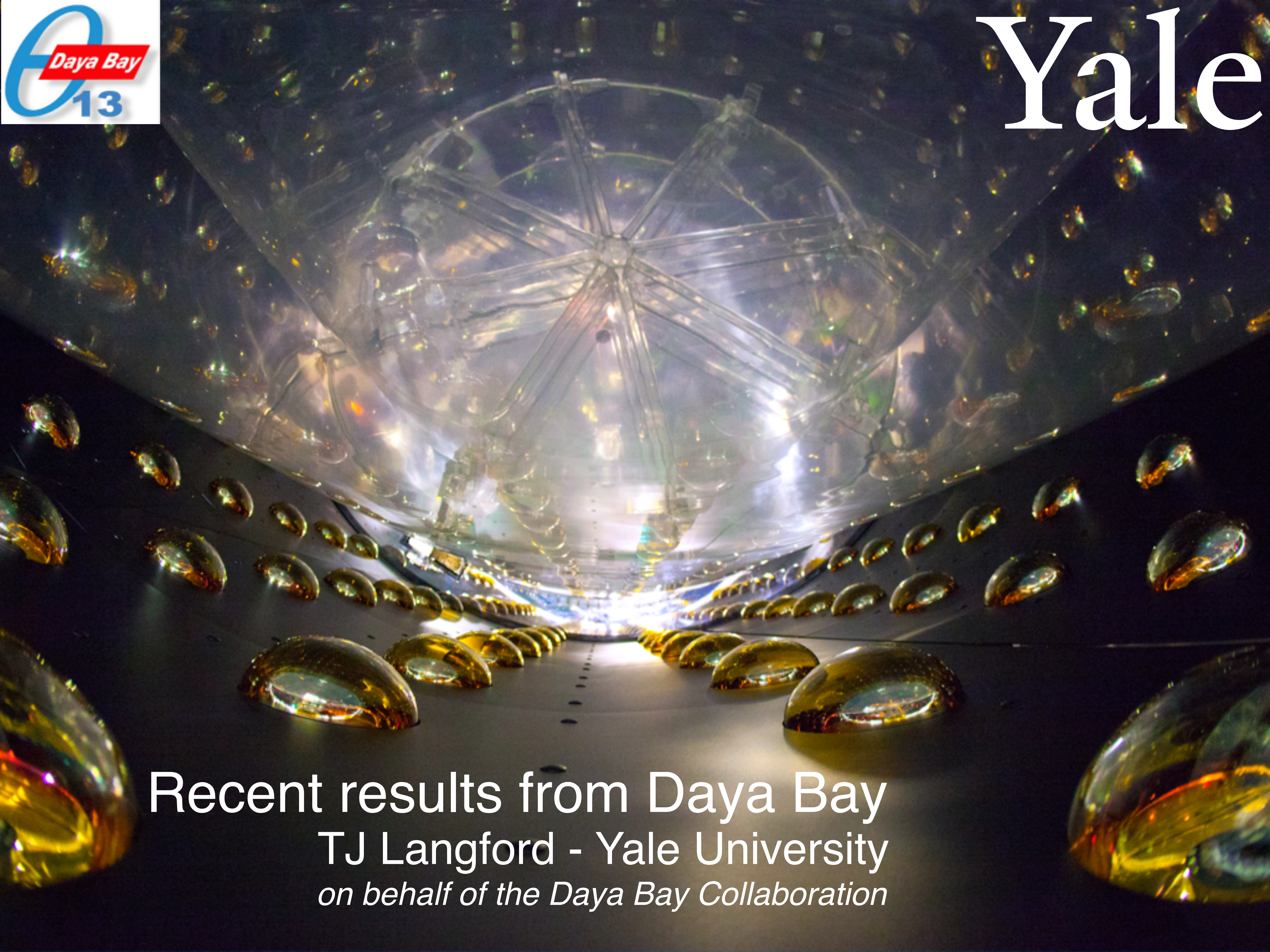


Yale

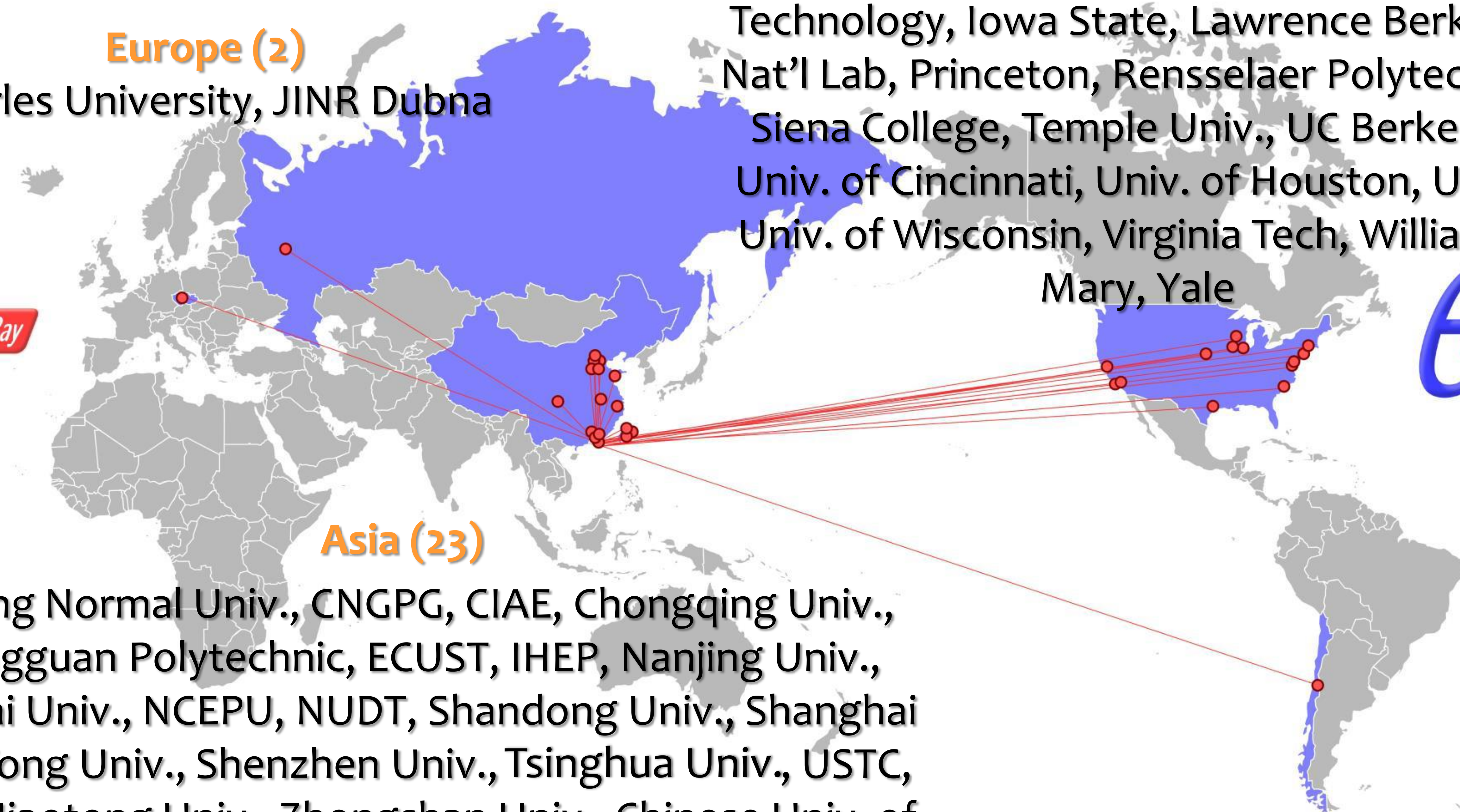
# Recent results from Daya Bay


TJ Langford - Yale University

*on behalf of the Daya Bay Collaboration*

# Daya Bay Collaboration

256 collaborators from 42 institutions:



**North America (16)**

Brookhaven Nat'l Lab, Illinois Institute of Technology, Iowa State, Lawrence Berkeley Nat'l Lab, Princeton, Rensselaer Polytechnic, Siena College, Temple Univ., UC Berkeley, Univ. of Cincinnati, Univ. of Houston, UIUC, Univ. of Wisconsin, Virginia Tech, William & Mary, Yale

**Europe (2)**

Charles University, JINR Dubna

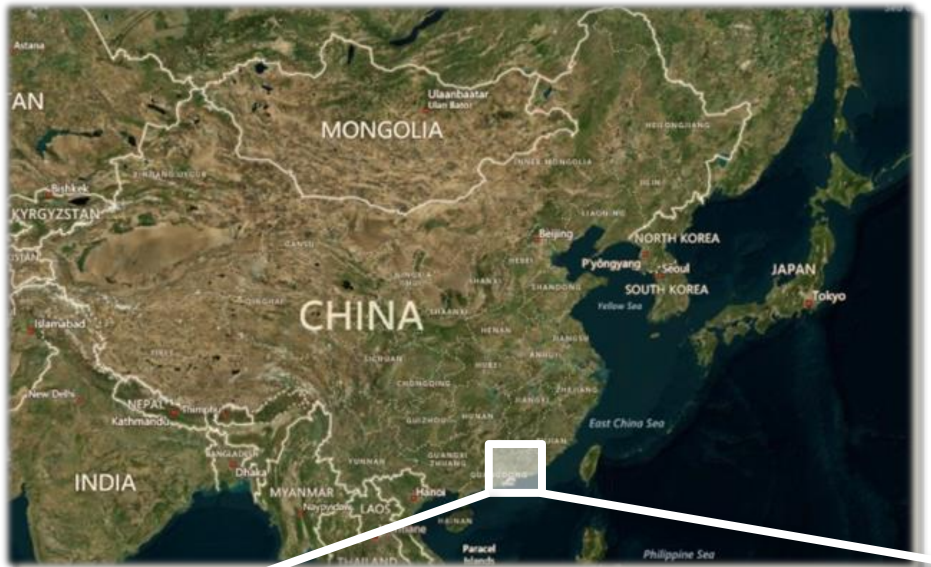
**Asia (23)**

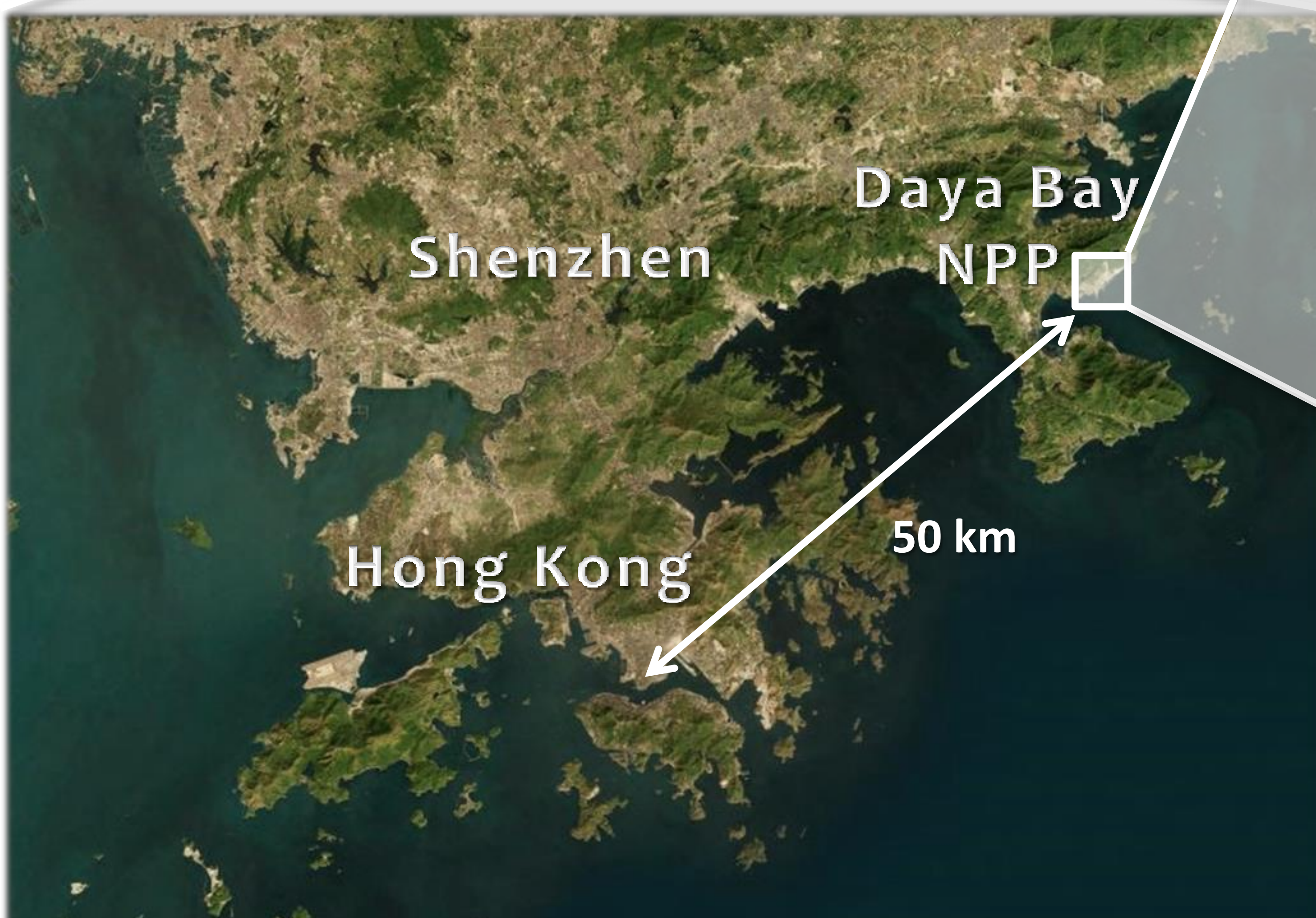
Beijing Normal Univ., CNGPG, CIAE, Chongqing Univ., Dongguan Polytechnic, ECUST, IHEP, Nanjing Univ., Nankai Univ., NCEPU, NUDT, Shandong Univ., Shanghai Jiao Tong Univ., Shenzhen Univ., Tsinghua Univ., USTC, Xi'an Jiaotong Univ., Zhongshan Univ., Chinese Univ. of Hong Kong, Univ. of Hong Kong, National Chiao Tung Univ., National Taiwan Univ., National United Univ.

**South America (1)**

Catholic Univ. of Chile

# Where is Daya Bay?




Daya Bay Nuclear Power Plant is located in Shenzhen, southern China.


It's about 50 km to the Victoria Harbour of Hong Kong.

# Neutrino Oscillations

*flavor states*

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = U \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

*mass states*

*production* *propagate*

| |
|---|
| Parameters: one CP phase, two mass splittings, and three mixing angles |

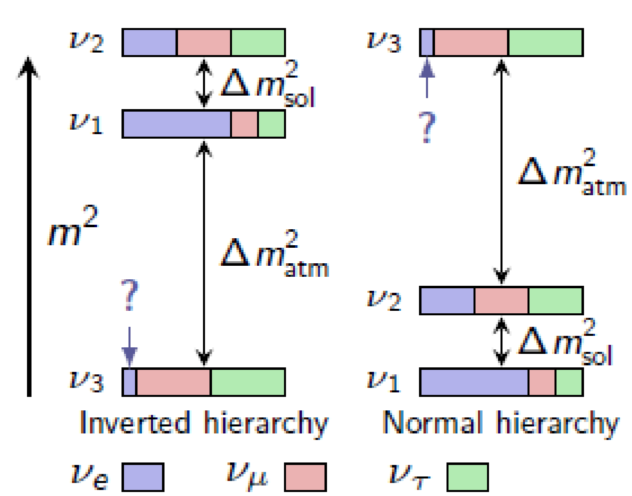
$$U = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}$$

**short baseline** **long baseline**

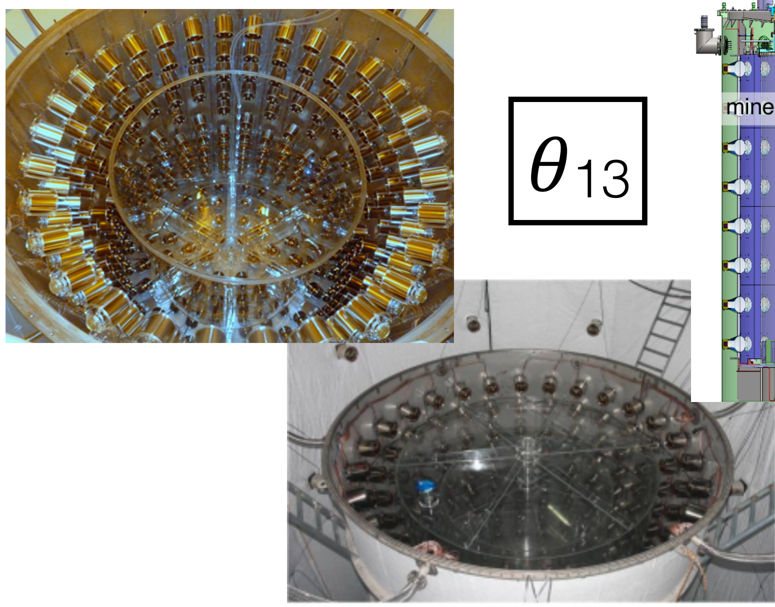
$$P_{\bar{\nu}_e\to\bar{\nu}_e} = 1 - \sin^2 2\theta_{13}\sin^2(\Delta m^2_{ee}\frac{L}{4E}) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2(\Delta m^2_{21}\frac{L}{4E})$$

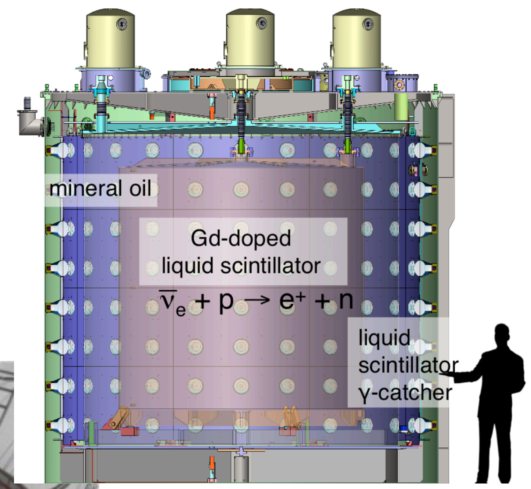
$$\sin^2(\Delta m^2_{ee}\frac{L}{4E}) \equiv \cos^2\theta_{12}\sin^2(\Delta m^2_{31}\frac{L}{4E}) + \sin^2\theta_{12}\sin^2(\Delta m^2_{32}\frac{L}{4E})$$

| |
|---|
| Remaining unknowns: mass hierarchy and CP Phase |

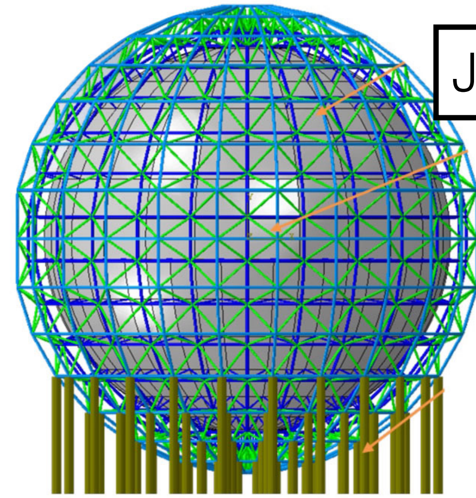


# Experiments at different Baselines

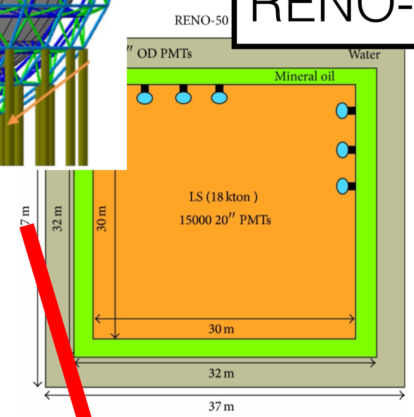




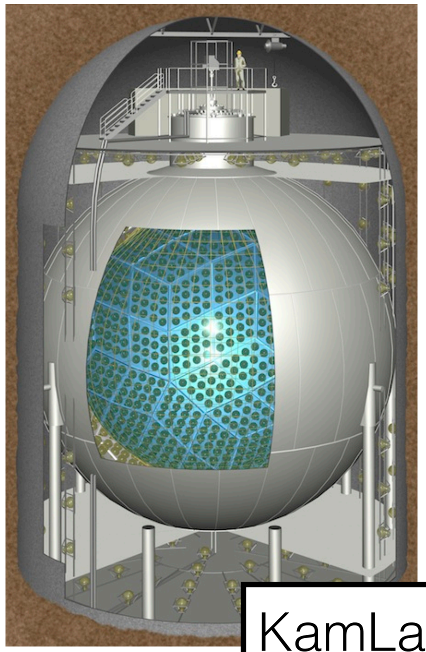

$\theta_{13}$



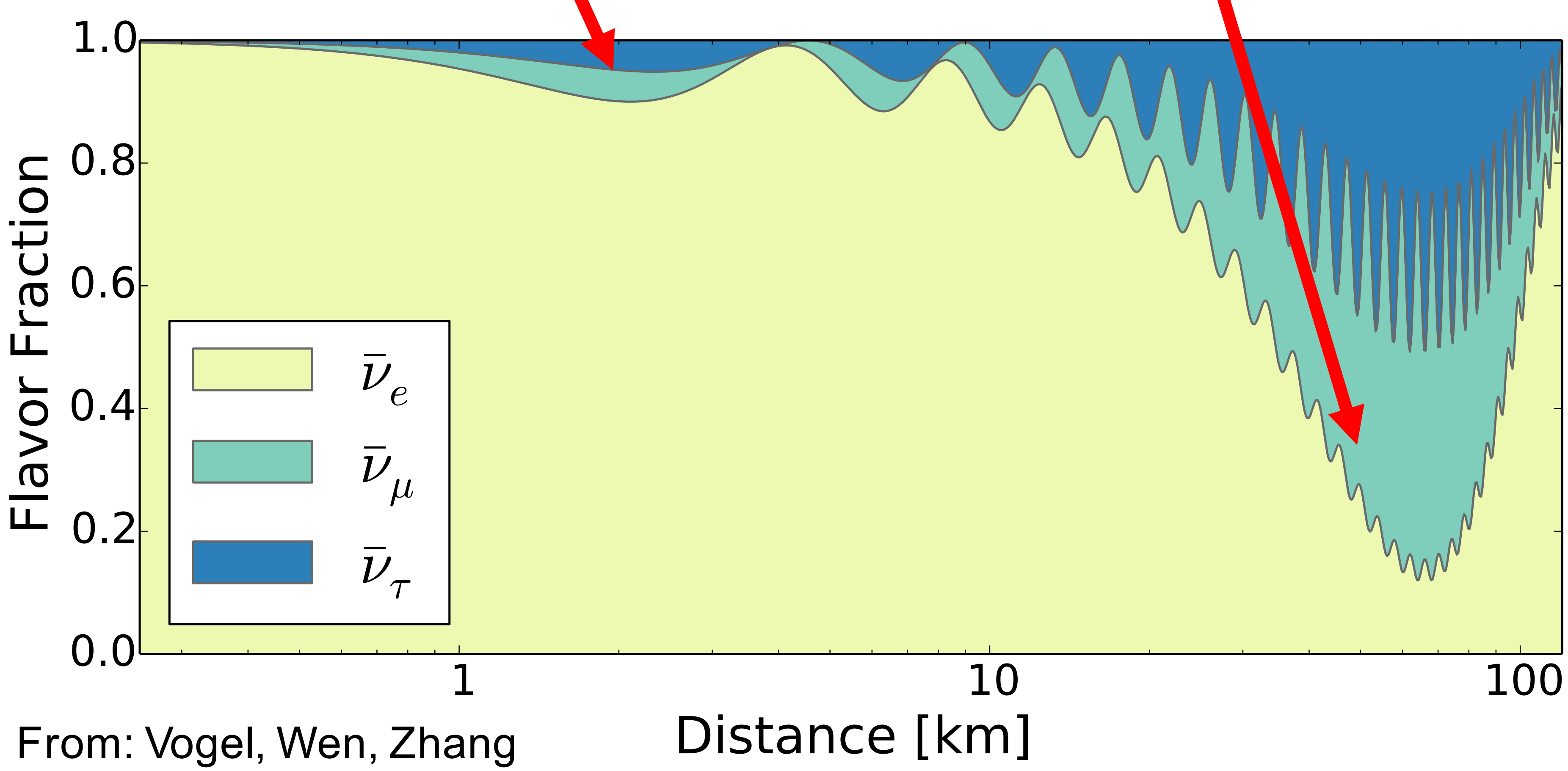
JUNO




RENO-50



KamLand




From: Vogel, Wen, Zhang

# Detecting Reactor Neutrinos

## Inverse Beta Decay

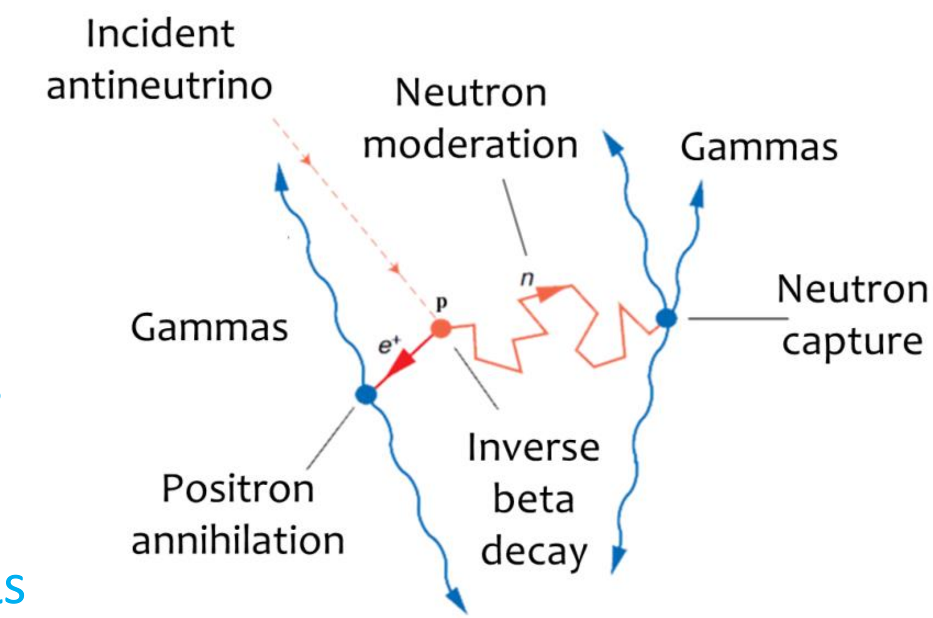
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

**Prompt signal** $e^+ + e^- \rightarrow \gamma s$

$$n + p \rightarrow D + \gamma$$ 2.2 MeV 200 µs

**Delayed signal**

$$n + Gd \rightarrow Gd^* \rightarrow Gd + \gamma s$$ 8/8.5 MeV 30 µs

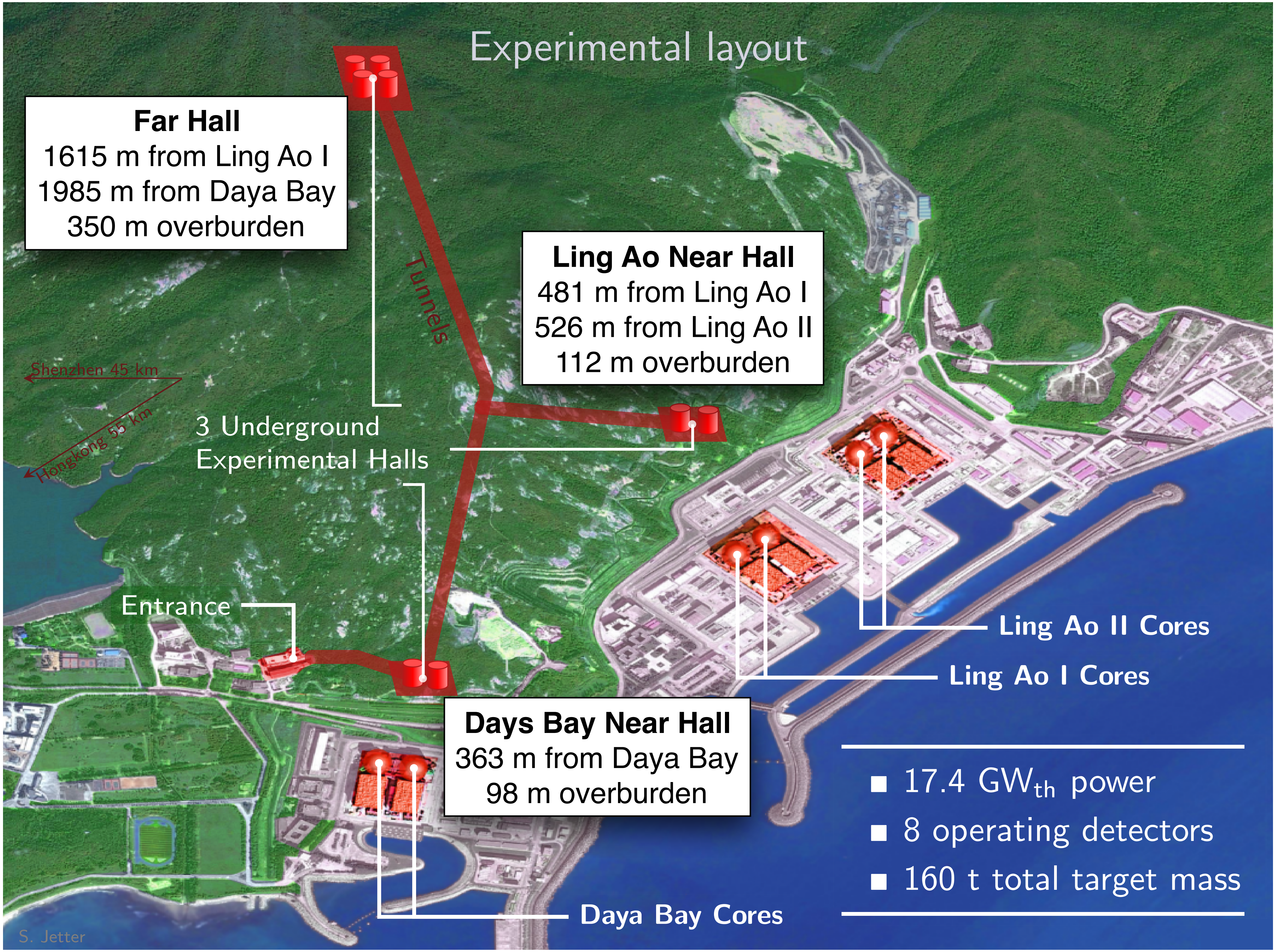



## Extract $\theta_{13}$ from $\overline{\nu_e}$ deficit

$$\frac{N_{\text{Far}}}{N_{\text{Near}}} = \left(\frac{N_{\text{target,Far}}}{N_{\text{target,Near}}}\right)\left(\frac{L_{\text{Near}}}{L_{\text{Far}}}\right)^2\left(\frac{\varepsilon_{\text{Far}}}{\varepsilon_{\text{Near}}}\right)\left[\frac{P_{\text{survival}}(E, L_{\text{Far}})}{P_{\text{survival}}(E, L_{\text{Near}})}\right]$$

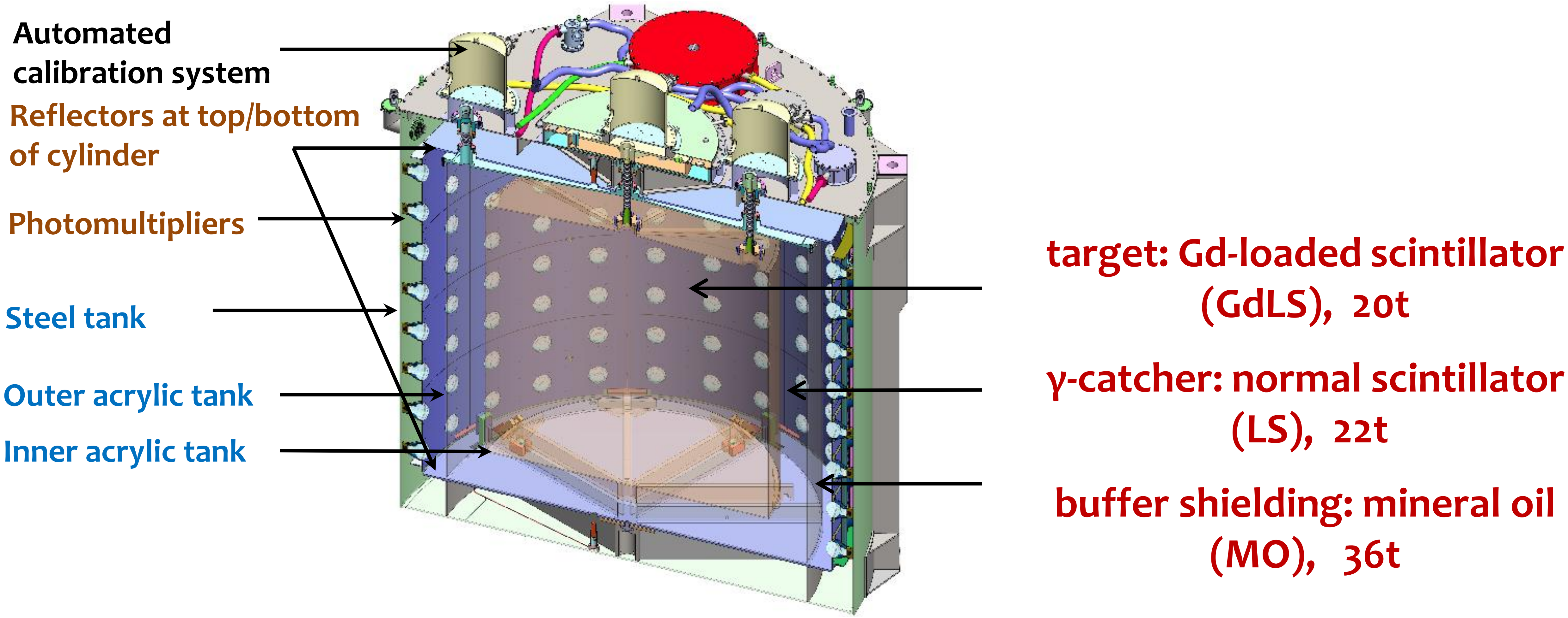
*Study Far/Near event ratio and spectral distortion*

# Eight Detectors in Three Halls




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

# Antineutrino Detectors (AD)



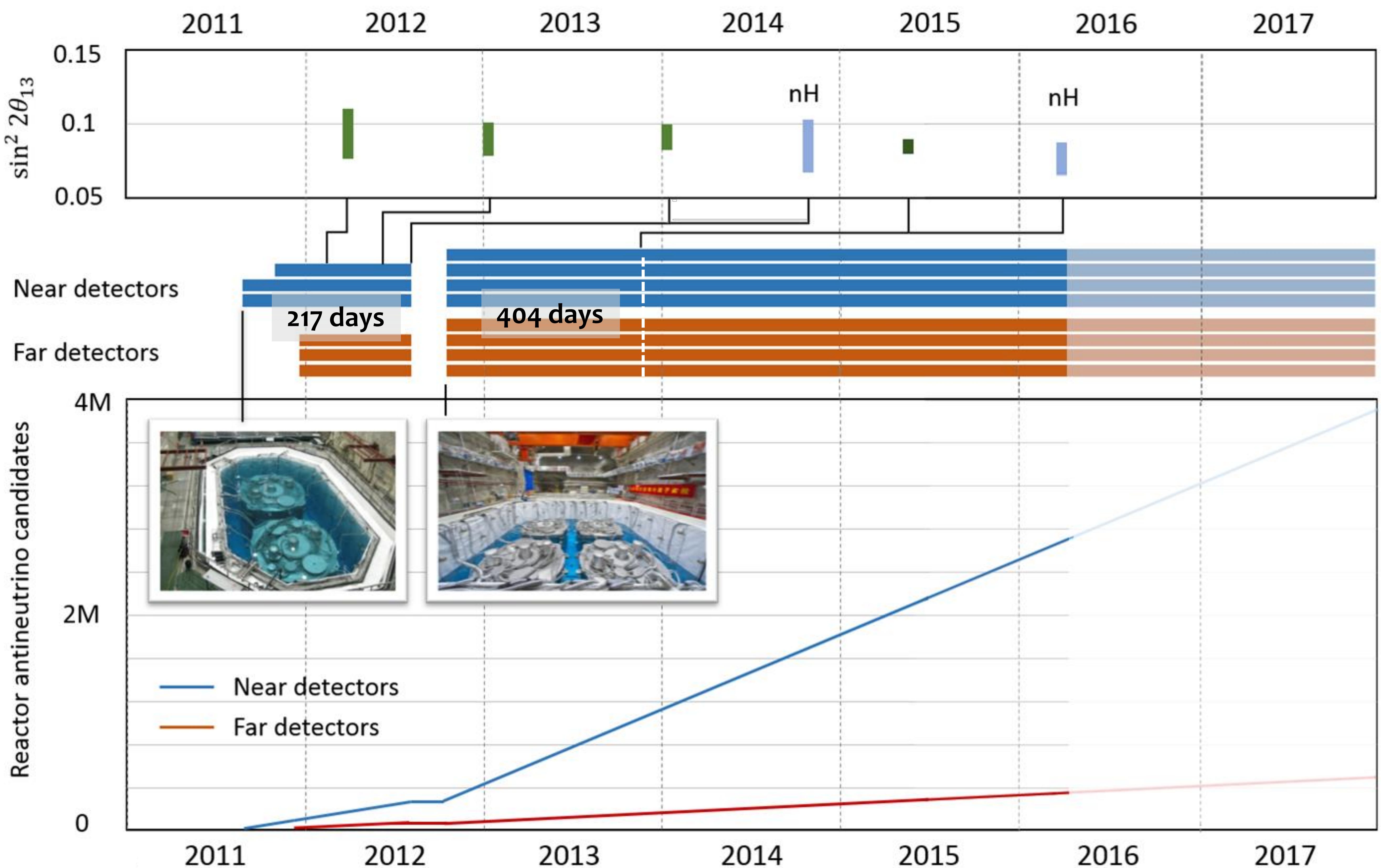

**Detector Tanks:** Two acrylic vessels and outer steel tank

**Detector Liquids:** 20t GdLS and 22t LS target, 36t MO buffer and shield

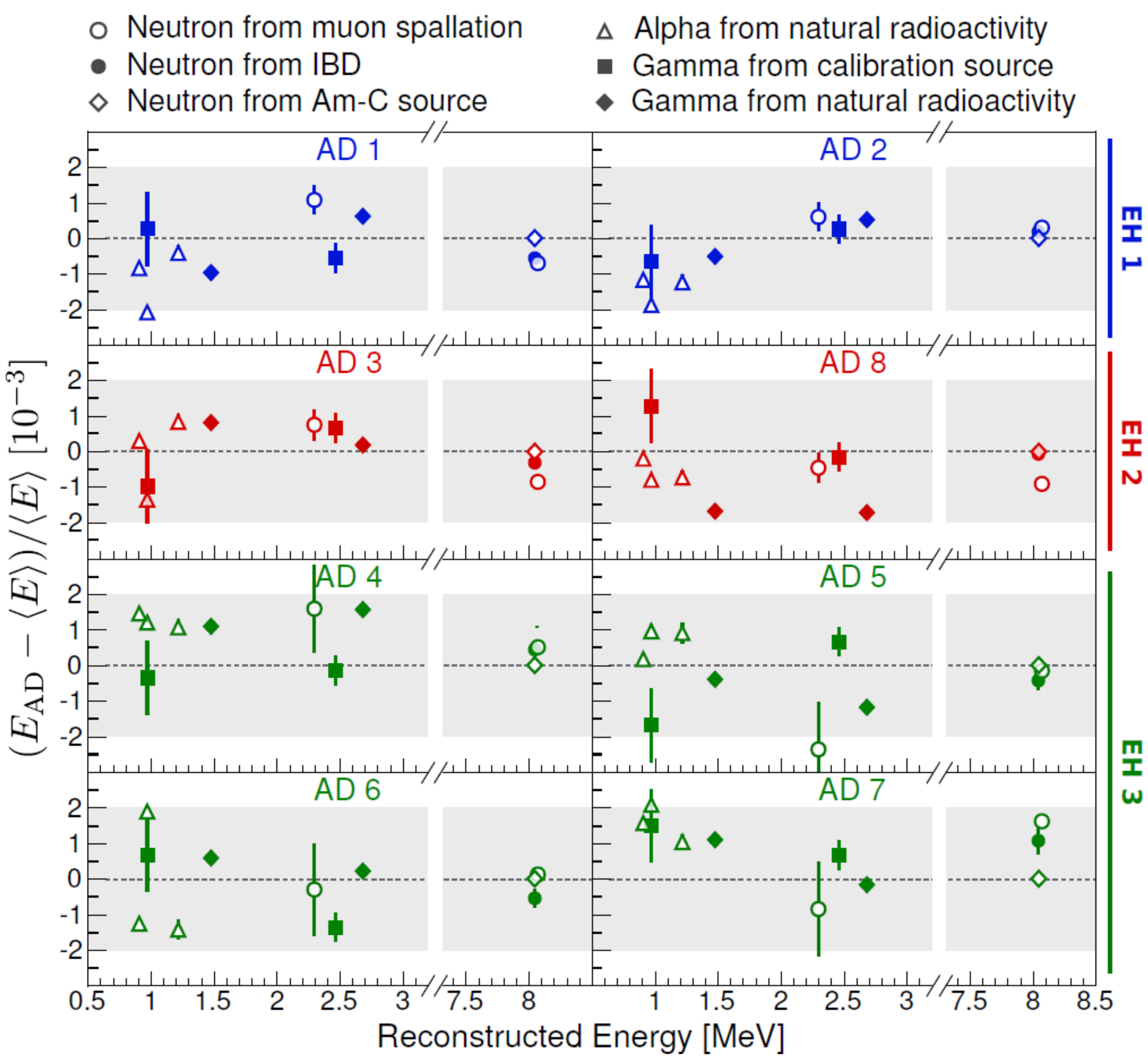
**Light Detection:** 192 20cm PMTs around side, top and bottom reflector

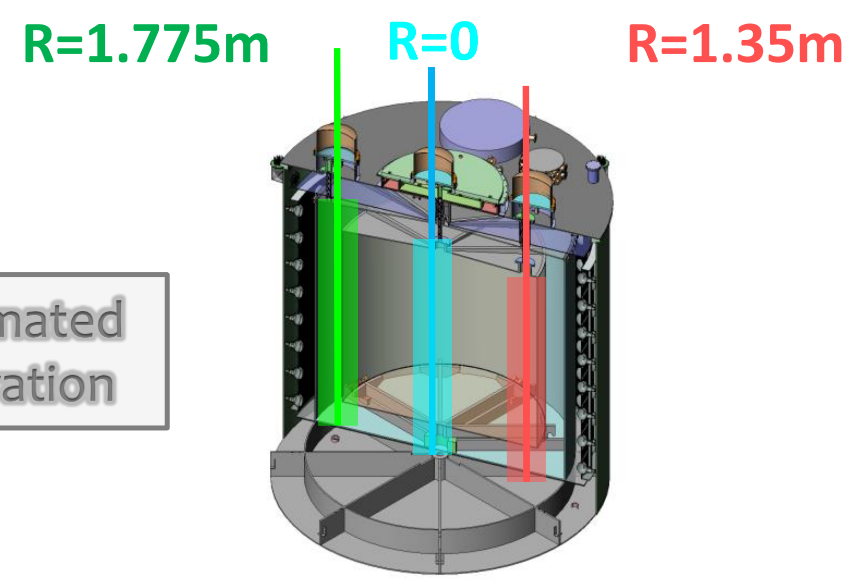
**Calibration Systems:** Three automated calibration units, LED, neutron, and gamma sources

# Data Collection



# AD Energy Calibration



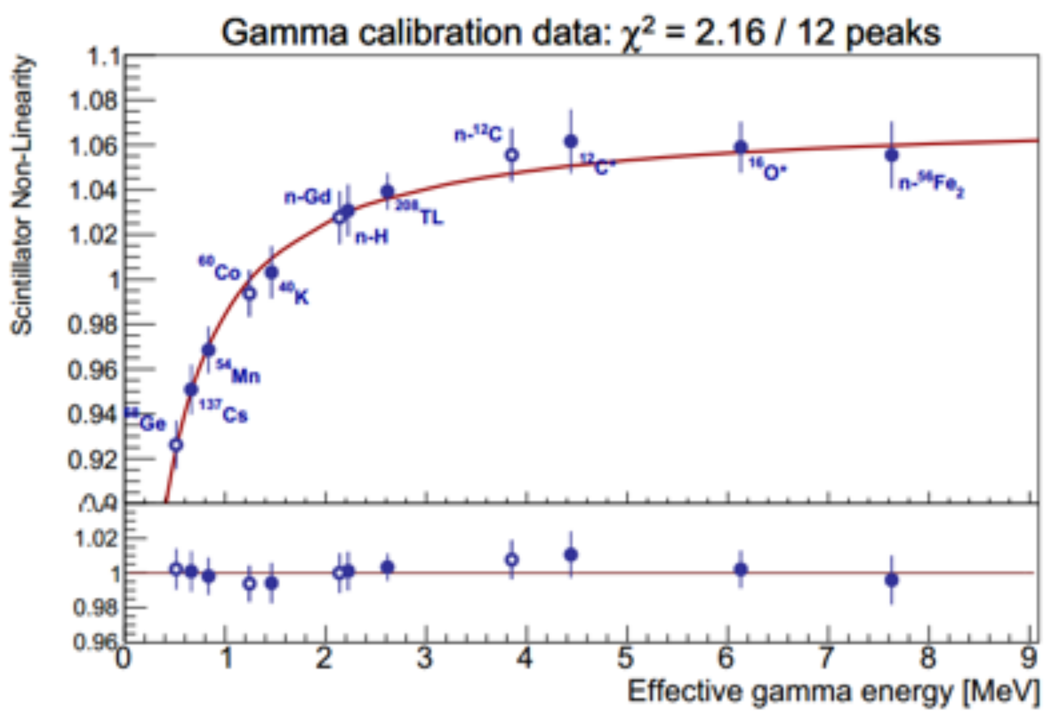



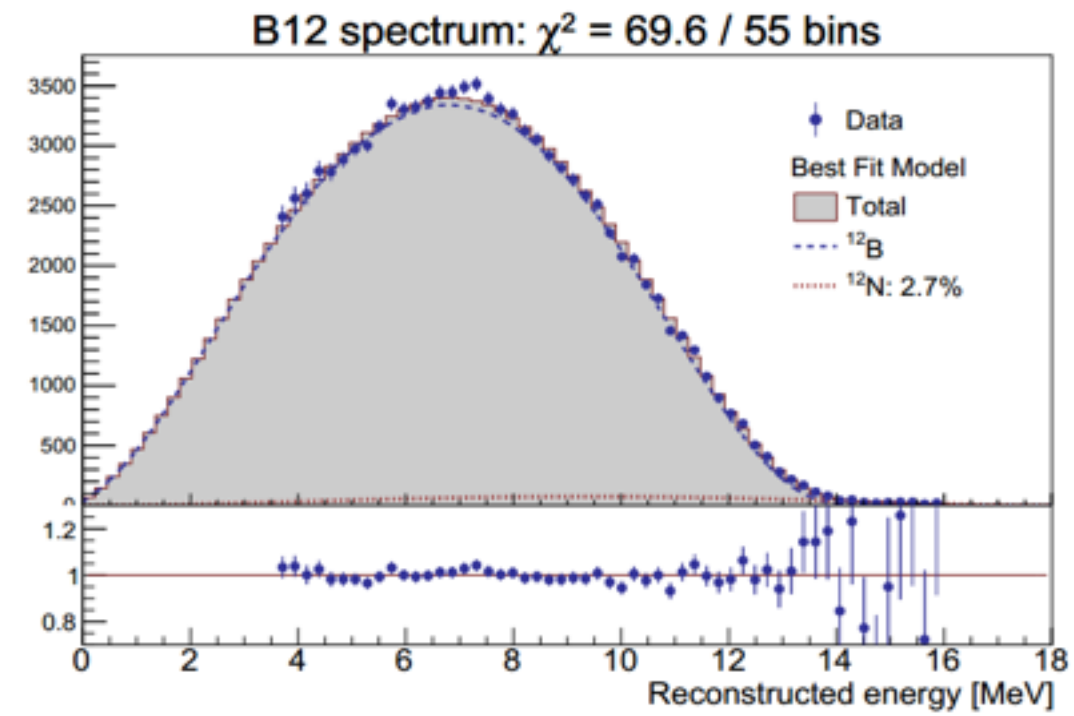

Automated calibration

- **PMT Gain:** rolling SPE calibration
- **Absolute energy scale:** Am-C at detector center
- **Time Variation:** $^{60}$Co at detector center
- **Non-uniformity:** $^{60}$Co off-axis at multiple positions

**Relative energy scale uncertainty: 0.2%**

# Energy non-linearity calibration

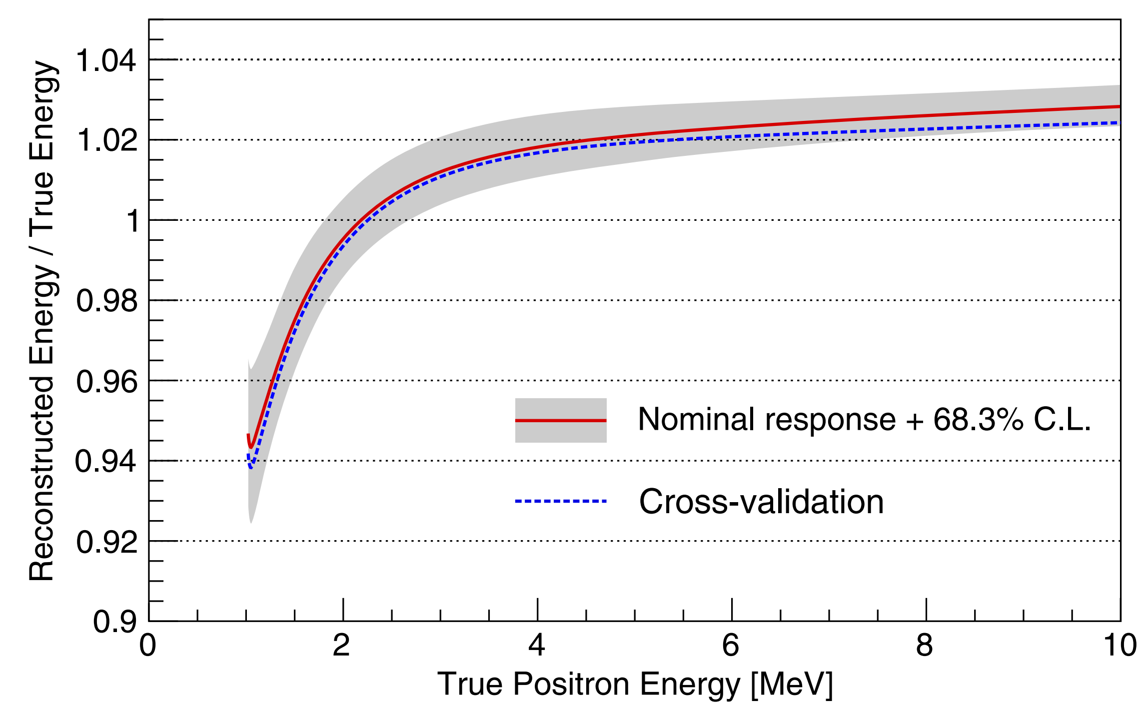


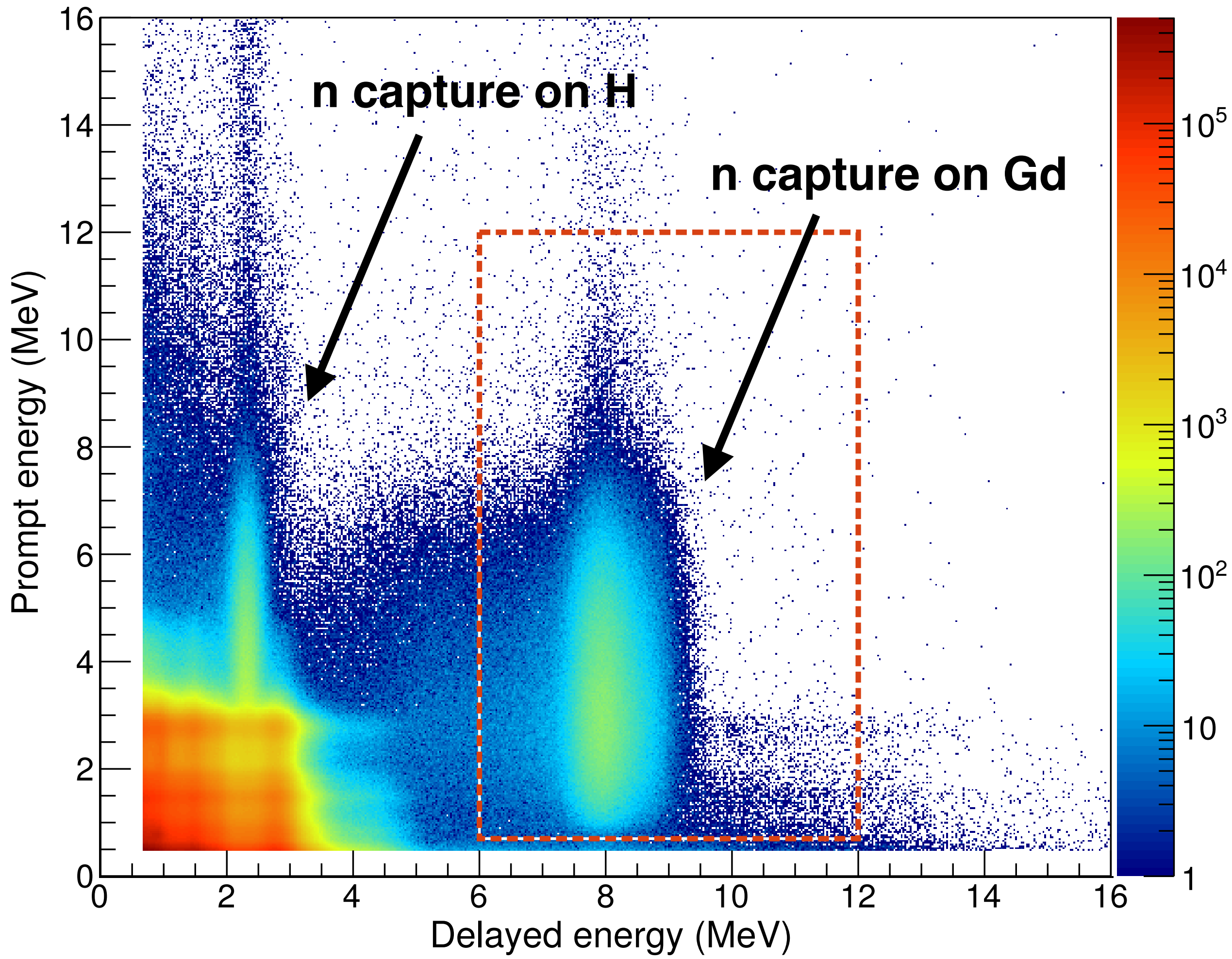

- Discrete and continuous calibration sources map out detector response

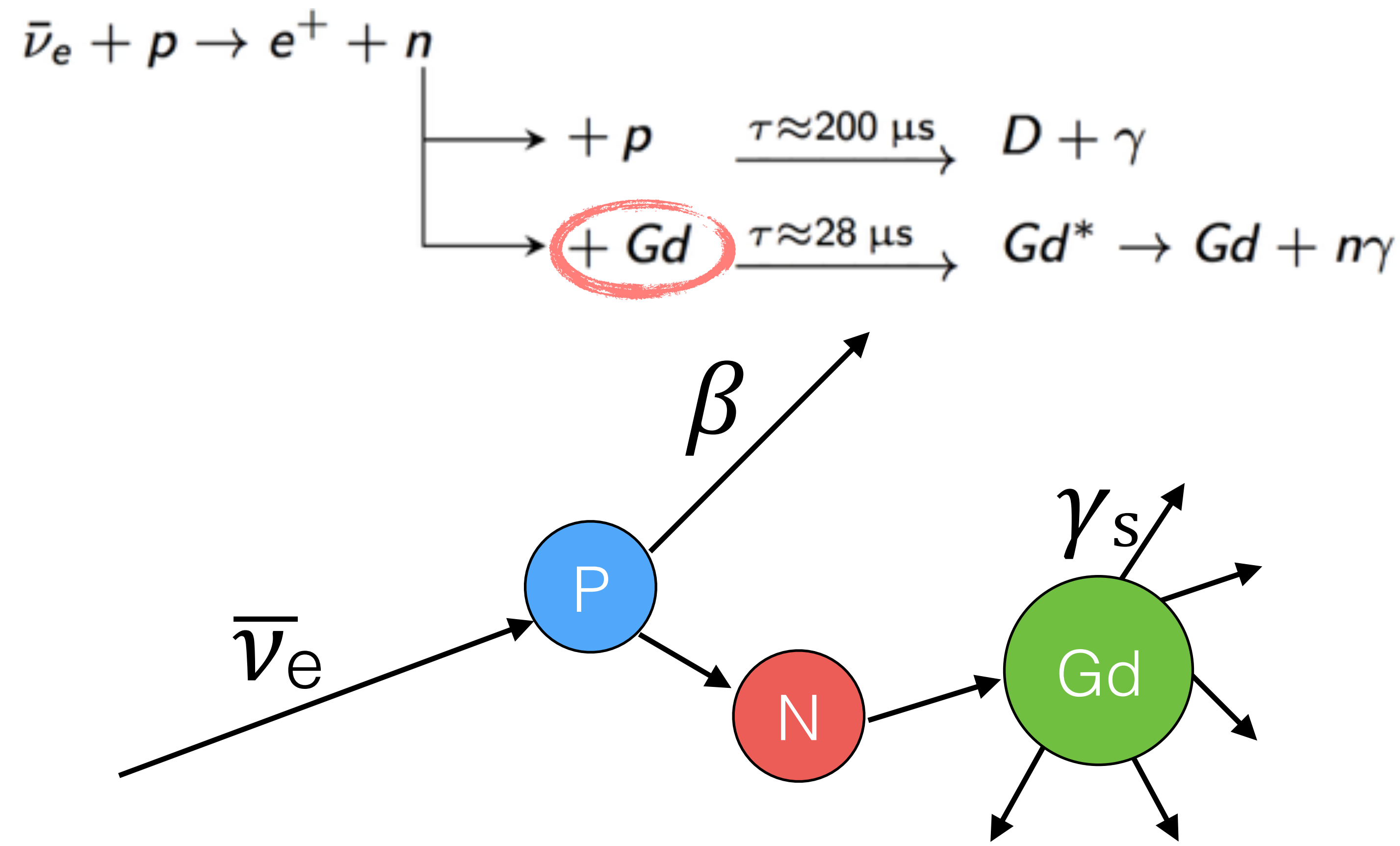
- Address scintillator and electronics non-linearities

- **Uncertainty <1% above 2MeV**



# Antineutrino Event Selection



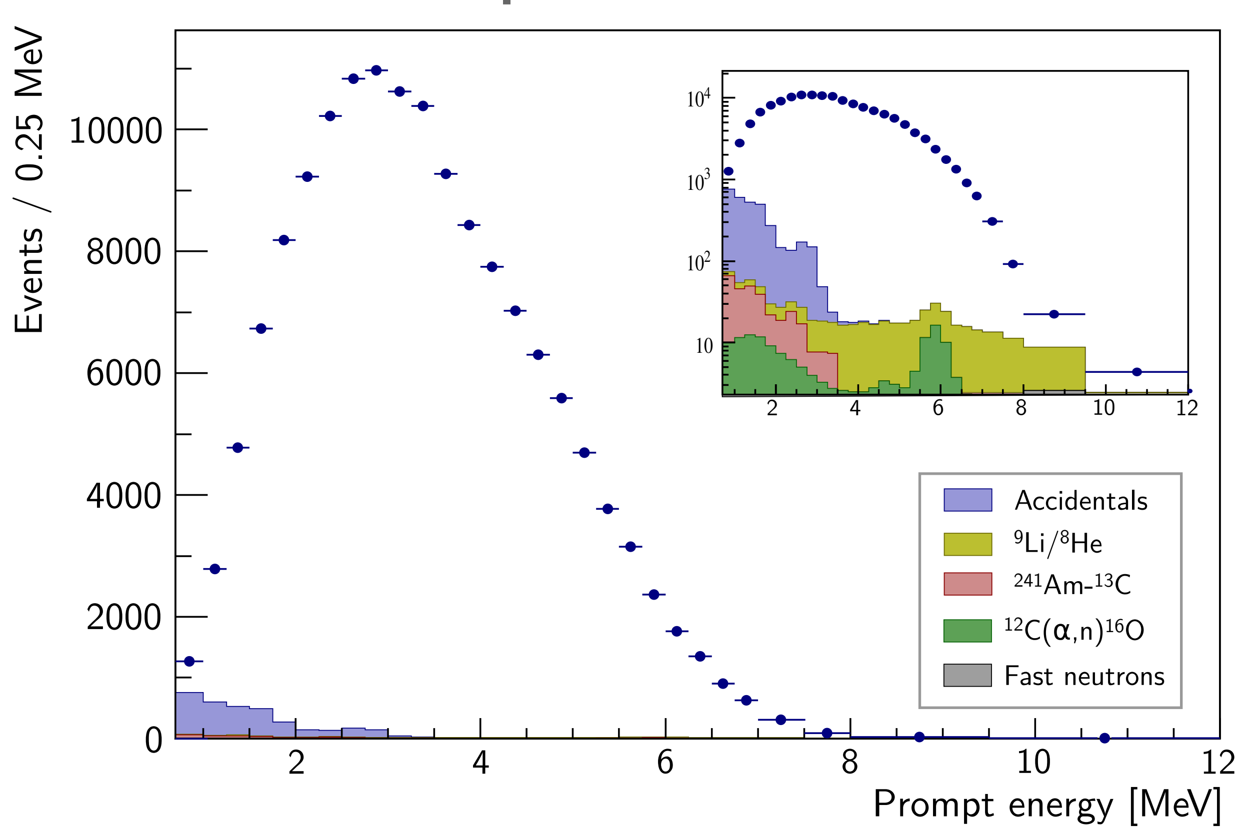




| | Pool Muon Veto (us) | AD Muon Veto (us) | Shower Muon Veto | Prompt Energy (MeV) | Delay Energy (MeV) | Capture Time (us) | Distance Cut (mm) |
|---|---|---|---|---|---|---|---|
| **nH** | 400us | 800us | 1s | [1.5,12] | peak + $3\sigma$ | [1,400] | 500 |
| **nGD** | 600us | 1000us | 1s | [0.7,12] | [6,12] | [1,200] | NA |

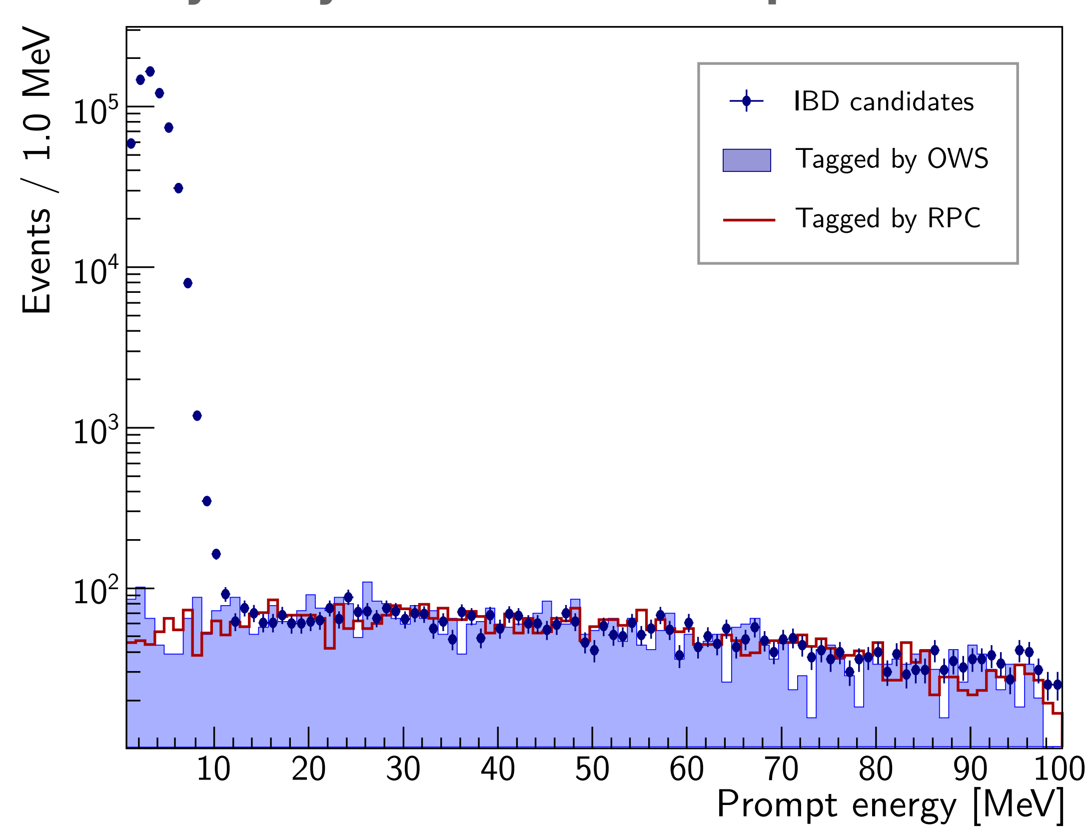
# Backgrounds

| Background | Near Hall | Far Hall | Uncertainty | Method |
|---|---|---|---|---|
| Accidentals | 1.4% | 2.3% | ~1% | Statistically determined from uncorrelated events |
| $^9Li/^8He$ | 0.4% | 0.4% | ~50% | Measured with muon-tagged events |
| $^{241}Am$-$^{13}C$ | 0.1% | 0.1% | ~50% | Tuned with MC |
| Fast Neutrons | 0.03% | 0.2% | ~30% | Measured with muon-tagged events |
| $(\alpha$,n) | 0.01% | 0.1% | ~50% | Calculated from measured radioactivity |

**Far hall IBD spectrum**



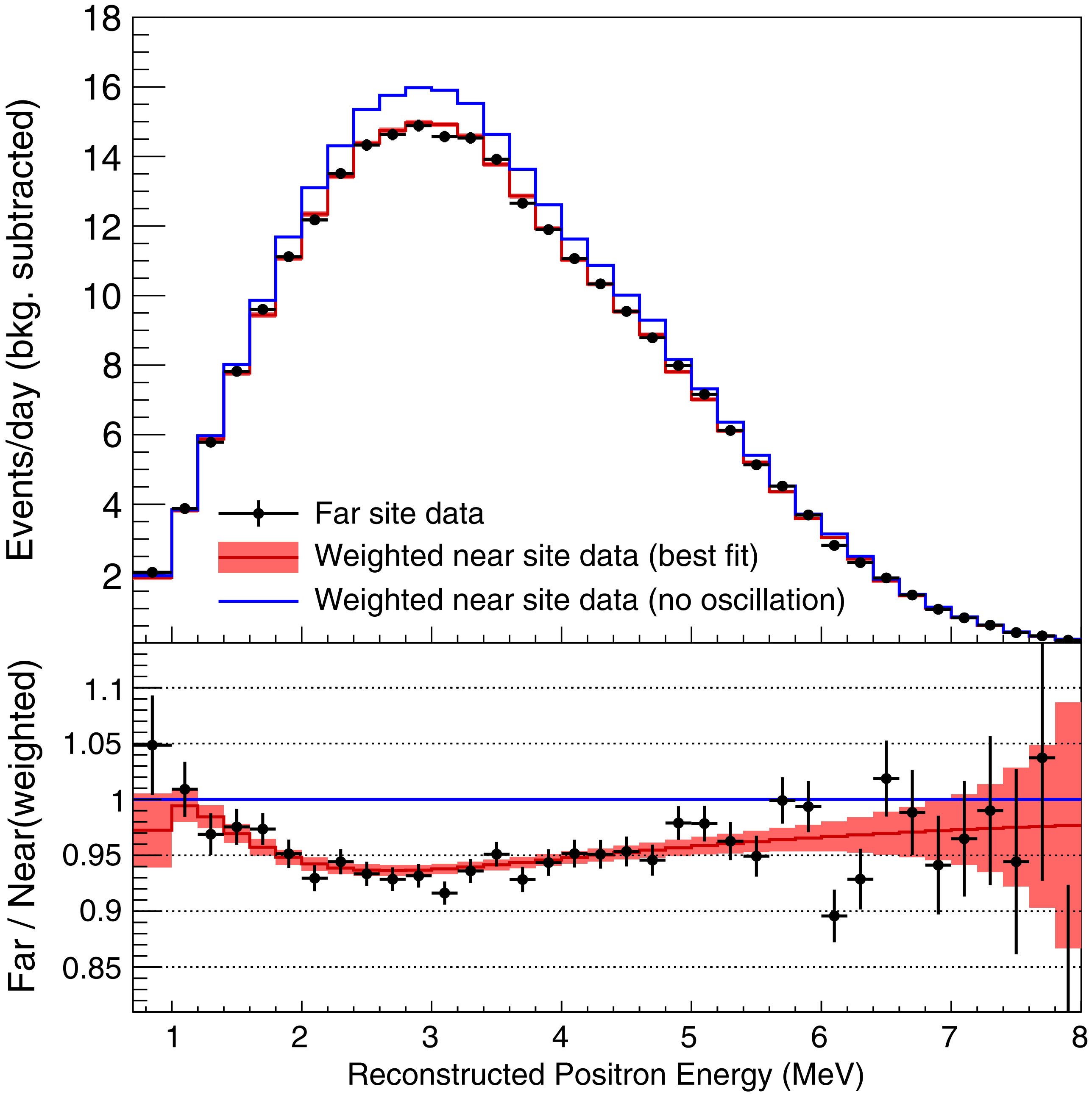

**Daya Bay near hall fast n spectrum**



# Updated nGd Oscillation

PRL 115, 111802 (2015) PHYSICAL REVIEW LETTERS week ending 11 SEPTEMBER 2015

**New Measurement of Antineutrino Oscillation with the Full Detector Configuration at Daya Bay**




- $6.9\times10^{5}$ $GW_{th}$-Ton-Day exposure, 150k IBDs in far detectors
- Use near hall to predict far hall spectrum with and without oscillations
- **Uncertainties dominated by statistics**

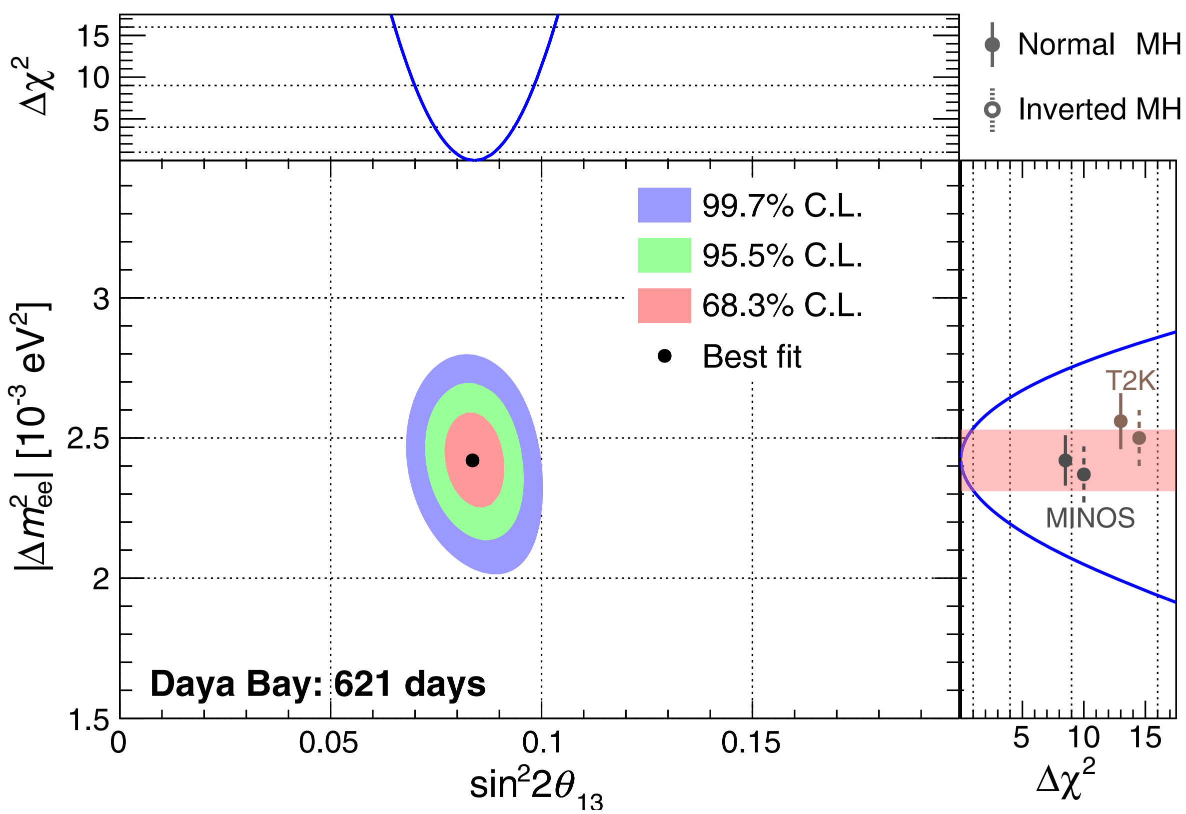
$\sin^2(2\theta_{13}) = 0.084\pm0.005$ $|\Delta m^2_{ee}| = (2.42\pm0.11)\cdot10^{-3}\,\mathrm{eV}^2$

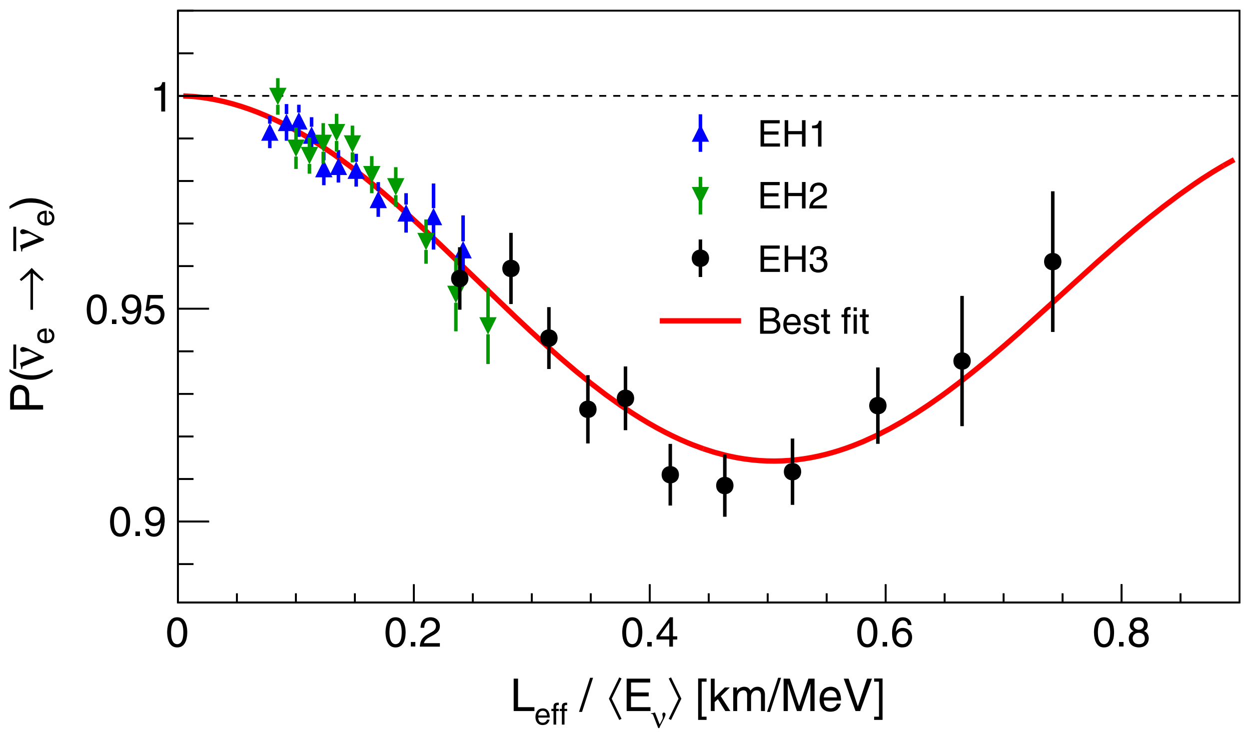
$|\Delta m^2_{32}|$ (NH) $= (2.37\pm0.11)\cdot10^{-3}\,\mathrm{eV}^2$ $|\Delta m^2_{32}|$ (IH) $= (2.47\pm0.11)\cdot10^{-3}\,\mathrm{eV}^2$

# Updated nGd Oscillation

PRL **115,** 111802 (2015) PHYSICAL REVIEW LETTERS week ending 11 SEPTEMBER 2015

**New Measurement of Antineutrino Oscillation with the Full Detector Configuration at Daya Bay**




- Mass splitting consistent with n_mu measurements from Minos and T2K
- Map out full L/E curve using energy information from each experimental hall
  - $L_{eff}$ takes into account multiple detectors and multiple reactor cores
  - $E_\nu$ has detector response removed from prompt energy

# New nH Oscillation Results

**Data Sample:**

- Same exposure as recent nGd results

**Key Features:**

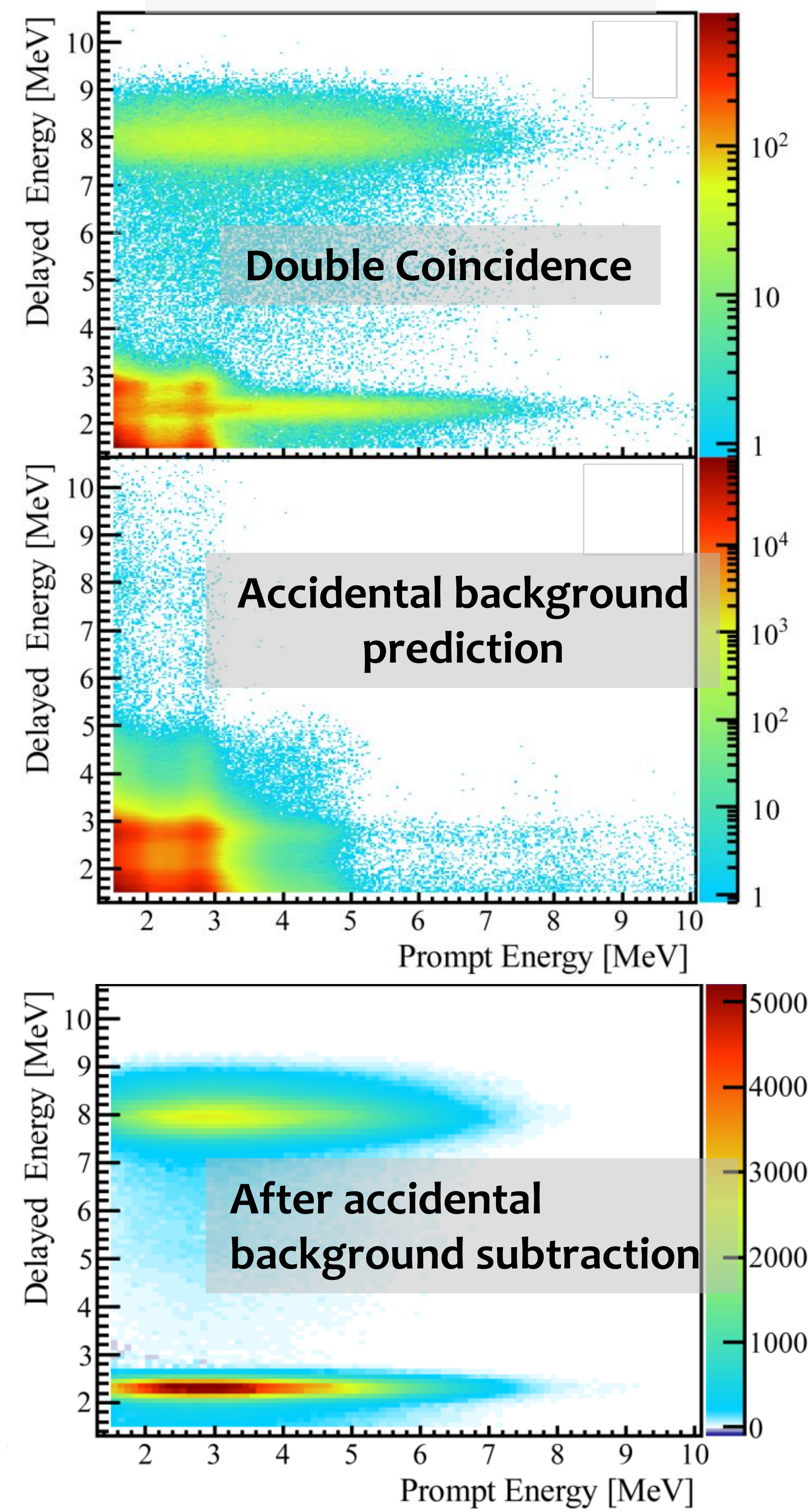
- Independent sample of IBD events
- Different systematics

**Challenges:**

- Higher accidental backgrounds
- More energy leakage at detector edge

**Strategy:**

- Prompt Energy Cut: 1.5MeV
- Delay Energy: Peak ±3$\sigma$ (1.9-2.7MeV)
- Distance between prompt and delay: 0.5m
- Statistical accidental subtraction (from data)

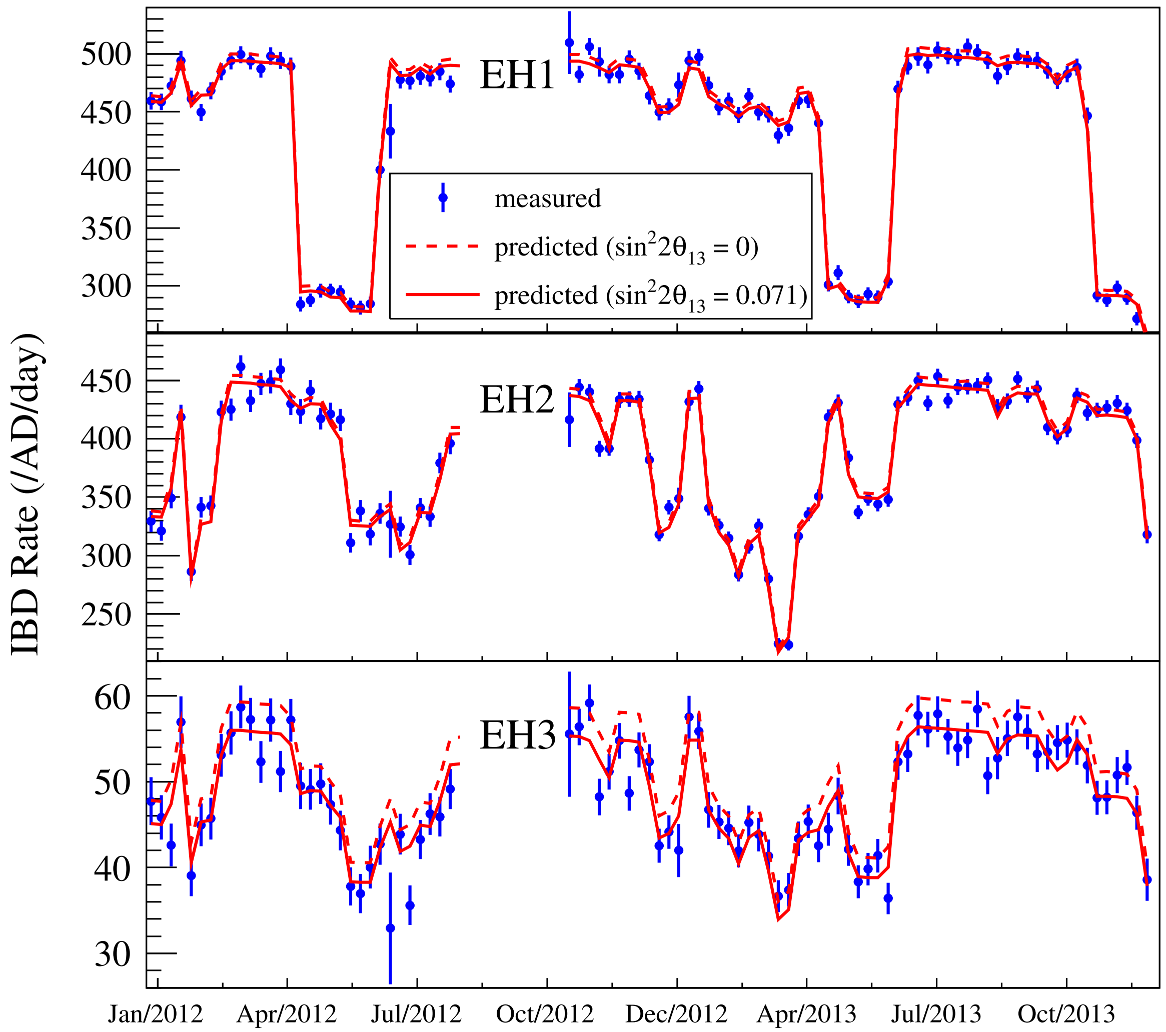


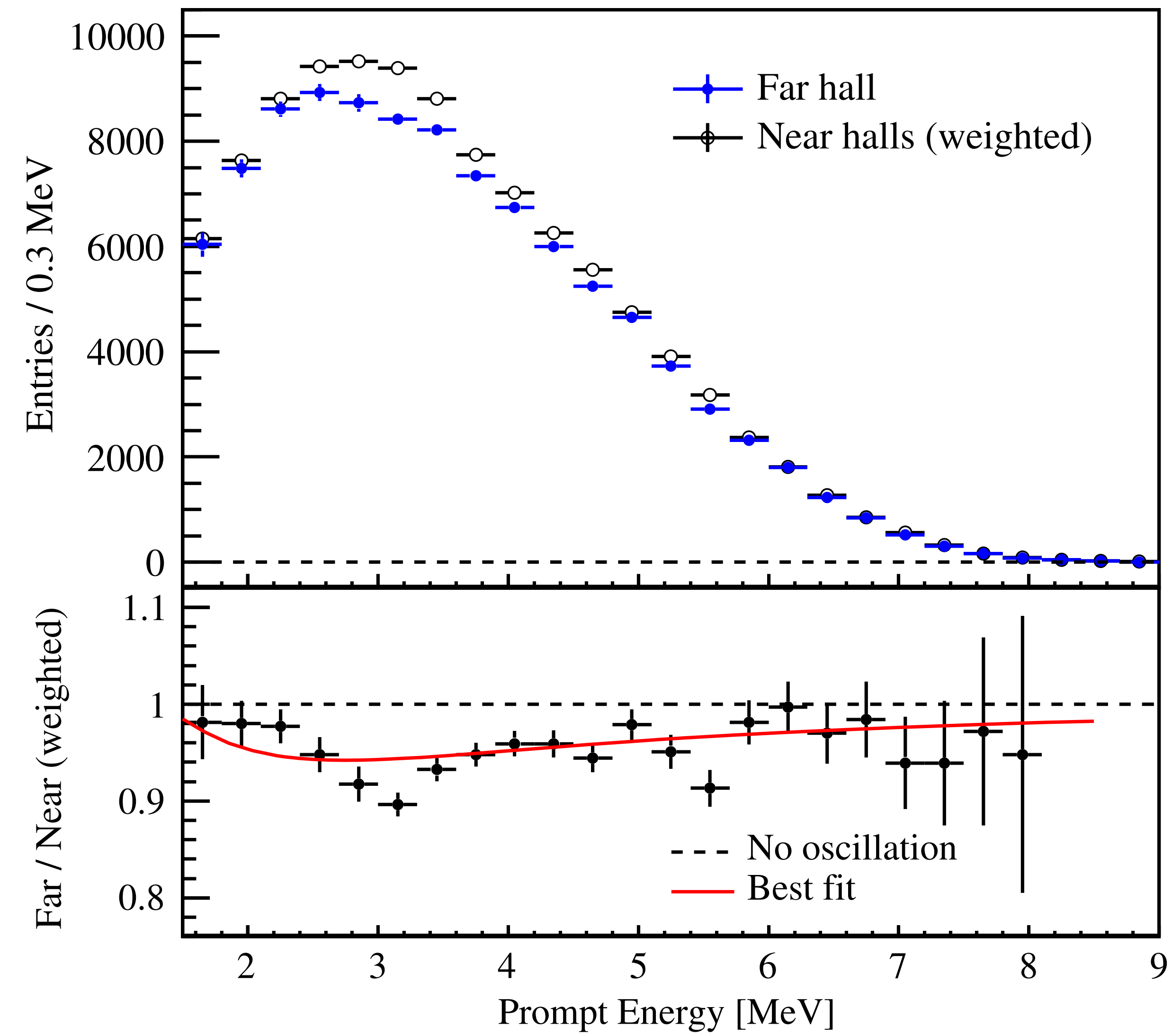

PHYSICAL REVIEW D **93,** 072011 (2016)

**New measurement of $\theta_{13}$ via neutron capture on hydrogen at Daya Bay**

F. P. An,[1] A. B. Balantekin,[2] H. R. Band,[3] M. Bishai,[4] S. Blyth,[5,6] D. Cao,[7] G. F. Cao,[8] J. Cao,[8] W. R. Cen,[8] Y. L. Chan,[9] J. F. Chang,[8] L. C. Chang,[10] Y. Chang,[6] H. S. Chen,[8] Q. Y. Chen,[11] S. M. Chen,[12] Y. X. Chen,[13] Y. Chen,[14] J. H. Cheng,[10]

# New nH Oscillation Results




- Statistical uncertainty reduced by 49% vs 6AD nH result
- Systematics reduced by 26%
  - *Improved study of cosmogenic backgrounds and neutron capture efficiency*

**Oscillation analysis based on rate information**

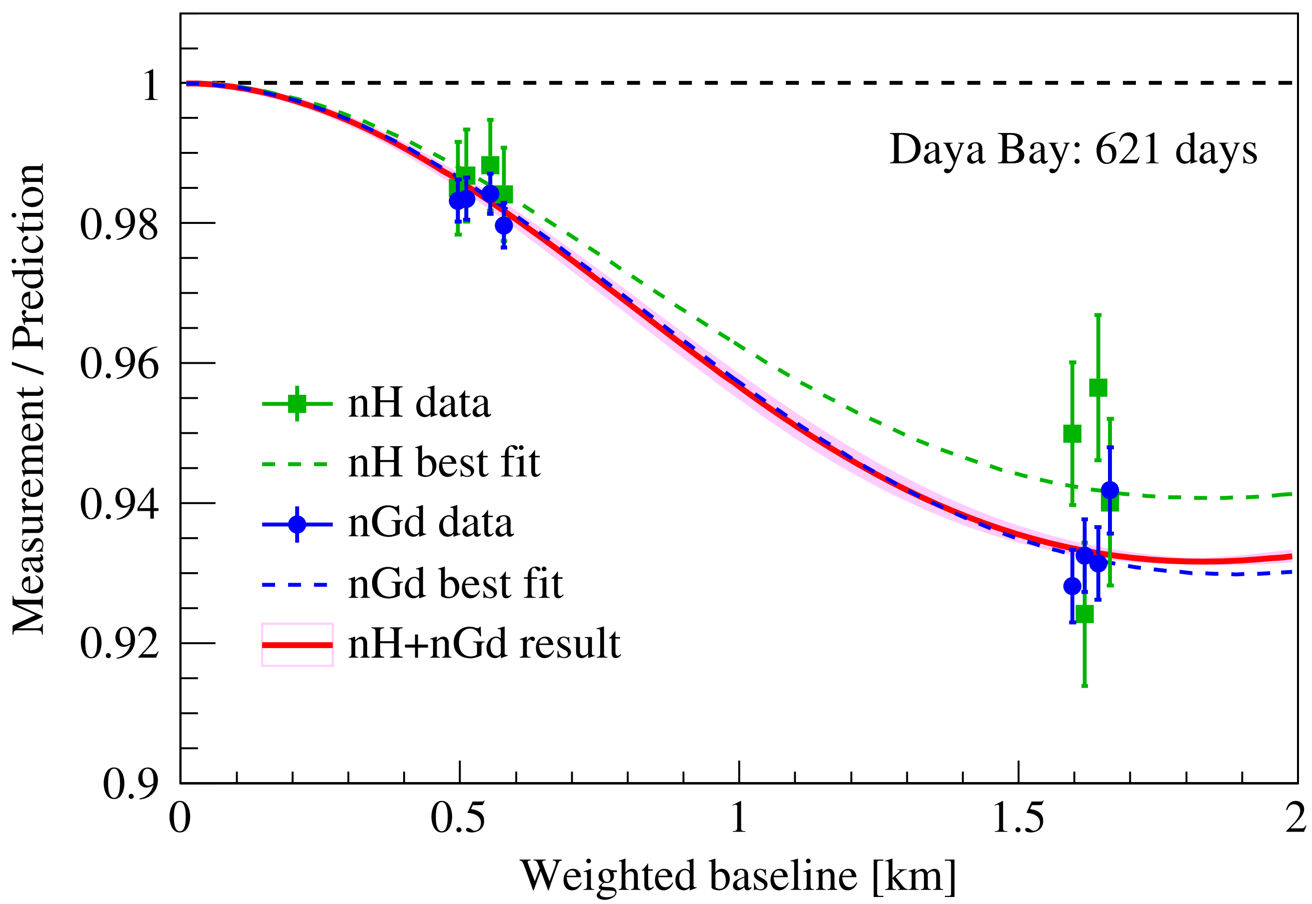
$$\sin^2 2\theta_{13} = 0.071 \pm 0.011$$

# Combined nGd and nH Results

Correlation between datasets estimated for efficiencies, backgrounds and reactor-related uncertainties

**Combine the nGd result with nH**

$$\sin^2 2\theta_{13} = 0.071 \pm 0.011 \quad \text{(nH)}$$
$$\sin^2 2\theta_{13} = 0.084 \pm 0.005 \quad \text{(nGd)}$$
$$\sin^2 2\theta_{13} = 0.082 \pm 0.004 \quad \text{(Combined)}$$



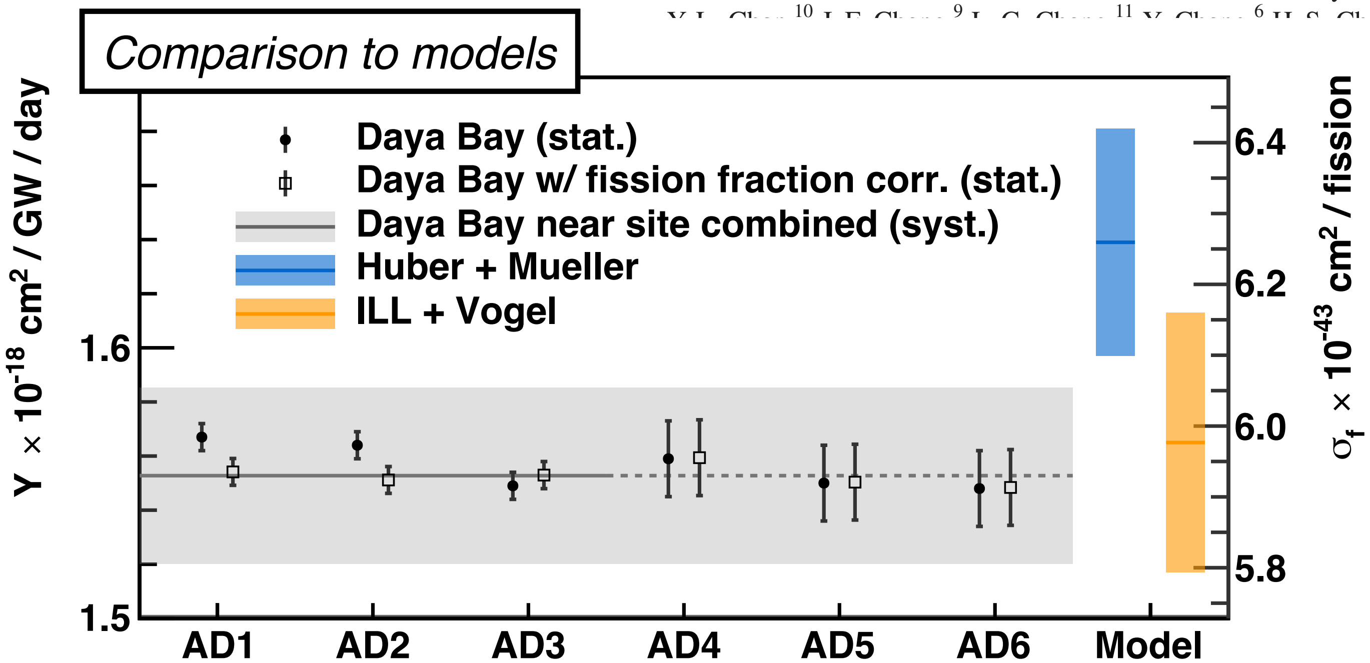

*Overall correlation coefficient of 0.02 indicates independence of the analyses*

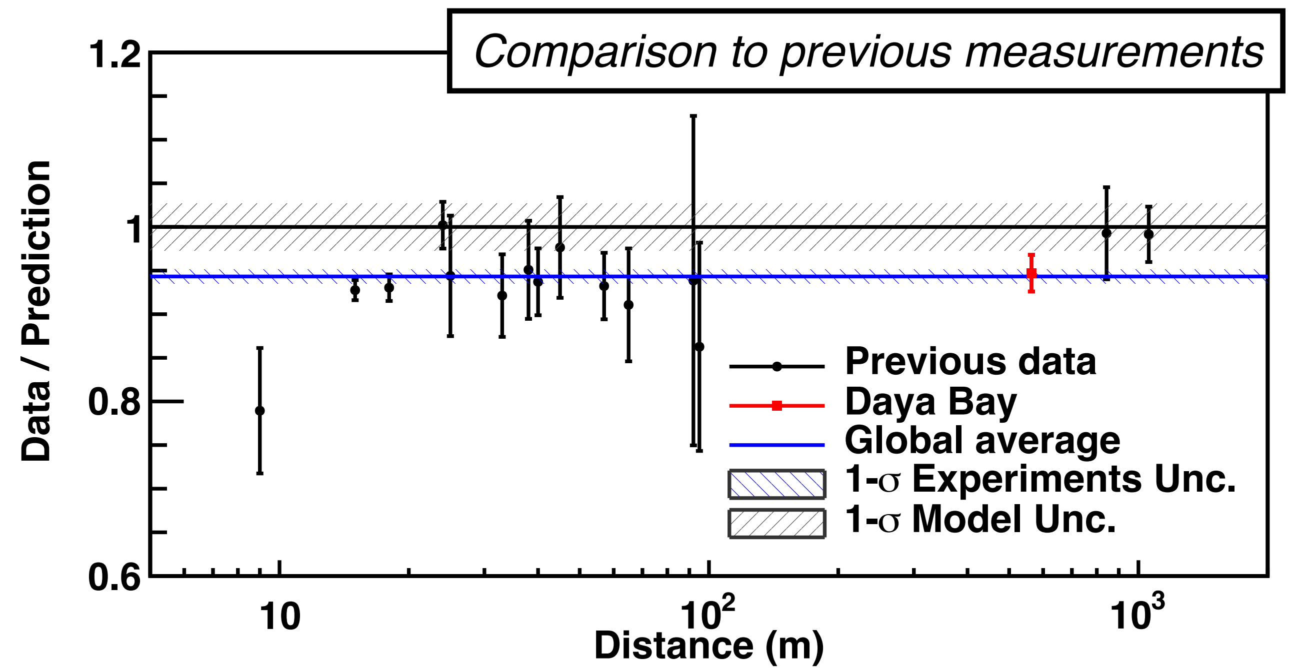
# Absolute Flux Measurement

PRL 116, 061801 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

**Measurement of the Reactor Antineutrino Flux and Spectrum at Daya Bay**

F. P. An,[1] A. B. Balantekin,[2] H. R. Band,[3] M. Bishai,[4] S. Blyth,[5,6] I. Butorov,[7] D. Cao,[8] G. F. Cao,[9] J. Cao,[9] W. R. Cen,[9]



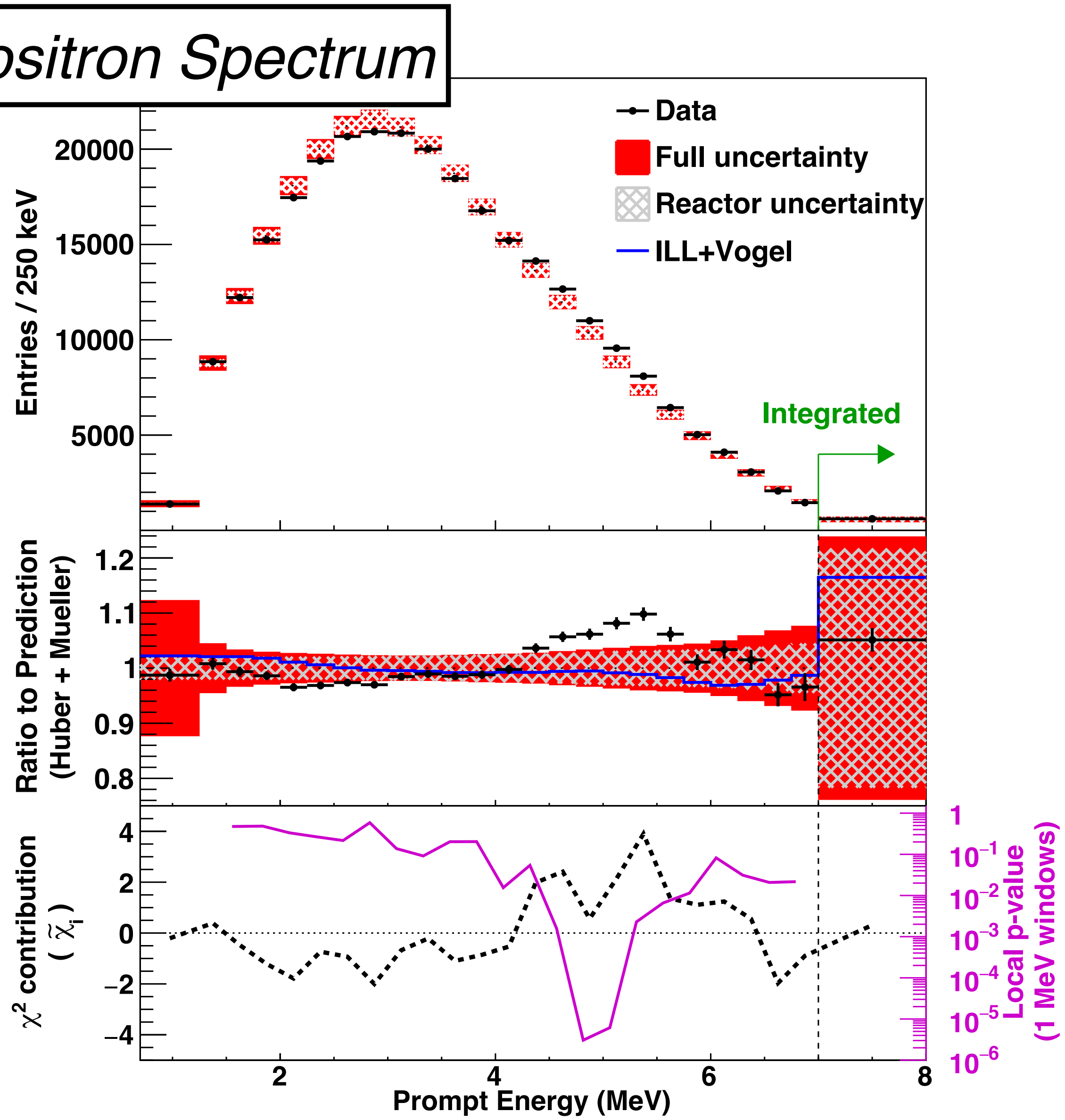



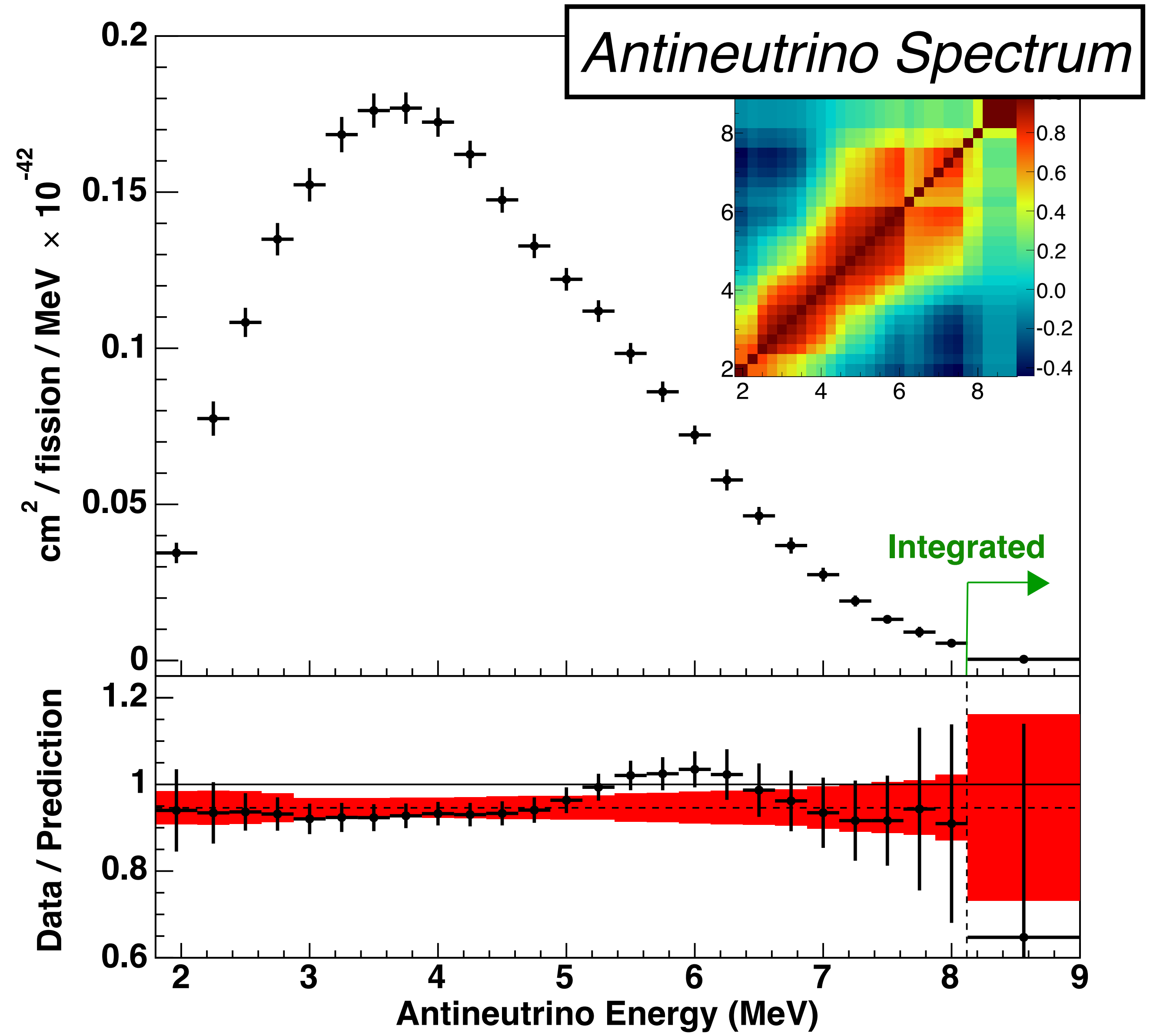

- Data from 6AD period (217days)
- Measured IBD rates corrected for oscillation
- Efficiencies and uncertainties determined for each cut
- R (Huber+Muller) = 0.946 ± 0.022
- Consistent with previous measurements

TABLE I. Summary of IBD selection efficiencies and their AD-correlated uncertainties. The uncertainties are given in relative units.

| | Efficiency ($\varepsilon$) | Uncertainty ($\delta_\varepsilon/\varepsilon$) |
|---|---|---|
| Target protons | | 0.47% |
| Flasher cut | 99.98% | 0.01% |
| Capture-time cut | 98.70% | 0.12% |
| Prompt-energy cut | 99.81% | 0.10% |
| Gd-capture fraction | 84.17% | 0.95% |
| Delayed-energy cut | 92.71% | 0.97% |
| Spill-in correction | 104.86% | 1.50% |
| Combined | 80.6% | 2.1% |

# Reactor Spectrum Measurement

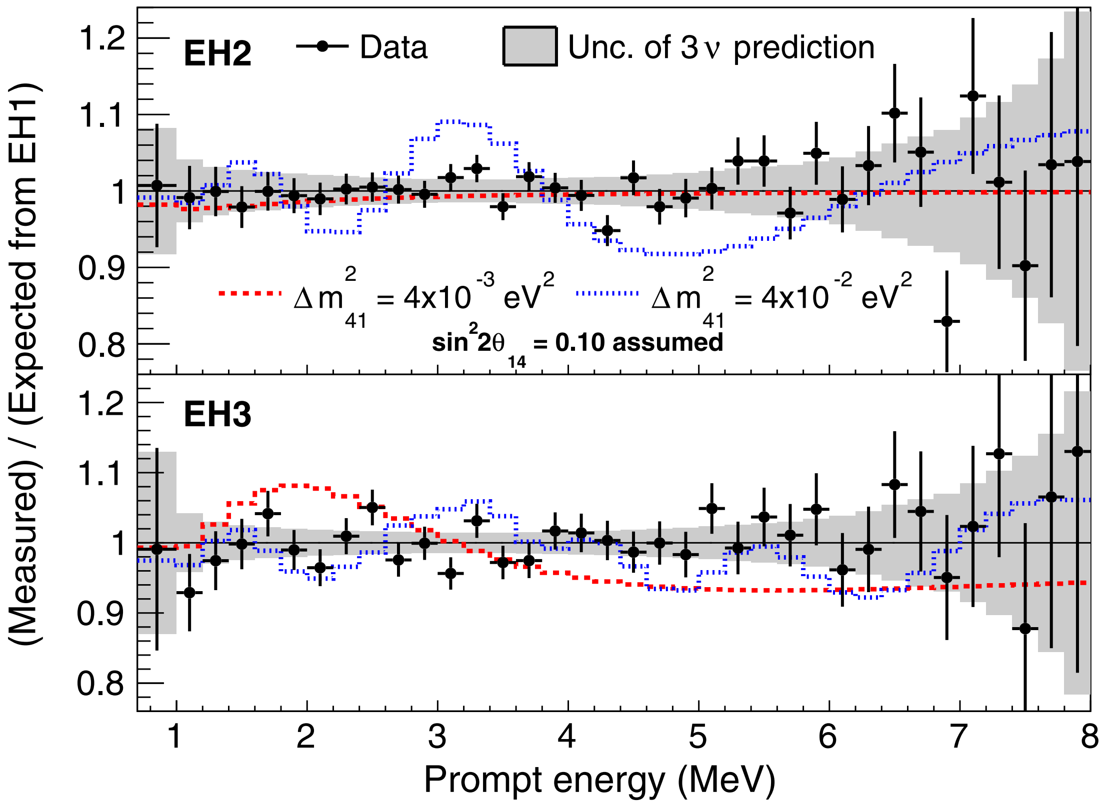


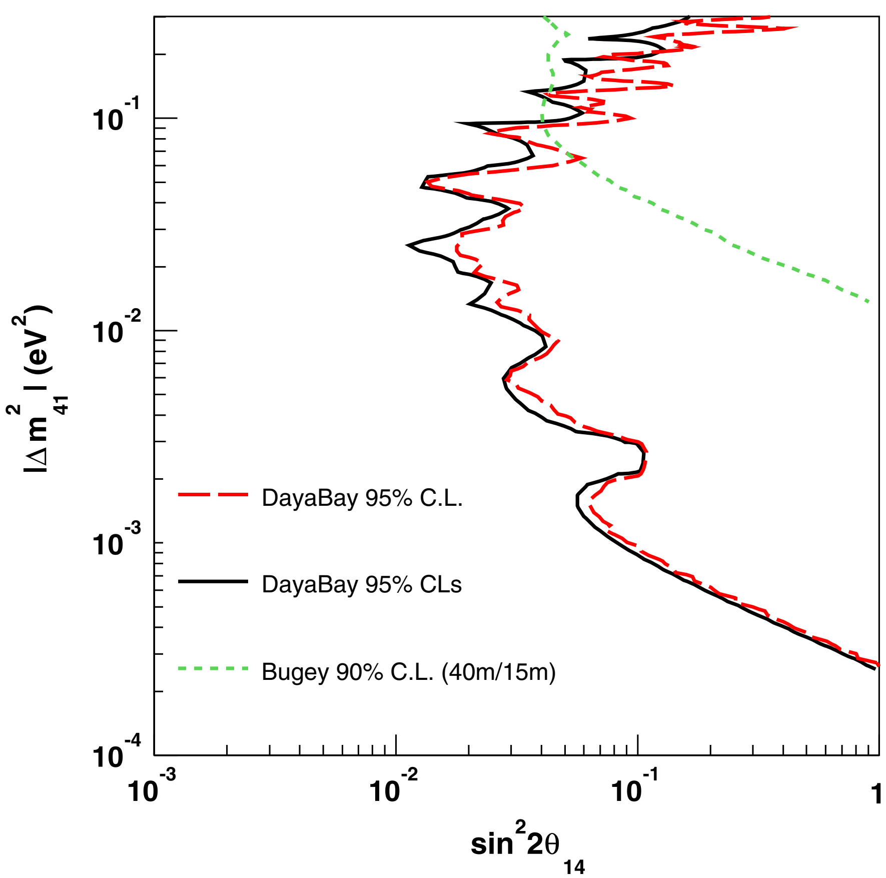




Spectral shape not consistent with Huber model
4$\sigma$ discrepancy between 4-6MeV

Antineutrino spectrum extracted via detector response unfolding
Reference spectrum for other experiments

# Sterile Neutrino Search




PRL **113,** 141802 (2014) PHYSICAL REVIEW LETTERS week ending 3 OCTOBER 2014

**Search for a Light Sterile Neutrino at Daya Bay**

F. P. An,[1] A. B. Balantekin,[2] H. R. Band,[2] W. Beriguete,[3] M. Bishai,[3] S. Blyth,[4] I. Butorov,[5] G. F. Cao,[6] J. Cao,[6] Y. L. Chan,[7]

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

- Multiple detectors at different baselines provide unique probe for sterile neutrinos
- Relative measurement at different baselines
- No significant oscillation observed, consistent with 3-flavor neutrino oscillation
- Most stringent limit in the mass splitting range: $10^{-3}\mathrm{eV}^2 < |\Delta m^2_{14}| < 10^{-1}\mathrm{eV}^2$

# Summary

- Updated reactor oscillation analyses with enlarged datasets for both nGd and nH selections
- Combined analysis with 621 days of data: $\sin^2 2\theta_{13} = 0.082 \pm 0.004$
- Precision measurements of antineutrino flux and energy spectra performed with 217 days of data:
  - Flux consistent with previous short baseline experiments, Measured/Predicted = 0.946
  - Spectral measurement disagrees with Huber model at $4\sigma$ between 4-6MeV
- **Data collection will continue through 2017, precision will continue to improve for all measurements**