FPCP 2012

Status of Daya Bay: Observation of Electron-Antineutrino Disappearance

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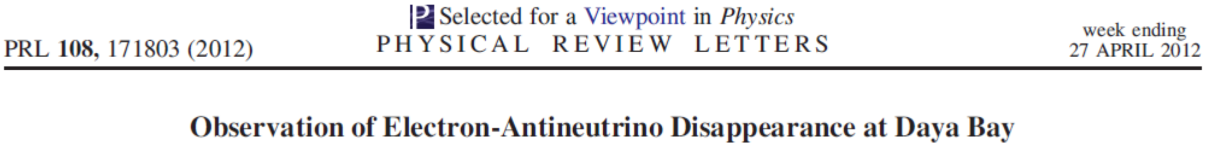
On behalf of the Daya Bay Collaboration



Selected for a Viewpoint in *Physics*

PRL **108,** 171803 (2012)

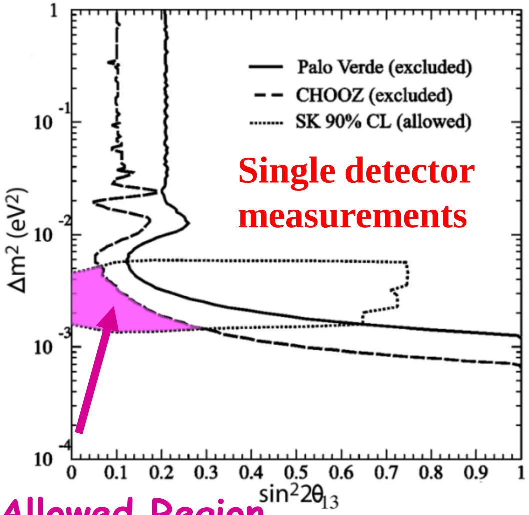
PHYSICAL REVIEW LETTERS

week ending
27 APRIL 2012

Observation of Electron-Antineutrino Disappearance at Daya Bay

Pre-2012 Knowledge on θ_{13}

Upper limit from reactors

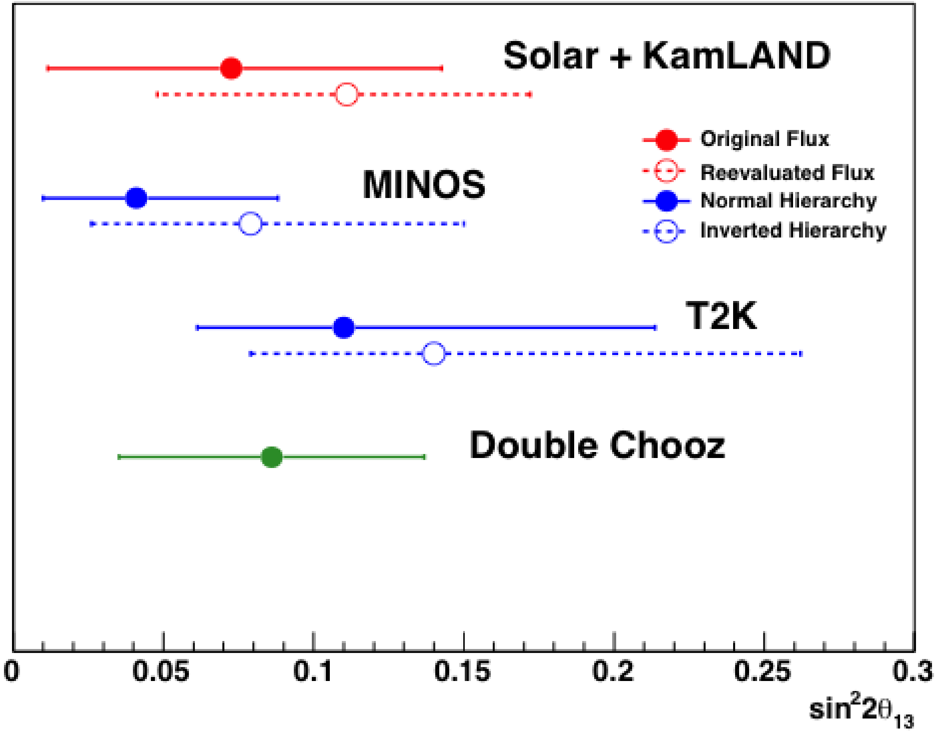


Single detector measurements

Allowed Region

$\sin^2 2\theta_{13} < 0.17$ (90% c.l.)

2011 has given many hints:

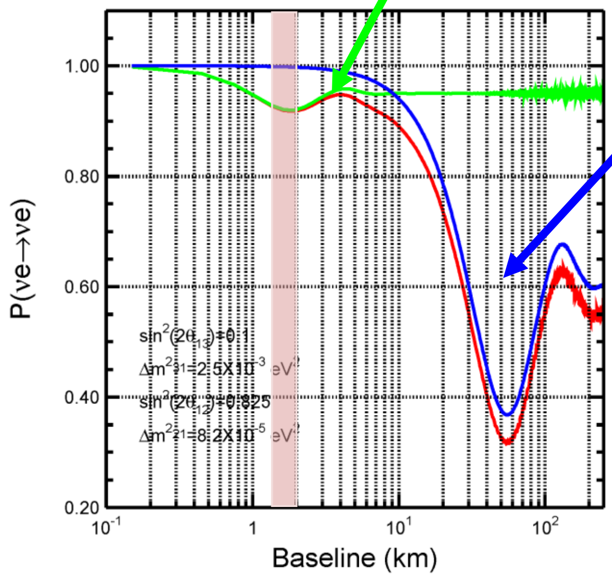


Solar + KamLAND: G.L.Fogli *et al.*, Phys. Rev. D 84, 053007 (2011)
T2K: K. Abe *et al.*, Phys. Rev. Lett. 107 041801 (2011)
MINOS: P. Adamson *et al.*, Phys. Rev. Lett. 107, 181802 (2011)
Double CHOOZ: Y. Abe *et al.*, arXiv:1112.6353

Measurement of θ_{13}: $\overline{\nu_e}$ Disappearance at Reactors

$$\frac{N_{obs}}{N_{\exp}} = 1 - \boxed{\sin^2 2\theta_{13} \sin^2(1.27\Delta m_{13}^2 \frac{L}{E})} - \boxed{\cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2(1.27\Delta m_{12}^2 \frac{L}{E})}$$

Osc prob. (integrated over E) vs distance



Game Plan:

$$P_{survival} = \frac{N_{obs}}{N_{\exp}} < 1$$?

Large oscillation >50 km; negligible <2 km

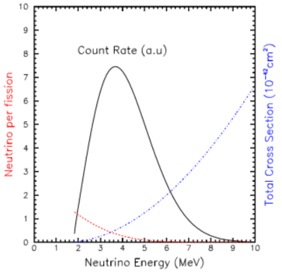
Disappearance of reactor $\overline{\nu_e}$ at ~2 km ⇒ unambiguous measurement of θ_{13}

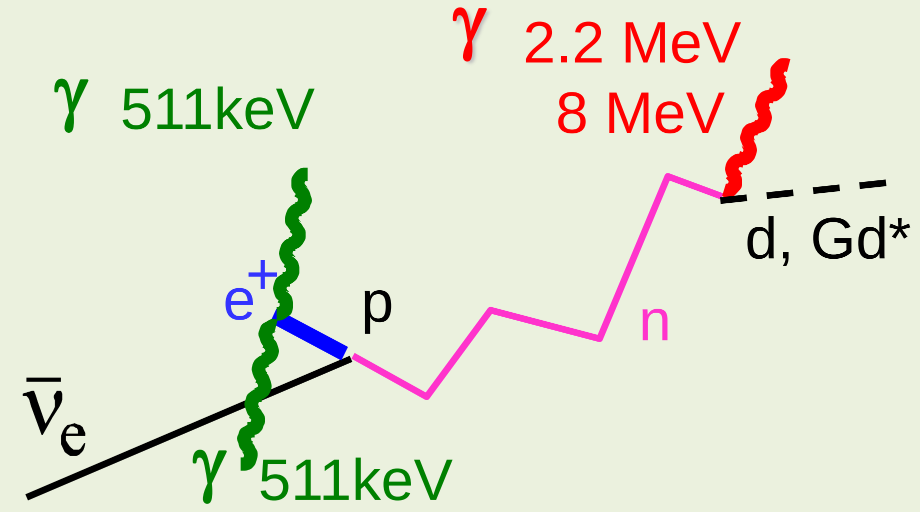
How to Measure $\overline{\nu}_e$

Use liquid scintillator ~ CH2 doped with Gd

Inverse Beta Decay

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





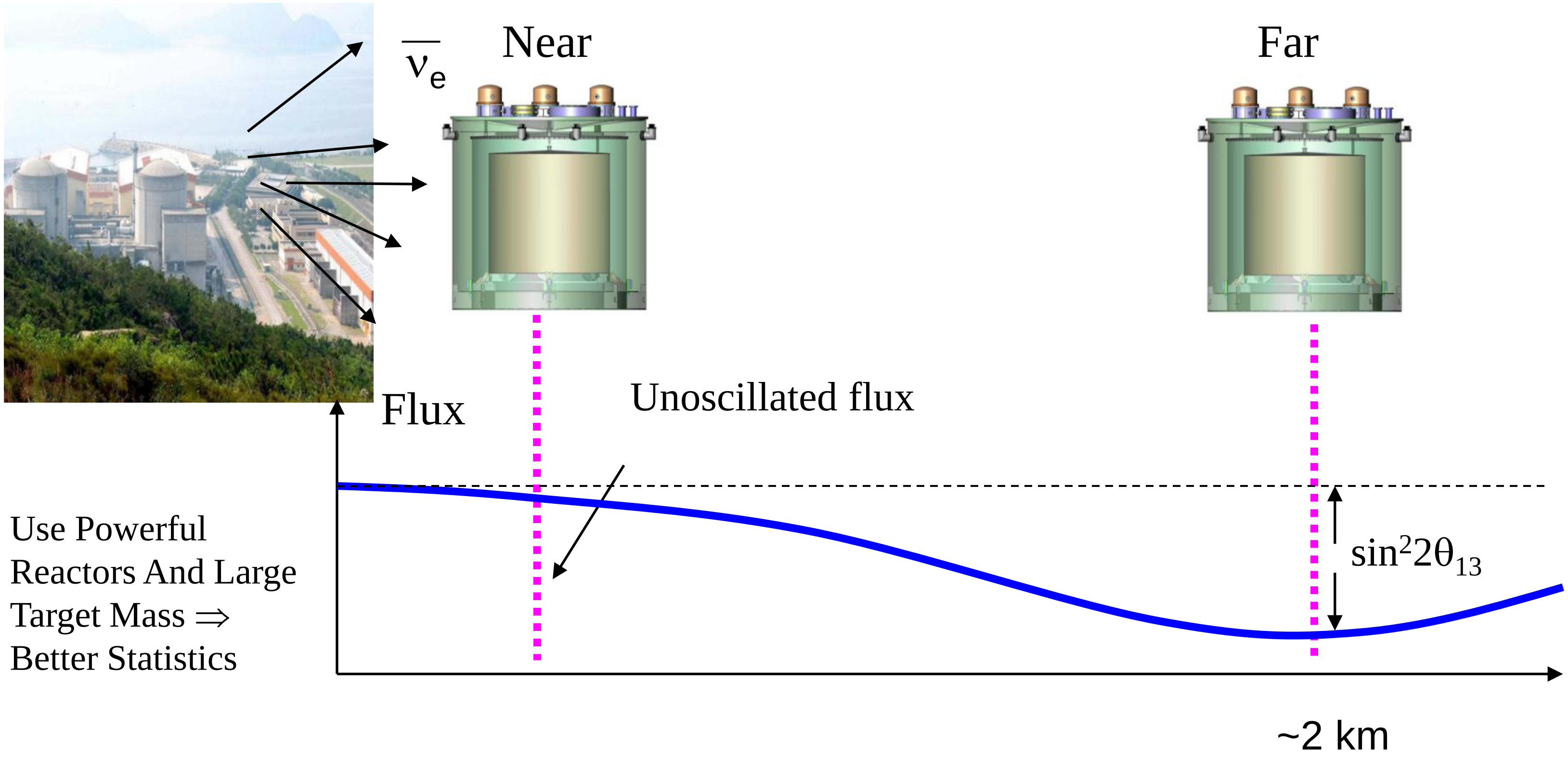
Coincidence signal: detect

Prompt: e^+ annihilation $E_\nu = KE_{e+} + 1.8$ MeV

Delayed: **n** capture on proton (2.2 MeV) or Gd (8 MeV)

Δt (delayed-prompt) ~ 28 usec for 0.1% Gd-doped LS

Push the Precision



Use Powerful Reactors And Large Target Mass ⇒ Better Statistics

- Use identical near/far detector pair

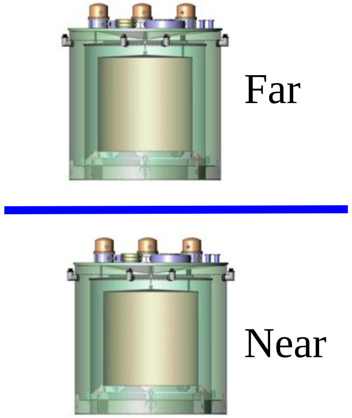
- Go deeper underground

Optimize the baseline:

$\Delta m_{13}^2 \sim 2.5\times10^{-3}$ eV^2, E~4 MeV, optimal L ~2 km

Relative Measurement

New Game Plan:



Systematics:

- ~~Reaction cross section~~
- ~~Reactor power~~
- ~~Number of protons in tar~~get
- ~~Detector efficiencies~~

$$\frac{N_f}{N_n} = \cancelto{1}{\left(\frac{N_{p,f}}{N_{p,n}}\right)} \left(\frac{L_n}{L_f}\right)^2 \cancelto{1}{\left(\frac{\varepsilon_f}{\varepsilon_n}\right)} \boxed{\frac{P_{survival}(E,L_f)}{P_{survival}(E,L_n)}} \Rightarrow \sin^2 2\theta_{13}$$

≀

$1-0.6\sin^2 2\theta_{13}$ @ Daya Bay

Daya Bay Collaborations

Europe (2)

JINR, Dubna, Russia

Charles University, Czech Republic

North America (16)

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

Asia (20)

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

~230 Collaborators

Daya Bay

Powerful nuclear power plant (top 5 in the world) by mountain

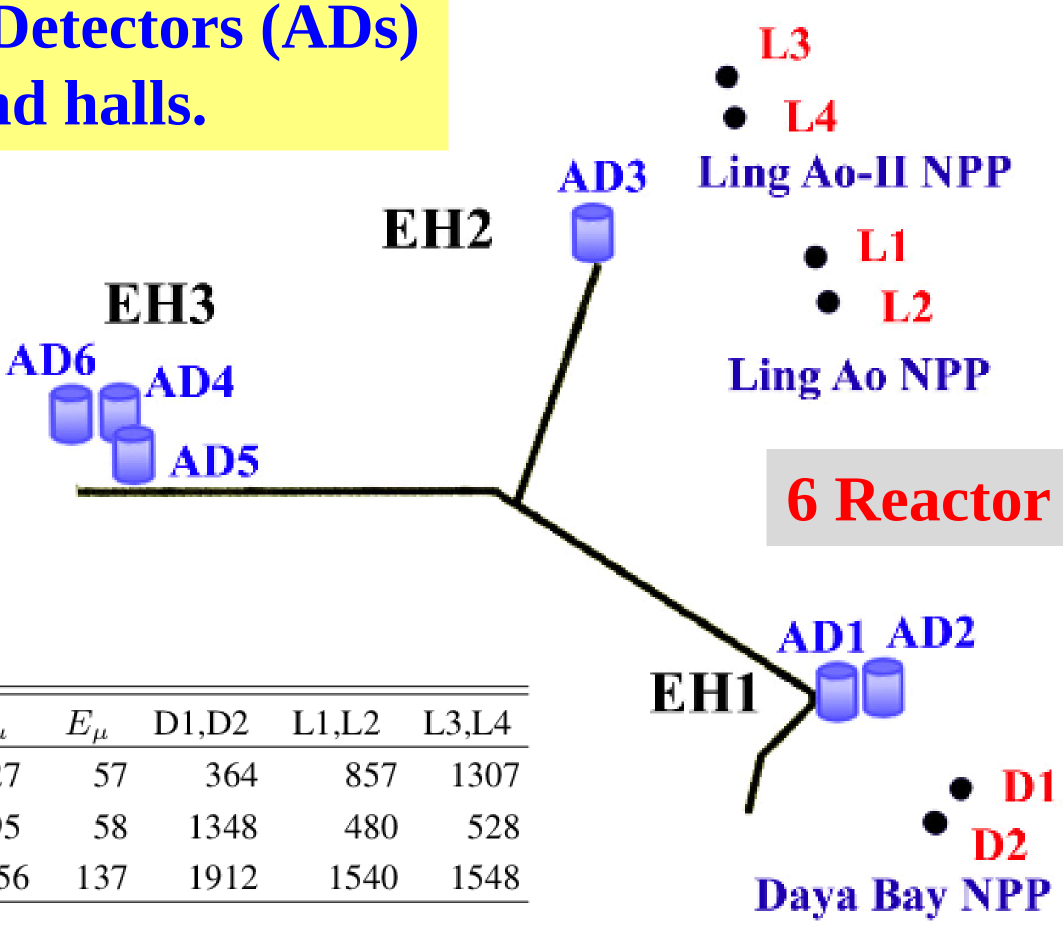
Daya Bay NPP $2.9\mathrm{GW}_{th}\times 2$

LingAo NPP $2.9\mathrm{GW}_{th}\times 2$

LingAo II NPP $2.9\mathrm{GW}_{th}\times 2$

Experiment Layout

6 Antineutrino Detectors (ADs) in 3 underground halls.

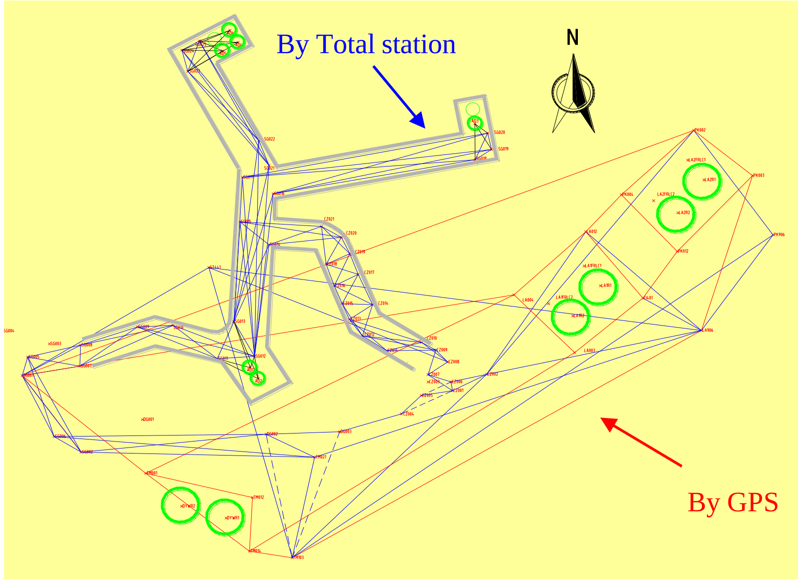


6 Reactor Cores

	Overburden	R_μ	E_μ	D1,D2	L1,L2	L3,L4
EH1	280	1.27	57	364	857	1307
EH2	300	0.95	58	1348	480	528
EH3	880	0.056	137	1912	1540	1548

TABLE I. Overburden (m.w.e), muon rate R_μ (Hz/m^2), and average muon energy E_μ (GeV) of the three EHs, and the distances (m) to the reactor pairs.

Experiment Survey



Detailed Survey:

- GPS above ground
- Modern theodolites underground
- Final precision: 28mm

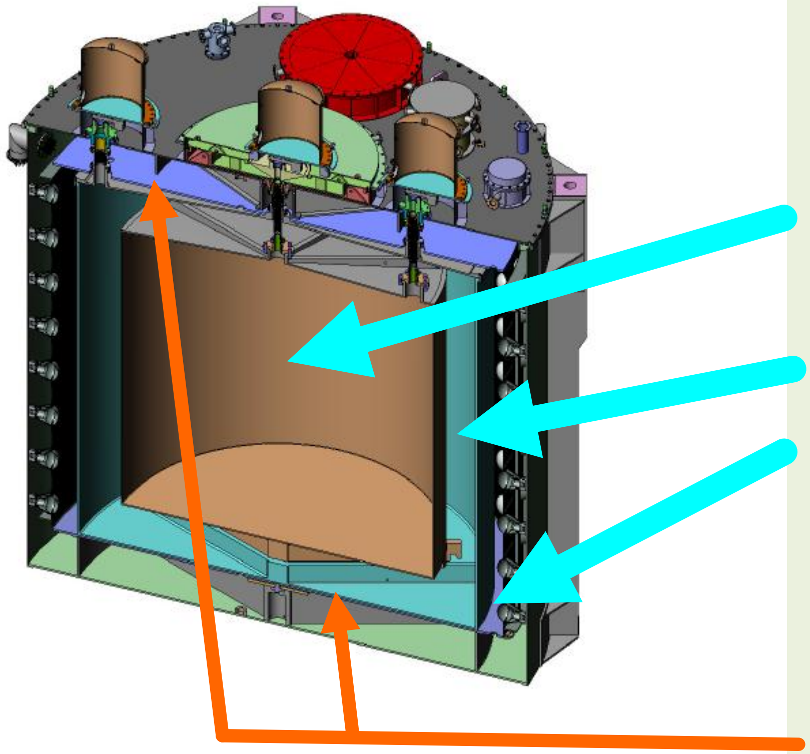
Validation:

- Three independent calculations
- Cross-check survey
- Consistent with reactor plant and design plans

Negligible reactor flux uncertainty (<0.02%) from precise survey.

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

Detector Design



Cylindrical 3-zone Structure
Separated By Acrylic Vessels:

I.Target: 0.1% Gd-loaded liquid scintillator, 20 ton

II. Gamma-catcher: liquid scintillator,

III. Buffer shielding: mineral oil

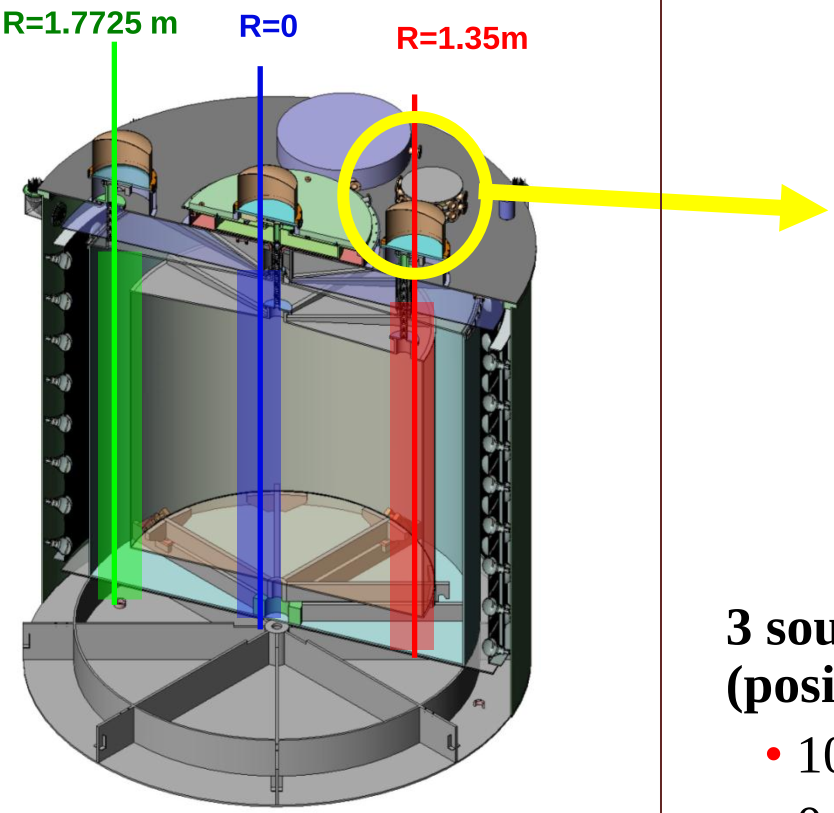
Acyrlic vessel thickness: 1.5 cm (outer) and 1 cm (inner)

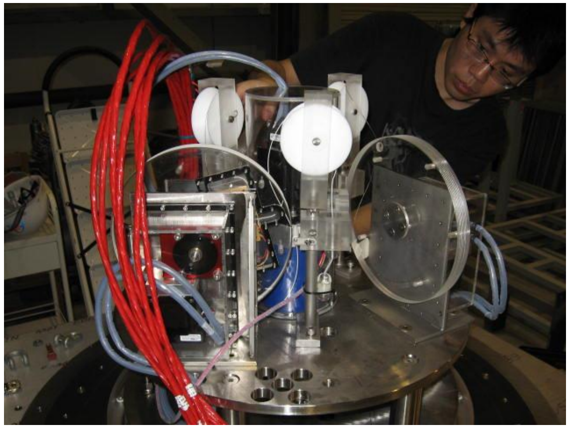
192 8” PMT’s on circumference and reflective reflectors on top and bottom.

6 ‘functionally identical’ detectors:
Reduce systematic uncertainties

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

Automated Calibration System



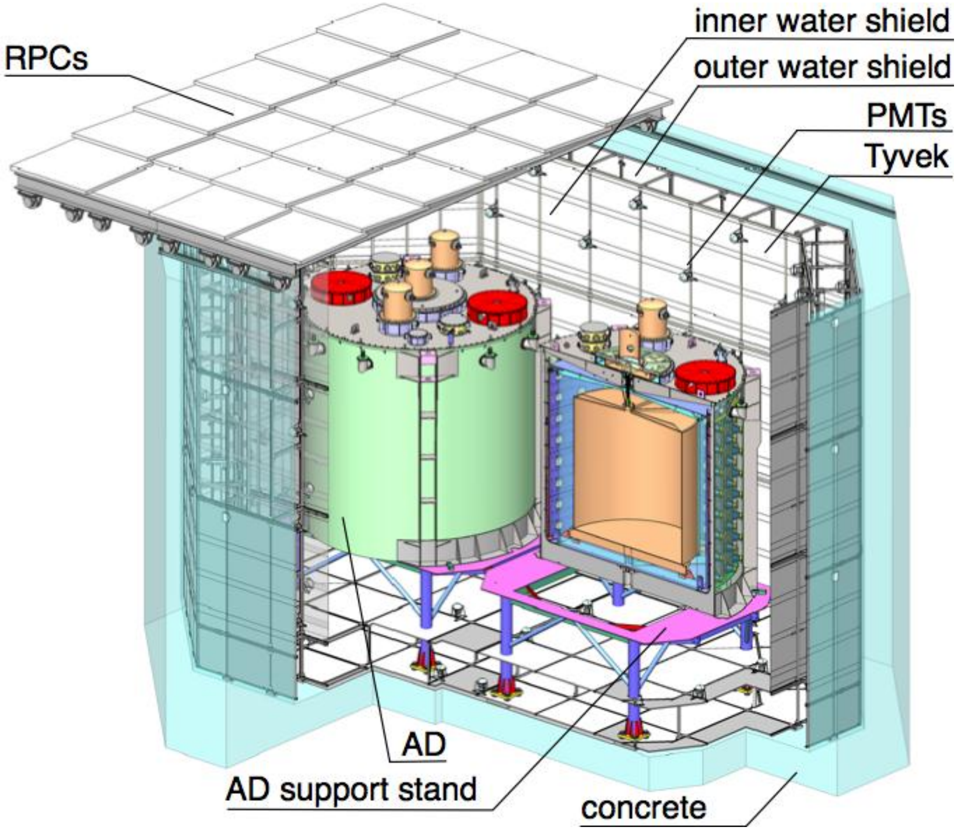


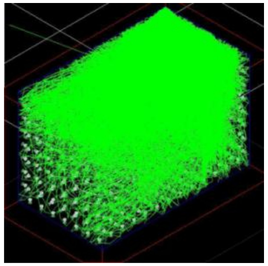
Three axes: center, edge of target, middle of gamma catcher

3 sources for each z axis on a turntable (position accuracy < 5 mm):

- 10 Hz ^{68}Ge
- 0.5 Hz ^{241}Am-^{13}C neutron source + 100 Hz ^{60}Co gamma source
- LED diffuser ball (500 Hz)

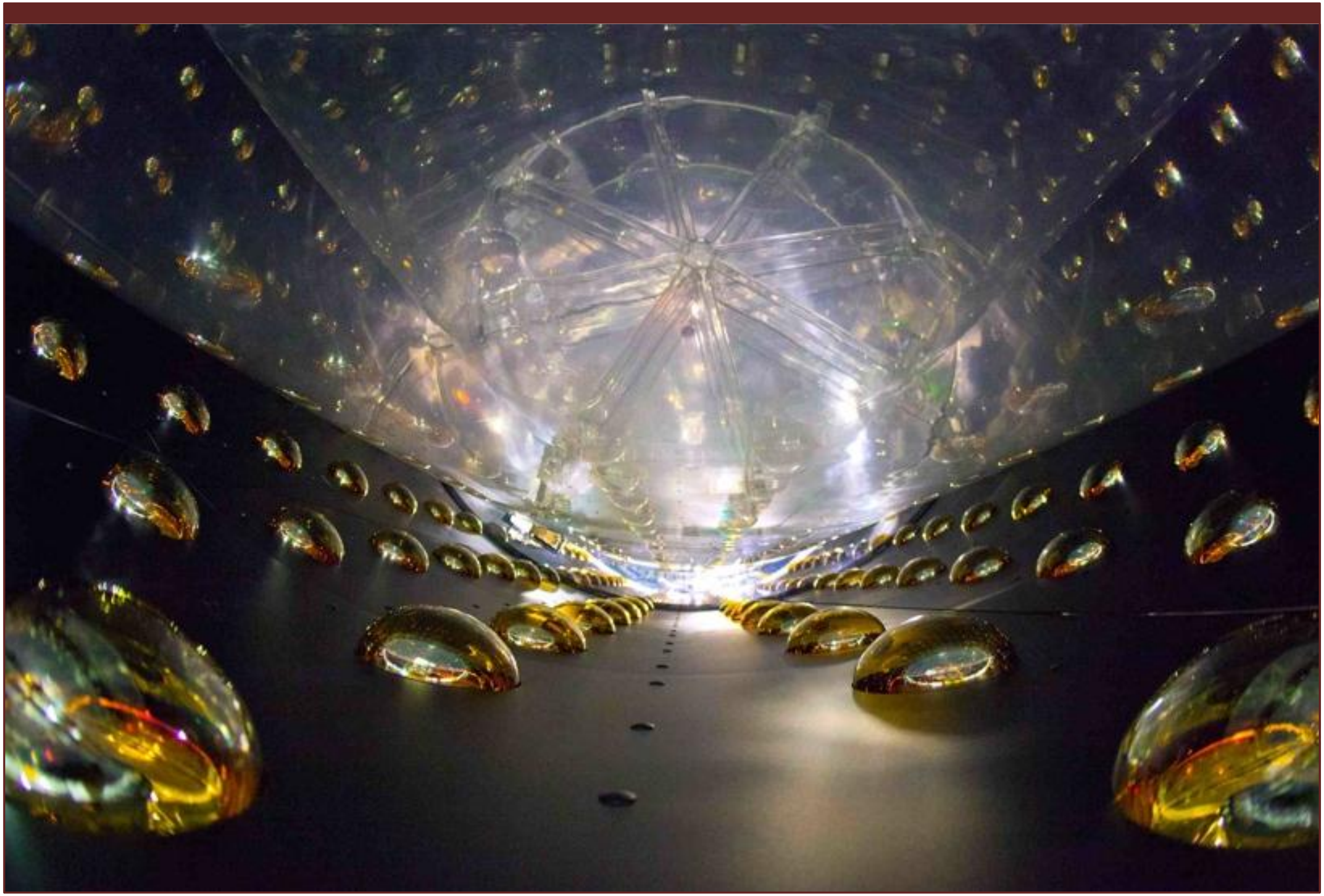
Muon Detector



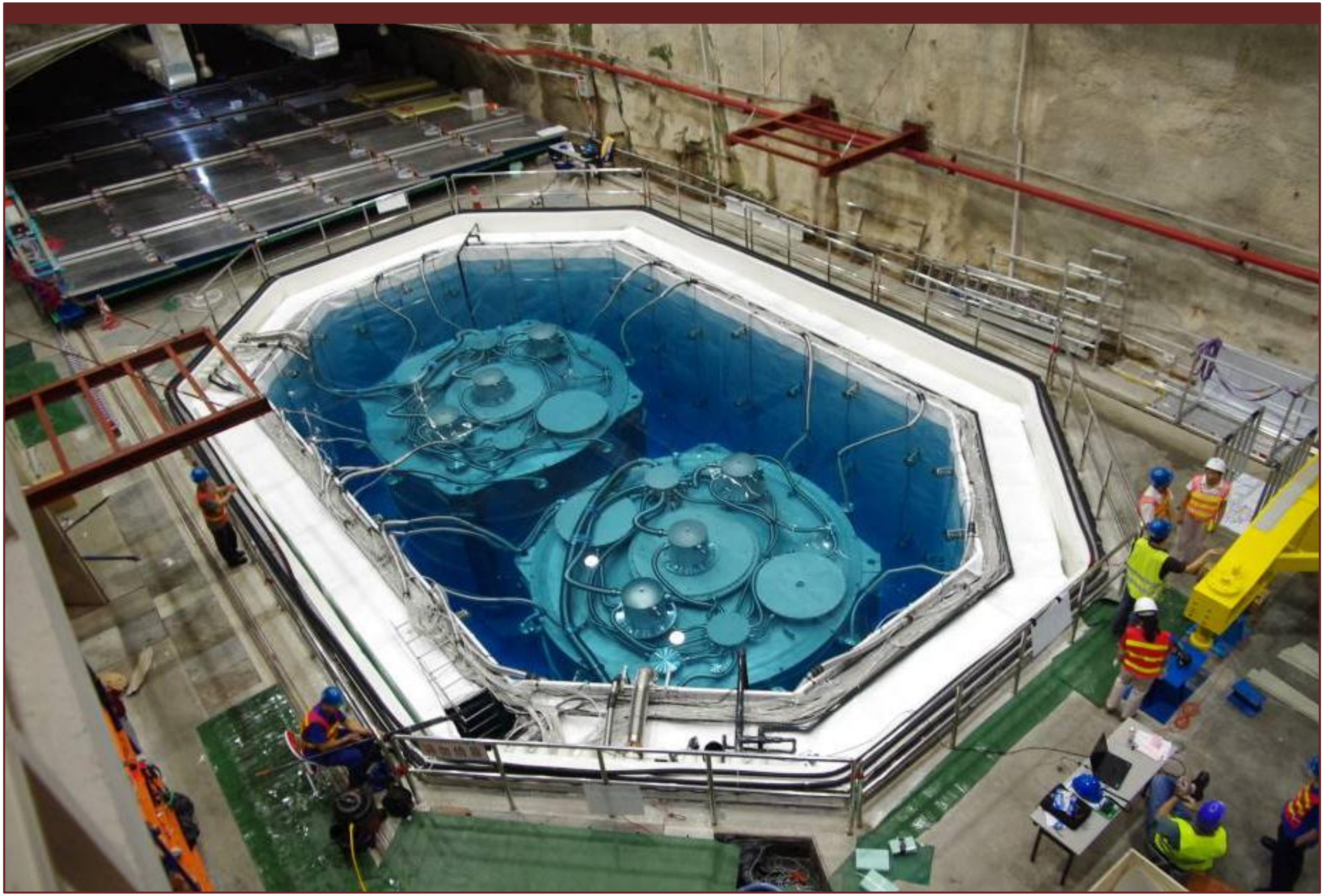


- Outer layer of water veto (on sides and bottom) is 1m thick, inner layer >1.5m. Water extends 2.5m above ADs
- 4-layer RPC modules above pool
- Efficiency:
  - Water > 97%
  - RPC > 88%

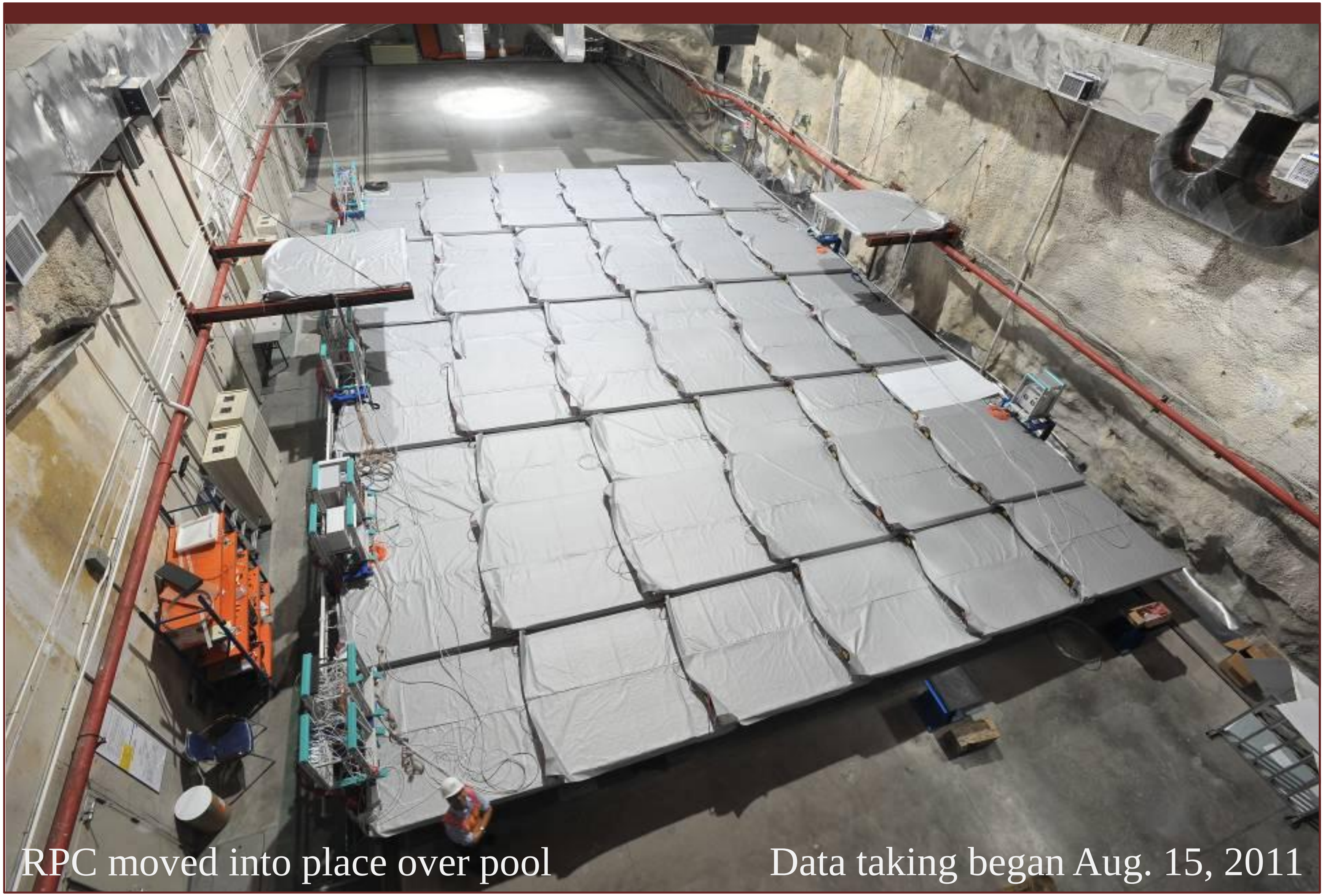
Interior of Antineutrino Detector



EH1: Pool Filled



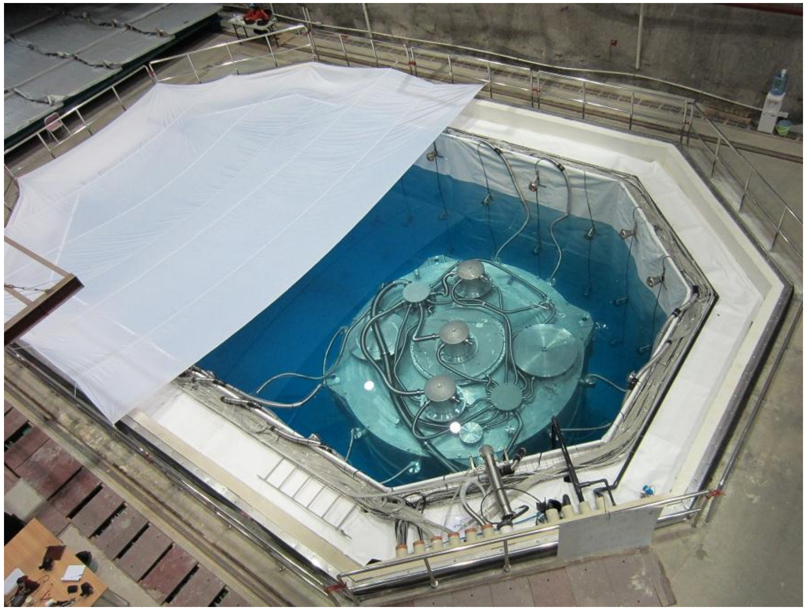
Hall 1: Completed



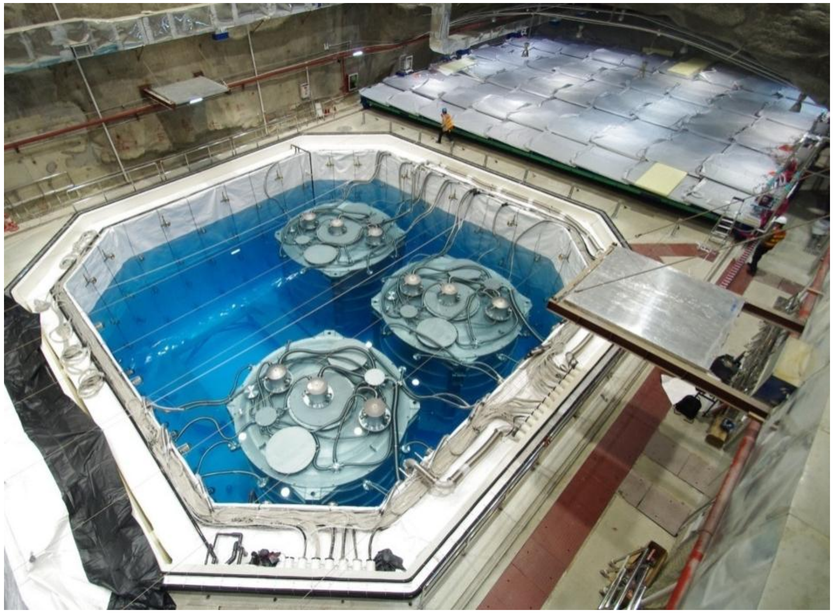
RPC moved into place over pool

Data taking began Aug. 15, 2011

Hall 2 and Hall 3



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



Hall 3: Began 3 AD operation on Dec. 24, 2011

2 more ADs still in assembly; installation planned for Summer 2012

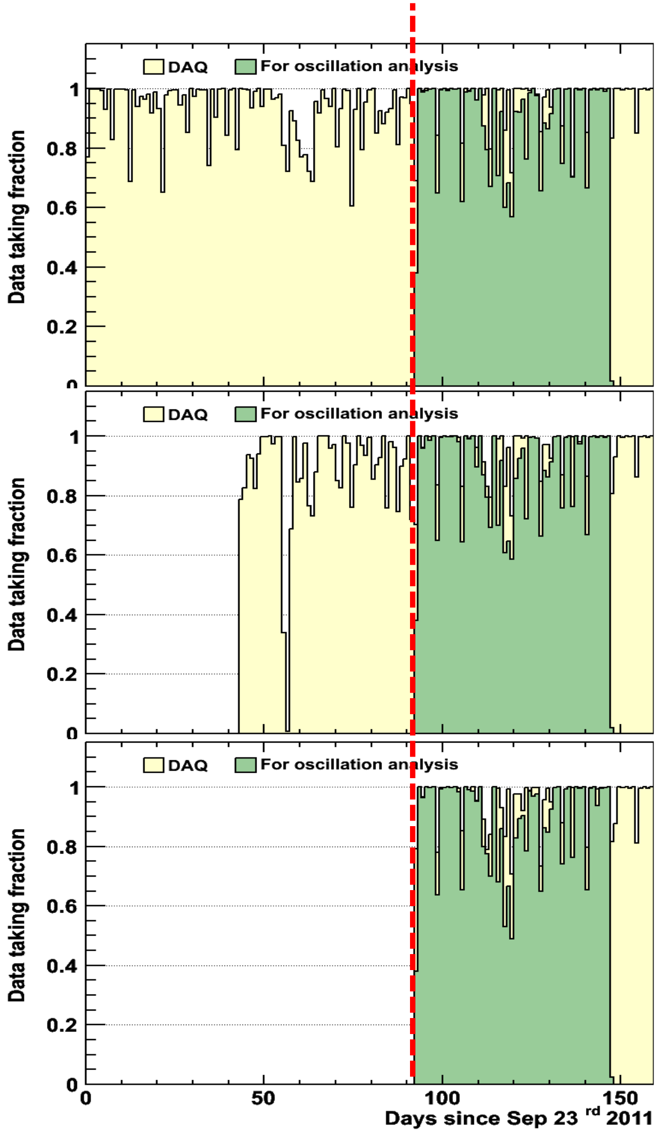
Data Period

Two Detector Comparison:

- Sep. 23, 2011 – Dec. 23, 2011
- Side-by-side comparison of 2 detectors
- Demonstrated detector systematics better than requirements.
- Details presented in: F.P. An et al., arXiv:1202.6181 (2012)

Current Oscillation Analysis:

- Dec. 24, 2011 – Feb. 17, 2012
- All 3 halls (6 ADs) operating
- DAQ uptime: >97%
- Antineutrino data: ~89%

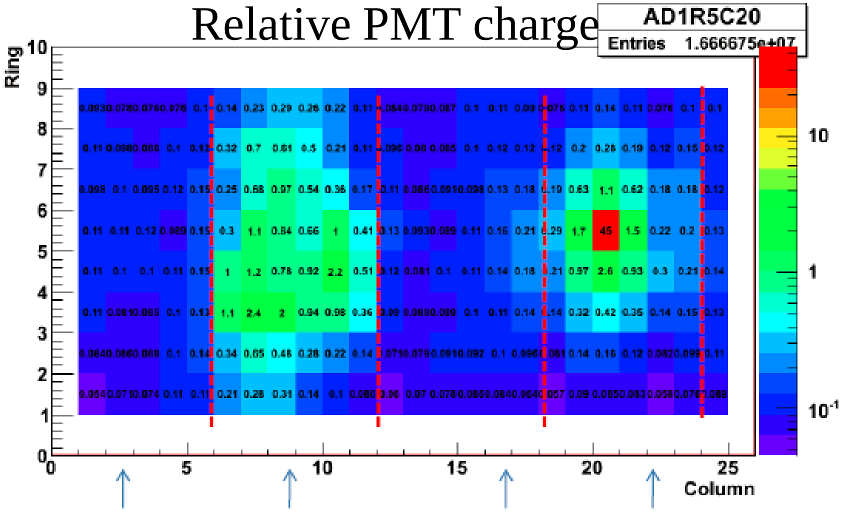


PMT Light Emission (Flashing)

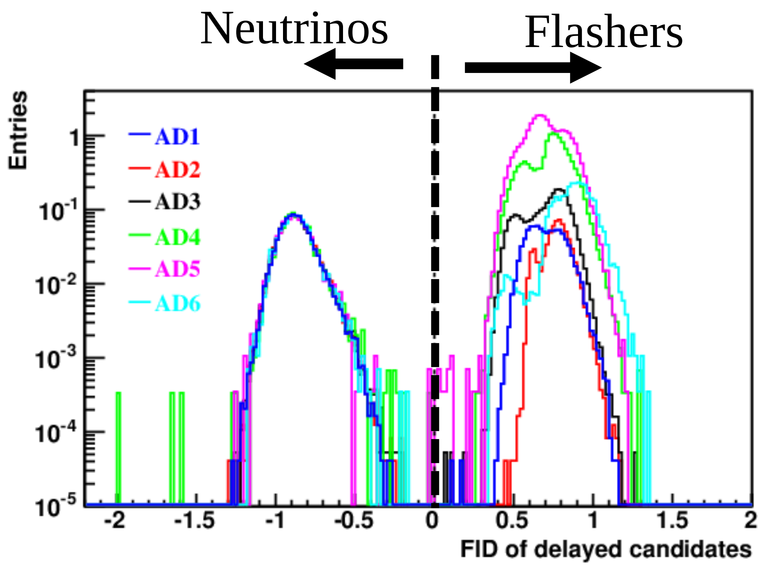
Flashing PMTs:

- Instrumental background from ~5% of PMTs
- ‘Shines’ light to opposite side of detector
- Easily discriminated from normal signals

Relative PMT charge



Quadrant 4 Quadrant 3 Quadrant 2 Quadrant 1, where the hottest PMT locates



$$FID = \log_{10}((MaxQ)^2/(0.45)^2 + (Quad)^2).$$

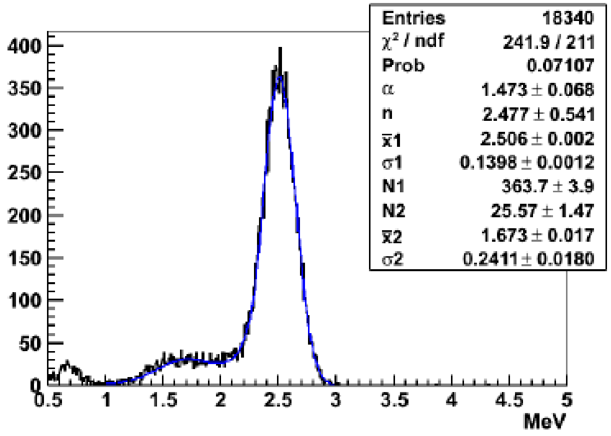
Quadrant = Q3/(Q2+Q4)

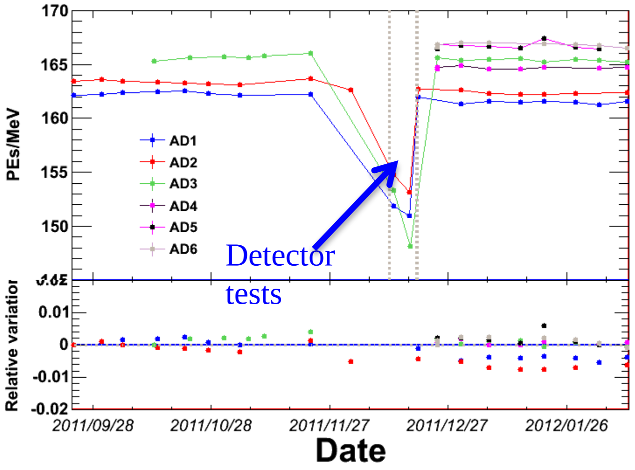
MaxQ = maxQ/sumQ

- Inefficiency to neutrinos: 0.024% ± 0.006%(stat)
- Contamination: < 0.01%

Energy Calibration

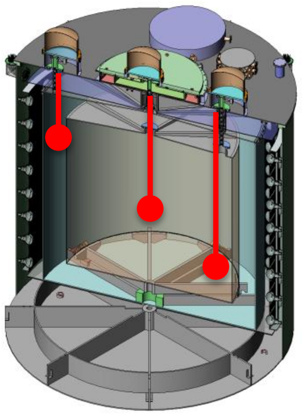
Weekly deployments of ^{60}Co at detector center: Monitor photoelectrons collected per MeV

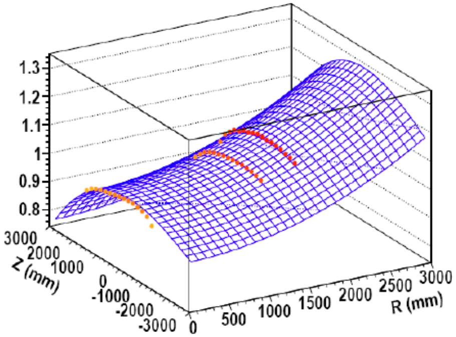


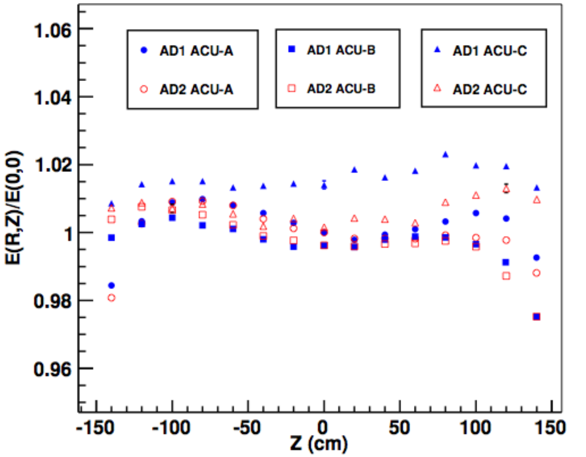


Detector tests

3 sources along 3 axes

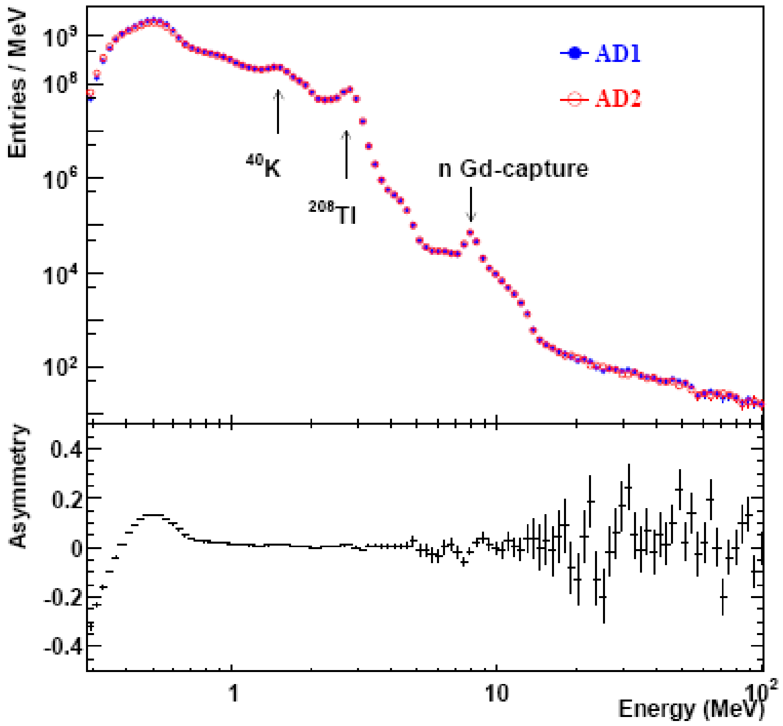






After first-order correction, energy is more uniform (tested with IBD spall neutrons).

Singles Spectrum: Understood



Measured Rates:

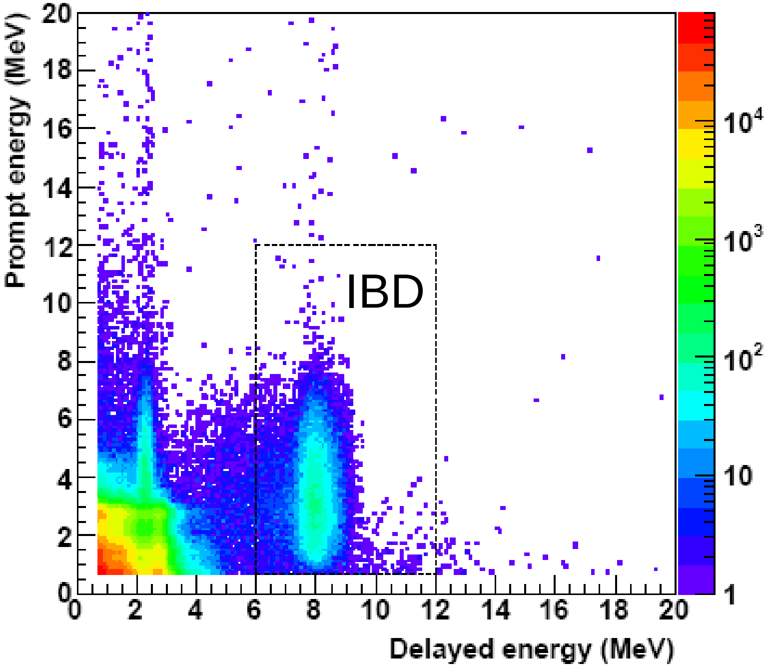
~65 Hz in each detector
(>0.7 MeV)

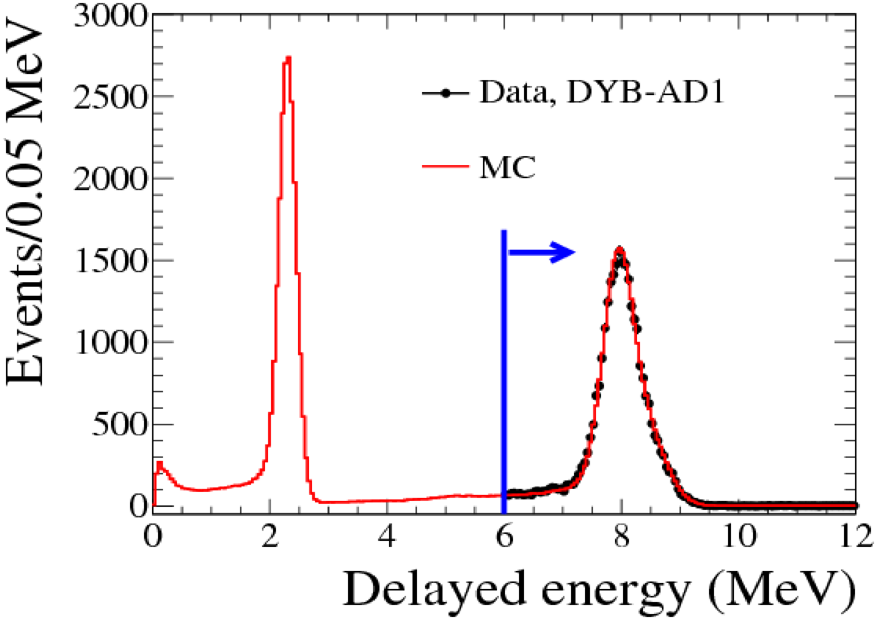
Triggered signals dominated by low-energy radioactivity

Sources:

Stainless Steel: U/Th chains
PMTs: 40K, U/Th chains
Scintillator: Radon/U/Th chains

Prompt/Delayed Energy



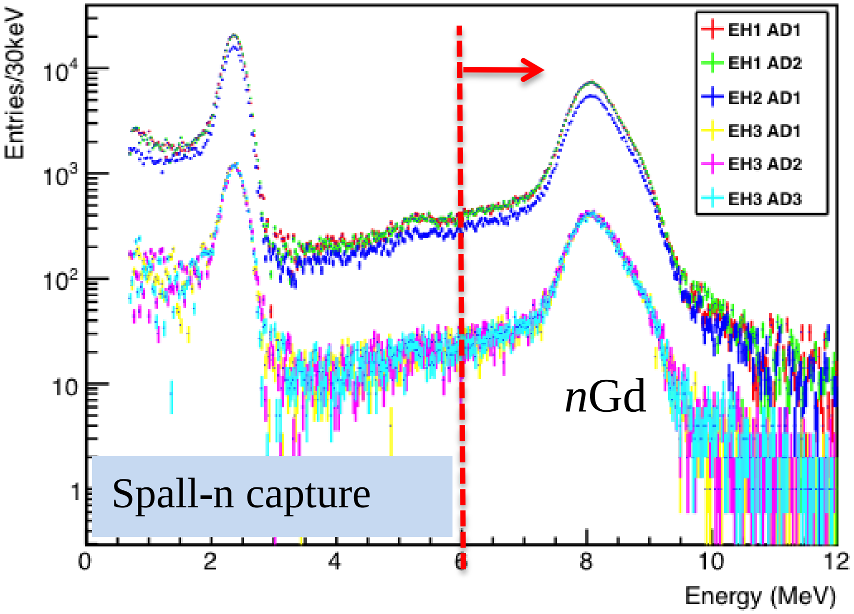


Clear separation of antineutrino events from most other signals

Delayed Energy Cut

Largest uncertainty between detectors

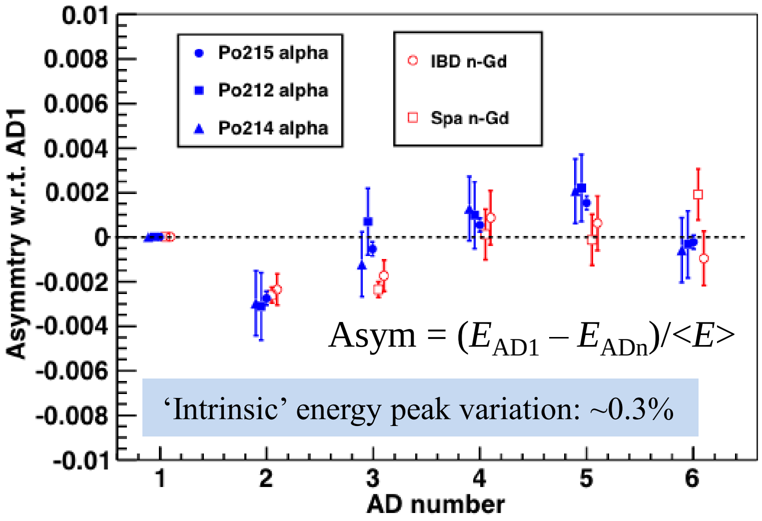
Some *n*-Gd gammas escape scintillator region, visible as tail of *n*-Gd energy peak.



*n*Gd

Spall-n capture

Use variations in energy peaks to constrain relative efficiency.

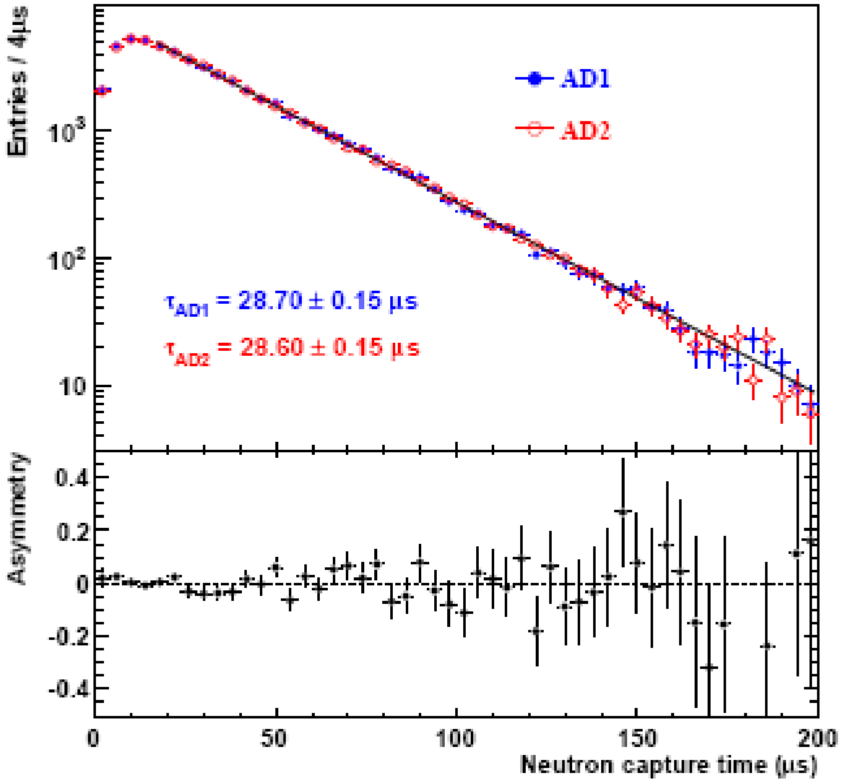


Asym = $(E_{AD1} - E_{ADn})/\langle E \rangle$

'Intrinsic' energy peak variation: ~0.3%

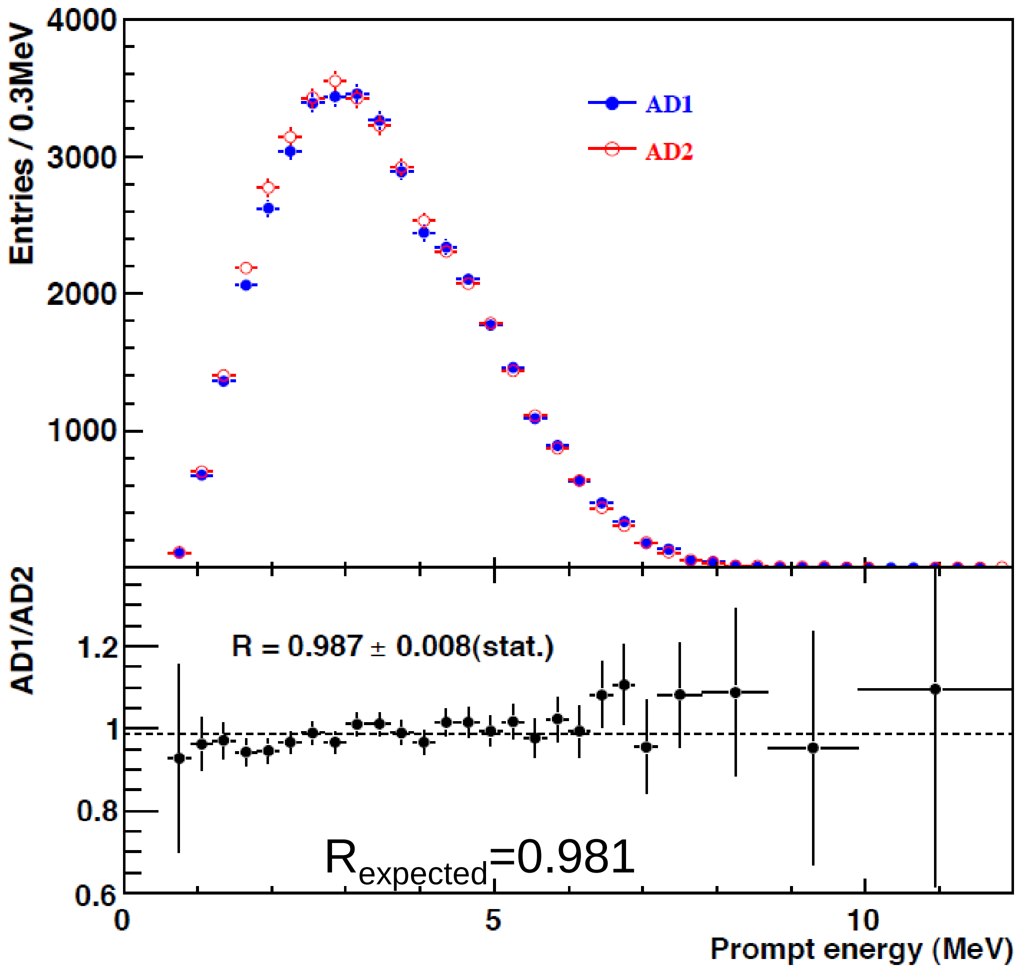
- Efficiency variation estimated at 0.12% based on 0.5% energy scale uncertainty
- Motivation for 3-zone design

Gd Capture Ratio



Am-C neutron capture time to constrain uncertainty in relative H/Gd capture efficiency to < 0.1% between detectors.

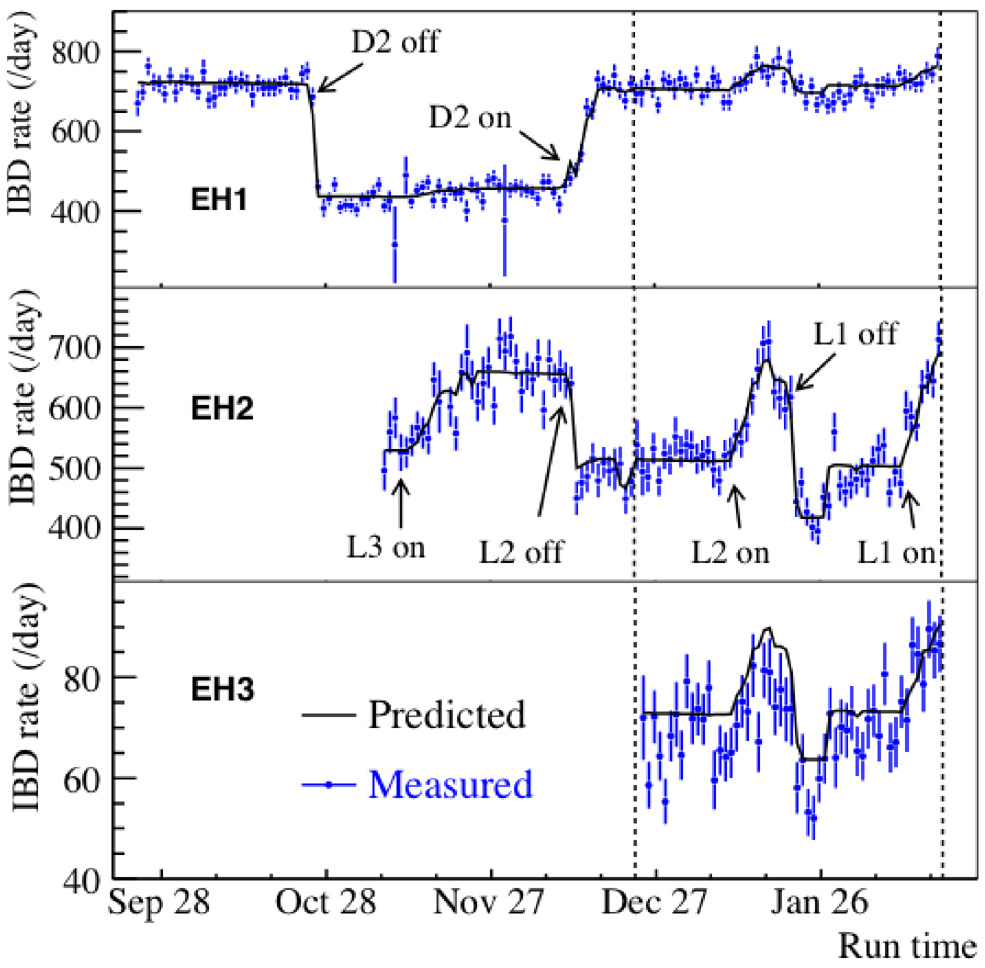
Side-by-side Comparison of 2 ADs



Powerful demonstration of detector identicality and control of systematics

arXiv:1202.6181

Antineutrino Rate vs. Time



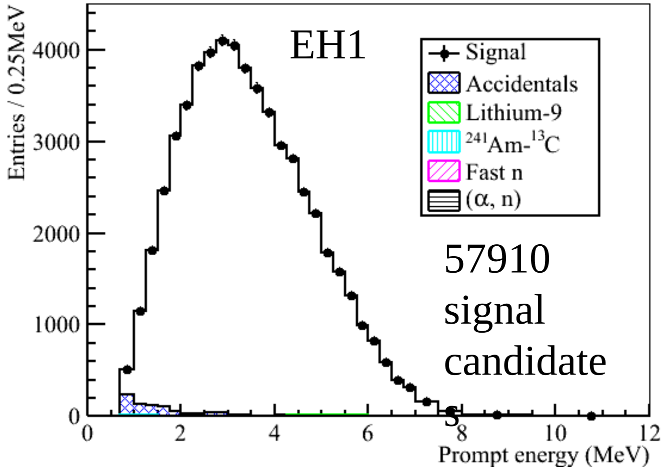
Detected rate tracks with reactor fuel cycle!

Predicted rate: (in figure)

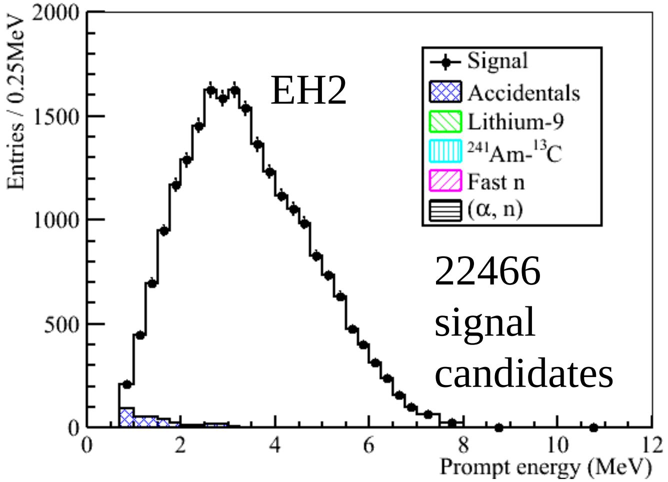
- Assumes no oscillation.
- Normalization is determined by fit to data.

Near-Far Site Prompt Positron Spectra

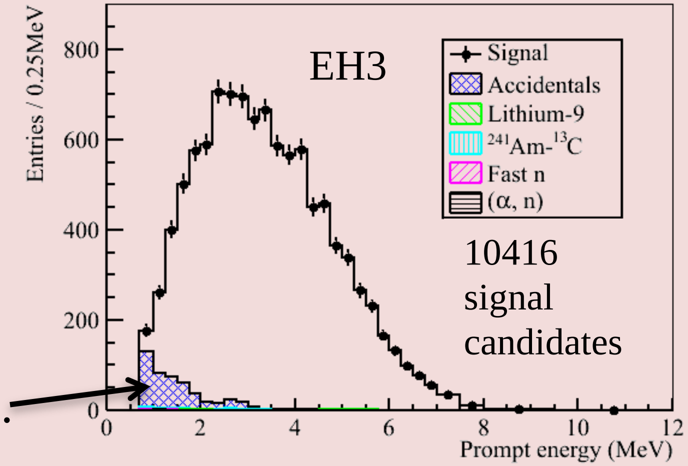
High-statistics reactor antineutrino spectra.



57910 signal candidate



22466 signal candidates



10416 signal candidates

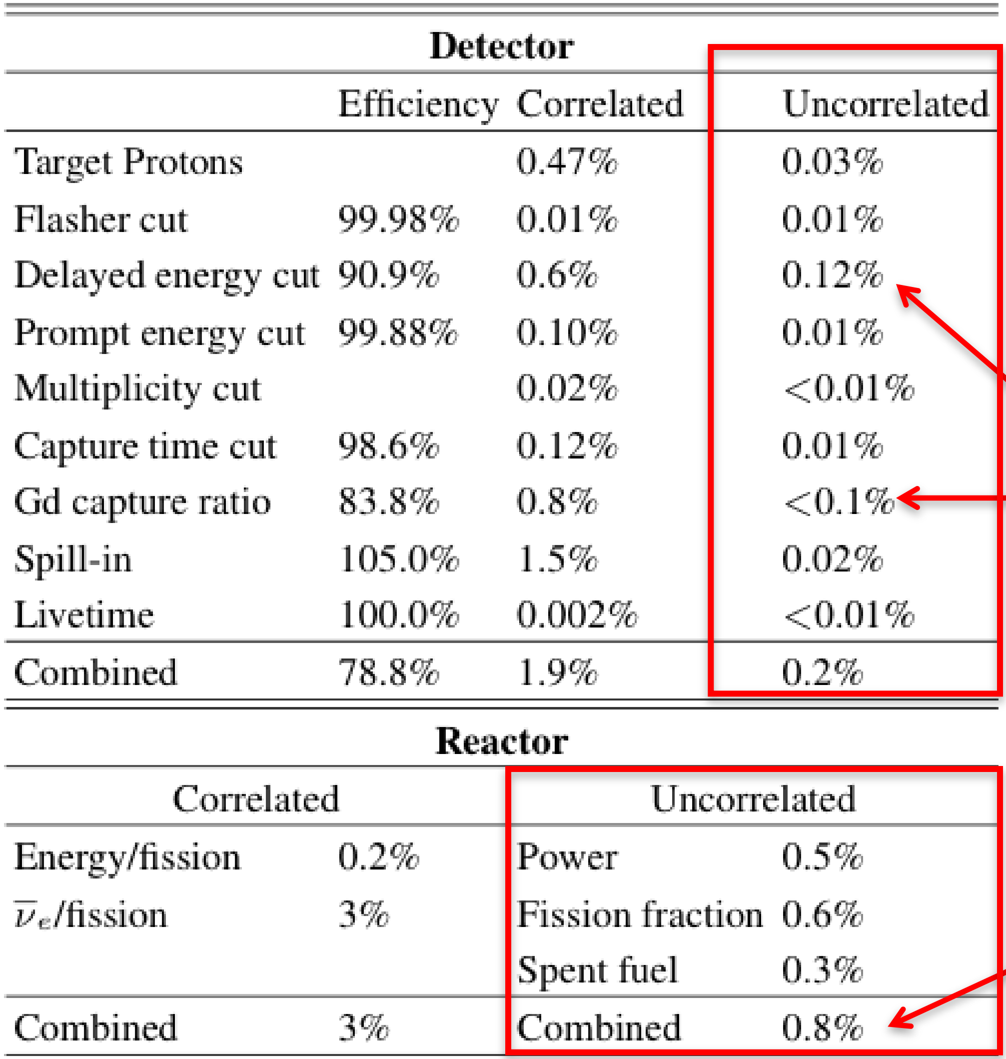
B/S ratio is 5% (2%) at far (near) sites.

Background Summary

	Background	Near	Far	Fractional Accuracy (%)	Control
	Accidental	~1.4 %	~4.5 %	<1%	Use data
Cosmogenic	Fast Neutrons	~0.1%	~0.06%	<100%	Use data to constrain
	Li9/He8	~0.4%	~0.2%	<70%	Use data to constrain
Internal	Am-C	~0.03%	~0.3%	100%	Data/MC combined
	(alpha, n)	~0.01%	~0.04%	<70%	Data/MC combined

Backgrounds are small, and under control using real data

Uncertainty Summary



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

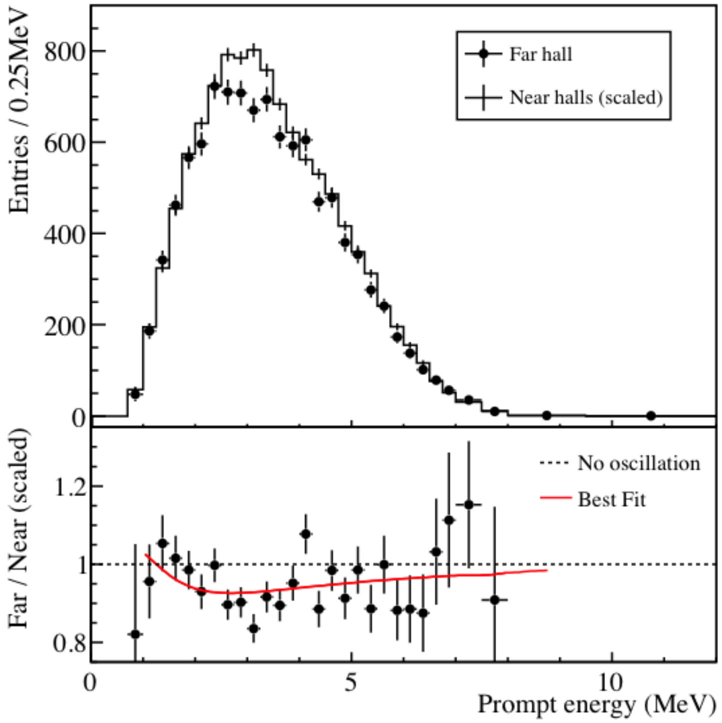
Correlated		Uncorrelated	
Energy/fission	0.2%	Power	0.5%
$\overline{\nu}_e$/fission	3%	Fission fraction	0.6%
		Spent fuel	0.3%
Combined	3%	Combined	0.8%

For near/far oscillation, only uncorrelated uncertainties are used

Largest systematics are much smaller than far site statistics (~1%)

Influence of uncorrelated reactor systematics reduced by far vs. near measurement.

Far vs. Near Comparison



$$R = \frac{\mathrm{Far}_{\mathrm{measured}}}{\mathrm{Far}_{\mathrm{expected}}}$$

$$= \mathbf{0.940 \pm 0.011\ (stat) \pm 0.004\ (syst)}$$

Recall: $R \sim 1-0.6\sin^2 2\theta_{13}$ @ Daya Bay

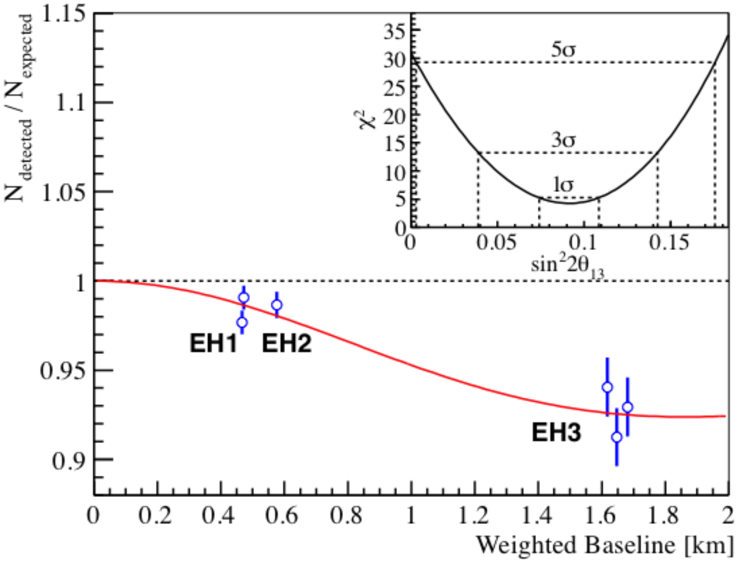
$\mathrm{Far}_{\mathrm{expected}}$ predicted from near sites

Clear observation of far site deficit relative to near

Spectral distortion consistent with oscillation*.

*Caveat: Spectral systematics not fully studied. θ_{13} value from shape analysis is not recommended at this point.

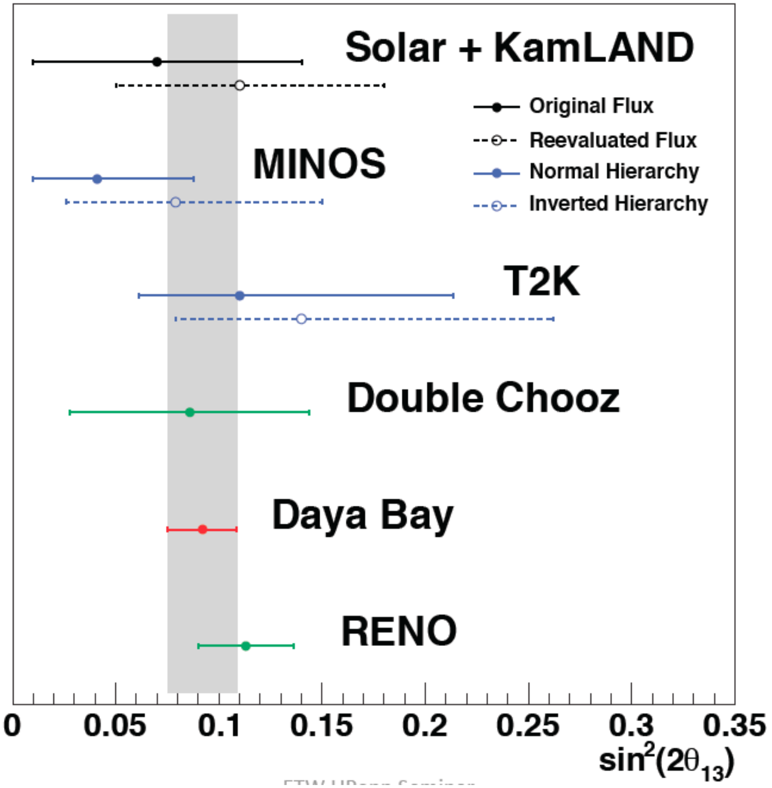
Rate Analysis

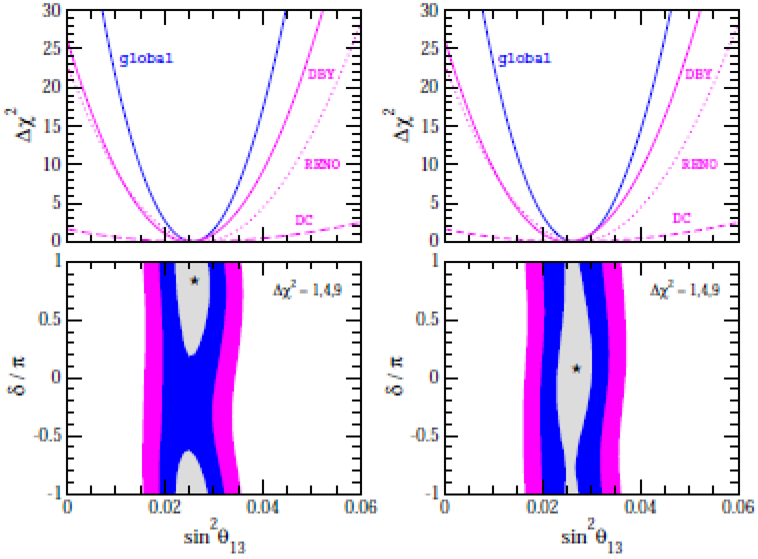


$\sin^2 2\theta_{13} = 0.092 \pm 0.016$ (stat) $\pm\ 0.005$ (syst)

$\sin^2 2\theta_{13} = 0$ excluded at 5.2σ

Summary of All Existing θ_{13} Measurements



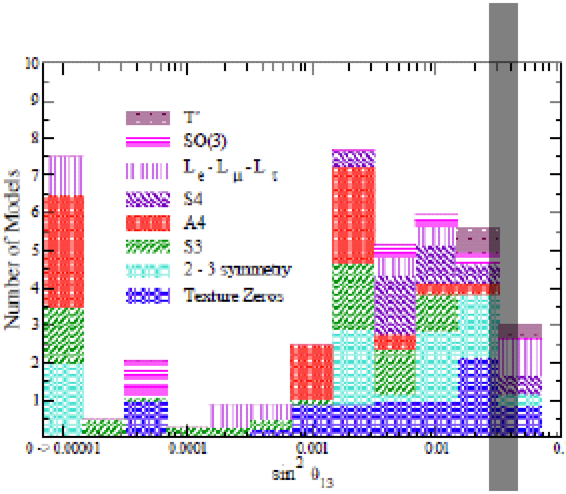


M. Tórtola, et al., **arXiv:1205.4018**

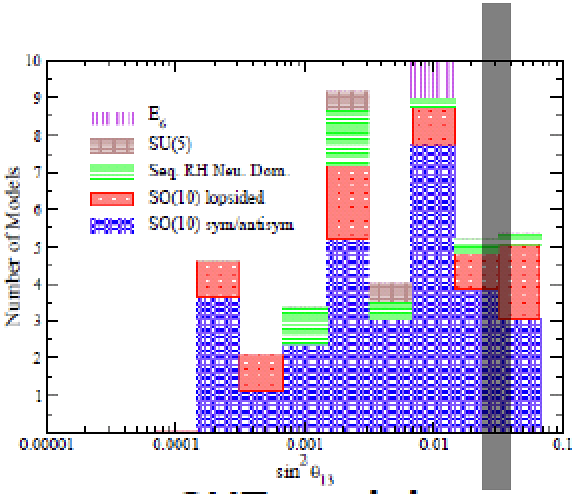
Non-zero $\sin^2\theta_{13}$ at 8 σ

Implications

Albright: arxiv0911.2437



Lepton flavor models



GUT models

Bottom line: with θ_{13} nailed, many model have to confront the new data!

Forthcoming from Daya Bay

We already have

$\sin^2 2\theta_{13} = 0.092$

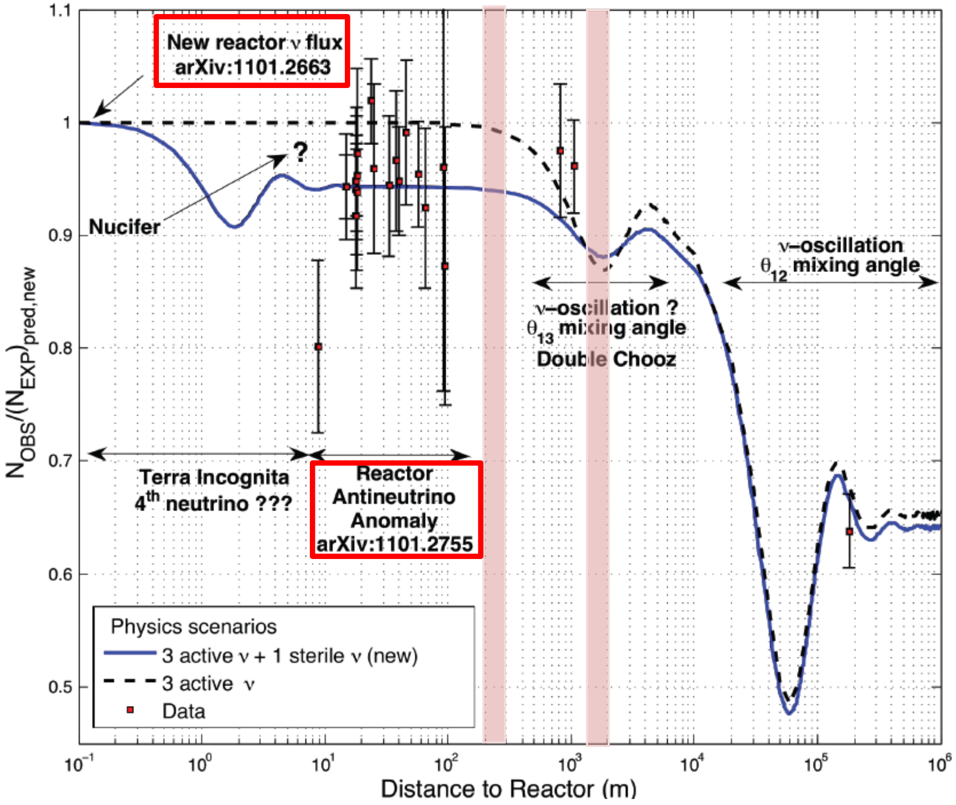
$\pm$ 0.016 (stat)

$\pm$ 0.005 (syst)

- More precise rate analysis (update 6 AD rate analysis this summer)
- Extensive calibration program this summer for spectrum analysis
- 8 detector data taking after summer, with ultimate precision of <0.01 (90% C. L.) on **$\sin^2 2\theta_{13}$**
- Precise near site reactor spectrum measurement

Backup

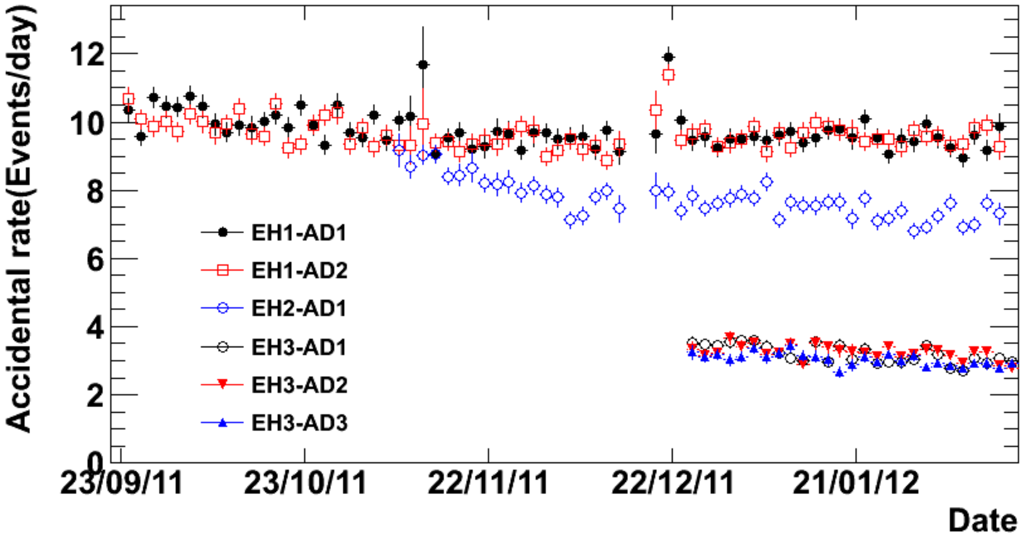
Reactor Neutrino "Anomaly"



Thierry Lasserre, TAUP 2011

A near-far relative measurement of reactor neutrino disappearance <u>remains</u> to be an unambiguous measurement of θ_{13}

Background: Accidentals



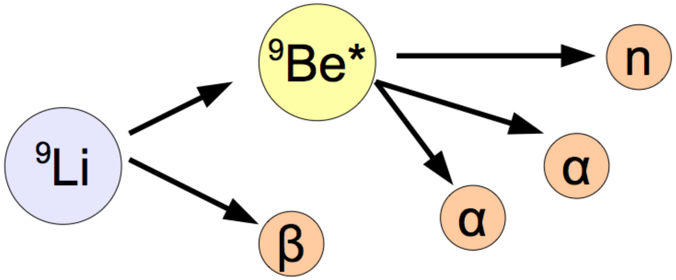
$$N_{\text{accBkg}} = \sum_i N^i_{\text{n-like singles}} \bullet \left(1 - e^{-R^i_{e^+\text{-like triggers}} \bullet 200\,\mu s}\right)$$

	EH1-AD1	**EH1-AD2**	**EH2-AD1**	**EH3-AD1**	**EH3-AD2**	**EH3-AD3**
Accidental rate(/day)	**9.82±0.06**	**9.88±0.06**	**7.67±0.05**	**3.29±0.03**	**3.33±0.03**	**3.12±0.03**
B/S	**1.37%**	**1.38%**	**1.44%**	**4.58%**	**4.77%**	**4.43%**

- Cross checked with Off-window & Distance between prompt-delay pair
- Consistent to 1%

Background: β-n decay

β-n decay:
- Prompt: β-decay
- Delayed: neutron capture

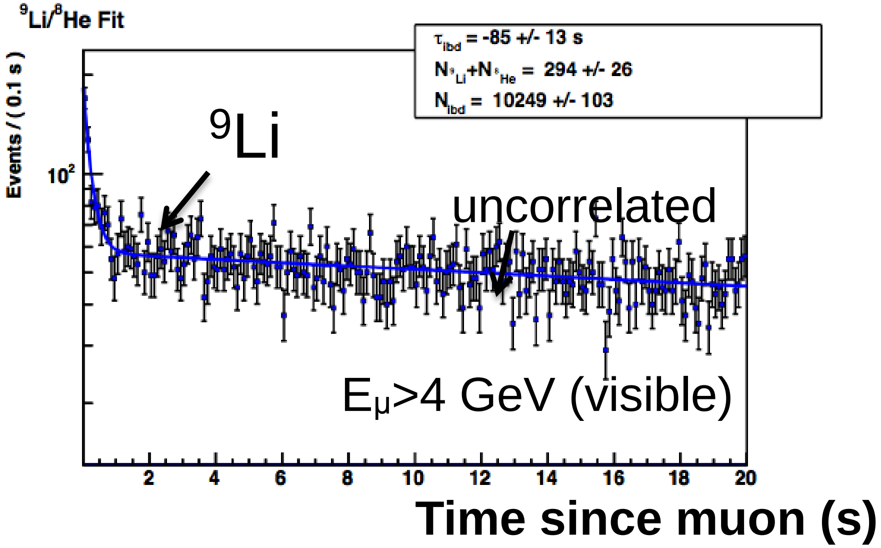


- Generated by cosmic rays
- Long-lived
- Mimic antineutrino signal

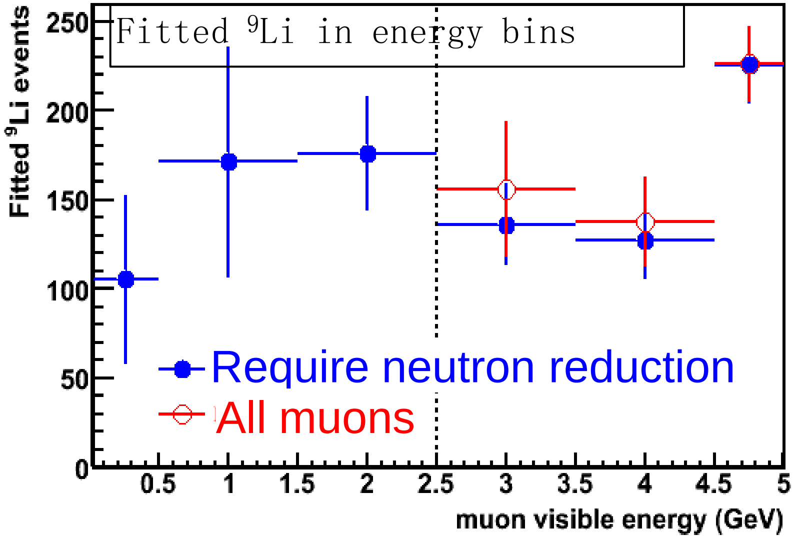
^{9}Li: $\tau_{1/2}$ = 178 ms, Q = 13. 6 MeV

^{8}He: $\tau_{1/2}$ = 119 ms, Q = 10.6 MeV

Basic technique: use time-since-muon fits



Lower muon visible energy: impose neutron-generating requirements to muons



Analysis muon veto cuts control B/S to ~0.4±0.2%.

Background: Fast neutrons

Fast Neutrons:

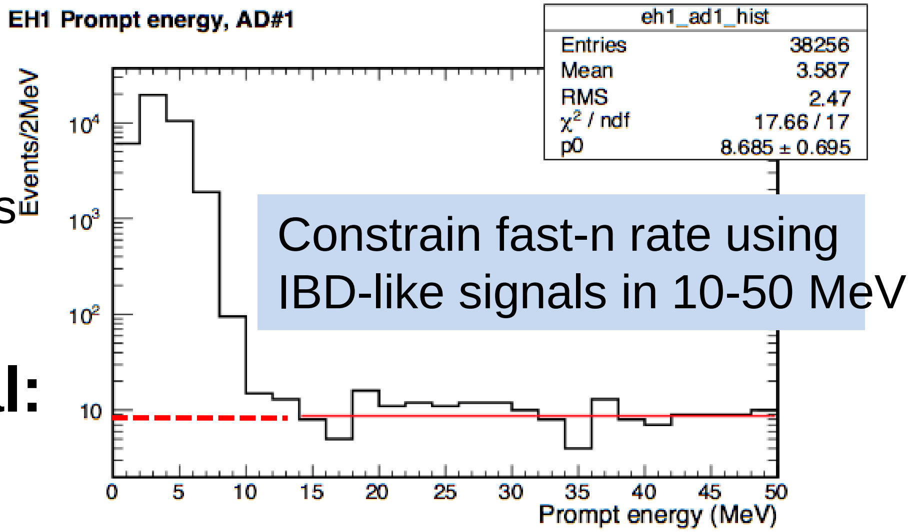
Energetic neutrons produced by cosmic rays (inside and outside of muon veto system)

Mimics antineutrino (IBD) signal:

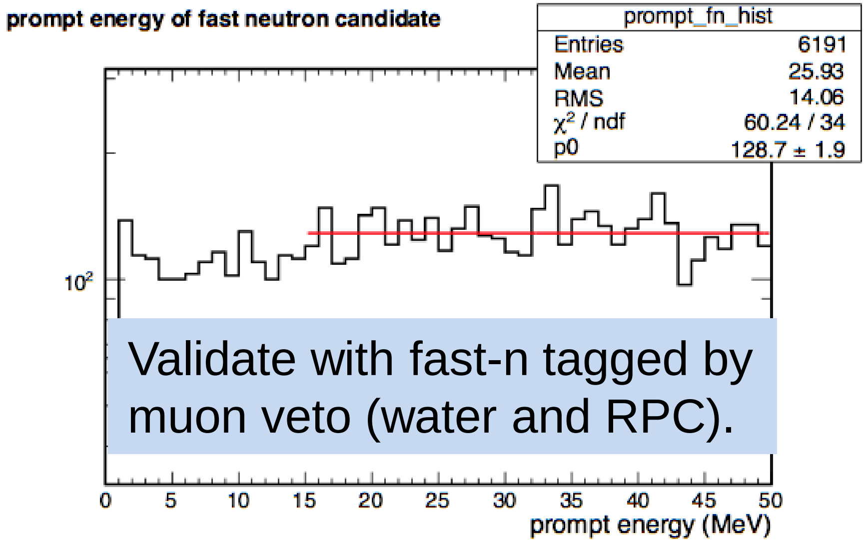
- Prompt: Neutron collides/stops in target
- Delayed: Neutron captures on Gd

Analysis muon veto cuts control B/S to 0.06% (0.1%) of far (near) signal.

Agrees with alternative method: combined tagged fast neutrons ×muon veto inefficiency (water neutrons) and Monte Carlo (rock neutrons)

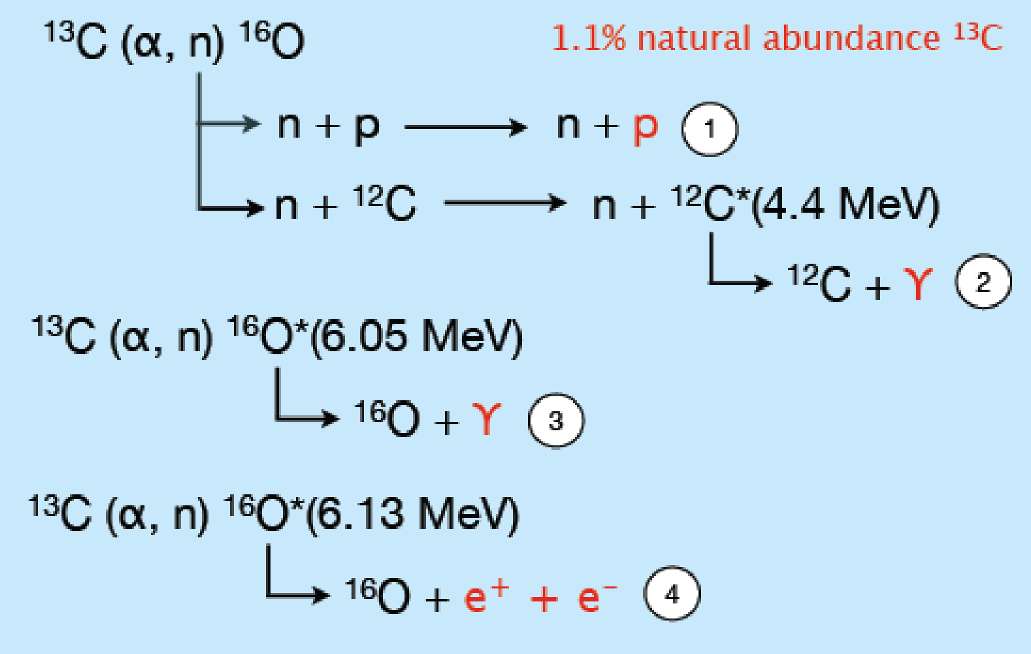


Constrain fast-n rate using IBD-like signals in 10-50 MeV



Validate with fast-n tagged by muon veto (water and RPC).

Background: $^{13}C(\alpha,n)^{16}O$



$^{13}C(\alpha, n)^{16}O$

1.1% natural abundance ^{13}C

$\rightarrow n + p \longrightarrow n + p$ ①

$\rightarrow n + {}^{12}C \longrightarrow n + {}^{12}C^*(4.4\ \text{MeV}) \rightarrow {}^{12}C + \gamma$ ②

$^{13}C(\alpha, n)^{16}O^*(6.05\ \text{MeV}) \rightarrow {}^{16}O + \gamma$ ③

$^{13}C(\alpha, n)^{16}O^*(6.13\ \text{MeV}) \rightarrow {}^{16}O + e^+ + e^-$ ④

Example alpha rate in AD1	^{238}U	^{232}Th	^{235}U	^{210}Po
Bq	0.05	1.2	1.4	10

Potential alpha source:

^{238}U, ^{232}Th, ^{235}U, ^{210}Po:

Each of them are measured in-situ:

- U&Th: cascading decay of

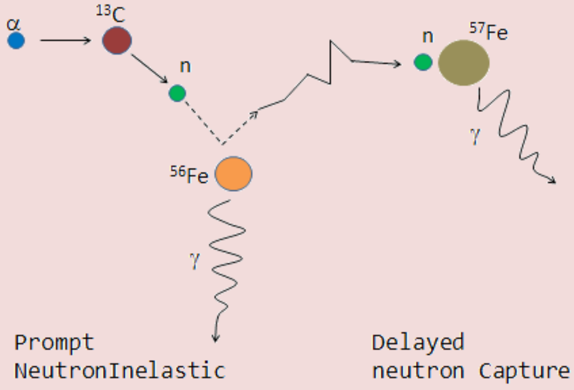
  Bi(or Rn) – Po – Pb
- ^{210}Po: spectrum fitting

Combining (α,n) cross-section, correlated background rate is determined.

Near Site: 0.04+-0.02 per day, B/S (0.006±0.004)%

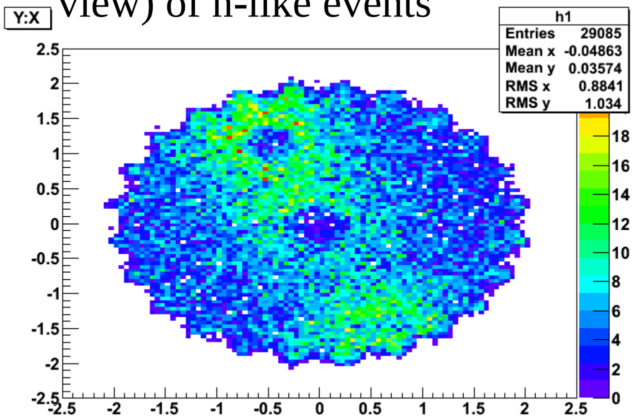
Far Site: 0.03+-0.02 per day, B/S (0.04±0.02)%

Background: ^{241}Am-^{13}C neutrons



- Weak (0.5Hz) neutron source in ACU can mimic IBD via inelastic scattering and capture on iron.
- Internal background: can not veto

Data: position distribution (top view) of n-like events



Constrain far site B/S to 0.3 ± 0.3%:

- Measure uncorrelated gamma rays from ACU in data (agreed very well with Monte Carlo)
- Estimate ratio of correlated/uncorrelated rate using Monte Carlo
- Assume 100% uncertainty from simulation

Reactor Flux Expectation

Antineutrino flux is estimated for each reactor core

Flux estimated using:

$$S(E_\nu) = \frac{W_{th}}{\sum_i (f_i/F) e_i} \sum_i^{istopes} (f_i/F) S_i(E_\nu)$$

Reactor operators provide:

- Thermal power data: W_{th}
- Relative isotope fission fractions: f_i

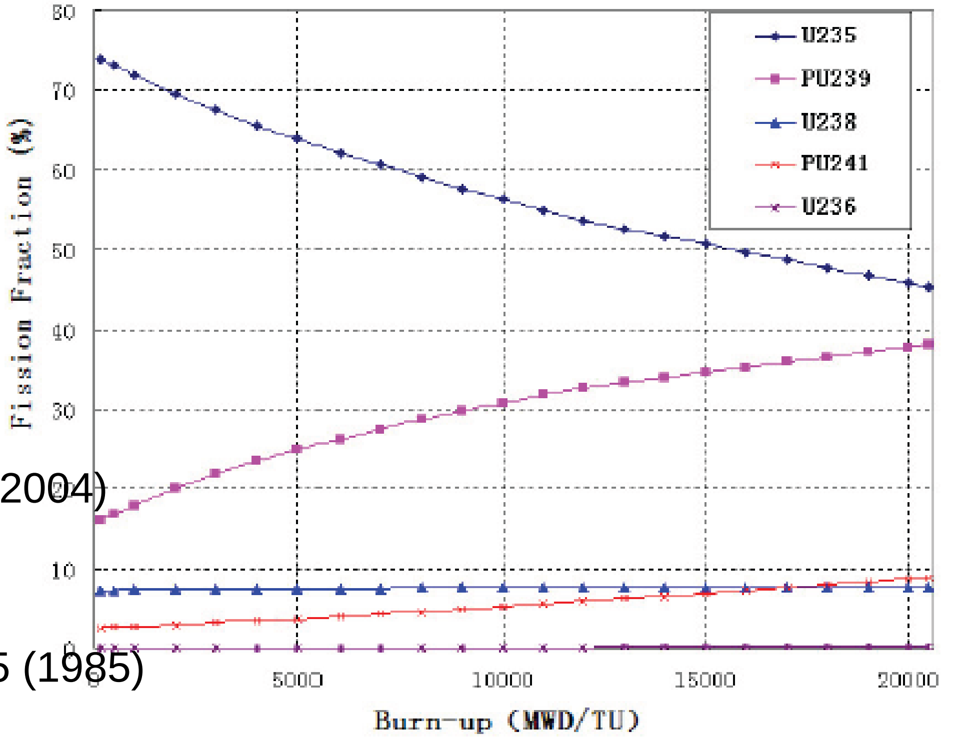
Energy released per fission: e_i

V. Kopekin et al., Phys. Atom. Nucl. 67, 1892 (2004)

Antineutrino spectra per fission: $S_i(E_\nu)$

K. Schreckenbach et al., Phys. Lett. B160, 325 (1985)
A. A. Hahn et al., Phys. Lett. B218, 365 (1989)
P. Vogel et al., Phys. Rev. C24, 1543 (1981)
T. Mueller et al., Phys. Rev. C83, 054615 (2011)
P. Huber, Phys. Rev. C84, 024617 (2011)

Isotope fission rates vs. reactor burnup



Flux model has negligible impact on far vs. near oscillation measurement