Observation of Electron Anti-neutrino Disappearance at Daya Bay

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Institute of High Energy Physics

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Special seminar at IHEP

Outline

- Introduction
- Data set & quality control
- Calibration and Event reconstruction
- Event selection
- Backgrounds & uncertainties
- Efficiencies & systematic errors
- Expectation
- Results of neutrino oscillation
- Summary

F.P. An et al., Daya Bay Coll., " A side-by-side comparison of Daya Bay anti-neutrino detectors", arXiv: 1202.6181(2012), submitted to NIM

F.P. An et al., Daya Bay Coll., "Observation of electron anti-neutrino disappearance at Daya Bay", submitted to PRL

Neutrinos & Neutrino Oscillation

- **Fundamental building blocks of matter:**

$$\begin{pmatrix} e & \mu & \tau \\ \nu_e & \nu_\mu & \nu_\tau \end{pmatrix} \qquad \begin{pmatrix} u & c & t \\ d & s & b \end{pmatrix}$$

- **Neutrino mass: the central issue of neutrino physics**
  - ⇨ **Tiny mass but huge amount**
  - ⇨ **Influence to Cosmology: evolution, large scale structure, …**
  - ⇨ **Only evidence beyond the Standard Model**
- **Neutrino oscillation: a great method to probe the mass**

$$\xrightarrow{\nu_e}\quad\xrightarrow{\nu_\mu}\quad\xrightarrow{\nu_e}\quad\xrightarrow{\nu_\mu}$$

Oscillation probability:

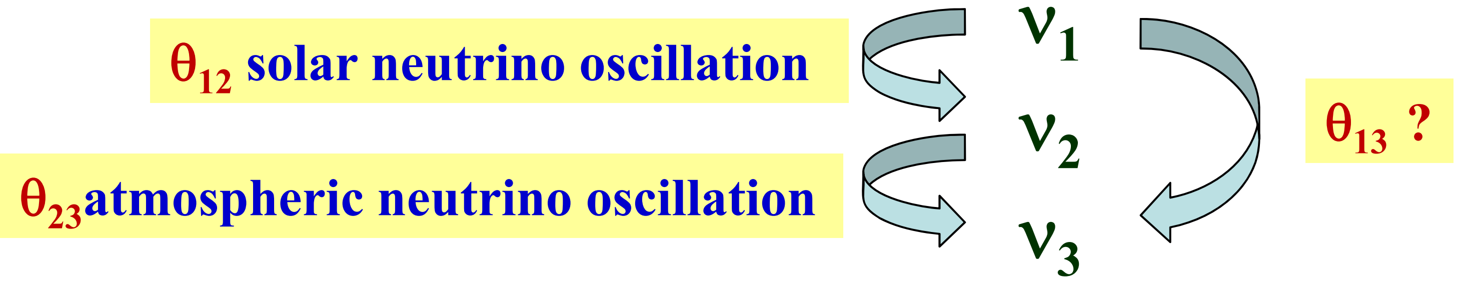
$$P(\nu_e -> \nu_\mu) = \sin^2(2\theta)\,\sin^2(1.27\Delta m^2 L/E)$$

Oscillation amplitude

Oscillation frequency

Daya Bay: for a New Type of Oscillation

- **Goal: search for a new oscillation mode θ_{13} ?**



θ_{12} solar neutrino oscillation

θ_{23}atmospheric neutrino oscillation

ν_1

ν_2

ν_3

θ_{13} ?

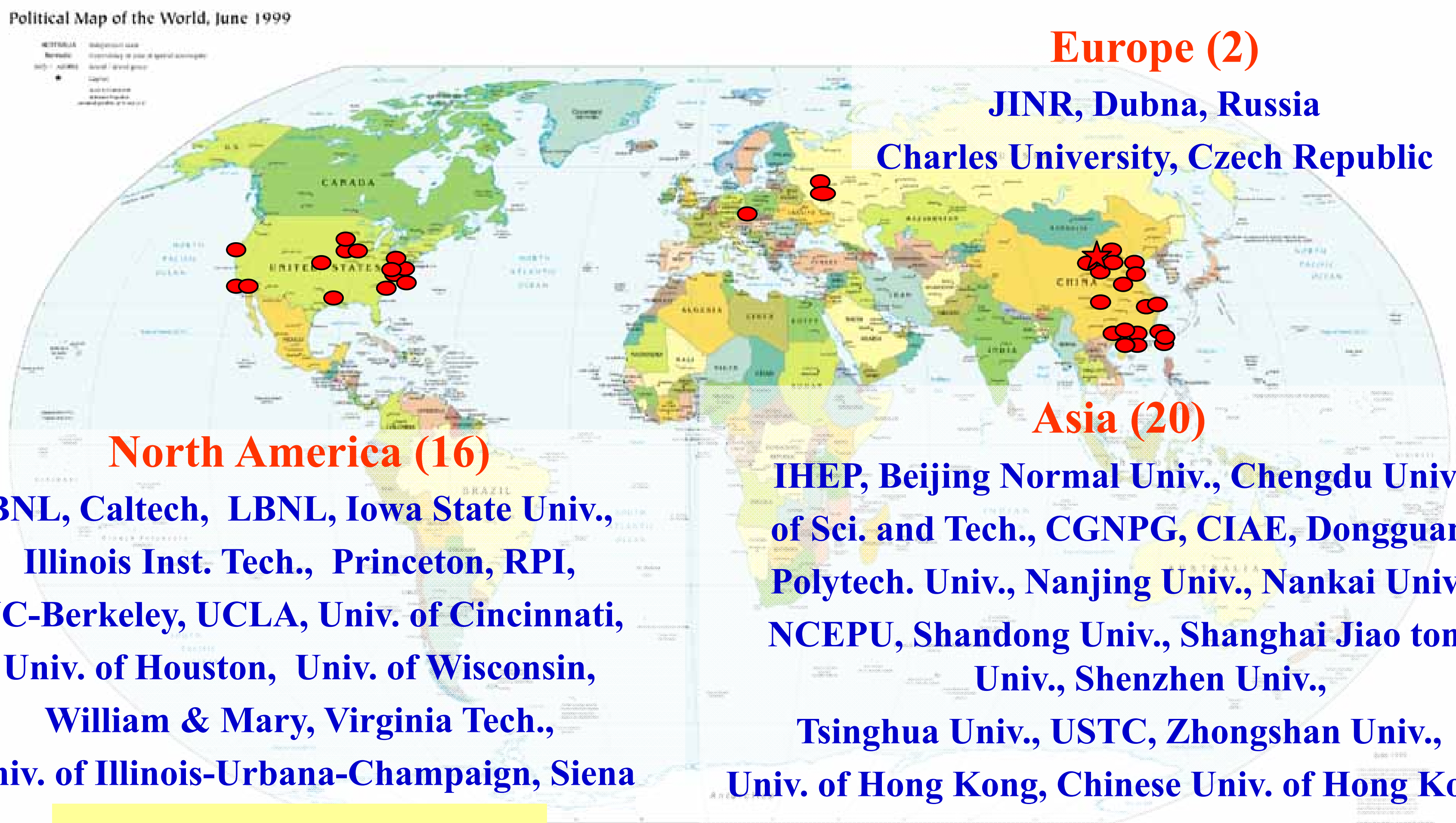
- **Neutrino mixing matrix:**

$$\mathbf{V} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & \boxed{s_{13}} \\ 0 & e^{-i\delta} & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\rho} & 0 & 0 \\ 0 & e^{i\sigma} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Unknown mixing parameters: θ_{13}, δ + 2 Majorana phases

Need sizable θ_{13} for the δ measurement

The Daya Bay Collaboration



Europe (2)

JINR, Dubna, Russia

Charles University, Czech Republic

North America (16)

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

~250 Collaborators

Asia (20)

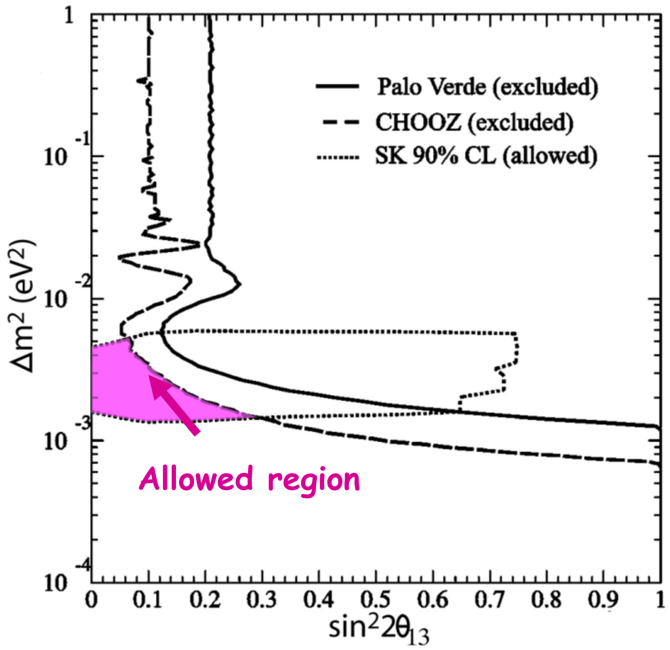
IHEP, Beijing Normal Univ., Chengdu Univ. of Sci. and Tech., CGNPG, CIAE, Dongguan Polytech. Univ., Nanjing Univ., Nankai Univ., NCEPU, Shandong Univ., Shanghai Jiao tong Univ., Shenzhen Univ., Tsinghua Univ., USTC, Zhongshan Univ., Univ. of Hong Kong, Chinese Univ. of Hong Kong, National Taiwan Univ.,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

Direct Searches in the Past

- **Palo Verde & Chooz: no signal**

$\mathrm{Sin}^2 2\theta_{13} < 0.12$ @ 90%C.L.

if $\Delta M^2_{23} = 0.0024\ \mathrm{eV}^2$



- **T2K: 2.5 σ over bkg**

$0.03 < \mathrm{Sin}^2 2\theta_{13} < 0.28$ @ 90%C.L. for NH

$0.04 < \mathrm{Sin}^2 2\theta_{13} < 0.34$ @ 90%C.L. for IH

- **Minos: 1.7 σ over bkg**

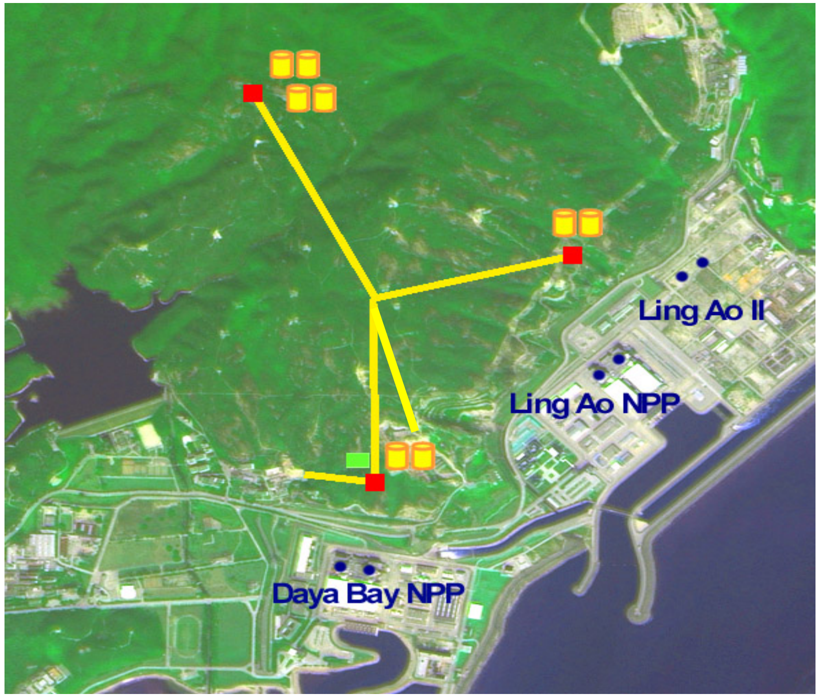
$0 < \mathrm{Sin}^2 2\theta_{13} < 0.12$ @ 90%C.L. NH

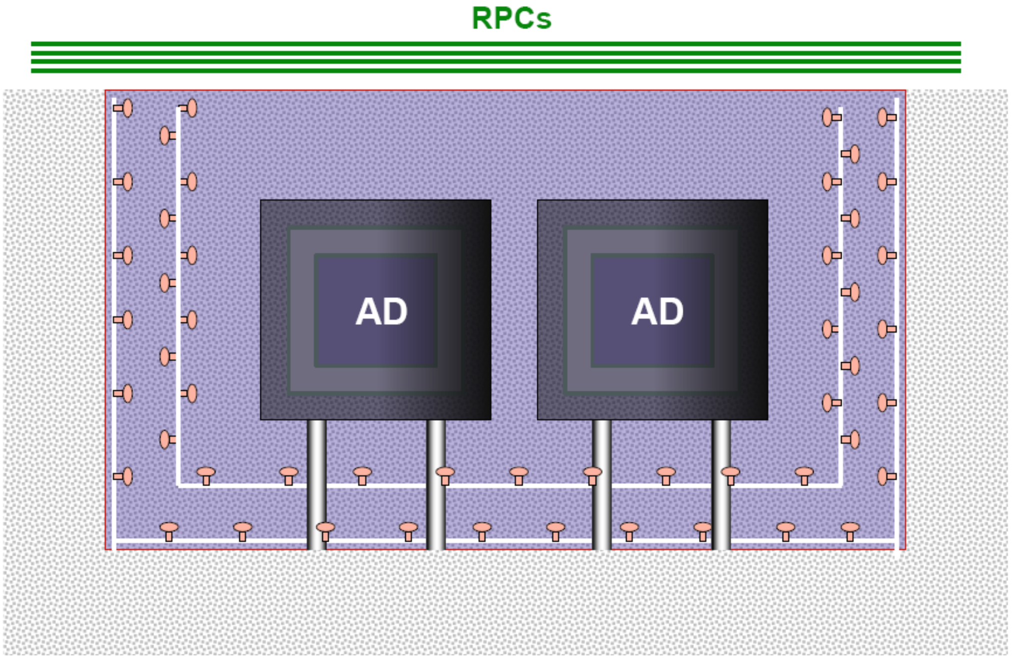
$0 < \mathrm{Sin}^2 2\theta_{13} < 0.19$ @ 90%C.L. IH

- **Double Chooz: 1.7 σ**

$\sin^2 2\theta_{13} = 0.086 \pm 0.041(\mathrm{stat}) \pm 0.030(\mathrm{sys})$

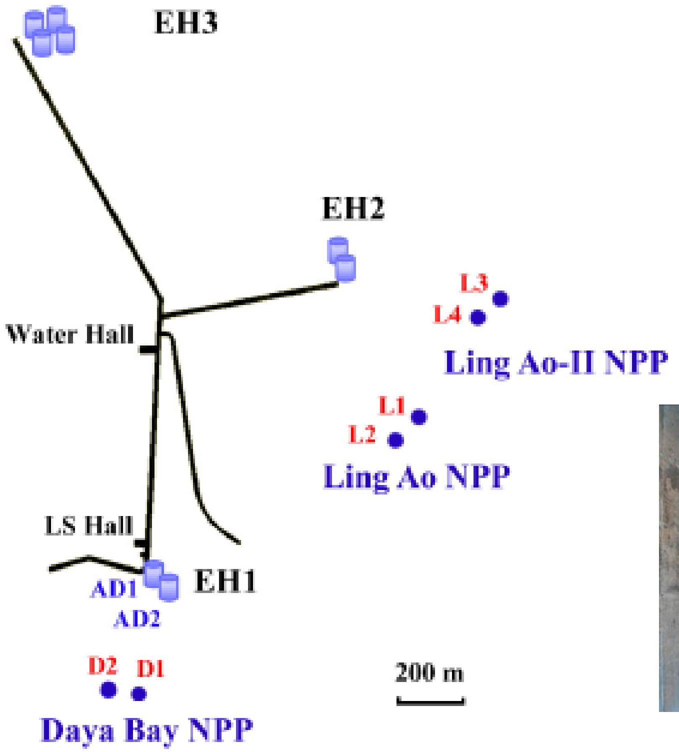
Daya Bay Experiment: Layout





- Relative measurement to cancel Corr. Syst. Err.
  - ⇨ 2 near sites, 1 far site
- Multiple AD modules at each site to reduce 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

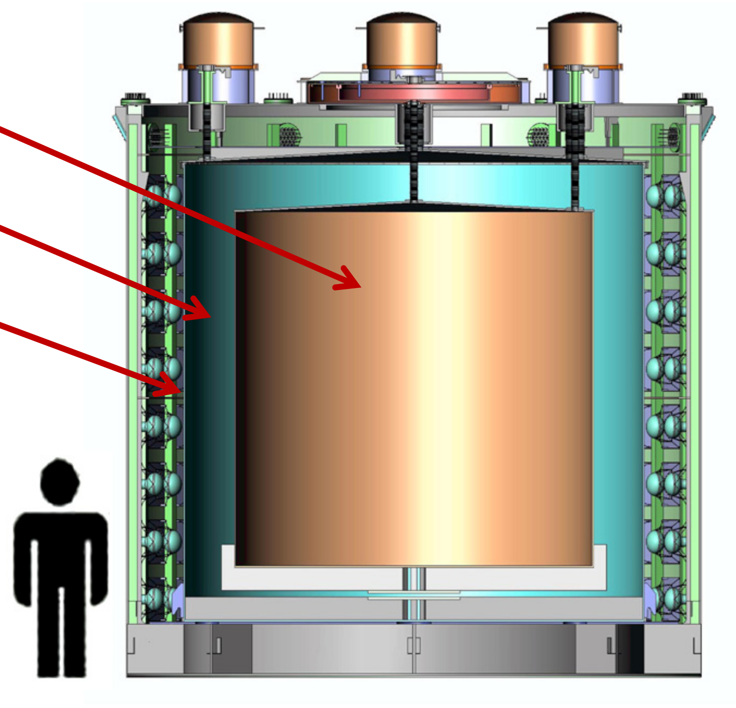
Underground Labs

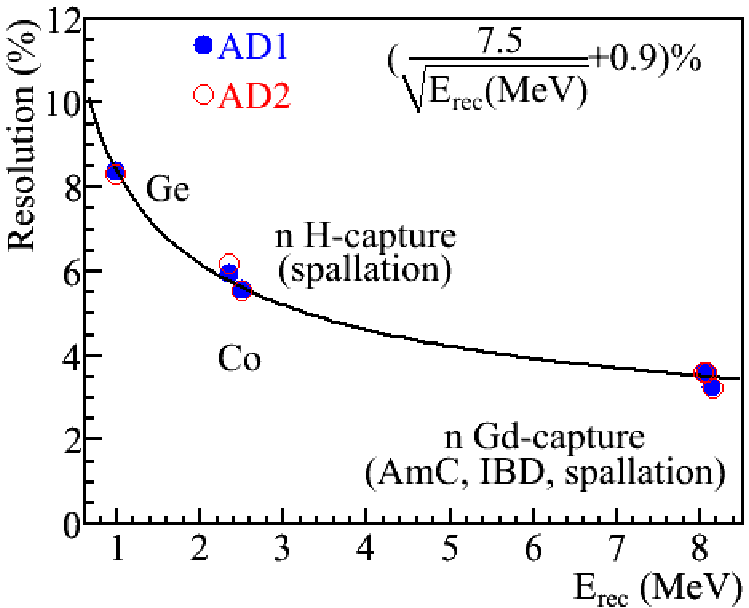


	Overburden（MWE）	R_μ（Hz/m^2）	E_μ（GeV）	D1,2 (m)	L1,2 (m)	L3,4 (m)
EH1	250	1.27	57	364	857	1307
EH2	265	0.95	58	1348	480	528
EH3	860	0.056	137	1912	1540	1548

Anti-neutrino Detector (AD)

- **Three zones modular structure:**
  - I. target: Gd-loaded scintillator
  - II. γ-catcher: normal scintillator
  - III. buffer shielding: oil
- **192 8" PMTs/module**
- **Two optical reflectors at the top and the bottom,** Photocathode coverage increased from 5.6% to 12%

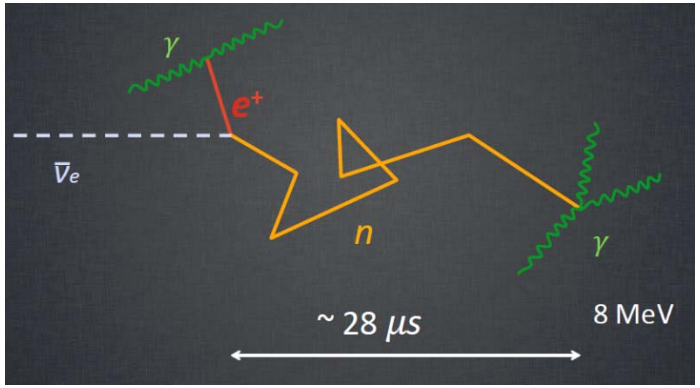




Target: 20 t, 1.6m
γ-catcher: 20t, 45cm
Buffer: 40t, 45cm
Total weight: ~110 t

Neutrino Detection: Gd-loaded Liquid Scintillator

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

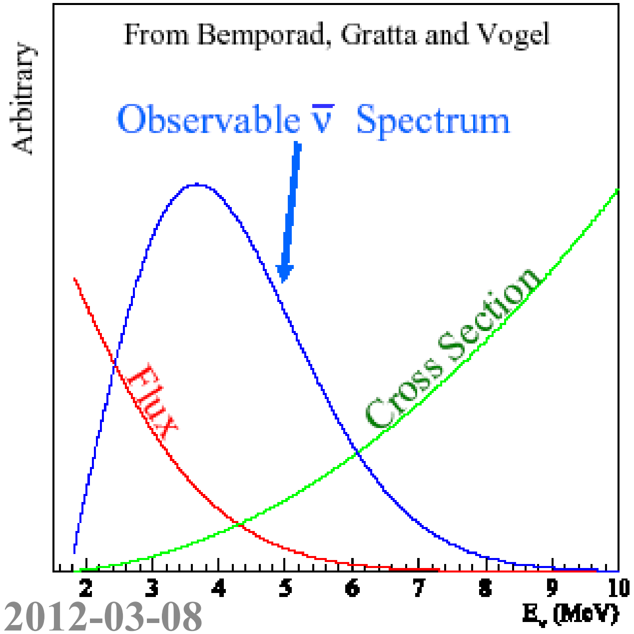


τ ≈ 28 μs(0.1% Gd)

n + p → d + γ (2.2 MeV)

n + Gd → Gd* + γ (8 MeV)

Neutrino Event: coincidence in time, space and energy


From Bemporad, Gratta and Vogel

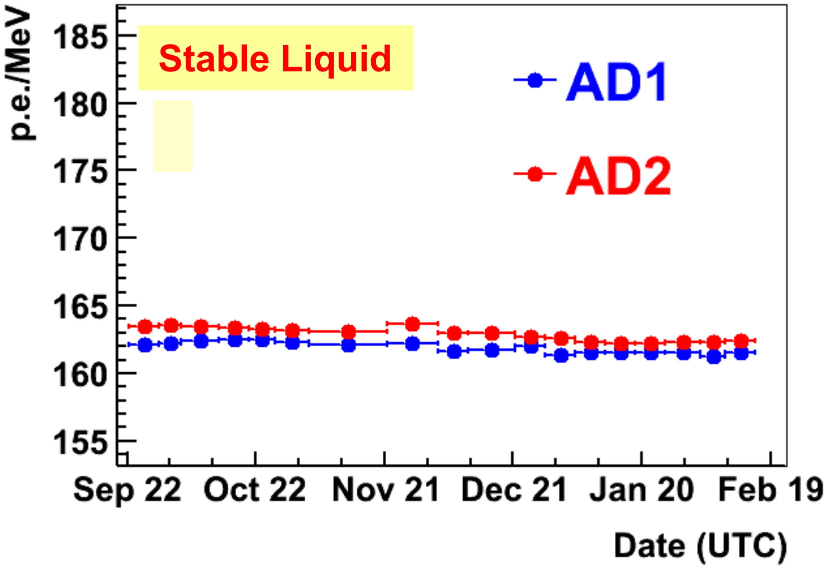
Neutrino energy:

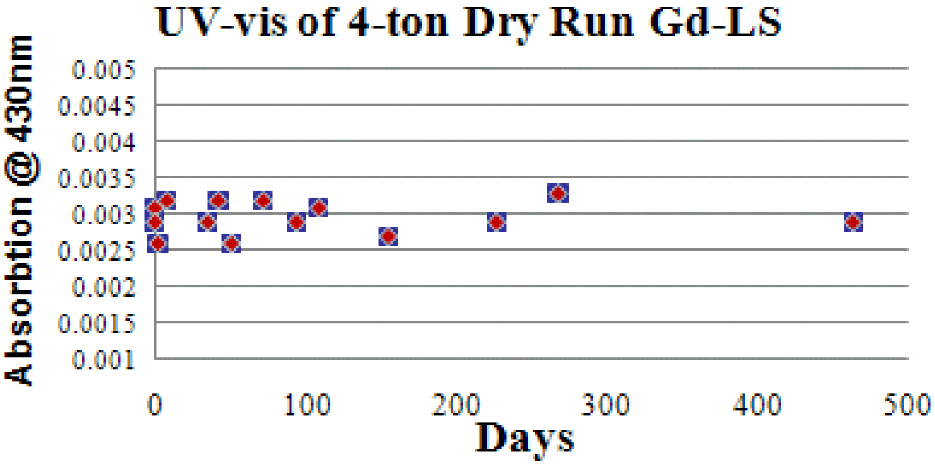
$$E_{\bar{\nu}} \cong \boxed{T_{e^+}} + \underbrace{T_n}_{10\text{-}40\text{ keV}} + \underbrace{(M_n - M_p) + m_{e^+}}_{1.8\text{ MeV: Threshold}}$$

Gd-loaded Liquid Scintillator

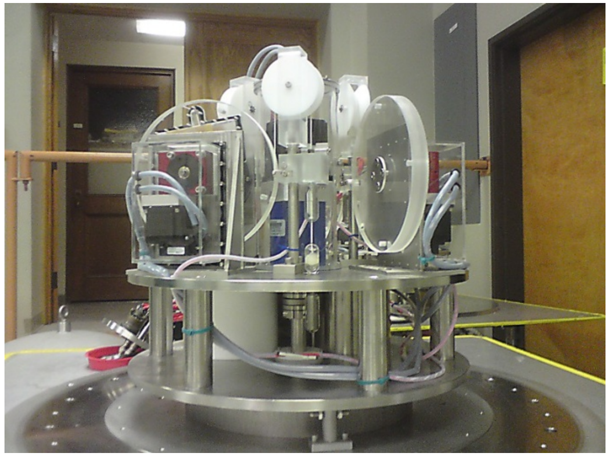
- Liquid production, QA, storage and filling at Hall 5
  - 185t Gd-LS, ~180t LS, ~320t oil
- LAB+Gd $(TMHA)^3$+PPO+BisMSB
- Stable over time
  - Light yield: ~163 PE/MeV

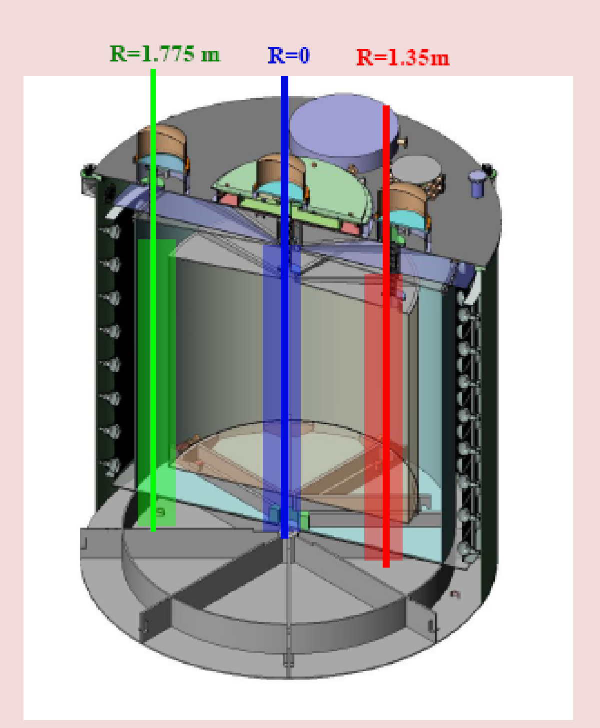
Liquid hall：LS production and filling





Automatic Calibration System

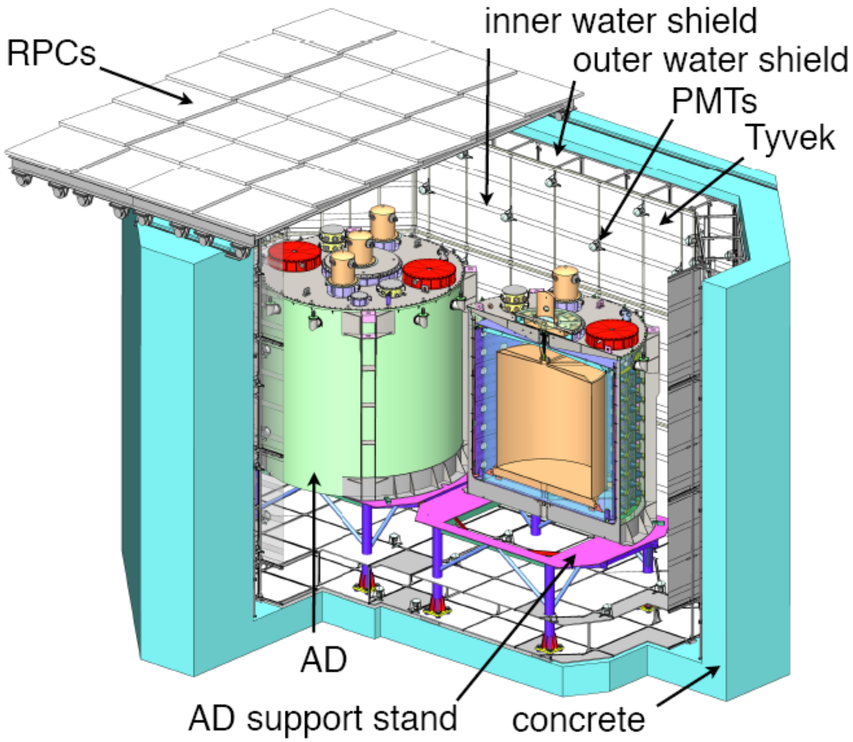




Automated Calibration

- Three Z axis:
  - ⇨ One at the center
    - ✓ For time evolution, energy scale, non-linearity…
  - ⇨ One at the edge
    - ✓ For efficiency, space response
  - ⇨ One in the γ-catcher
    - ✓ For efficiency, space response
- 3 sources for each z axis:
  - ⇨ LED
    - ✓ for T_0, gain and relative QE
  - ⇨ ^{68}Ge (2×0.511 MeV γ's)
    - ✓ for positron threshold & non-linearity…
  - ⇨ ^{241}Am-^{13}C + ^{60}Co (1.17+1.33 MeV γ's)
    - ✓ For neutron capture time, …
    - ✓ For energy scale, response function, …
- Once every week:
  - ⇨ 3 axis, 5 points in Z, 3 sources

Muon Veto Detector

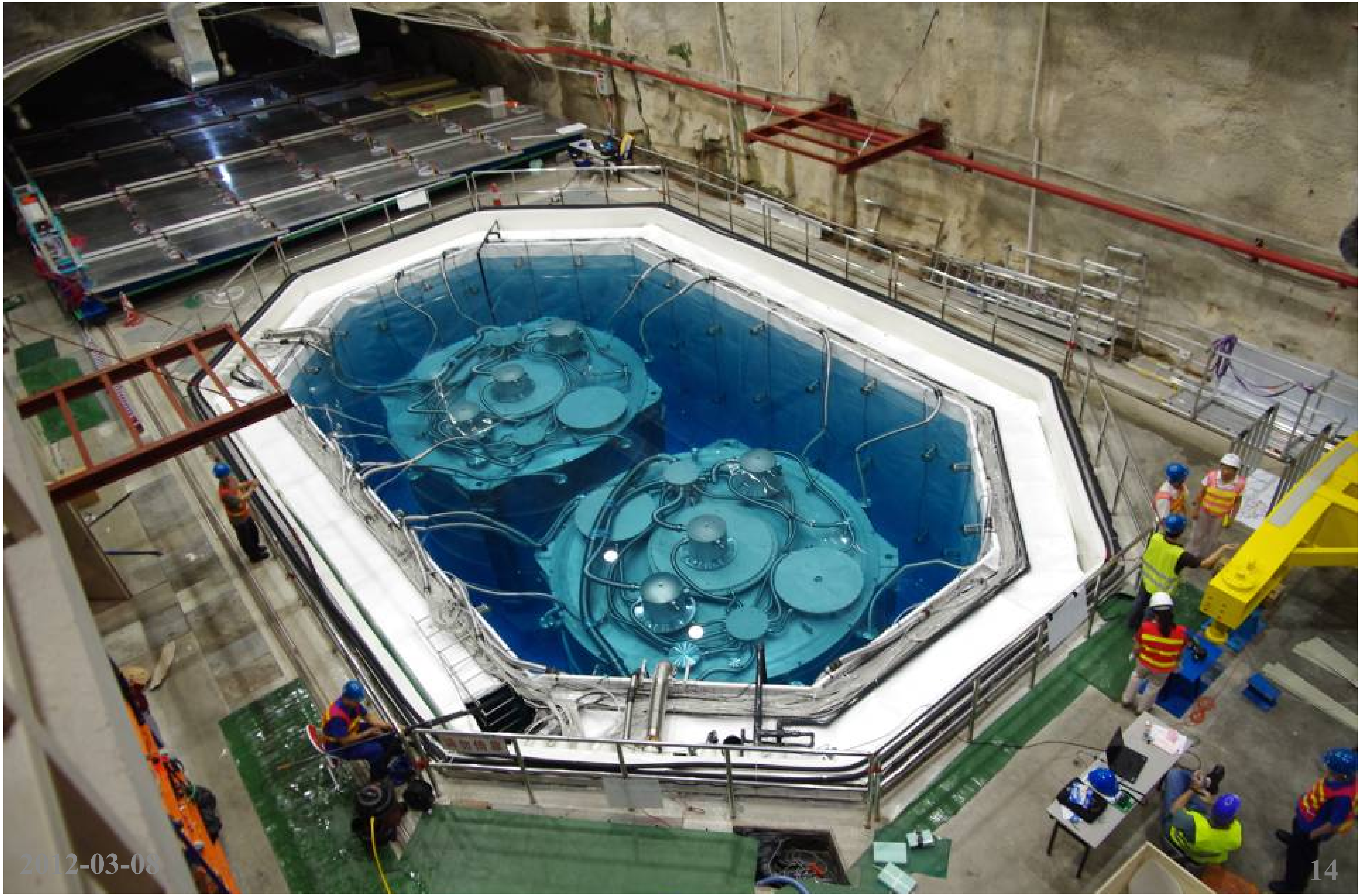


Two active cosmic-muon veto's

- **Water Cerenkov: Eff.>97%**
- **RPC Muon tracker: Eff. > 88%**

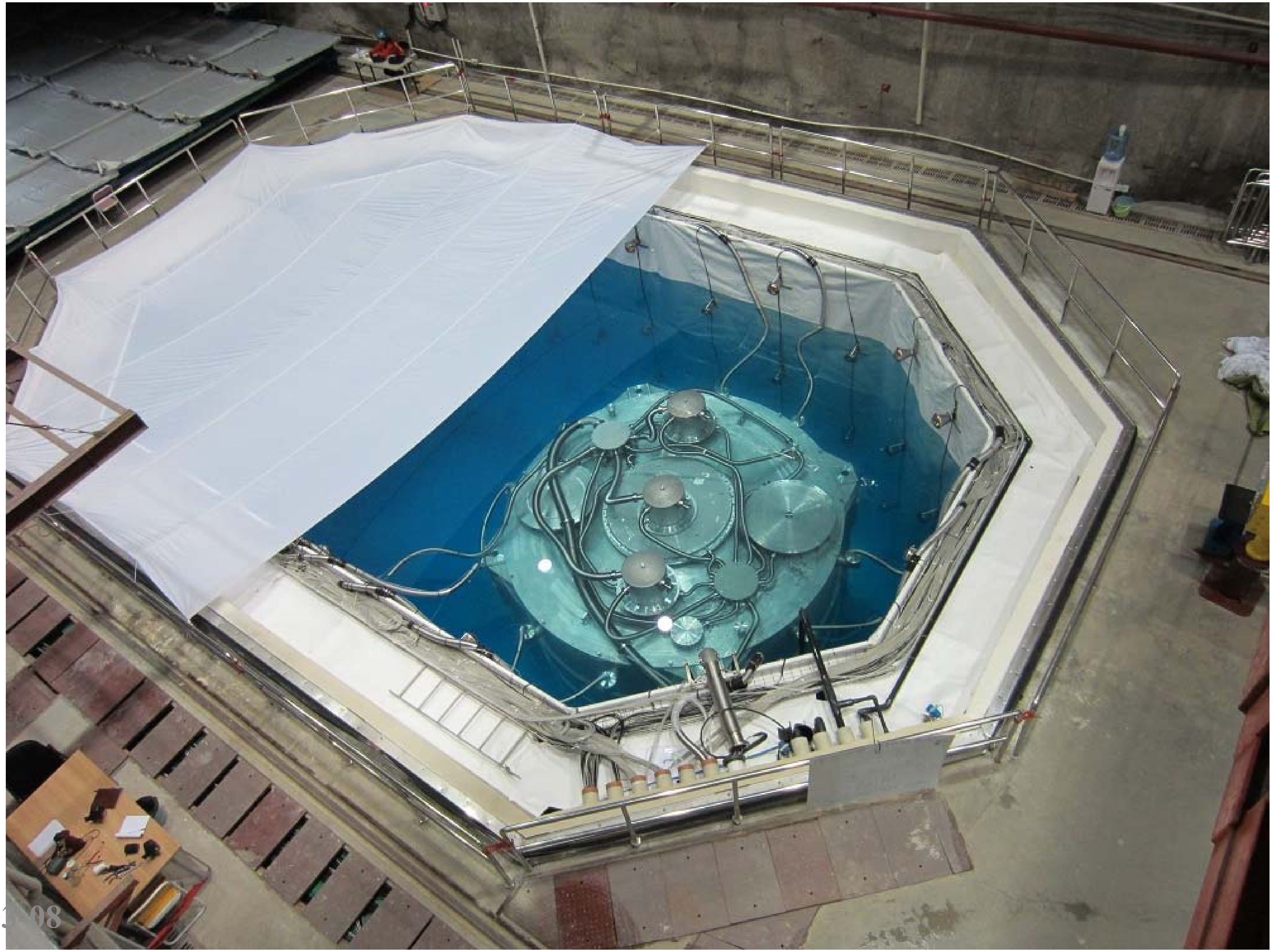
- **Water Cerenkov detector**
  - **High purity de-ionized water in pools also for shielding**
  - **First stage water production in hall 4**
  - **Local water re-circulation & purification**
- **RPCs**
  - **4 layers/module**
  - **54 modules/near hall, 81 modules/far hall**
  - **2 telescope modules/hall**
- **Water Cerenkov detector**
  - **Two layers, separated by Tyvek/PE/Tyvek film**
  - **288 8" PMTs for near halls; 384 8" PMTs for the far hall**

Two ADs Installed in Hall 1

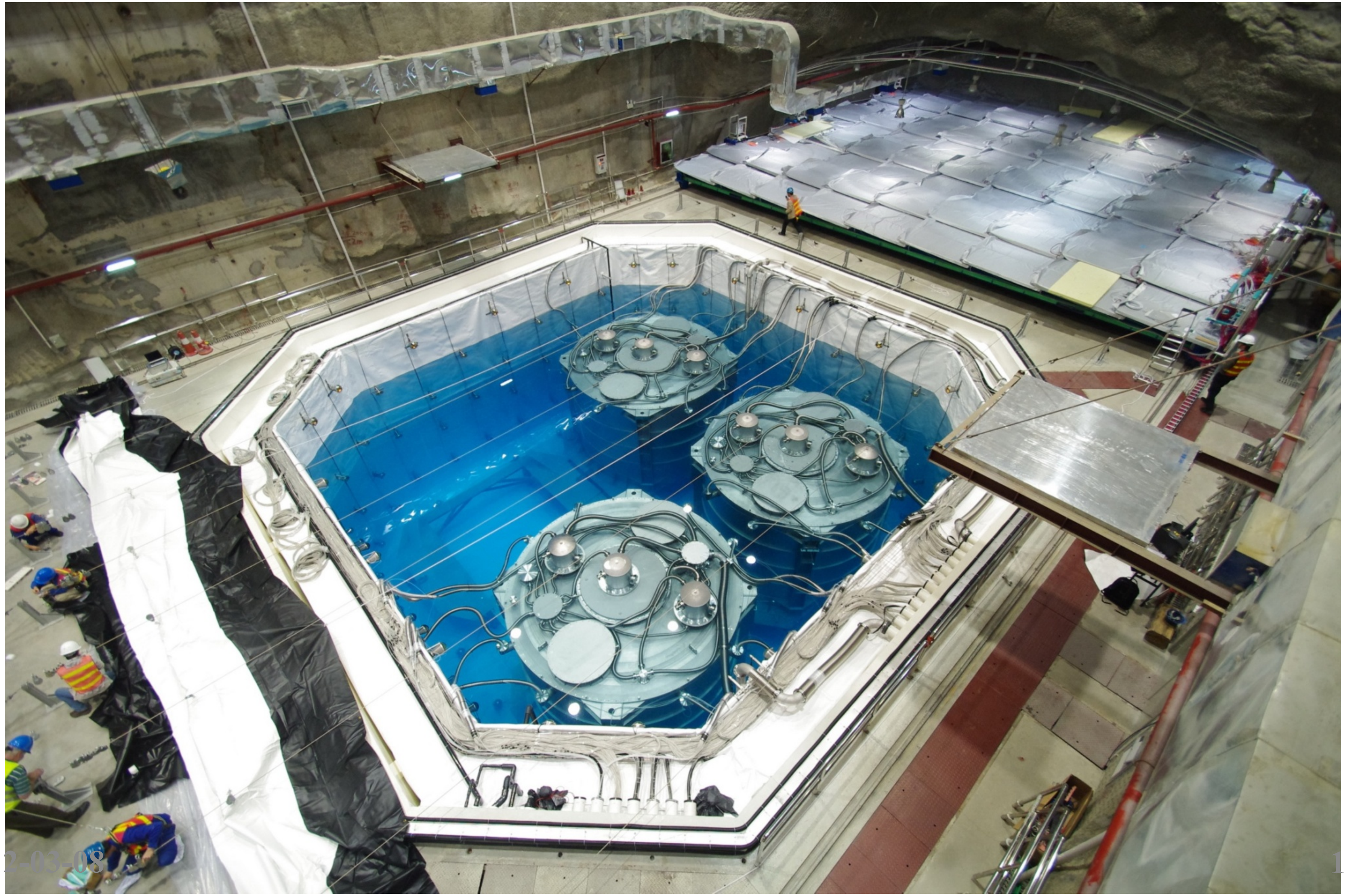


Hall 1(two ADs) Started the Operation on Aug. 15, 2011

One AD insalled in Hall 2
Physics Data Taking Started on Nov.5, 2011

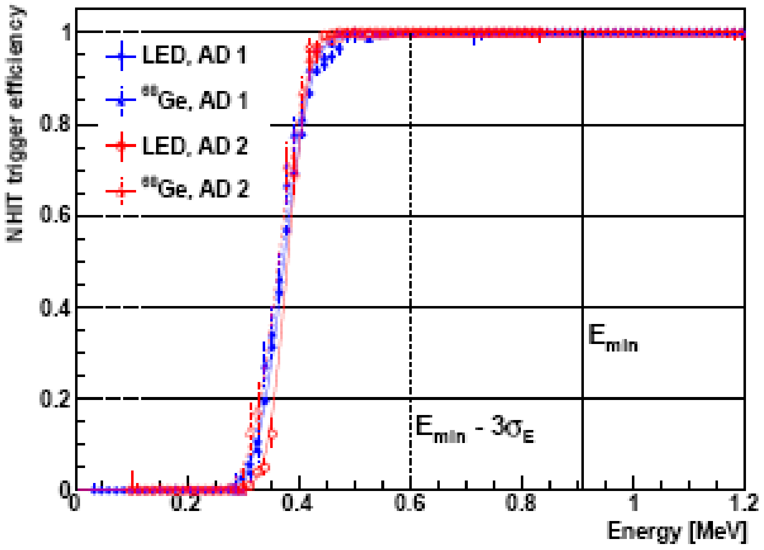


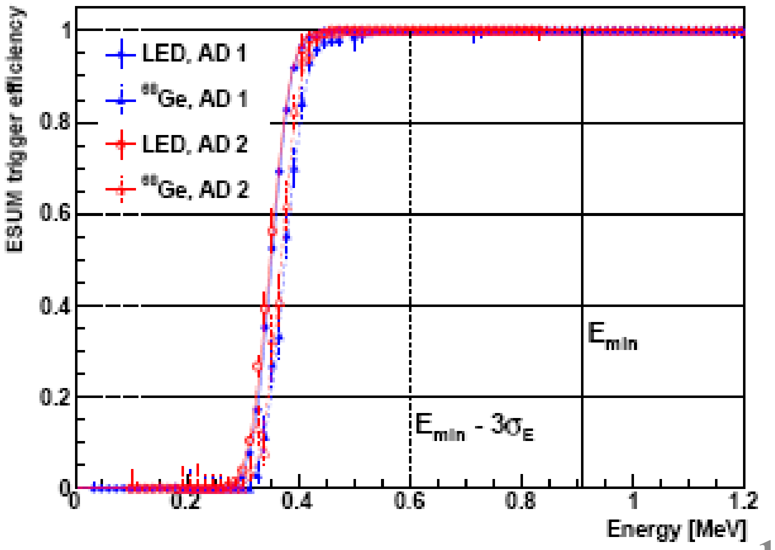
Three ADs insalled in Hall 3
Physics Data Taking Started on Dec.24, 2011



Trigger Performance

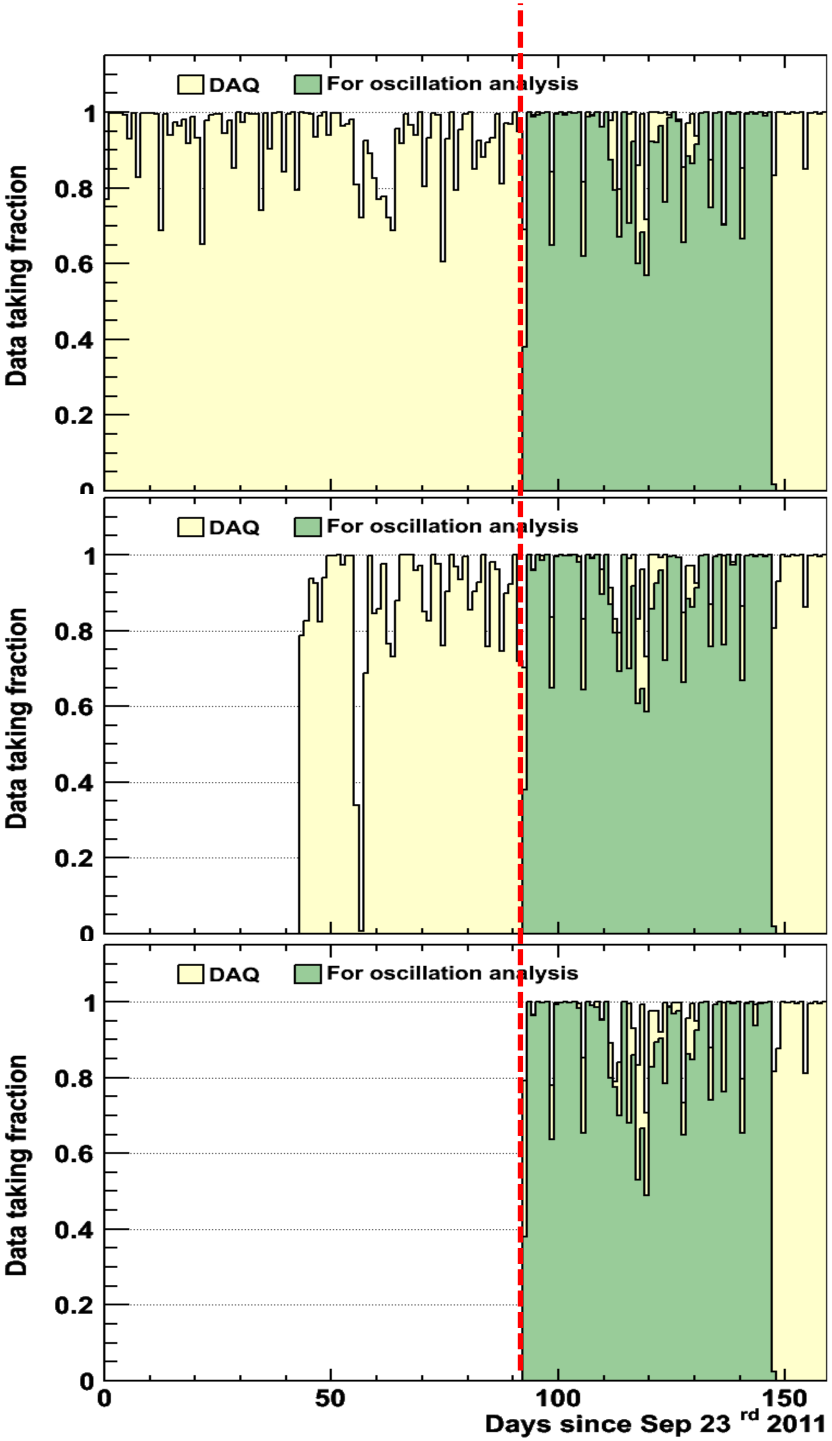
- **Threshold for a hit:**
  - AD & pool: ¼ PE
- **Trigger thresholds:**
  - AD: ~ N_{HIT}=45, E_{tot}= ~ 0.4 MeV
  - Inner pool: N_{HIT}=6
  - Outer pool: N_{HIT}=7 (8 for far hall)
  - RPC: 3/4 layers in each module
- **Trigger rate(EH1)**
  - AD singles rate:
    - ✓ >0.4MeV, ~ 280Hz
    - ✓ >0.7MeV,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



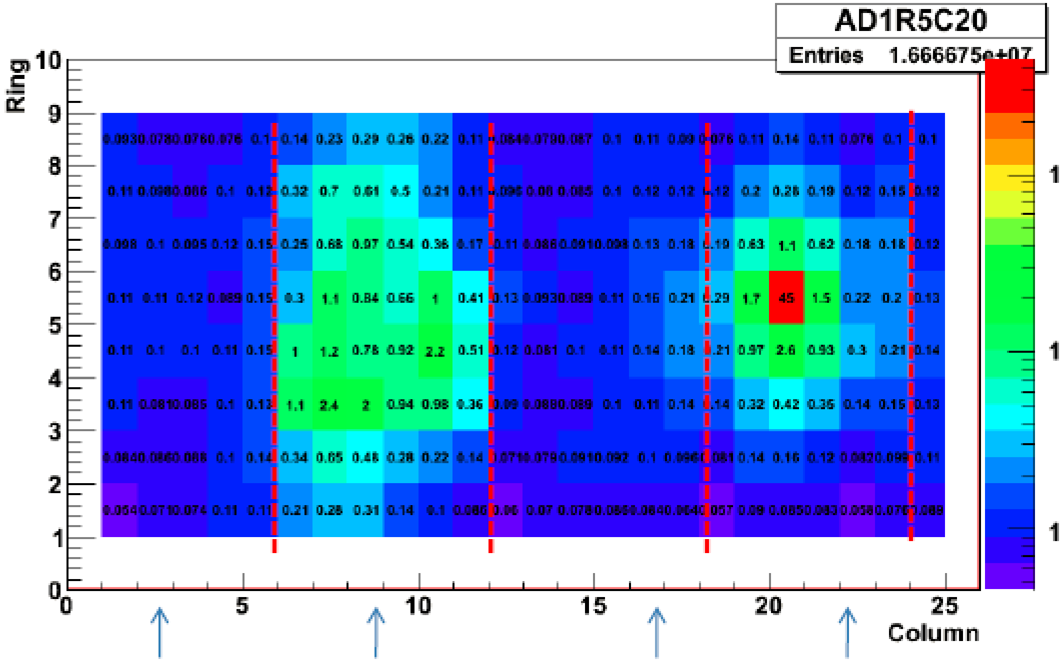


Data Set

- Dec. 24, 2011- Feb. 17, 2012， 55 days
- Data volume: 15TB
- DAQ eff. ～97%
- Data taking for physics: ～89%



Flashers: Imperfect PMTs

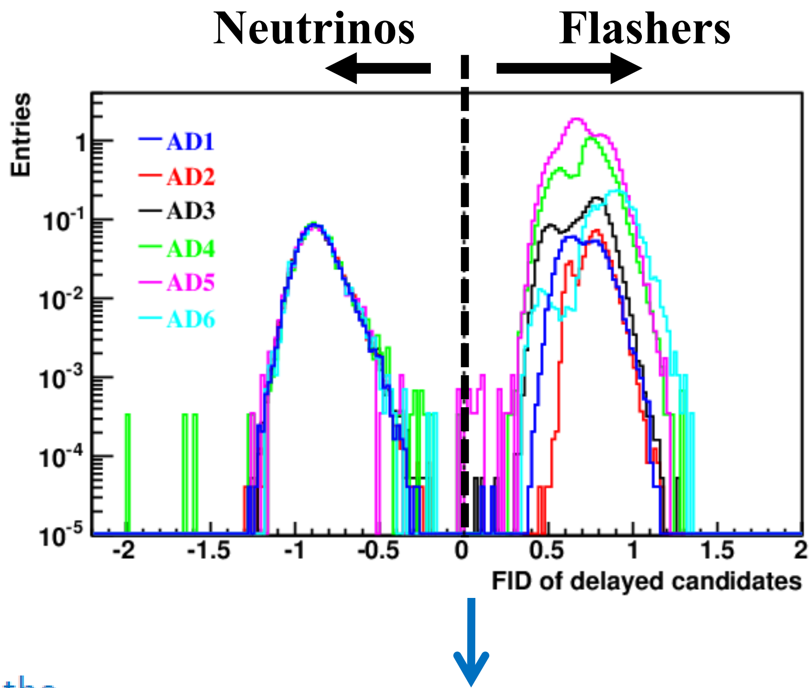


Quadrant 4

Quadrant 3

Quadrant 2

Quadrant 1, where the hottest PMT locates



$$\log_{10}\left(\left(\frac{Quadrant}{1.}\right)^2+\left(\frac{MaxQ}{0.45}\right)^2\right)<0$$

Quadrant = Q3/(Q2+Q4)

MaxQ = maxQ/sumQ

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

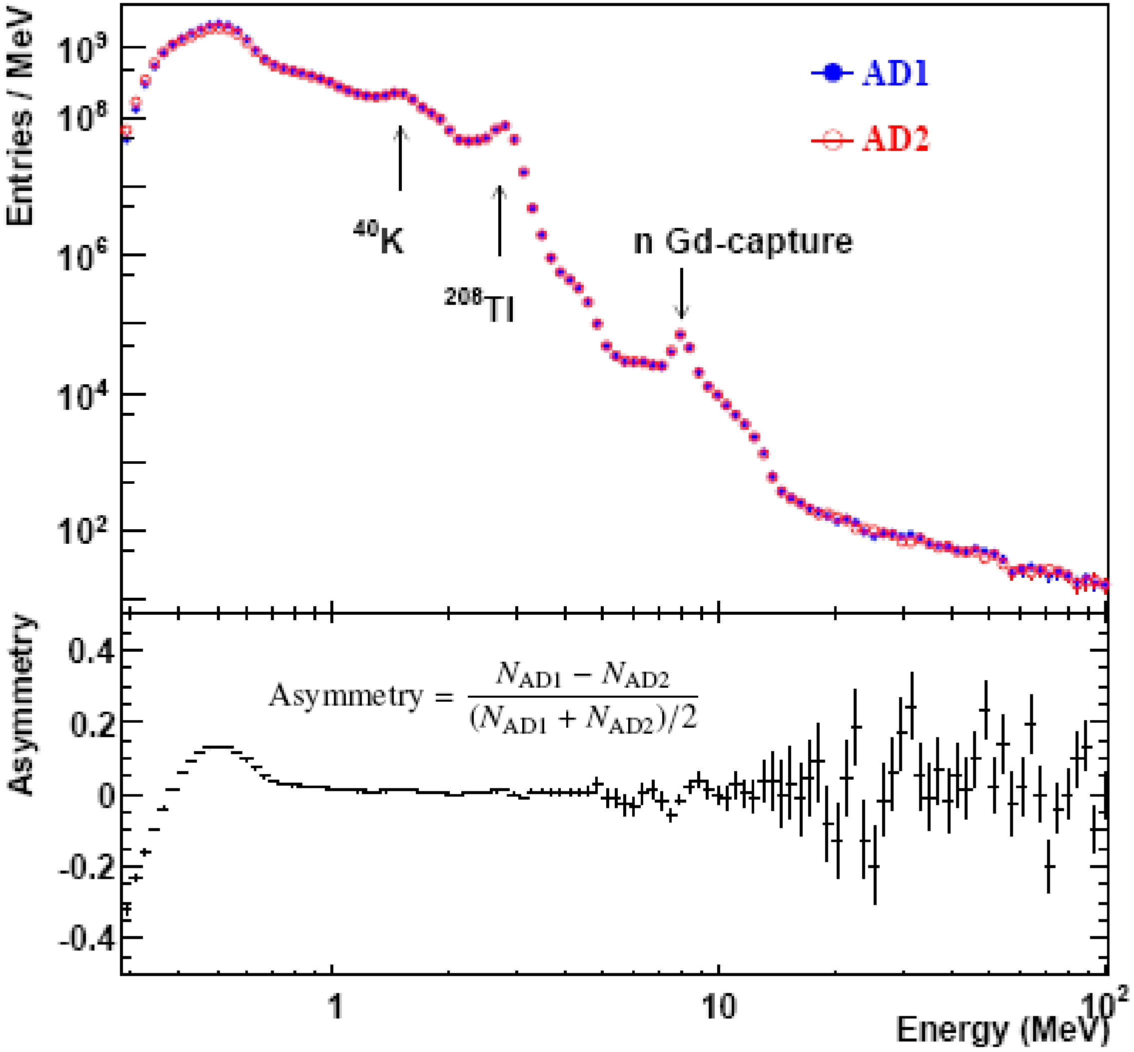
Inefficiency to neutrinos:

0.024% ± 0.006%(stat)

Contamination: < 0.01%

Single Rate: Understood

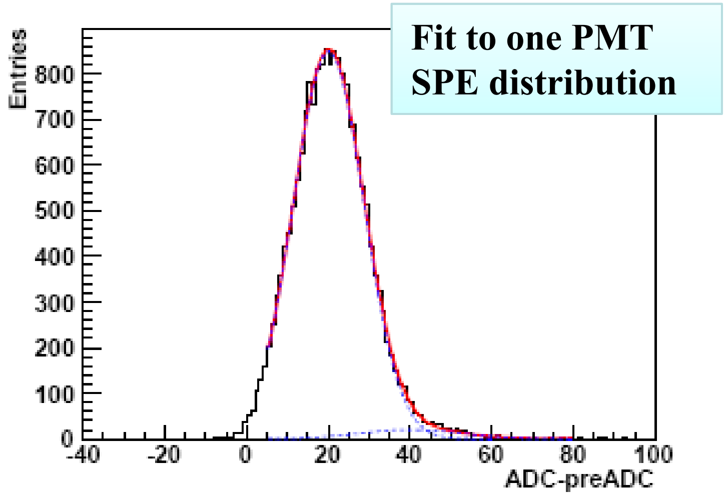
- Design: ~50Hz above 1 MeV
- Data: ~60Hz above 0.7 MeV, ~40Hz above 1 MeV
- From sample purity and MC simulation, each of the following component contribute to singles
  - ⇨ ~ 5 Hz from SSV
  - ⇨ ~ 10 Hz from LS
  - ⇨ ~ 25 Hz from PMT
  - ⇨ ~ 5 Hz from rock
- All numbers are consistent

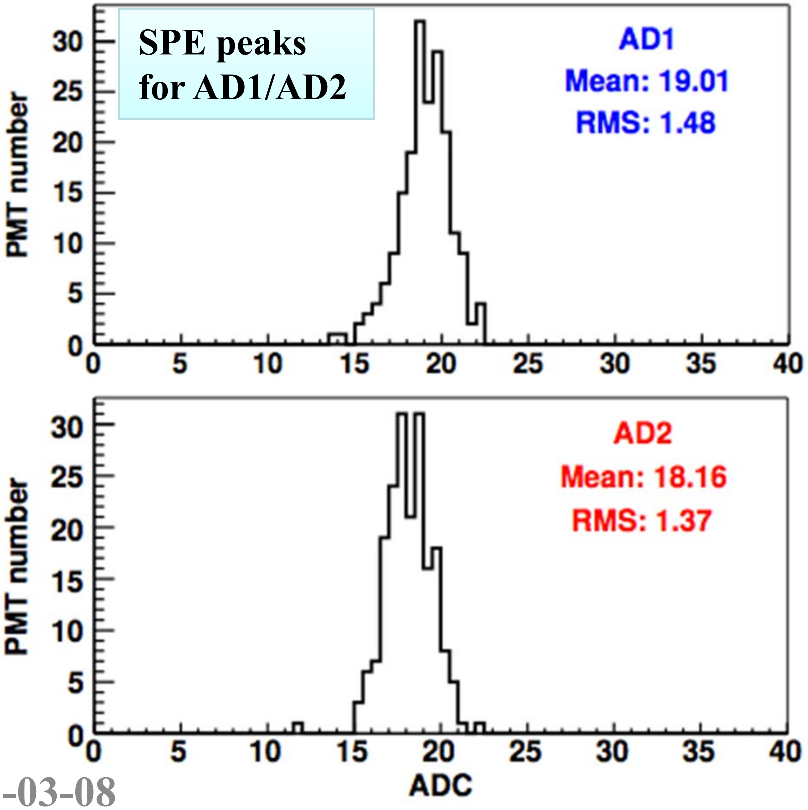


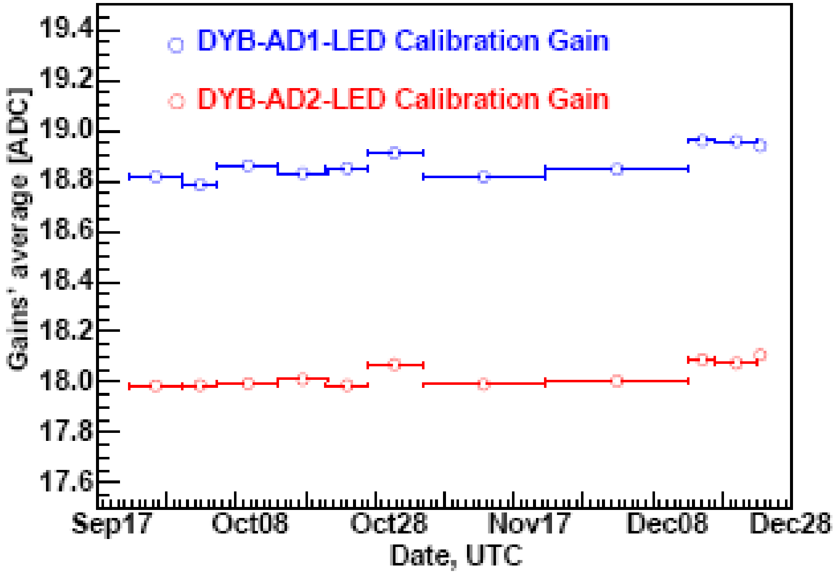
$$\text{Asymmetry} = \frac{N_{AD1} - N_{AD2}}{(N_{AD1} + N_{AD2})/2}$$

Event Reconstruction: PMT Calibration

- PMT gains from low-intensity LED:
  - ⇨ PMT HV is set for a gain of 1×10^7
  - ⇨ Gain stability depends on environments such as temperature
  - ⇨ All three halls in all the time are kept in a temperature ± 1 ^oC

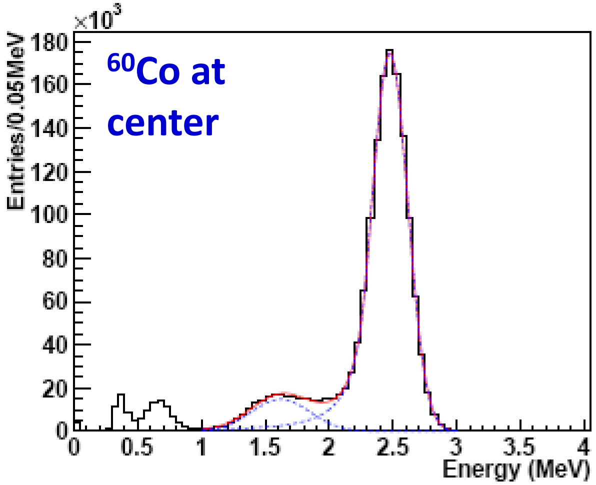

Fit to one PMT SPE distribution

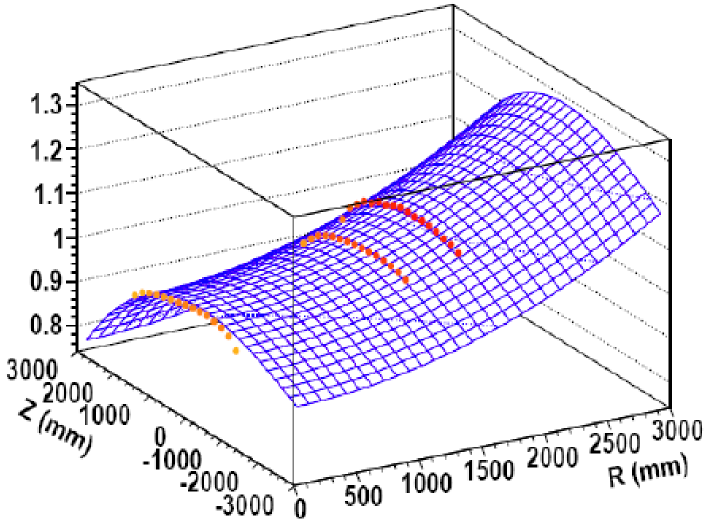

SPE peaks for AD1/AD2

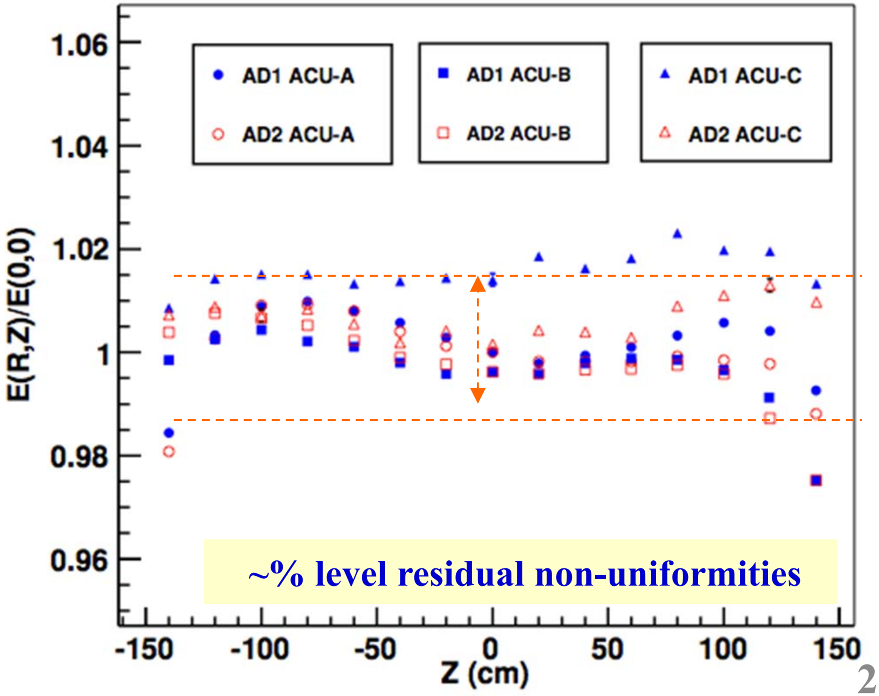


Event Reconstruction: Energy Calibration

- **PMT gain calibration ➔ No. of PEs in an AD**
- **^{60}Co at the center ➔ raw energies,**
  - **time dependence corrected**
  - **different for different ADs**
- **^{60}Co at different R & Z to obtain the correction function,** $f(R,Z) = f_1(R) * f_2(Z)$
  - **space dependence corrected**
  - **same for all the ADs**



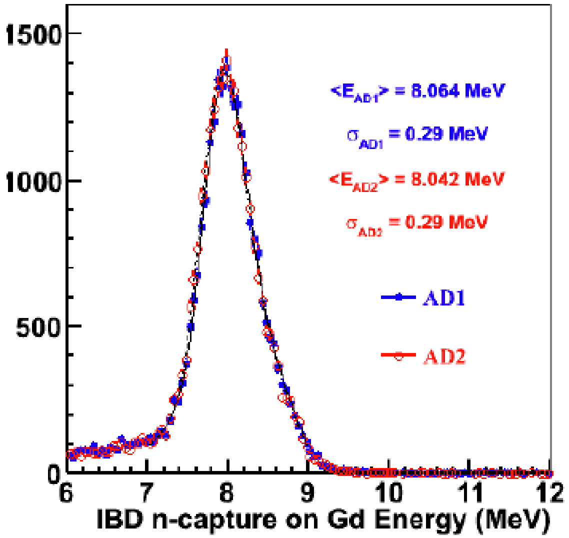




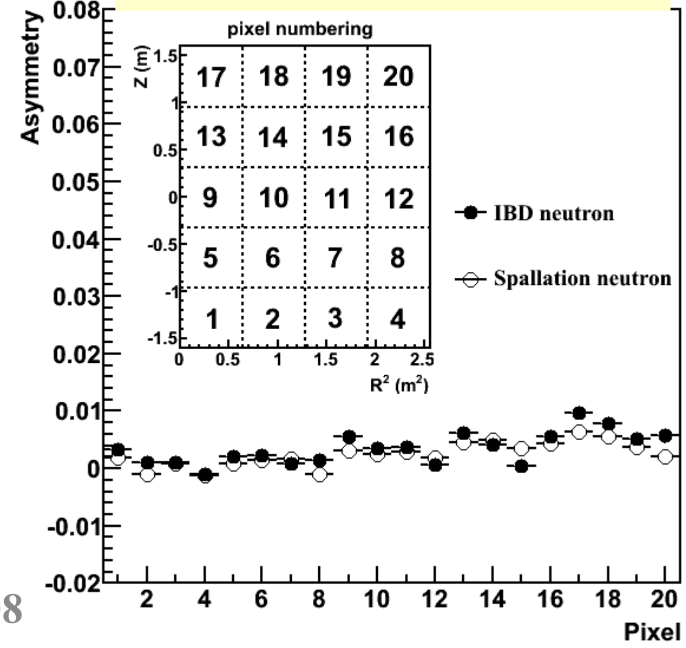
~% level residual non-uniformities

Event Reconstruction: Energy Calibration

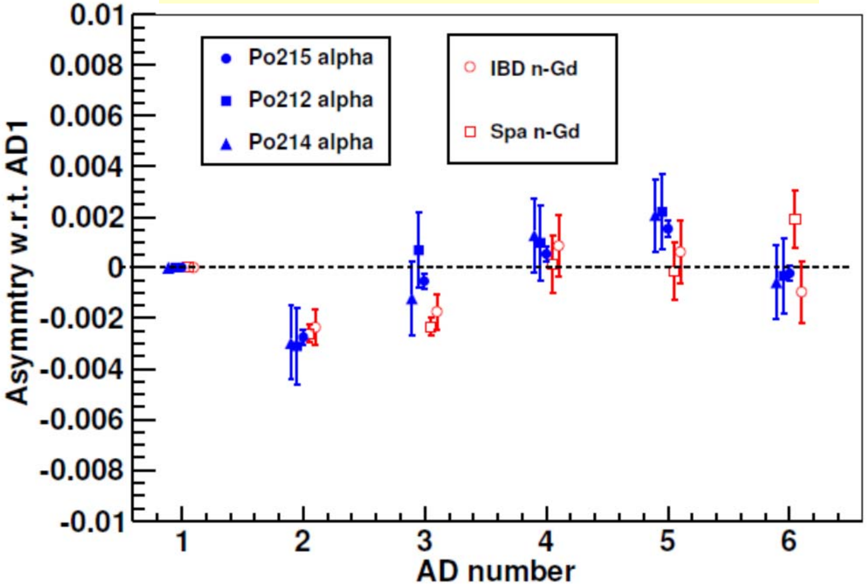
- Correct for energy non-linearity: normalize to neutron capture peak
- Energy uncertainty among 6 ADs (uncorrelated):
  - ⇨ Relative difference in reconstructed energy among ADs is better than 0.5%
  - ⇨ Systematic uncertainties from time-variation, non-linearity, non-uniformity… are also within 0.5%



Uniformity at different location



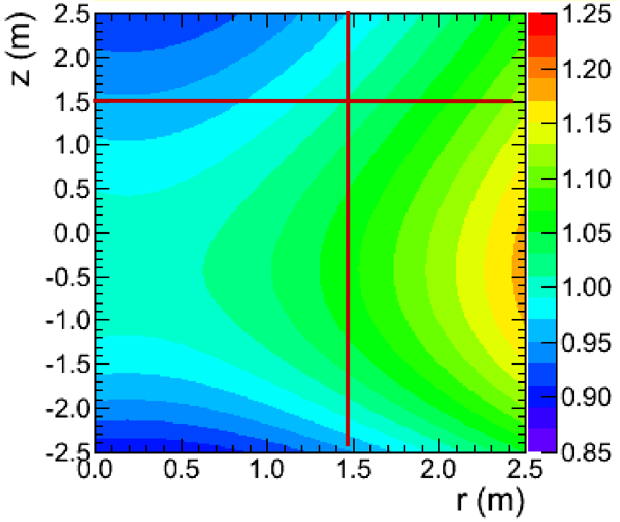
Peak energy of different sources



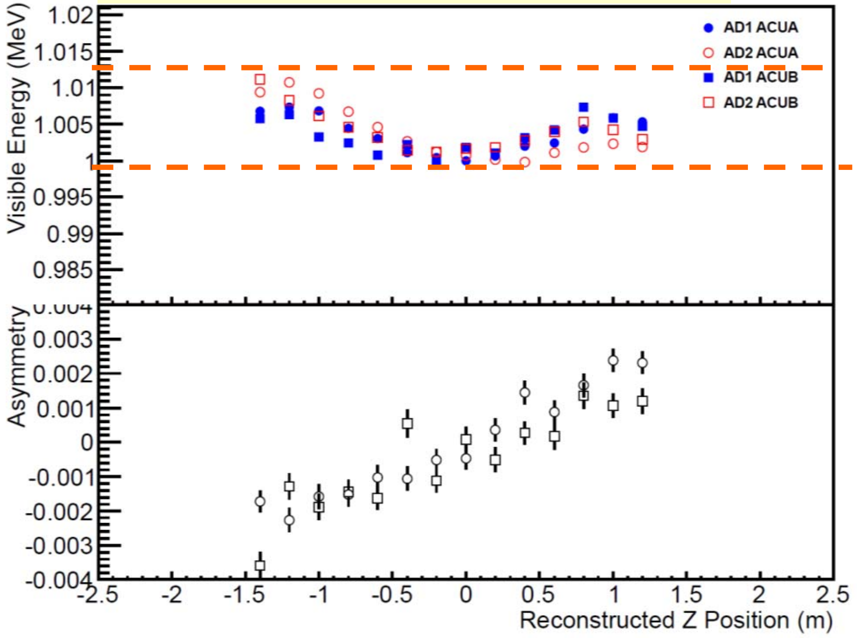
An Alternative Method

- Using spallation neutrons in each space grid to calibrate the energy response
- Neutrons from neutrinos can then be reconstructed correctly
- Consistent with methods within 0.5%

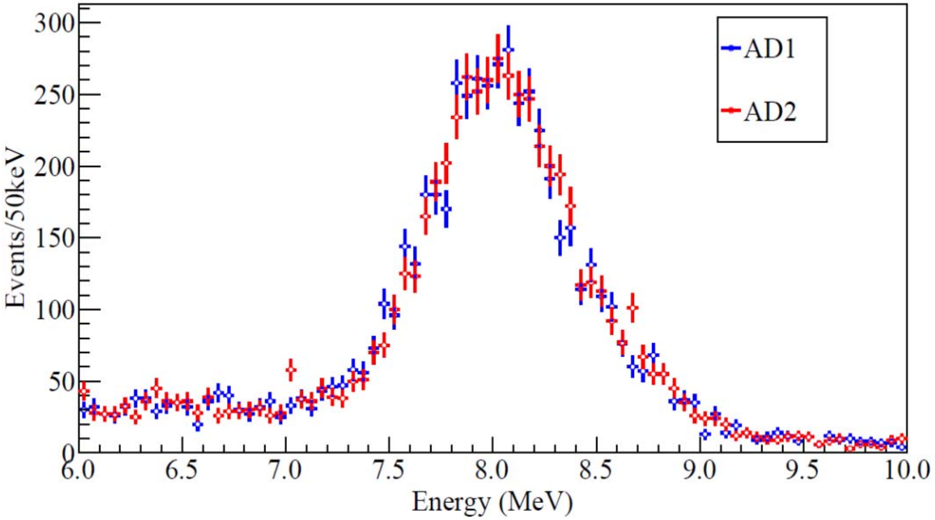
Uniformity of energy response



Residual non-uniformities

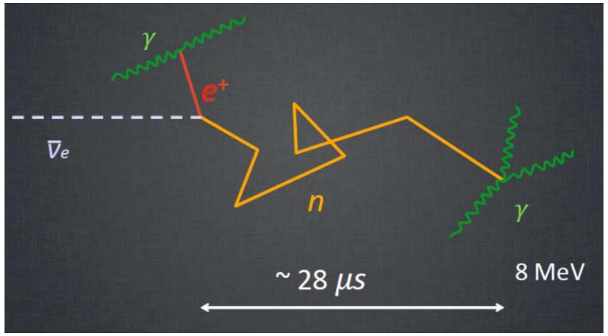


Energy of spallation neutron



Event Signature and Backgrounds

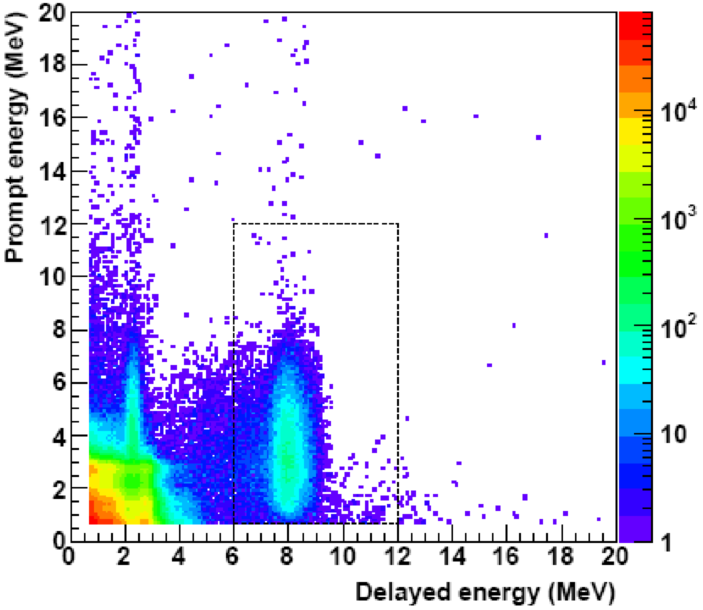
- **Signature:** $\overline{\nu}_e + p \rightarrow e^+ + n$
  - ⇨ **Prompt: e^+, E: 1-10 MeV,**
  - ⇨ **Delayed: n, E: 2.2 MeV@H, 8 MeV @ Gd**
  - ⇨ **Capture time: 28 μs in 0.1% Gd-LS**



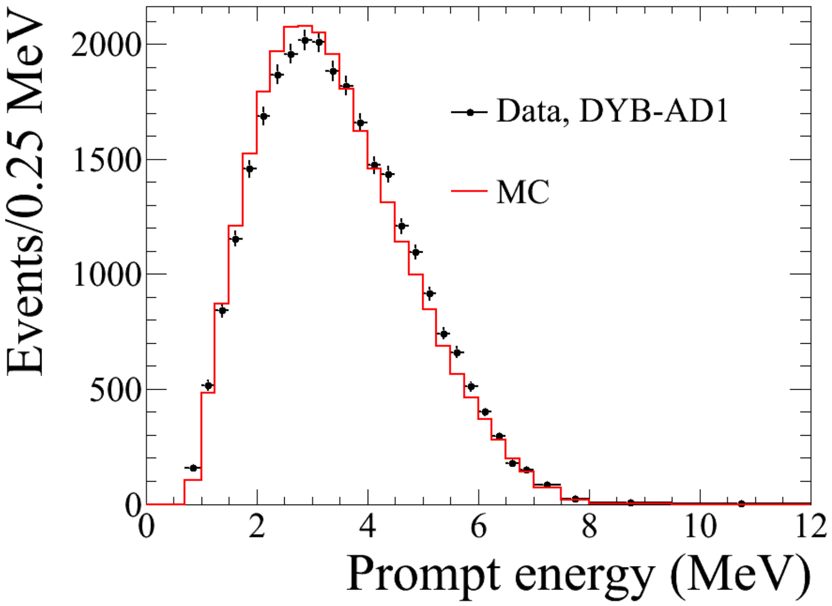
- **Backgrounds**
  - ⇨ **Uncorrelated: random coincidence of γγ, γn & nn**
    - ✓ **γ from U/Th/K/Rn/Co… in LS, SS, PMT, Rock, …**
    - ✓ **n from α-n, μ-capture, μ-spallation in LS, water & rock**
  - ⇨ **Correlated:**
    - ✓ **Fast neutrons: prompt—n scattering, delayed —n capture**
    - ✓ **8He/9Li: prompt —β decay, delayed —n capture**
    - ✓ **Am-C source: prompt —γ rays, delayed —n capture**
    - ✓ **α-n: $^{13}C(\alpha,n)^{16}O$**

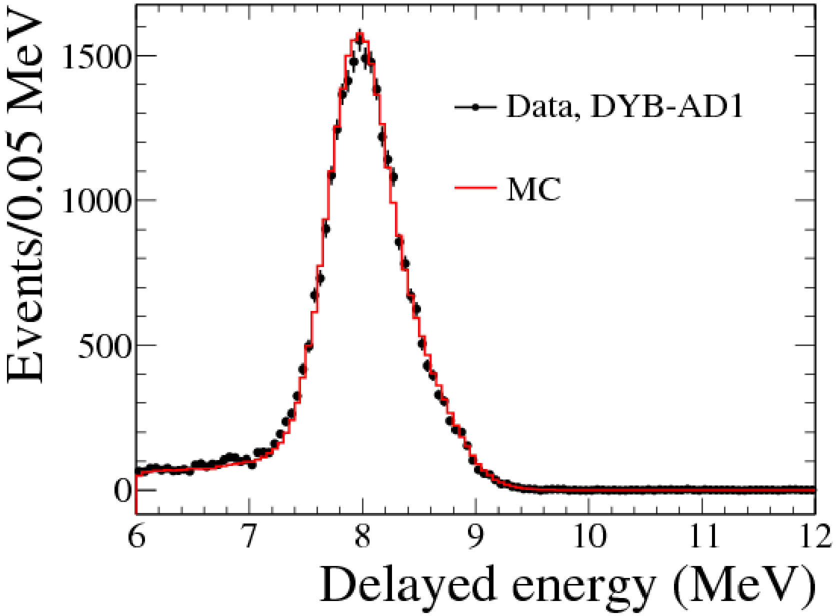
Neutrino Event Selection

- **Pre-selection**
  - **Reject Flashers**
  - **Reject Triggers within (-2 μs, 200 μs) to a tagged water pool muon**
- **Neutrino event selection**
  - **Multiplicity cut**
    - ✓ Prompt-delayed pairs within a time interval of 200 μs
    - ✓ No triggers(E > 0.7MeV) before the prompt signal and after the delayed signal by 200 μs
  - **Muon veto**
    - ✓ *1s* after an AD shower muon
    - ✓ *1ms* after an AD muon
    - ✓ *0.6ms* after an WP muon
  - **$0.7\text{MeV} < E_{prompt} < 12.0\text{MeV}$**
  - **$6.0\text{MeV} < E_{delayed} < 12.0\text{MeV}$**
  - **$1\mu s < \Delta t_{e+-n} < 200\mu s$**

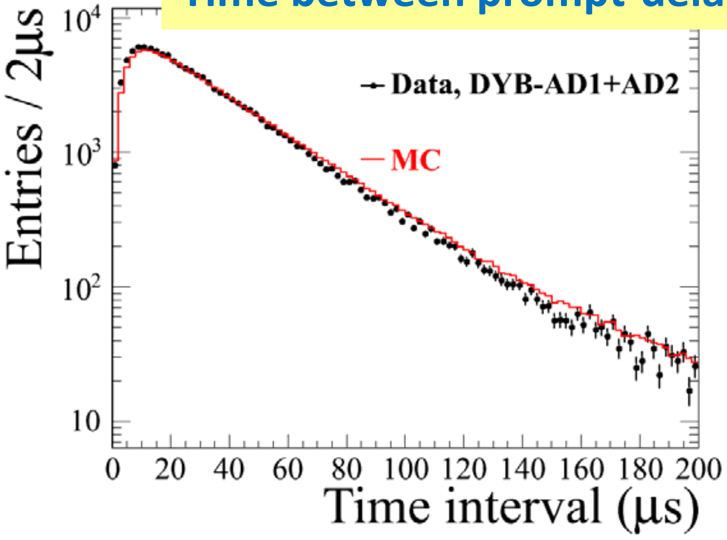


Selected Signal Events：Good Agreement with MC

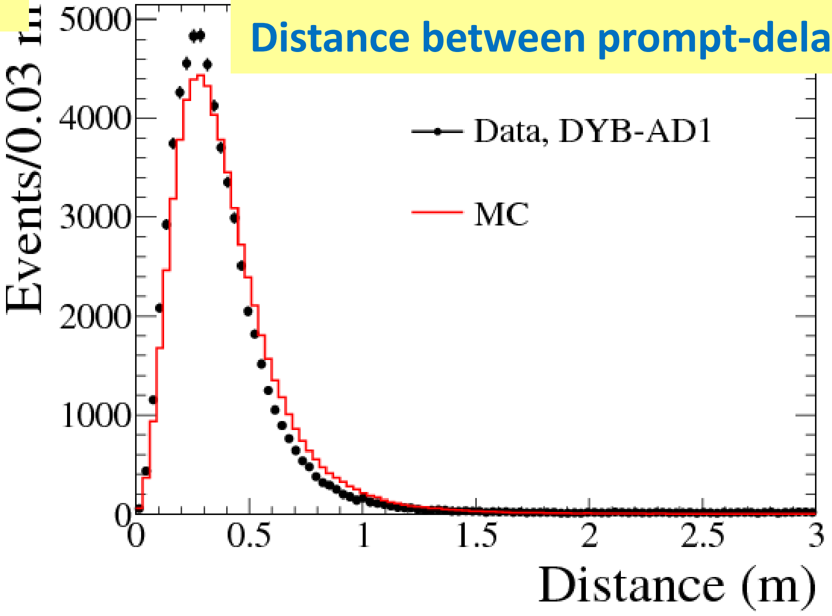




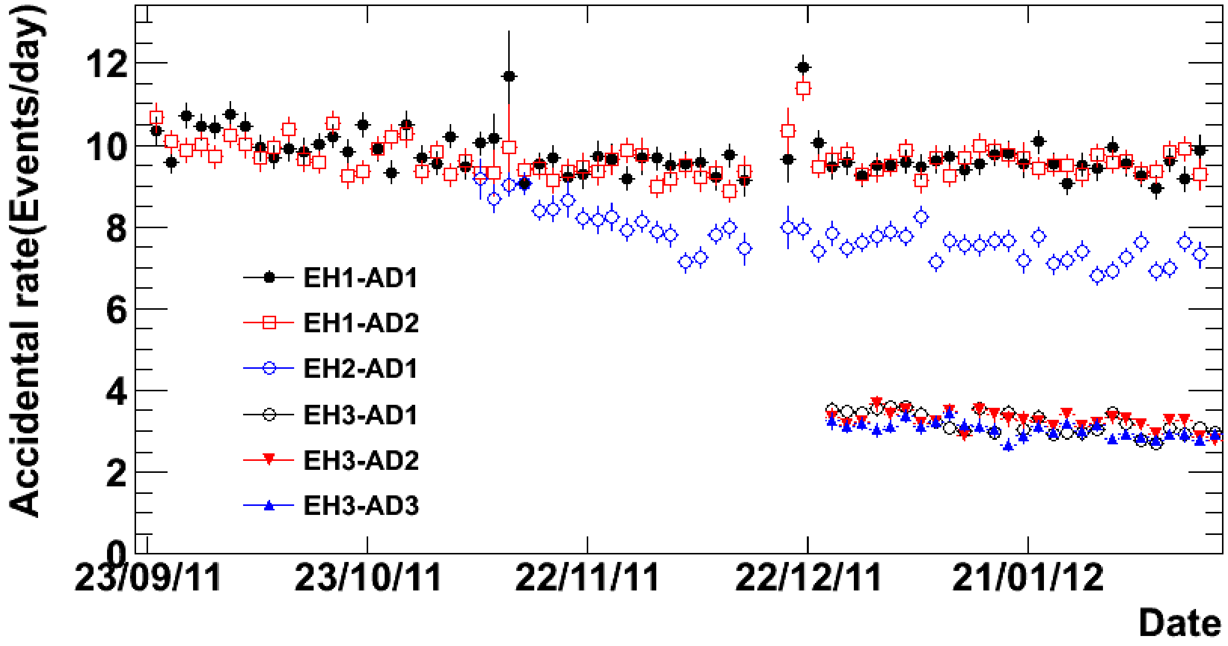
Time between prompt-delayed



Distance between prompt-delayed



Accidental Backgrounds

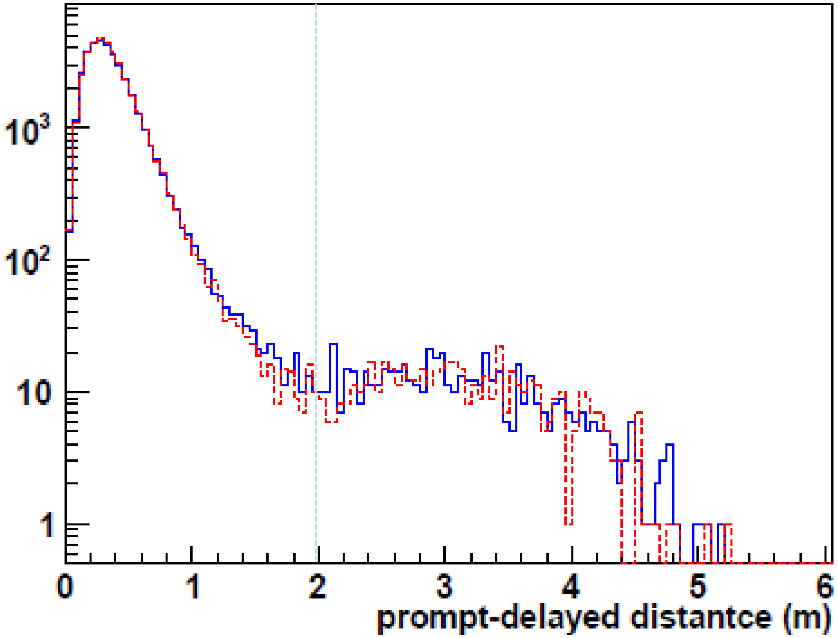


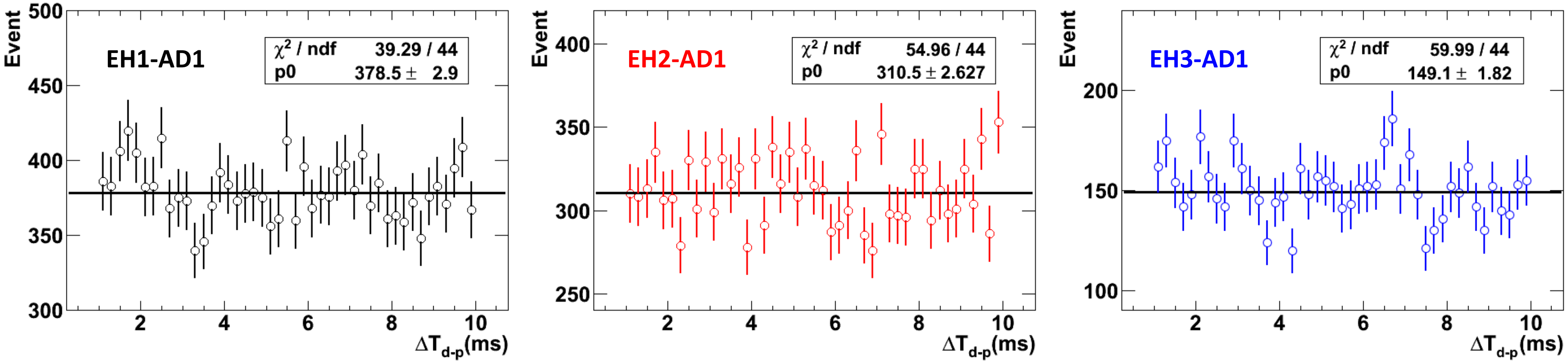
$$N_{\text{accBkg}} = \sum_i N^i_{\text{n-like singles}} \bullet \left(1 - e^{-R^i_{e^+\text{-like triggers}} \bullet 200\,\mu s}\right) \pm \frac{N_{\text{accBkg}}}{\sqrt{\sum_i N^i_{\text{n-like singles}}}}$$

	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%

Accidental Backgrounds: Cross Checks

- Prompt-delayed distance distribution. Check the fraction of prompt-delayed pair with distance>2m
- Off-window coincidence → ‘measure’ the accidental background
- Results in agreement within 1%.

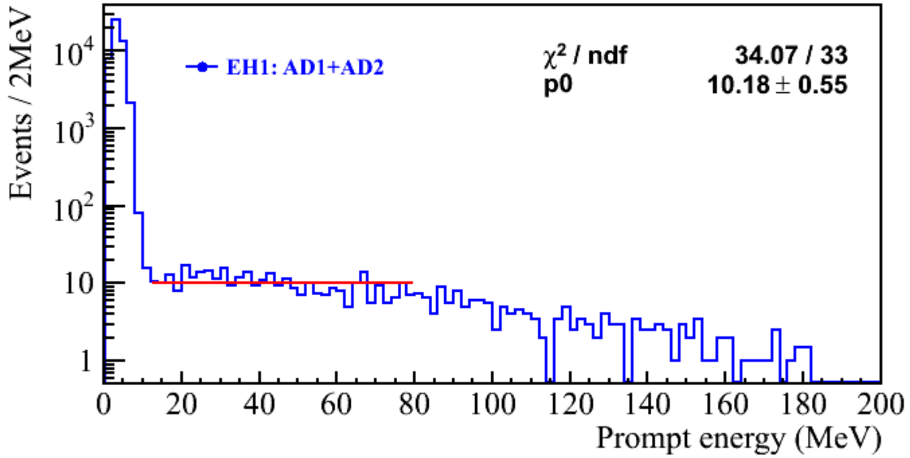


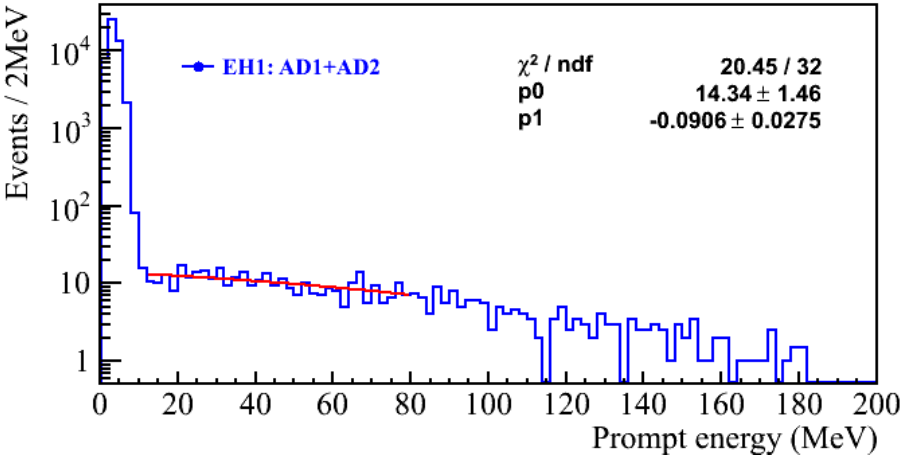


Uncertainty: < 1%

Fast Neutrons

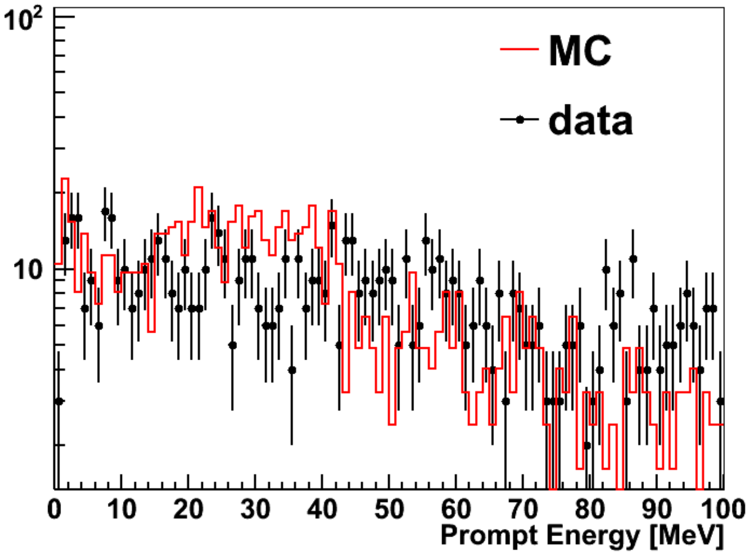
- Extend the prompt energy spectrum to high energy by relax the prompt energy cut
- Fit the energy spectrum in the [12MeV, 100MeV] range, and estimate backgrounds in the [0.7MeV, 12MeV] region
- Take a zero-order or first order polynomial fit, and take their differences as systematics





Cross Checks

- **Fast neutrons from water pools**
  - **Obtain the rate and energy spectrum of fast neutrons by tagged muons in water pool. Consistent with MC simulation.**
  - **Estimate the untagged fast neutron by using water pool inefficiency**
- **Fast neutrons from nearby rock**
  - **Estimated based on MC simulation**



	Fast neutron (event/day)	Cross checks(event/day)
AD1	0.84±0.28	0.6±0.4
AD2	0.84±0.28	0.6±0.4
AD3	0.74±0.44	0.6±0.4
AD4	0.04±0.04	0.04±0.04
AD5	0.04±0.04	0.04±0.04
AD6	0.04±0.04	0.04±0.04

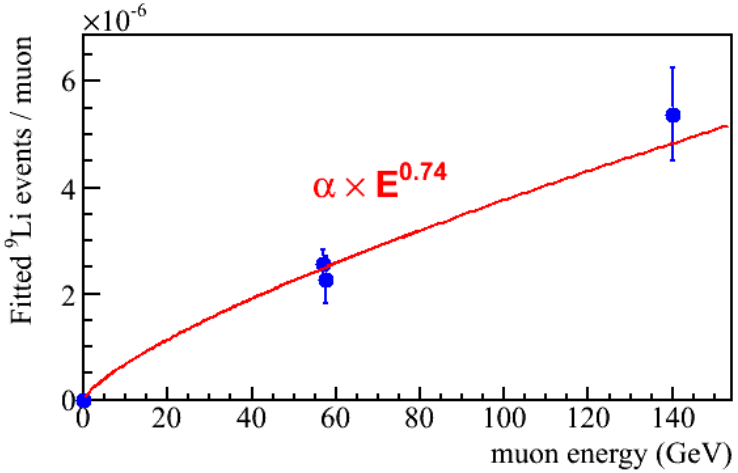
Results are consistent

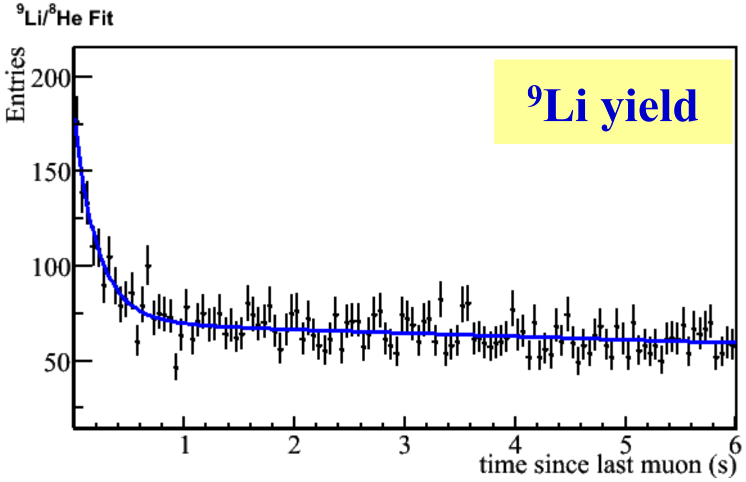
Backgrounds –^{8}He/^{9}Li

- **Cosmic μ produced ^{9}Li/^{8}He in LS**
  - **β-decay + neutron emitter**
  - **τ(^{8}He/^{9}Li) = 171.7ms/257.2ms**
  - **^{8}He/^{9}Li, Br(n) = 12%/48%, ^{9}Li dominant**
  - **Production rate follow $E_{\mu}^{0.74}$ power law**
- **Measurement:**
  - **Time-since-last-muon fit**

$$f(t) = B/\lambda \cdot e^{-t/\lambda} + S/T \cdot e^{-t/T}$$

  - **Improve the precision by reducing the muon rate:**
    - ✓ **Select only muons with an energy deposit >1.8MeV within a [10us, 200us] window**
    - ✓ **Issue: possible inefficiency of ^{9}Li**
  - **Results w/ and w/o the reduction is studied**





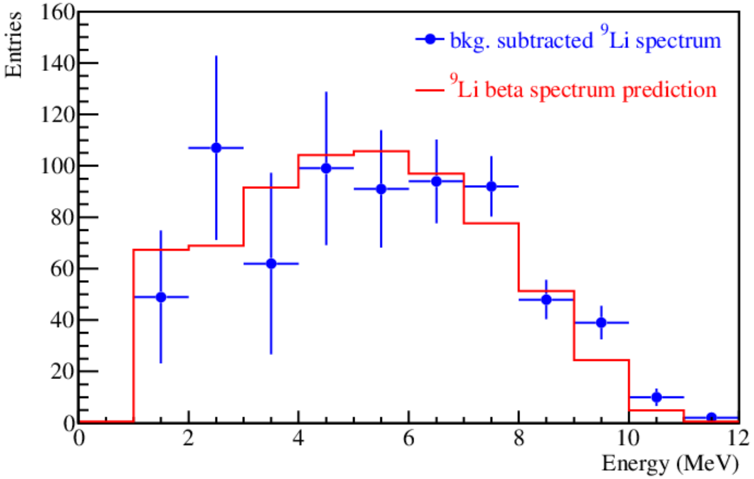
Error follows

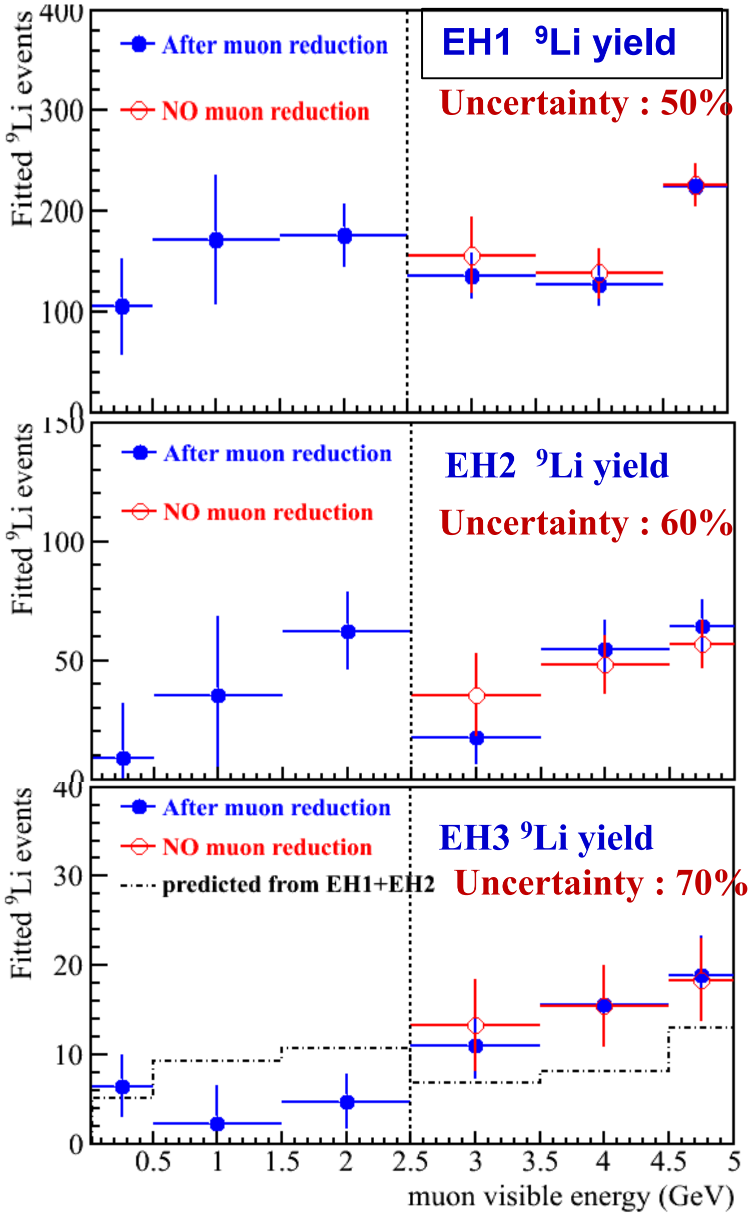
$$\boxed{\sigma_b = \frac{1}{N} \cdot \sqrt{(1 + \tau R_\mu)^2 - 1}}$$

NIM A564 (2006)471

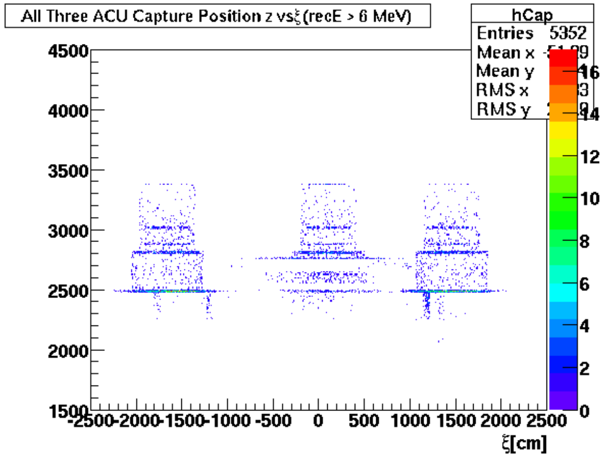
Measurement in EH1+EH2 & Prediction in EH3

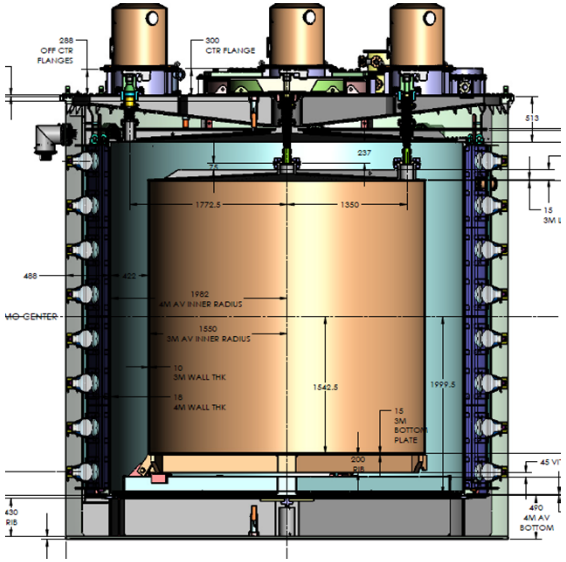
- Measurement in EH1/EH2 with good precision, but EH3 suffers from poor statistics
- Results w/ and w/o the muon reduction consistent within 10%
- Correlated ^{9}Li production ($E_{\mu}^{0.74}$ power law) allow us to further constraint ^{9}Li yield in EH3
- Energy spectrum consistent with expectation.





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





- **Uncorrelated backgrounds:**

  R = 50 Hz × 200 μs × $R_{\text{n-like}}$ (events/day/AD)

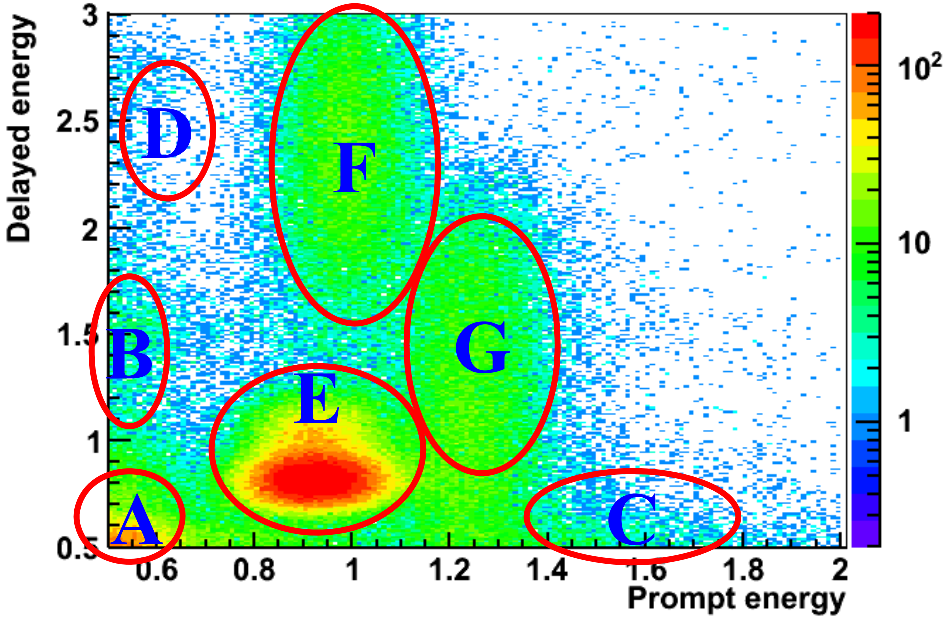
  - $R_{\text{n-like}}$ Measured to be ~230/day/AD, in consistent with MC Simulation
  - R is not a negligible amount, particularly at the far site (B/S ~ 3.17%)
  - Measured together with all the other uncorrelated backgrounds

- **Correlated backgrounds:**
  - Neutron inelastic scattering with ^{56}Fe + neutron capture on ^{57}Fe
  - Simulation shows that correlated background is 0.2 events/day/AD, corresponding to a B/S ratio of 0.03% at near site, 0.3% at far site

Uncertainty: 100%

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

- Potential α sources:
  ^{238}U, ^{232}Th, ^{227}Ac, ^{210}Po
- Alpha rate determined from cascade decays
- Neutron yield calculated from Alpha rate and (α,n) cross sections
- Backgrounds are then understood



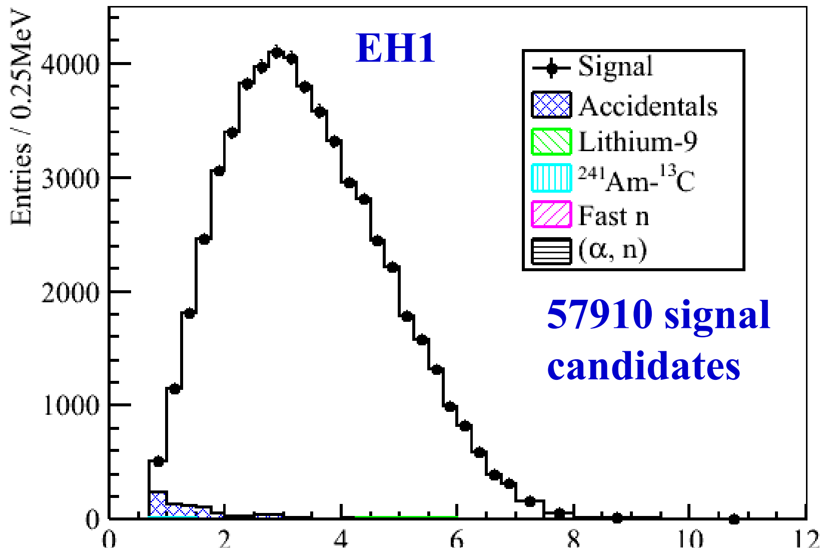
	Components	Total α rate	BG rate
Region A	Acc. Coincidence of ^{210}Po & ^{210}Po	^{210}Po: 10Hz at EH1 8Hz at EH2 6Hz at EH3	0.02/day at EH1 0.015/day at EH2 0.01/day at EH3
Region B	Acc. Coincidence of ^{210}Po & ^{40}K		
Region C	Acc. Coincidence of ^{40}K & ^{210}Po		
Region D	Acc. Coincidence of ^{208}Tl & ^{210}Po		
Region E	Cascade decay in ^{227}Ac chain	1.4 Bq	0.01/day
Region F	Cascade decay in ^{238}U chain	0.07Bq	0.001/day
Region G	Cascade decay in ^{232}Th chain	1.2Bq	0.01/day

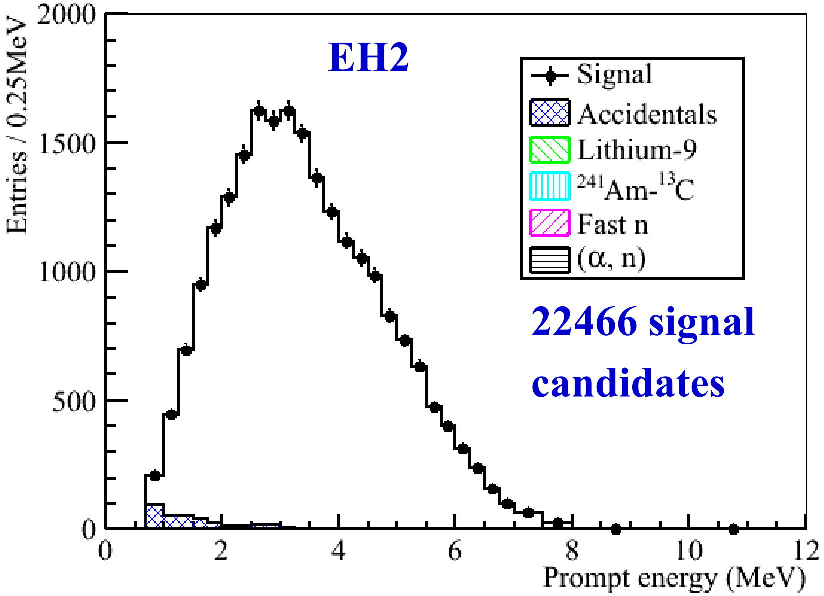
Uncertainty: 50%

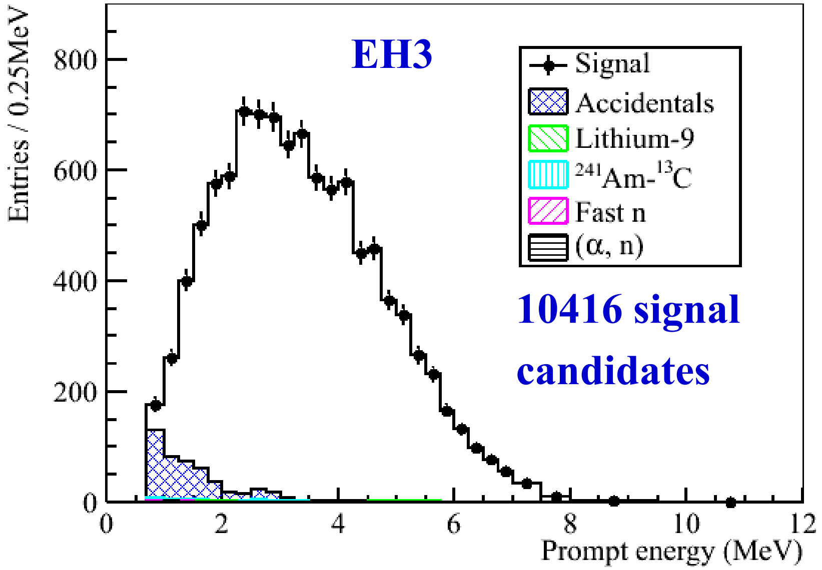
Signals and Backgrounds

	AD1	AD2	AD3	AD4	AD5	AD6
Neutrino candidates	28935	28975	22466	3528	3436	3452
DAQ live time (day)	49.5530		49.4971	48.9473		
Veto time (day)	8.7418	8.9109	7.0389	0.8785	0. 8800	0.8952
Efficiency $\varepsilon_\mu * \varepsilon_m$	0.8019	0.7989	0.8363	0.9547	0.9543	0.9538
Accidentals (/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
Fast neutron (/day)	0.84±0.28	0.84±0.28	0.74±0.44	0.04±0.04	0.04±0.04	0.04±0.04
^{8}He/^{9}Li (/day)	3.1±1.6		1.8±1.1	0.16±0.11		
Am-C corr. (/day)	0.2±0.2					
$^{13}C(\alpha, n)^{16}O$ background (/day)	0.04±0.02	0.04±0.02	0.035 ±0.02	0.03±0.02	0.03±0.02	0.03±0.02
Neutrino rate (/day)	714.17 ±4.58	717.86 ±4.60	532.29 ±3.82	71.78 ±1.29	69.80 ±1.28	70.39 ±1.28

Signal+Backgound Spectrum



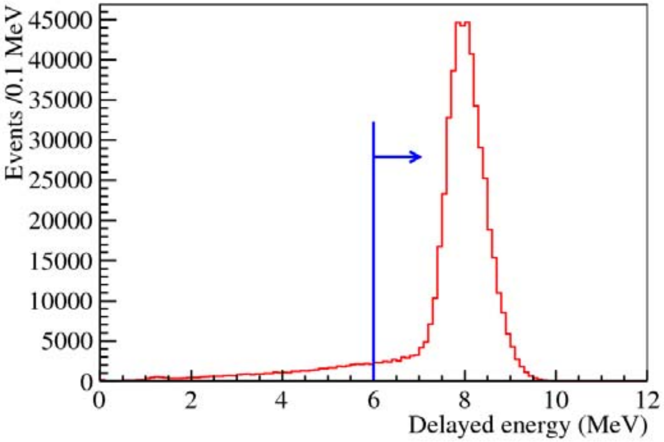




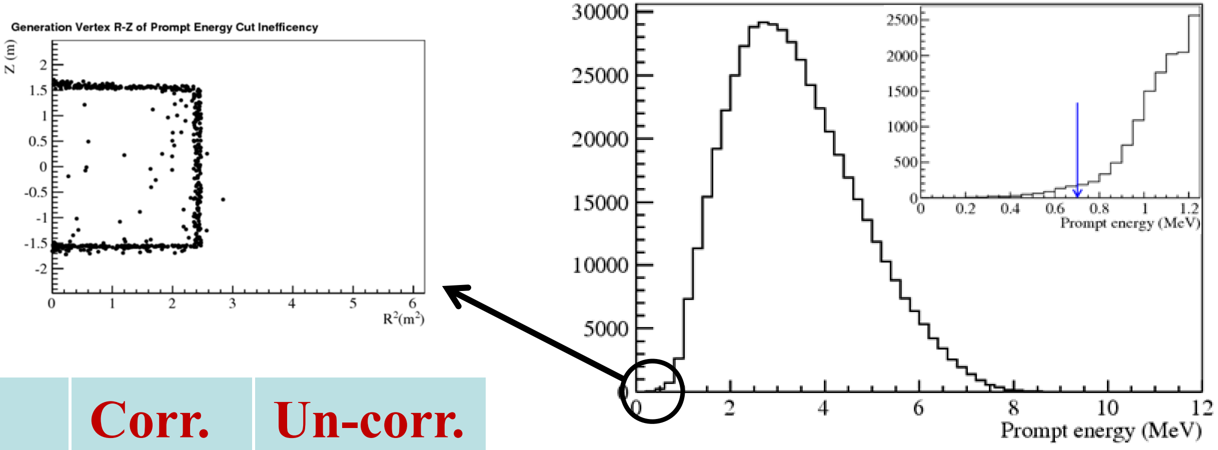
	B/S @EH1/2	**B/S @EH3**
Accidentals	**~1.4%**	**~4.5%**
Fast neutrons	**~0.1%**	**~0.06%**
^{8}He/^{9}Li	**~0.4%**	**~0.2%**
Am-C	**~0.03%**	**~0.3%**
α-n	**~0.01%**	**~0.04%**
Sum	**1.5%**	**4.7%**

Energy Cuts Efficiency and Systematics

- **Delayed energy cut $E_n > 6$ MeV**
  - Uncertainty from the energy scale, which is evaluated previously to be 0.5%
- **Prompt energy cut $E_p > 0.7$ MeV**
  - Uncertainty mainly from the energy scale(~2%)and positrons in acrylic



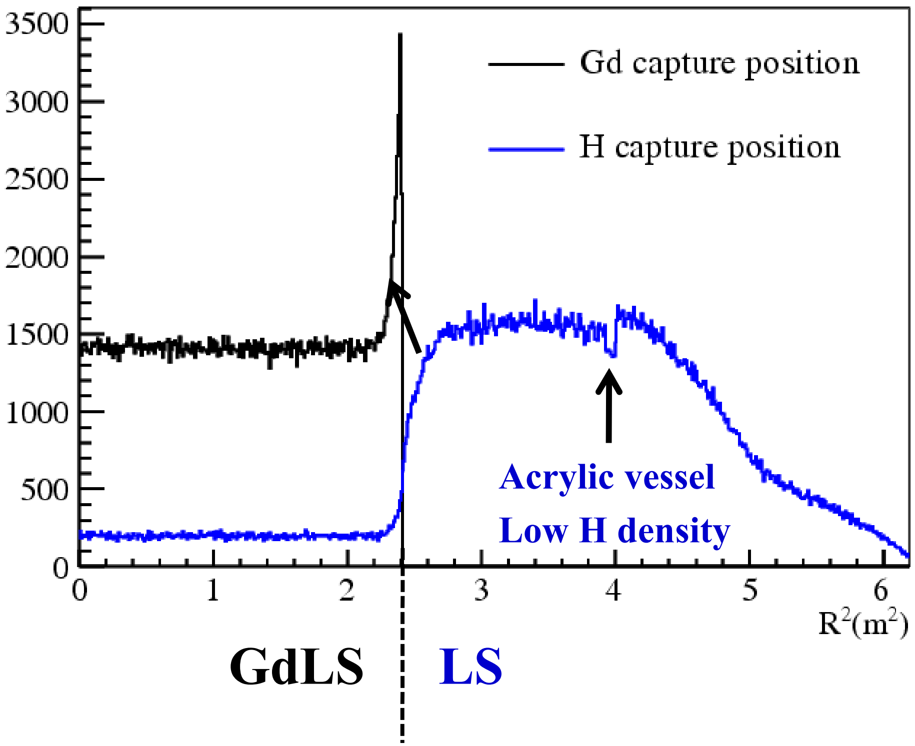
The inefficiency mainly comes from edges



	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

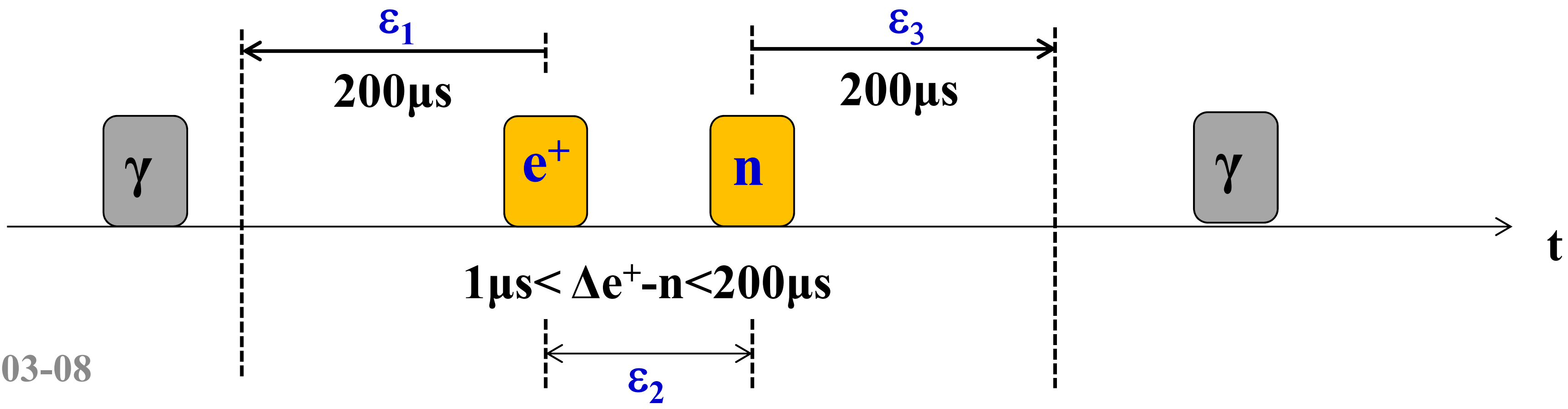
- Muon veto
  - Total veto time is the sum of all the veto time windows
  - Temporal overlap is taken into account
- Multiplicity cut
  - Efficiency = $\varepsilon_1 \times \varepsilon_2 \times \varepsilon_3$
- Total efficiency
  - Uncertainty coming mainly from the average neutron capture time. it is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

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

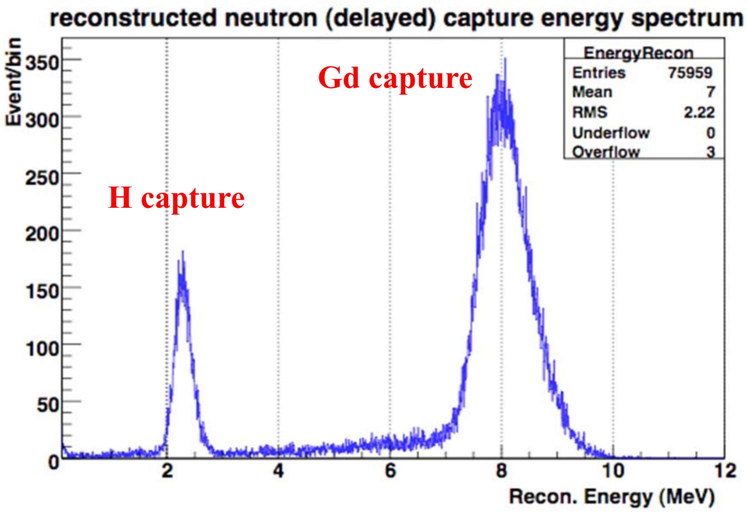
Prompt-delayed pairs within 200 μs
No triggers before the prompt and after the delayed signal by 200 μs

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

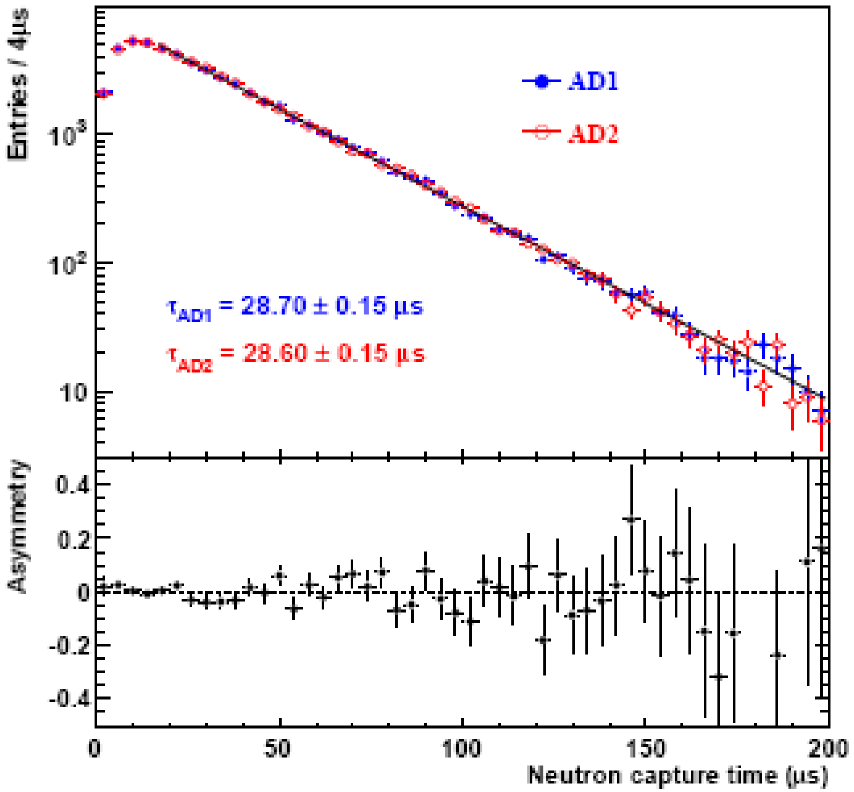
Efficiency is AD dependent, see page 37



Gd Capture Fraction: H/Gd and Systematics



Neutron capture time from Am-C

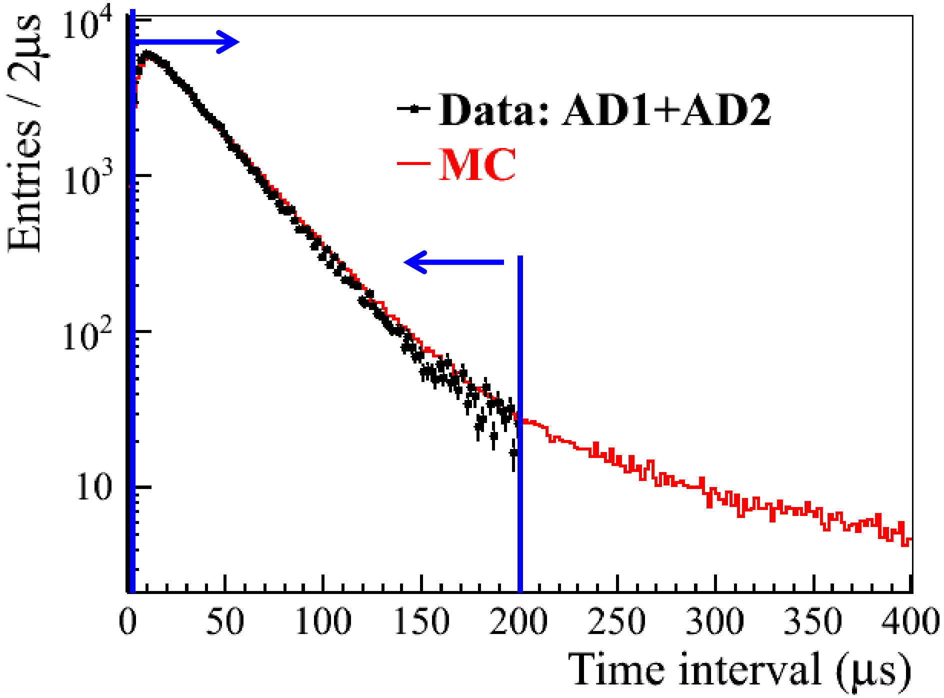


- **Uncertainties :**
  - Relative Gd content variation 0.1% → evaluated from neutron capture time
  - Geometry effect on spill-in/out 0.02% → relative differences in acrylic vessel thickness and density and liquid density are modeled in MC

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

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

- 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%

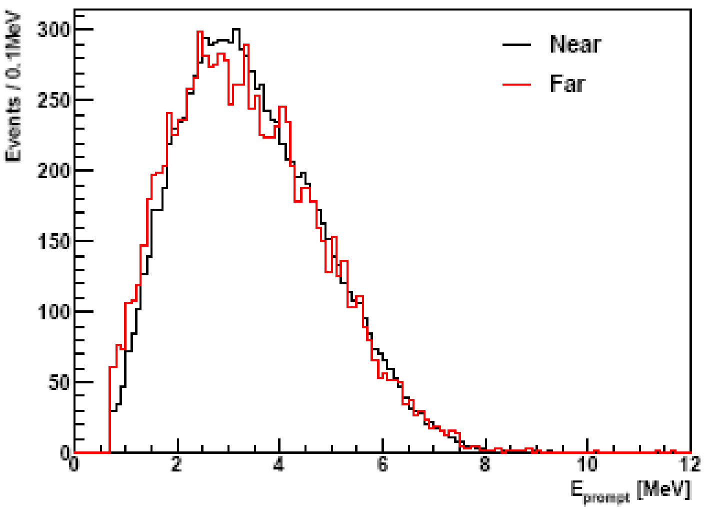
Livetime

- **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.**

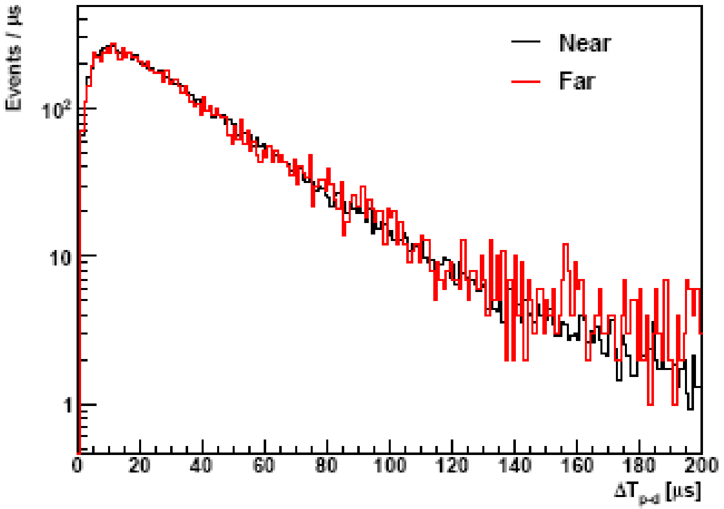
	Eff.	Corr.	Un-corr.
livetime	100%	0.002%	< 0.01%

Alternative Analysis

- **Using an alternative energy calibration algorithm based on spallation neutron peak**
- **Different neutrino selection criteria**
  - **Muon cut:** 0.4s after an AD shower muon (different shower muon threshold), 1.4ms after an AD muon, 0.6ms after a WP muon
  - **A different multiplicity cut**
- **Results: consistent within statistical errors**



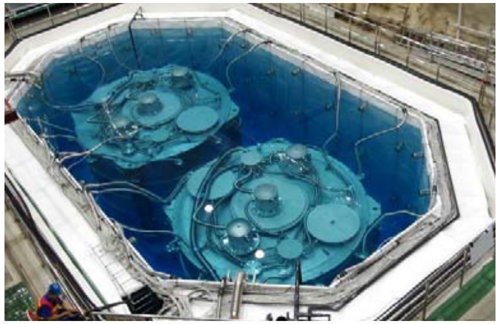
IBD Prompt Visible Energy



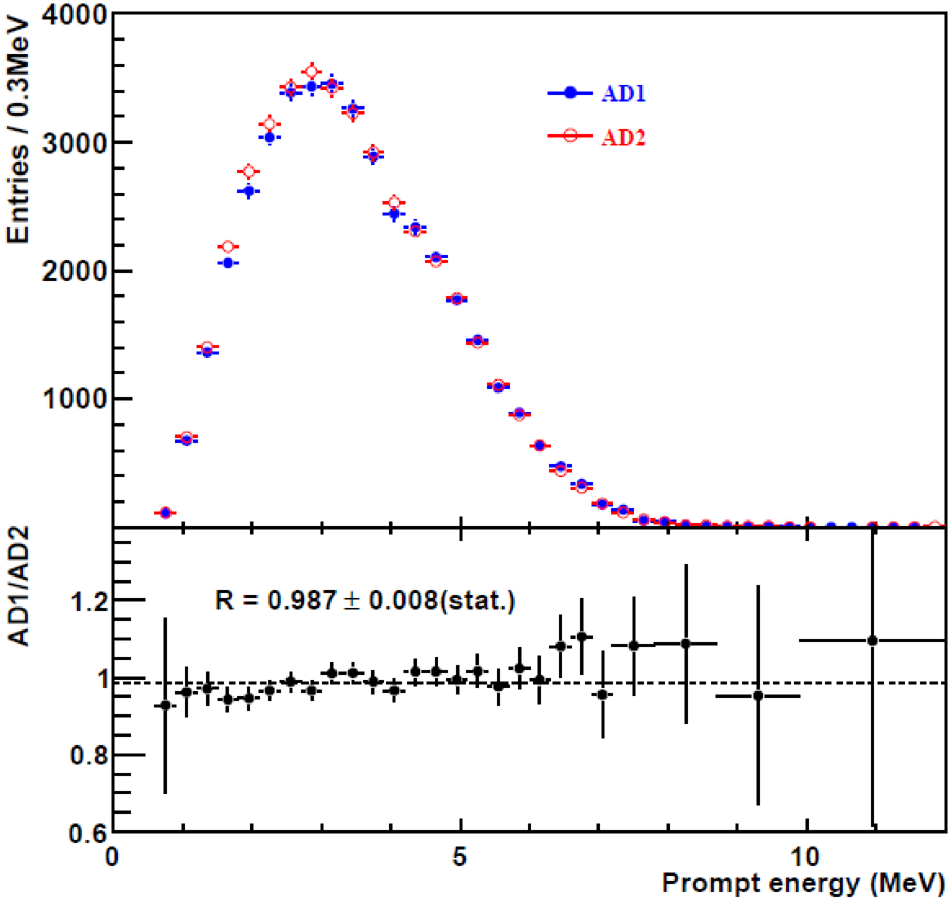
Time Between IBD Prompt and Delayed

Side-by-side Comparison

- Expected ratio of neutrino events from AD1 and AD2: 0.981
- Measured ratio: 0.987 ± 0.008(stat) ± 0.003



- The ratio is not 1 because of target mass, baseline, etc.
- This final check shows that systematic errors are under control



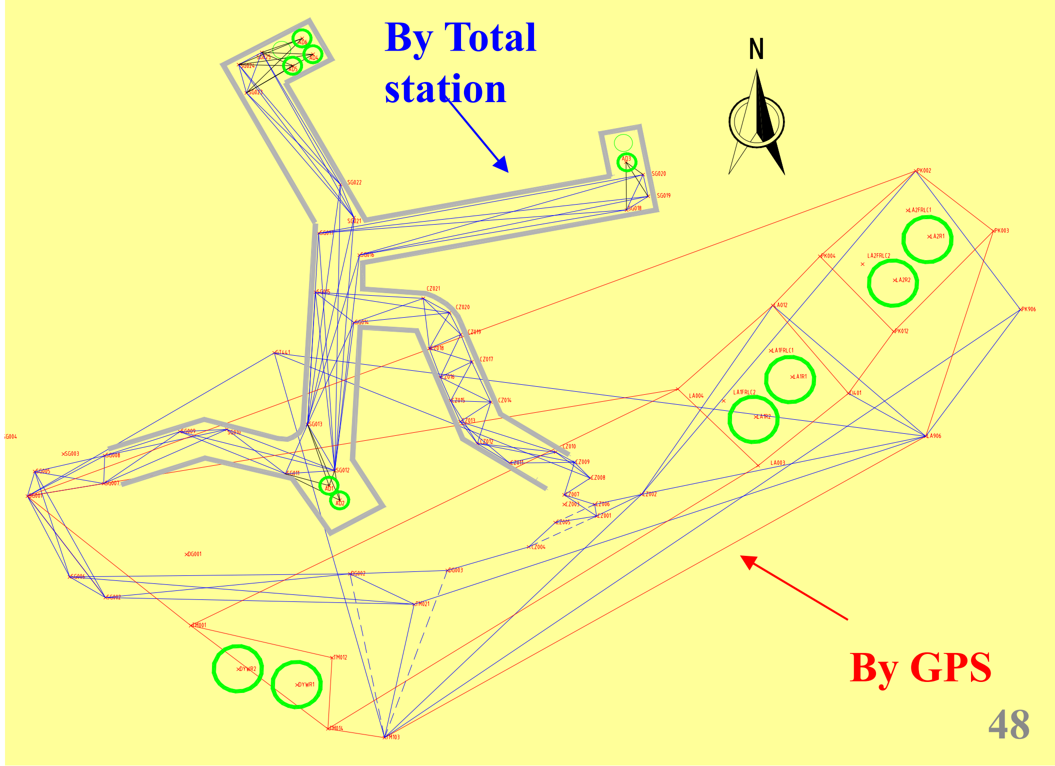
Predictions

- **Baseline**
- **Target mass**
- **Reactor neutrino flux**

- **The reactor neutrino flux, baseline and target mass are blinded before we fix our analysis cut and procedure.**

Baseline

- Various measurements: GPS, Total Station, laser tracker, level instruments, …
- Compared with design values, and NPP coordinates
- Data processing by three independent software
- Final baseline uncertainty is 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%)

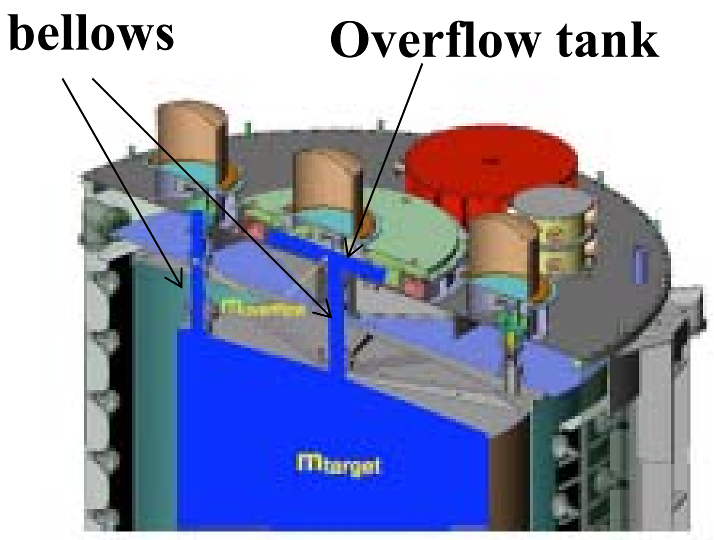


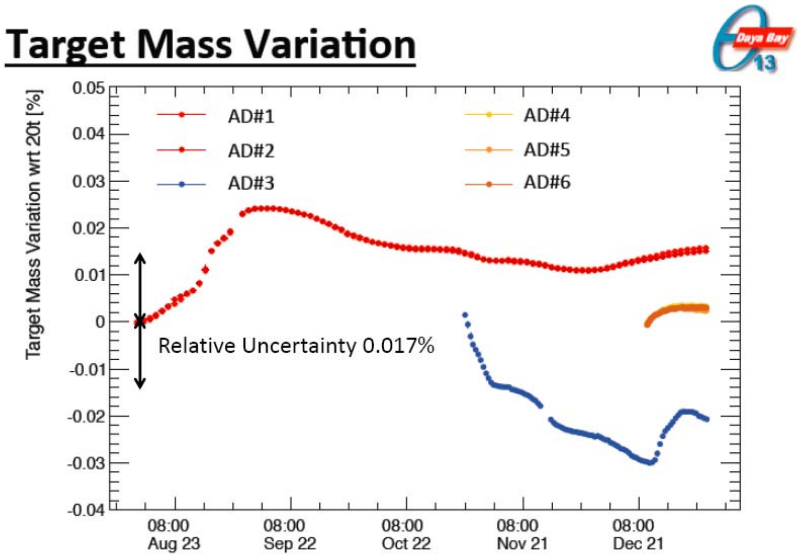
Target Mass & No. of Protons

- 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

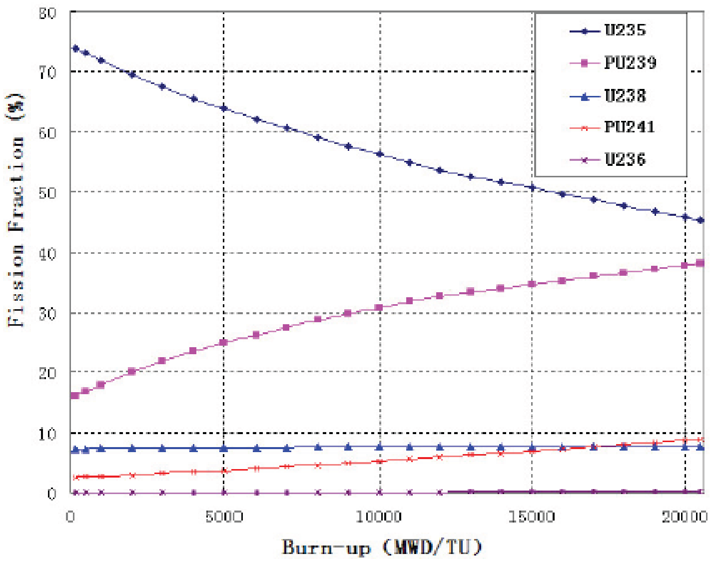
Quantity	Relative	Absolute
Free protons/Kg	neg.	0.47%
density	neg.	0.0002%
Total mass	0.015%	0.015%
Bellows	0.0025%	0.0025
Overflow tank	0.02%	0.02%
Total	0.03%	0.47%

Reactor Neutrinos

- **Reactor neutrino spectrum**

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

- **Thermal power, W_{th}, measured by KIT system, calibrated by KME method**
- **Fission fraction, f_i, determined by reactor core simulation**
- **Neutrino spectrum of fission isotopes $S_i(E_\nu)$ from measurements**
- **Energy released per fission e_i**



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

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%

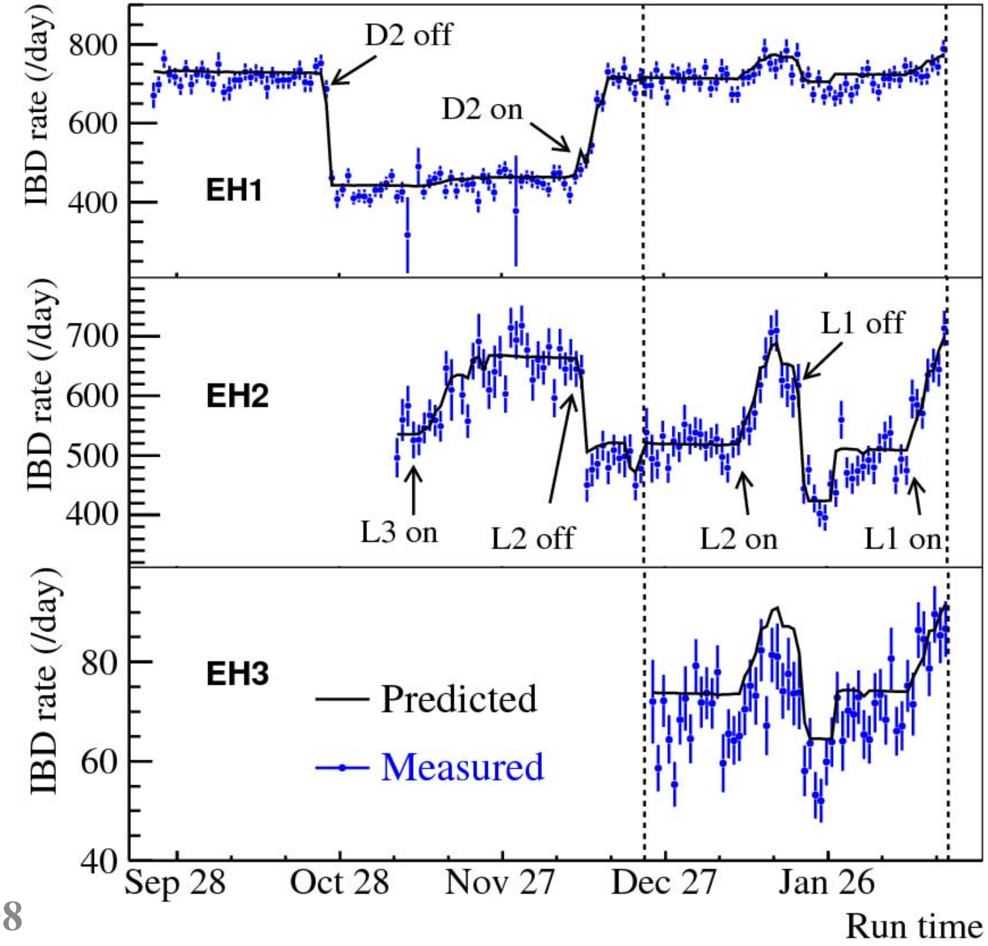
Kopeikin et al, Physics of Atomic Nuclei, Vol. 67, No. 10, 1892 (2004)

Relative measurement ➔ independent from the neutrino spectrum prediction

Daily Rate

◆ **Three halls taking data synchronously allows near-far cancellation of reactor related uncertainties**

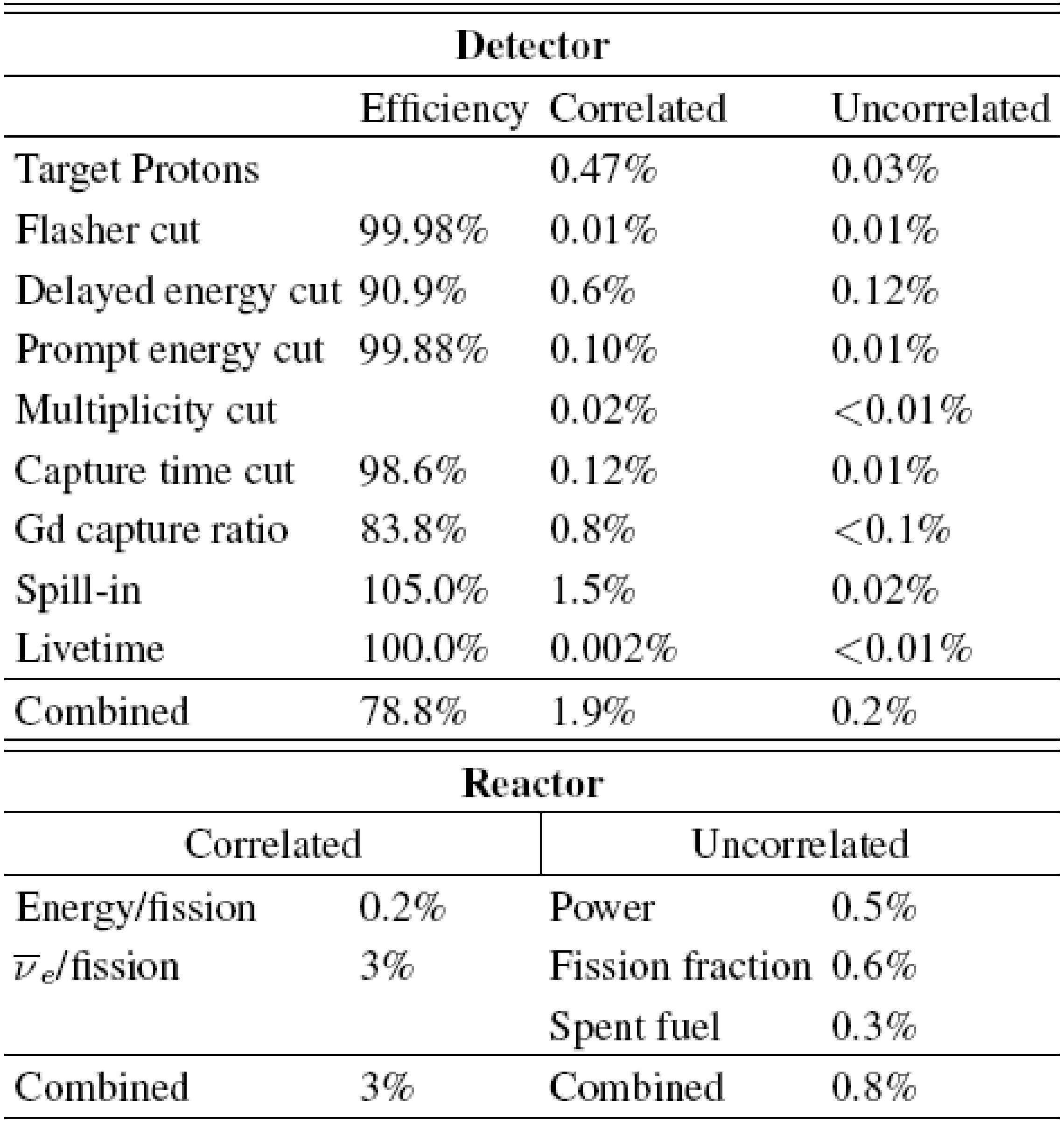
◆ **Rate changes reflect the reactor on/off.**



Prediction is absolute, multiplied by a normalization factor from fitting

Complete Efficiency and Systematics

- **Uncorrelated detector uncertainty 0.2%**
- **Total correlated uncertainty 3.6%**
- **Uncorrelated reactor uncertainty 0.8%**



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

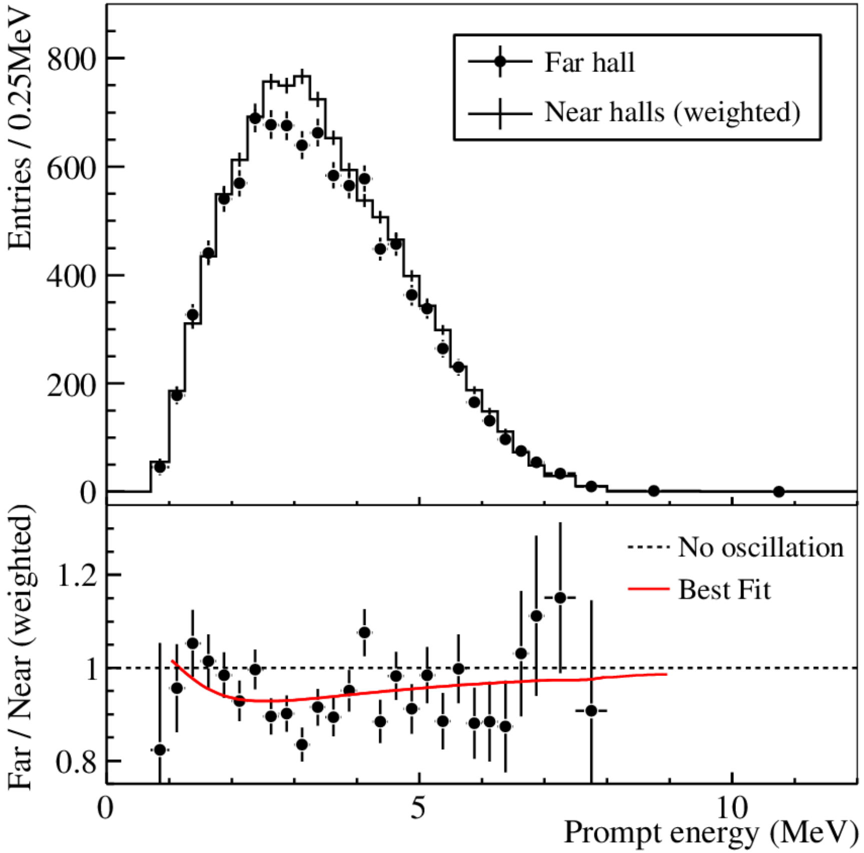
Correlated		Uncorrelated	
Energy/fission	0.2%	Power	0.5%
$\overline{\nu}_e$/fission	3%	Fission fraction	0.6%
		Spent fuel	0.3%
Combined	3%	Combined	0.8%

Electron Anti-neutrino Disappearence

Using near to predict far

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

$$M_i = \frac{IBD_i - B_i^{Acc} - B_i^{FNeutron} - B_i^{9Li/8He} - B_i^{AmC} - B_i^{\alpha-n}}{\epsilon_i^{muon}\epsilon_i^{multi}TMass_i}$$



Determination of α, β:

1) **Set R=1 if no oscillation**
2) **Minimize the residual reactor uncertainty**

Observed: 9901 neutrinos at far site,
Prediction: 10530 neutrinos if no oscillation

R = 0.940 ±0.011 (stat) ±0.004 (syst)

Spectral distortion
Consistent with oscillation

χ^2 Analysis

$$\chi^2 = \mathrm{m}$$

$$+ \sum_{a=1}$$

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

$\chi^2/\mathrm{NDF} = 4.26/4$

5.2 σ for non-zero θ_{13}

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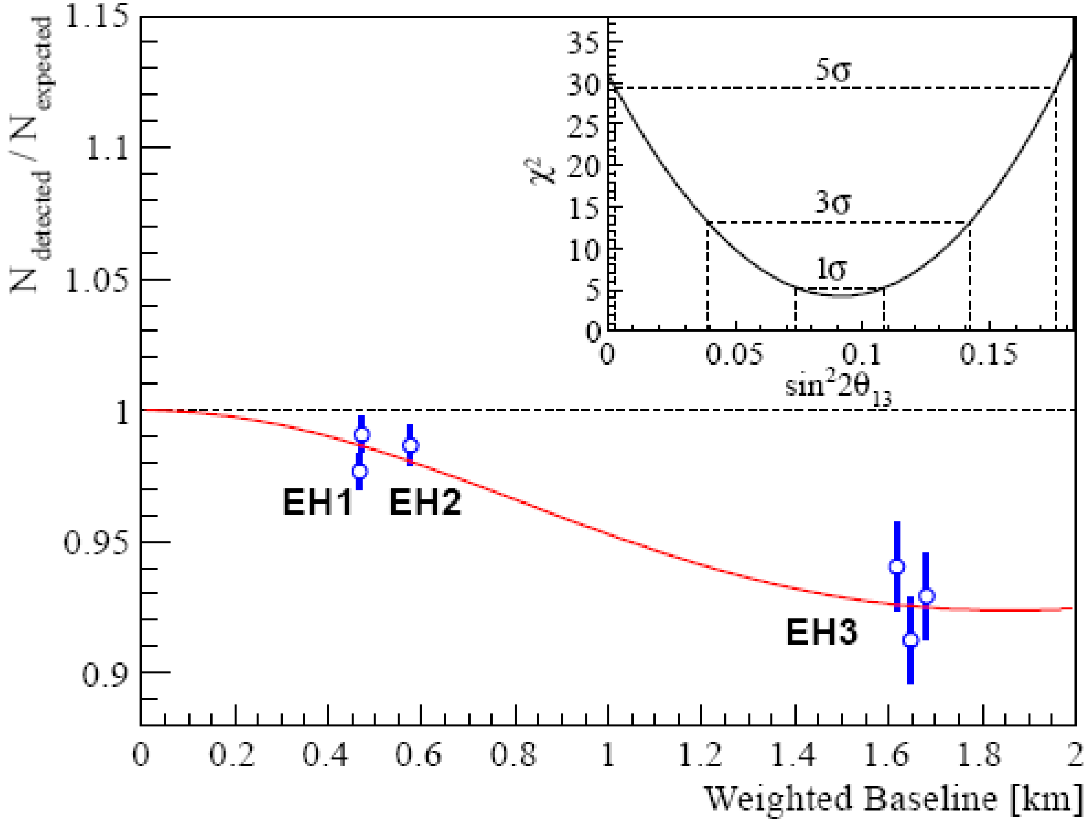


Summary

- Electron anti-neutrino disappearance is observed at Daya Bay,

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

  together with a spectral distortion
- A new type of neutrino oscillation is thus discovered

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

χ^2/NDF = 4.26/4

5.2 σ for non-zero θ_{13}

Acknowledgement

All collaboration funding agencies

China Guangdong Nuclear power group
Yellow River Engineering Consulting Co., Ltd.
China railway 15th Bureau Group Co., Ltd.

And many other supporters

Backup

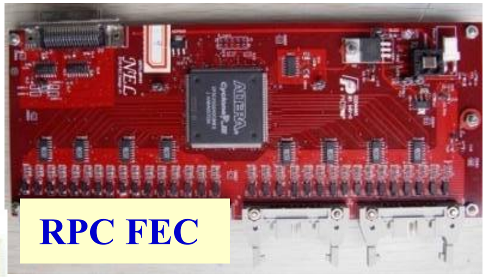
Future plan

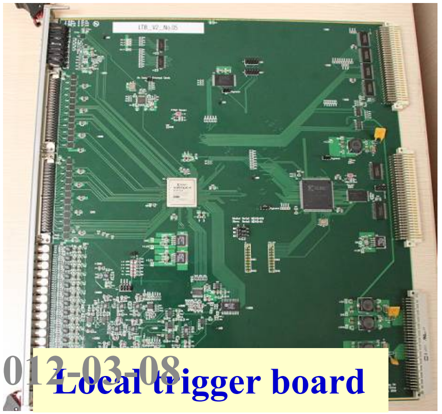
- Assembly of AD7 and AD8, to be completed before summer
- Continue the data taking until summer
- Installation of AD7 & AD8 in summer
- Detector calibration
- Re-start data taking after summer

Readout Electronics & Trigger

- 1536+960 ch. PMT readout:
  - For charge and timing
- 48+30 ch. 1GHz FADC:
  - 1/32, for trigger and cross check
- 6240 ch. RPC readout:
  - Bit info. for every strip
  - FEC➔ ROT ➔ ROM/RTM
- Trigger scheme:
  - For PMT: energy and multiplicity
  - For RPC: 2/4 or ¾
- GPS clock distributed to all halls
- Master trigger boards


Electronics room in Hall 1


RPC FEC


Local trigger board

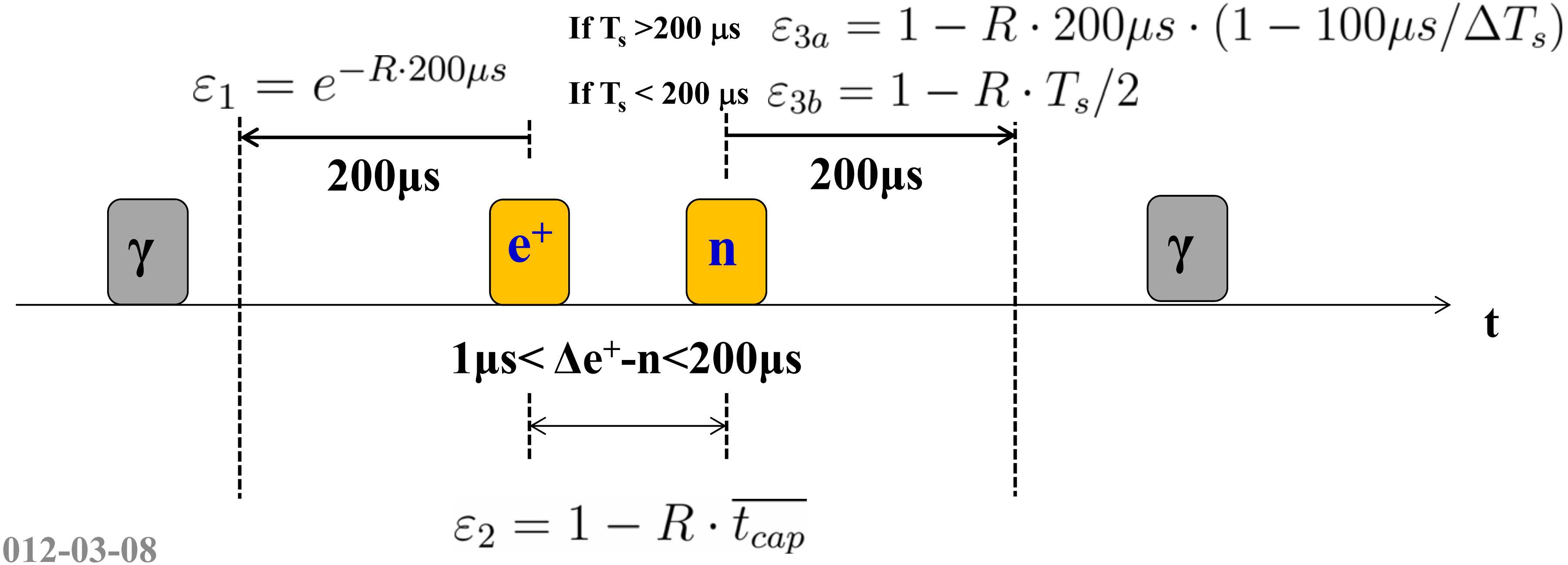

PMT readout


FADC


RPC ROT

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**



If T_s >200 μs $\varepsilon_{3a} = 1 - R \cdot 200\mu s \cdot (1 - 100\mu s/\Delta T_s)$

$$\varepsilon_1 = e^{-R \cdot 200\mu s}$$

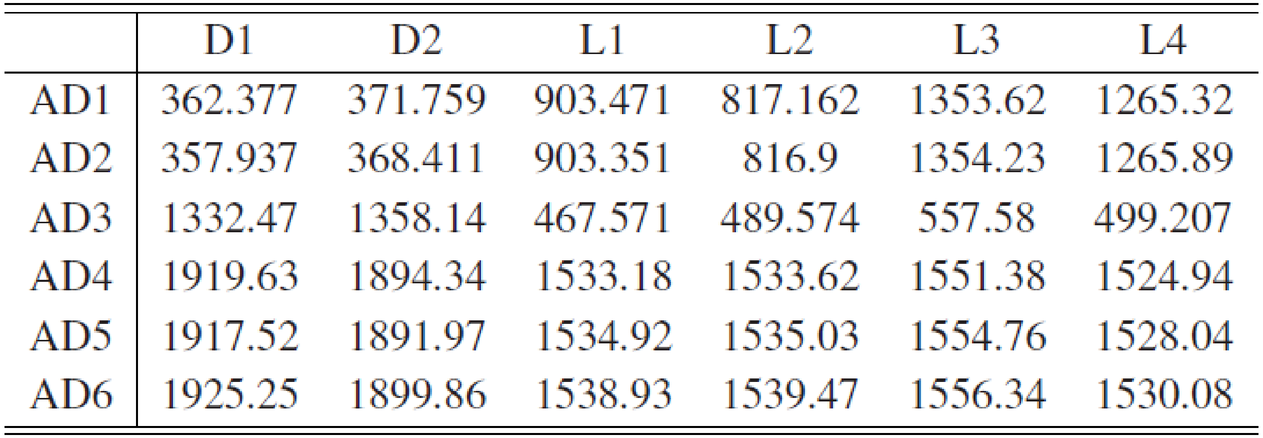
If T_s < 200 μs $\varepsilon_{3b} = 1 - R \cdot T_s/2$

1μs< Δe^+-n<200μs

$$\varepsilon_2 = 1 - R \cdot \overline{t_{cap}}$$

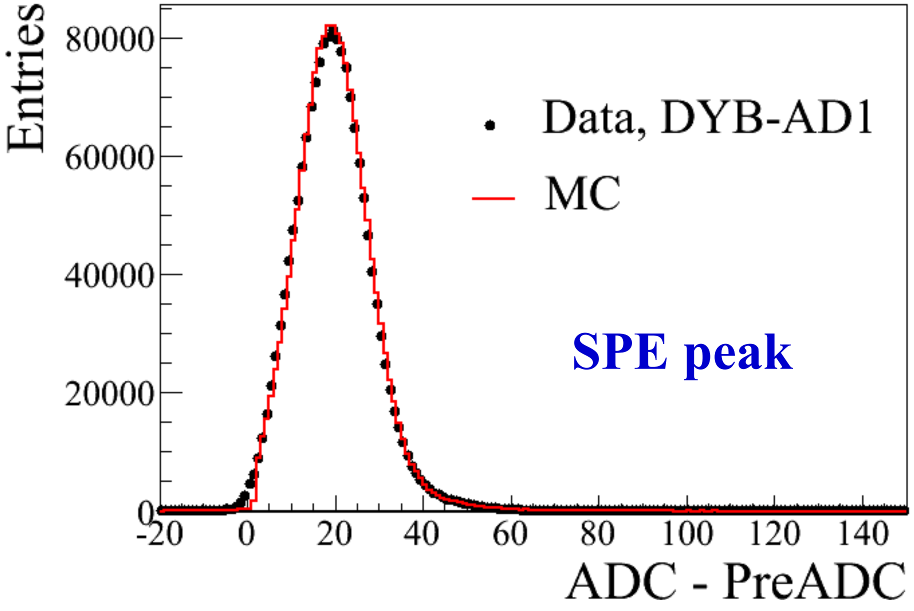
Baseline

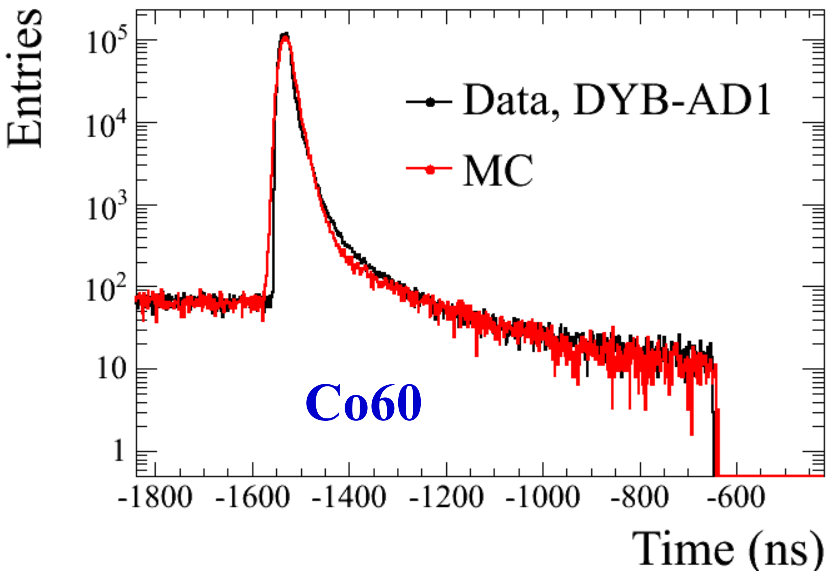
- Outside the tunnel, measurements by the Total Station & the GPS are consistent within 9mm
- Inside the tunnel, measurements by the Total Station and the level instrument are consistent within 1.7 mm
- In the experimental hall, measurements by the Total station and the laser tracker are consistent within 0.2mm
- GPS measurements are consistent with the coordination provided by NPP ,within 5.9 mm
- Laser tracker results consistent with the design within 2.2mm
- Detector coordination consistent with the design within 0.73m
- Data processing by three software, consistent within 6mm.



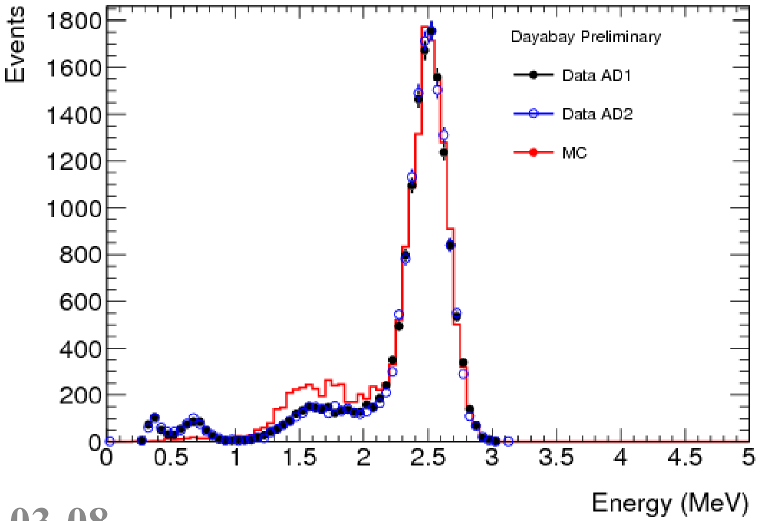
	D1	D2	L1	L2	L3	L4
AD1	362.377	371.759	903.471	817.162	1353.62	1265.32
AD2	357.937	368.411	903.351	816.9	1354.23	1265.89
AD3	1332.47	1358.14	467.571	489.574	557.58	499.207
AD4	1919.63	1894.34	1533.18	1533.62	1551.38	1524.94
AD5	1917.52	1891.97	1534.92	1535.03	1554.76	1528.04
AD6	1925.25	1899.86	1538.93	1539.47	1556.34	1530.08

Data & MC comparison





Co60 at ACUA center



Ge68 at ACUA center