Improved Measurement of Electron-antineutrino Disappearance at Daya Bay

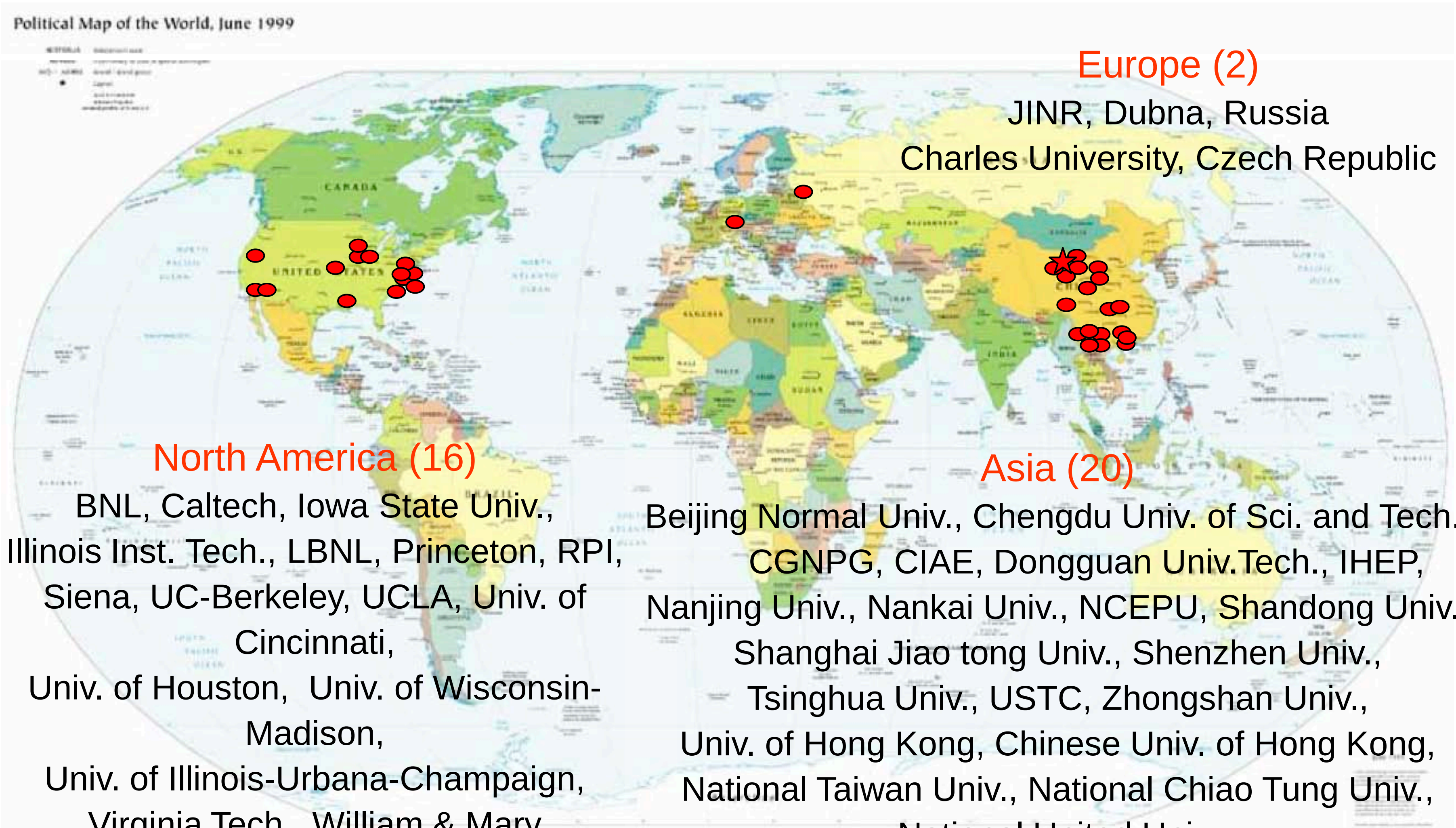
Liangjian Wen

Institute of High Energy Physics, China

On behalf of the Daya Bay Collaboration

36th ICHEP, Melbourne, 5 July, 2012

The Daya Bay Collaboration



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

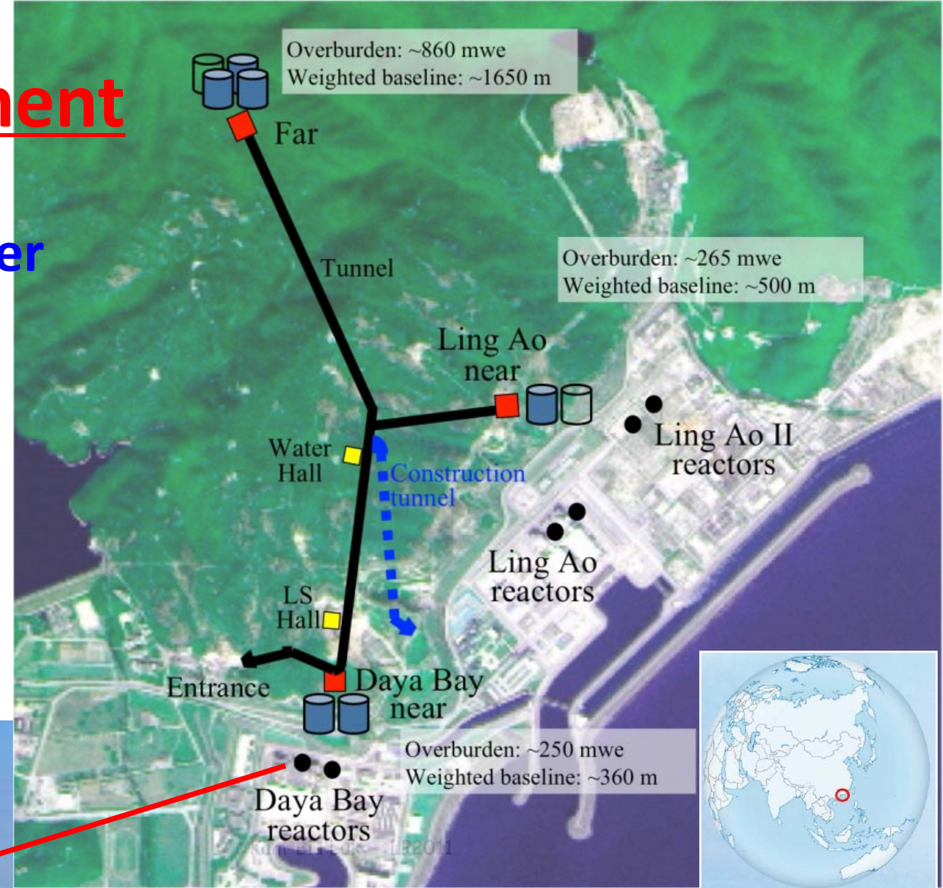
Asia (20)

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.

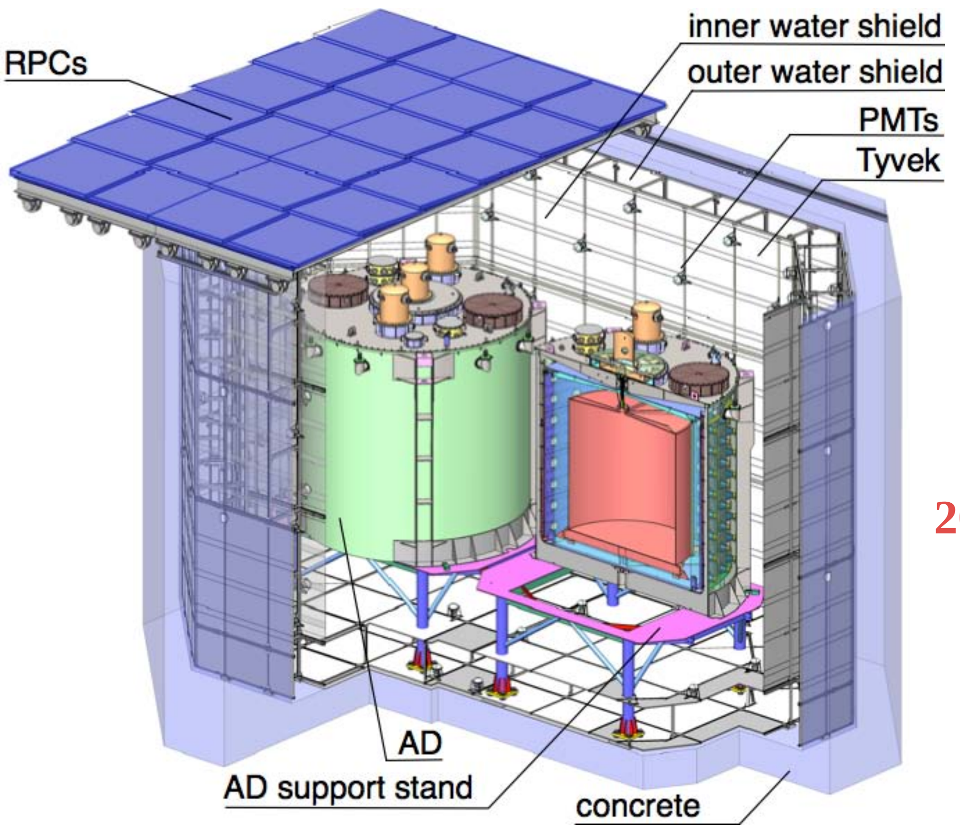
~250 Collaborators

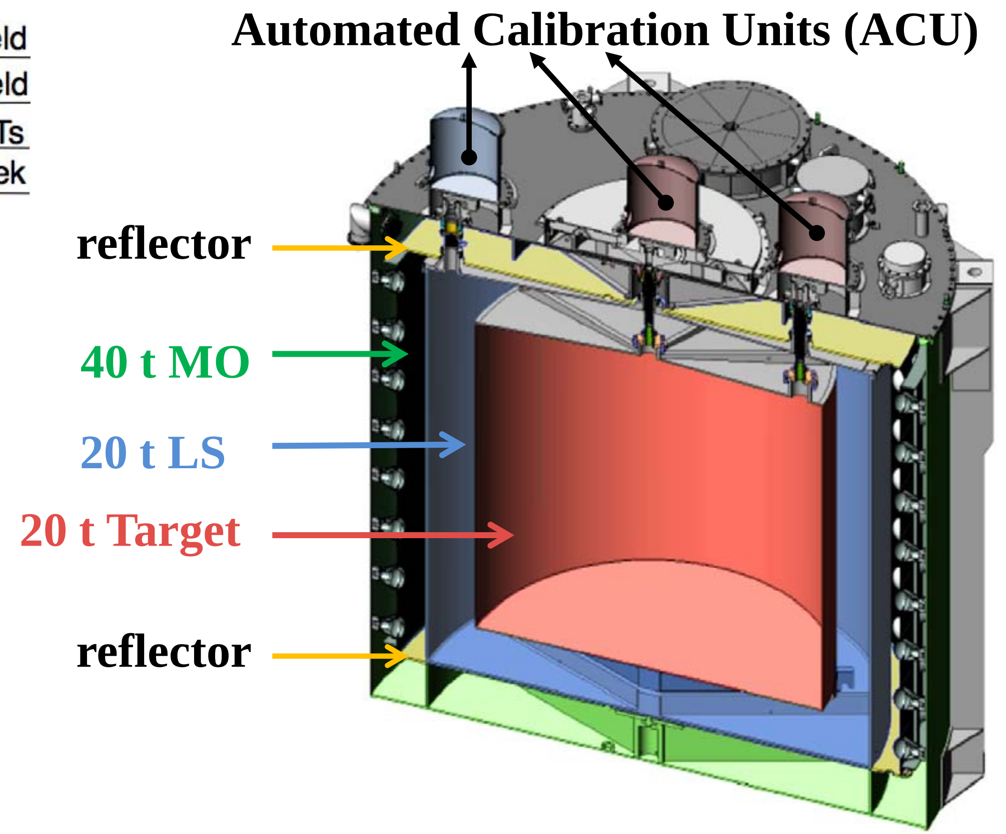
The Daya Bay Experiment

- 6 reactor cores, 17.4 GW_{th} total power
- Relative measurement
  - 2 near sites, 1 far site
- Multiple detector modules
- Good cosmic shielding
  - 250 m.w.e @ Daya Bay near
    860 m.w.e @ far site



The Daya Bay Detectors



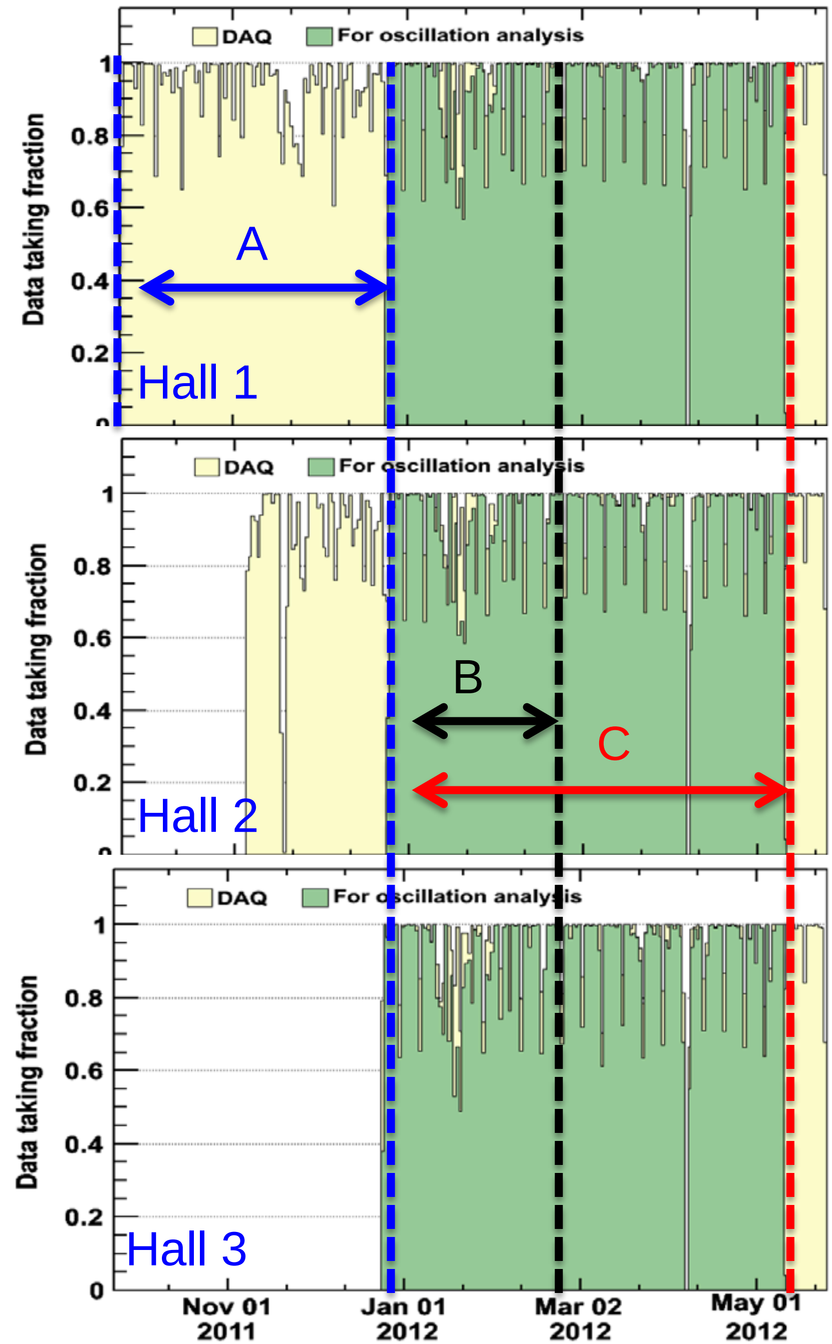


- Multiple AD modules at each site to check Uncorr. Syst. Err.
  - Far: 4 modules， near: 2 modules
- Multiple muon detectors to reduce veto eff. uncertainties
  - Water Cherenkov： 2 layers
  - RPC： 4 layers at the top + telescopes

Redundancy !!!

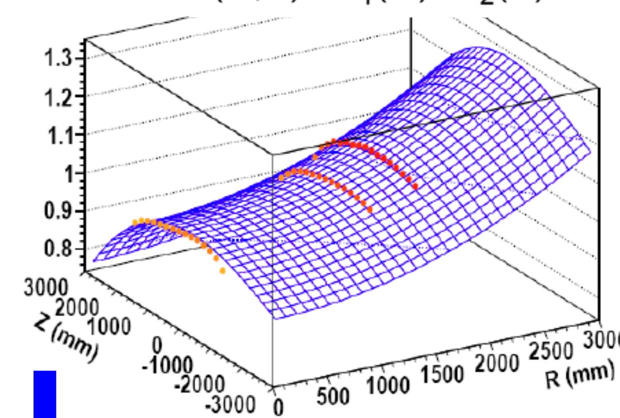
Data Period

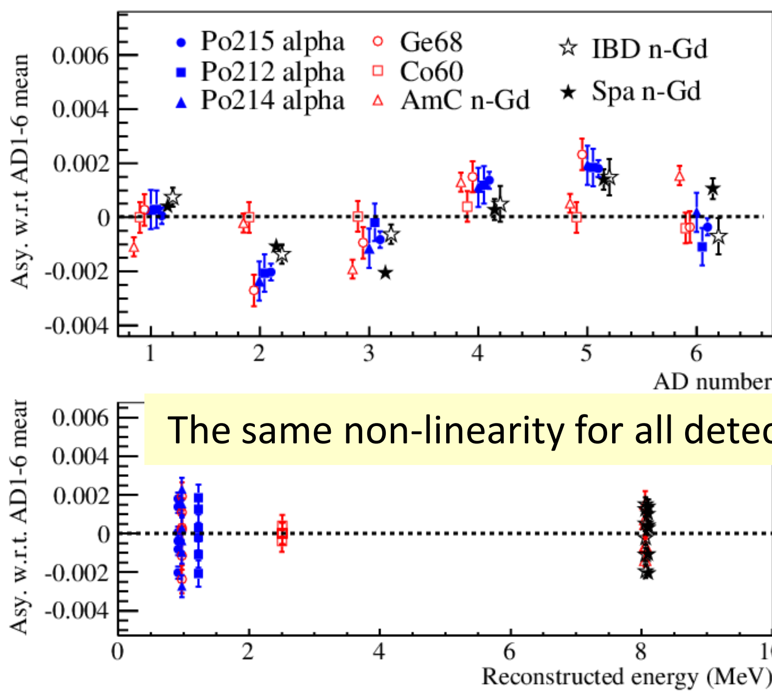
- A→Two Detector Comparison: Sep. 23, 2011 – Dec. 23, 2011
  Nucl. Inst. and Meth. A 685 (2012), pp. 78-97
- B→First Oscillation Result: Dec. 24, 2011 – Feb. 17, 2012
  Phys. Rev. Lett. 108, 171803 (2012)
- C→Updated analysis: Dec. 24, 2011 – May 11, 2012
  To be submitted to Chinese Physics C
  - Data volume: 40TB
  - DAQ eff. ~ 96%
  - Eff. for physics: ~ 94%



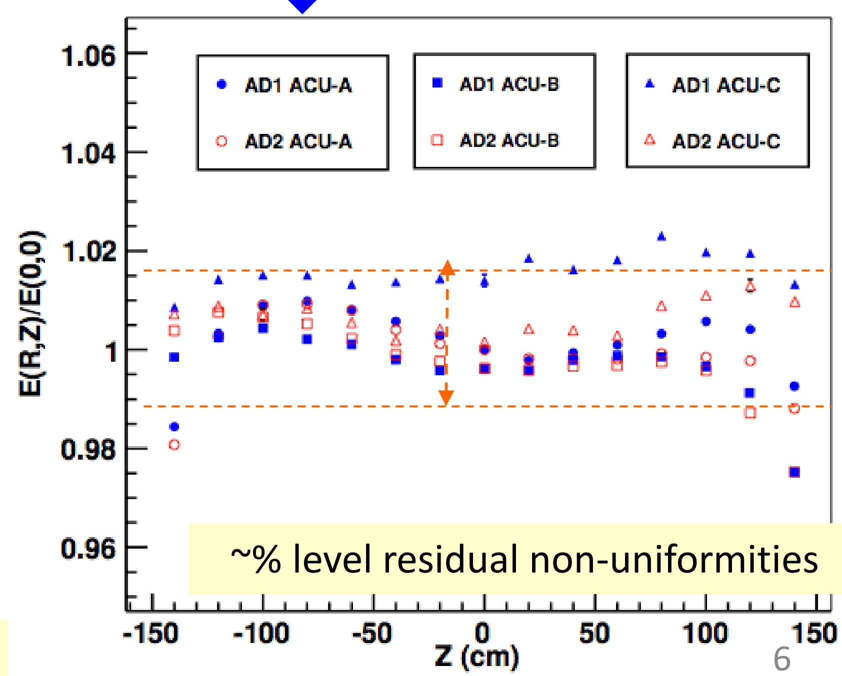
Energy calibration & reconstruction

- Low-intensity LED → PMT gains are stable to 0.3%
- ^{60}Co at the detector center → raw energies
  - Correct small (0.2%) time dependence
- ^{60}Co at different positions in detector
  - Correct spatial dependence . Common correction for all the ADs
- Calibrate energy scale using neutron capture peak





The same non-linearity for all detectors

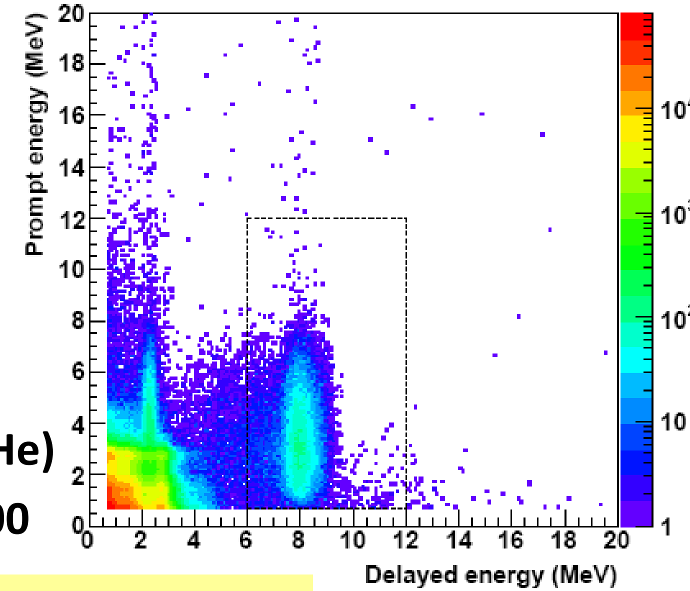


~% level residual non-uniformities

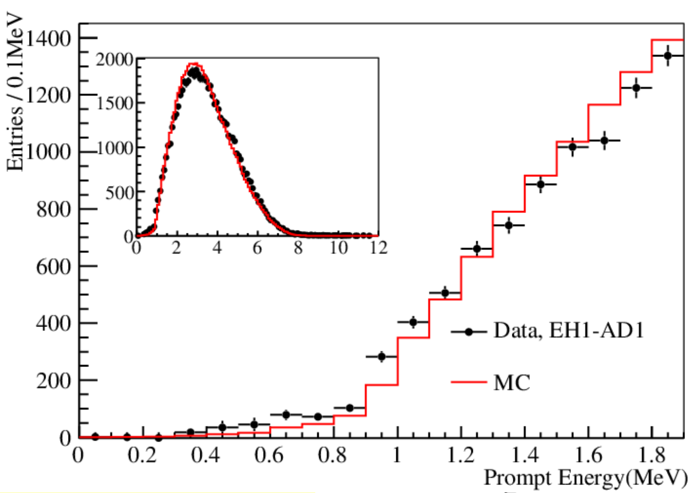
→ 0.12% efficiency difference among detectors

Anti-neutrino Events Selection

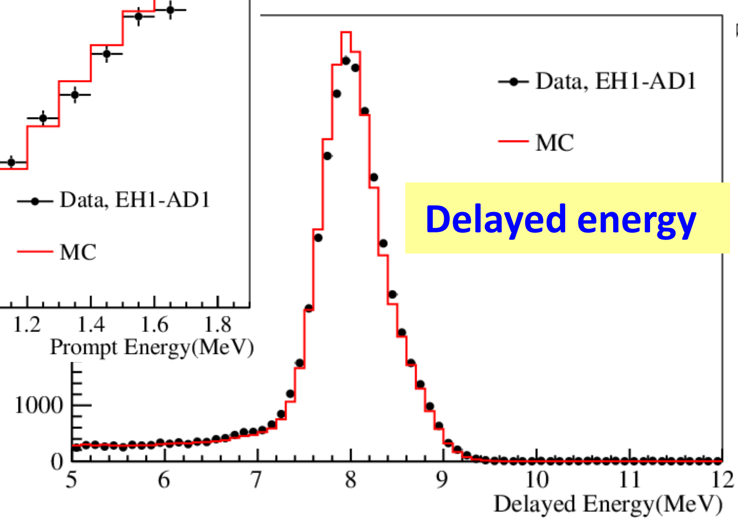
- **Anti-neutrino event selection**
  - 0.7 MeV < E_p < 12.0 MeV
  - 6.0 MeV < E_d < 12.0 MeV
  - 1 μs < Δt_{p-d} < 200 μs
  - **Muon Veto**: 0.6 ms after a Pool muon (reject fast neutron), 1 ms after an AD muon (reject double neutron), 1 s after an AD shower muon (reject $^{9}Li/^{8}He$)
  - **Multiplicity cut**: No other >0.7 MeV trigger in (t_p-200 μs , t_d+200 μs)



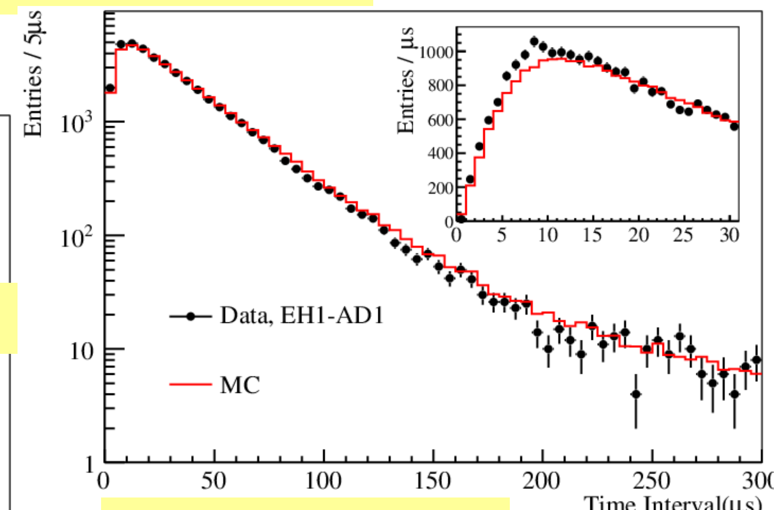
Good Agreement with MC



Prompt energy



Delayed energy



Time between prompt-delayed

Efficiencies & 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%
Live time	100.0%	0.002%	<0.01%
Combined	78.8%	1.9%	0.2%

All detectors use one common batch of target scintillator

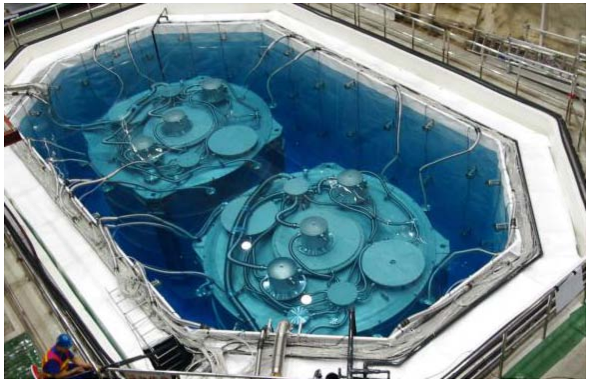
Quantity	Relative	Absolute
Free protons/kg	neg.	0.47%
Density	neg.	0.0002%
Total mass	0.015%	0.015%
Bellows	0.0025%	0.0025
Overflow tank	0.02%	0.02%
Total	0.03%	0.47%

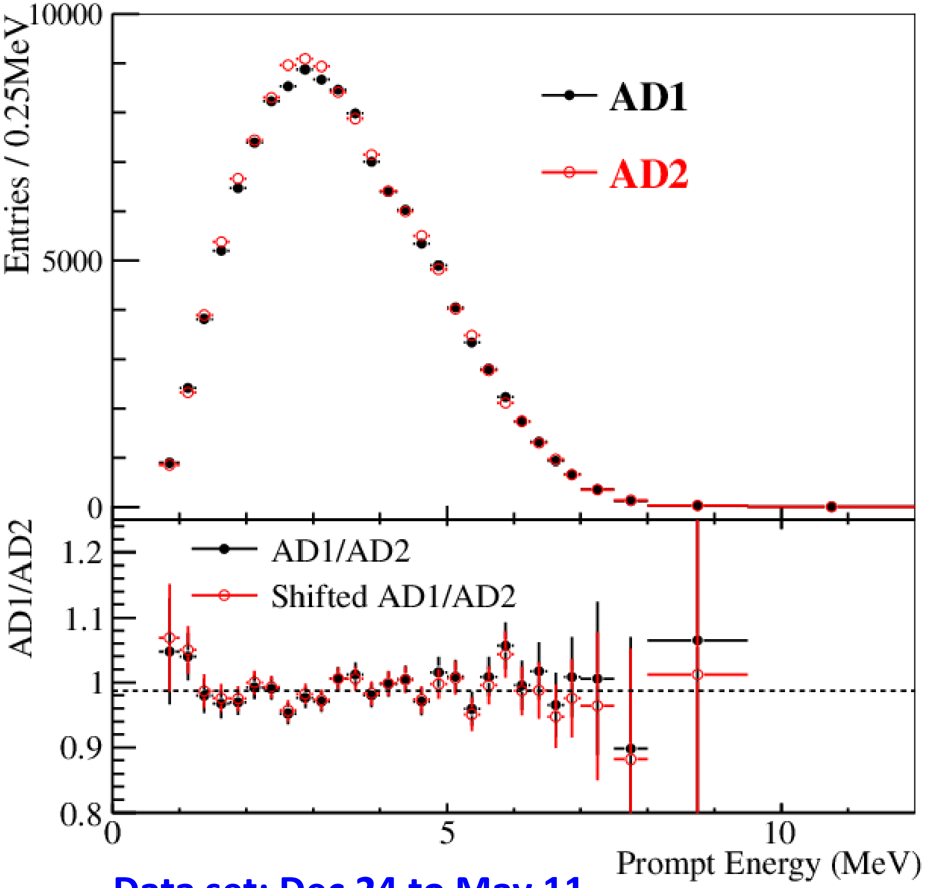
Target Protons Uncertainty

Design value
Baseline: 0.38%
Goal: 0.18%

Side-by-side Comparison

- **Expected ratio of neutrino events: R(AD1/AD2) = 0.982**
  - The ratio is not 1 because of target mass, baseline, etc.
- **Measured ratio: 0.987 ± 0.004(stat) ± 0.003(syst)**



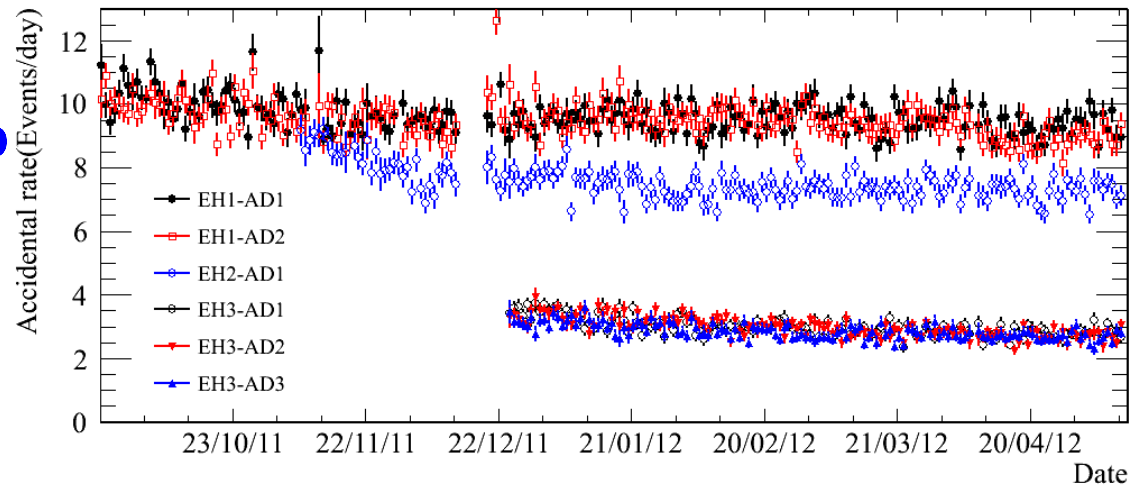


Data set: Dec 24 to May 11

This check shows that systematic errors are under control, and will determine the final systematic error

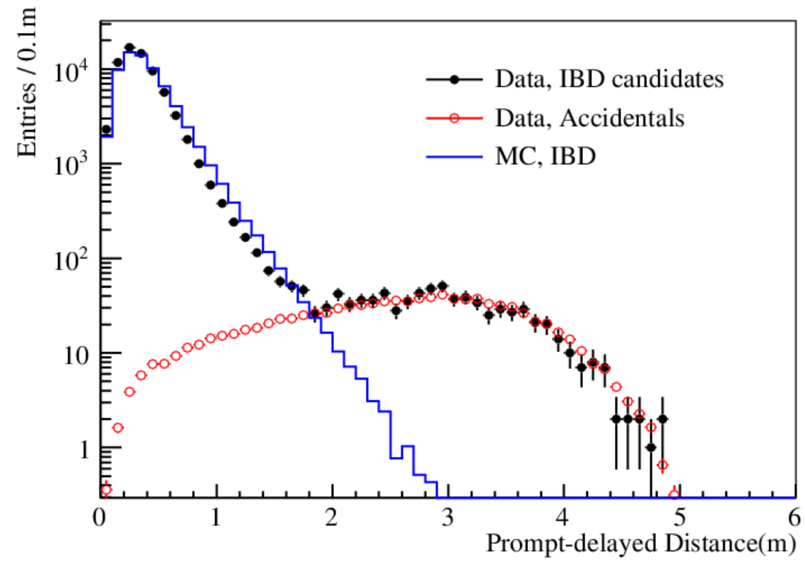
Backgrounds: Accidentals

- **Two signals accidentally satisfied the anti-neutrino event selection criteria**



- **Calculation:** use the rate of prompt- and delayed-signals

- **Cross-checks**
  - Prompt-delayed distance distribution→ Check the fraction of prompt-delayed pair with distance>2m
  - Off-window coincidence → measure the accidental background

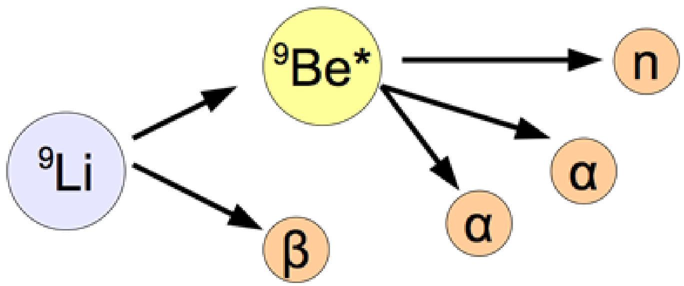


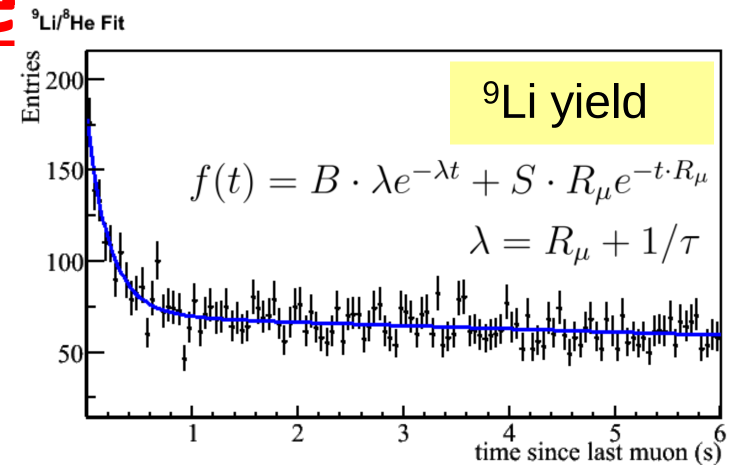
B/S @ EH1/2 ~ 1.4%, B/S @ EH3 ~ 4.0% ΔB/B ~ 1%

Backgrounds: $^{9}Li/^{8}He$

- **Cosmic μ produced $^{9}Li/^{8}He$ in LS**

  β-decay + neutron emitter





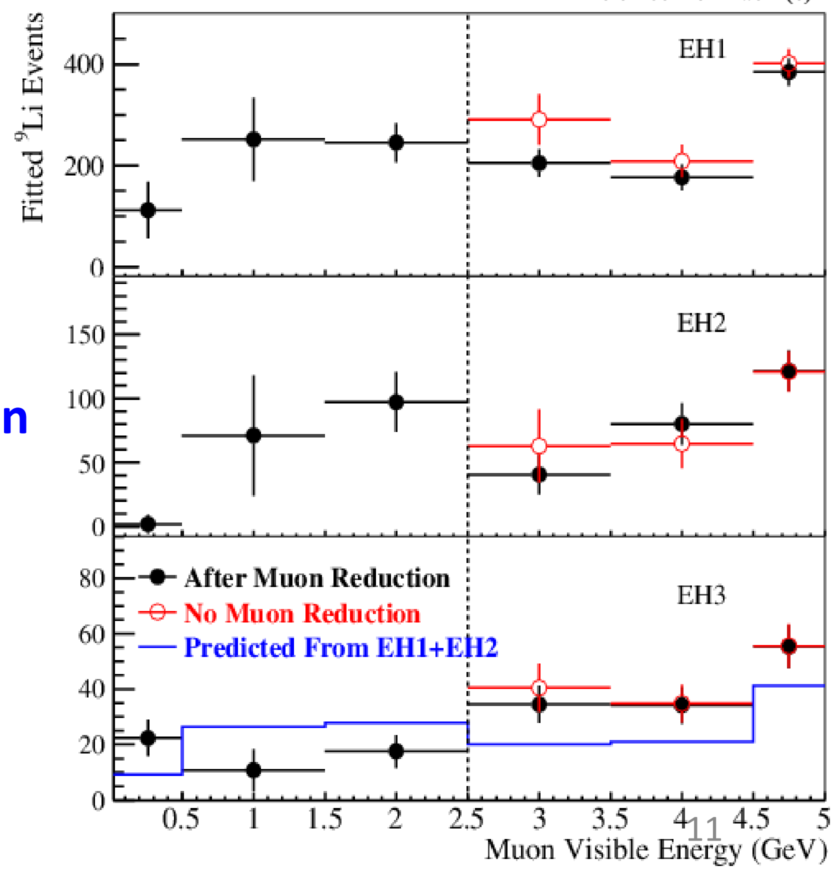
- **Measurement:**
  - **Time-since-last-muon fit method**

B/S uncertainty: $\sigma_b = \frac{1}{\sqrt{N}} \cdot \sqrt{(1+\tau R_\mu)^2 - 1}$

  - **Improve the precision by preparing muon samples w/ and w/o followed neutrons**
  - **Set a lower limit. Muons with small visible energy also produce $^{9}Li/^{8}He$**

B/S @ EH1/2 ~ 0.4%, B/S @ EH3 ~ 0.3%

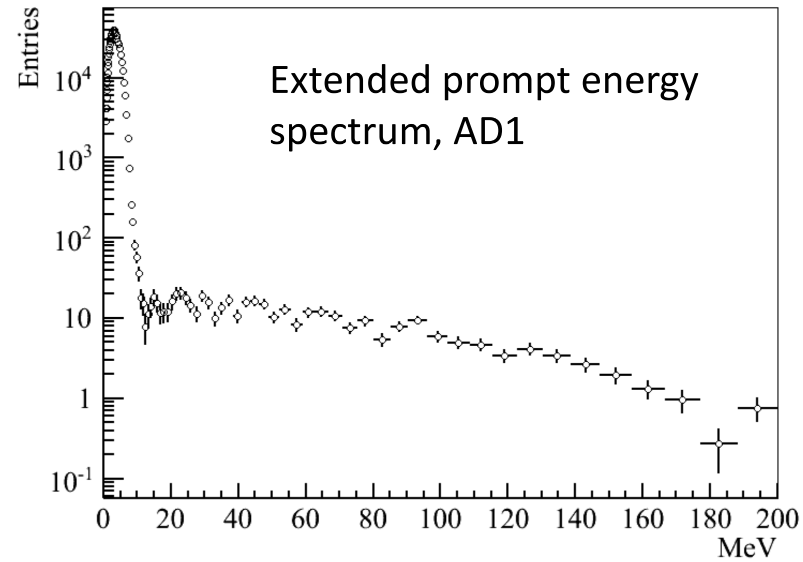
ΔB/B ~ 50%



Backgrounds: Fast neutrons

Method I:

Relax the E_p<12MeV criterion. Extrapolation into the (0.7 MeV, 12.0 MeV) region gave an estimate for the residual fast-neutron background.

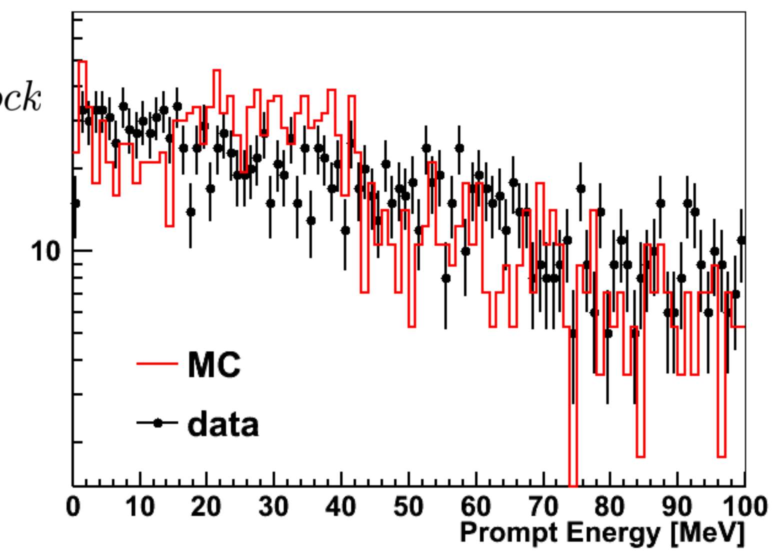


Method II:

Use water pool to determine the spectra of fast neutron, and estimate the residual fast neutron background and water pool inefficiency

$$n_f = n_f^{iws} \cdot (1 - \epsilon_{iws}) + n_f^{ows} \cdot (1 - \epsilon_{ows}) + n_f^{rock}$$

efficiency of IWS muon — efficiency of OWS *ONLY* muons



Results are consistent

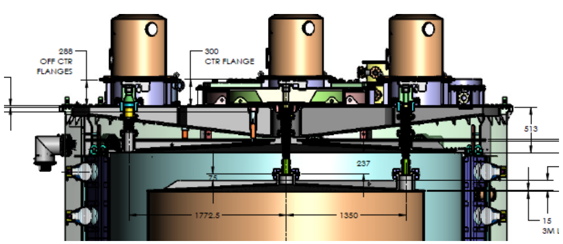
B/S @ EH1/2 ~ 0.12%, B/S @ EH3 ~ 0.07%

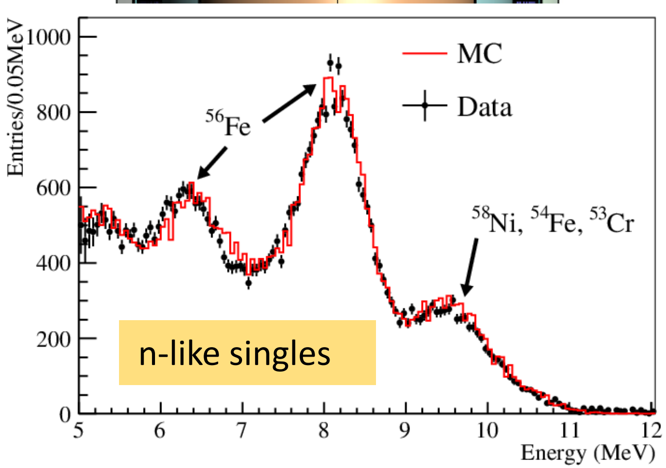
ΔB/B ~ 40%

Backgrounds: ^{241}Am-^{13}C source & ^{13}C(α,n)^{16}O

- **Correlated backgrounds from ^{241}Am-^{13}C source inside ACUs :**
  - Neutron inelastic scattering with ^{56}Fe + neutron capture on ^{57}Fe
  - Simulation shows that correlated background is 0.2 events/day/AD

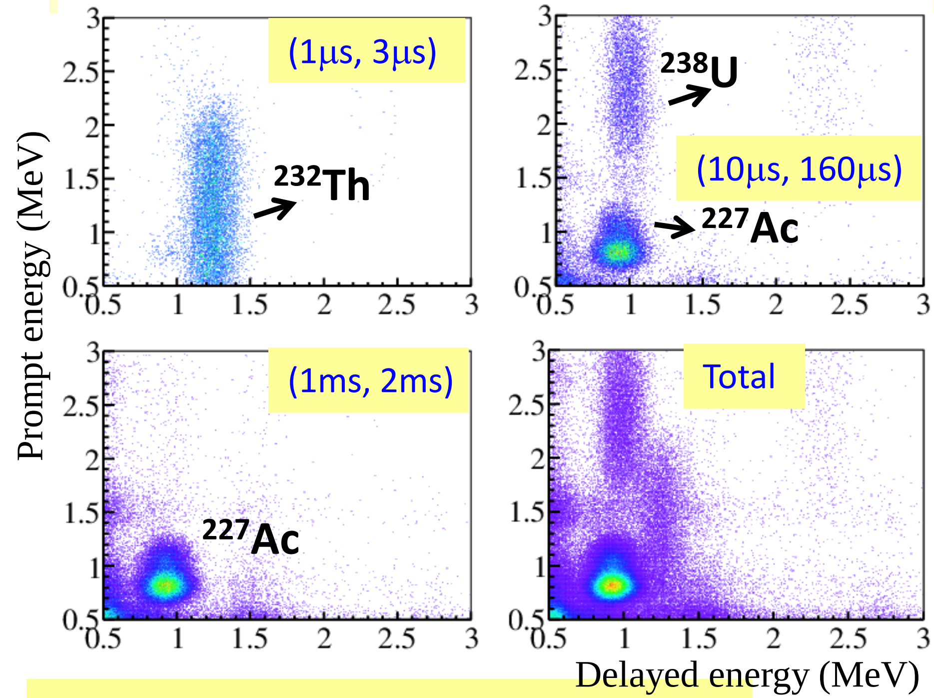
B/S @ EH1/2 ~ 0.03%, B/S @ EH3 ~ 0.3%, ΔB/B ~ 100%





- **^{13}C(α,n)^{16}O correlated backgrounds**
  - Identified α sources(^{238}U, ^{232}Th, ^{227}Ac, ^{210}Po) and rates from cascade decays and spatial distribution
  - Calculate backgrounds from α rate + (α,n) cross sections

B/S @ EH1/2 ~ 0.01%, B/S @ EH3 ~ 0.05% ΔB/B ~ 50%



Time correlations of the cascade decays

Backgrounds summary

	Near Halls		Far Hall		
	B/S %	$\sigma_{B/S}$ %	B/S %	$\sigma_{B/S}$ %	ΔB/B
Accidentals	1.5	0.02	4.0	0.05	~1%
Fast neutrons	0.12	0.05	0.07	0.03	~40%
$^{9}Li/^{8}He$	0.4	0.2	0.3	0.2	~50%
^{241}Am-^{13}C	0.03	0.03	0.3	0.3	~100%
$^{13}C(\alpha, n)^{16}O$	0.01	0.006	0.05	0.03	~50%
Sum	2.1	0.21	4.7	0.37	~10%

Total backgrounds are 5% (2%) in far (near) halls
Background uncertainties are 0.4% (0.2%) in far (near) halls

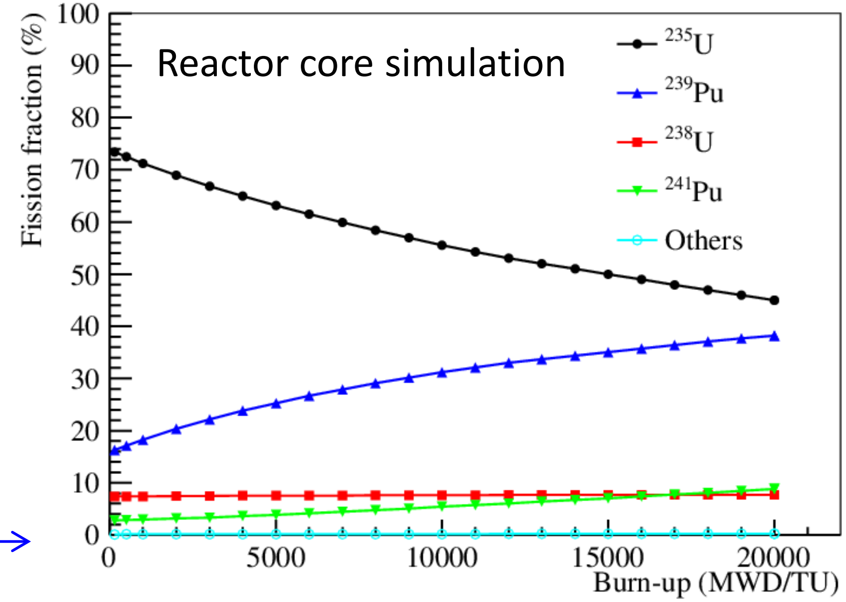
Reactor Neutrinos

- **Reactor neutrino spectrum**

$$S(E) = \sum_i F_i S_i(E)$$

$S_i(E)$: neutrino spectra per fission of each isotope

F_i: simulated fission rate



The measured thermal power W_{th} is used for normalization when simulating fission rate

$$F_i = W_{th} f_i / \sum_k f_k e_k$$

Energy release per fission

Isotope	E_{fi}, MeV/fission
^{235}U	201.92 ± 0.46
^{238}U	205.52 ± 0.96
^{239}Pu	209.99 ± 0.60
^{241}Pu	213.60 ± 0.65

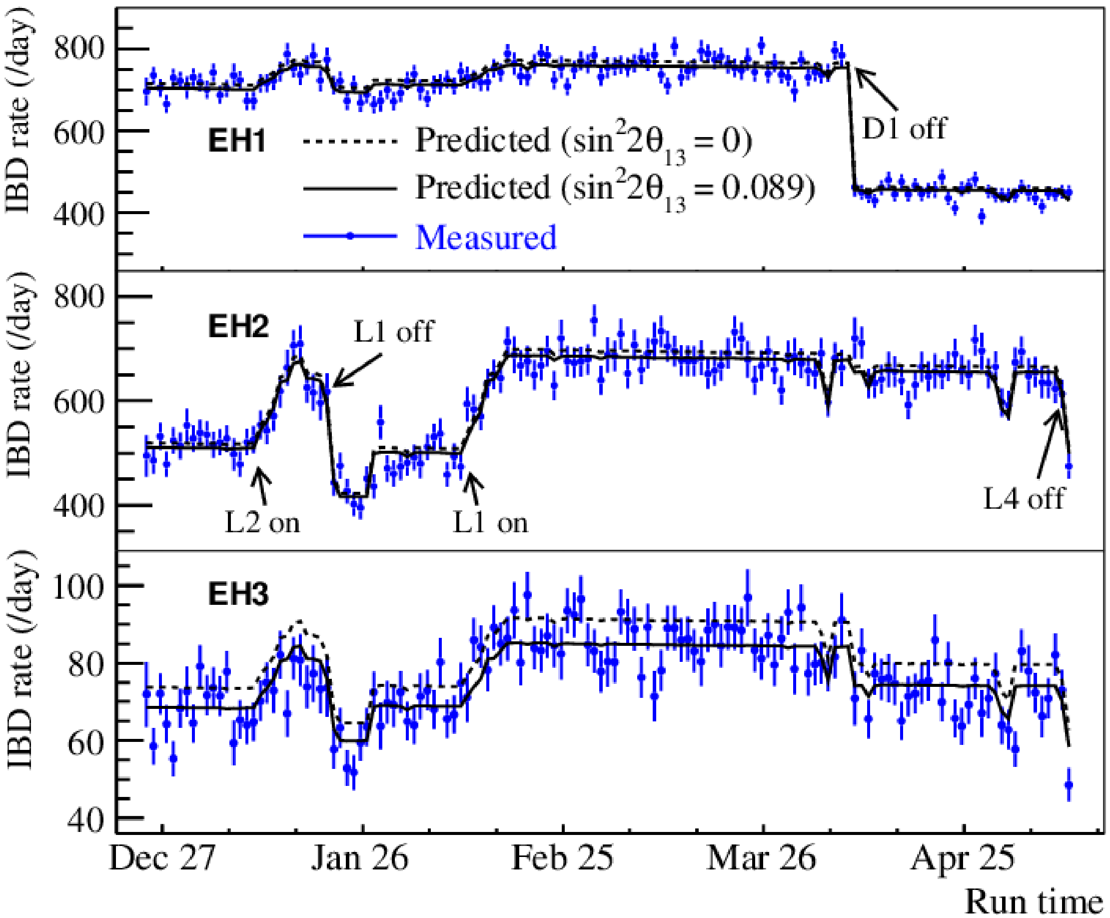
Kopeikin et al, Physics of Atomic Nuclei, Vol. 67, No. 10, 1892 (2004)

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%

Relative measurement → flux model has negligible impact on far v.s near oscillation measurement

Daily Anti-neutrino Rate

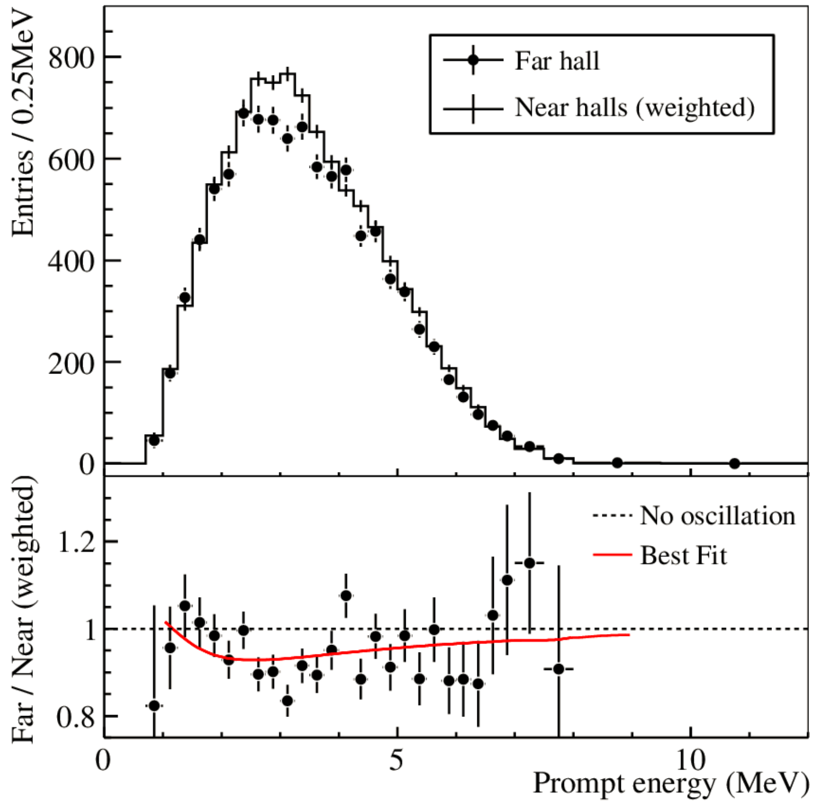
- **Three halls taking data synchronously allows near-far cancellation of reactor related uncertainties**
- **Rate changes reflect the reactor on/off.**

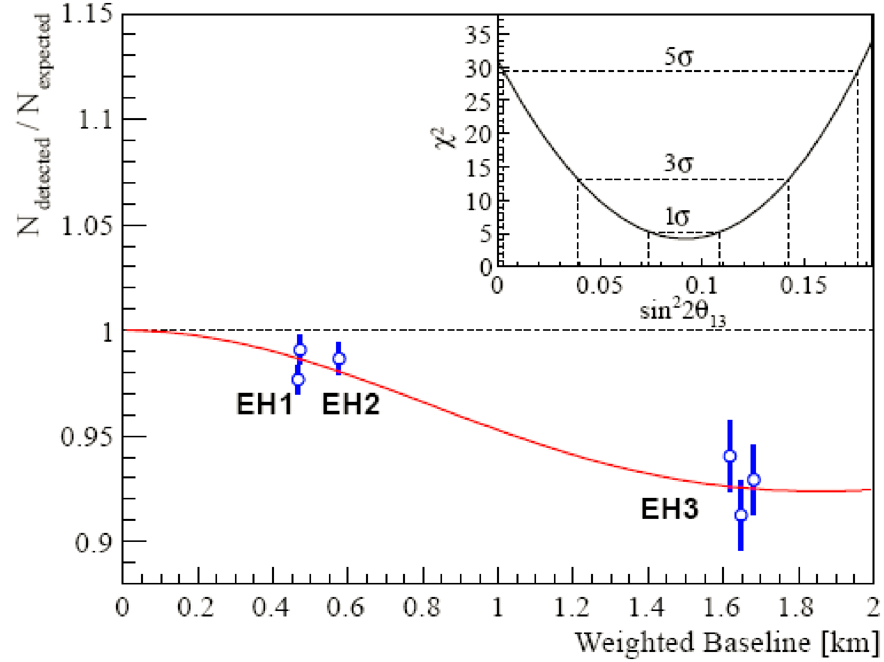


Via GPS and modern theodolites, relative detector-core positions are known to 3cm

Predictions are scaled by a common absolute normalization factor from the fitting

Discovery of a non-zero value of θ_{13}



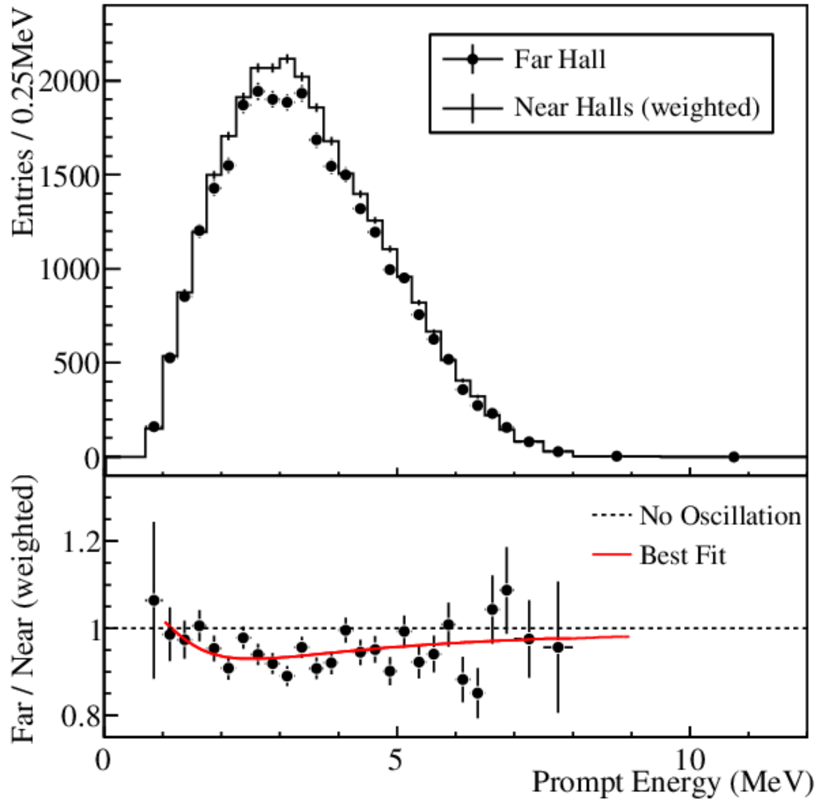


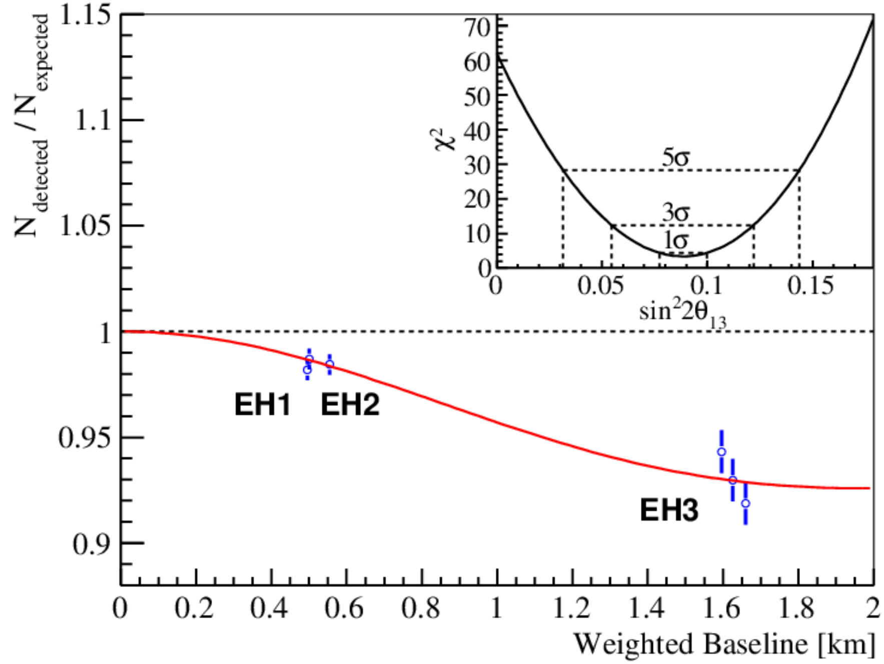
R = 0.940 ± 0.011 (stat) ± 0.004 (syst)

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

A clear observation of far site deficit with the first 55 days' data.
5.2 σ for non-zero value of θ_{13}
Spectral distortion consistent with oscillation.

Improved results





R = 0.944 ± 0.007 (stat) ± 0.003 (syst)

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

With 2.5x more statistics, an improved measurement to θ_{13}

Summary & Outlook

- Daya Bay has unambiguously observed reactor electron-antineutrino disappearance

$$R = 0.944 \pm 0.007\ (\text{stat}) \pm 0.003\ (\text{syst})$$

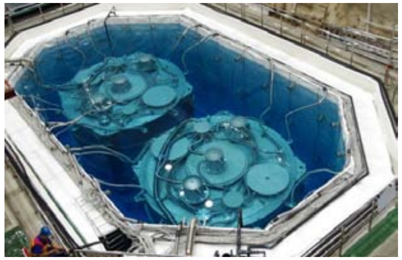
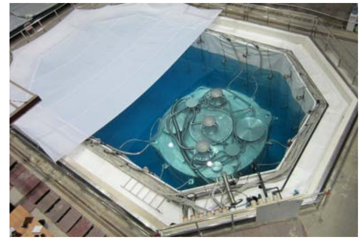
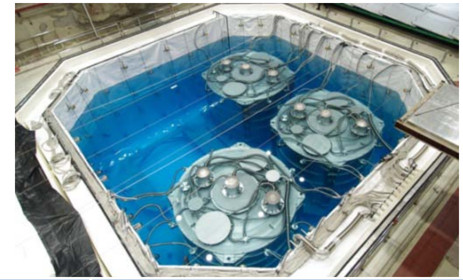
- Interpreting the disappearance as neutrino oscillation yields the most precise measurement of θ_{13}:

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

- Install the last two antineutrino detectors this year, measure $\sin^2 2\theta_{13}$ to ~5% precision
- Persue other physics, such as precise reactor $\bar{\nu}_e$ flux and spectrum, and measurement of Δm^2_{31} (~5% precision)

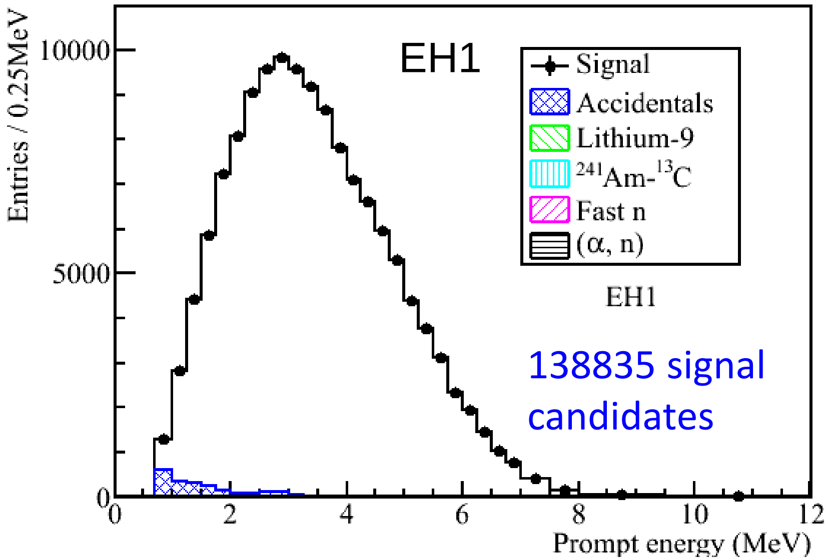
Backup Slides

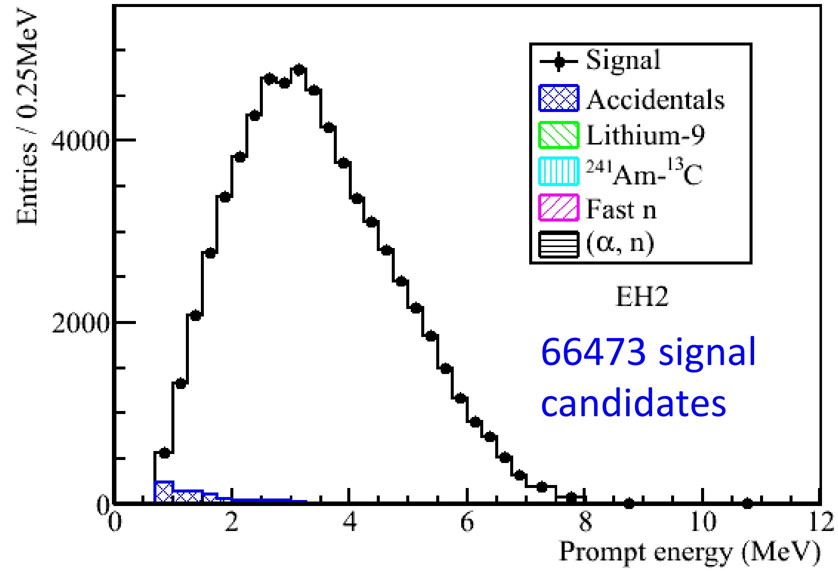
Signals and Backgrounds

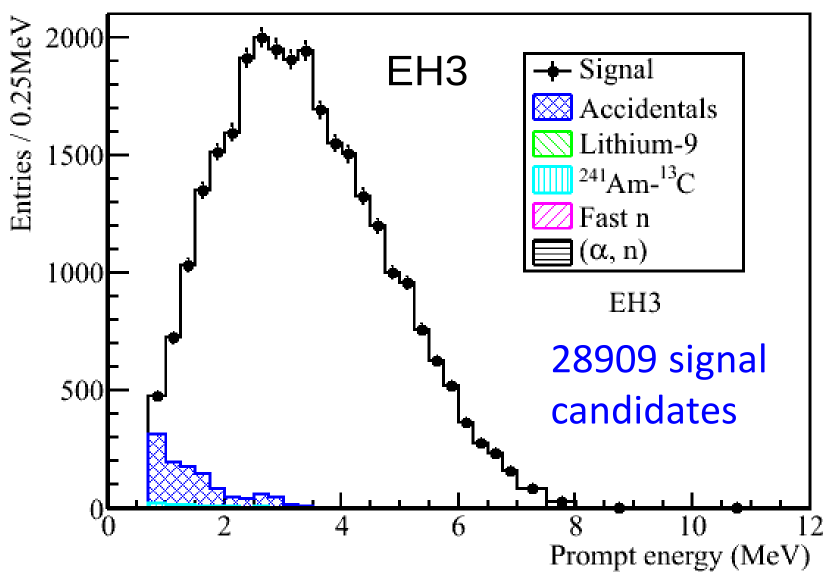




	AD1	AD2	AD3	AD4	AD5	AD6
Antineutrino candidates	69121	69714	66473	9788	9669	9452
DAQ live time (day)	127.5470		127.3763	126.2646		
Efficiency $\varepsilon_\mu * \varepsilon_m$	0.8015	0.7986	0.8364	0.9555	0.9552	0.9547
Accidentals (/day)	9.73±0.10	9.61±0.10	7.55±0.08	3.05±0.04	3.04±0.04	2.93±0.03
Fast neutron (/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 (/day)	2.9±1.5		2.0±1.1	0.22±0.12		
Am-C corr. (/day)	0.2±0.2					
^{13}C(α, n)^{16}O (/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 (/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**

Signal+Backgound Spectrum

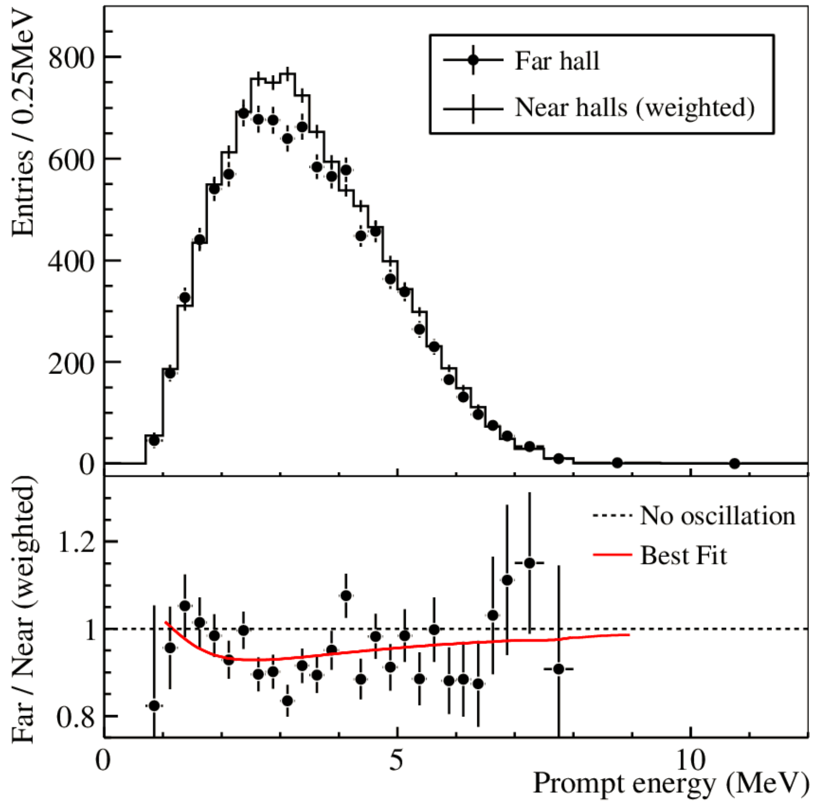


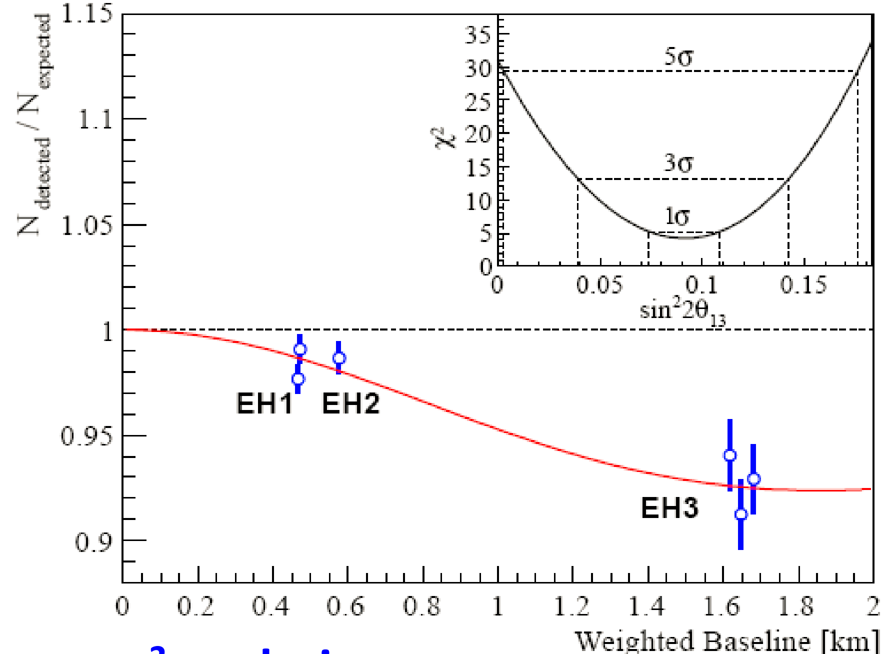




	Near Halls		Far Hall		
	B/S %	$\sigma_{B/S}$ %	B/S %	$\sigma_{B/S}$ %	ΔB/B
Accidentals	1.5	0.02	4.0	0.05	~1%
Fast neutrons	0.12	0.05	0.07	0.03	~40%
^{9}Li/^{8}He	0.4	0.2	0.3	0.2	~50%
^{241}Am-^{13}C	0.03	0.03	0.3	0.3	~100%
^{13}C(α, n)^{16}O	0.01	0.006	0.05	0.03	~50%

Discovery of a non-zero value of θ_{13}





$$R = \frac{Far_{measured}}{Far_{expected}} = \frac{M_4 + M_5 + M_6}{\sum_{i=4}^{6}(\alpha_i(M_1 + M_2) + \beta_i M_3)}$$

χ^2 analysis:

Far vs. near relative measurement

(Absolute rate is not constrained)

Consistent results obtained by independed analysis, different reactor flux models.

R = 0.940 ± 0.011 (stat) ± 0.004 (syst)

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

A clear observation of far site deficit with the first 55 days' data.

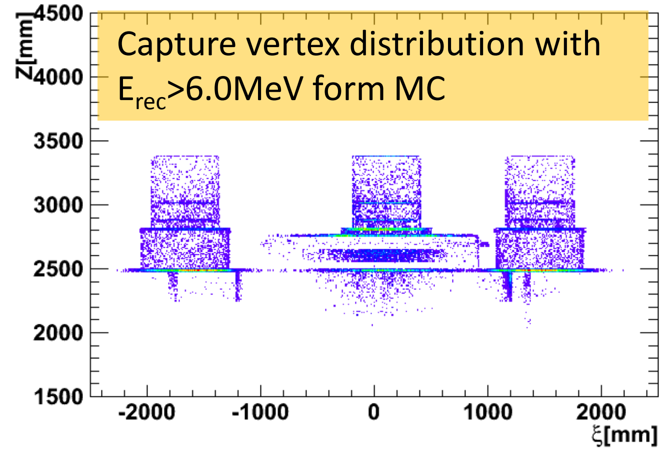
5.2 σ for non-zero value of θ_{13}

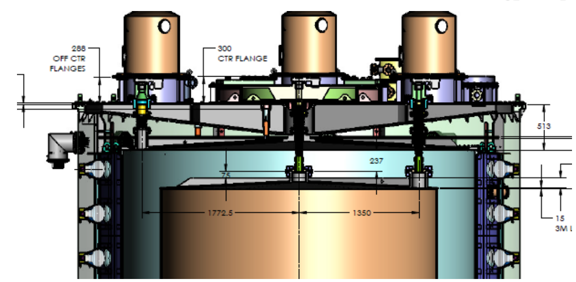
Spectral distortion consistent with oscillation.

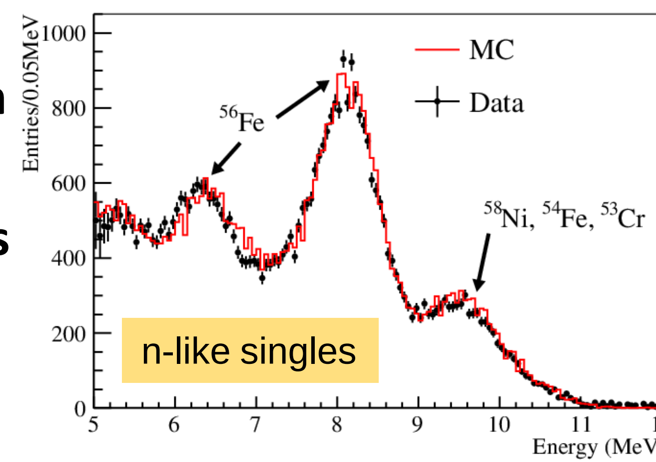
Backgrounds: ^{241}Am-^{13}C source

- **Neutrons emitted from ^{241}Am-^{13}C source inside ACUs could generate γ-rays via inelastic scattering or capture in steel, as well as capture on Gd/H**
- **The neutron-like singles from ACUs were measured by subtracting neutron-like singles in Z<0 region from that in Z>0 region**
  - Measurement is consistent with MC
- **Correlated backgrounds:**
  - Neutron inelastic scattering with ^{56}Fe + neutron capture on ^{57}Fe
  - Simulation shows that correlated background is 0.2 events/day/AD

B/S @ EH1/2 ~ 0.03%, B/S @ EH3 ~ 0.3%
ΔB/B ~ 100%

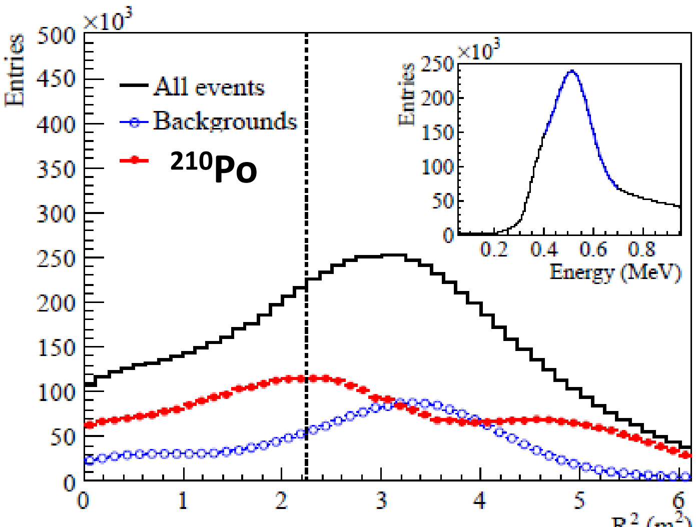


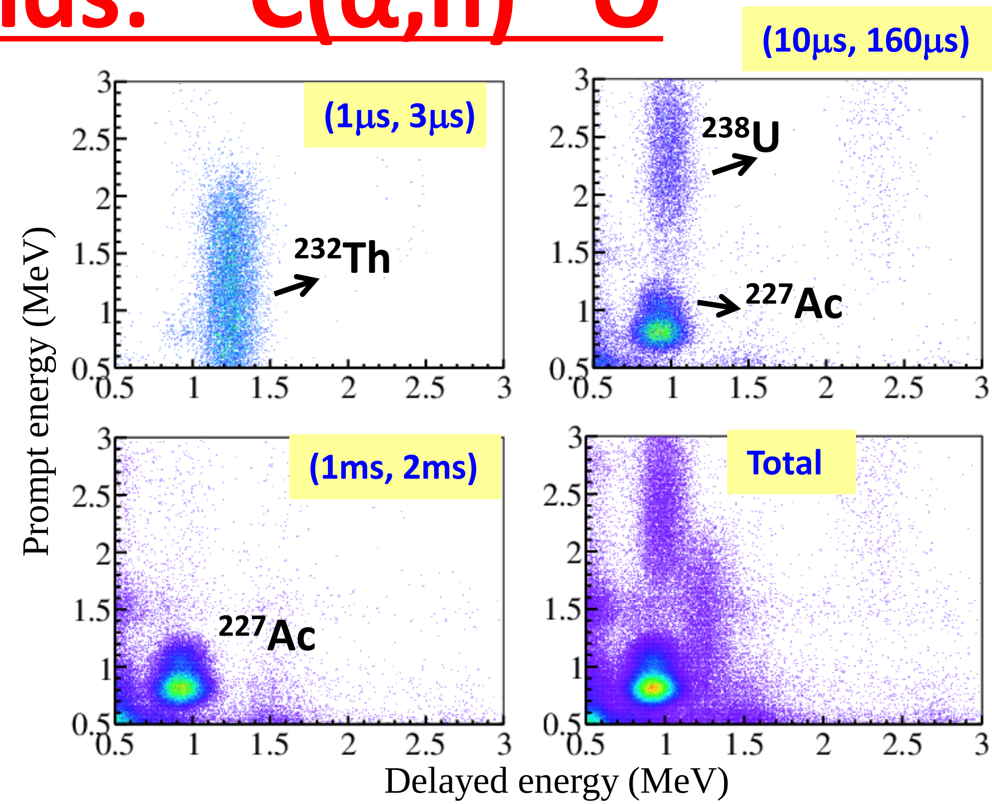




Backgrounds: $^{13}C(\alpha,n)^{16}O$

- **Identified α sources:**
  - ^{238}U, ^{232}Th, ^{227}Ac, ^{210}Po
- **Determine α rate from cascade decays and spatial distribution for singles around ^{210}Po peak**
- **Calculate backgrounds from α rate + (α,n) cross sections**





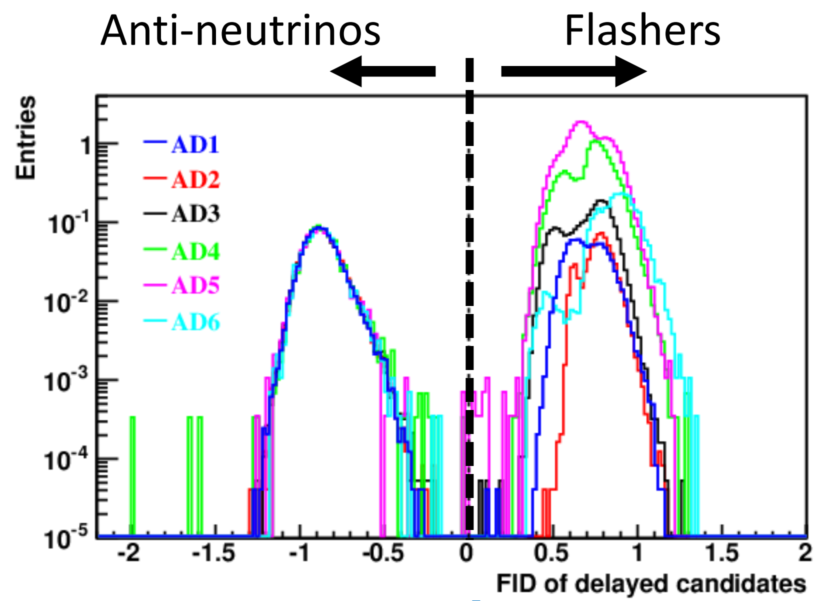
Time correlations of the cascade decay

α source	Total α rate	BG rate
^{210}Po	22Hz at EH1 14Hz at EH2 5Hz at EH3	0.06/day at EH1 0.04/day at EH2 0.02/day at EH3
^{227}Ac	1.4 Bq	0.01/day
^{238}U	0.07Bq	0.001/day
^{232}Th	1.2Bq	0.01/day

B/S @ EH1/2 ~ 0.01%, B/S @ EH3 ~ 0.04%
ΔB/B ~ 50%

Flashers: Imperfect PMTs

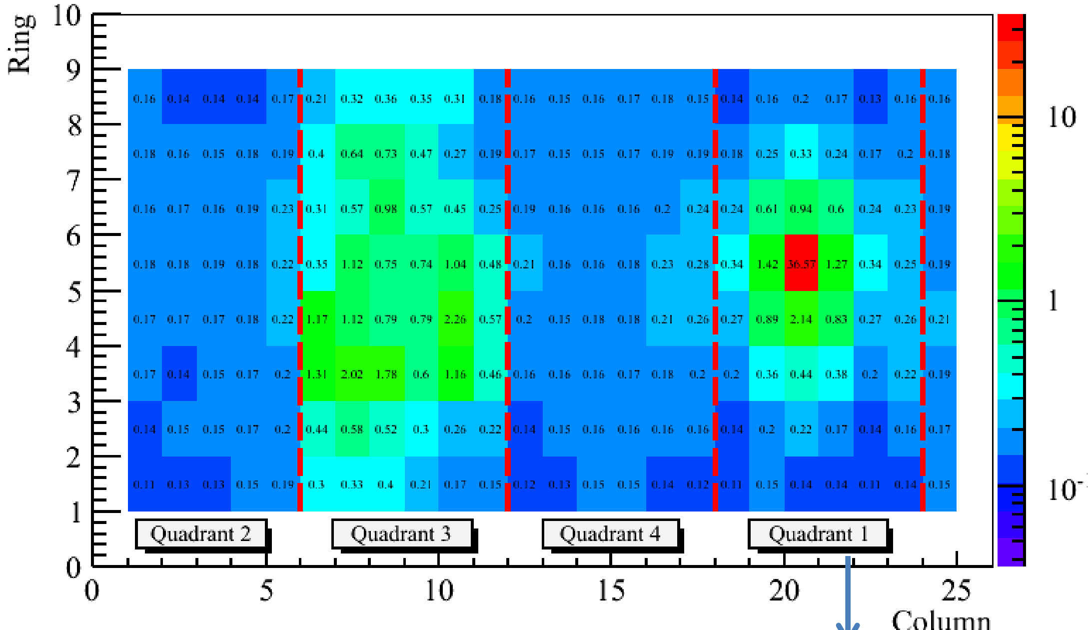
- **Spontaneous light emission by PMT**
- **~ 5% of PMT, ~5% of event**
- **Rejection: pattern of fired PMTs**
  - **Topology: a hot PMT + near-by PMTs and opposite PMTs**



$$FID = \log_{10}\left[\left(\frac{d_{quad}}{1.}\right)^2 + \left(\frac{d_{max}}{0.45}\right)^2\right] < 0$$

$$d_{quad} = Q_{quad3}/(Q_{quad2} + Q_{quad4})$$

$$d_{max} = Q_{max}/Q_{sum}$$



Contain the hottest PMT

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

Backgrounds: fast neutron

Method I:

Relax the E_p<12MeV criterion. Extrapolation into the (0.7 MeV, 12.0 MeV) region gave an estimate for the residual fast-neutron background.

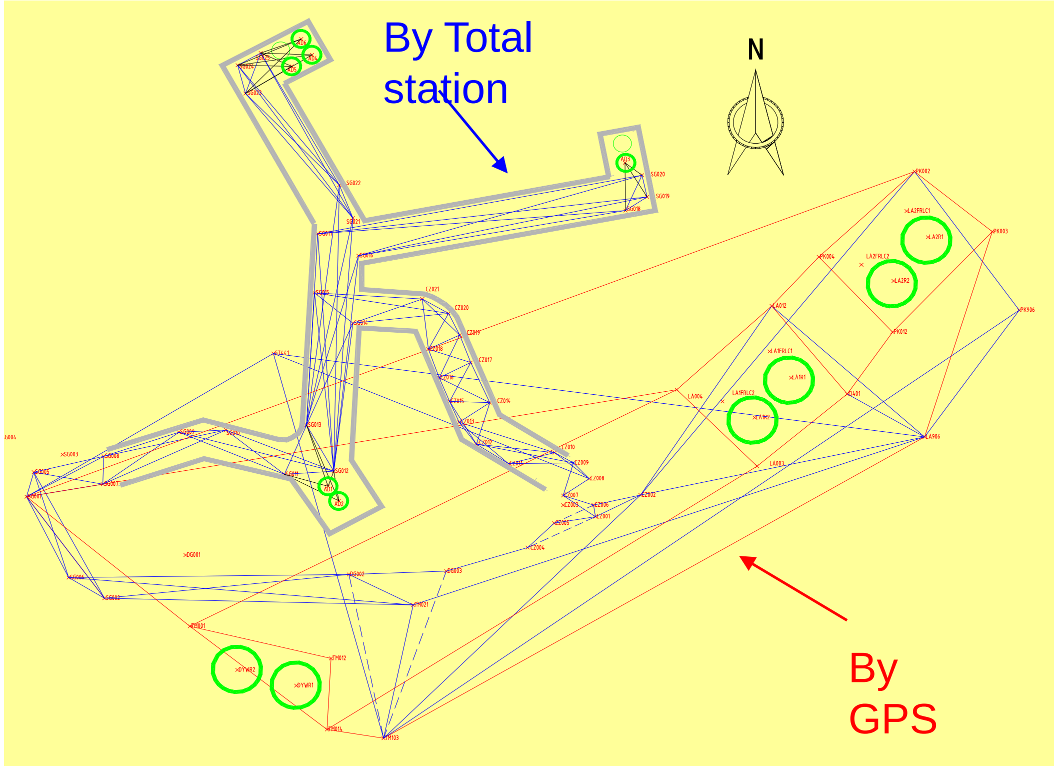
Method II:

Use water pool to determine the spectra of fast neutron, and estimate the residual fast neutron background and water pool inefficiency

	Method I (/day)	Method II (/day)
EH1	0.77±0.24	0.71±0.35
EH2	0.58±0.33	0.51±0.25
EH3	0.05±0.02	0.02±0.02

Baseline

- **Survey:**
  - **Methods: GPS, Total Station, laser tracker, level instruments, …**
  - **Results are compared with design values, and NPP coordinates**
  - **Data processed by three independent software**
- **Results: sum of all the difference less than 28 mm**
- **Uncertainty of the fission center from reactor simulation:**
  - **2 cm horizontally**
  - **20 cm vertically**
- **The combined baseline error is 35mm, corresponding to a negligible reactor flux uncertainty (<0.02%)**

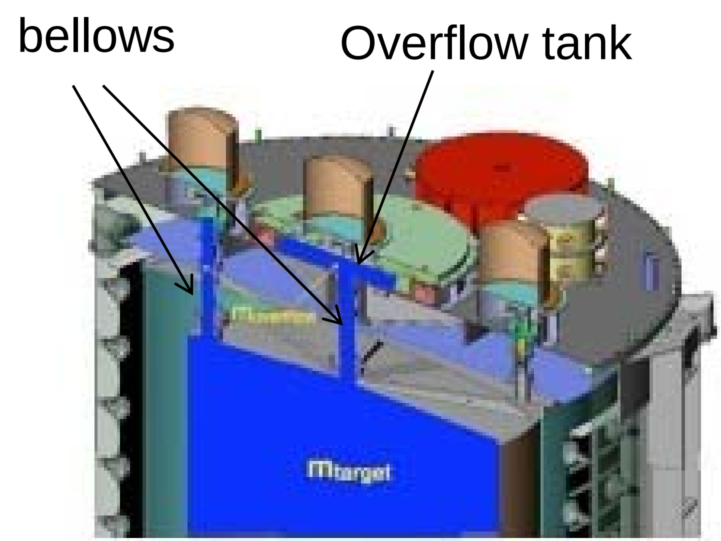


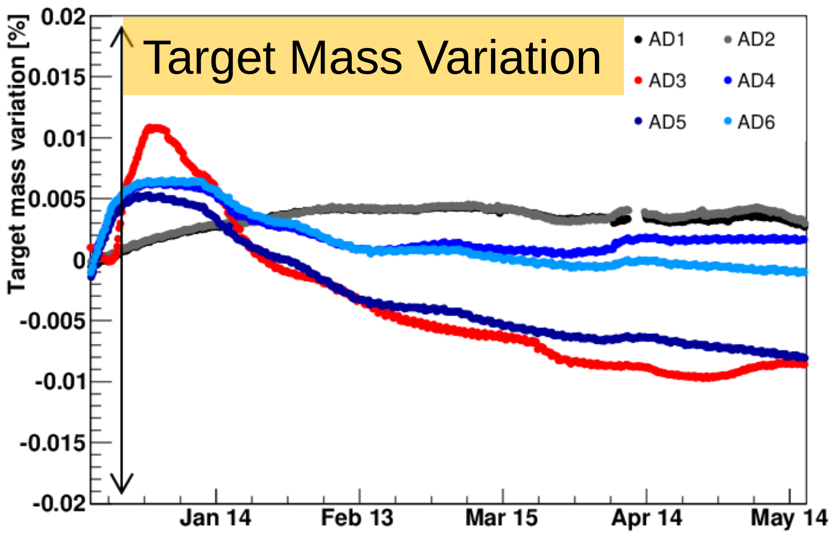
Target Mass & No. of Protons

- Target mass during the filling measured by the load cell, precision ~ 3kg → 0.015%
- Checked by Coriolis flow meters, precision ~ 0.1%
- Actually target mass:

$$M_{target} = M_{fill} - M_{overflow} - M_{bellow}$$

- $M_{overflow}$ and $M_{bellows}$ are determined by geometry
- $M_{overflow}$ is monitored by sensors



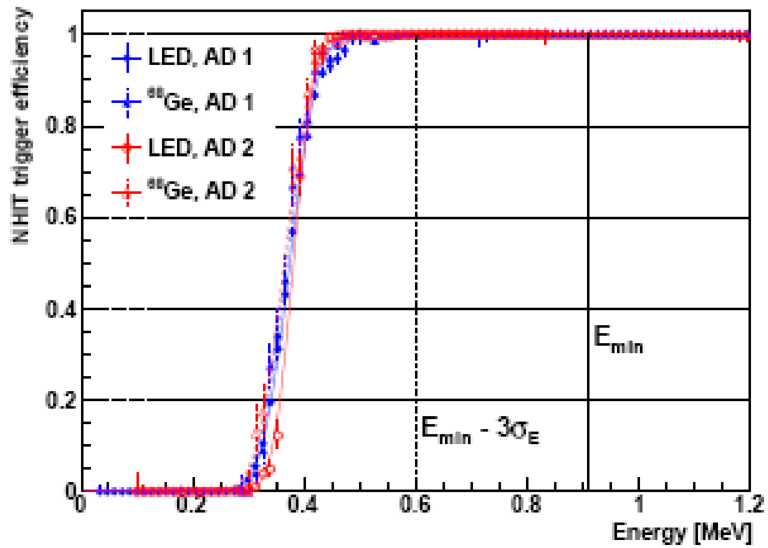


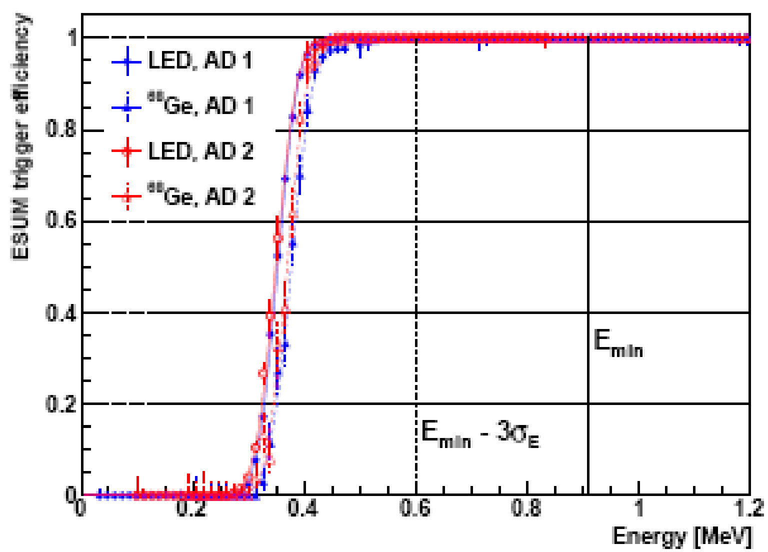
One batch LAB

Quantity	Relative	Absolute
Free protons/Kg	neg.	0.47%
Density	neg.	0.0002%
Total mass	0.015%	0.015%
Bellows	0.0025%	0.0025
Overflow tank	0.02%	0.02%
Total	0.03%	0.47%

Trigger Performance

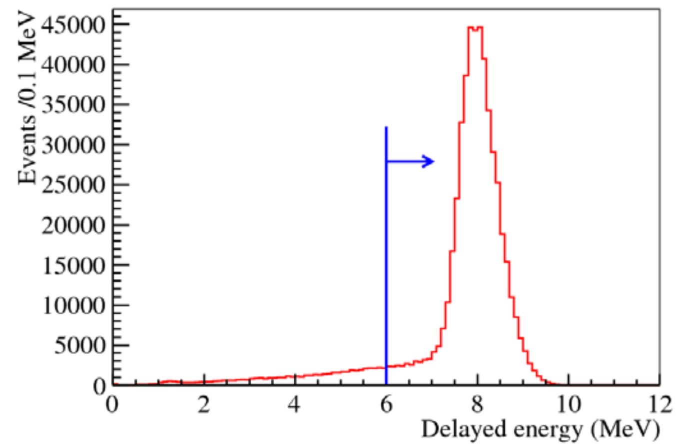
- **Threshold for a hit:**
  - AD & pool: ¼ PE
- **Trigger thresholds:**
  - AD: ~ N_{HIT}=45, E_{tot}= ~ 0.4 MeV
  - Inner pool: N_{HIT}=6
  - Outer pool: N_{HIT}=7 (8 for far hall)
  - RPC: 3/4 layers in each module
- **Trigger rate(EH1)**
  - AD singles rate:
    - >0.4MeV, ~ 280Hz
    - >0.7MeV, ~ 60Hz
  - Inner pool rate: ~170 Hz
  - Outer pool rate: ~ 230 Hz



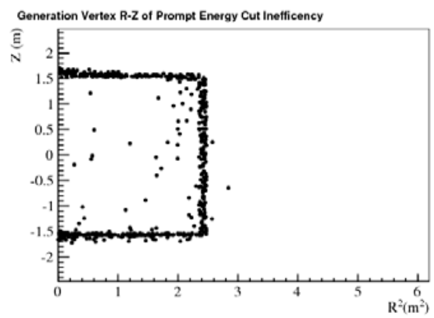


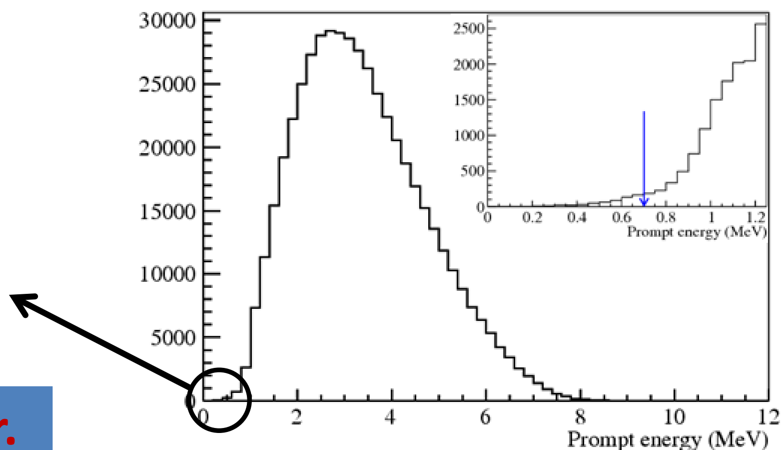
Energy Cuts Efficiency and Systematics

- **Delayed energy cut $E_n > 6$ MeV**
  - Energy scale uncertainty 0.5% ➔
  - Efficiency uncertainty ~ 0.12%
- **Prompt energy cut $E_p > 0.7$ MeV**
  - Energy scale uncertainty 2 % ➔
  - Efficiency uncertainty ~ 0.01%



The inefficiency mainly comes from edges

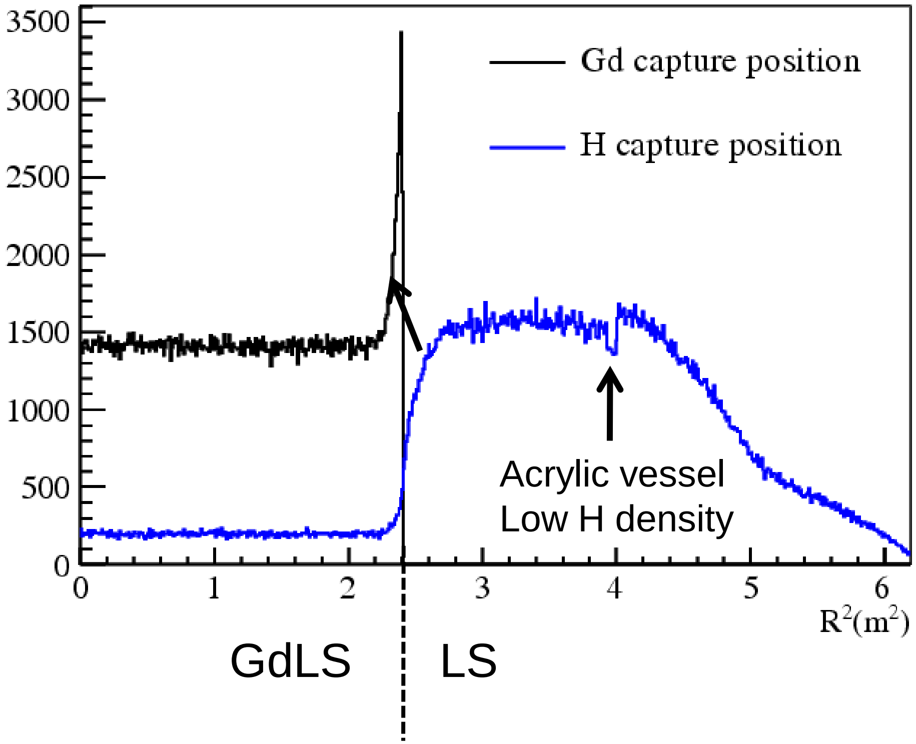




	Eff.	Corr.	Un-corr.
Delayed energy cut	90.9%	0.6%	0.12%
Prompt energy cut	99.88%	0.10%	0.01%

Spill-in effect and Systematics

- Neutrons generated in acrylic and LS can spill into Gd-LS and be captured on Gd.
- Simulation shows that Gd capture is increased by 5%.
- The relative differences in acrylic vessel thickness, acrylic density and liquid density are modeled in MC



	Eff.	Corr.	Un-corr.
Spill-in	105.0%	1.5%	0.02%

Muon Veto and Multiplicity Cut

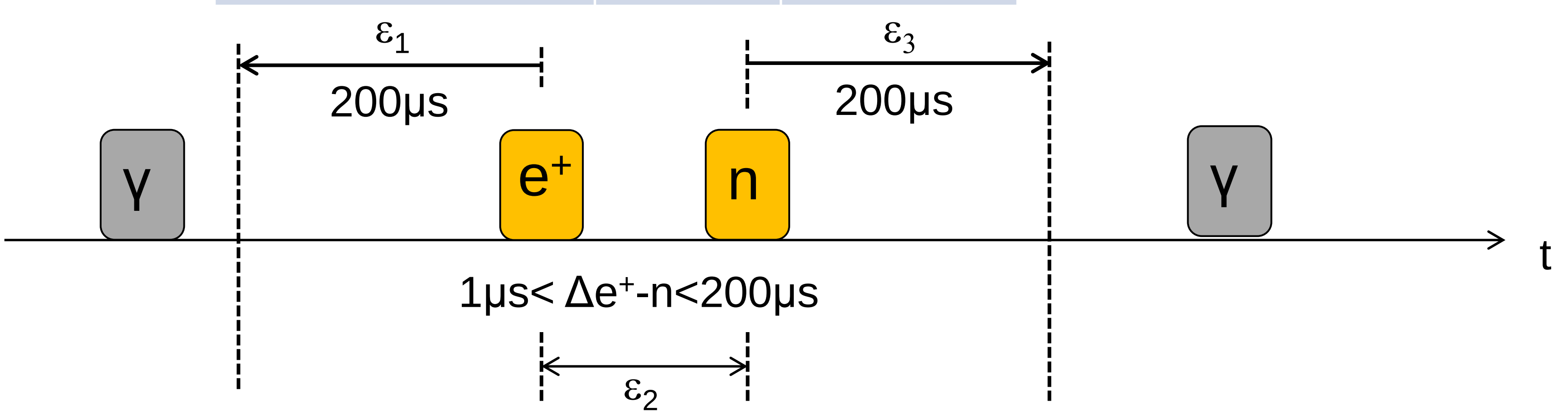
- **Muon veto**
  - Total veto time is the sum of all the veto time windows
  - Temporal overlap is taken into account
- **Multiplicity cut**
  - Efficiency = $\varepsilon_1 \times \varepsilon_2 \times \varepsilon_3$
- **Total efficiency**
  - Uncertainty coming mainly from the average neutron capture time. It is correlated

1s after an AD shower mu
1ms after an AD mu
0.6ms after an WP mu

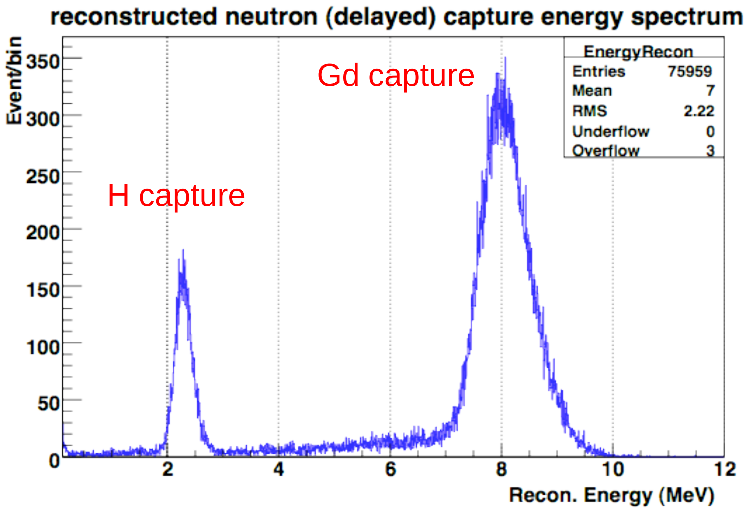
Prompt-delayed pairs within 200 μs
No triggers before the prompt and after the delayed signal by 200 μs

	Corr.	Un-corr.
Multiplicity cut	0.02%	< 0.01%

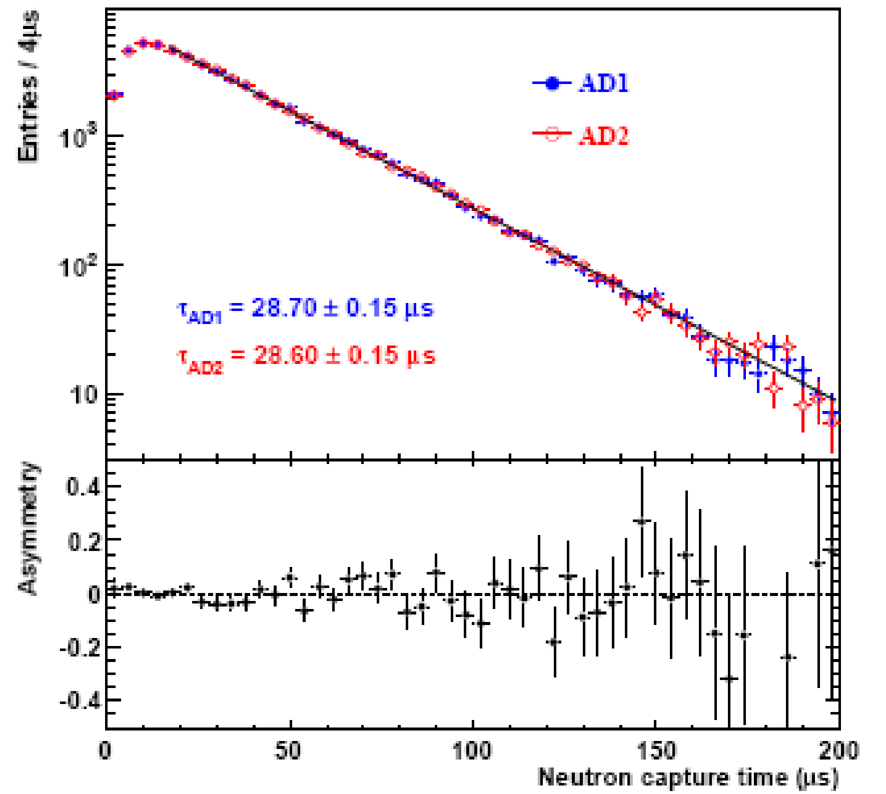
Efficiency is AD dependent



Gd Capture Fraction: H/Gd and Systematics



Neutron capture time from Am-C

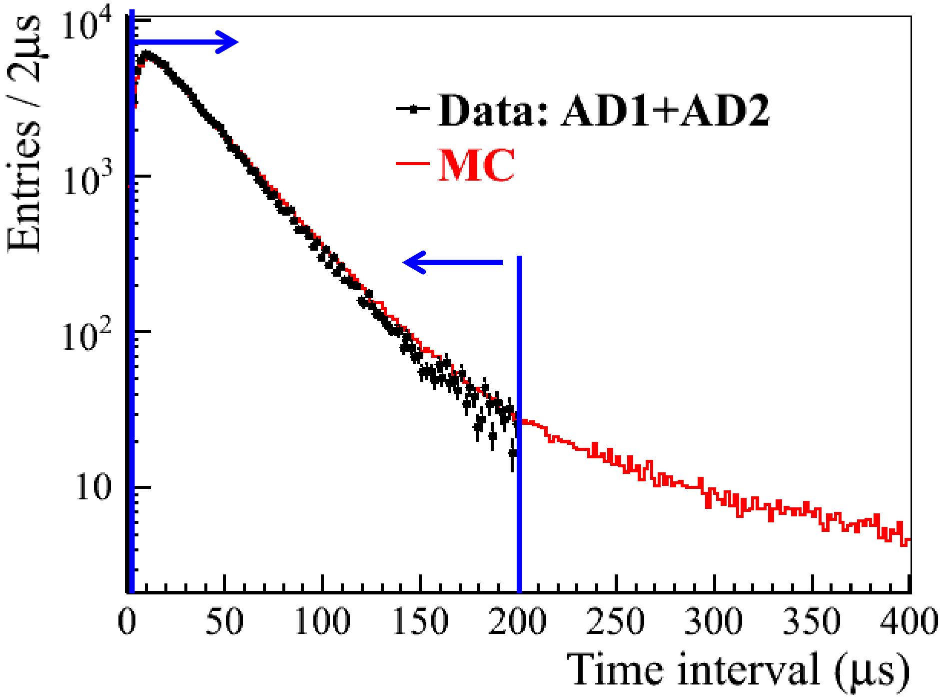


- Uncertainty is large if takes simply the ratio of area
- Relative Gd content variation 0.1% → evaluated from neutron capture time
- Geometry effect on spill-in/out 0.02% → relative differences in acrylic thickness, acrylic density and liquid density are modeled in MC

	Eff.	Corr.	Un-corr.
Gd capture ratio	83.8%	0.8%	<0.1%

Time Correlation Cut: $1\mu s < \Delta t_{e+-n} < 200\mu s$

- **Uncertainty comes from Gd concentration difference and possible trigger time walk effect (assuming 20ns)**



	Eff.	Corr.	Un-corr.
Capture time cut	98.6%	0.12%	0.01%

Livetime

- **Synchronization of 3 Halls**
  - Divide data taking time into one-hour slices
  - Discard data in a whole slice if not all 3 halls are running
- **Uncertainty**
  - Comes from the case when electronics buffer is full.
  - This estimated to be less than 0.0025%, by either blocked trigger ratio or accumulating all buffer full periods

	Eff.	Corr.	Un-corr.
Livetime	100%	0.002%	< 0.01%