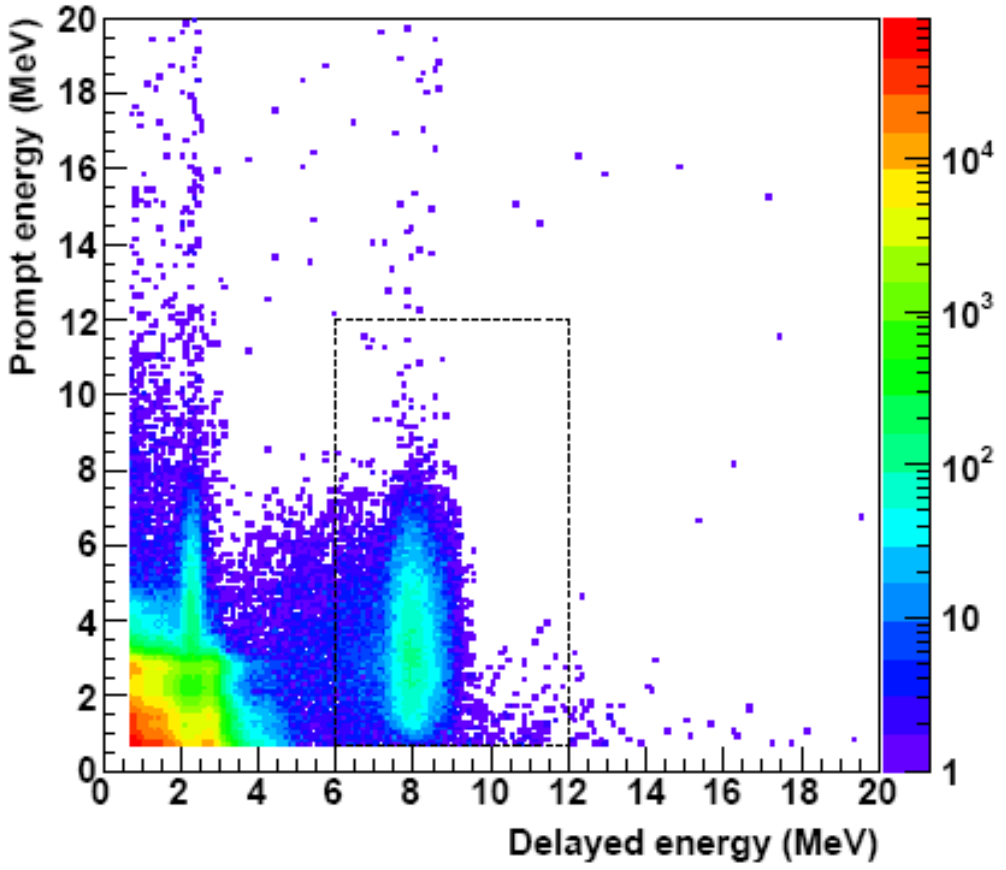
6AD period

8AD period

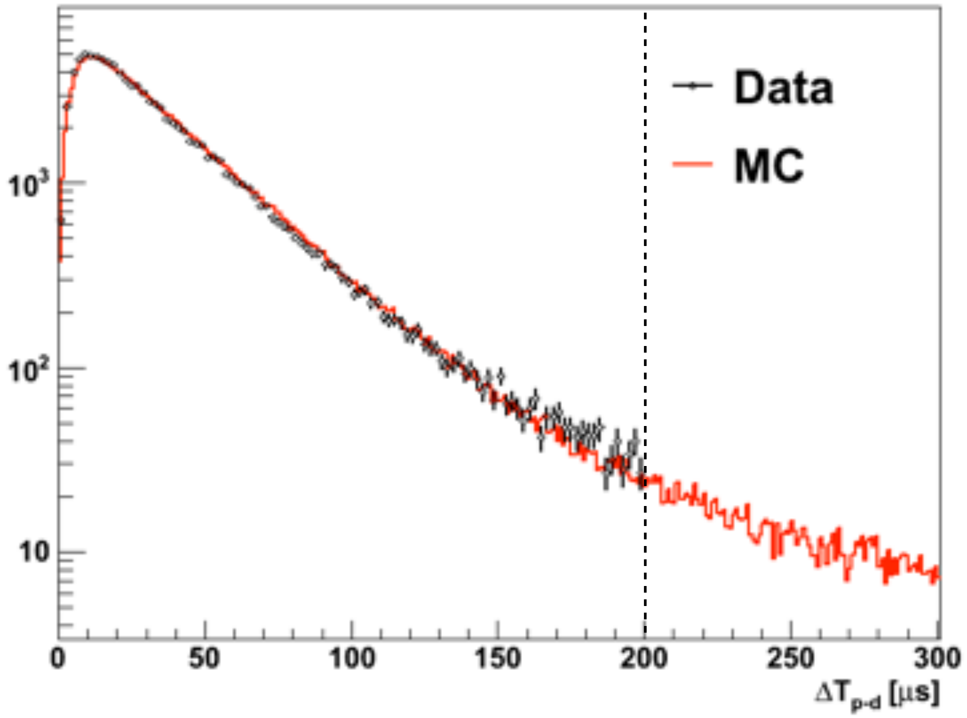
6-AD period: 2011/12/24 - 2012/07/28 (217 days)
8-AD period: 2012/10/19 - 2013/11/27 (404 days)

Antineutrino 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



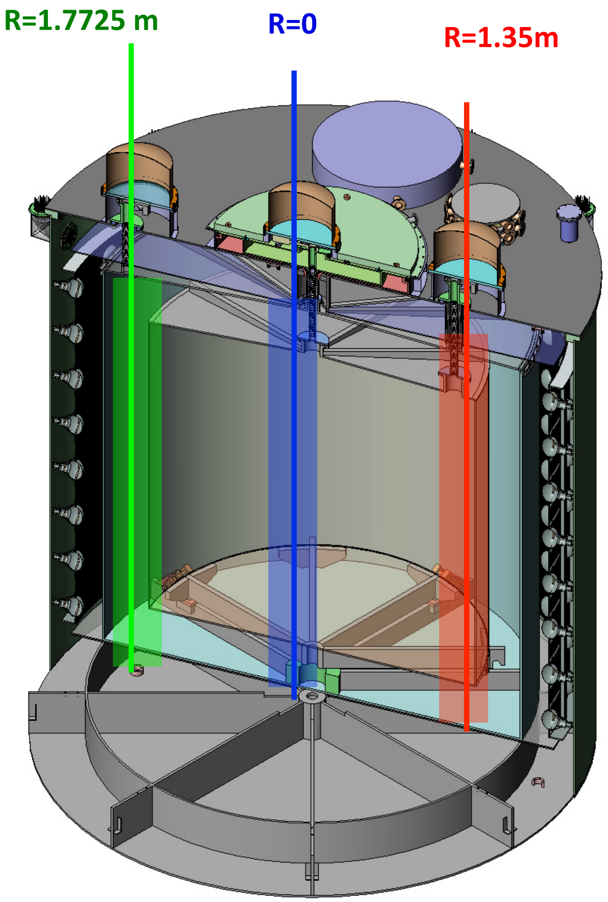
	Efficiency	Uncertainty	
		Correlated	Uncorrelated
Target Protons		0.47%	0.03%
Flasher cut	99.98%	0.01%	0.01%
Delayed Energy cut	92.7%	0.97%	0.12%
Prompt Energy cut	99.81%	0.10%	0.01%
Capture time cut	98.70%	0.12%	0.01%
Gd capture ratio	84.2%	0.95%	0.10%
Spill-in correction	104.9%	1.50%	0.02%
Combined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



Calibration System

3 Automated Calibration Units (ACUs) per detector

- 3 sources for each z axis on a turntable (position accuracy < 7 mm)



- 10 Hz **^{68}Ge** (2 x 0.511 MeV γ's)
- 100 Hz **^{60}Co** gamma source (1.173 + 1.332 MeV γ's) + 0.7 Hz **^{241}Am^{13}C** neutron source (3.5 MeV n without γ)
- **LED** diffuser ball for PMT gain and timing


31/08/2012 15:55

Manual Calibration System (one-time)

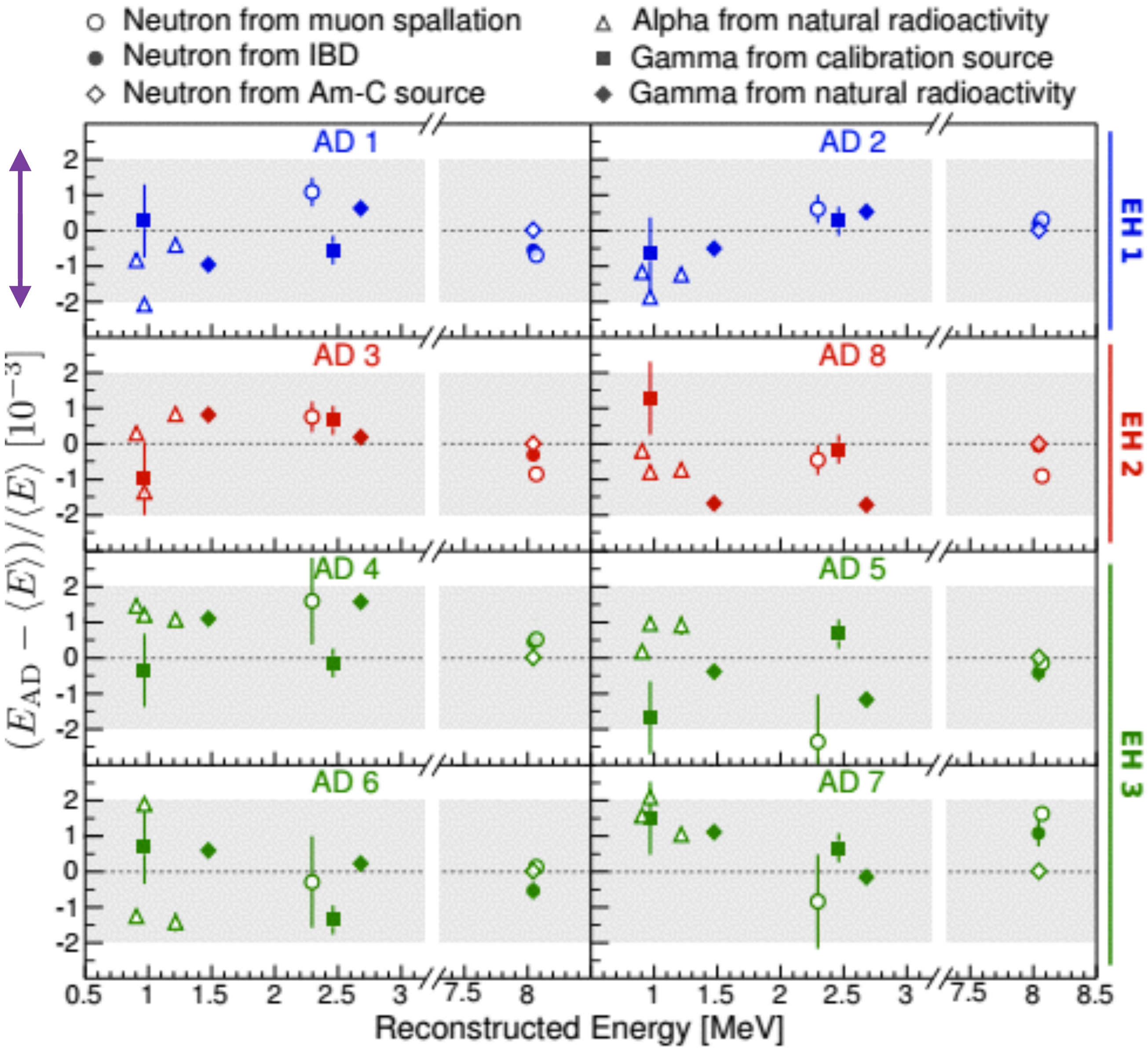
- MCS installed on AD#1 in summer 2012
- ^{60}Co + ^{239}Pu^{13}C composite source
- 4π deployment

- **Simultaneous, fully-automated weekly deployment for all 8 ADs**
- Special calibration campaign during summer 2012 with temporary sources
  - ^{137}Cs, ^{54}Mn, ^{40}K, ^{241}Am^{9}Be, ^{239}Pu^{13}C
- Also have methods to calibrate **in-situ**
  - PMT gains: dark noise
  - Energy (light-yield): spallation neutron

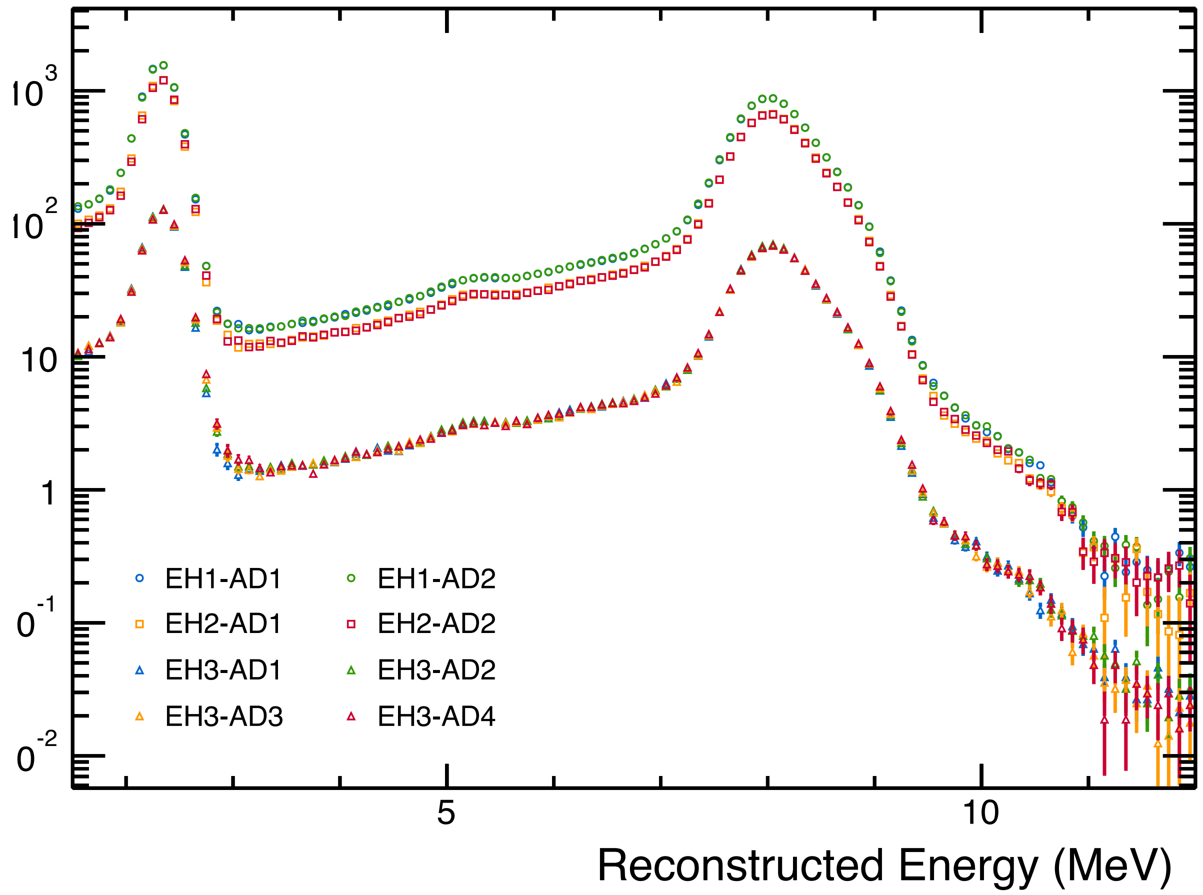
Relative Energy Scale

ACU: ^{60}Co, ^{68}Ge, AmC
Spallation: nGd, nH
Gamma: ^{40}K, ^{208}Tl
Alpha: ^{212}Po, ^{214}Po, ^{215}Po

0.2%

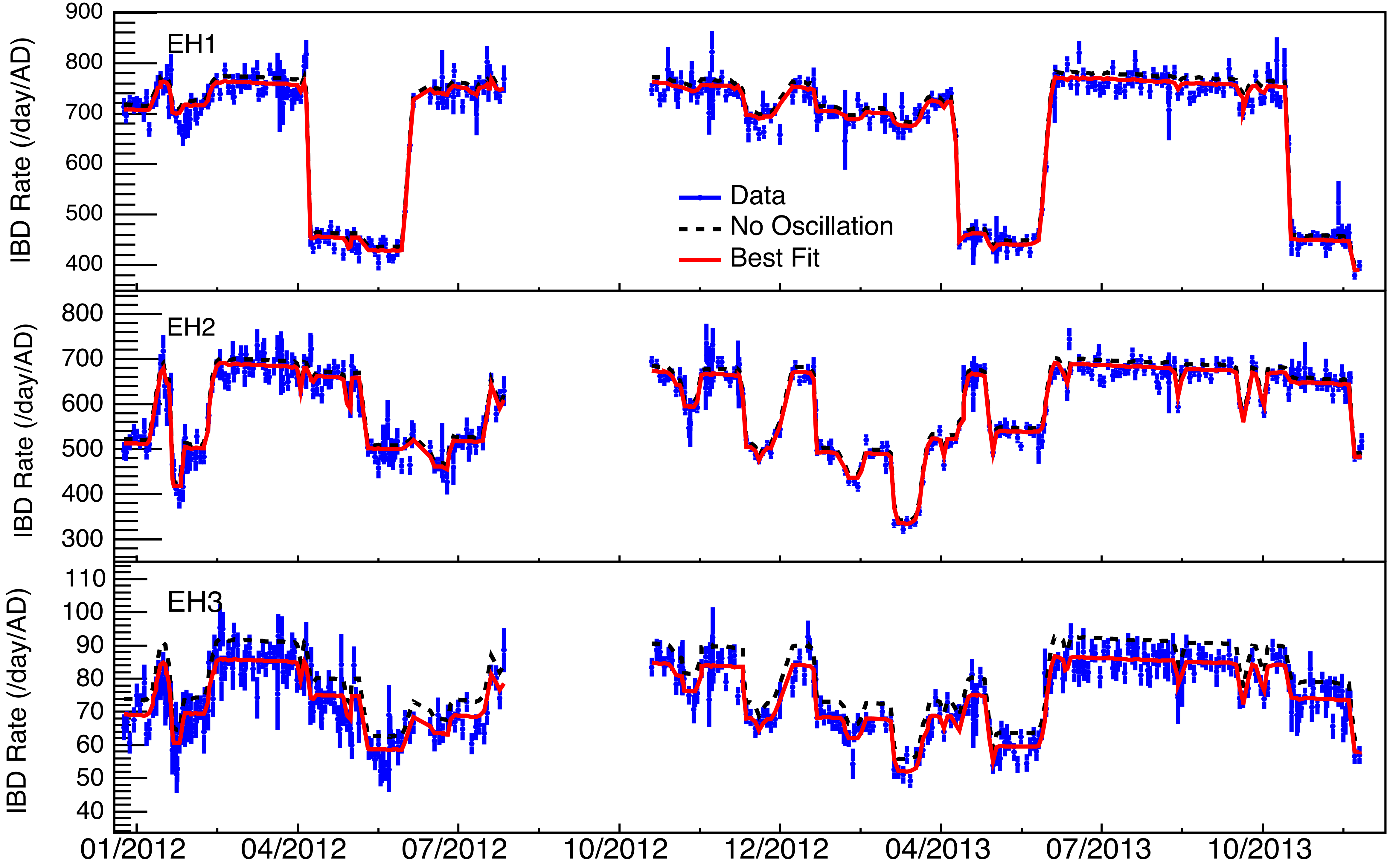


spallation neutron capture spectrum



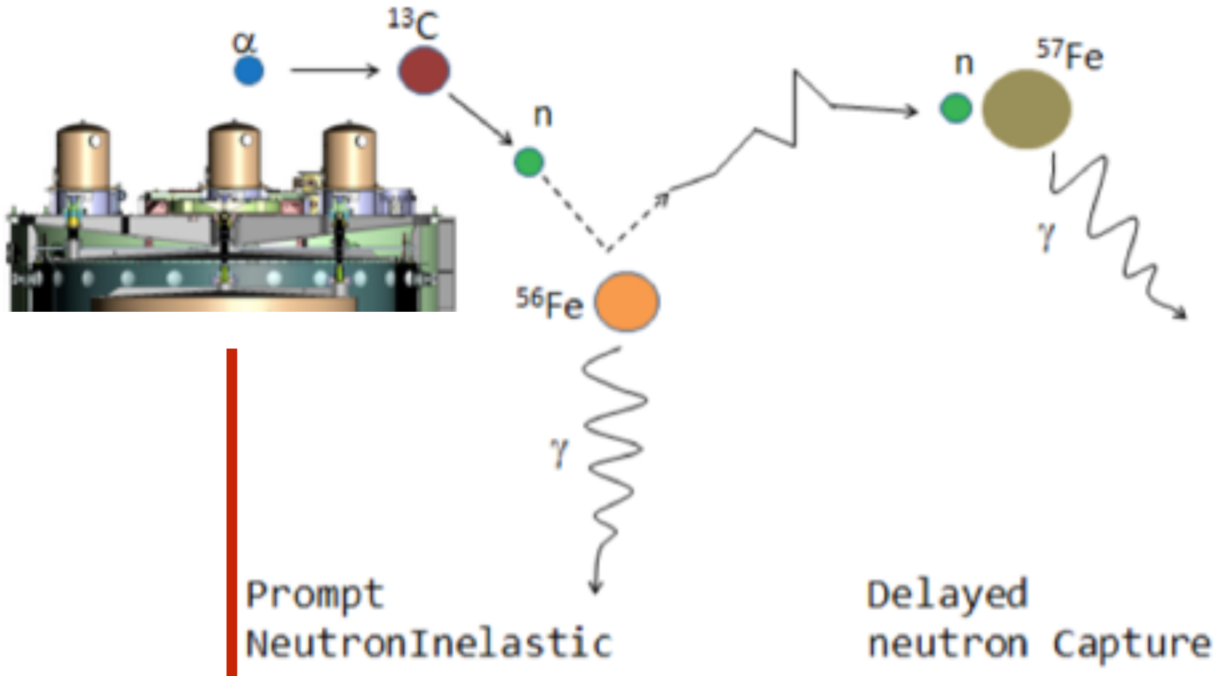
< 0.2% variation in reconstructed energy between ADs

Over 1 million antineutrino interactions!
(150k at the far site)

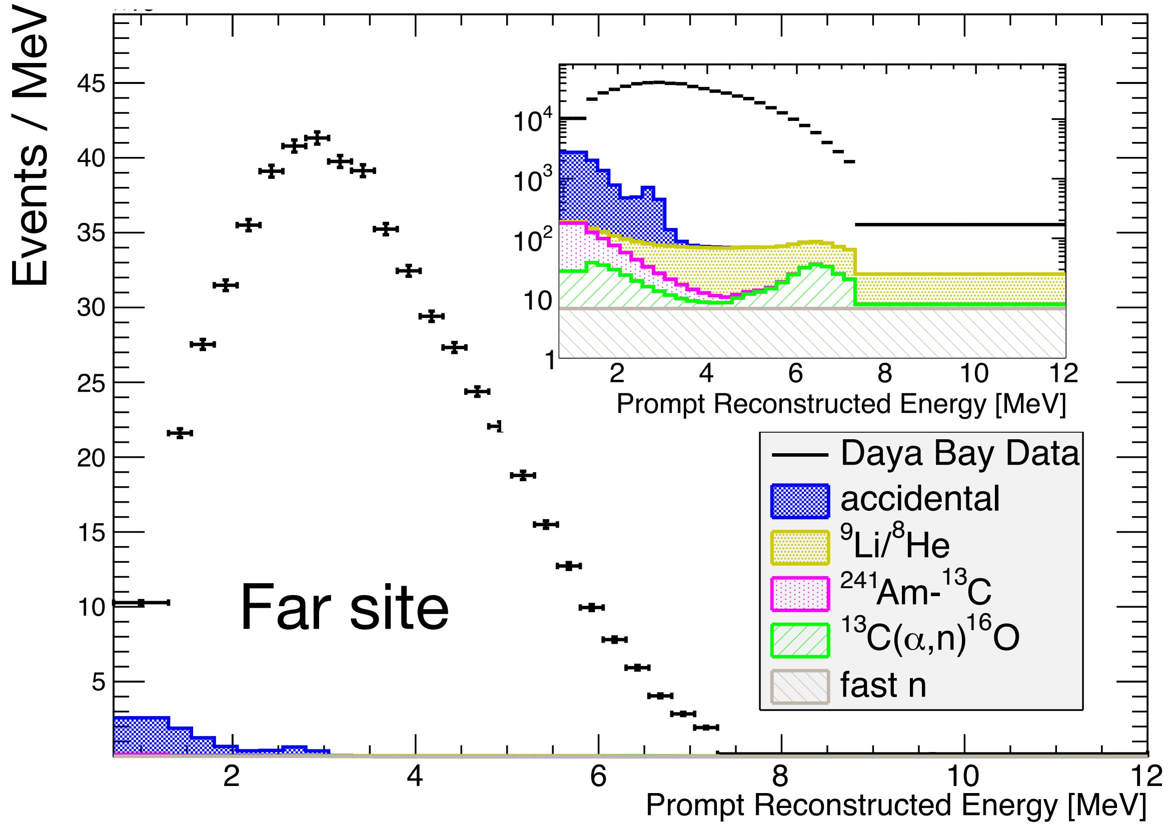


Detected rate strongly correlated with reactor flux

Background Budget



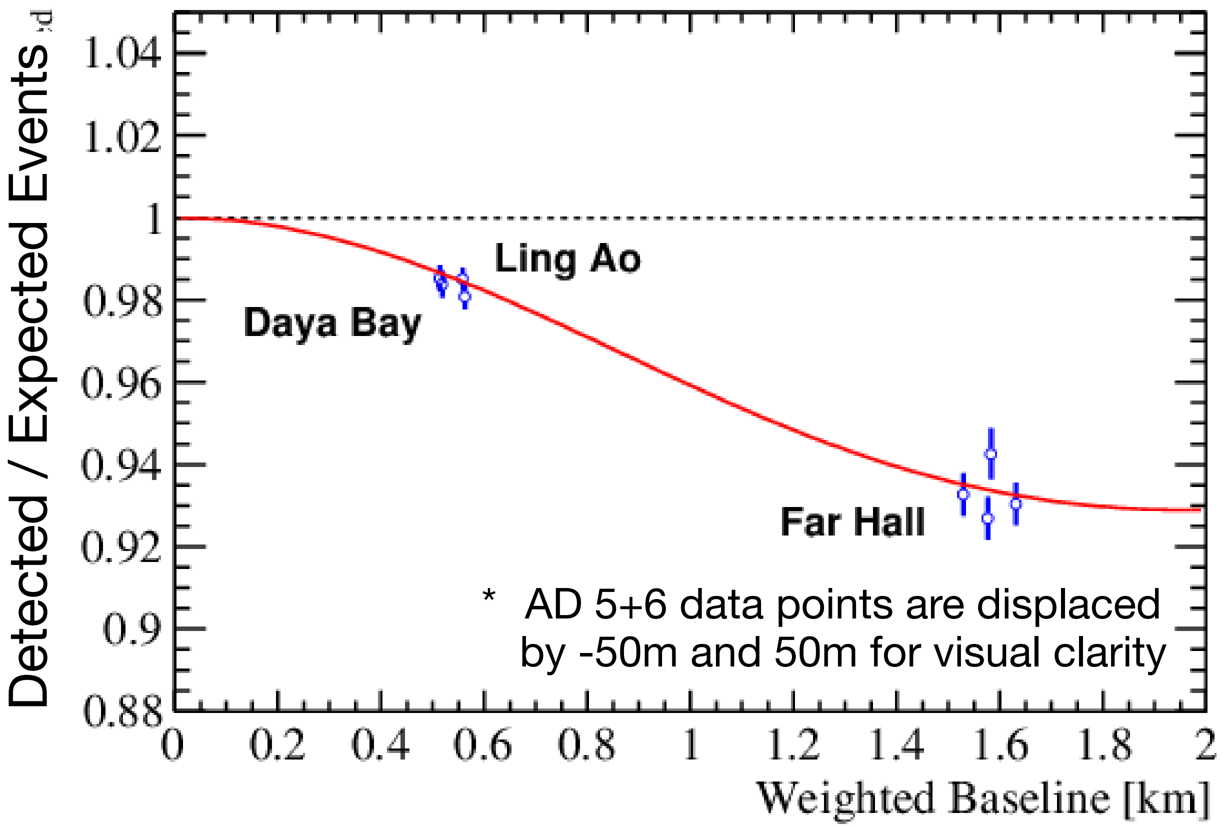
a low background experiment



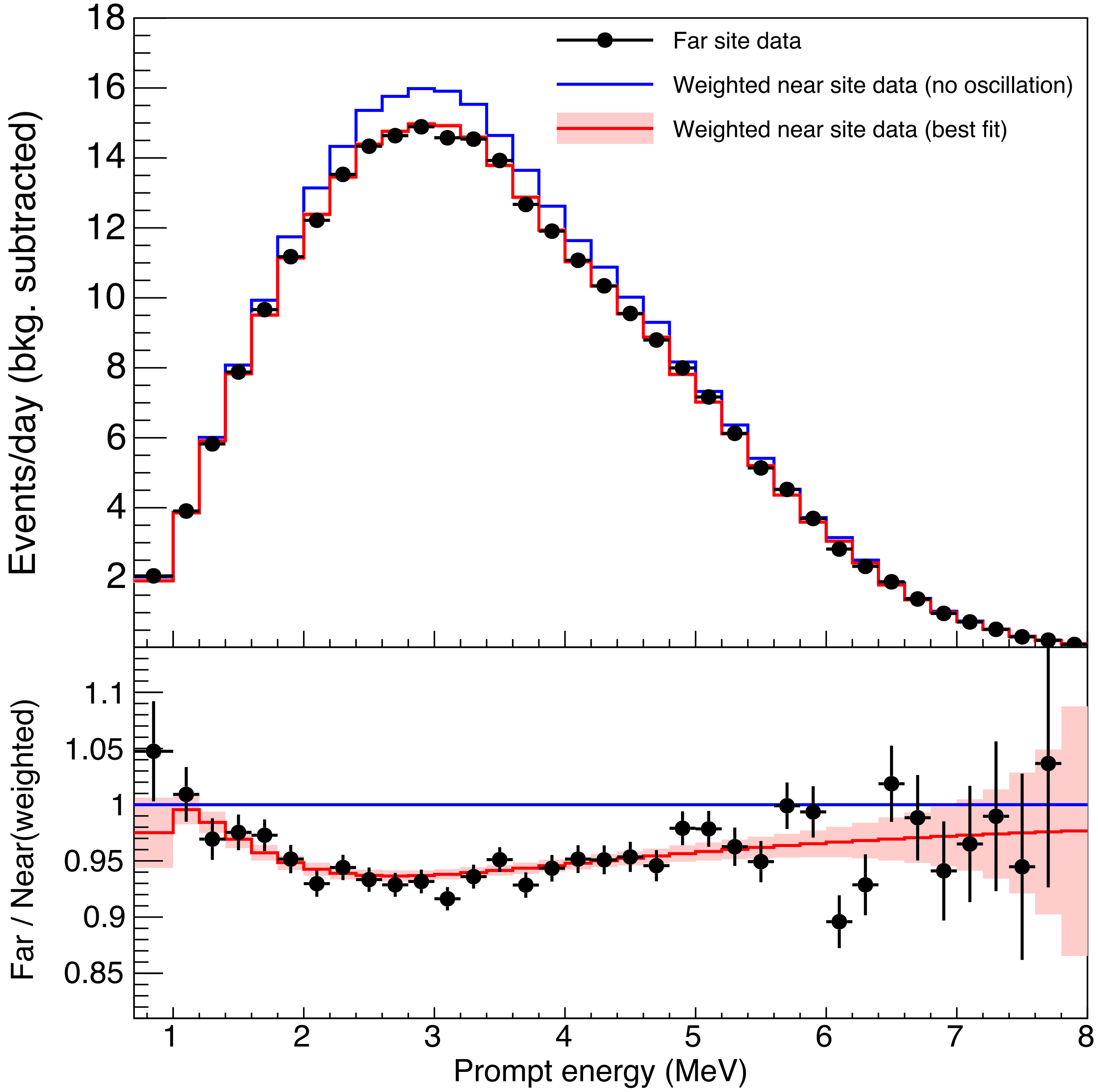
Background	Near	Far	Uncertainty	Method
Accidentals	1.4%	2.3%	negligible	statistically calculated from uncorrelated singles
AmC source	0.03%	0.2%	~50%	MC benchmarked with single gamma and strong AmC source
Li-9 / He-8	0.4%	0.4%	~50%	measured with after-muon events
Fast neutron	0.1%	0.1%	~30%	measured from AD/water/RPC tagged muon events
Alpha-n	0.01%	0.1%	~50%	calculated from measured radioactivity

Far v.s. Near Comparison

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \simeq 1 - \sin^2 2\theta_{13} \sin^2(\Delta m^2_{ee} \frac{L}{4E}) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2(\Delta m^2_{21} \frac{L}{4E})$$



* AD 5+6 data points are displaced by -50m and 50m for visual clarity



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

Oscillation Results

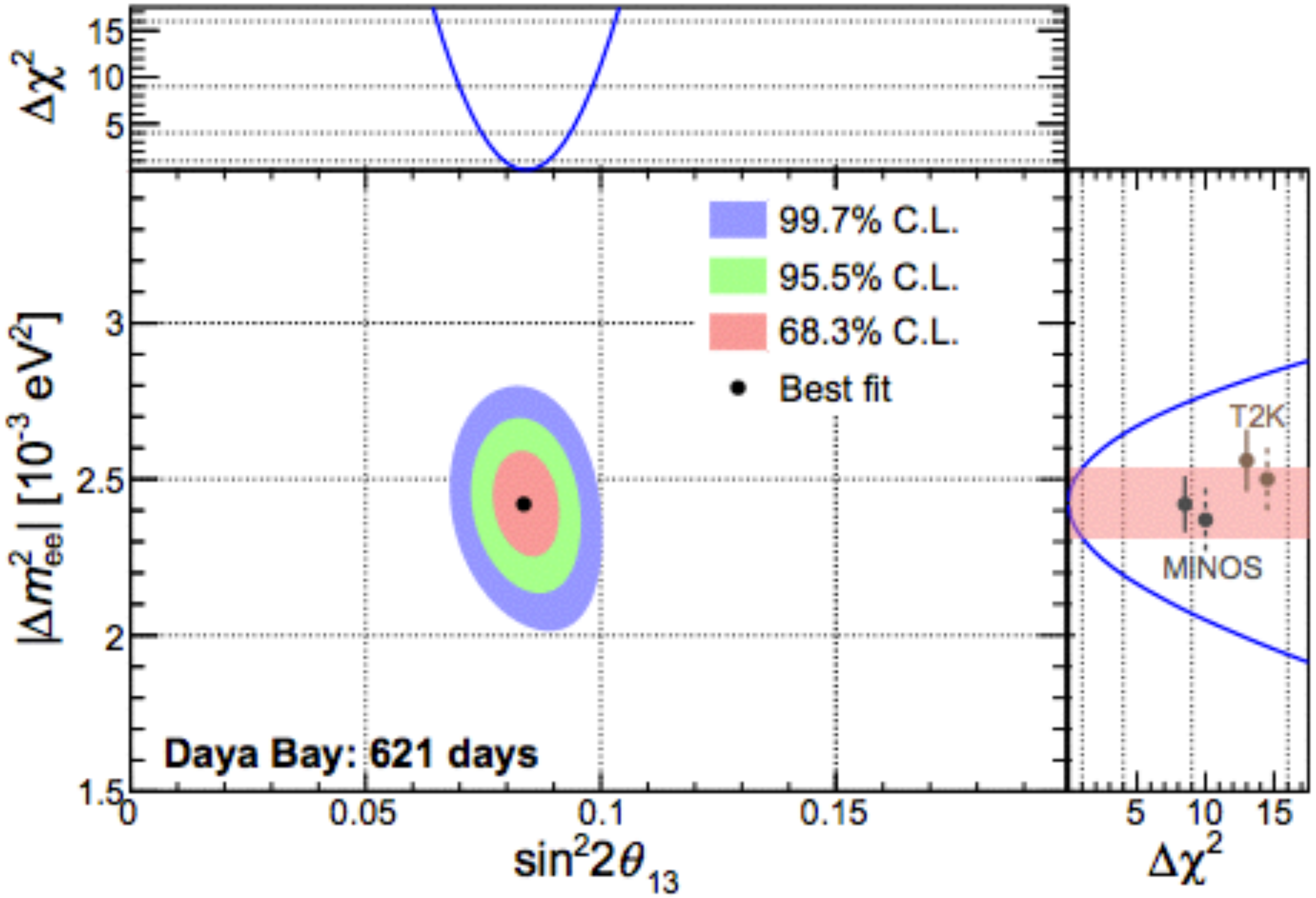
$$\sin^2 2\theta_{13} = 0.084 \pm 0.005$$

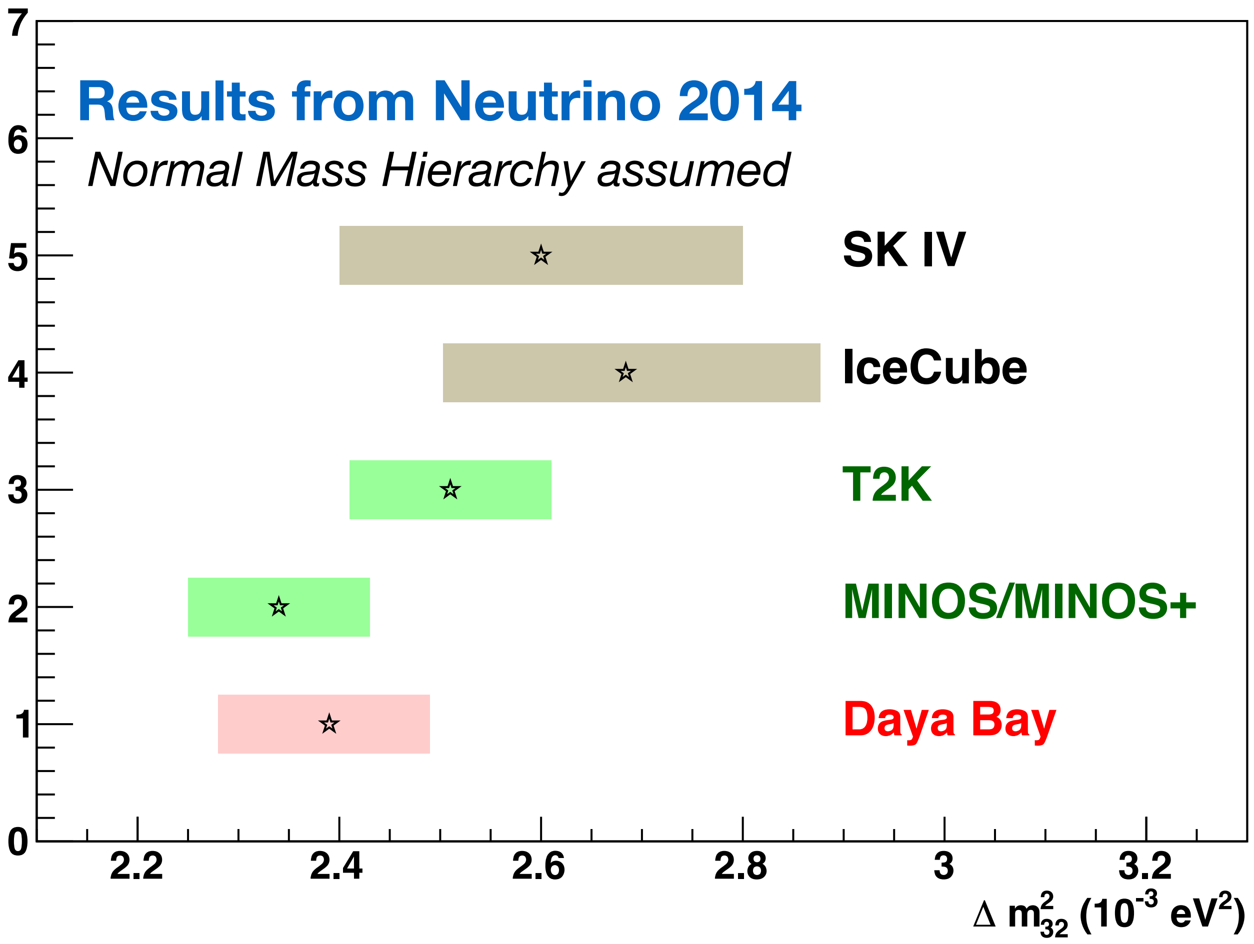
$$|\Delta m^2_{ee}| = (2.42 \pm 0.11) \times 10^{-3}\,\mathrm{eV}^2$$

$$\chi^2/\mathrm{NDF} = 134.6/146$$

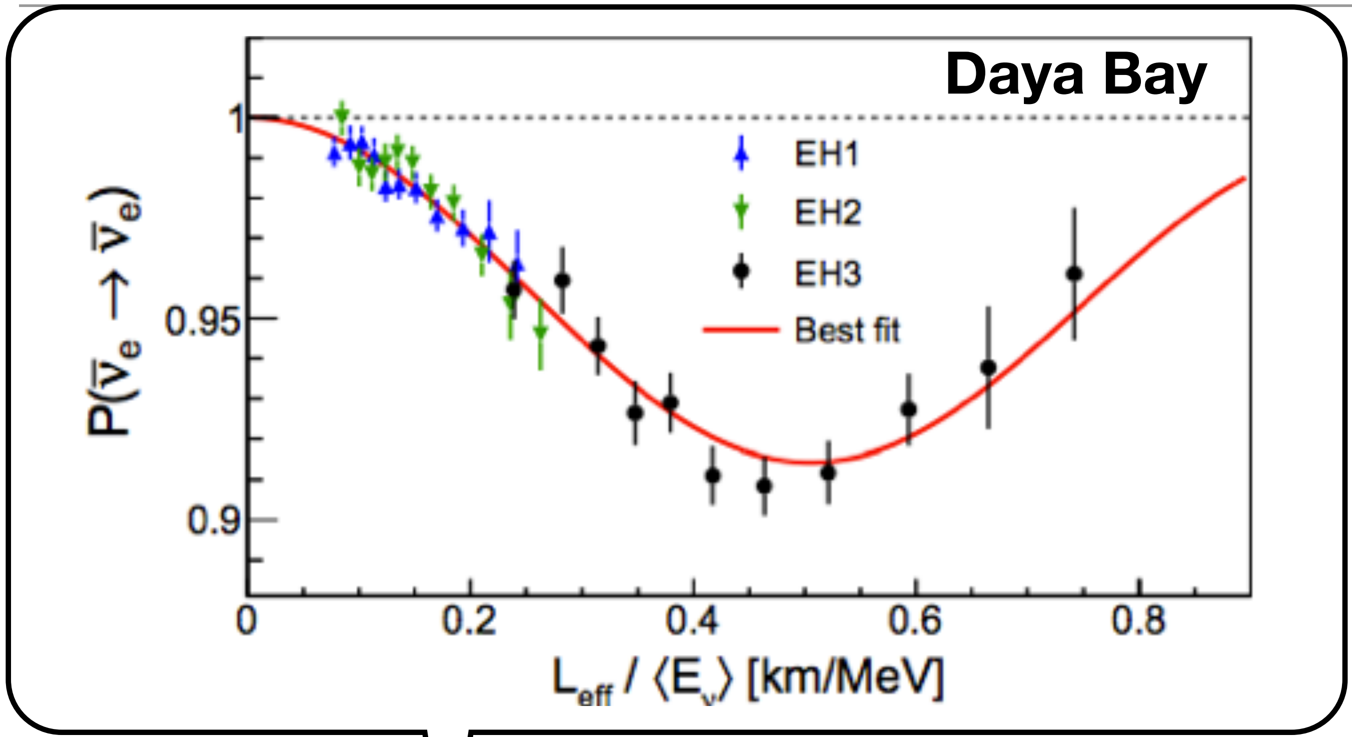
- **Most precise measurement of** **$\sin^2 2\theta_{13}$**, precision reached < 6%
- **Most precise measurement of** **atmospheric mass splitting** **in the electron neutrino disappearance channel**
  - consistent and of comparable preciseness with the muon neutrino disappearance experiments

"A new measurement of antineutrino oscillation with the full detector configuration at Daya Bay"
arXiv:1505.03456, accepted by PRL

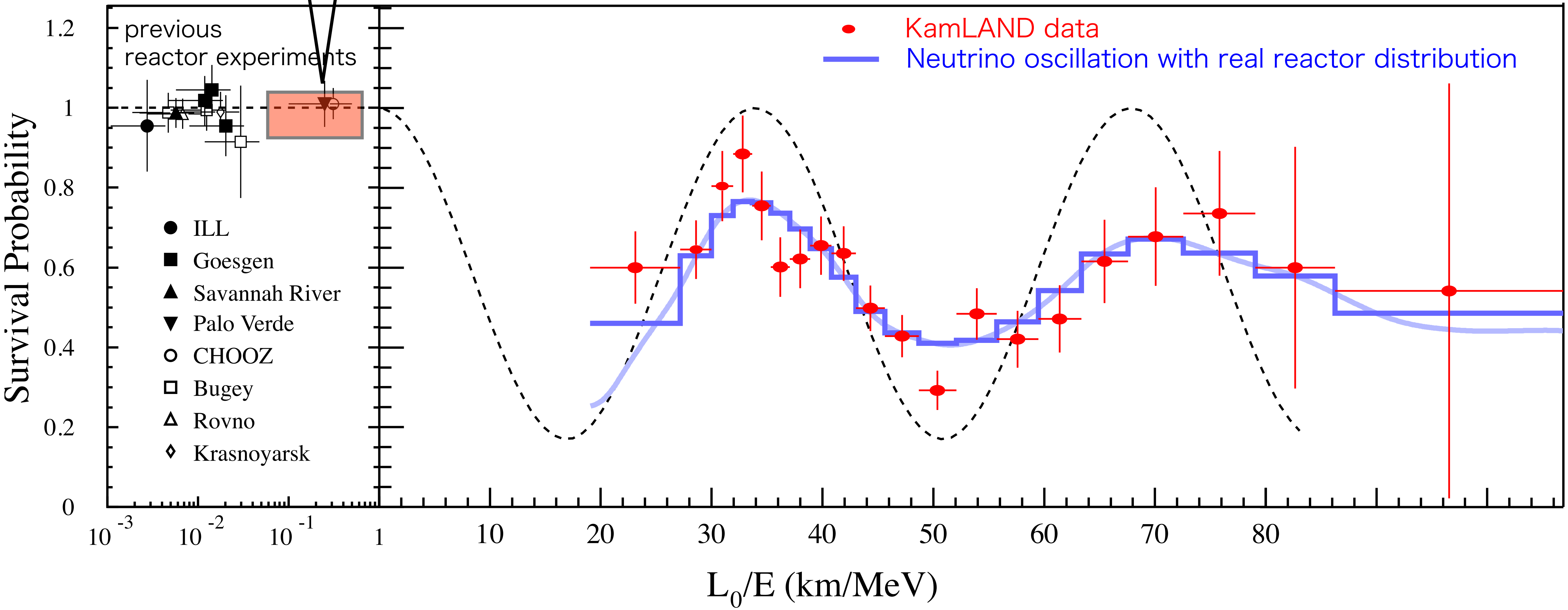




L/E Oscillation in Daya Bay



Both atmospheric scale and solar scale oscillations are beautifully demonstrated by reactor neutrino experiments!

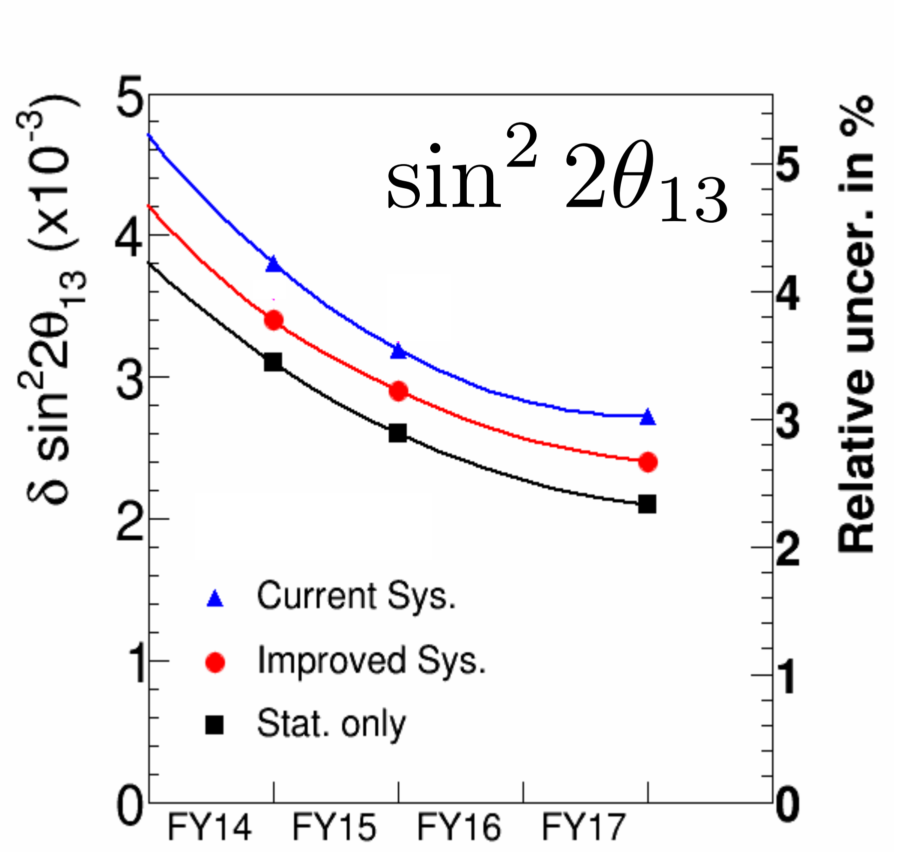


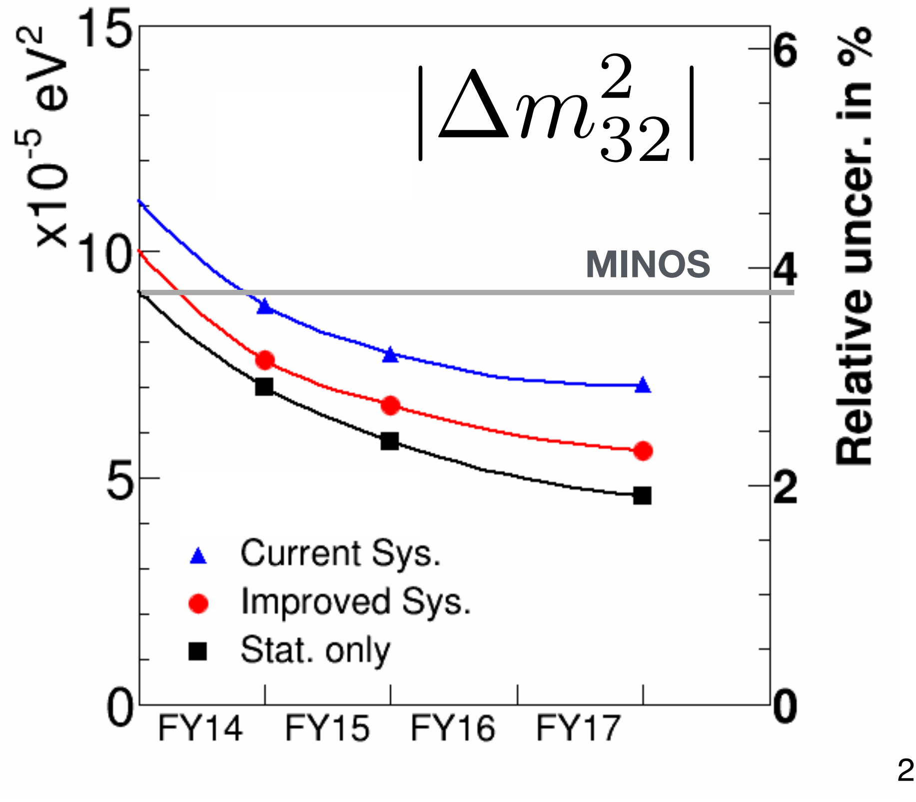
Projected Sensitivity in Oscillation Parameters

Operations through 2017

- Further improve world's most precise measurement of $\sin^2 2\theta_{13}$
  - Enhance the CPV sensitivity for DUNE
  - Test unitarity of PMNS matrix

- Further improve the precision measurement of atmosphere mass splitting in the electron neutrino channel
  - competitive with and complementary to accelerator based experiments, testing 3-flavor model
  - potential hints for neutrino mass hierarchy





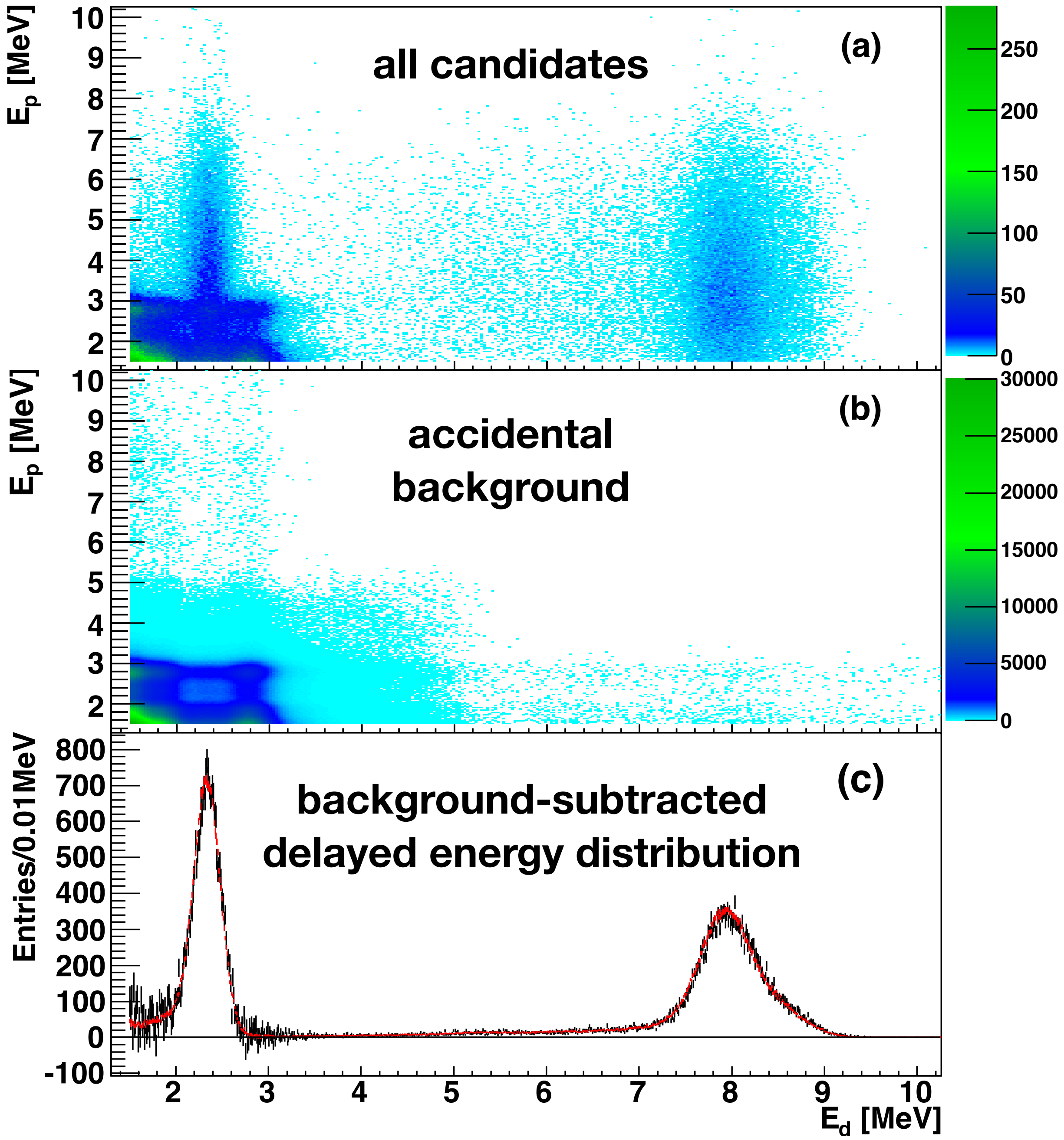
Independent $\sin^2 2\theta_{13}$ measurement through nH

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

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

$$+H \rightarrow D + \gamma \qquad 2.2\ \text{MeV} \quad 200\ \mu s$$

$$+Gd \rightarrow Gd^* \rightarrow Gd + \gamma ' s \qquad 8\text{MeV} \quad 30\ \mu s$$

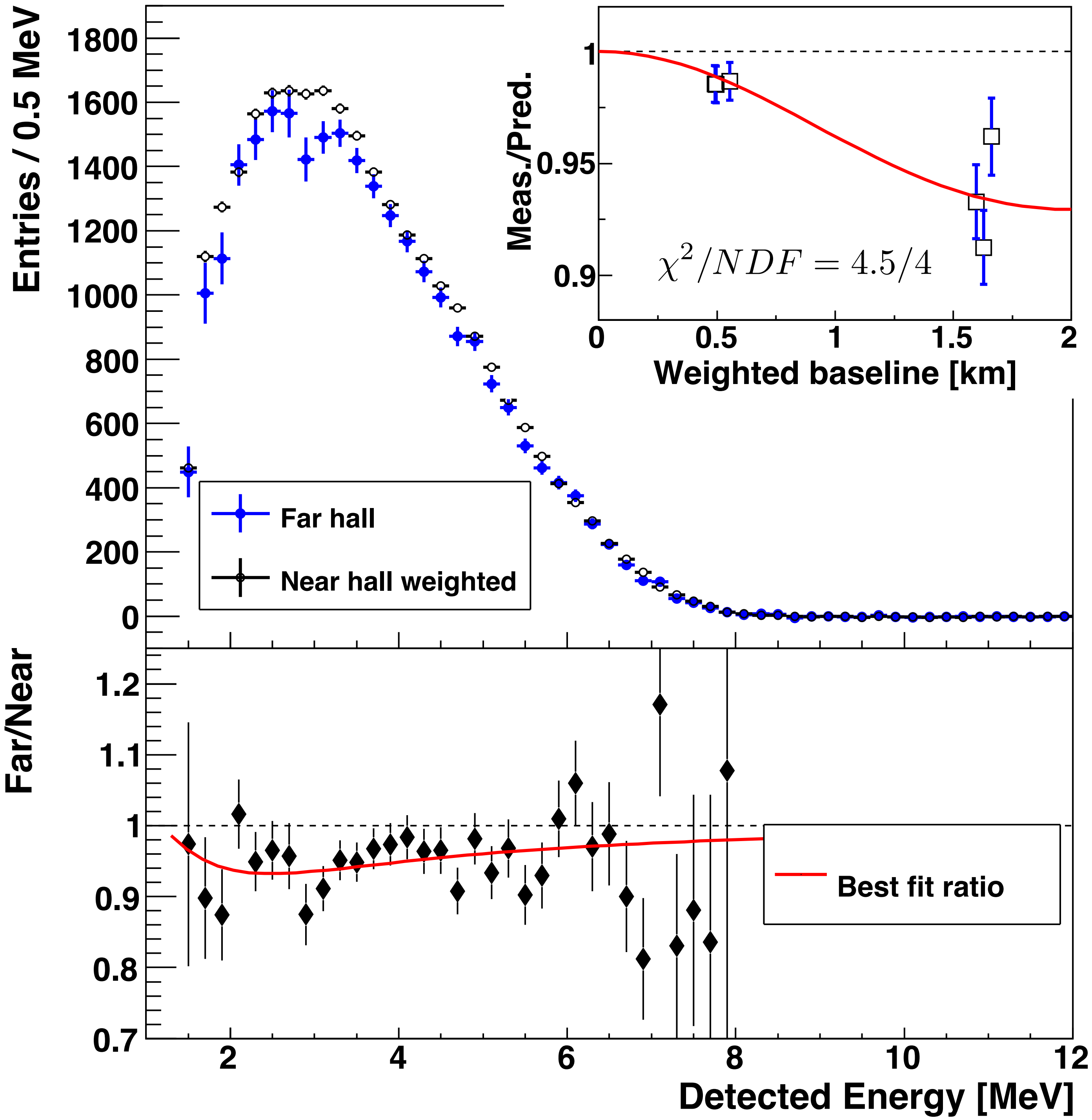


nH Analysis Results

- 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



- Independent θ_{13} measurement with nH, *PRD 90, 071101(R) (2014)*

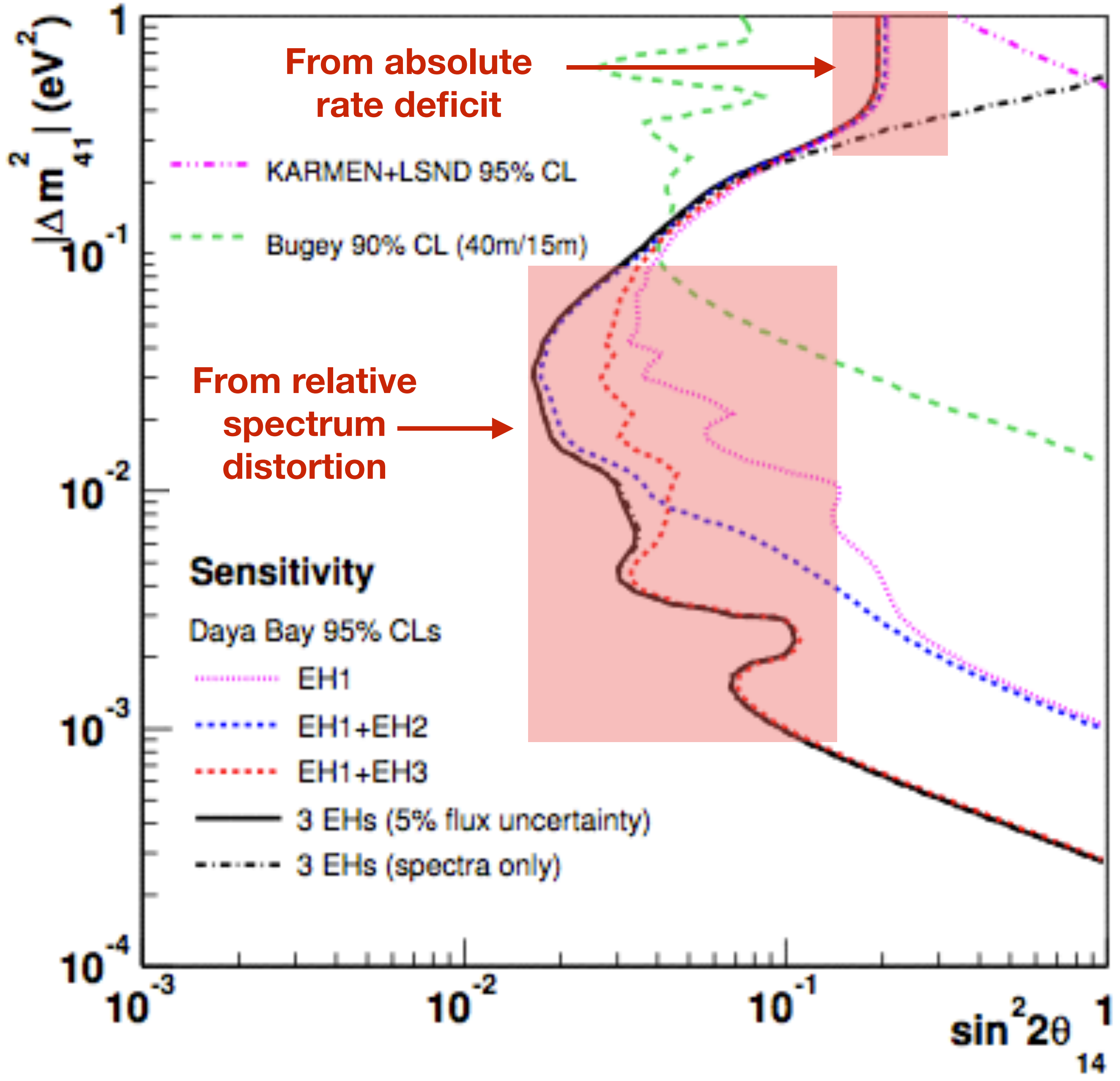
Light Sterile Neutrino Search

- Daya Bay has a unique combination of multiple baselines: EH1 (~350m), EH2 (~500m), EH3 (~1600m)
  - Sterile neutrinos will cause additional spectrum difference between different sites

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

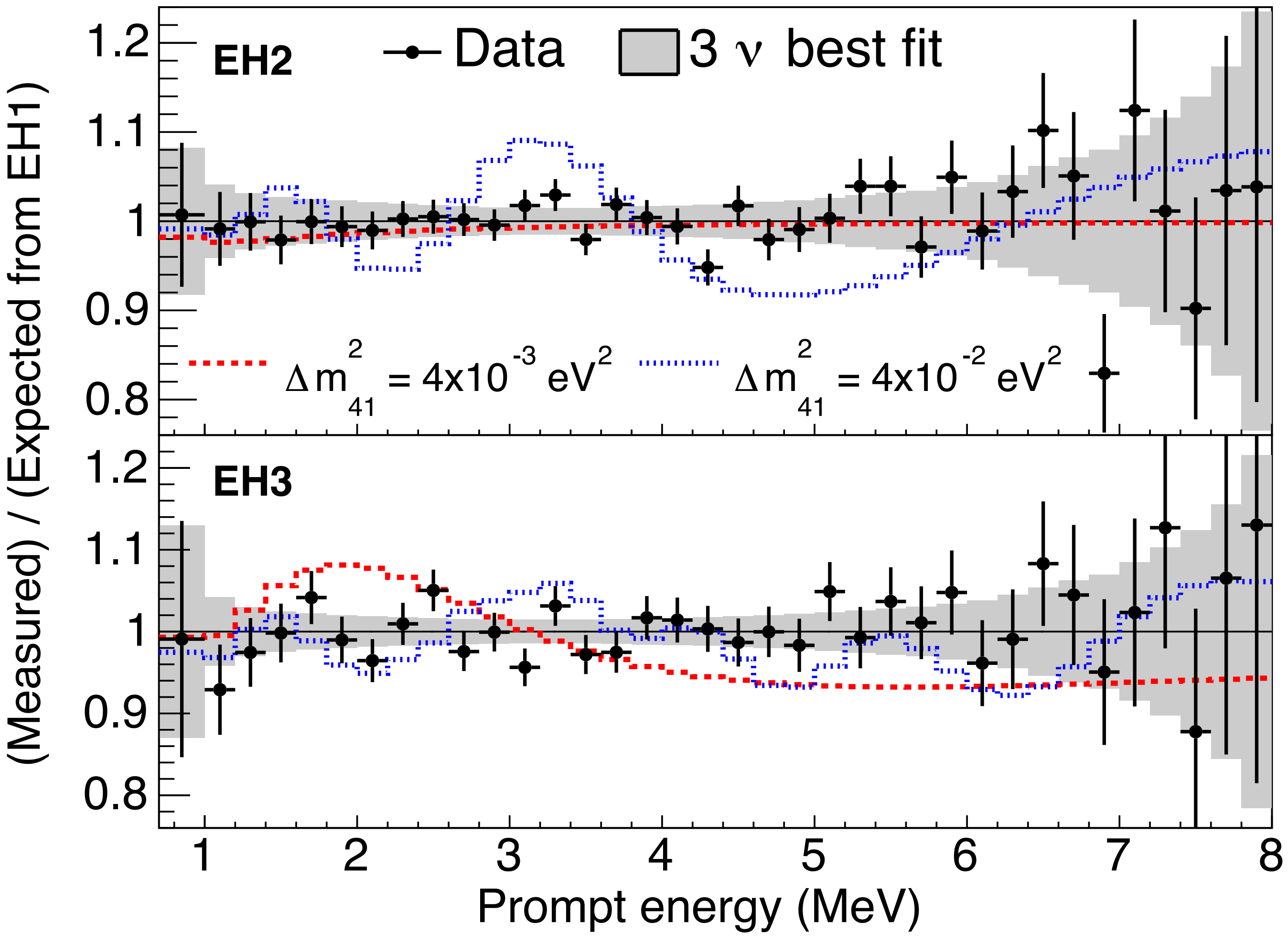
  - High sensitivity in the largely unexplored region $\underline{\Delta m^2_{41} < 0.1\ \mathrm{eV}^2}$
  - A robust relative measurement independent of reactor related uncertainties

Expected Sensitivity

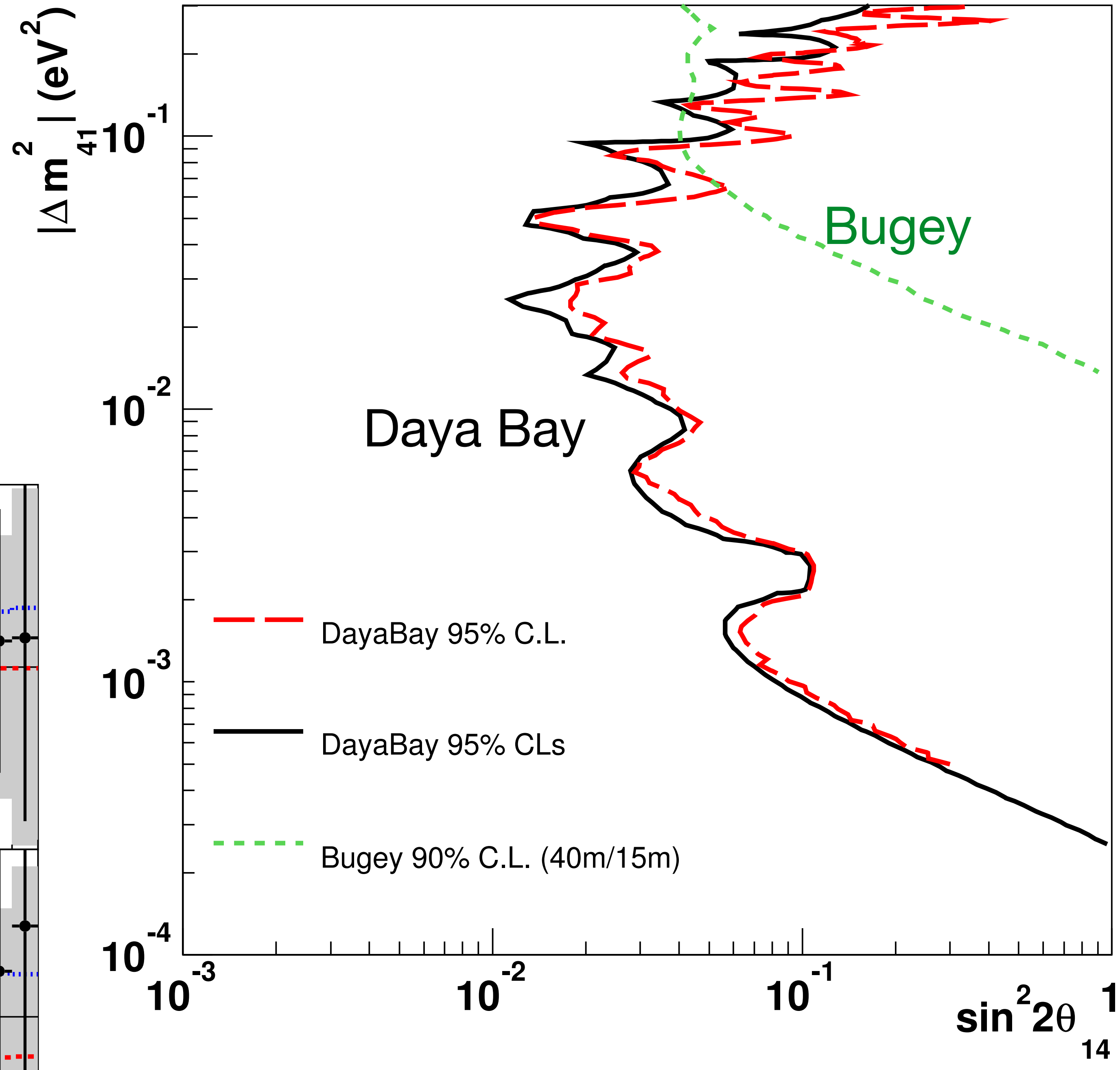


Light Sterile Neutrino Search Results

- All 217 days of 6-AD period
- Consistent with standard 3-flavor neutrino oscillation model
- Able to set stringent limits in the previously unexplored region $10^{-3}\ \mathrm{eV}^2 < \Delta m^2_{41} < 0.1\ \mathrm{eV}^2$



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



- Search for light sterile neutrinos, *PRL 113, 141802 (2014)*

Reactor Antineutrino Flux and Spectrum

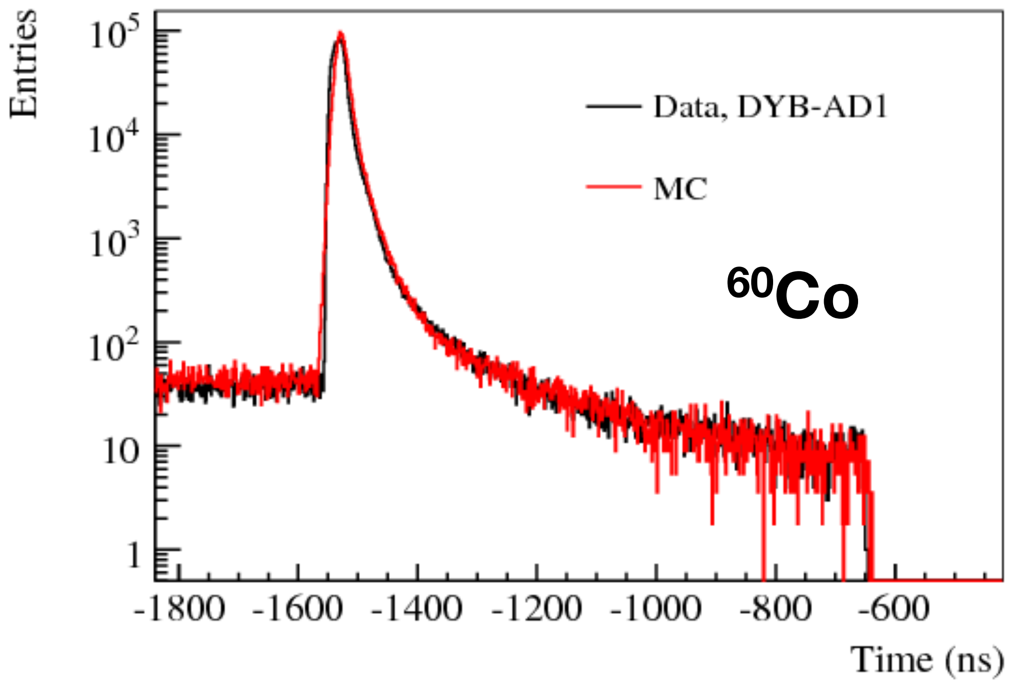
- Integrated Flux: absolute detection efficiency
  - Data /MC comparison

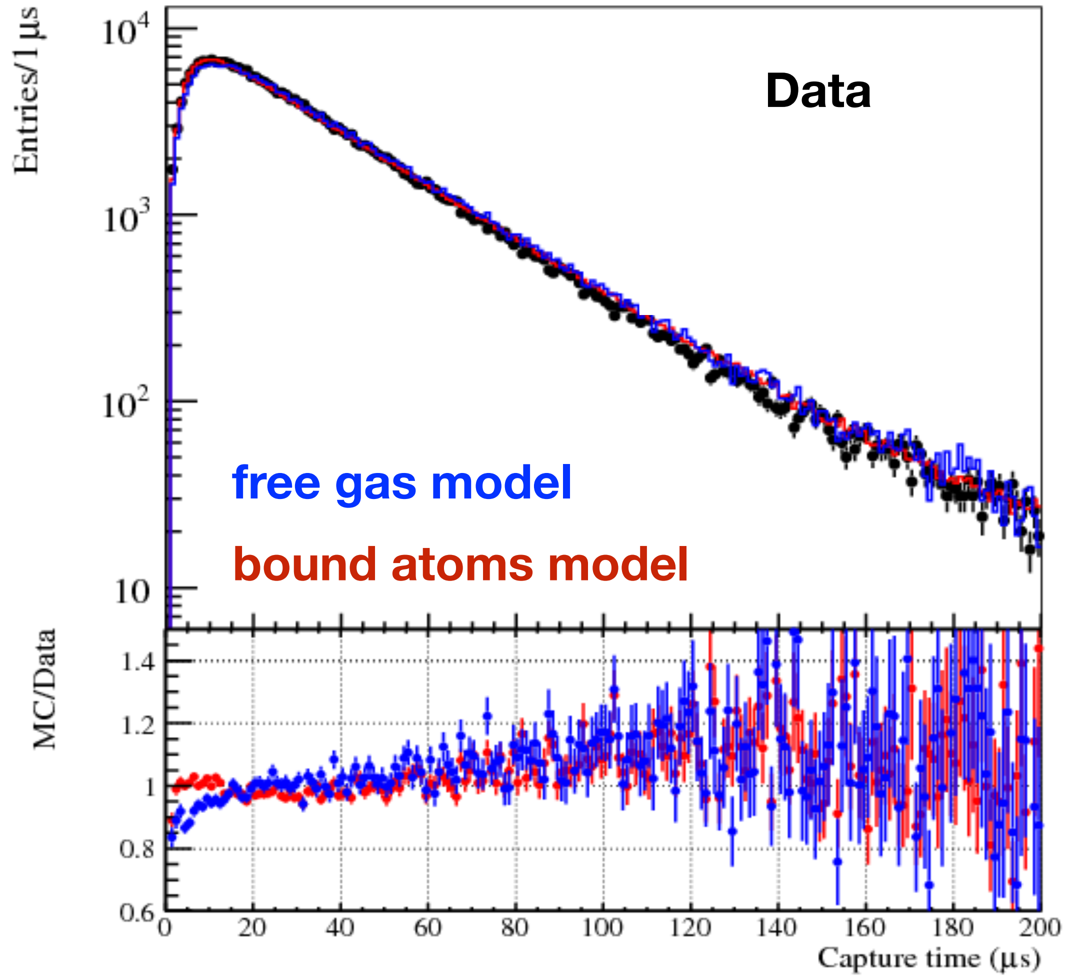
	Efficiency	Uncertainty	
		Correlated	Uncorrelated
Target Protons		0.47%	0.03%
Flasher cut	99.98%	0.01%	0.01%
Delayed Energy cut	92.7%	0.97%	0.12%
Prompt Energy cut	99.81%	0.10%	0.01%
Capture time cut	98.70%	0.12%	0.01%
Gd capture ratio	84.2%	0.95%	0.10%
Spill-in correction	104.9%	1.50%	0.02%
Combined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

- Antineutrino Energy Spectrum: absolute energy scale
  - Extensive calibration
  - Energy model building

Daya Bay Monte Carlo

- Full-detector Geant4 simulation implemented in an offline *Gaudi*-based framework known as NuWa
- Tuning and validation with data
  - Time component of LS
    - Fast (1 ns) 70%, Medium (26 ns) 25.5%, Slow (200 ns) 4.5%
  - Improved thermal neutron scattering simulation
    - free gas model v.s. bound atoms





Gd-Capture Ratio

	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%
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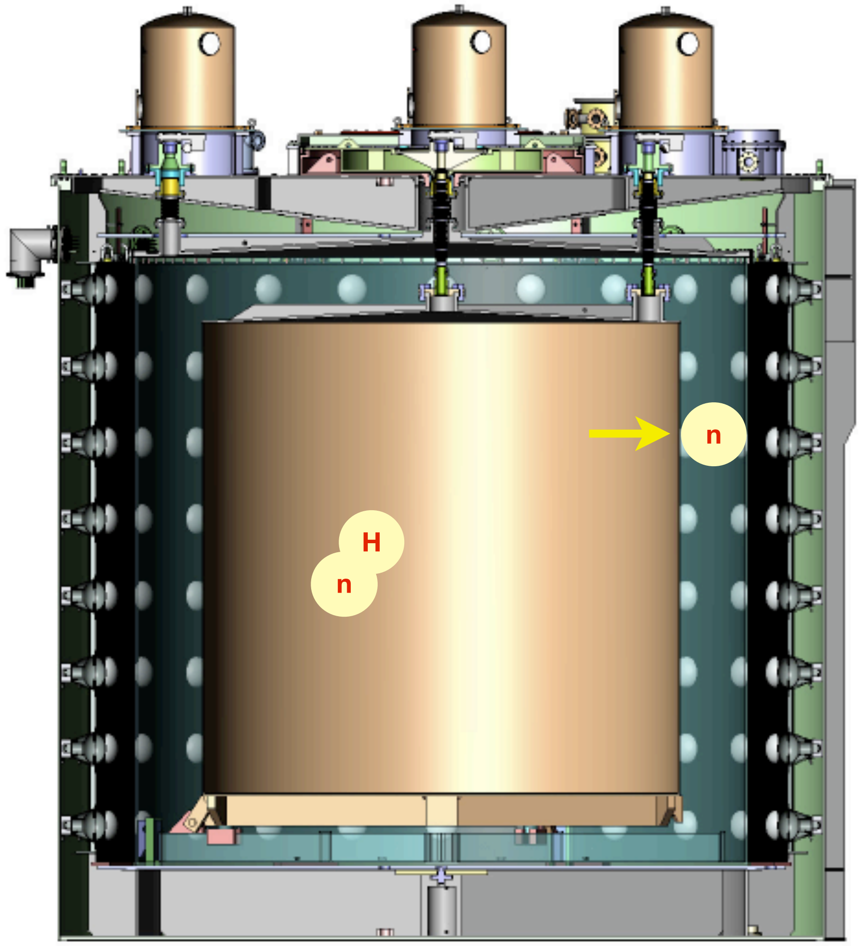
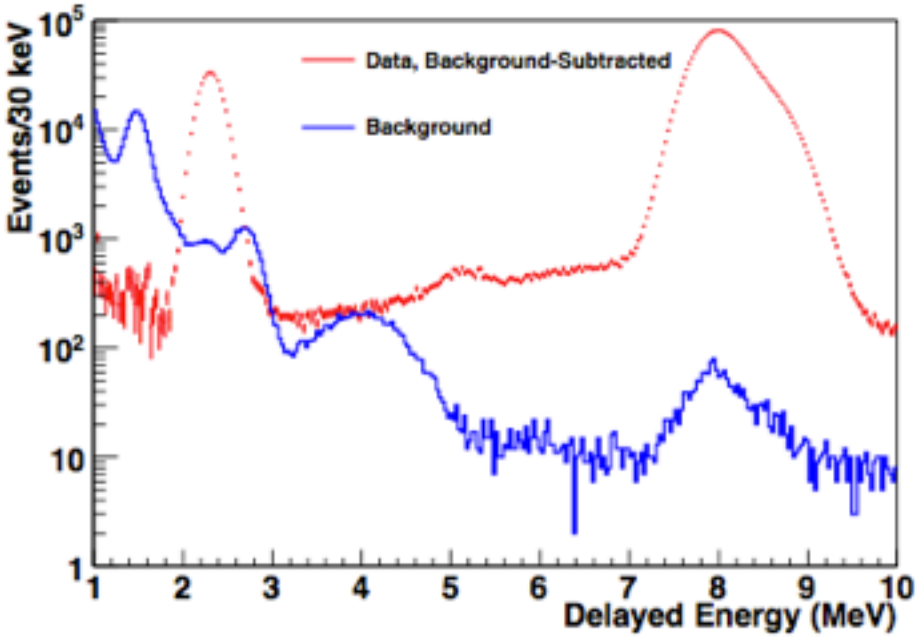
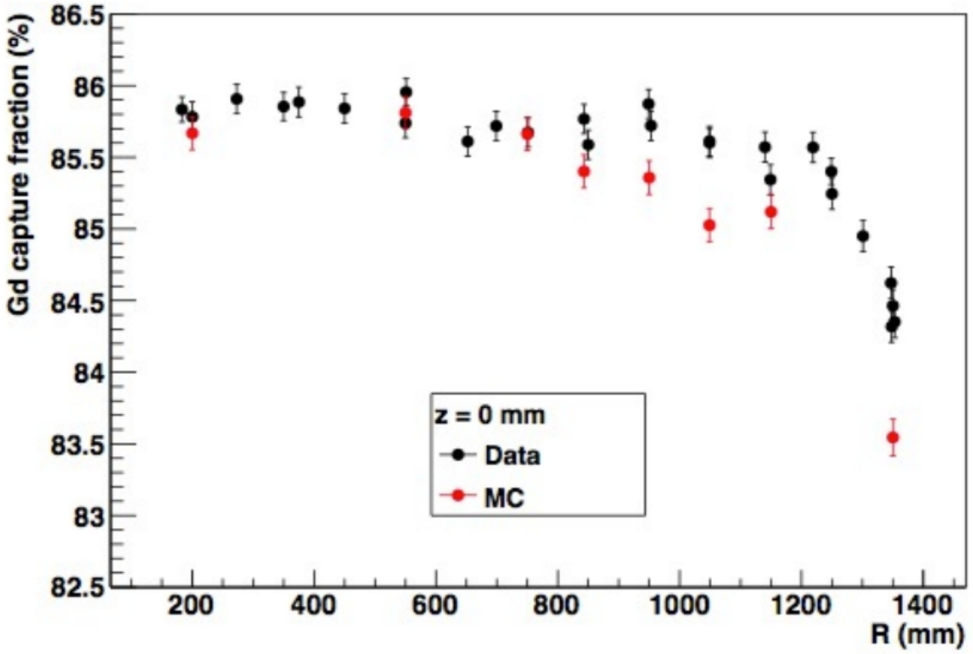


- IBD neutron can capture on other target such as Hydrogen



measured with center neutron source

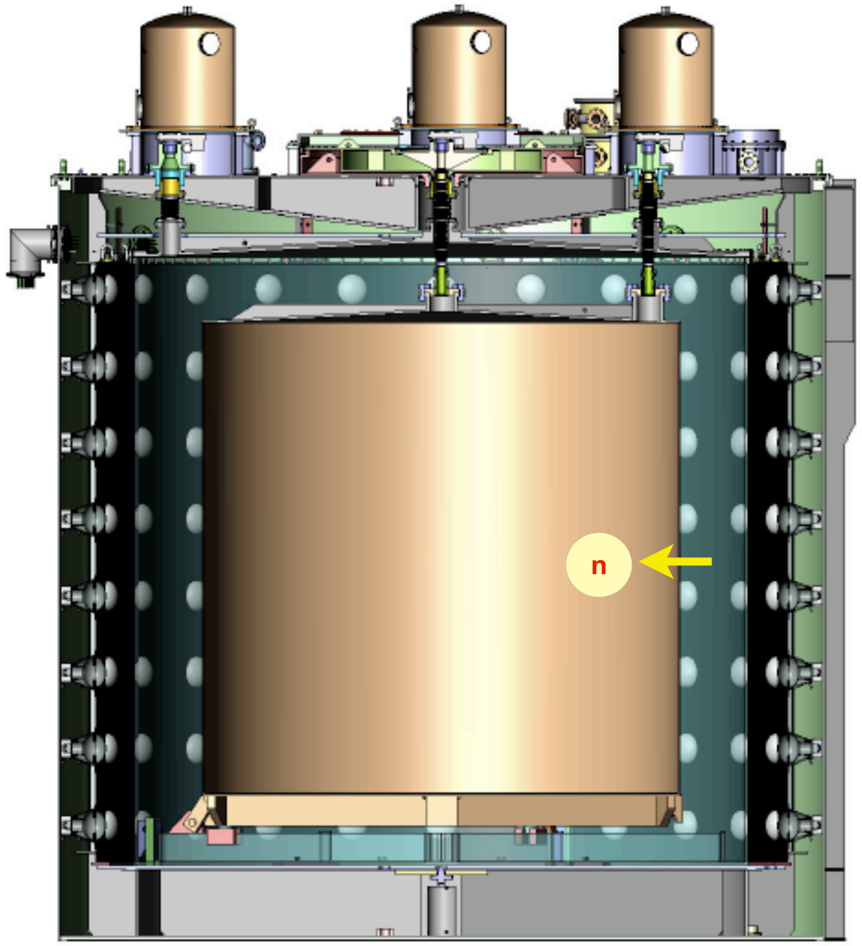
- IBD neutron can leave the GdLS region and capture somewhere else (spill-out)



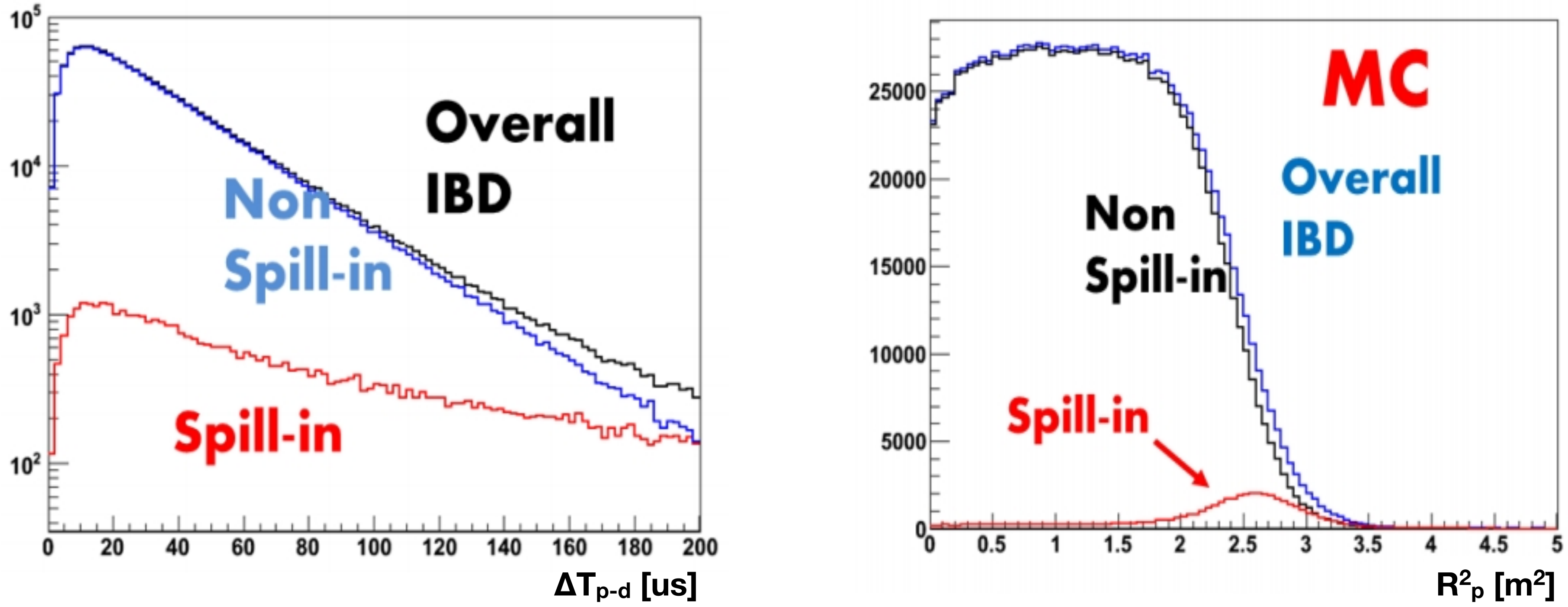
measured with MCS neutron source

Spill-in

	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%



- IBDs can happen outside of GdLS, but the neutron leaks in and capture on Gd (spill-in)



Predicted by MC, benchmarked by IBD time / vertex distribution, and off-center neutron source in LS

Delayed Energy Cut

	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%
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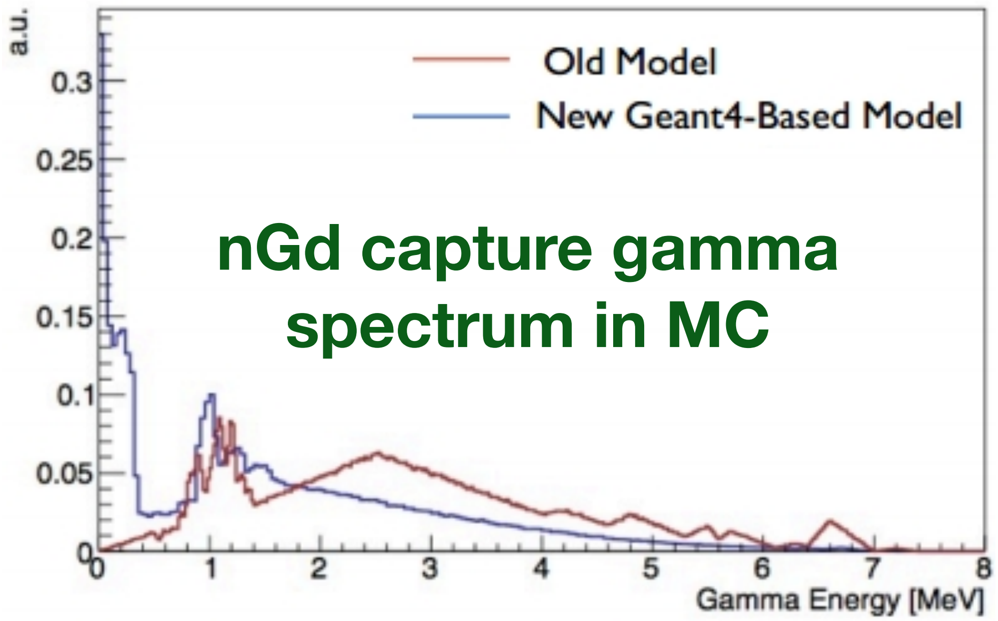
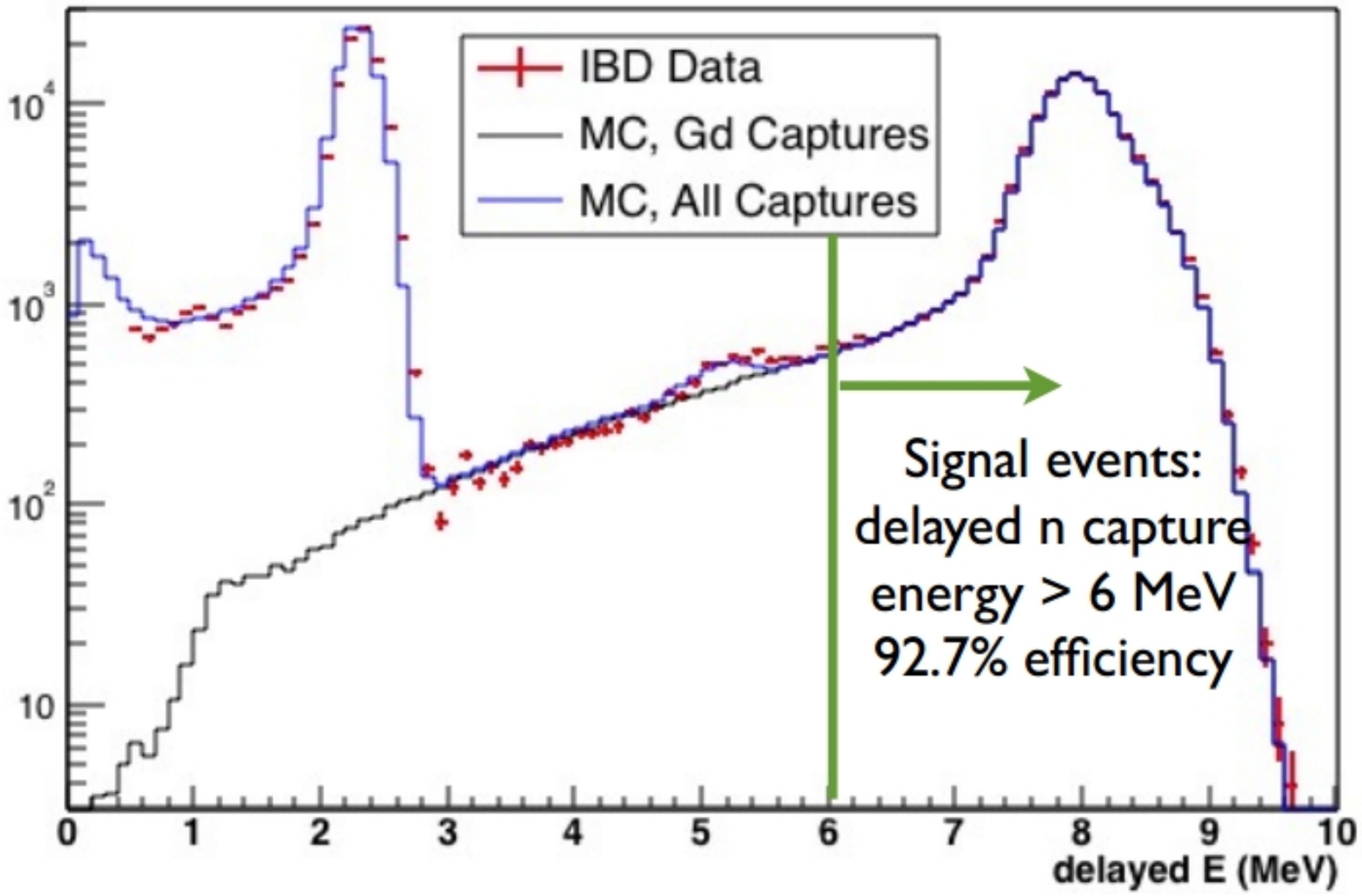


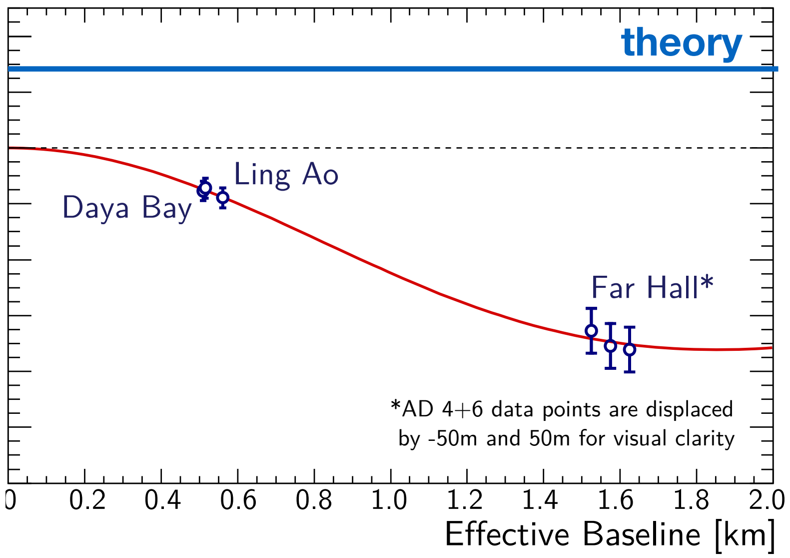
nGd capture gamma spectrum in MC

- The Cascading gammas from nGd Capture can leak out of the scintillator region and cause a long low energy tail
  - **measure the tail distribution and validate with different input nGd gamma spectrum models**



Signal events:
delayed n capture
energy > 6 MeV
92.7% efficiency

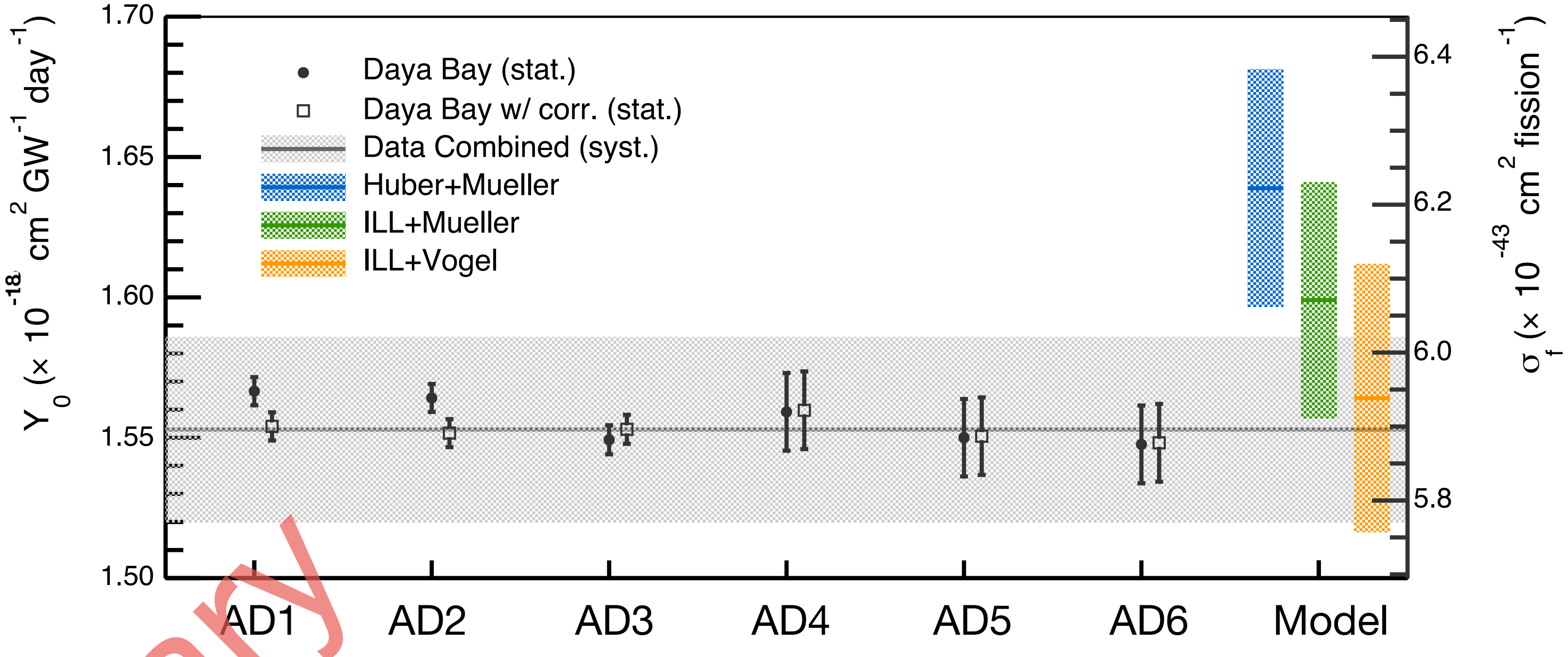
Integrated Reactor Antineutrino Flux



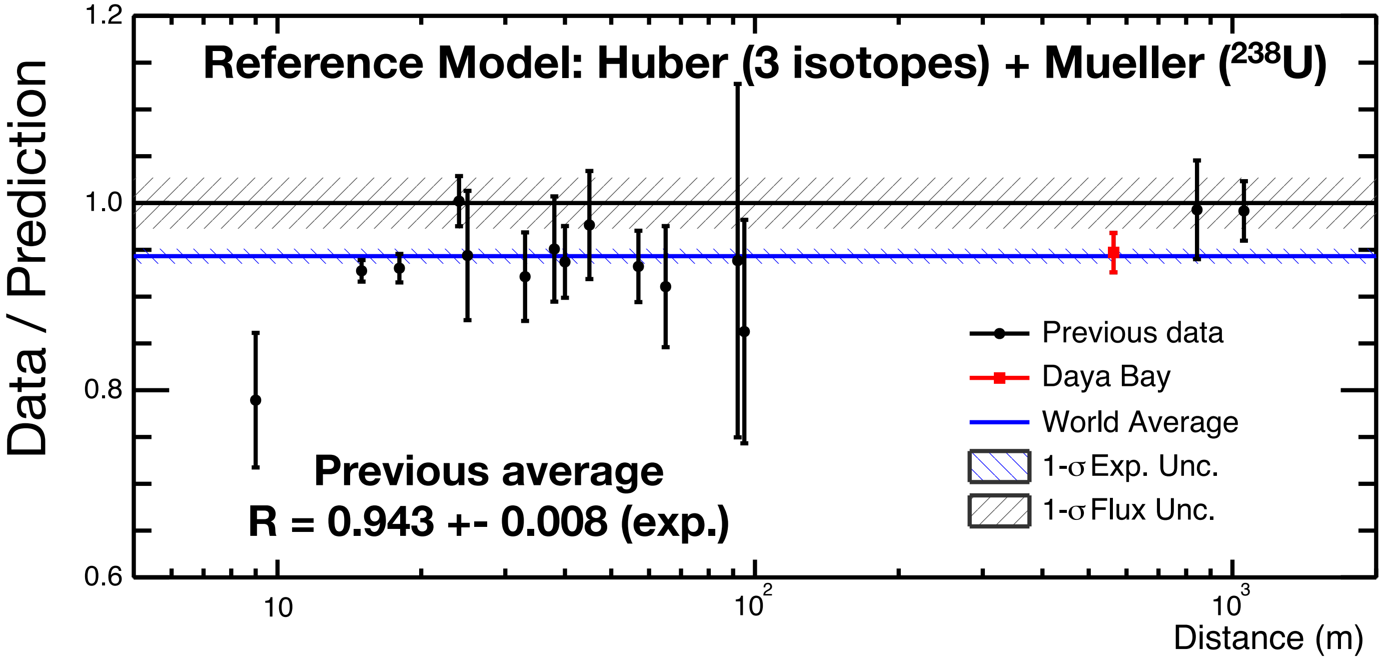
Flux Measurement Uncertainty

	Uncertainty
statistics	0.2%
θ_{13}	0.2%
reactor	0.9%
detector efficiency	2.1%
Total	2.3%

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



^{235}U : ^{238}U : ^{239}Pu : ^{241}Pu	0.586 : 0.076 : 0.288 : 0.050
Y_0 (cm^2 GW^{-1} day^{-1})	1.553×10^{-18}
σ_f (cm^2 fission^{-1})	5.934×10^{-43}
Data / Prediction (Huber+Mueller)	0.947 ± 0.022
Data / Prediction (ILL+Vogel)	0.992 ± 0.023

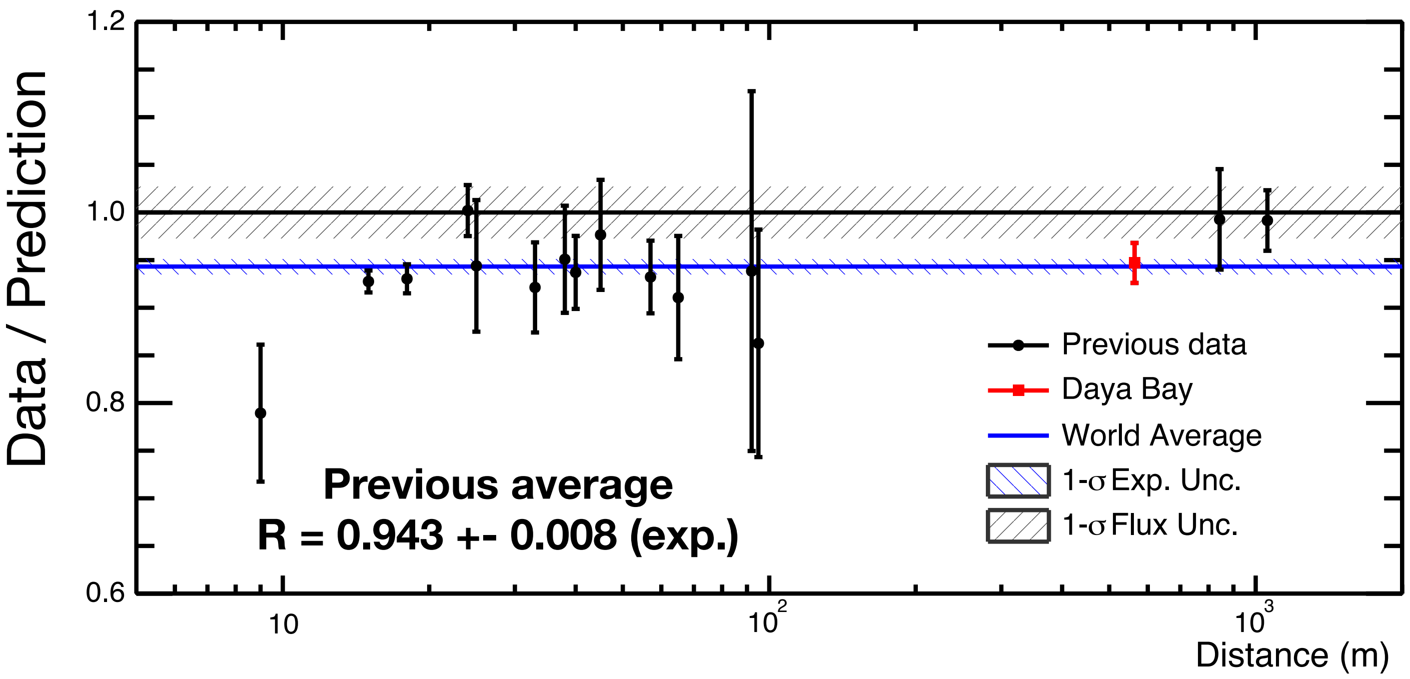


About Flux Measurement Result

- Interpretation one: Daya Bay saw 5.3% 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.

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.



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

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

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

which should be

R^{theory} R^{theory}

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

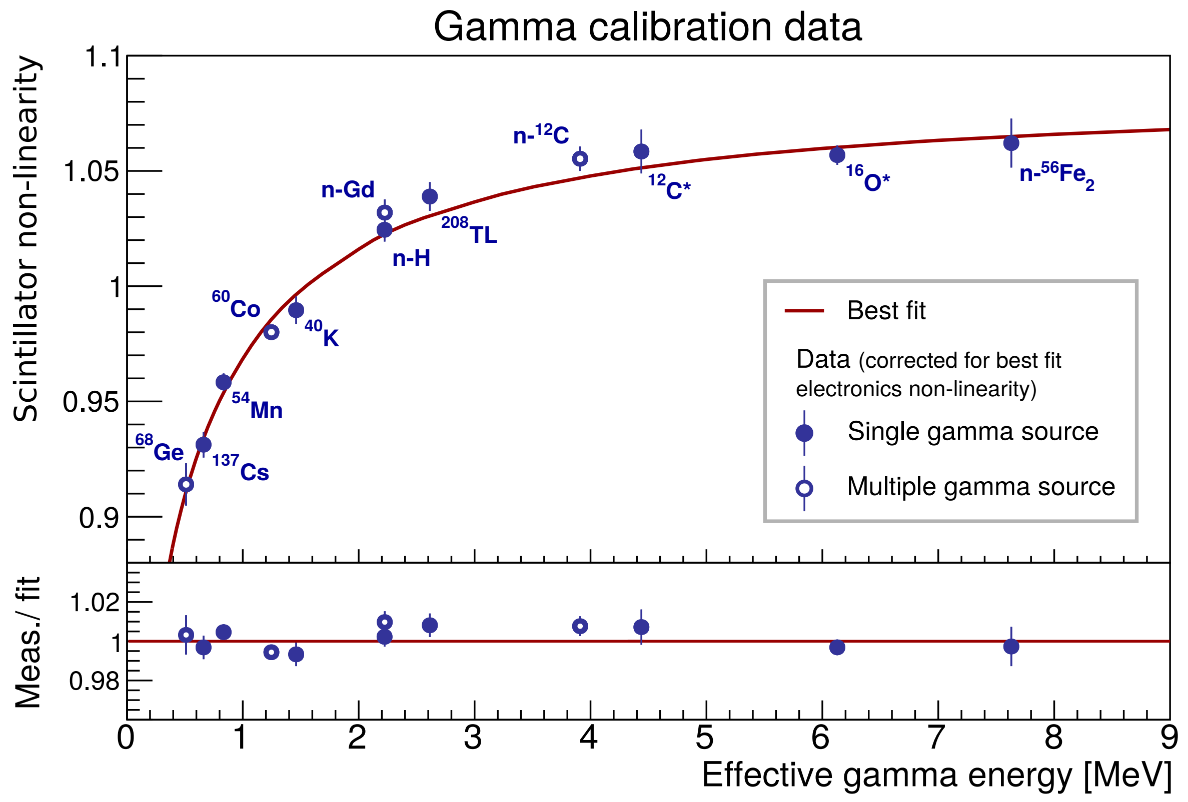
a well known statistics problem originally described in
G. D'Agostini, NIMA 346 (1994) 306

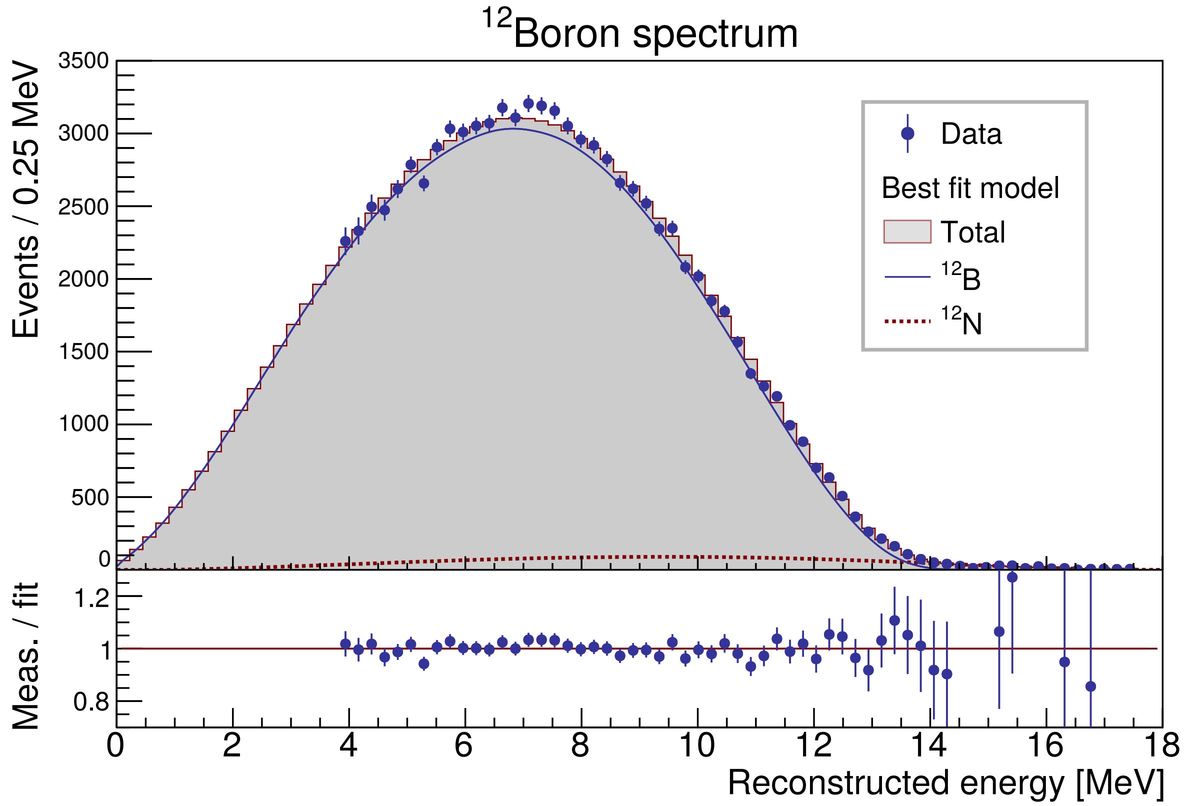
see also

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

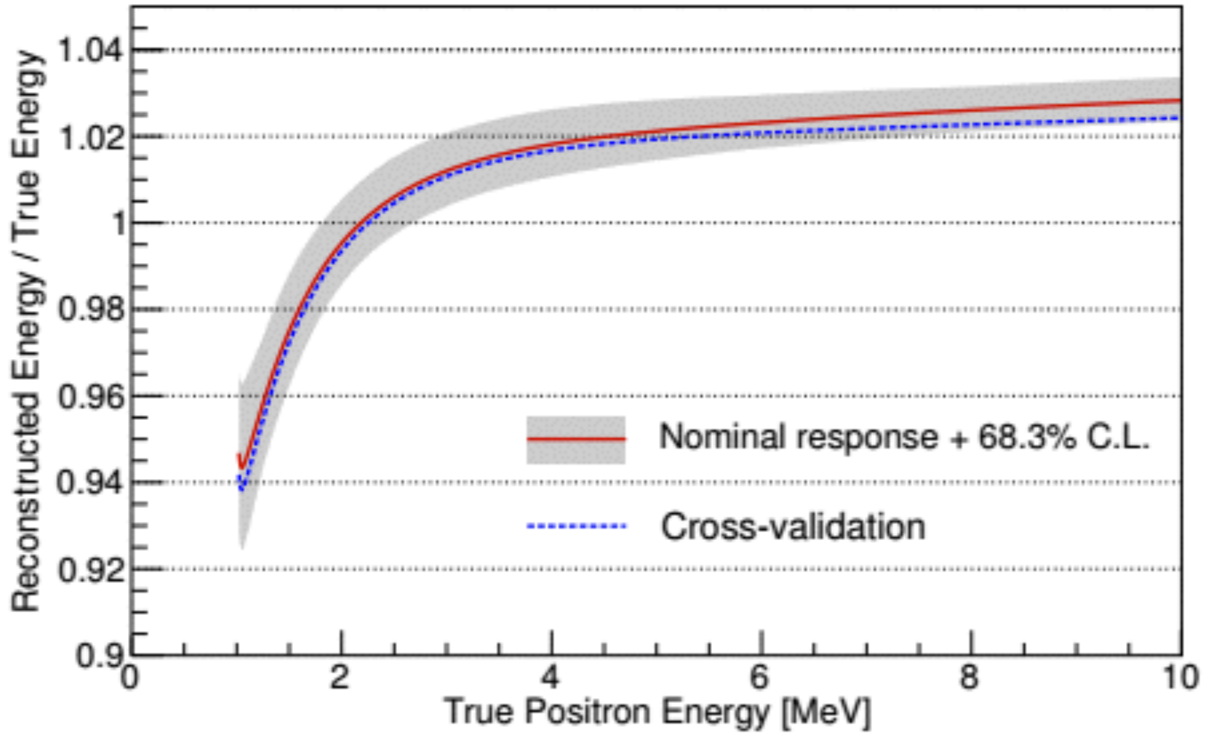
B. Roe arXiv:1506.09077

Energy Nonlinearity Calibration



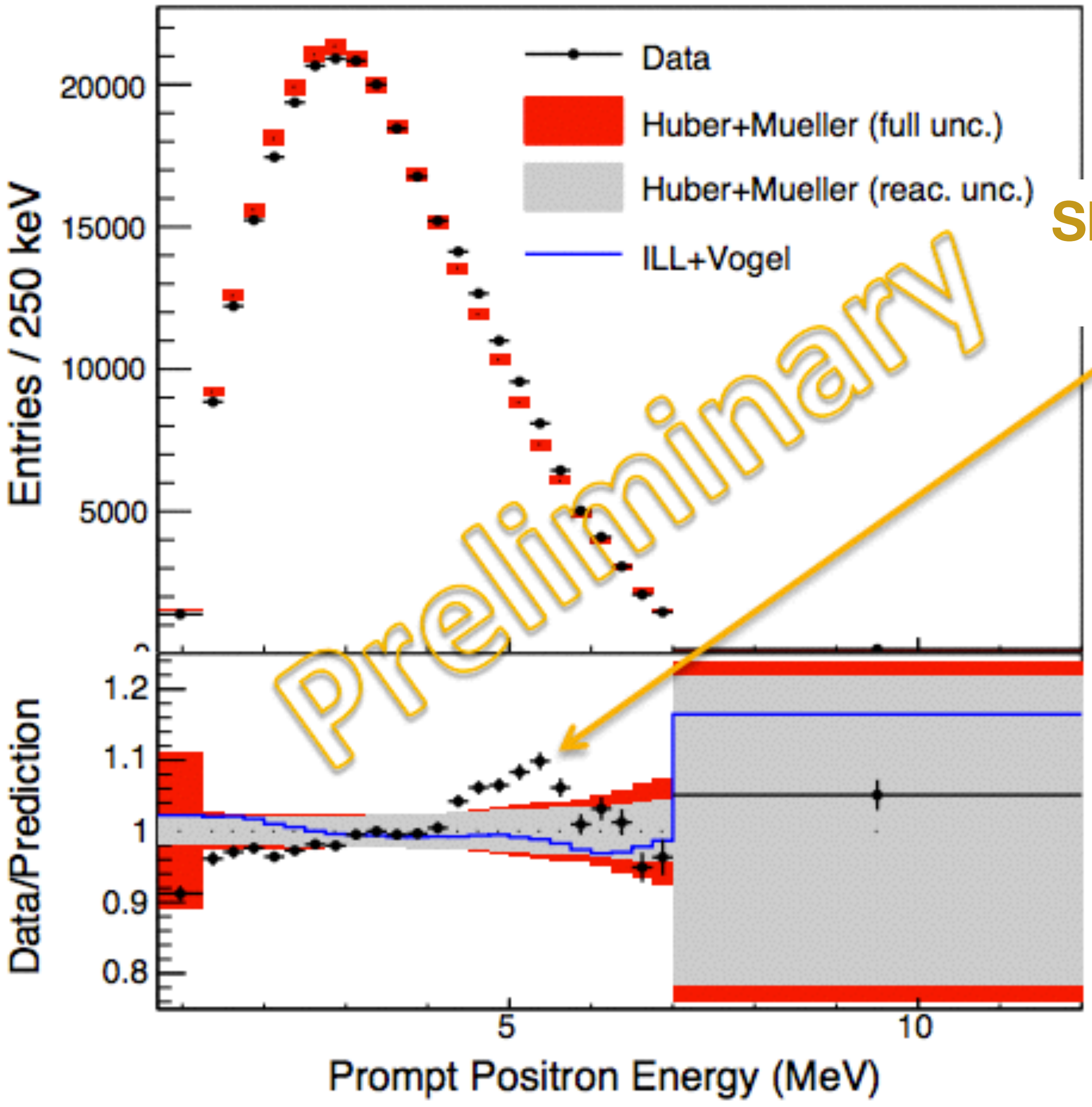


- Two major sources of non-linearity
  - **scintillator response:** modeled with Birks formula and Cherenkov contribution
  - **electronics:** modeled with MC and single channel FADC measurement
- **Nominal Model**: Combined fit with mono-energetic gamma peaks and ^{12}B beta-decay spectrum
- **Cross-validation Model**: ^{212}Bi, ^{214}Bi, ^{208}Tl beta-decay spectrum, Michel electron spectrum and standalone bench-top Compton scattering measurement.



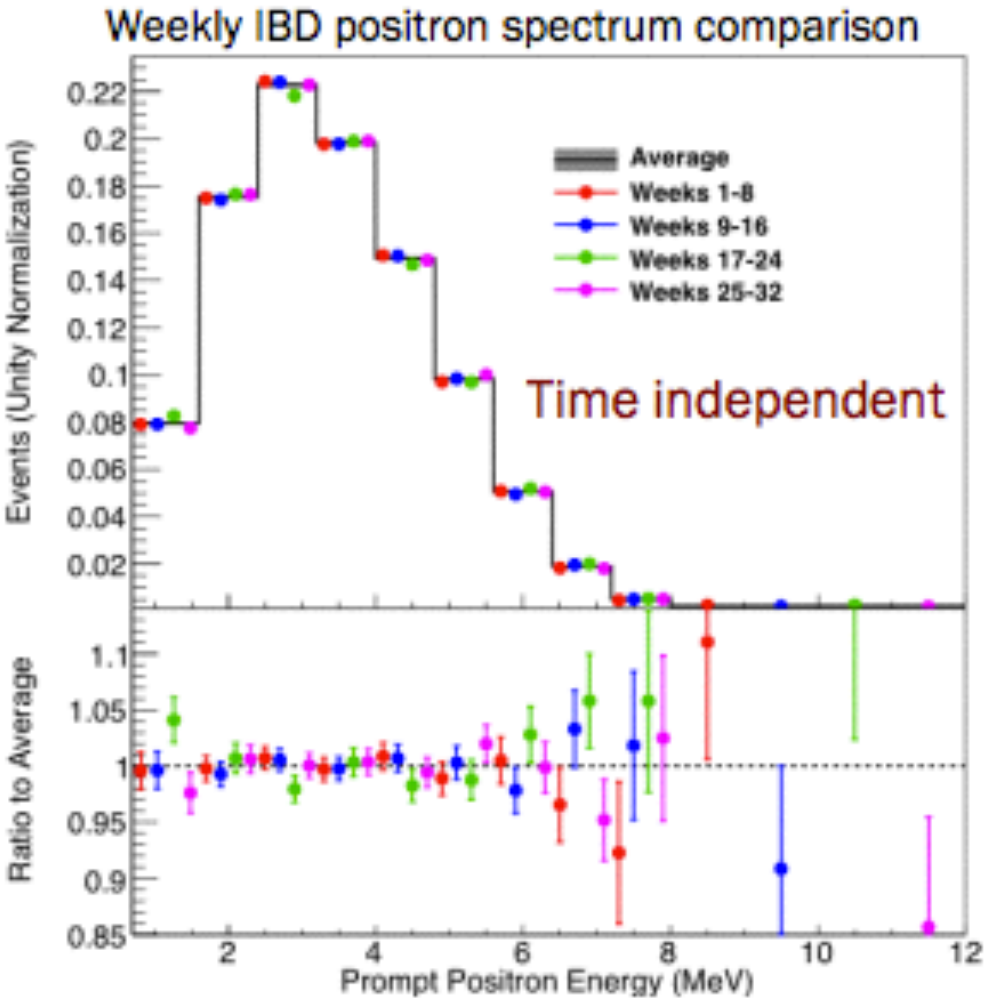
< 1% uncertainty above 2 MeV

Prompt Positron Spectrum



Shoulder?
Bump?

combining the spectrum from the three near-site detectors and compare with theoretical predictions

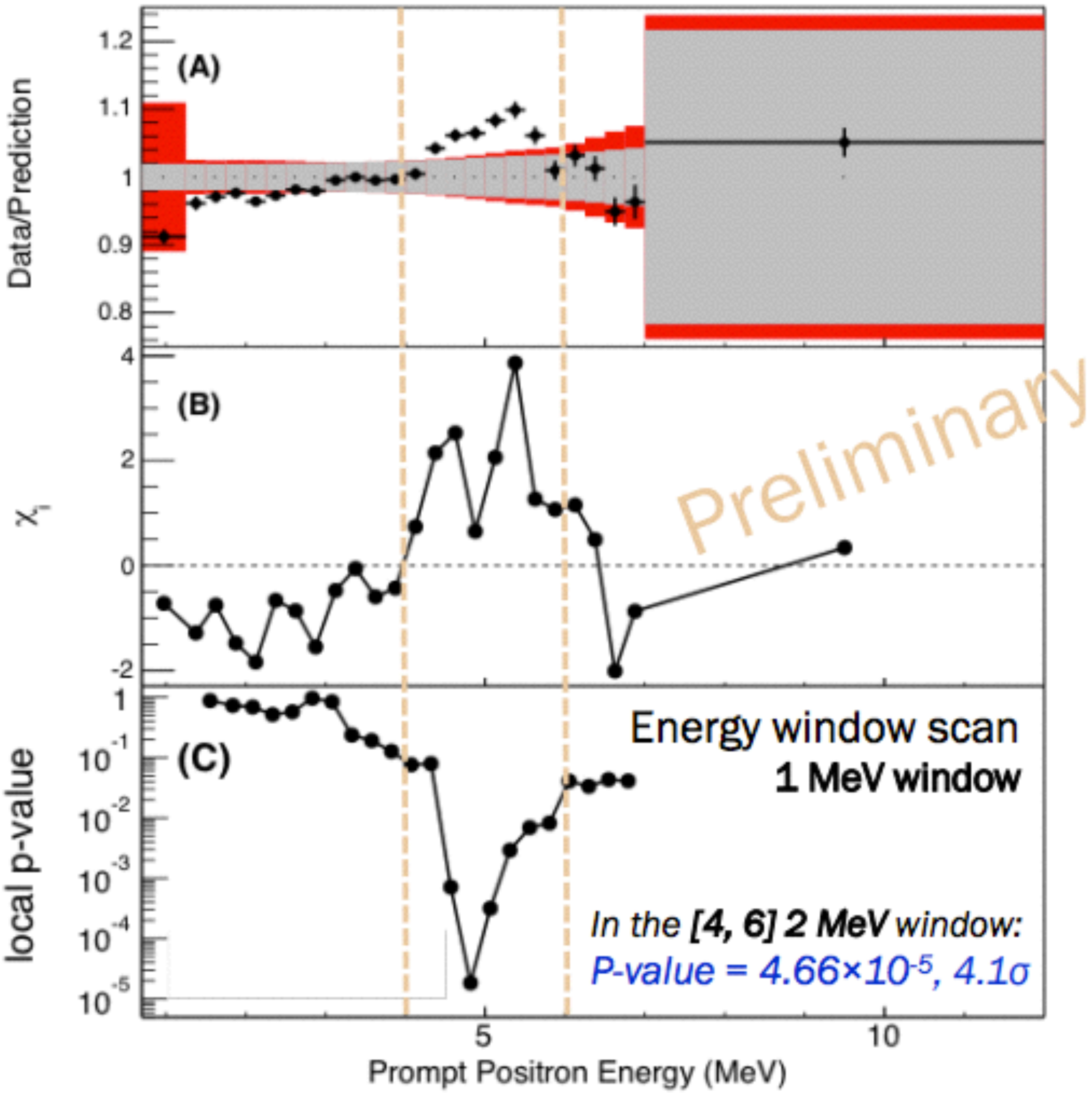


Time independent

The [4, 6] MeV "bump"

- Feature is time independent
- Rate correlated with reactor
- vertex/time distribution consistent with IBD
- Not seen in other sample such as ^{12}B beta-decay sample
- Also seen by RENO and DC

Significance of Local Deviation



In the ***[4, 6] 2 MeV*** *window:*

P-value = 4.66×10^{-5}, 4.1σ

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

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

$$\tilde{\chi}_i = \frac{N_i^{\mathrm{obs}} - N_i^{\mathrm{pred}}}{\left|N_i^{\mathrm{obs}} - N_i^{\mathrm{pred}}\right|}\sqrt{\sum_j \chi_{ij}^2},$$

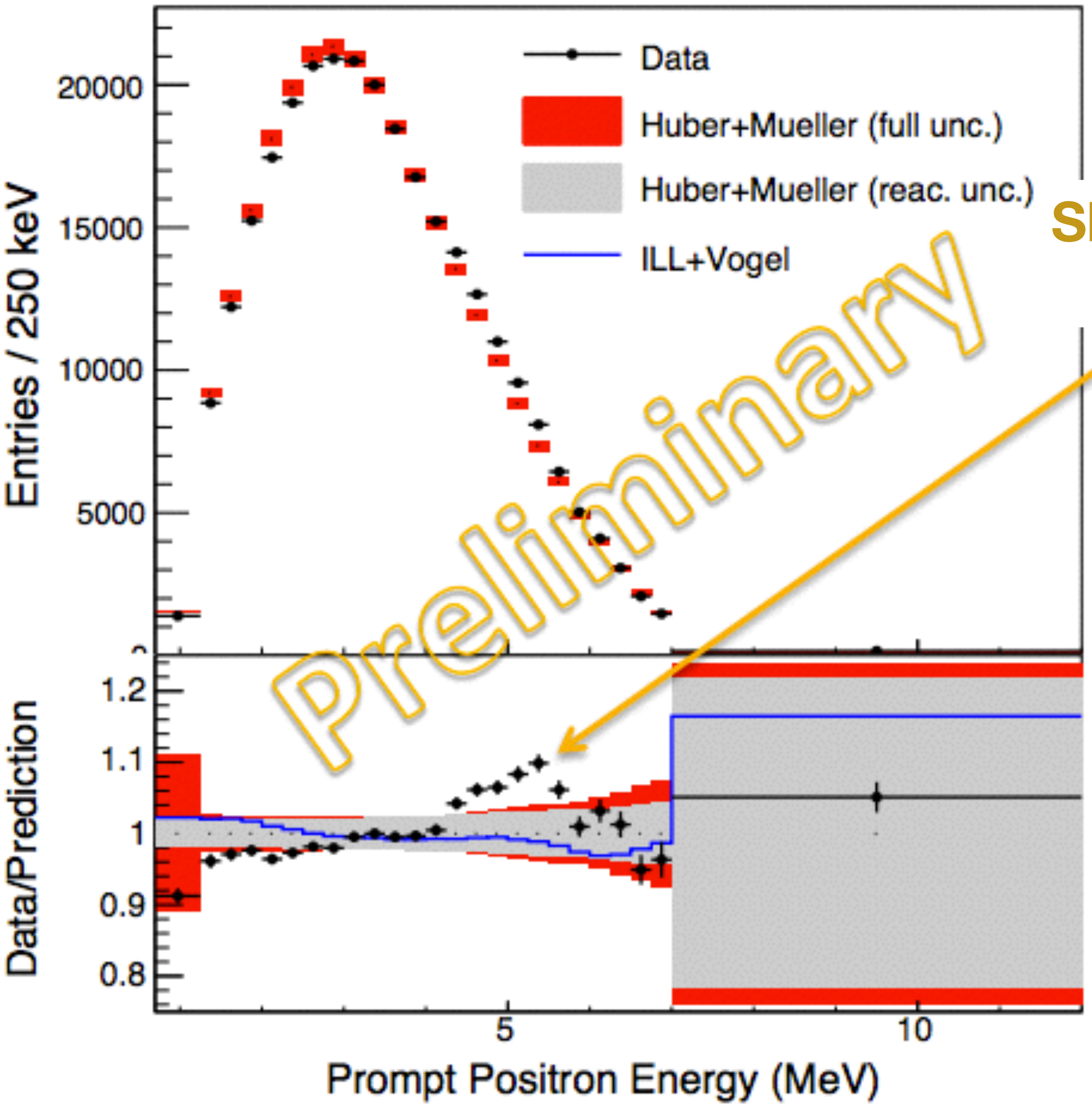
where $\chi_{ij}^2 = (N_i^{obs} - N_i^{pred})(V^{-1})_{ij}(N_j^{obs} - N_j^{pred})$

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

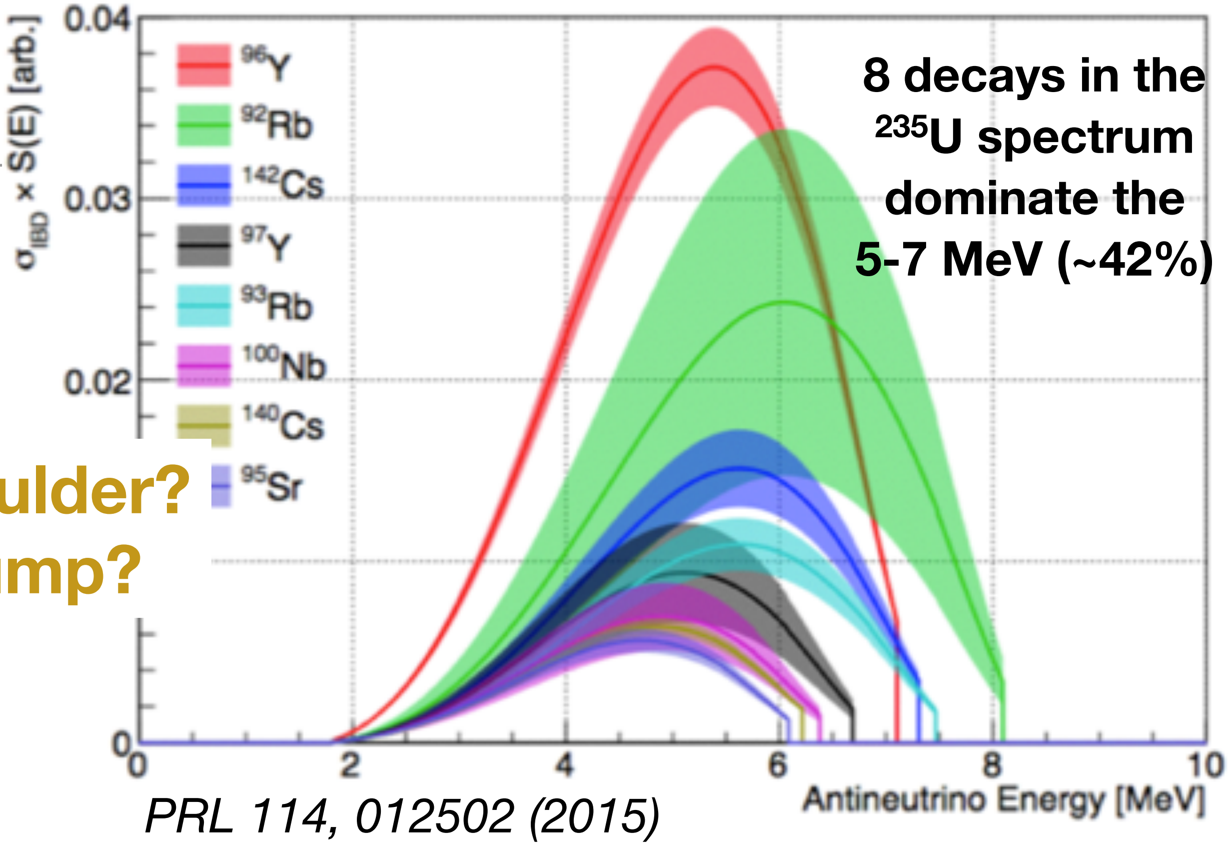
Introduce N (# of bins) nuisance parameters with no pull terms to oscillation fitter.

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

What causes the “bump”?



Shoulder? Bump?



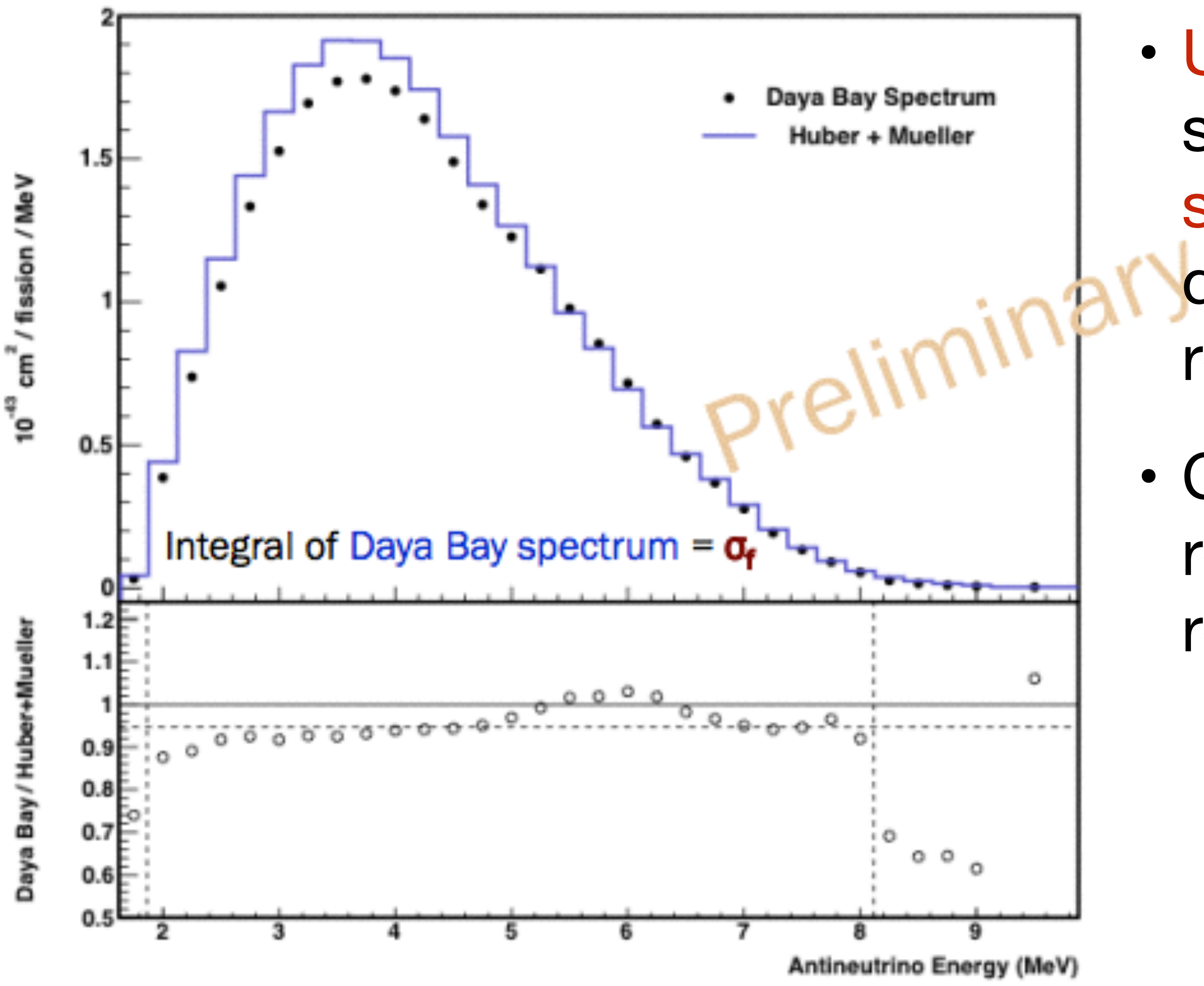
8 decays in the ^{235}U spectrum dominate the 5-7 MeV (~42%)

PRL 114, 012502 (2015)

- Discrepancy possibly due to uncertainties in predicting the neutrino spectra from the measured beta spectra
  - *D. Dwyer, T. Lanford PRL 114, 012502 (2015)*
  - *A. Hayes et.al, arXiv: 1506.00583*

combining the spectrum from the three near detectors and compare with theoretical predictions

Unfolded Reactor Antineutrino Spectrum



- Unfold the measured positron spectrum into the antineutrino spectrum by removing the detector response and energy resolution effects.
- Can be used directly by future reactor experiments as a reference spectrum
  - more precise than theoretical prediction
  - need small experiment-dependent fission fraction corrections

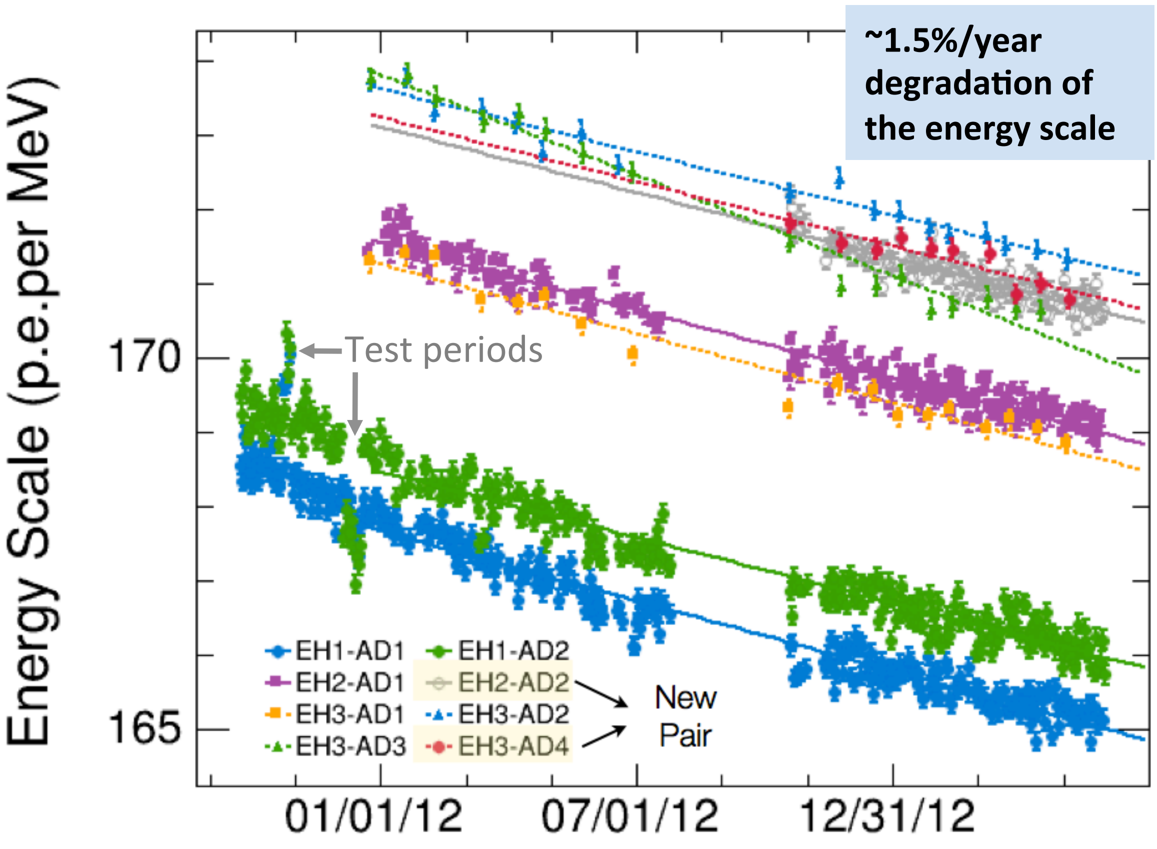
Summary

- Daya Bay updated the oscillation analysis with the full detector configuration
  - Most precise measurement of $\sin^2 2\theta_{13}$: 6%
  - Most precise measurement of $|\Delta m^2_{32}|$ in the electron neutrino disappearance channel: 4%
- Independent measurement of $\sin^2 2\theta_{13}$ from nH sample
- Set best limit to light sterile neutrinos in 10^{-3} eV^2 < Δm^2_{41} < 0.1 eV^2
- Precision measurement of reactor antineutrino flux and spectrum
  - Flux is consistent with previous short baseline reactor experiments
  - Spectrum has local deviation from prediction in [4, 6] MeV at 4σ level

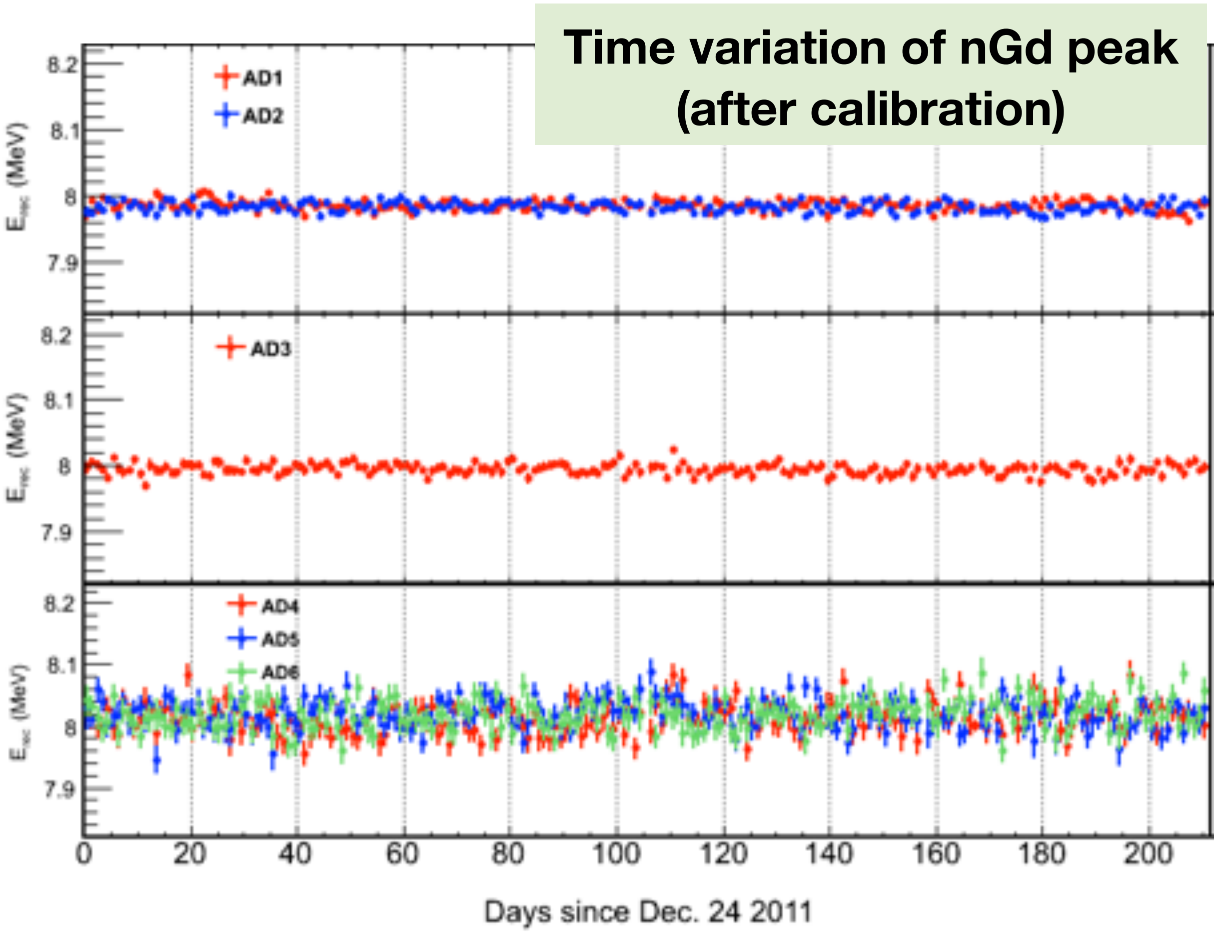
More results coming out soon!

Backup Slides

Scintillator Stability



~1.5%/year degradation of the energy scale



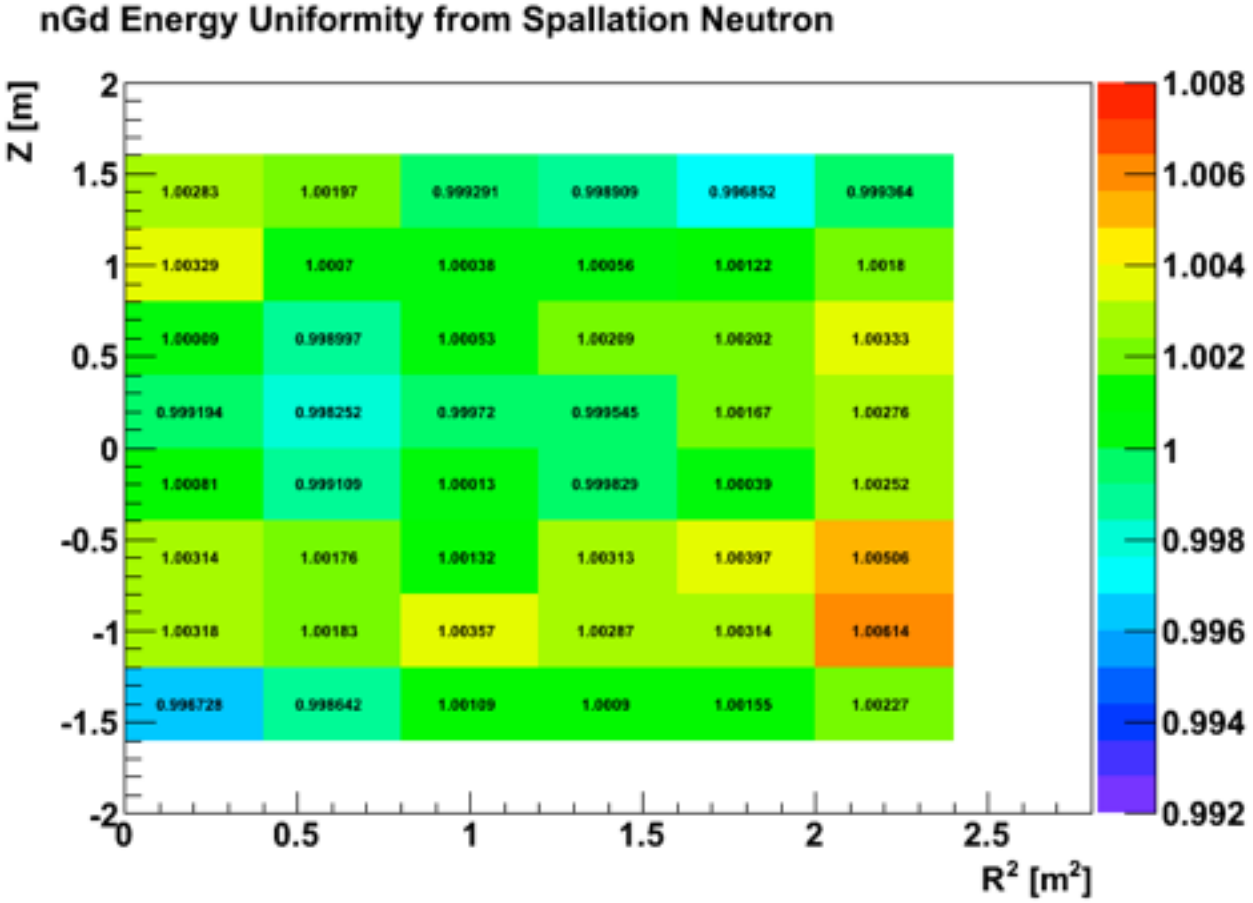
Time variation of nGd peak (after calibration)

- Small degradation of light yield (**~1.5%/year**) is seen with nGd, ^{60}Co and other event types. Its origin is still unknown (suspect from degradation of attenuation length), but do not anticipate any problems in Daya Bay’s lifetime.
- After calibration, achieved energy response that is **stable to ~0.1%** in all detectors

Energy Uniformity

With Spallation Neutron

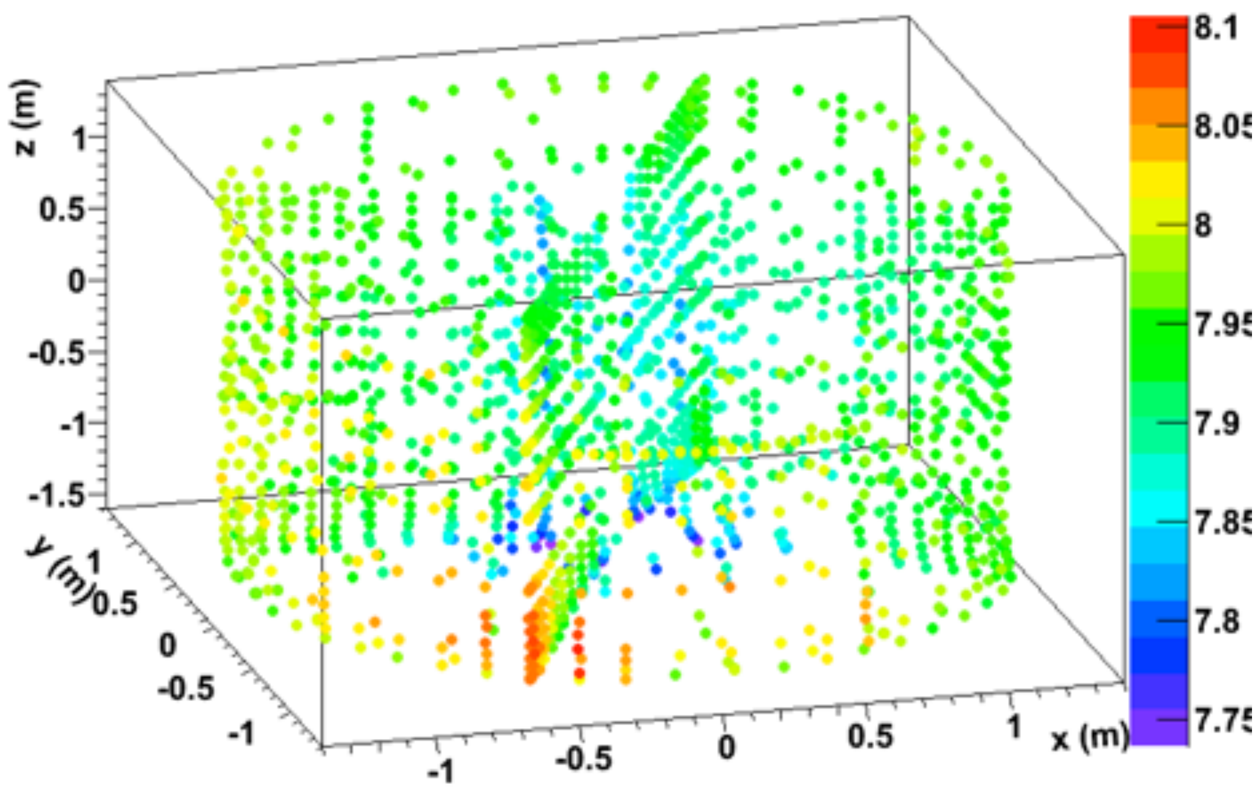
nGd Energy Uniformity from Spallation Neutron



1.00283	1.00197	0.999291	0.998909	0.996852	0.999364
1.00329	1.0007	1.00038	1.00056	1.00122	1.0018
1.00009	0.998997	1.00053	1.00209	1.00202	1.00333
0.999194	0.998252	0.99972	0.999545	1.00167	1.00276
1.00081	0.999109	1.00013	0.999829	1.00039	1.00252
1.00314	1.00176	1.00132	1.00313	1.00397	1.00506
1.00318	1.00183	1.00357	1.00287	1.00314	1.00614
0.996728	0.998642	1.00109	1.0009	1.00155	1.00227

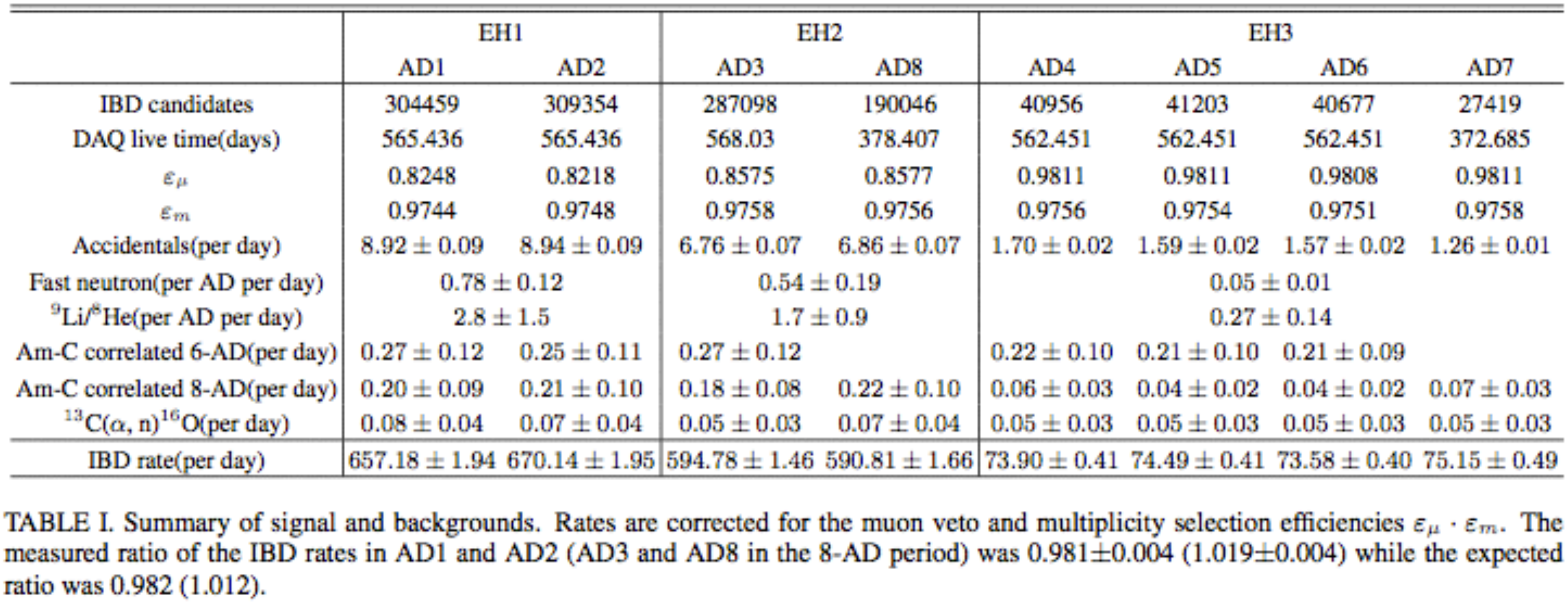
With MCS Source

nGd Energy at Various MCS PuC Source Location



Inside GdLS volume, < 0.3% variation

Data Table



	EH1		EH2		EH3			
	AD1	AD2	AD3	AD8	AD4	AD5	AD6	AD7
IBD candidates	304459	309354	287098	190046	40956	41203	40677	27419
DAQ live time(days)	565.436	565.436	568.03	378.407	562.451	562.451	562.451	372.685
ε_μ	0.8248	0.8218	0.8575	0.8577	0.9811	0.9811	0.9808	0.9811
ε_m	0.9744	0.9748	0.9758	0.9756	0.9756	0.9754	0.9751	0.9758
Accidentals(per day)	8.92 ± 0.09	8.94 ± 0.09	6.76 ± 0.07	6.86 ± 0.07	1.70 ± 0.02	1.59 ± 0.02	1.57 ± 0.02	1.26 ± 0.01
Fast neutron(per AD per day)	0.78 ± 0.12		0.54 ± 0.19		0.05 ± 0.01			
^{9}Li/^{8}He(per AD per day)	2.8 ± 1.5		1.7 ± 0.9		0.27 ± 0.14			
Am-C correlated 6-AD(per day)	0.27 ± 0.12	0.25 ± 0.11	0.27 ± 0.12		0.22 ± 0.10	0.21 ± 0.10	0.21 ± 0.09	
Am-C correlated 8-AD(per 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 ± 0.03
^{13}C(α, n)^{16}O(per 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(per day)	657.18 ± 1.94	670.14 ± 1.95	594.78 ± 1.46	590.81 ± 1.66	73.90 ± 0.41	74.49 ± 0.41	73.58 ± 0.40	75.15 ± 0.49

TABLE I. Summary of signal and backgrounds. Rates are corrected for the muon veto and multiplicity selection efficiencies $\varepsilon_\mu \cdot \varepsilon_m$. The measured ratio of the IBD rates in AD1 and AD2 (AD3 and AD8 in the 8-AD period) was 0.981±0.004 (1.019±0.004) while the expected ratio was 0.982 (1.012).