Observation of Electron Antineutrino Disappearance at Daya Bay

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DPF 2013, UC Santa Cruz

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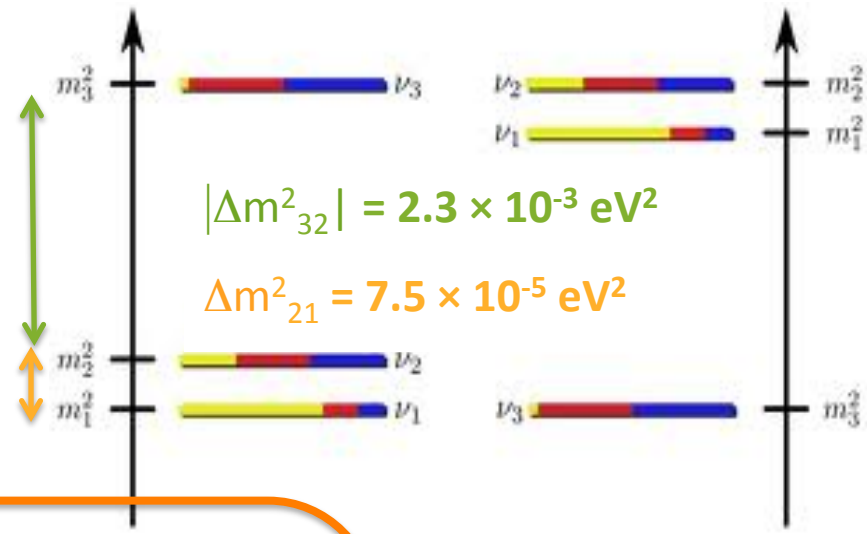
3 Neutrino Model

- $|\nu_i\rangle = \sum_\alpha U^*_{\alpha i} |\nu_\alpha\rangle$
- Flavor composition of neutrinos change as they propagate



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

- $\theta_{23} \approx 45^o$
- Atmospheric, Accelerator
- Octant unknown

- $\theta_{13} \approx 10^o$
- Short-Baseline Reactor, Accelerator
- δ_{CP} unknown

- $\theta_{12} \approx 35^o$
- Solar, Long-Baseline Reactor

Daya Bay Experiment

Asia (20)

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

North America (16)

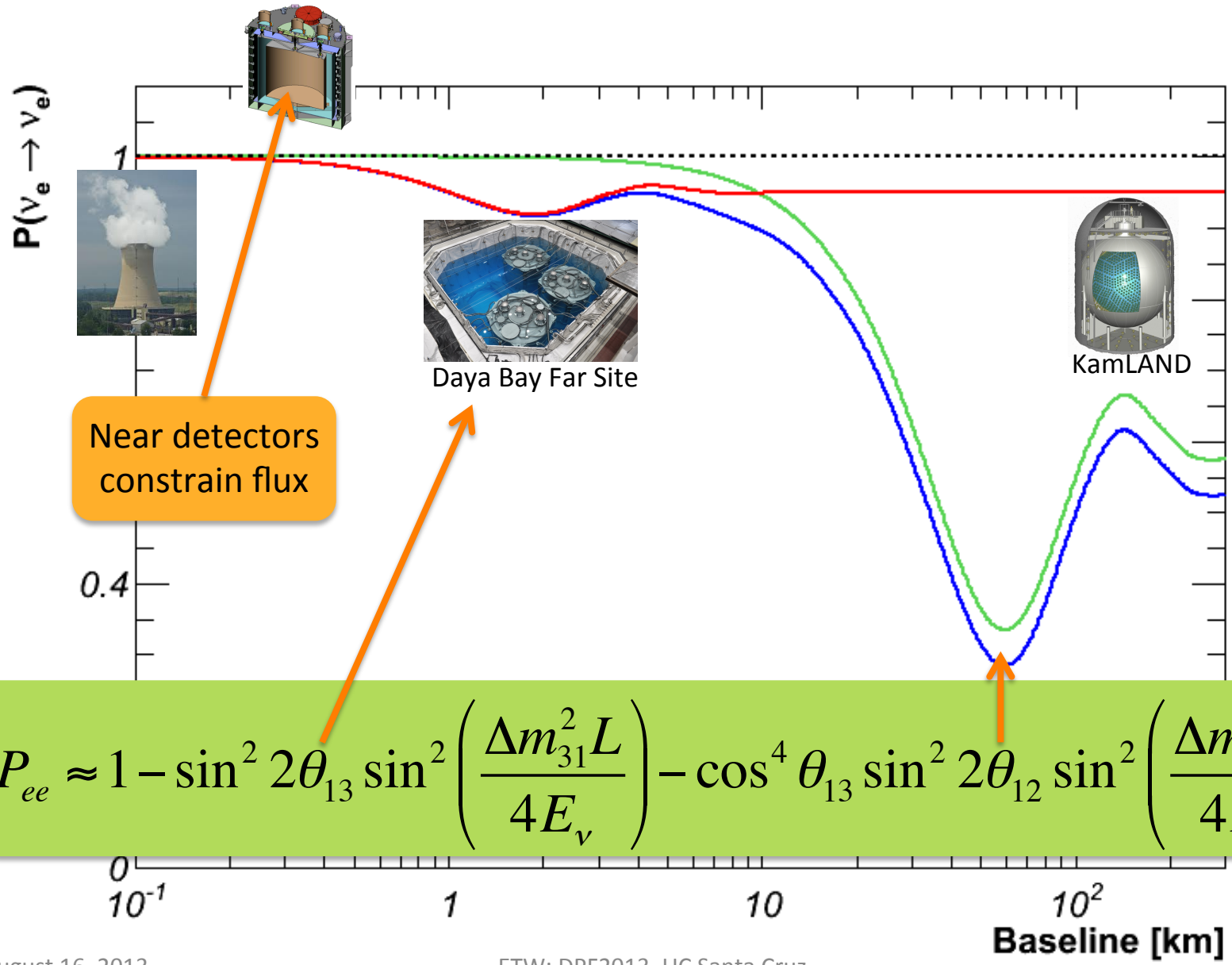
Brookhaven Natl' Lab, Cal Tech, Cincinnati, Houston, Illinois, Illinois Institute of Technology, Iowa State, Lawrence Berkeley Natl' Lab, Princeton, Rensselaer Polytech, Siena College, UC Berkeley, UCLA, Wisconsin, William & Mary, Virginia Tech

Europe (2)

Charles Univ., Dubna

~230 collaborators

Reactor Neutrino Oscillation



$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E_\nu}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}^2 L}{4E_\nu}\right)$$

Site: Guangdong, China

Entrance to Daya Bay experiment tunnels

Daya Bay NPP 2.9GW×2

Ling Ao NPP 2.9GW×2

Ling Ao II NPP 2.9GW×2

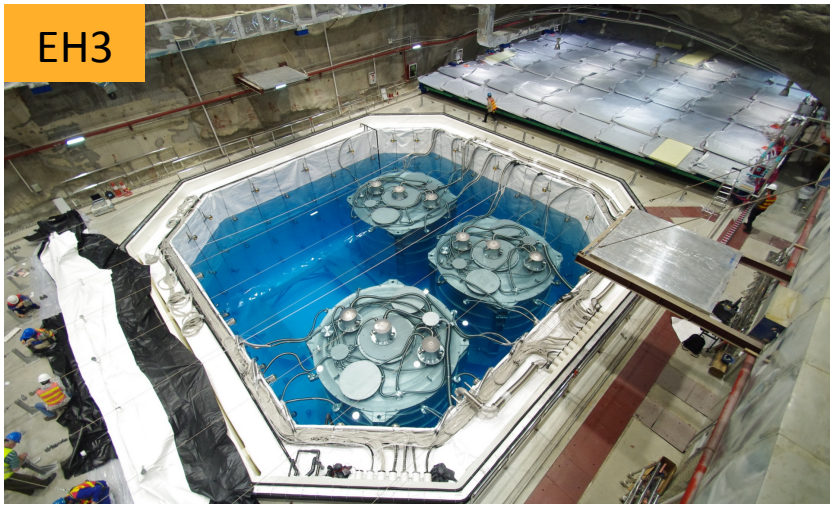
Mountains shield detectors from cosmic-ray induced background

6 reactors:

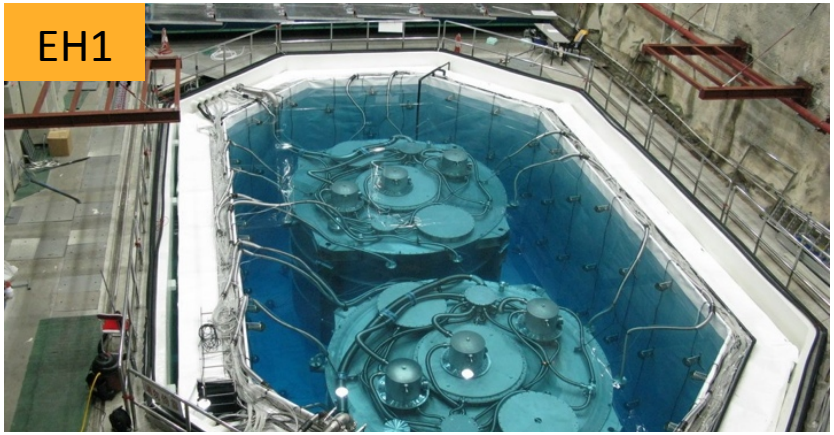
- 17.4 GW (thermal) total power
- produce ~2×10^{20} antineutrinos/ s/GW

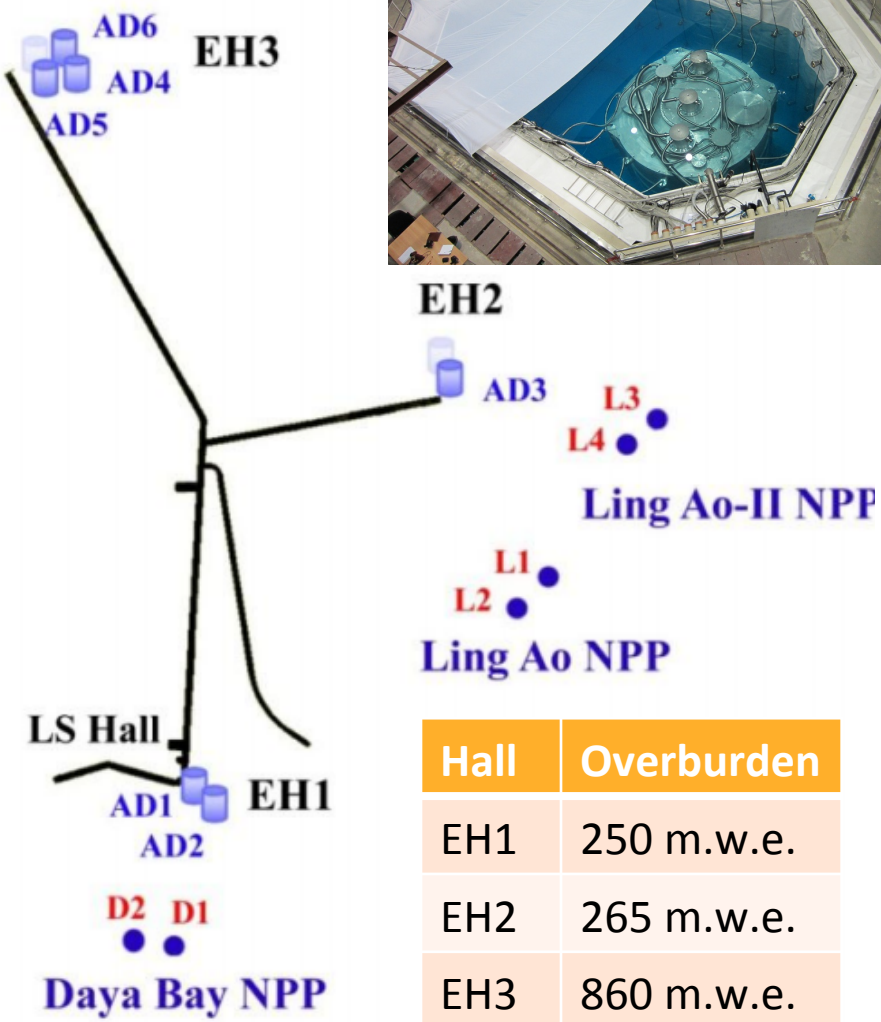
Experiment Layout

EH3

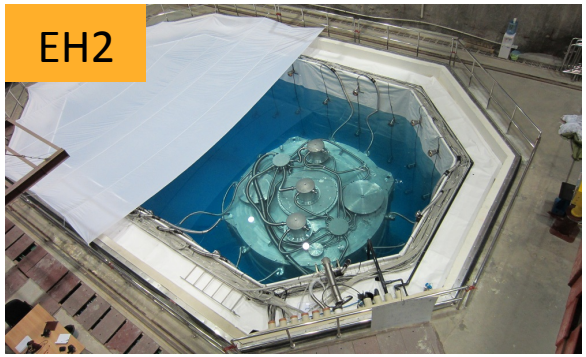


EH1





EH2

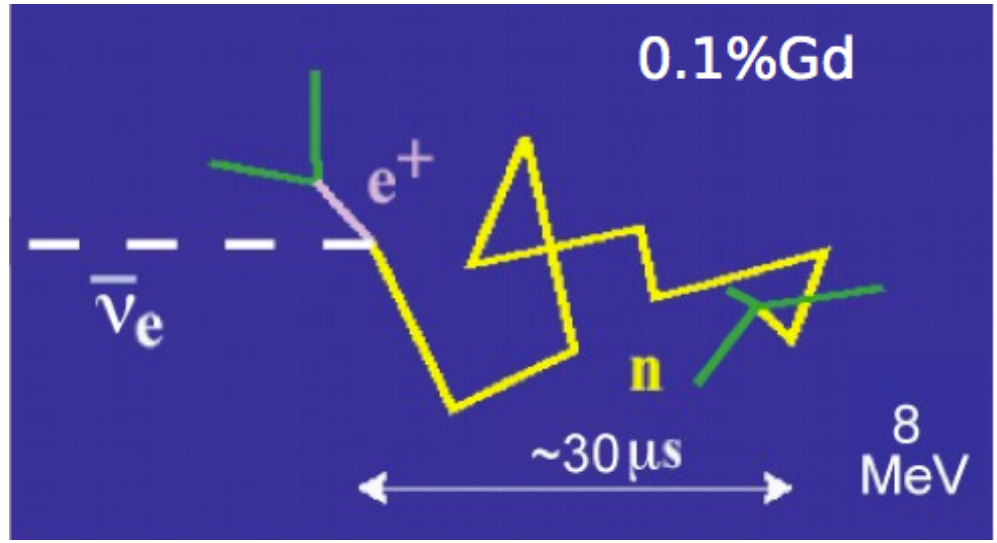


Hall	Overburden
EH1	250 m.w.e.
EH2	265 m.w.e.
EH3	860 m.w.e.

Antineutrino Detection

Inverse β-decay (IBD):

$$\bar{\nu}_e + p \rightarrow e^+ + n$$
$$\downarrow$$
$$n + {}^{x}Gd \rightarrow {}^{x+1}Gd + \gamma s$$



Prompt positron:

Carries antineutrino energy

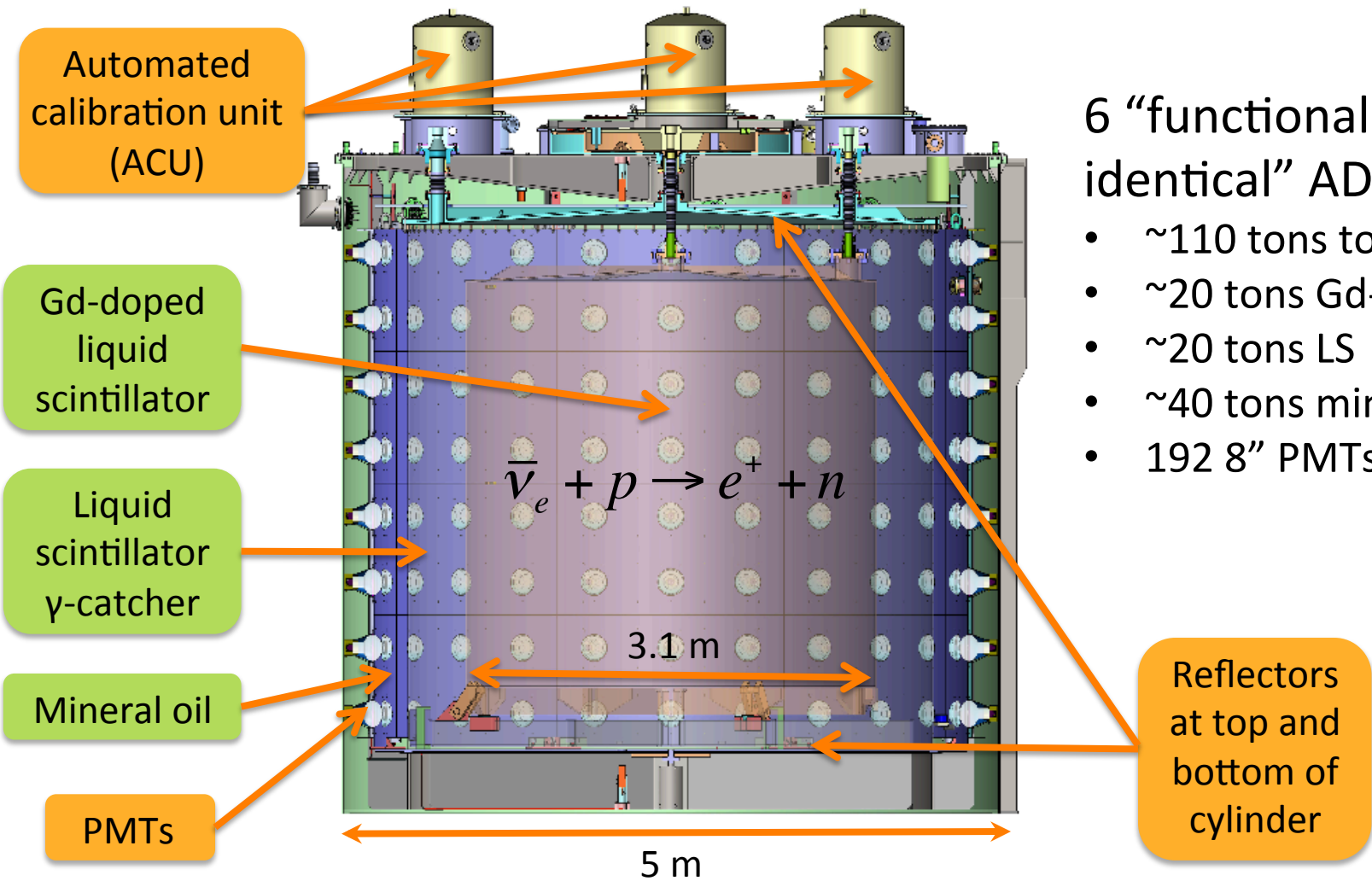
$E_{e+} \approx E_\nu - 0.8$ MeV

Delayed neutron capture:

Efficiently tags antineutrino signal

Prompt + Delayed coincidence provides distinctive signature

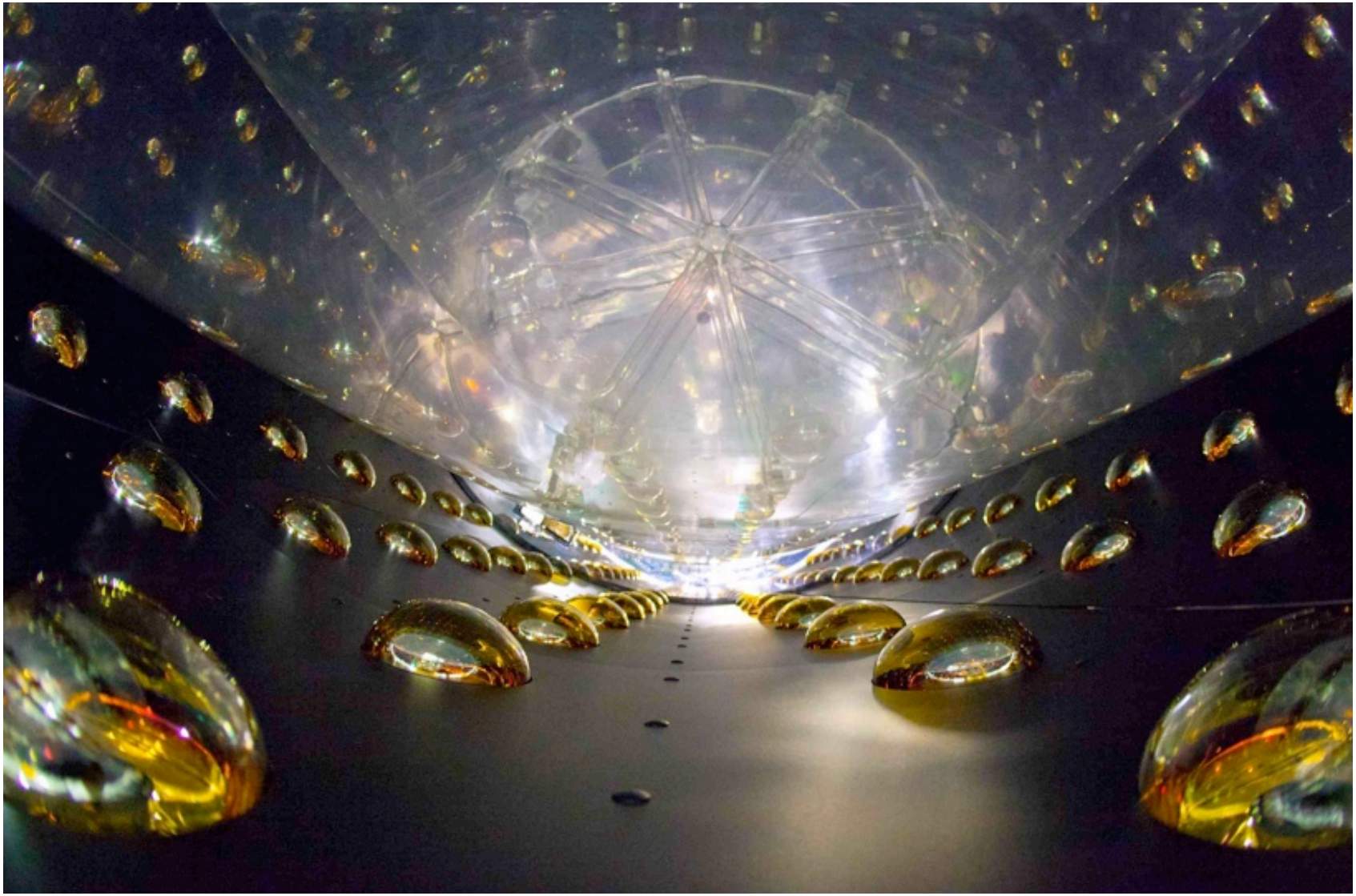
Antineutrino Detectors (ADs)



6 "functionally identical" ADs

- ~110 tons total
- ~20 tons Gd-doped LS
- ~20 tons LS
- ~40 tons mineral oil
- 192 8" PMTs

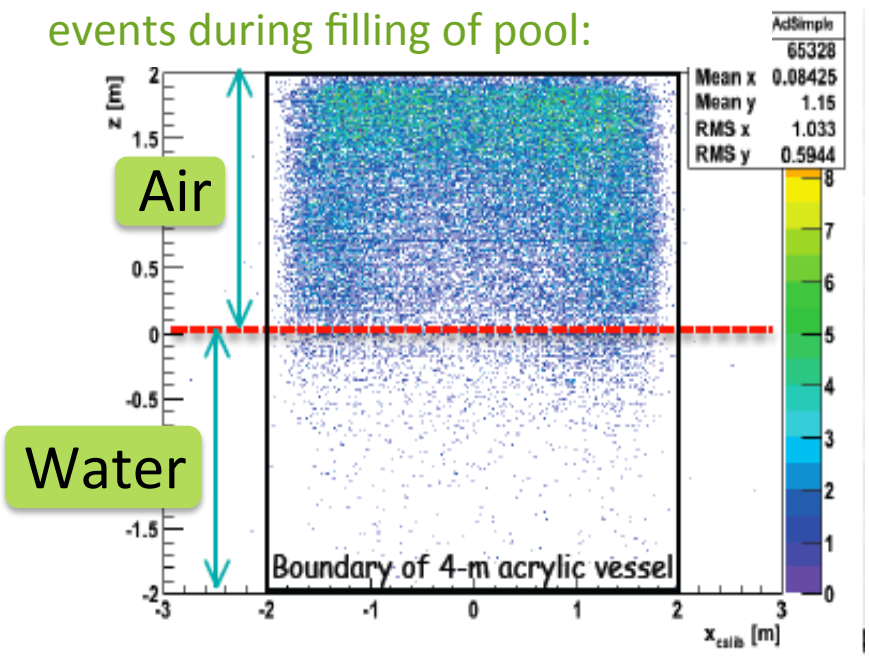
Interior of AD

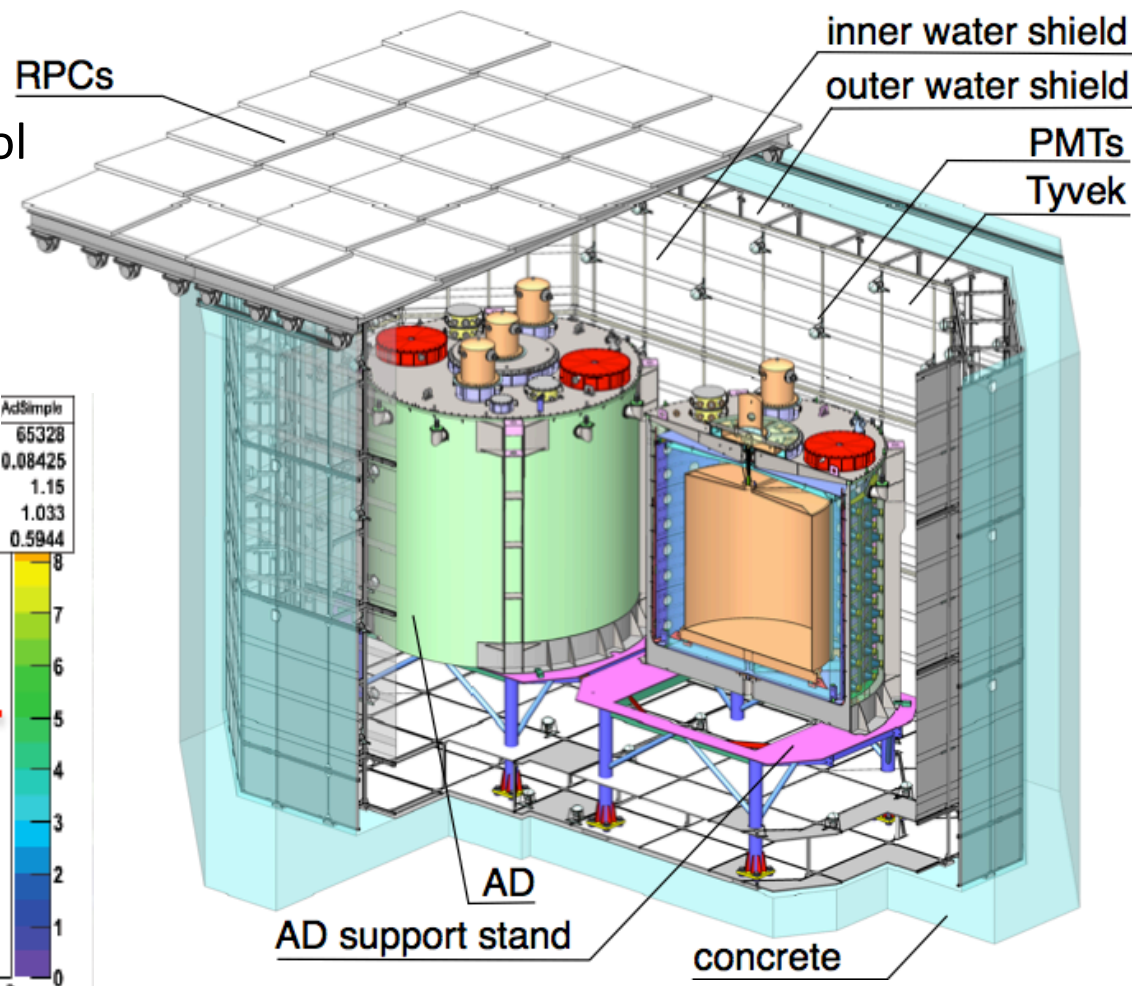


Muon Tagging System

- Water Pool acts as shield and Cerenkov detector
- 4-layer RPC modules above pool

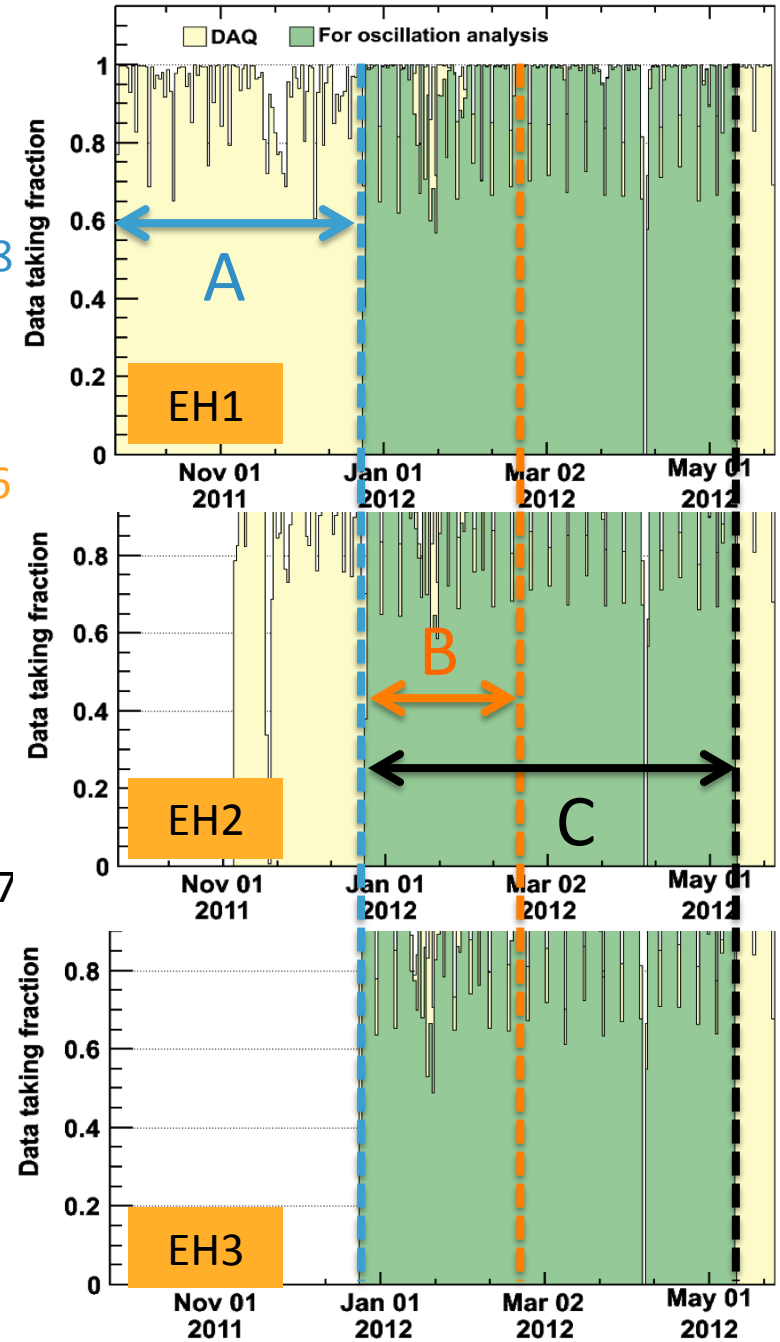
Passive shielding demonstration: reconstructed position of AD single events during filling of pool:





Data Collection

- **A. Two Detector Comparison:** arXiv: 1202.618
  - Sep. 23, 2011 – Dec. 23, 2011
  - Side-by-side comparison of two EH1 detectors
- **B. First Oscillation Result:** arXiv:1203.166
  - Dec. 24, 2011 – Feb. 17, 2012
  - All 3 halls (6 ADs) operating
  - First observation of $\bar{\nu}_e$ disappearance
- **C. Current Oscillation Result:** arXiv: 1210.6327
  - Dec 24, 2011 – May 11, 2012
  - More than 2.5x the previous data set
- **D. 6-AD Rate + Shape Analysis**
  - Dec 24, 2011 – July 28, 2012
  - Results coming soon



Data Analysis Strategy

$$\frac{N_f}{N_n} = \left(\frac{N_{p,f}}{N_{p,n}}\right)\left(\frac{L_n}{L_f}\right)^2\left(\frac{\epsilon_f}{\epsilon_n}\right)\left[\frac{P_{sur}(E, L_f)}{P_{sur}(E, L_n)}\right]$$

Number of anti-neutrinos detected

Detector target mass

Distance from reactor to detector

Detector efficiency

Oscillation survival probability

Blinded information:

- True target masses
- True distance from reactors to detectors
- True reactor flux history

Multiple Independent Analyses:

- Common data set
- Different
  - Energy calibration/reconstruction
  - Event selection/efficiency estimation
  - Background estimation
  - θ_{13} rate analysis
- All yield consistent results

Calibration: ACUs

Each ACU contains 3 sources on turntable:

^{68}Ge source

- 0 KE e^+ = 2×0.511 MeV γ
- 10 Hz

^{241}Am-^{13}C neutron source

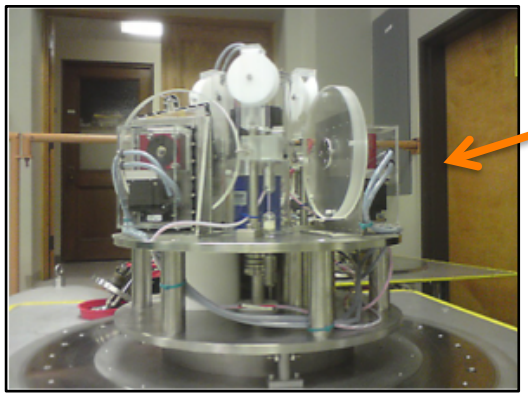
- 3.5 MeV n without γ
- 0.5 Hz

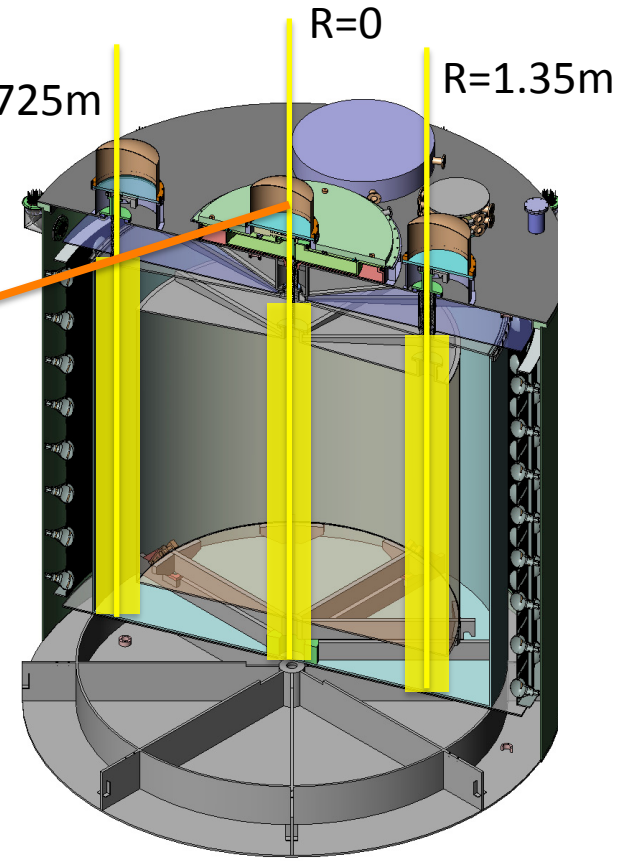
^{60}Co gamma source

- 1.173+1.332 MeV γ
- 100 Hz

LED diffuser ball

- 500 Hz





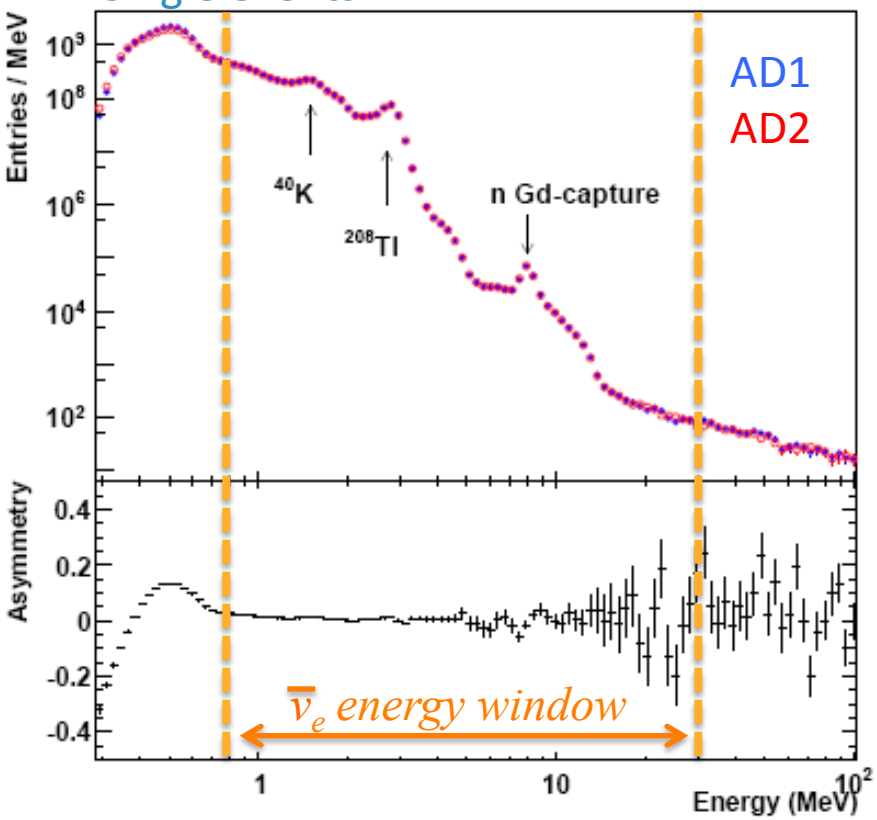
ACUs deploy sources along 3 axes: center of target, edge of target, center of gamma catcher

Calibration also makes use of spallation neutron data taken simultaneously with IBD data during regular physics data collection.

Side-by-Side Comparison

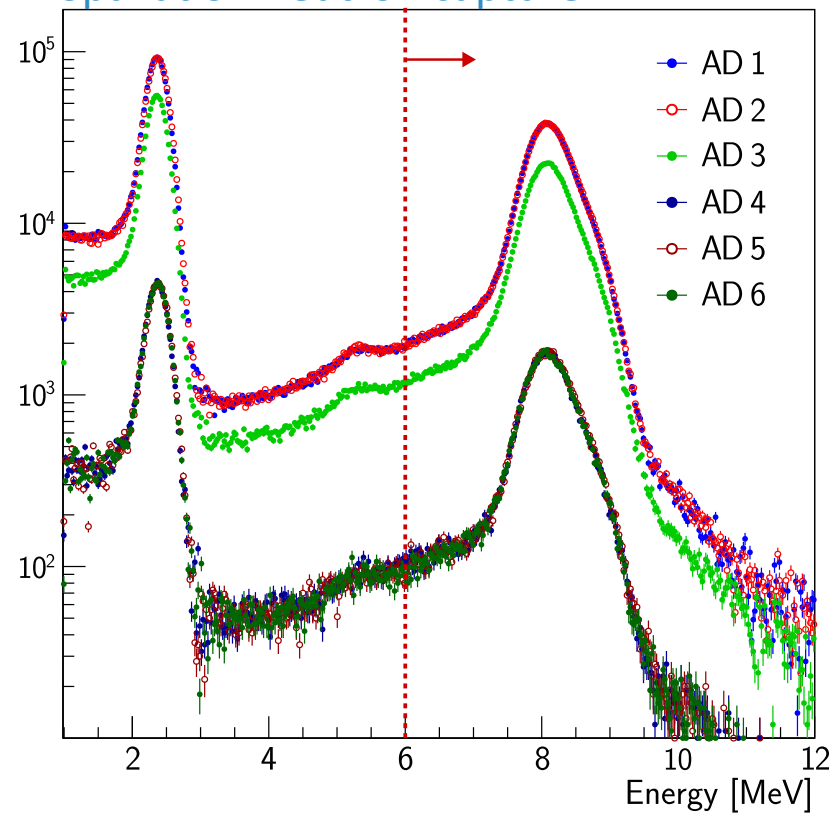
Detailed comparisons and crosschecks possible with multiple detectors.

Single events:



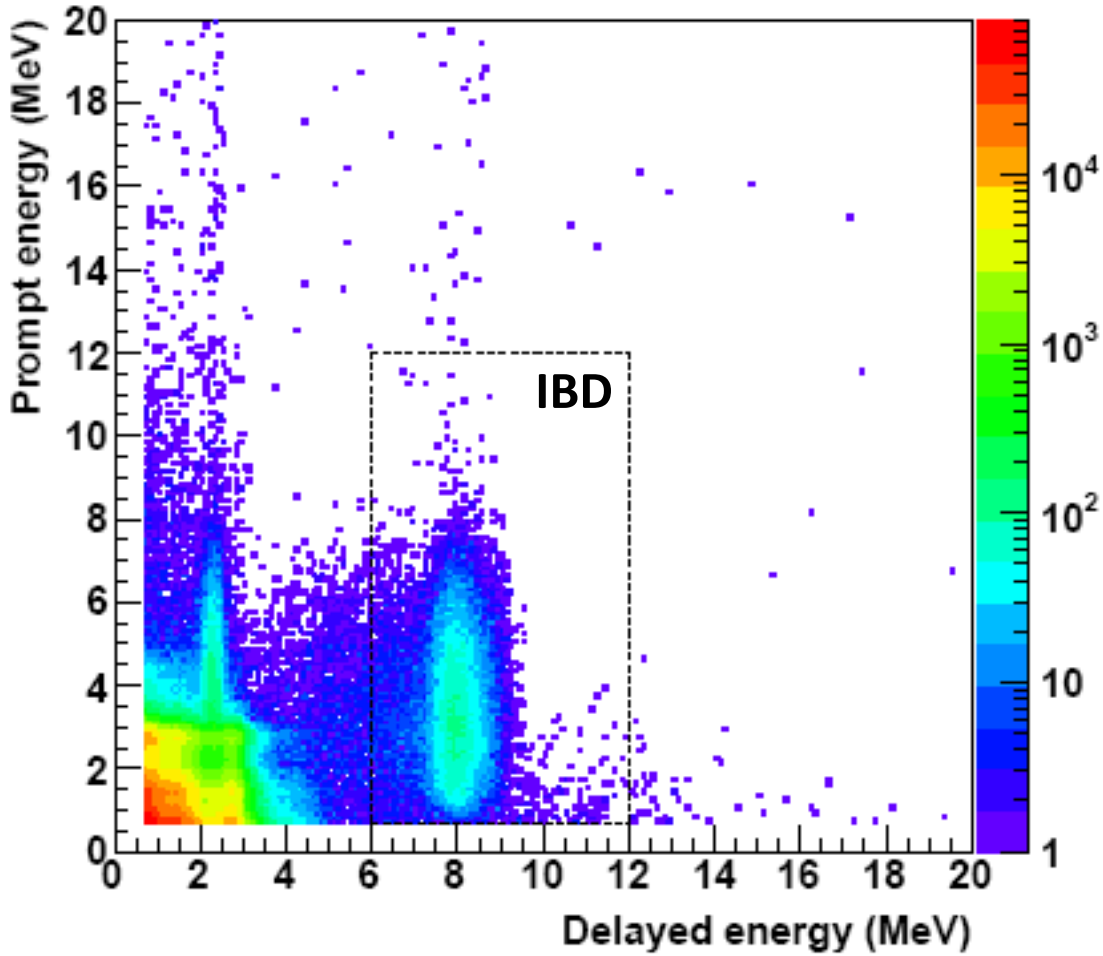
The two ADs in Hall 1 have functionally identical spectra and response.

Spallation neutron capture:



Response of all detectors to neutrons constrains largest uncorrelated systematic uncertainty.

Correlated IBD Signature

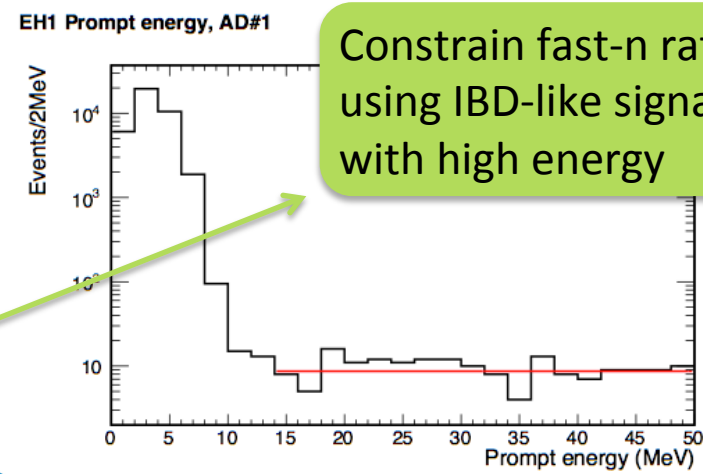


- IBD Selection
  - Reject "flashers"
  - Prompt positron: 0.7 MeV < E_p < 12 MeV
  - Delayed neutron: 6.0 MeV < E_d < 12 MeV
  - Capture Time: 1 μs < Δt < 200 μs
- Muon Veto
  - Pool muon: veto following 0.6 ms
  - AD muon (> 20 MeV): veto following 1 ms
  - AD shower muon (>2.5 GeV): veto following 1 s
- Multiplicity
  - No other signal > 0.7 MeV within ±200 μs of IBD

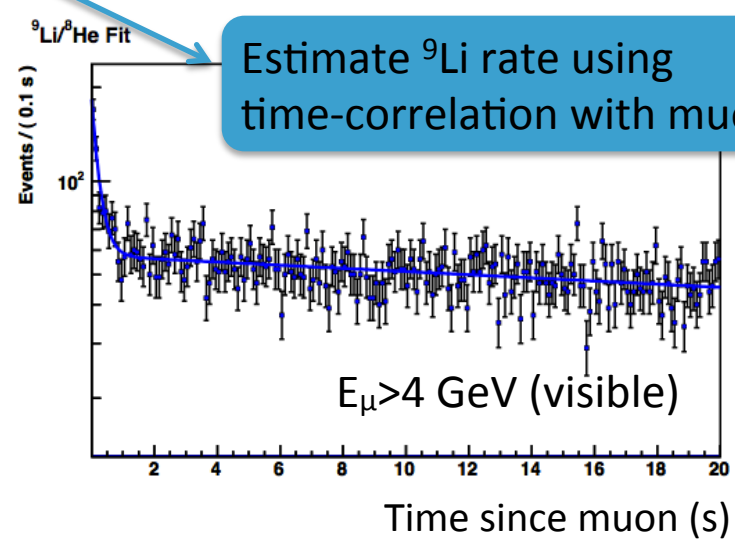
Clear separation of antineutrino IBD events from most other signals

Background

	Near Halls		Far Hall	
	B/S %	$\sigma_{B/S}$ %	B/S %	$\sigma_{B/S}$ %
Accidentals	1.5	0.02	4.0	0.05
Fast neutrons	0.12	0.05	0.07	0.03
^{9}Li/^{8}He	0.4	0.2	0.3	0.2
^{241}Am-^{13}C	0.03	0.03	0.3	0.3
^{13}C(α, n)^{16}O	0.01	0.006	0.05	0.03



Constrain fast-n rate using IBD-like signals with high energy



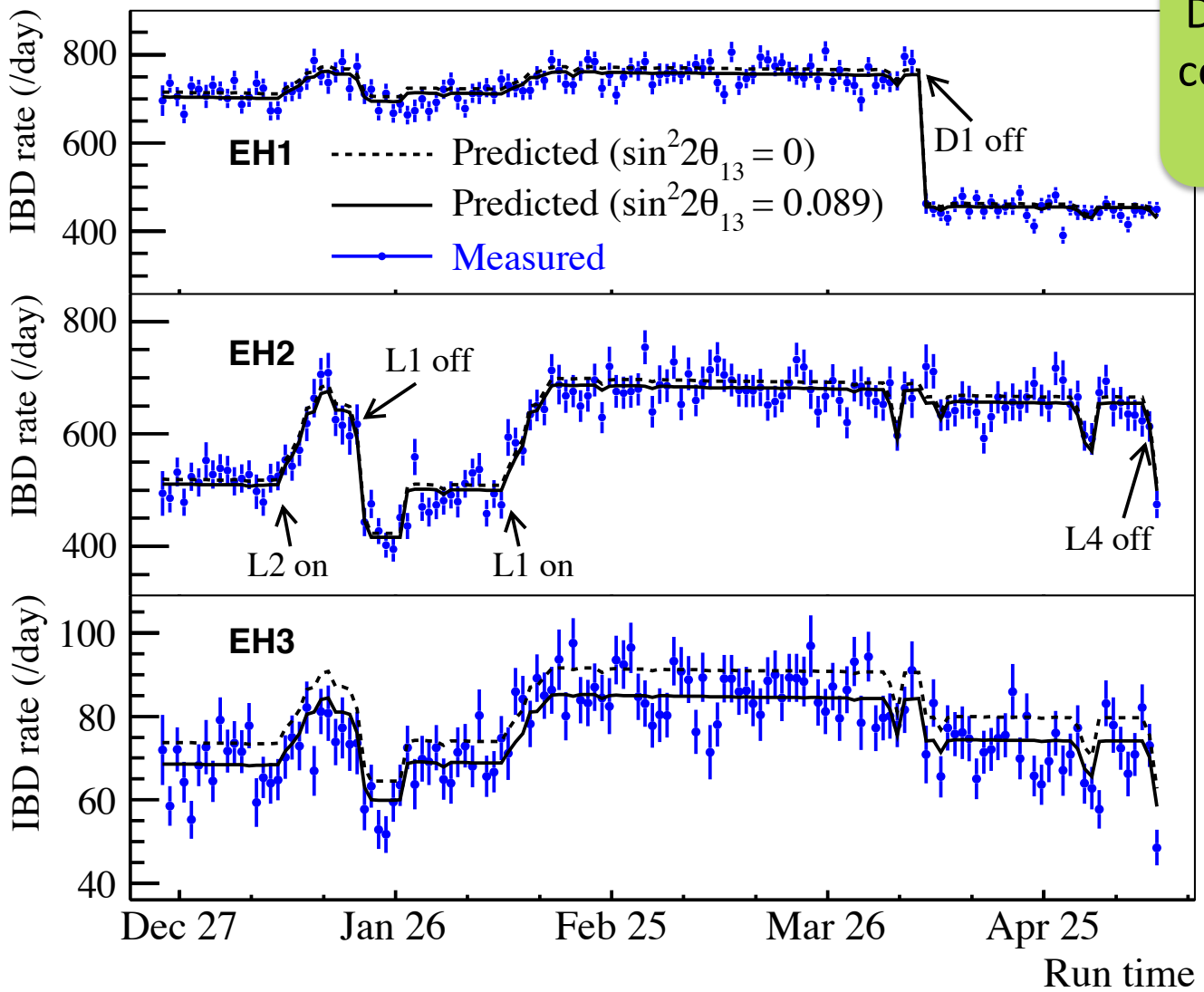
Estimate ^{9}Li rate using time-correlation with muon

- Total background:
- 5% (2%) in far (near) halls
- Uncertainty:
- 0.3% (0.2%) in far (near) halls

Data Summary

	AD1	AD2	AD3	AD4	AD5	AD6
Antineutrino candidates	**69121**	**69714**	**66473**	**9788**	**9699**	**9452**
DAQ live time (days)	127.5470		127.3763	126.2646		
Relative efficiency	0.8015	0.7986	0.8364	0.9555	0.9552	0.9547
Accidentals (/AD/day)	9.73±0.10	9.61±0.10	7.55±0.08	3.05±0.04	3.04±0.04	2.93±0.03
Fast Neutrons (/AD/day)	0.77±0.24	0.77±0.24	0.58±0.33	0.05±0.02	0.05±0.02	0.05±0.02
$^{8}He/^{9}Li$ (/AD/day)	2.9±1.5		2.0±1.1	0.22±0.12		
Am-C corr. (/AD/day)	0.2±0.2					
$^{13}C(\alpha, n)^{16}O$ (/AD/day)	0.08±0.04	0.07±0.04	0.05±0.03	0.04±0.02	0.04±0.02	0.04±0.02
Antineutrino Rate (/AD/day)	**662.47 ±3.00**	**670.87 ±3.01**	**613.53 ±2.69**	**77.57 ±0.85**	**76.62 ±0.85**	**74.97 ±0.84**

Antineutrino Rate vs. Time



Detected rate strongly correlated with reactor flux expectations.

Predicted Rate:
(in figure)

- Normalization is determined by fit to data
- Absolute normalization is within a few percent of expectations

Systematic Uncertainties

Detector	Efficiency	Correlated	Uncorrelated
Target Protons		0.47%	0.03%
Flasher cut	99.98%	0.01%	0.01%
Delayed energy cut	90.9%	0.6%	0.12%
Prompt energy cut	99.88%	0.10%	0.01%
Multiplicity cut		0.02%	<0.01%
Capture time cut	98.6%	0.12%	0.01%
Gd capture ratio	83.8%	0.8%	<0.1%
Spill-in	105.0%	1.5%	0.02%
Livetime	100.0%	0.002%	<0.01%
Combined	78.8%	1.9%	0.2%

Reactor			
Correlated		Uncorrelated	
Energy/fission	0.2%	Power	0.5%
$\bar{\nu}_e$/fission	3%	Fission fraction	0.6%
		Spent fuel	0.3%
Combined	3%	Combined	0.8%

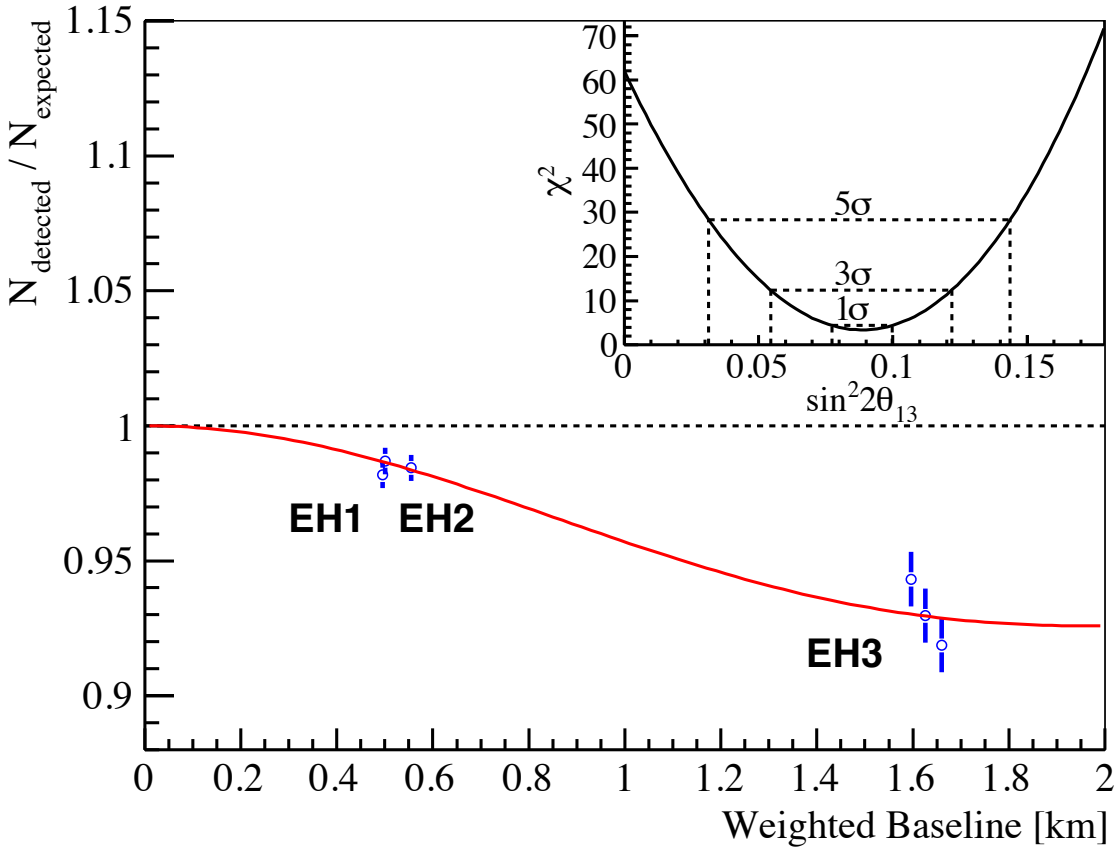
For oscillation analysis, only **uncorrelated** uncertainties are used.

Largest systematic uncertainties:

- Delayed energy cut
- Gd capture ratio
- Smaller than far site statistical uncertainty

Influence of uncorrelated reactor systematics (0.8%) is only **0.04%** on oscillation analysis.

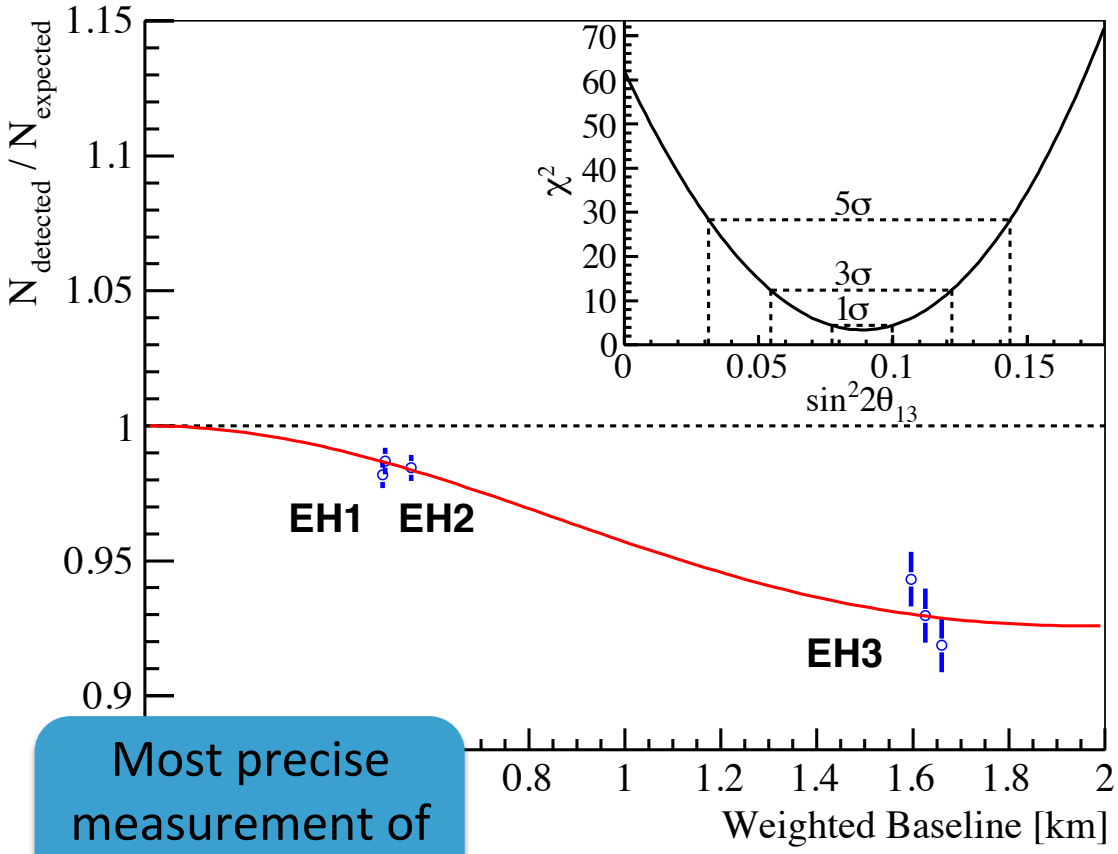
$\sin^2(2\theta_{13})$: Rate Analysis



- Uses standard χ^2 approach
- Far vs. near relative measurement
- Absolute rate is **not** constrained
- Consistent results obtained by independent analyses, different reactor flux models

$$\chi^2 = \sum_{d=1}^{6} \frac{\left[M_d - T_d\left(1+\varepsilon+\sum_r \omega_r^d \alpha_r + \varepsilon_d\right)+\eta_d\right]^2}{M_d + B_d} + \sum_r \frac{\alpha_r^2}{\sigma_r^2} + \sum_{d=1}^{6}\left(\frac{\varepsilon_d^2}{\sigma_d^2} + \frac{\eta_d^2}{\sigma_B^2}\right)$$

$\sin^2(2\theta_{13})$: Rate Analysis

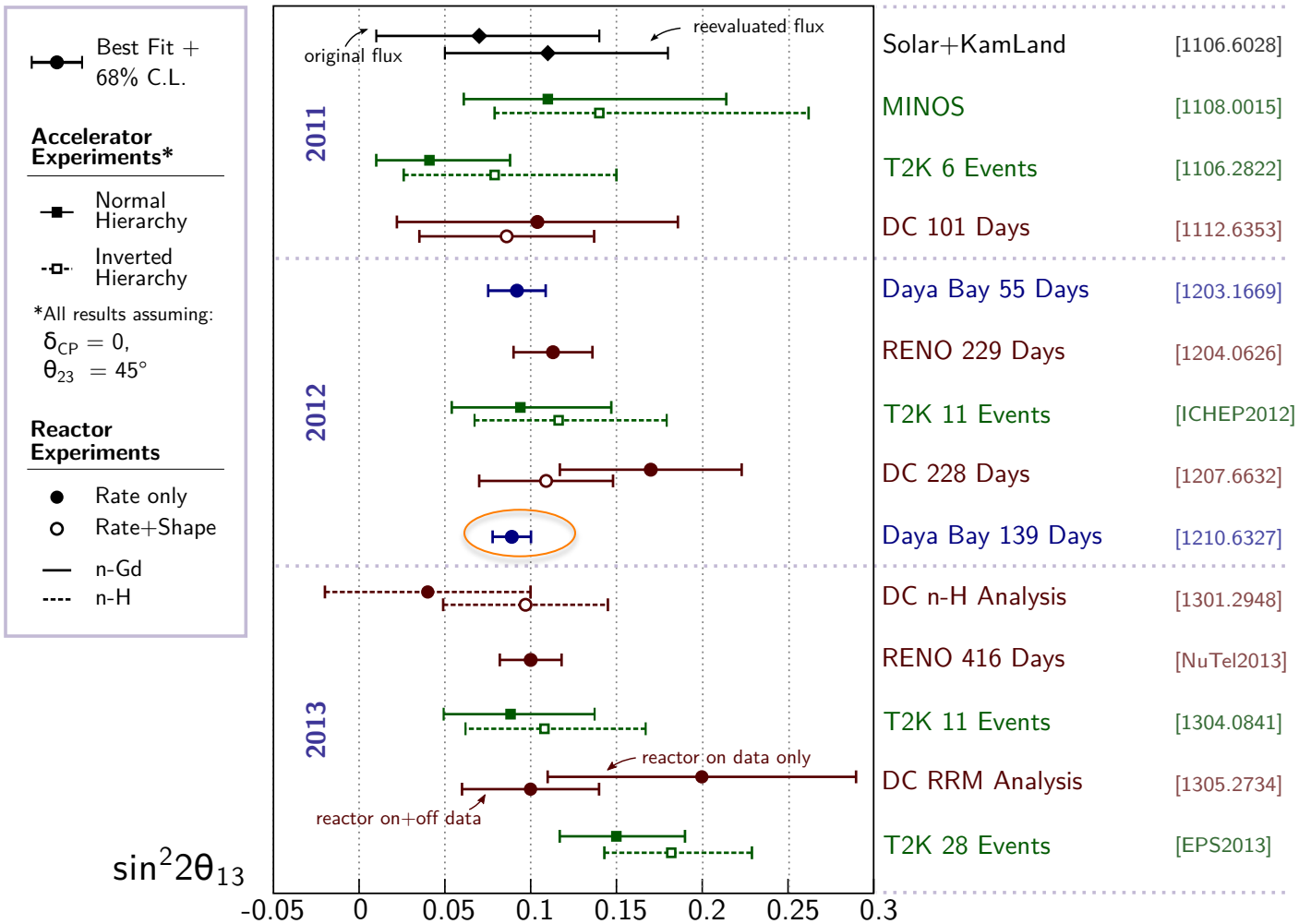


- Uses standard χ^2 approach
- Far vs. near relative measurement
- Absolute rate is **not** constrained
- Consistent results obtained by independent analyses, different reactor flux models

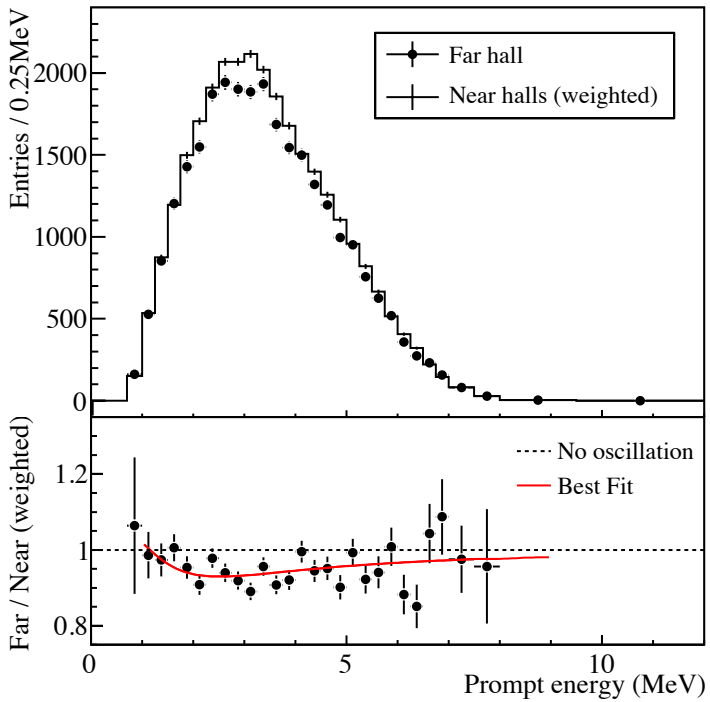
Most precise measurement of $\sin^2 2\theta_{13}$ to date

$$\sin^2 2\theta_{13} = 0.089 \pm 0.010\ (\text{stat}) \pm 0.005\ (\text{syst})$$

$\sin^2(2\theta_{13})$: Global Results



Far vs. Near Comparison



- Measurement of $\sin^2(2\theta_{13})$ is based only on deficit in rate of observed events at far site:

$R = N_{obs}/N_{exp} = 0.944 \pm 0.007$ (stat) ± 0.003 (syst)

Clear observation of far site deficit

Spectral distortion consistent with oscillation.*

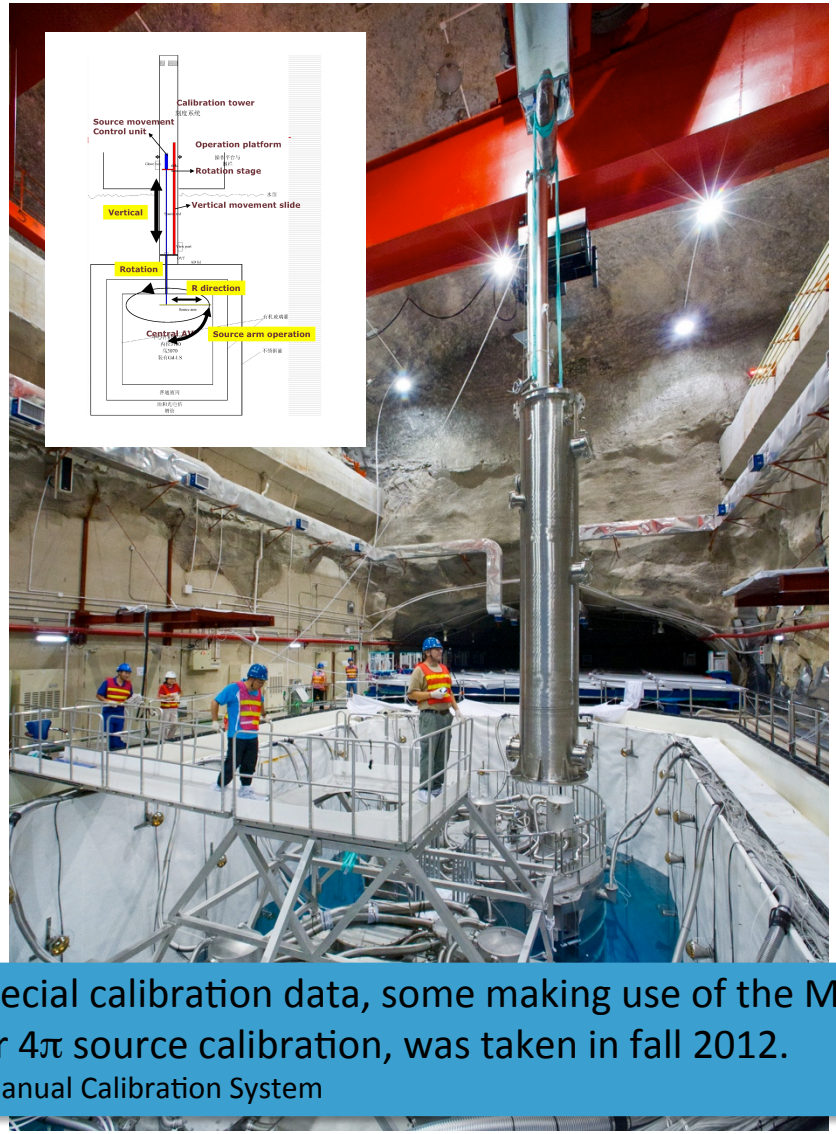
*Spectral systematics not fully studied;

θ_{13} value from shape analysis not recommended.

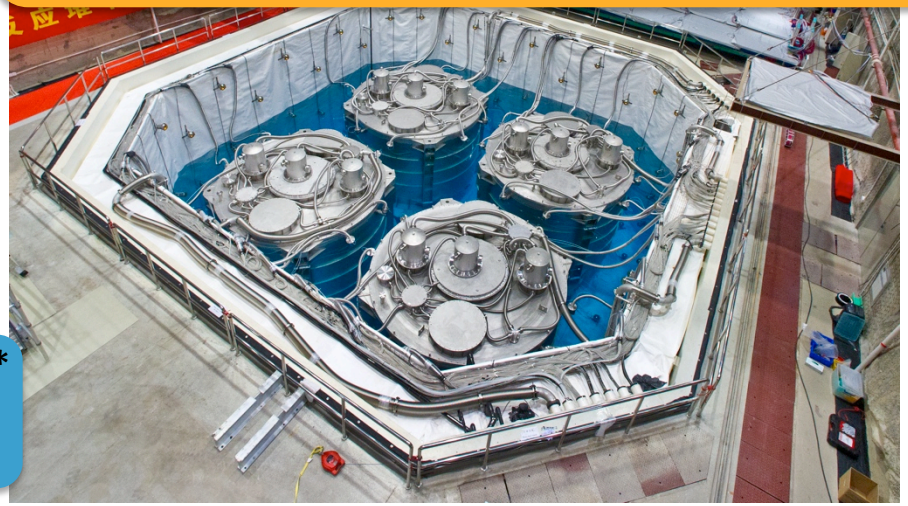
Rate + shape analysis in progress:

- Full analysis of spectral shape requires understanding of:
  - Spectral shape of background
  - Detector energy response
- Sensitive to both $\sin^2(2\theta_{13})$ and $|\Delta m^2_{ee}|$
- Rate + shape analysis using full 6-AD data period to be announced soon

Recent Activity

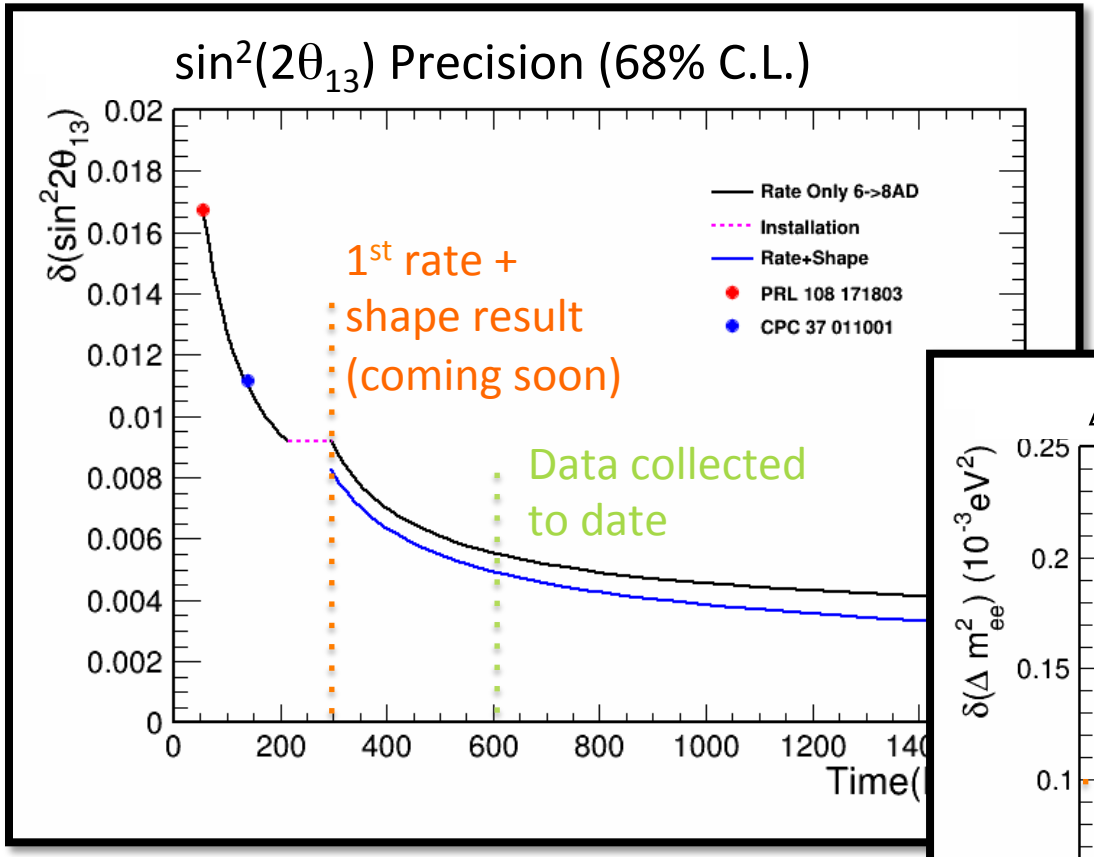


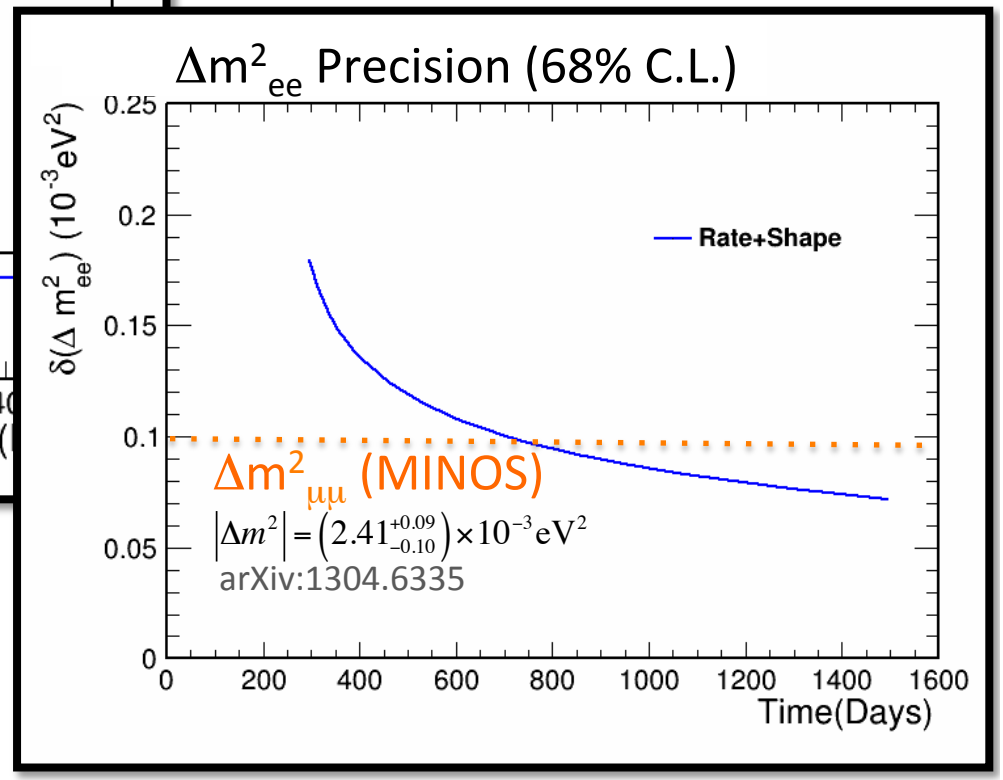
Final 2 ADs installed fall 2012.
Daya Bay has been taking data with 8 ADs since October 2012.



Special calibration data, some making use of the MCS* for 4π source calibration, was taken in fall 2012.
*Manual Calibration System

Projected Daya Bay Precision





Summary

- The Daya Bay reactor neutrino experiment has made an unambiguous observation of reactor electron-antineutrino disappearance at ~2 km:

  R = 0.944 ± 0.007 (stat) ± 0.003 (syst)
- Interpretation of disappearance as neutrino oscillation yields:

  $\sin^2 2\theta_{13}$ = 0.089 ± 0.010 (stat) ± 0.005 (syst)
- Special calibration data, including 4π calibration of AD1, was taken in fall 2012.
- Final two ADs were installed in fall 2012. Daya Bay has been taking 8-AD data since October 2012.
- Rate + shape measurement of $\sin^2(2\theta_{13})$ and $|\Delta m^2_{ee}|$ coming soon.