Observation of Electron Antineutrino Disappearance at Daya Bay

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on behalf of the Daya Bay Collaboration

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outline

- introduction
- data set & quality control
- calibration and event reconstruction
- event selection
- backgrounds & uncertainties
- efficiencies & systematic errors
- oscillation analysis
- results & plan

Daya Bay Collab (F.P. An et al.), " A side-by-side comparison of Daya Bay anti-neutrino detectors", arXiv: 1202.6181[physics.ins-det], submitted to NIM on 28 Feb. 2012
Daya Bay Collab (F.P. An et al.), "Observation of electron anti-neutrino disappearance at Daya Bay", submitted on 7 Mar. 2012, published on **PRL 108 (2012) 171803**, selected for a *Viewpoint in Physics*.

neutrino oscillation & Daya Bay

- neutrino mixing matrix

$s_{ij} = \sin\theta_{ij}$, $c_{ij} = \cos\theta_{ij}$

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

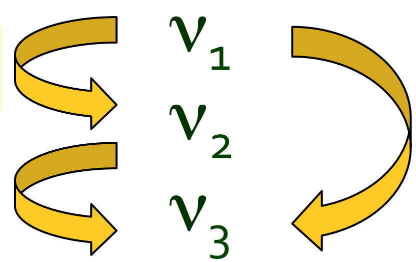
Unknown mixing parameters: θ_{13}, δ + 2 Majorana phases

Need sizable θ_{13} for the δ measurement

- Daya Bay: search for the 3rd oscillation mode: θ_{13}

θ_{12} solar neutrino oscillation

θ_{23} atmospheric neutrino oscillation



θ_{13} ?

two ways to measure θ_{13}

Reactor experiments:

$P_{ee} \approx 1 - \mathbf{\sin^2 2\theta_{13}} \sin^2(1.27\Delta m^2_{13} L/E) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2(1.27\Delta m^2_{12} L/E)$

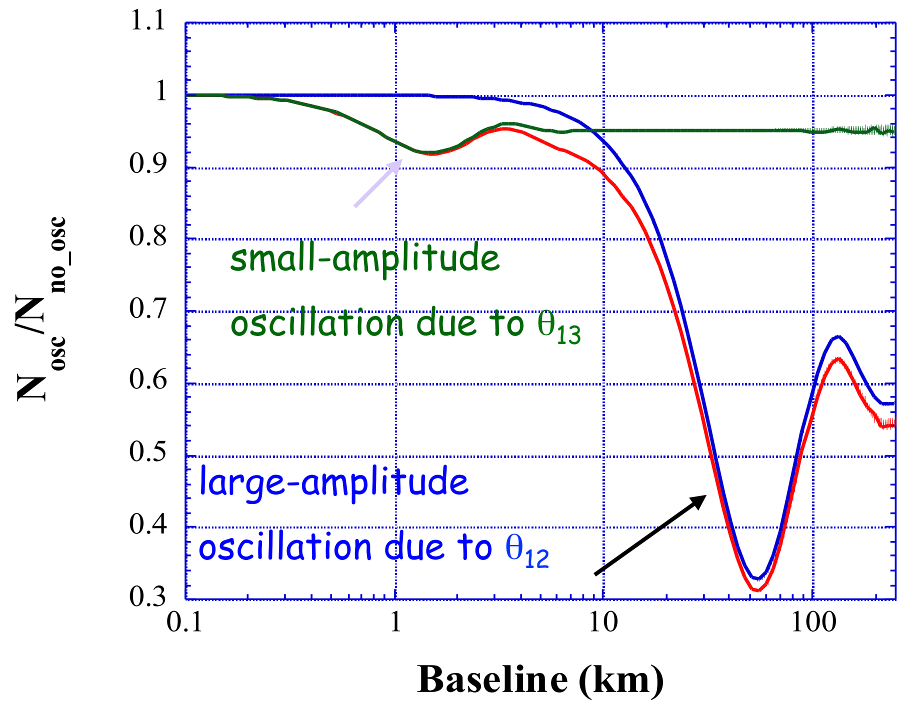
Long baseline accelerator experiments:

$P_{\mu e} \approx \sin^2\theta_{23} \mathbf{\sin^2 2\theta_{13}} \sin^2(1.27\Delta m^2_{23} L/E) + \cos^2\theta_{23} \sin^2 2\theta_{12} \sin^2(1.27\Delta m^2_{12} L/E)$

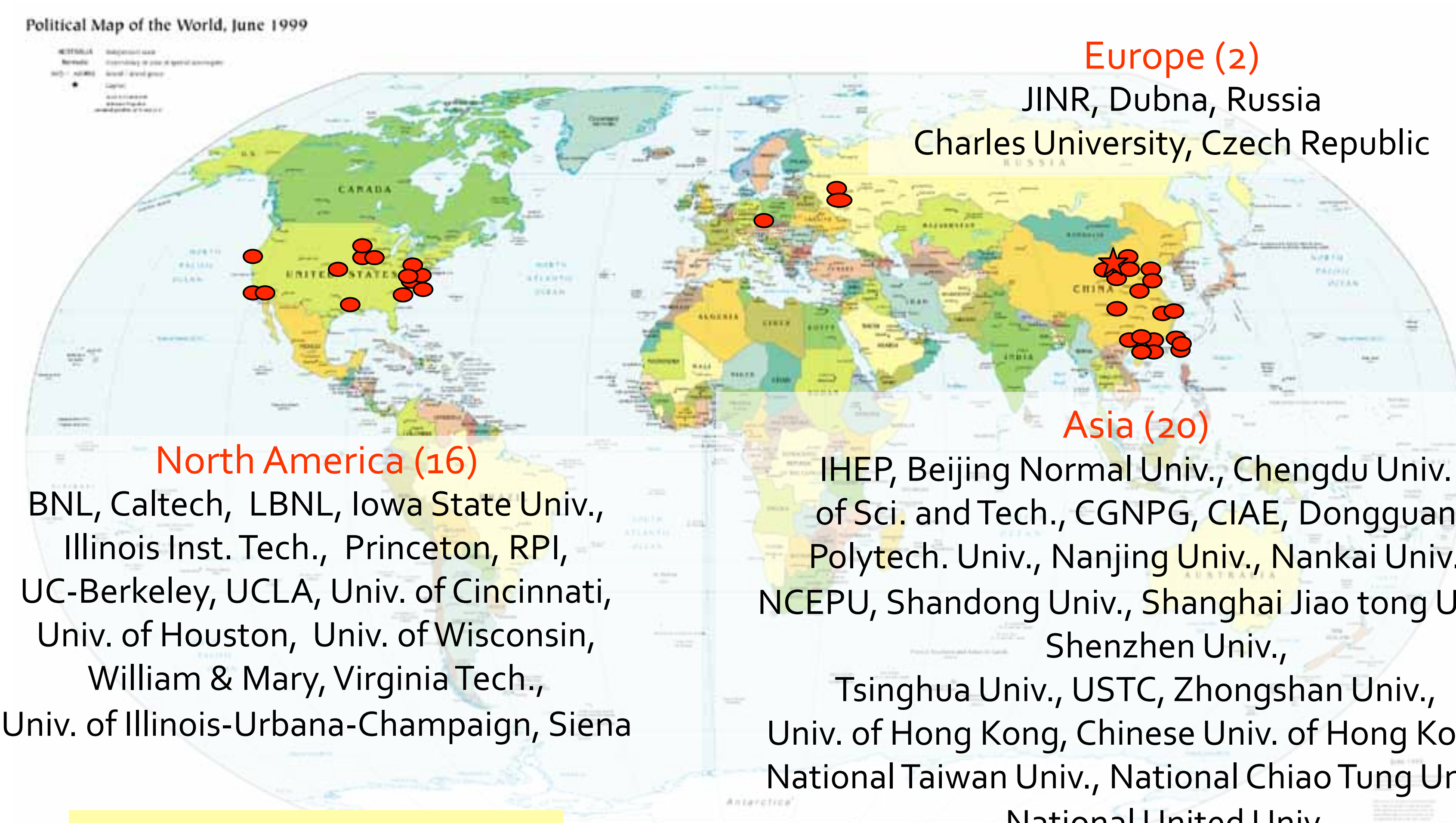
$\quad - \mathbf{A(\rho) \cos^2\theta_{13} \sin\theta_{13} \sin\delta}$

At reactors:

- Clean signal, no cross talk with δ and matter effects
- Relatively cheap compared to accelerator based experiments



Daya Bay Collaboraton



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

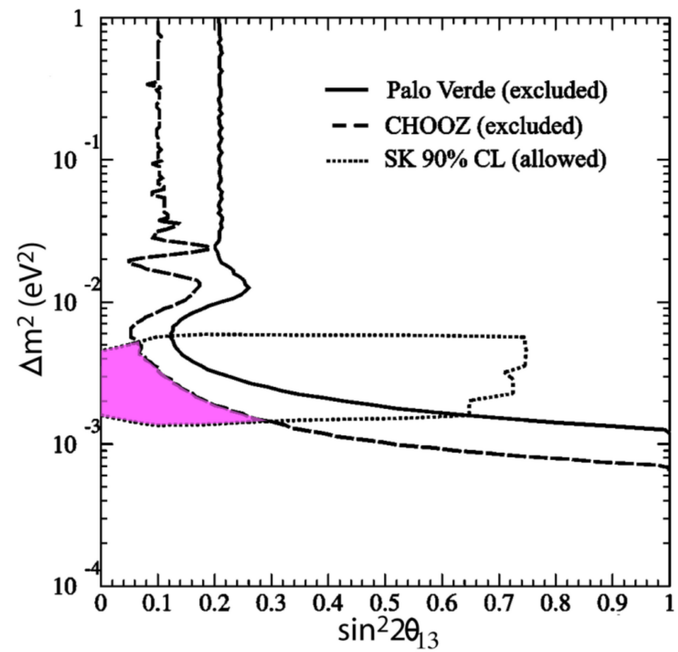
Asia (20)

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.

38 institutions
~250 collaborators

direct searches in the past

- Palo Verde & Chooz: no signal
  $\sin^2 2\theta_{13} < 0.12$ @ 90%C.L.
  if $\Delta m^2_{23} = 0.0024\ eV^2$

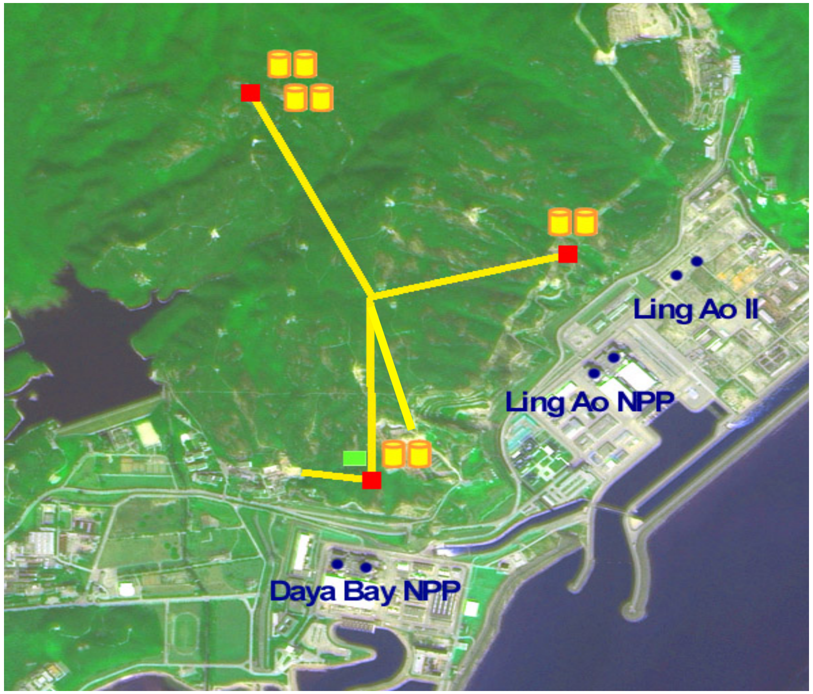


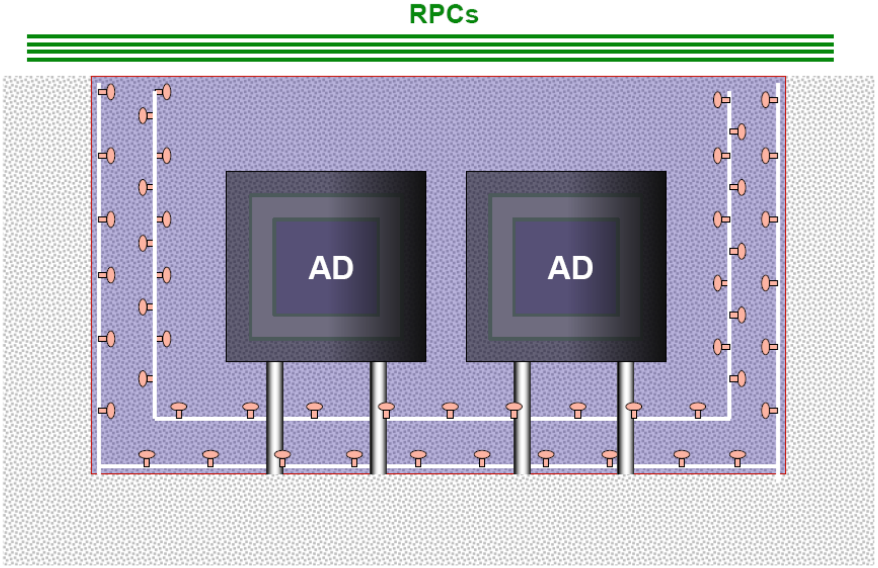
- T2K: 2.5σ over background
  $0.03 < \sin^2 2\theta_{13} < 0.28$ @ 90%C.L. for NH
  $0.04 < \sin^2 2\theta_{13} < 0.34$ @ 90%C.L. for IH

- Minos: 1.7σ over background
  $0 < \sin^2 2\theta_{13} < 0.12$ @ 90%C.L. NH
  $0 < \sin^2 2\theta_{13} < 0.19$ @ 90%C.L. IH

- Double Chooz: 1.7σ
  $\sin^2 2\theta_{13} = 0.086 \pm 0.041(stat) \pm 0.030(sys)$

experiment layout

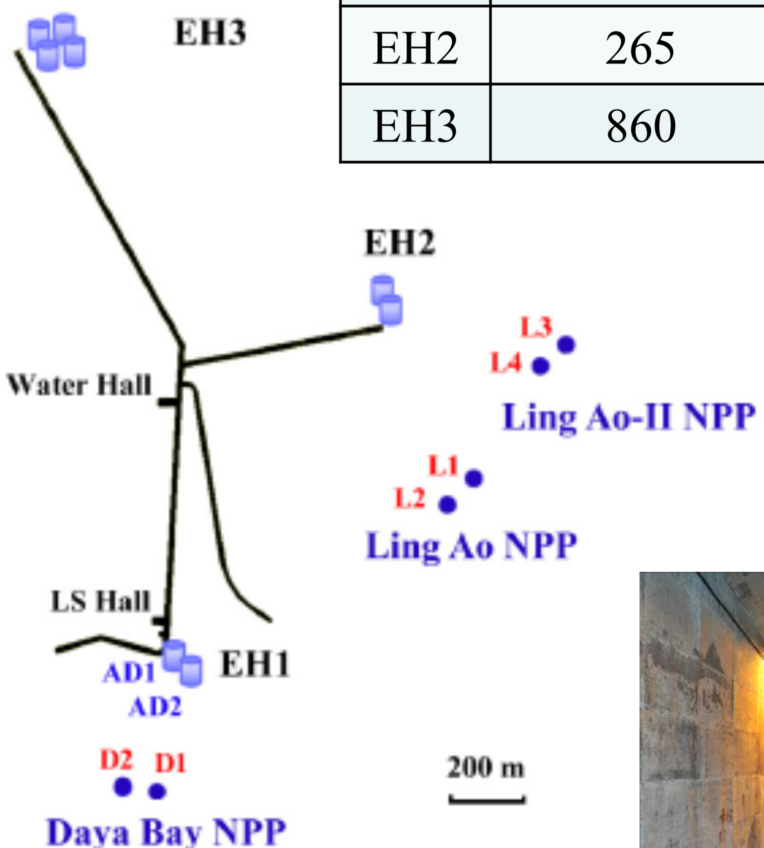




- relative measurement to cancel correlated syst. errors
  - 2 near sites, 1 far site
- multiple AD modules at each site to reduce uncorrelated syst. errors
  - far: 4 modules, near: 2 modules ➔ cross check, reduce errors by $1/\sqrt{N}$
- multiple muon detectors to reduce veto efficiency uncertainties
  - water Cherenkov: 2 layers
  - RPC: 4 layers at the top + telescopes

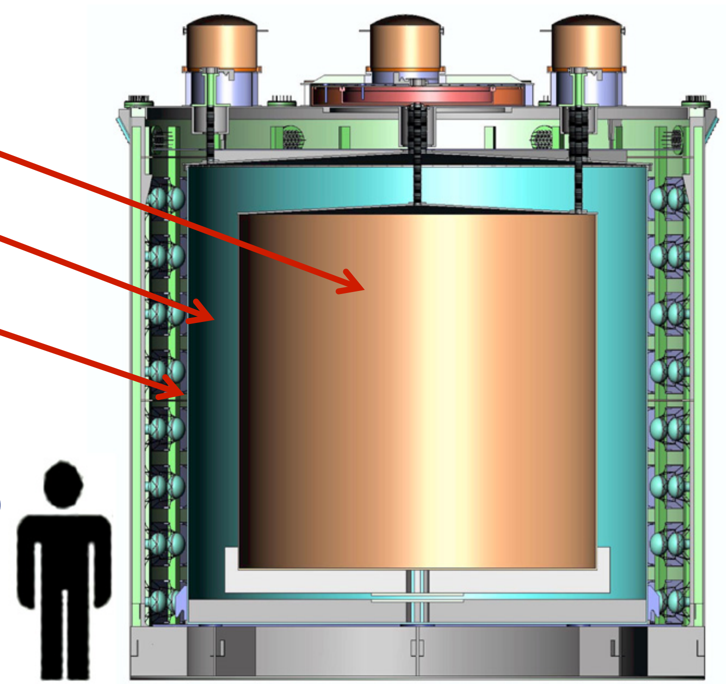
underground labs

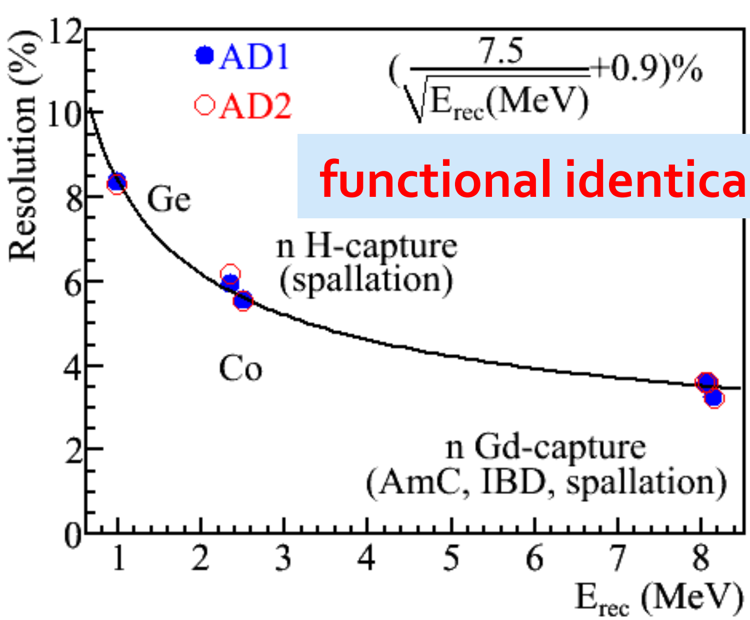
	Overburden (MWE)	R_μ (Hz/m^2)	E_μ (GeV)	D1,2 (m)	L1,2 (m)	L3,4 (m)
EH1	250	1.27	57	364	857	1307
EH2	265	0.95	58	1348	480	528
EH3	860	0.056	137	1912	1540	1548



antineutrino detector (AD)

- 3-zone modular structure
  - I. target: Gd-loaded liquid scintillator
  - II. γ-catcher: normal liquid scintillator
  - III. buffer shielding: mineral oil
- 192 8" PMTs/module
- 2 optical reflectors at the top and the bottom
  - PMT coverage increased from 5.6% to 12%



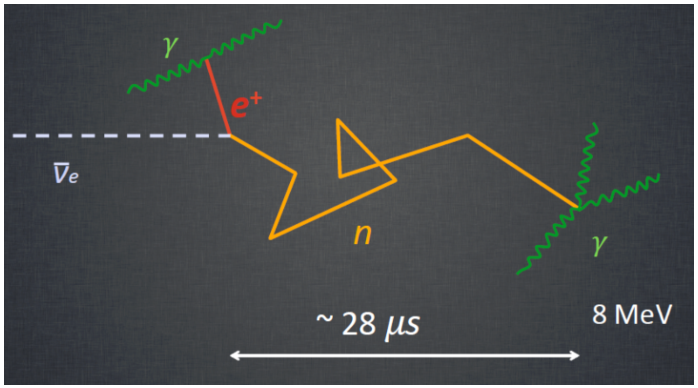


functional identical ADs

target: 20 ton, 1.6 m
γ-catcher: 20 ton, 45 cm
buffer: 40 ton, 45 cm
total weight: ~110 ton

neutrino detection

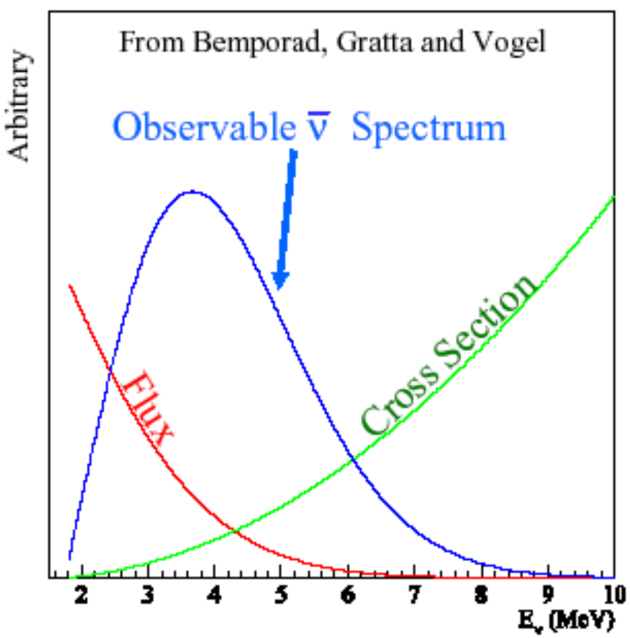
$$\bar{\nu}_e + p \rightarrow e^+ + n$$



τ ≈ 28 μs (0.1% Gd)

n + p → d + γ's (2.2 MeV)
n + Gd → Gd* + γ's (8 MeV)

Neutrino Event: coincidence in time, space and energy



Neutrino energy:

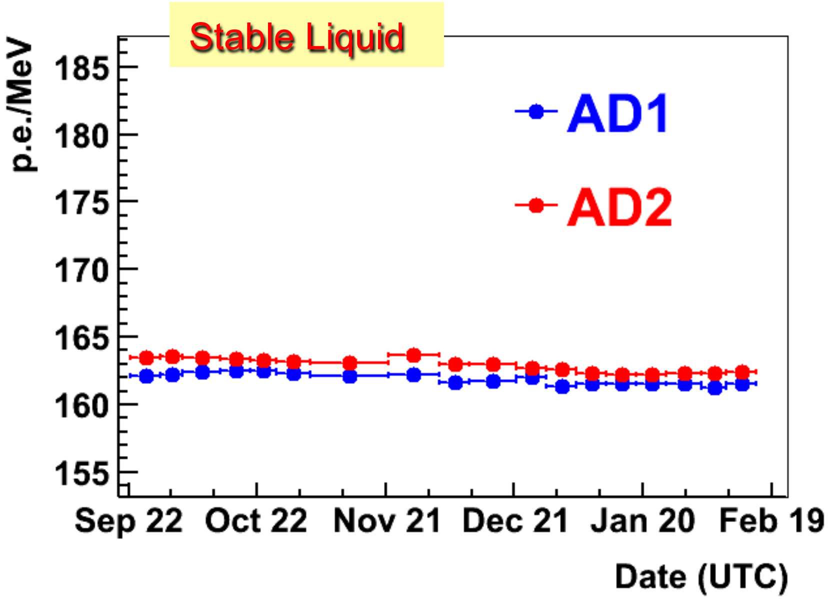
$$E_{\bar{\nu}} \cong T_{e^+} + \underbrace{T_n}_{10-40\ keV} + \underbrace{(M_n - M_p) + m_{e^+}}_{1.8\ MeV:\ \text{Threshold}}$$

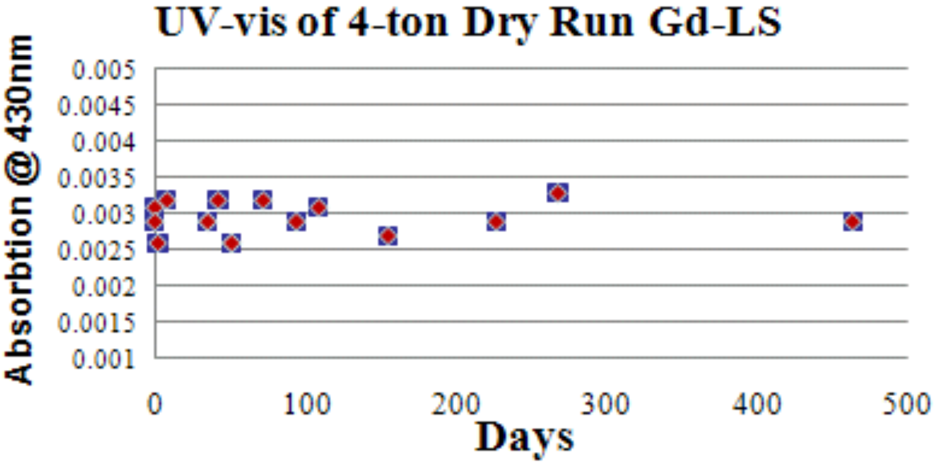
10–40 keV *1.8 MeV*: Threshold

Gd-loaded liquid scintillator

- liquid production, QA, storage and filling at Hall 5
  - 185 t Gd-LS, ~180 t LS, ~320 t oil
- LAB+Gd (TMHA)3+PPO+BisMSB
- stable over time
  - light yield: ~163 p.e./MeV

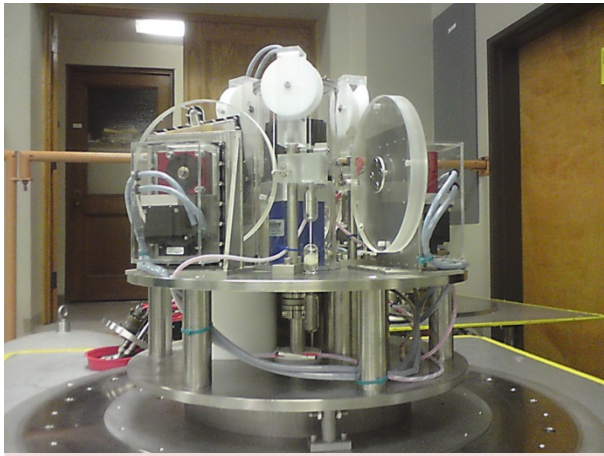
Liquid hall: LS production and filling

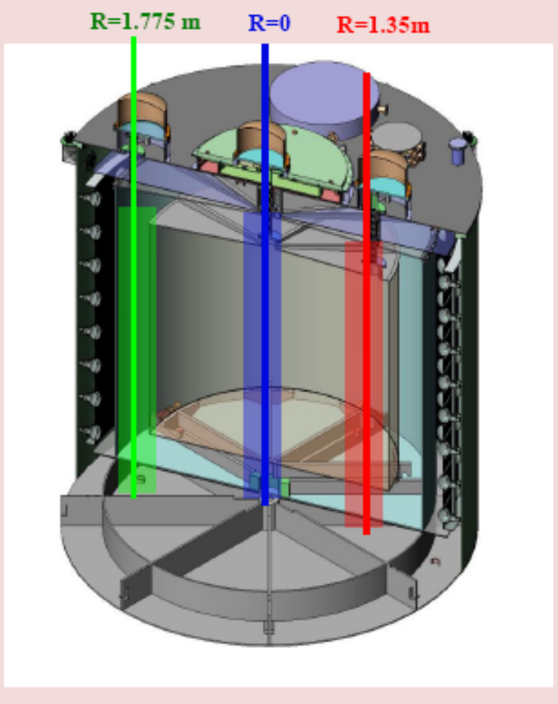




automatic calibration unit

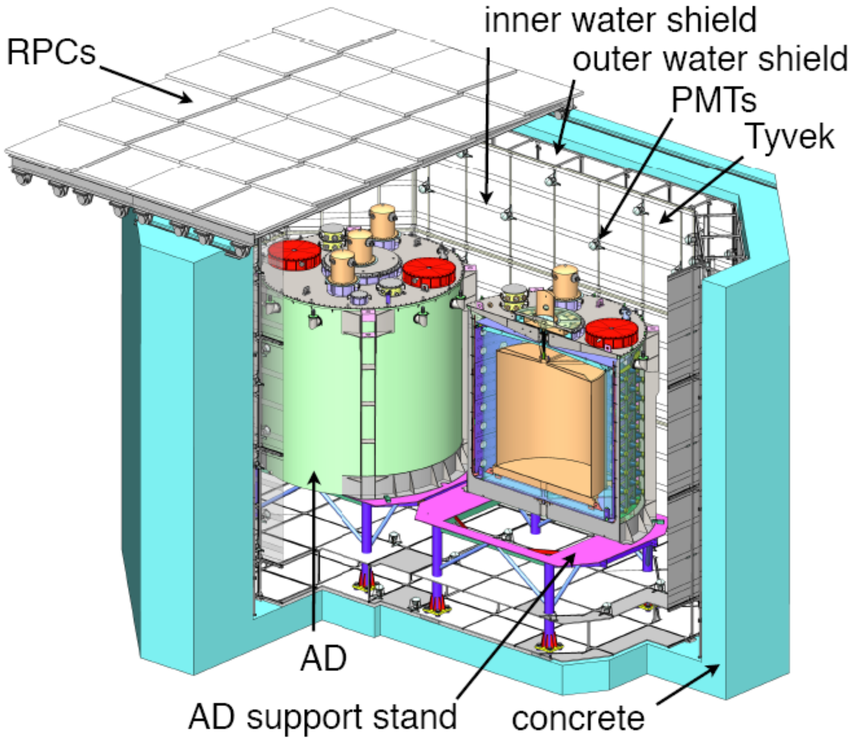
- three Z axes:
  - one at the center
    - for time evolution, energy scale, non-linearity
  - one at the edge of target
    - for efficiency, space response
  - one in the γ-catcher
    - for efficiency, space response
- 3 sources for each z axis:
  - LED
    - for T_0, gain and relative QE (quantum eff.)
  - ^{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
- calibrate once per week:
  - 3 axes x 5 points x 3 sources





Automated Calibration

muon veto system

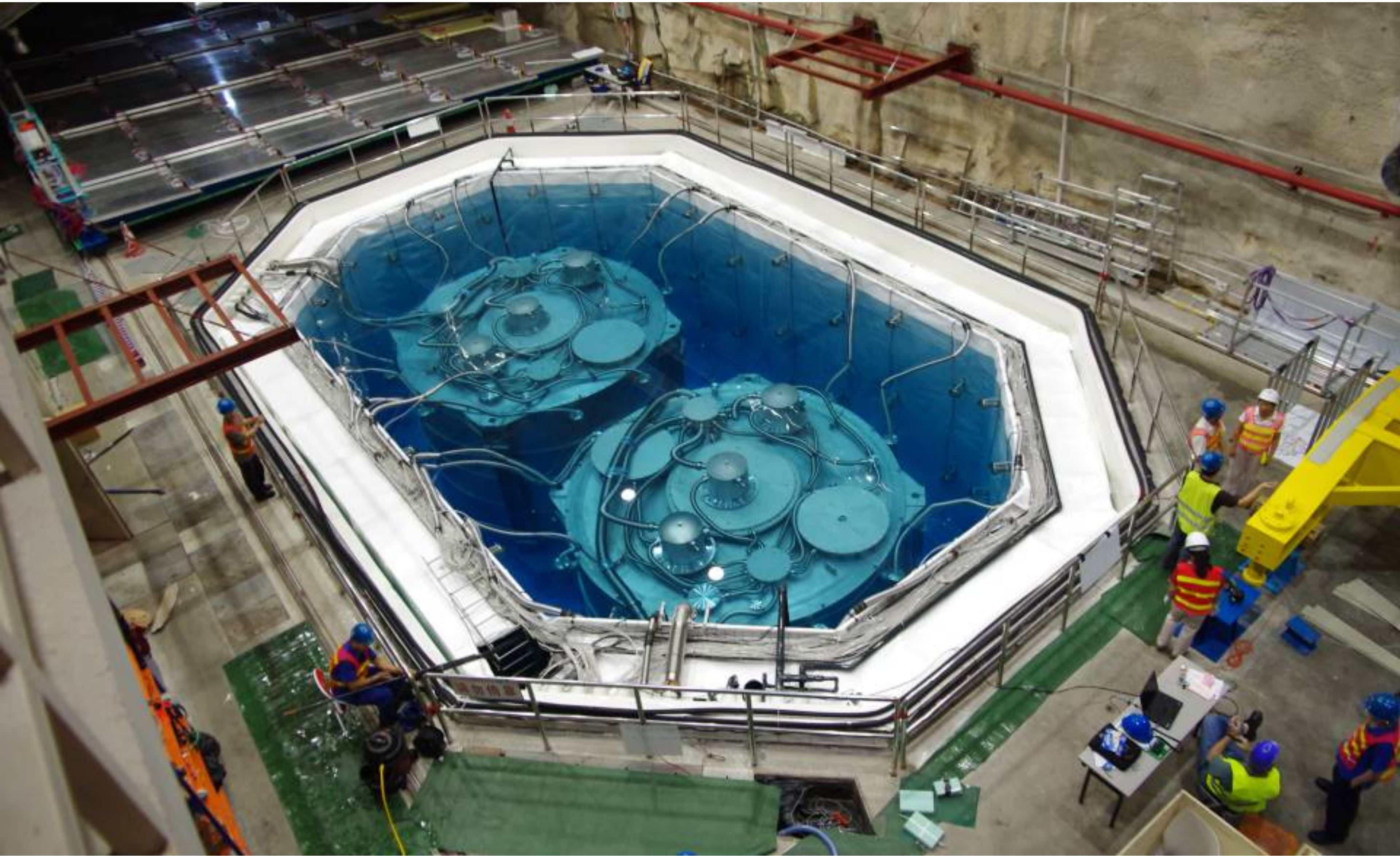


two active cosmic-muon veto's

- water Cerenkov: Eff.>97%
- RPC muon tracker: Eff. > 88%

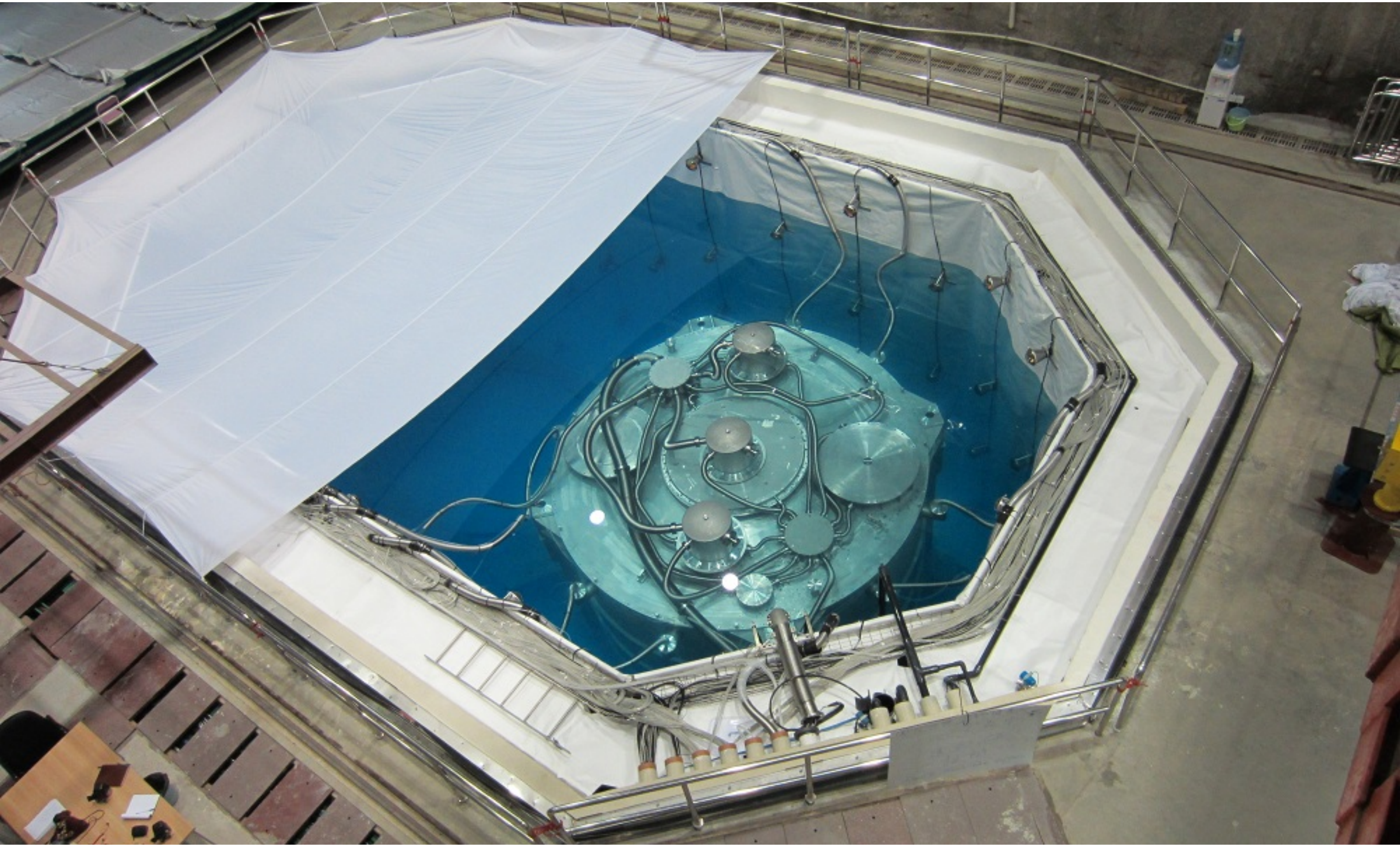
- RPCs
  - 4 layers/module
  - 54 modules/near hall, 81 modules/far hall
  - 2 telescope modules/hall
- water Cerenkov detector
  - Two layers, separated by Tyvek/PE/Tyvek film
  - 288 8" PMTs for near halls; 384 8" PMTs for the far hall
- water processing
  - high purity de-ionized water in pools also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

hall-1: 2 ADs installed

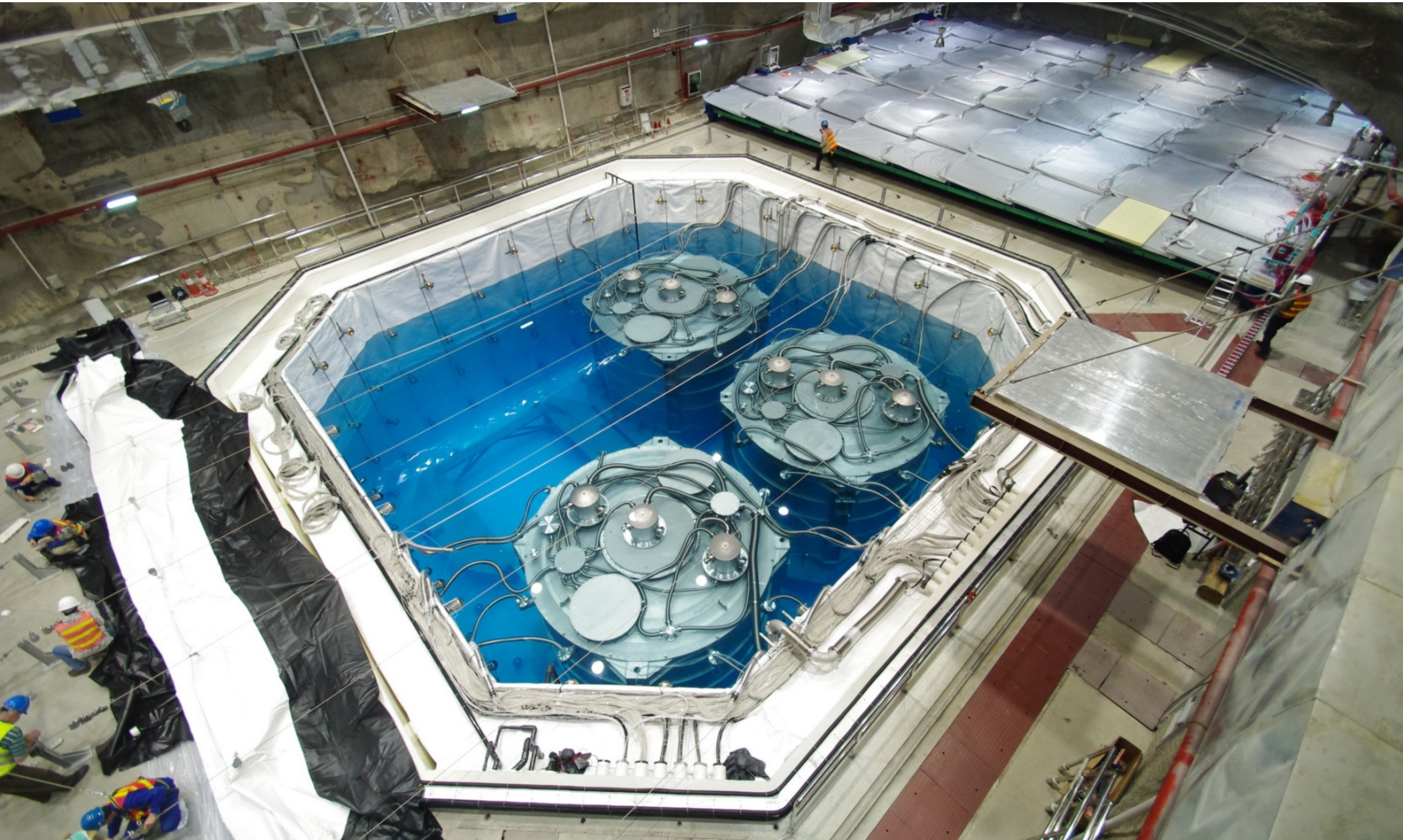


hall-1: operation started on **2011/08/15**

hall-2: 1 AD installed, started physics data taking on **2011/11/05**



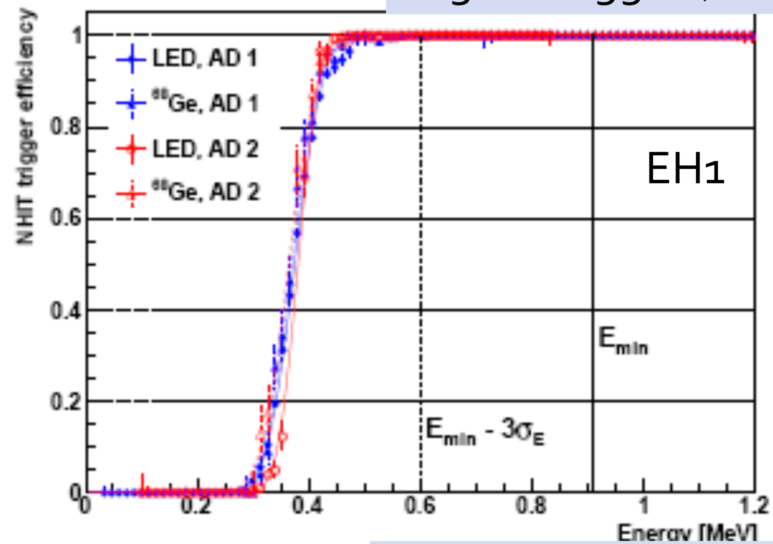
hall-3: 3 ADs installed, started physics data taking on **2011/12/24**



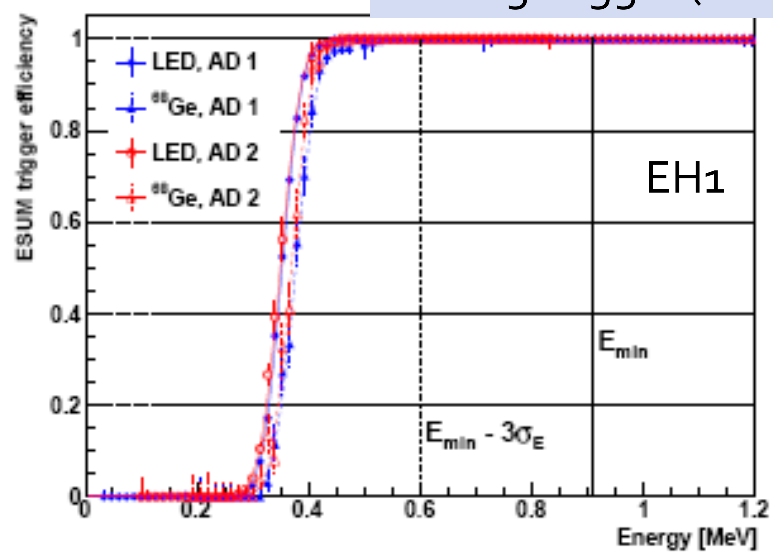
trigger performance

- threshold for a PMT hit:
  - AD & pool: ¼ p.e.
- trigger thresholds:
  - AD: Nhit=45, Esum = 0.4 MeV
  - inner pool: Nhit=6
  - outer pool: Nhit=7 (8 for far hall)
  - RPC: 3/4 layers in each module
- Trigger rate (EH1)
  - AD singles rate:
    - >0.4 MeV, ~ 280Hz
    - >0.7 MeV, ~ 60Hz
  - inner pool rate: ~170 Hz
  - outer pool rate: ~230 Hz

Digital Trigger (Nhit)

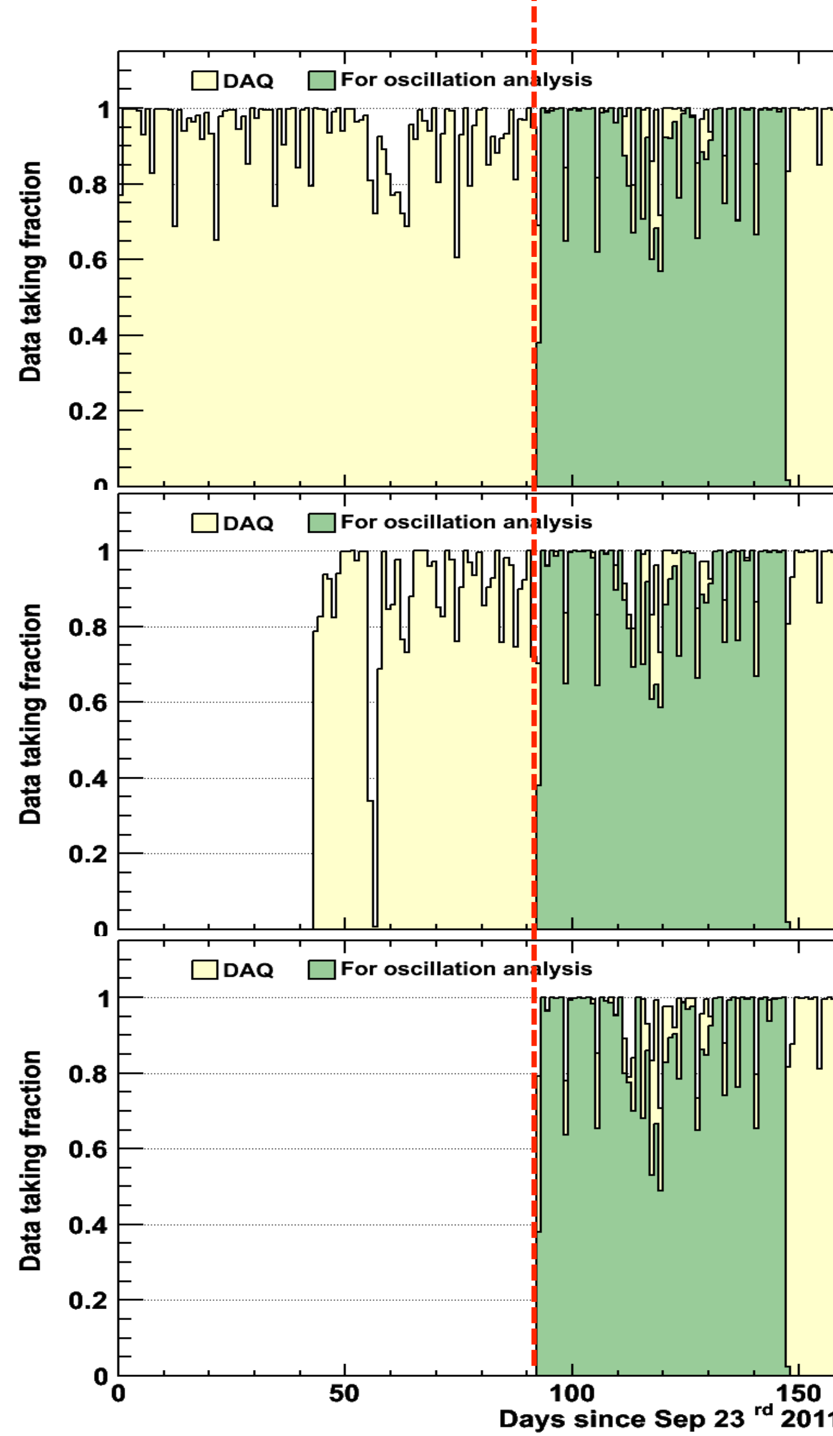


Analog Trigger (Esum)

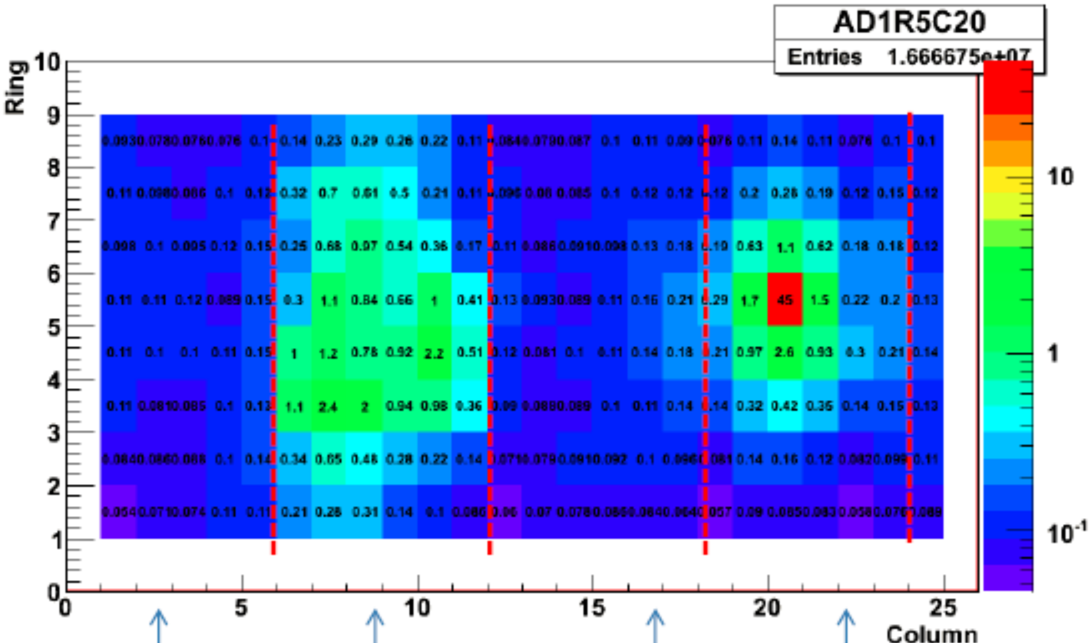


data set

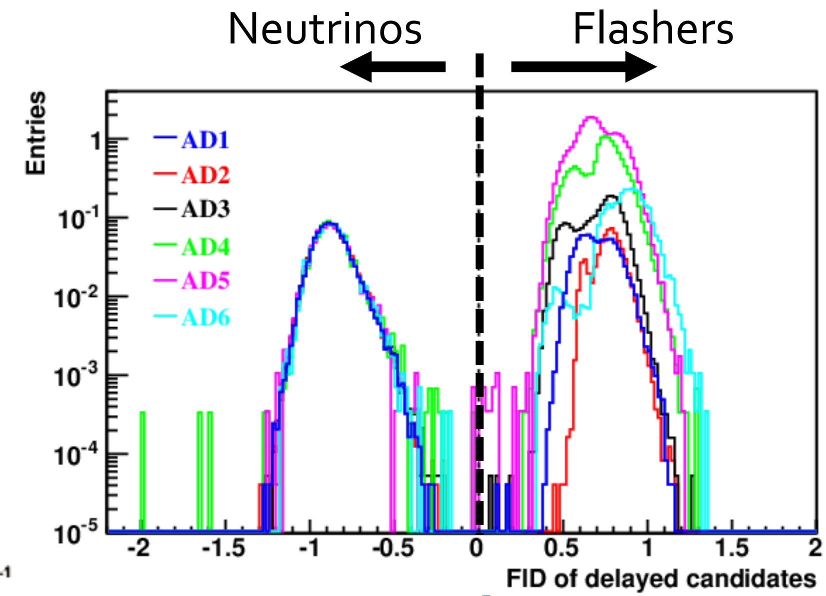
- 2011/12/24-2012/02/17
  ➔ 55 days
- data volume: 15TB
- DAQ eff. ~ 97%
- data taking for physics:
  ~ 89%



flashers: imperfect PMTs



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



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

Quadrant = Q3/(Q2+Q4)
MaxQ = maxQ/sumQ

- spontaneous light emission by PMTs
- topology: a hot PMT + near-by PMTs and opposite PMTs
- ~ 5% PMTs, 5% events
- rejection: pattern of fired PMTs

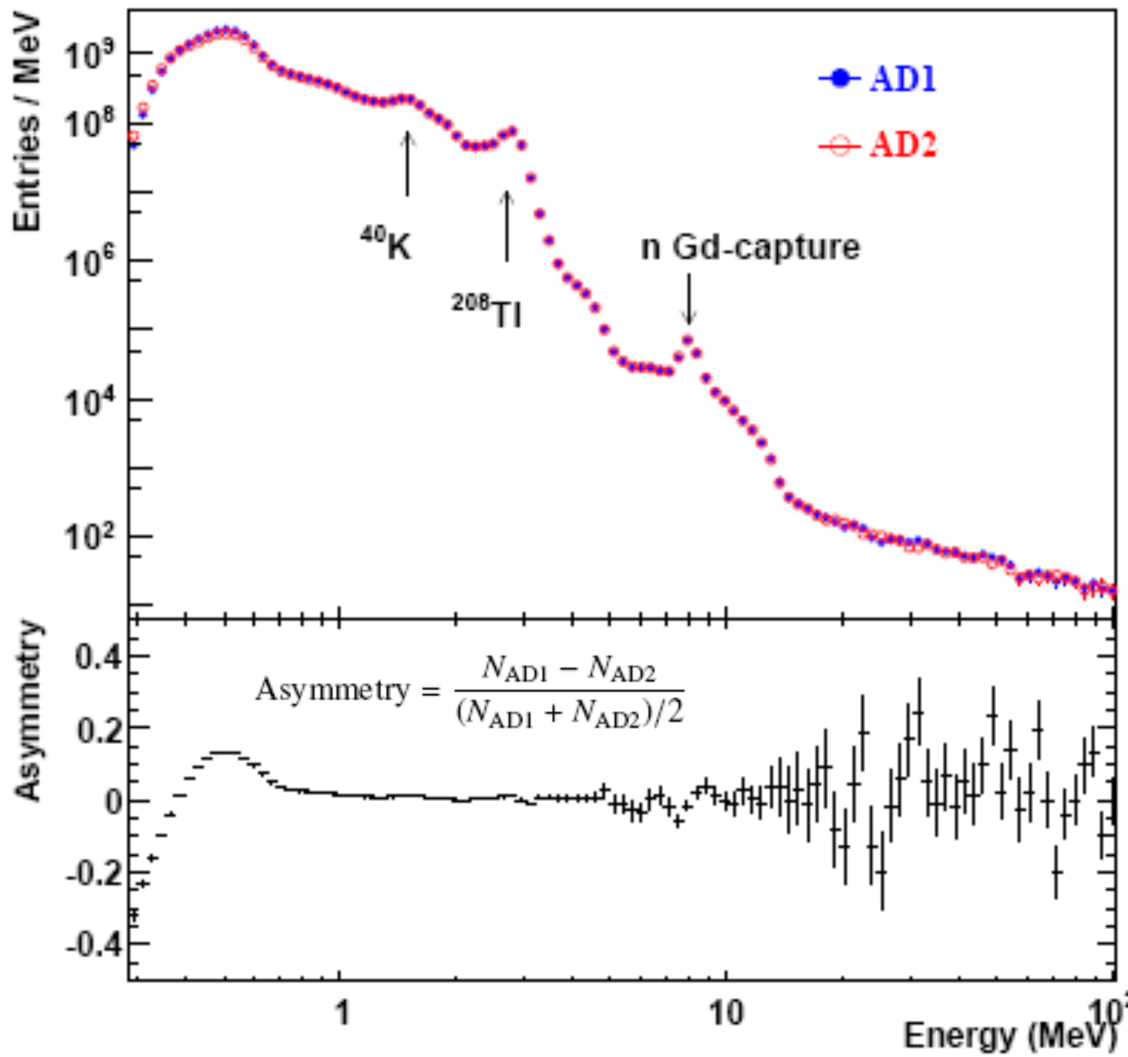
Inefficiency to neutrinos:
0.024% ± 0.006%(stat)
Contamination: < 0.01%

single rate: understood

- design
  - ~50 Hz above 1 MeV
- data
  - ~60 Hz above 0.7 MeV
  - ~40 Hz above 1 MeV

- from sample purity and MC simulation, each of the following component contributes to singles
  - ~ 5 Hz from SSV
  - ~ 10 Hz from LS
  - ~ 25 Hz from PMT
  - ~ 5 Hz from rock

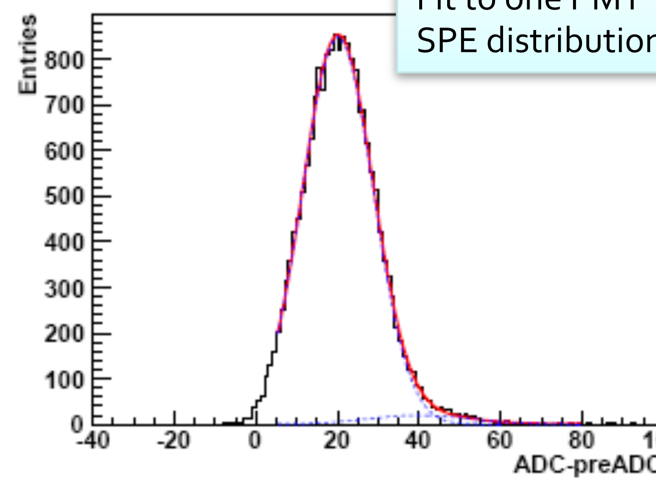
- All numbers are consistent



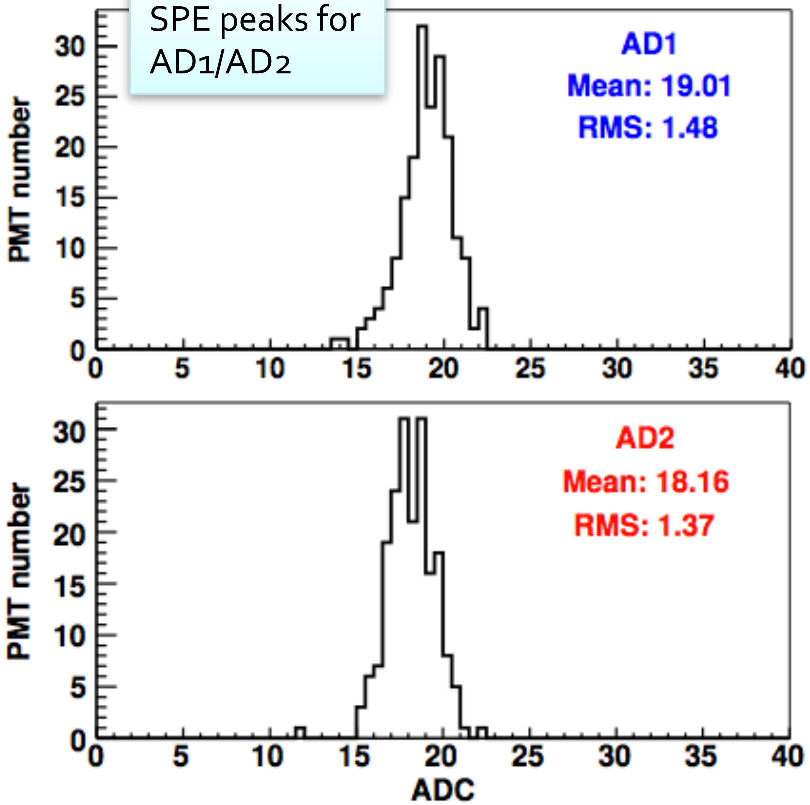
PMT calibration

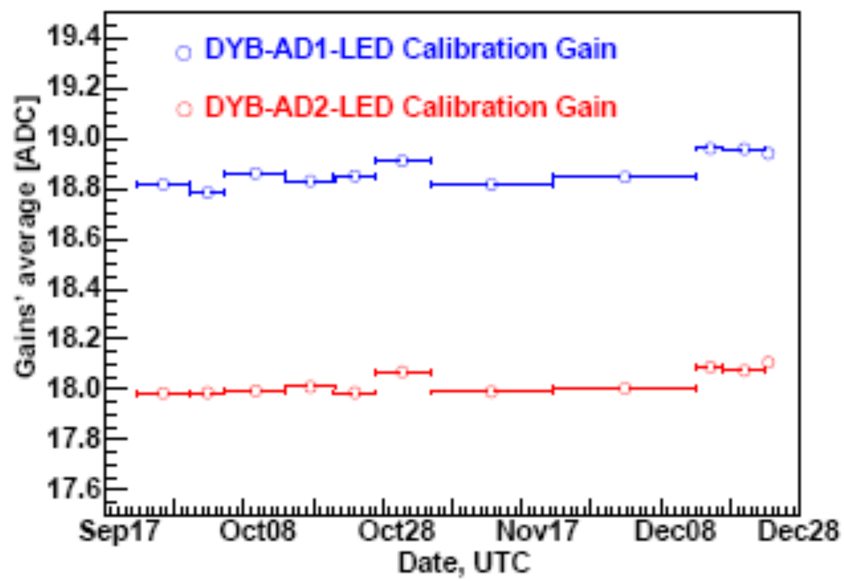
- PMT gains from low-intensity LED:
  - PMT HV is set for a gain of 1×10^7
  - gain stability depends on environment such as temperature
  - all three halls in all time are kept in a temperature $\pm 1\,^{o}C$

Fit to one PMT SPE distribution



SPE peaks for AD1/AD2

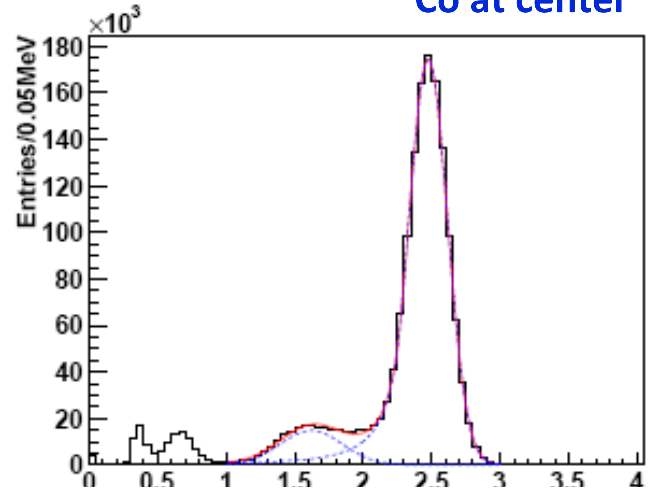


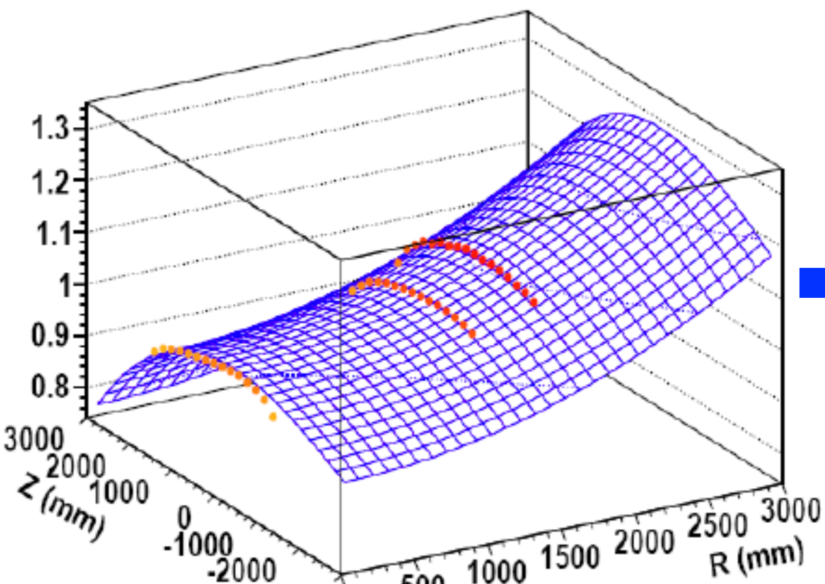


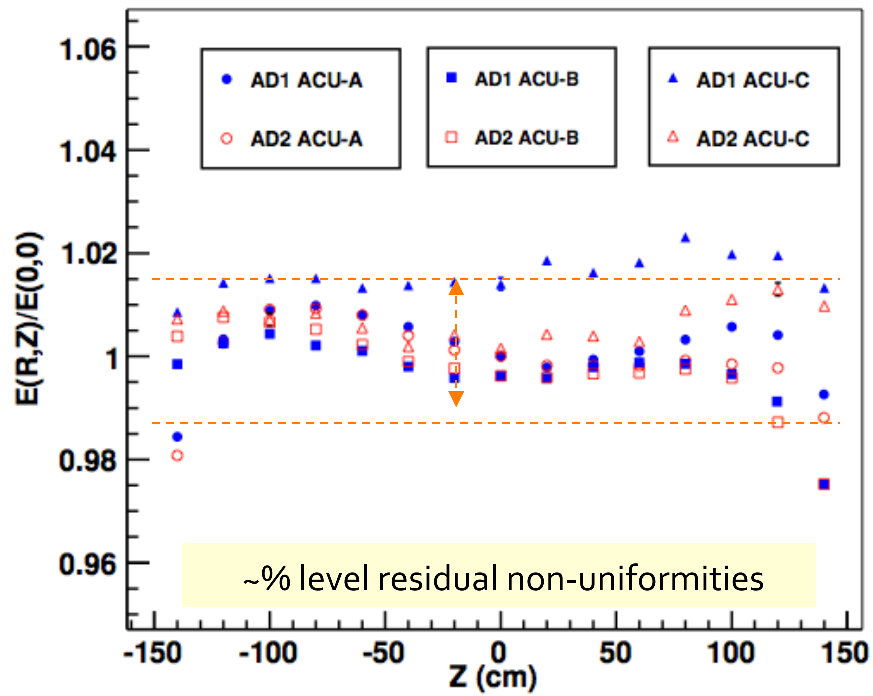
energy calibration

- PMT gain calibration ➔ No. of PEs in an AD
- ^{60}Co at the center ➔ raw energies,
  - time dependence corrected
  - difference for different ADs
- ^{60}Co at different R & Z to obtain the correction function: f(R, Z) = f1(R) * f2(Z)
  - space dependence corrected
  - same for all the ADs

^{60}Co at center

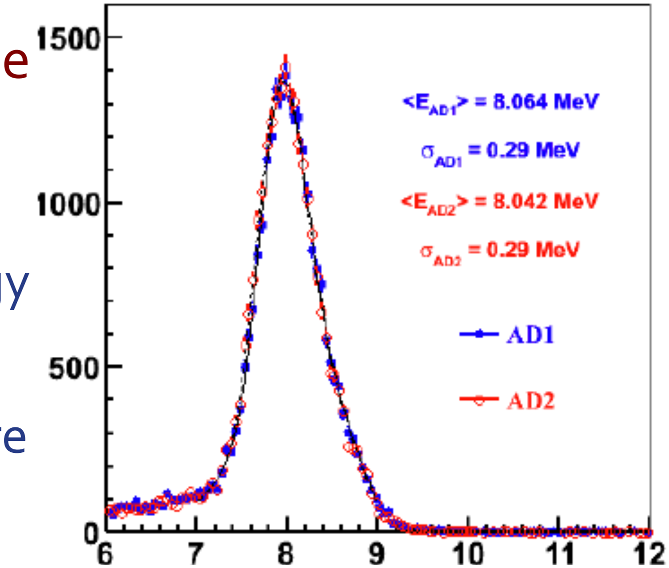


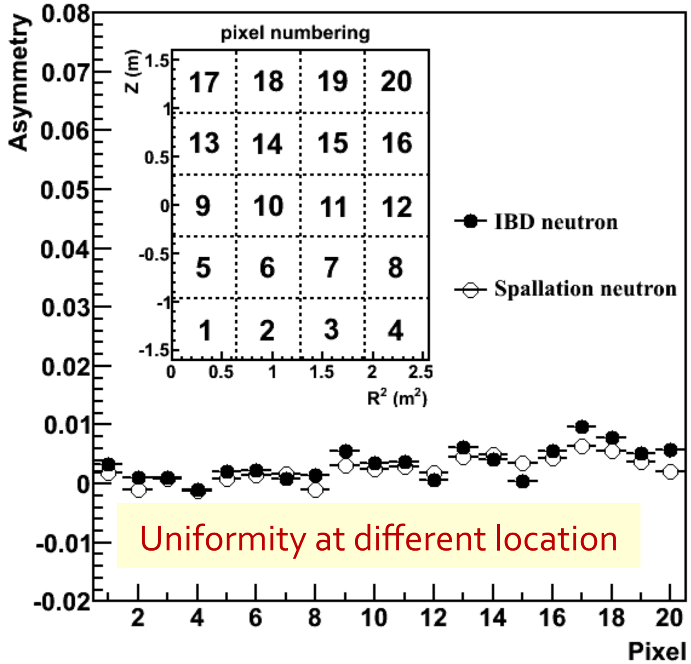


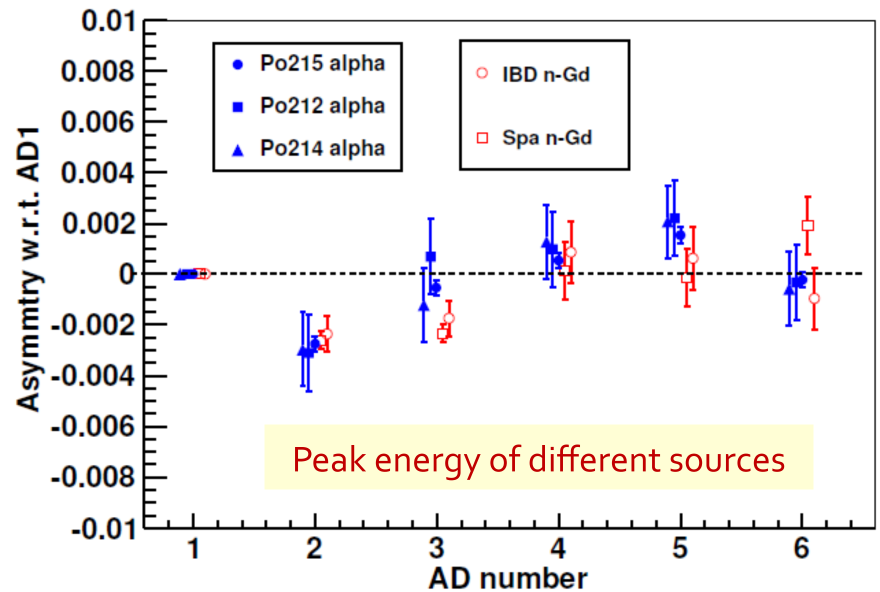


energy calibration (cont'd)

- 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%



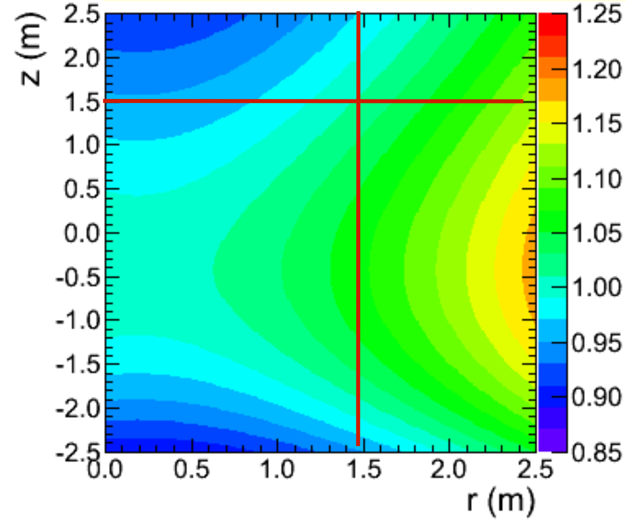




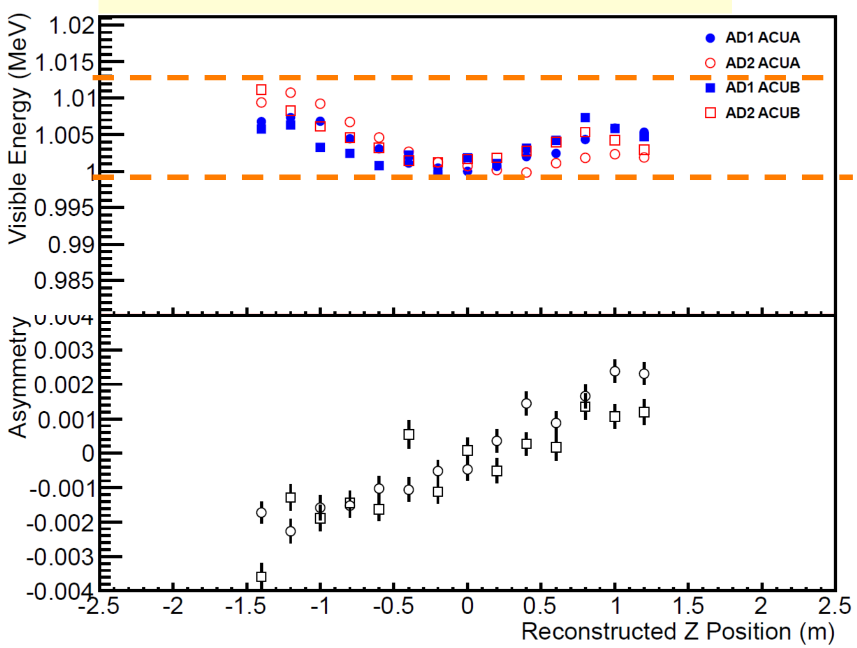
an alternative method

- using spallation neutrons in each space grid to calibrate the energy response
- neutrons from neutrinos can then be reconstructed
- consistent with methods within 0.5%

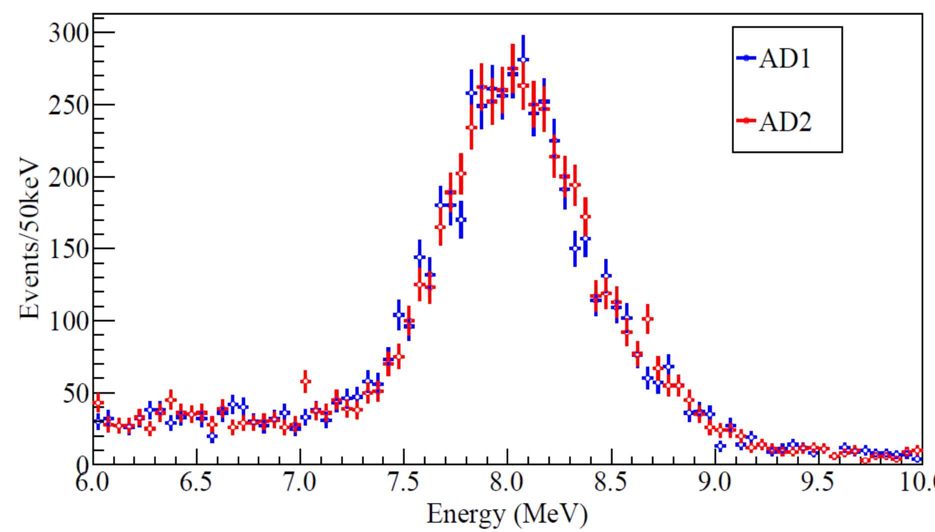
Uniformity of energy response



Residual non-uniformities

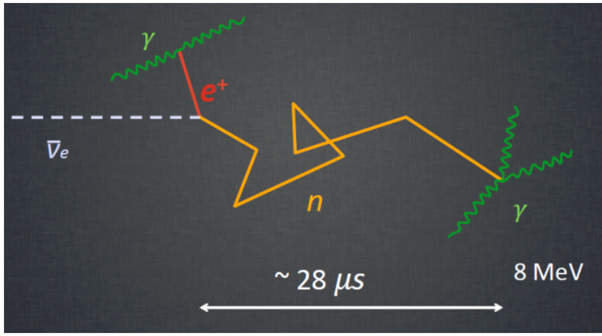


Energy of spallation neutron



event signatures & backgrounds

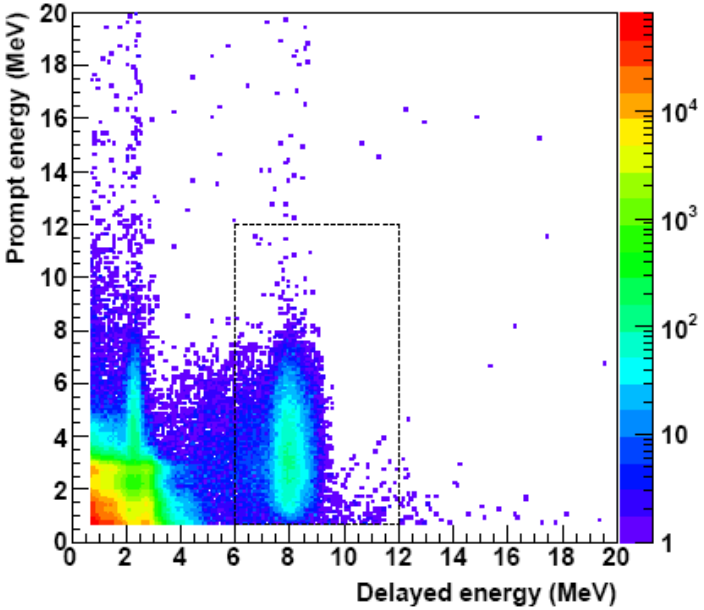
- signature: $\bar{\nu}_e + p \rightarrow e^+ + n$
  - prompt: e^+, 1-10 MeV,
  - delayed: n, 2.2 MeV@H, 8 MeV @ Gd
  - capture time: 28 μs in 0.1% Gd-LS



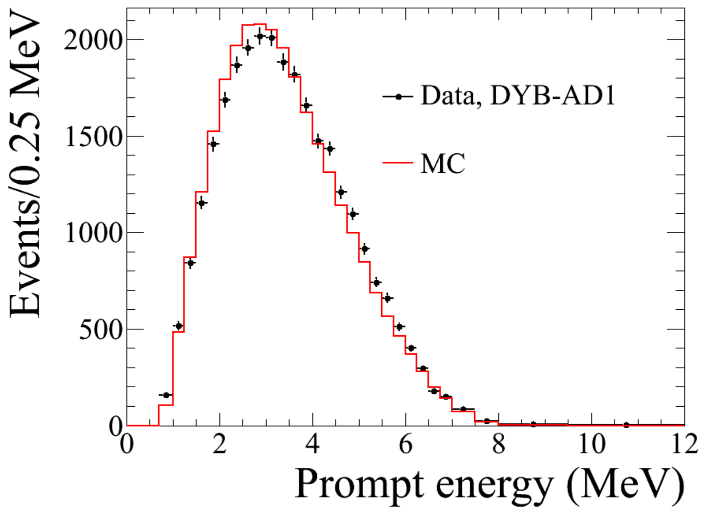
- backgrounds
  - uncorrelated: accidental coincidence of γγ, γn or nn
    - γ from U/Th/K/Rn/Co… in LS, SS, PMT, Rock, …
    - n from α-n, μ-capture, μ-spallation in LS, water & rock
  - correlated
    - fast neutrons: n scattering (prompt) + n capture (delayed)
    - ^{8}He/^{9}Li: β decay (prompt) + n capture (delayed)
    - Am-C source: γ rays (prompt) + n capture (delayed)
    - α-n: $^{13}C(\alpha,n)^{16}O$

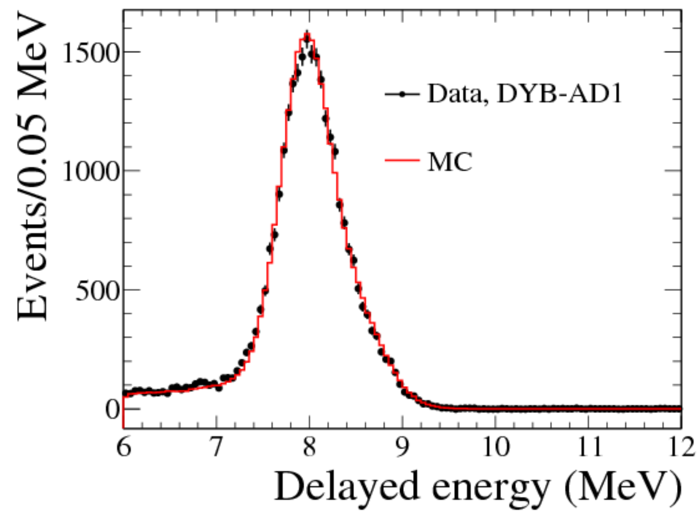
neutrino event selection

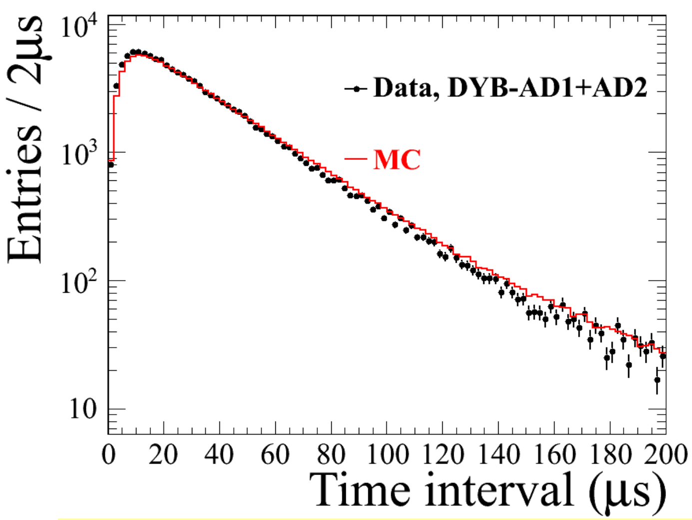
- Pre-selection
  - Reject Flashers
  - Reject Triggers within (-2 μs, 200 μs) to a tagged water pool muon
- Neutrino event selection
  - Multiplicity cut
    - Prompt-delayed pairs within a time interval of 200 μs
    - No triggers (E > 0.7MeV) before the prompt signal and after the delayed signal by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



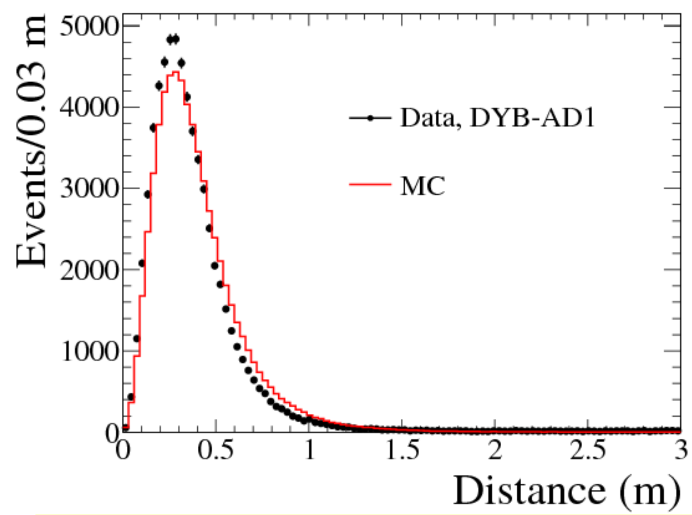
good agreement with MC





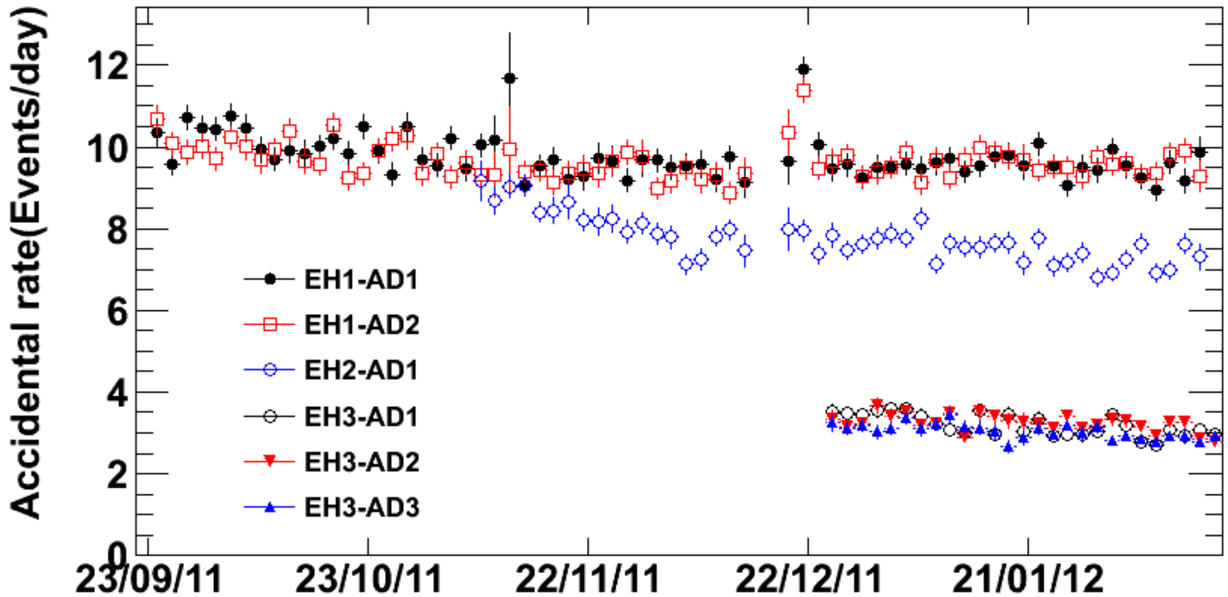


Time between prompt-delayed



Distance between prompt-delayed

accidental backgrounds

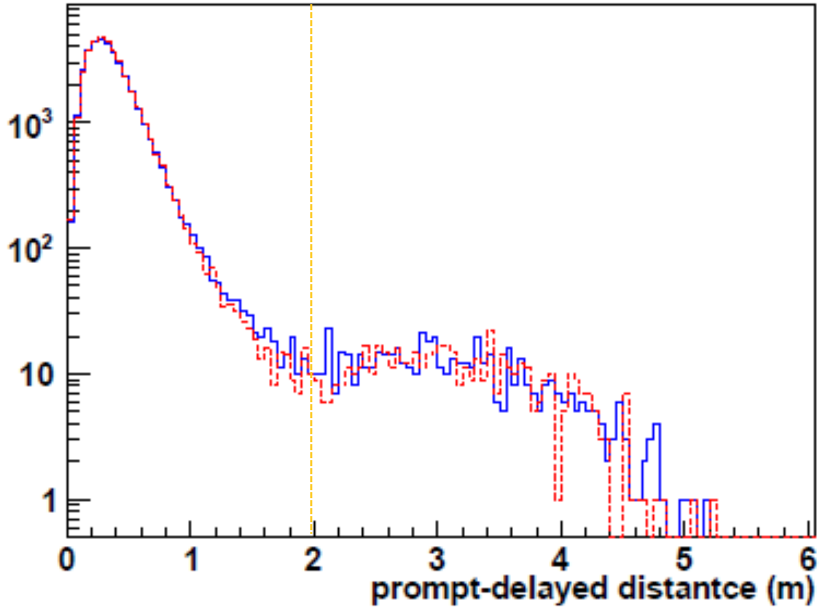


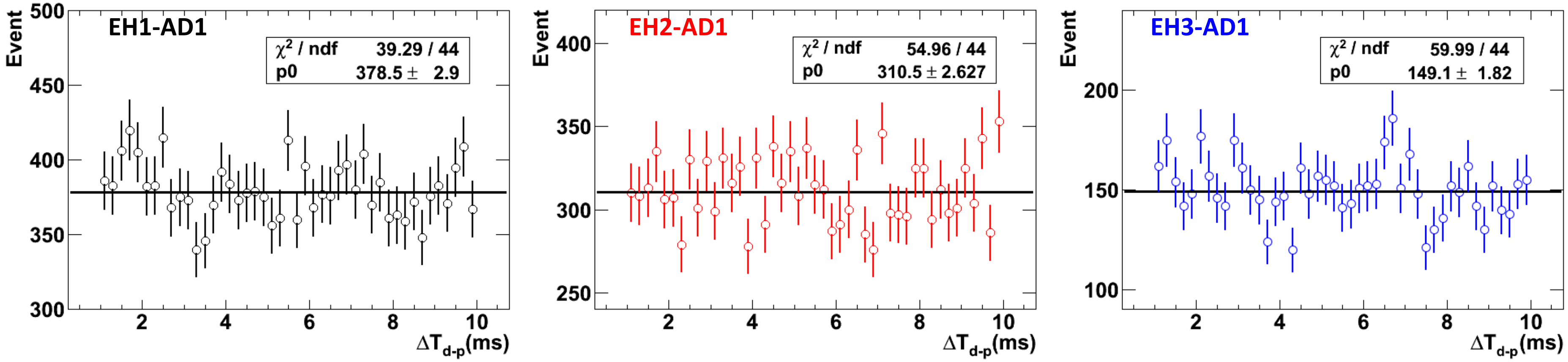
$$N_{\text{accBkg}} = \sum_i N^i_{\text{n-like singles}} \bullet \left(1 - e^{-R^i_{e^+\text{-like triggers}} \bullet 200\,\mu s}\right) \pm \frac{N_{\text{accBkg}}}{\sqrt{\sum_i N^i_{\text{n-like singles}}}}$$

	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%

…cross check: outside the space and time window

- prompt-delayed distance distribution. Check the fraction of prompt-delayed pair with distance > 2 m
- off-window coincidence ➔ 'measure' the accidental background
- results in agreement within 1%.

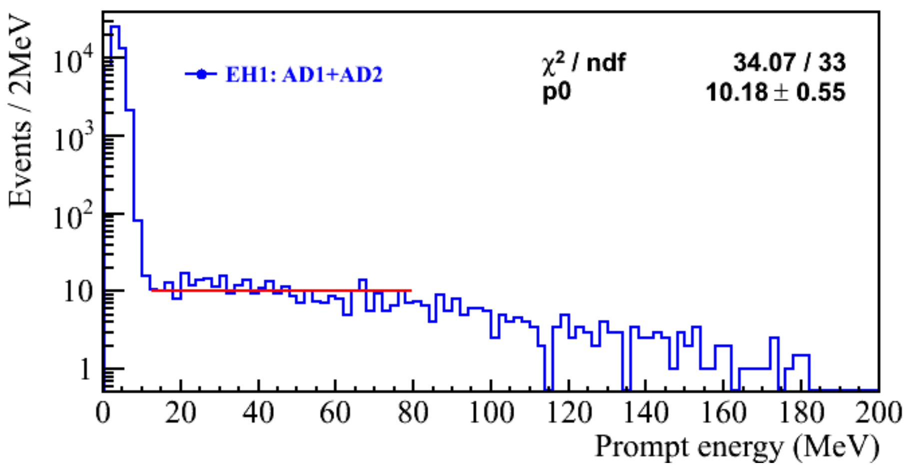


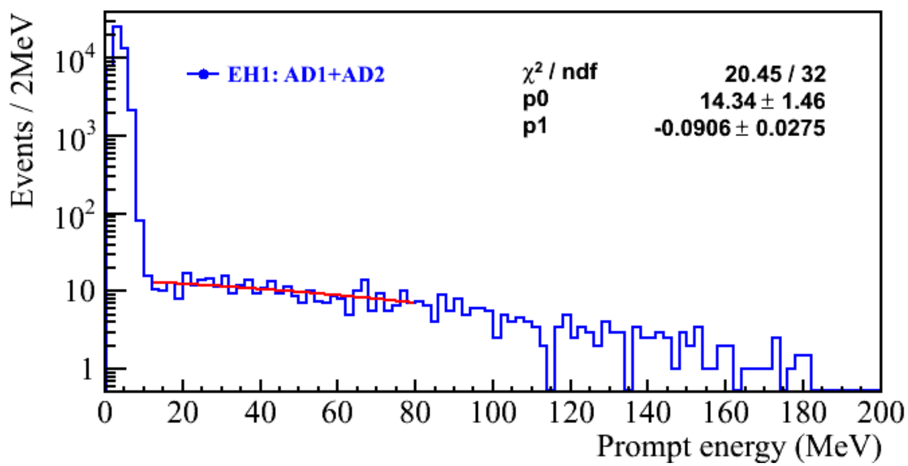


Uncertainty: < 1%

fast neutrons

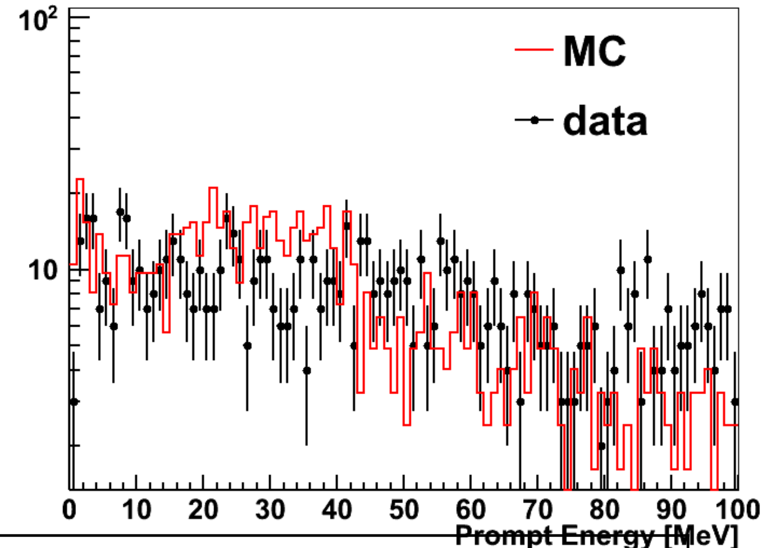
- look at the prompt energy spectrum above 12 MeV, to estimate backgrounds in the region of [0.7 MeV, 12 MeV]:
  - a fit to the spectrum in the region of [12 MeV, 80 MeV] ➔ extrapolate to [0.7 MeV, 12 MeV]
  - difference of the fitting function, 0th-order or 1st-order polynomial, gives systematic uncertainties





...cross check: sum up all sources

- 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

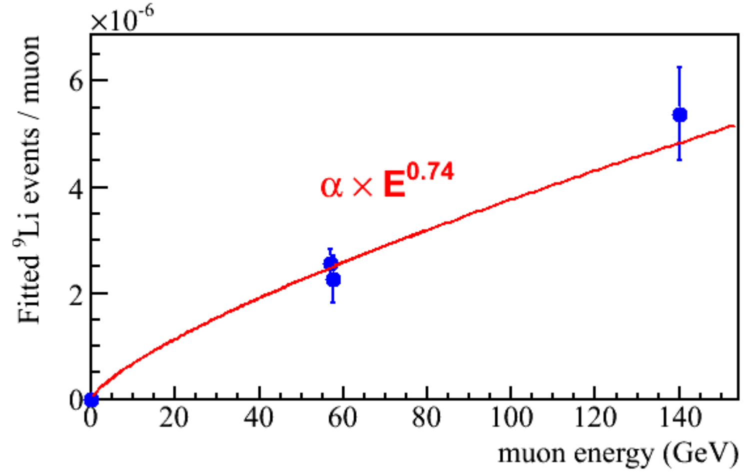
Results are consistent

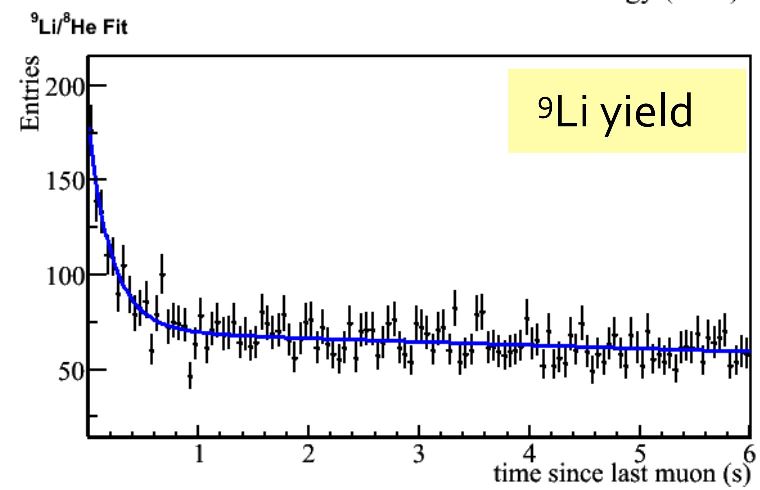
backgrounds: $^8He/^9Li$

- Cosmic μ produced $^8He/^9Li$ in LS
  - β-decay + neutron emitter
  - $\tau(^8He/^9Li)$ = 171.7 ms/257.2 ms
  - $^8He/^9Li$, Br(n) = 12% / 48%, ^9Li 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 ^9Li
  - results w/ and w/o the reduction is studied





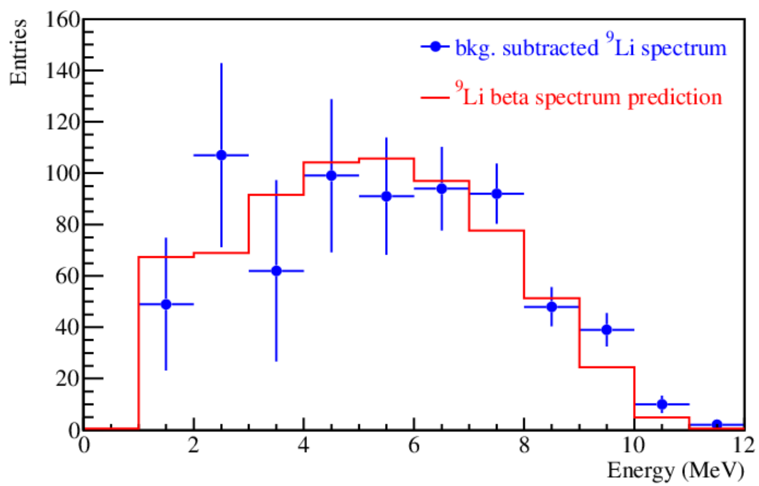
Error follows

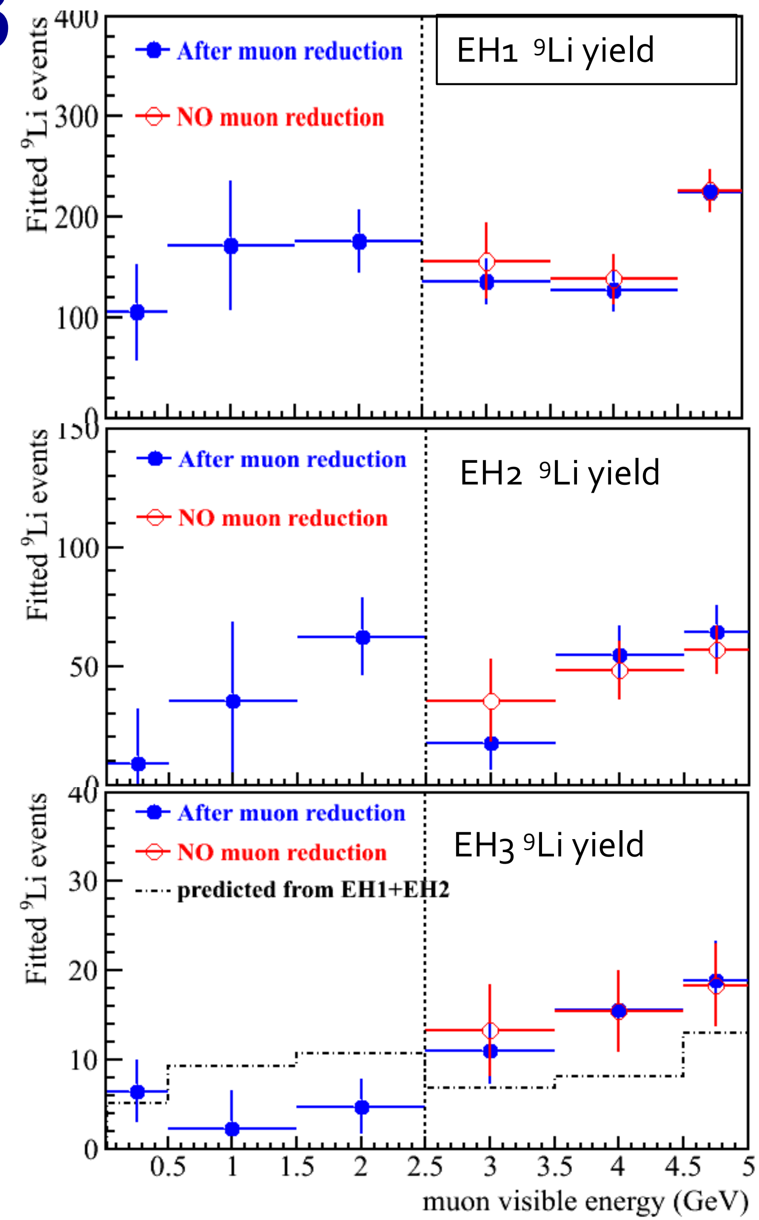
$$\sigma_b = \frac{1}{N} \cdot \sqrt{(1+\tau R_\mu)^2 - 1}$$

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 allows us to further constraint ^{9}Li yield in EH3
- cross check: Energy spectrum consistent with expectation





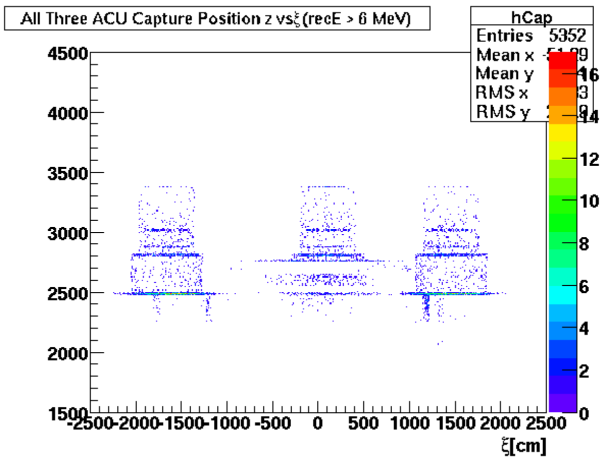
^{241}Am-^{13}C backgrounds

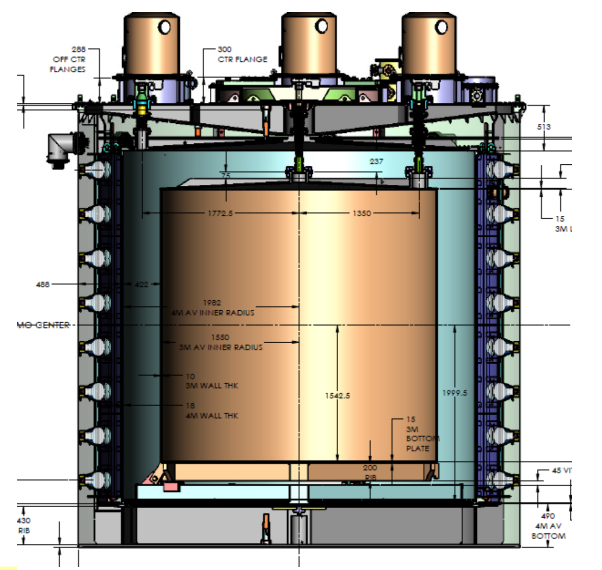
- Uncorrelated backgrounds:

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

  - $R_{n\text{-like}}$ 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 + n-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

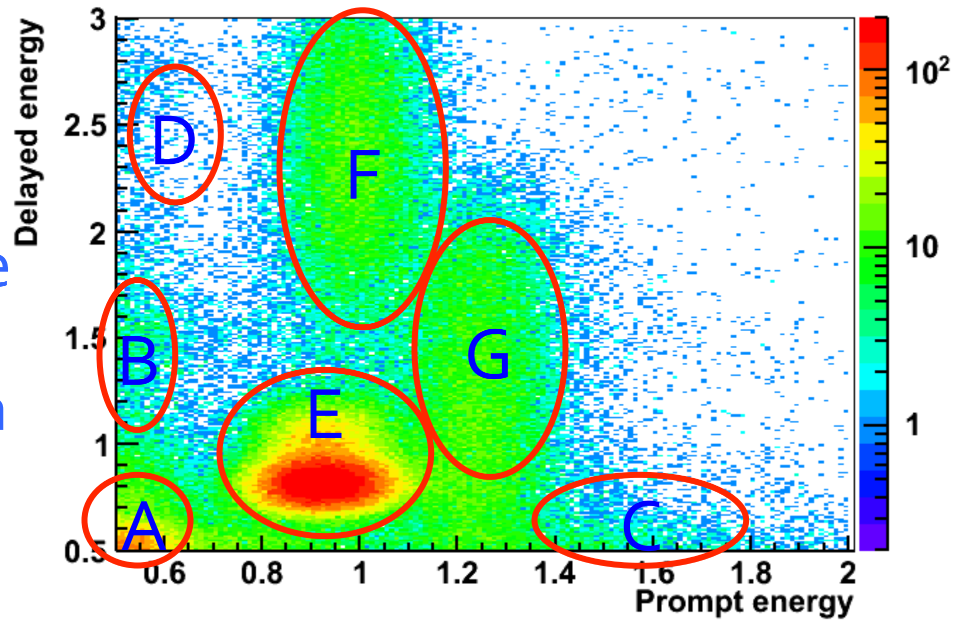




Uncertainty: 100%

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

- identify α sources:
  ^{238}U, ^{232}Th, ^{227}Ac, ^{210}Po …
- determine α rate from cascade decays
- calculate the background from α rate and (α, n) cross sections



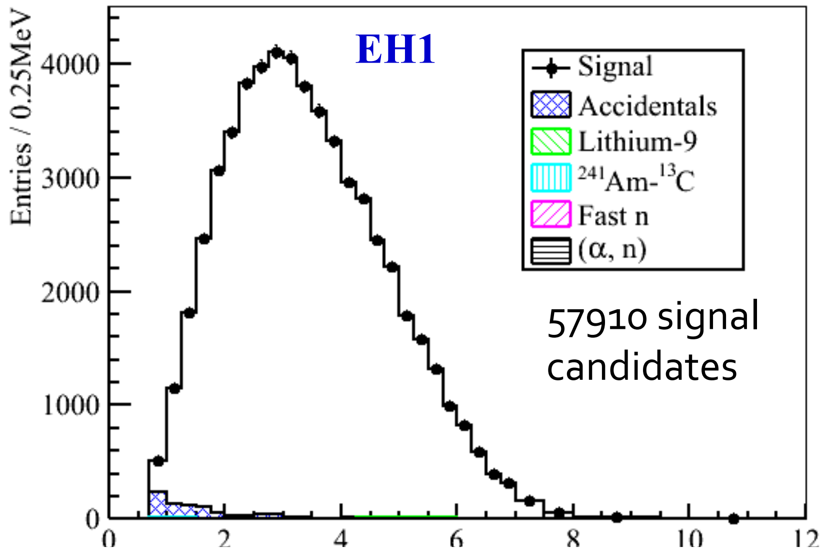
Uncertainty: 50%

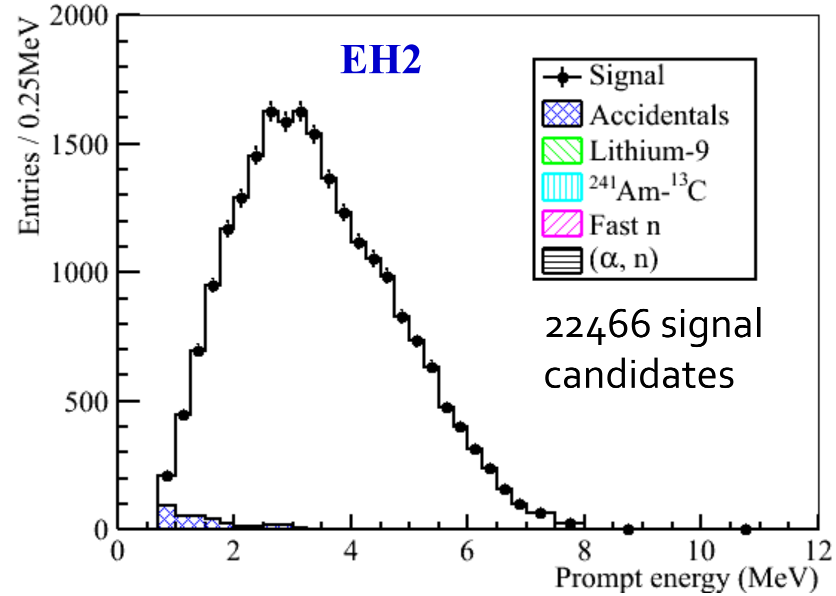
	Components	Total α rate	BG rate
Region A	Acc. Coincidence of ^{210}Po & ^{210}Po	^{210}Po: 10Hz at EH1 8Hz at EH2 6Hz at EH3	0.02/day at EH1 0.015/day at EH2 0.01/day at EH3
Region B	Acc. Coincidence of ^{210}Po & ^{40}K		
Region C	Acc. Coincidence of ^{40}K & ^{210}Po		
Region D	Acc. Coincidence of ^{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

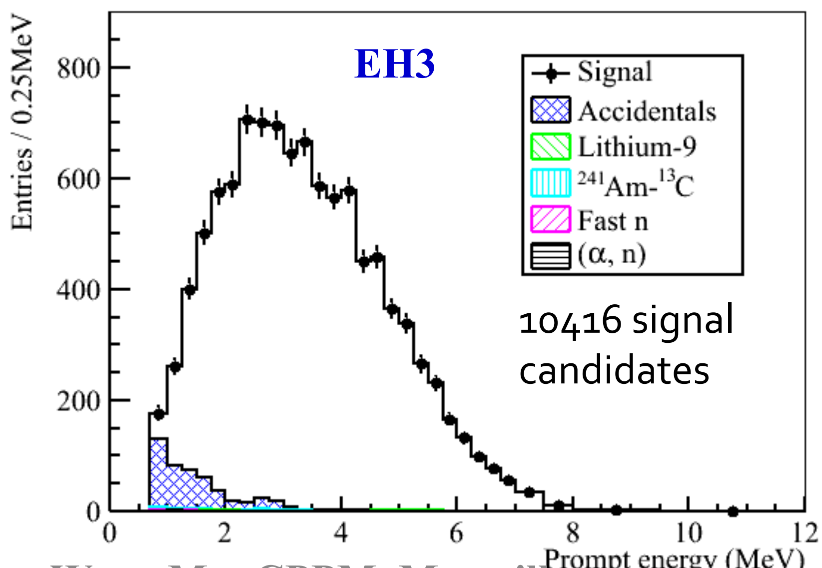
signals & backgrounds

	AD1	AD2	AD3	AD4	AD5	AD6
neutrino candidate	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
$^8He/^9Li$ (/day)	3.1±1.6		1.8±1.1		0.16±0.11	
Am-C corr. (/day)	0.2±0.2					
$^{13}C(\alpha, n)^{16}O$ (/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



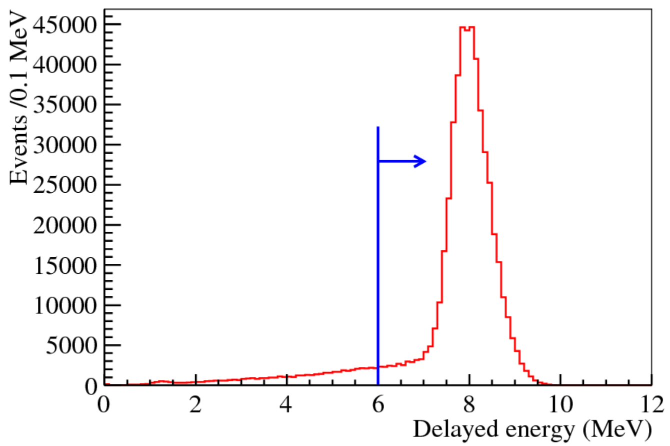




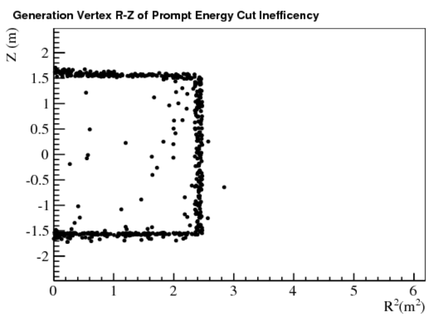
	B/S @EH1/2	B/S @EH3
Accidentals	~1.4%	~4.5%
Fast neutrons	~0.1%	~0.06%
$^{8}He/^{9}Li$	~0.4%	~0.2%
Am-C	~0.03%	~0.3%
α-n	~0.01%	~0.04%
Sum	1.5%	4.7%

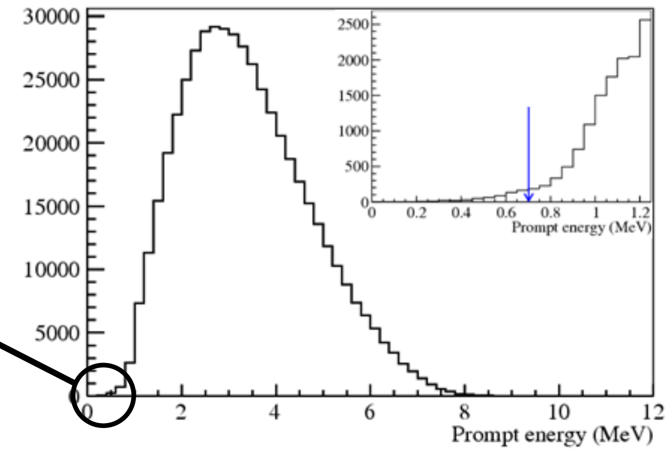
θ13 energy cuts efficiency and systematics

- 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

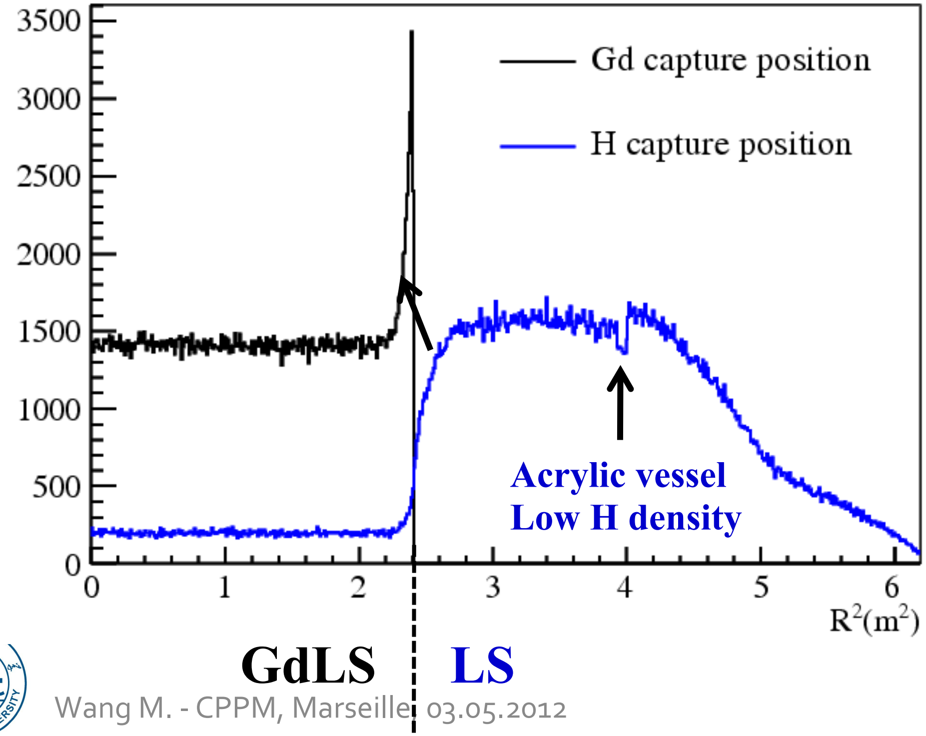




	Eff.	Corr.	Un-corr.
Delayed energy cut	90.9%	0.6%	0.12%
Prompt energy cut	99.88%	0.10%	0.01%

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

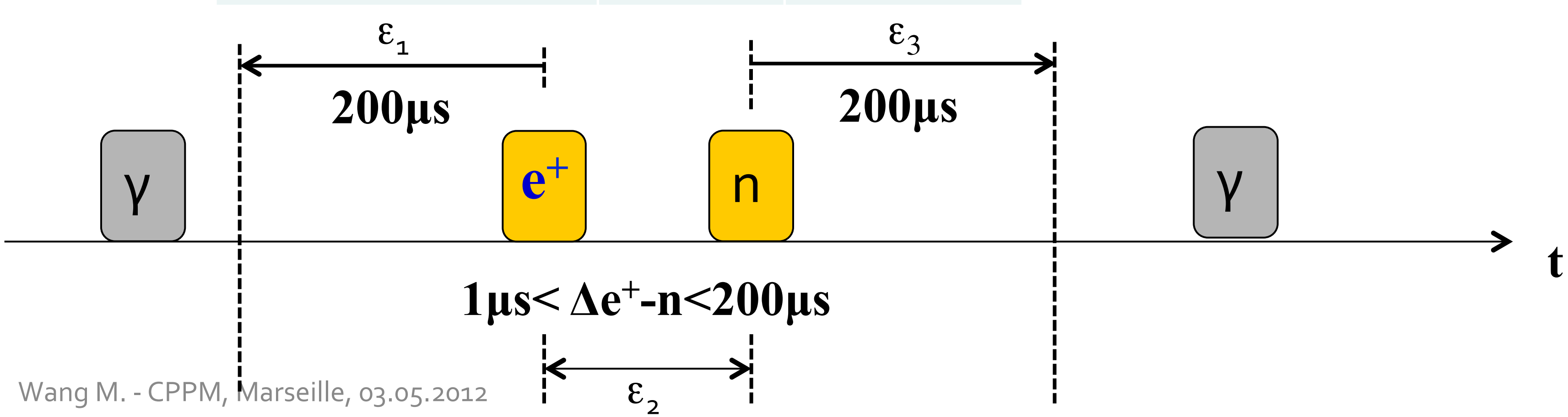
- Muon veto
  - Total veto time is the sum of all the veto time windows
  - Temporal overlap is taken into account
- Multiplicity cut
  - Efficiency = $\varepsilon_1 \times \varepsilon_2 \times \varepsilon_3$
- Total efficiency
  - Uncertainty coming mainly from the average neutron capture time. it is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

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

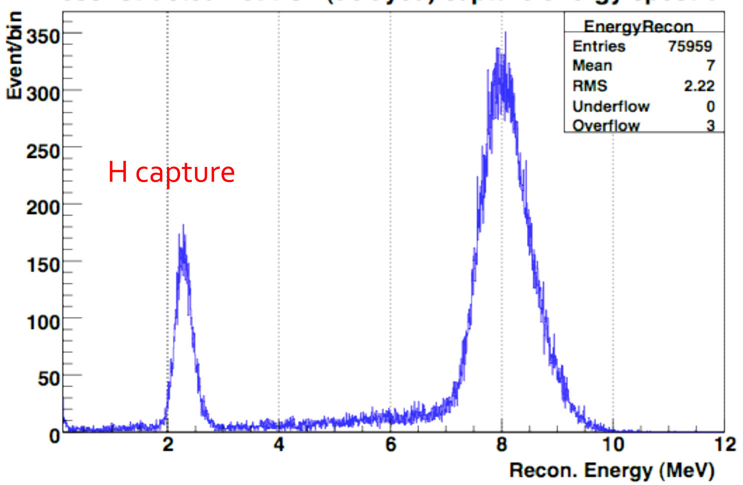
Prompt-delayed pairs within 200 μs
No triggers before the prompt and after the delayed signal by 200 μs

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

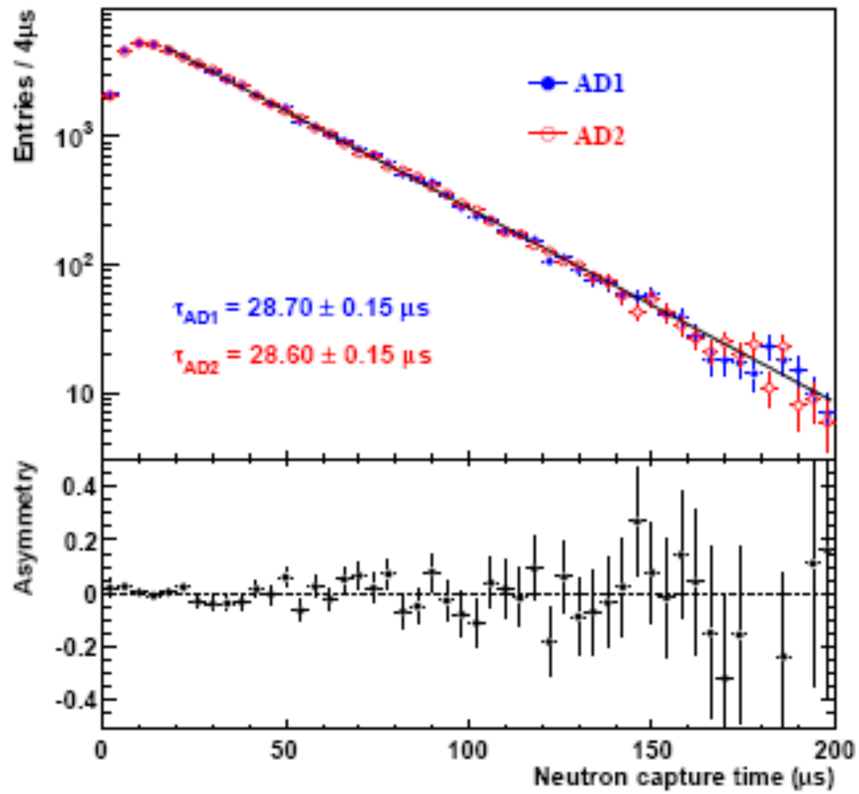
Efficiency is AD dependent



Gd capture fraction: H/Gd and systematics



Neutron capture time from Am-C

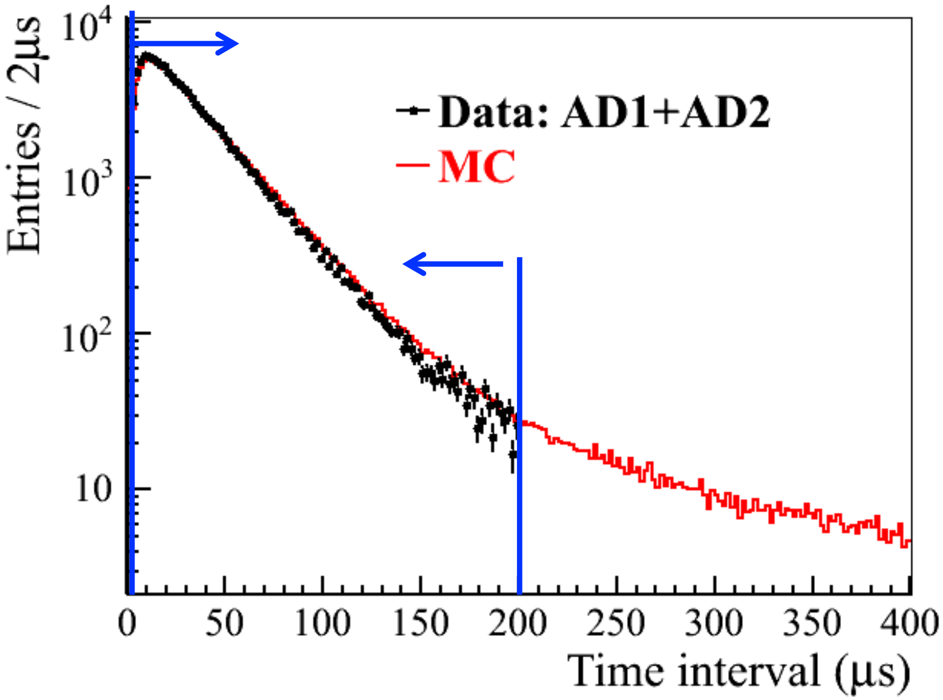


- Uncertainty is large if takes simply the ratio of area
- Relative Gd content variation 0.1%
  → evaluated from neutron capture time
- Geometry effect on spill-in/out 0.02%
  → relative differences in acrylic thickness, acrylic density and liquid density are modeled in MC

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

time correlation cut: 1μs < Δt_{e+-n} < 200μs

- 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%

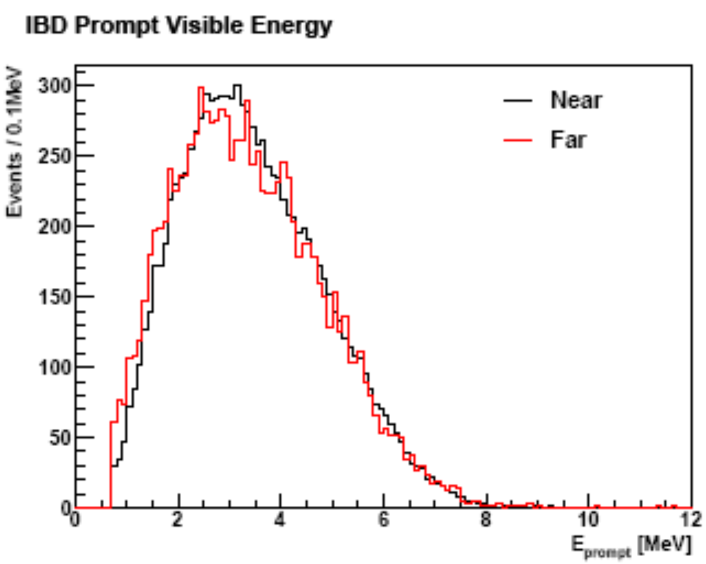
livetime

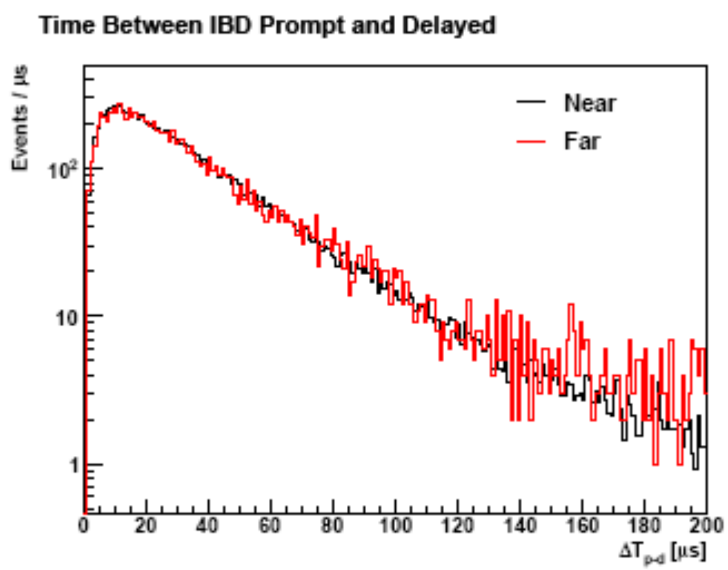
- Synchronization of 3 Halls
  - Divide data taking time into one-hour slices
  - Discard data in a whole slice if not all 3 halls are running
- Uncertainty
  - Comes from the case when electronics buffer is full.
  - This estimated to be less than 0.0025%, by either blocked trigger ratio or accumulating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

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

alternative analysis

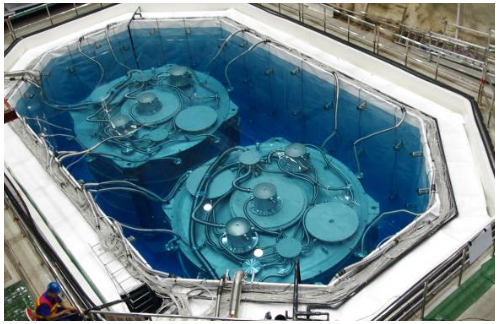
- Using an alternative energy calibration algorithm based on spallation neutron peak
- Different neutrino selection criteria
- Muon cut: 0.4s after an AD shower muon (different shower muon threshold), 1.4ms after an AD muon, 0.6ms after a WP muon
- A different multiplicity cut
- Results: consistent within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

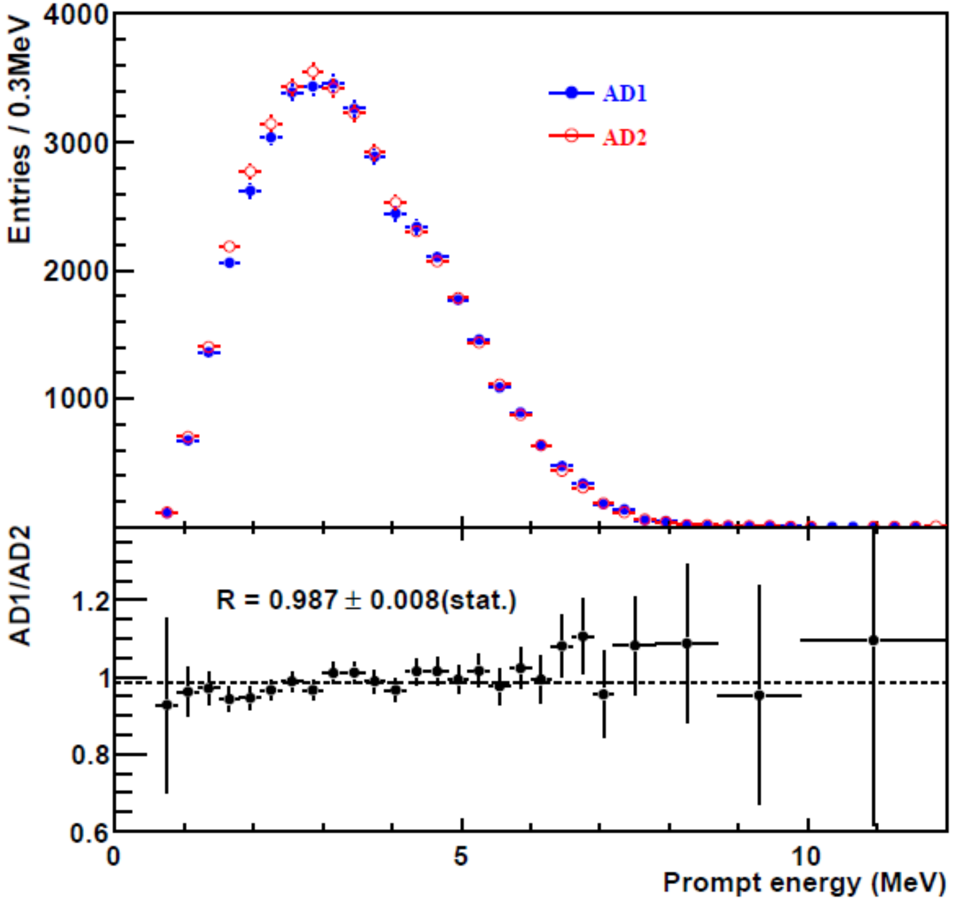




side-by-side comparison

- Expected ratio of neutrino events from AD1 and AD2: 0.981
  - NOT 1 because of difference in target mass, baseline, etc.
- Measured ratio: 0.987 ± 0.008(stat) ± 0.003





This final check shows that systematic errors are under control

predictions

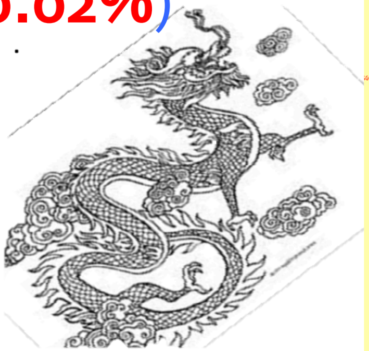
- Baseline
- Target mass
- Reactor neutrino flux

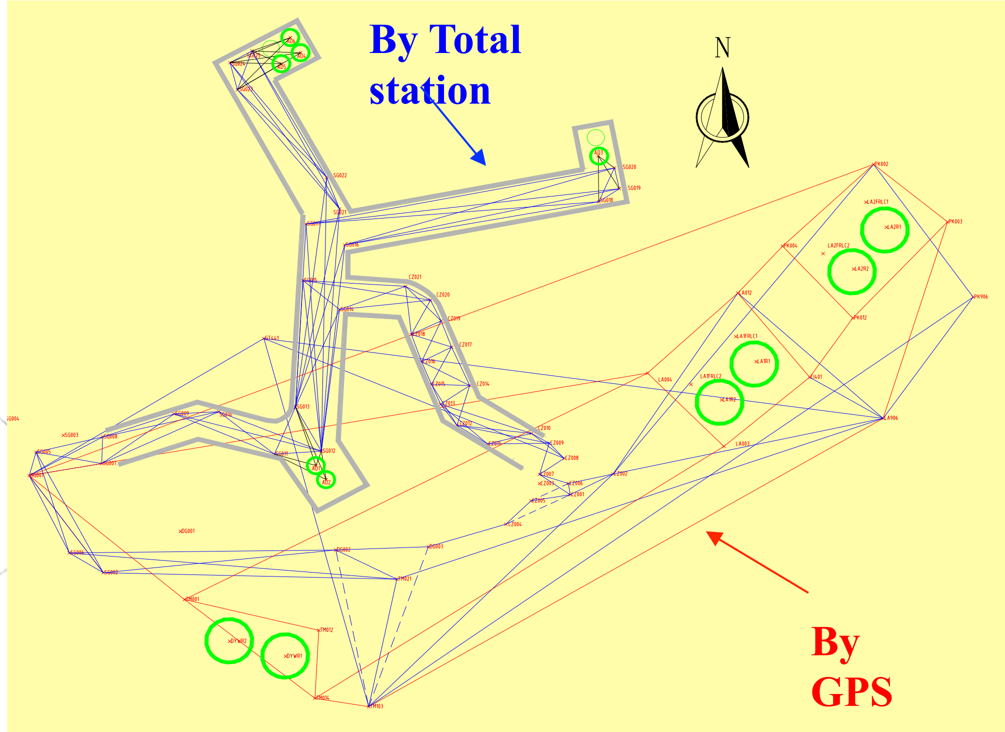
- These three predictions are **blinded** before we fix our analysis cuts and procedures
- They are opened on Feb. 29, 2012
- The physics paper is submitted to PRL on March 7, 2012

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 **35 mm**, corresponding to a negligible reactor flux uncertainty (<**0.02%**)

2012 = year of the dragon

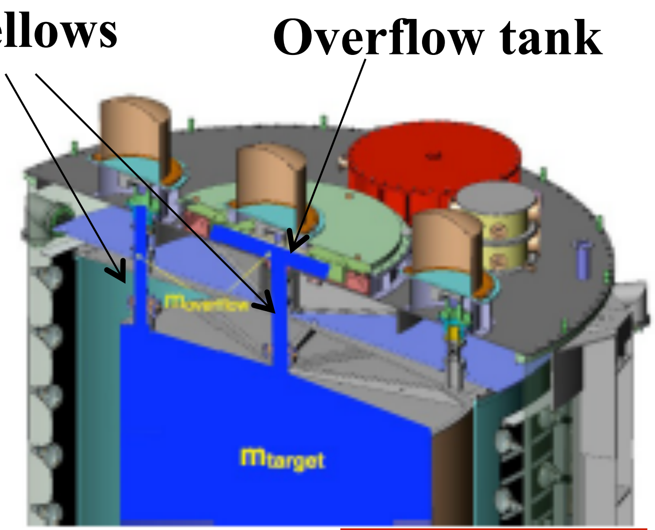


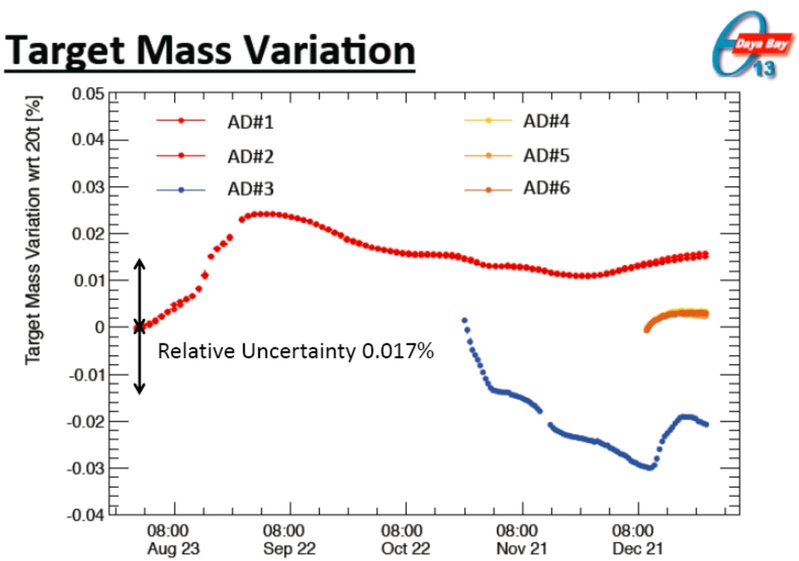


target mass & No. of protons

- 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_{bellow} are determined by geometry
- $M_{overflow}$ is monitored by sensors





One batch LAB

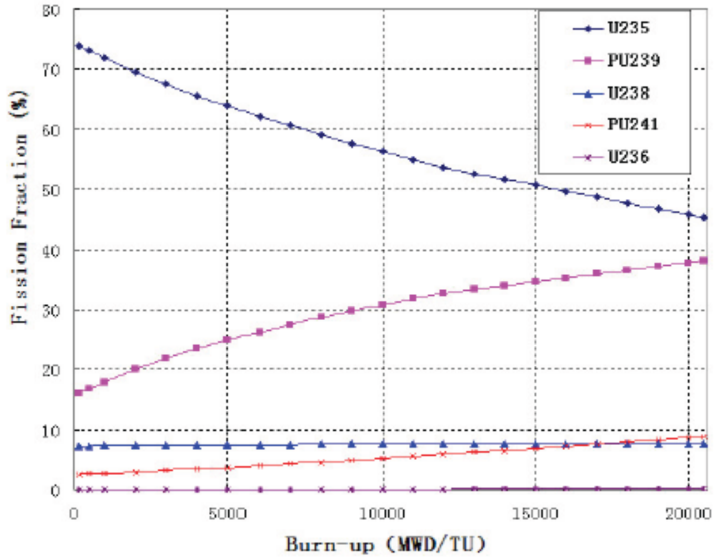
Quantity	Relative	Absolute
Free protons/Kg	neg.	0.47%
density	neg.	0.0002%
Total mass	0.015%	0.015%
Bellows	0.0025%	0.0025
Overflow tank	0.02%	0.02%
Total	0.03%	0.47%

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

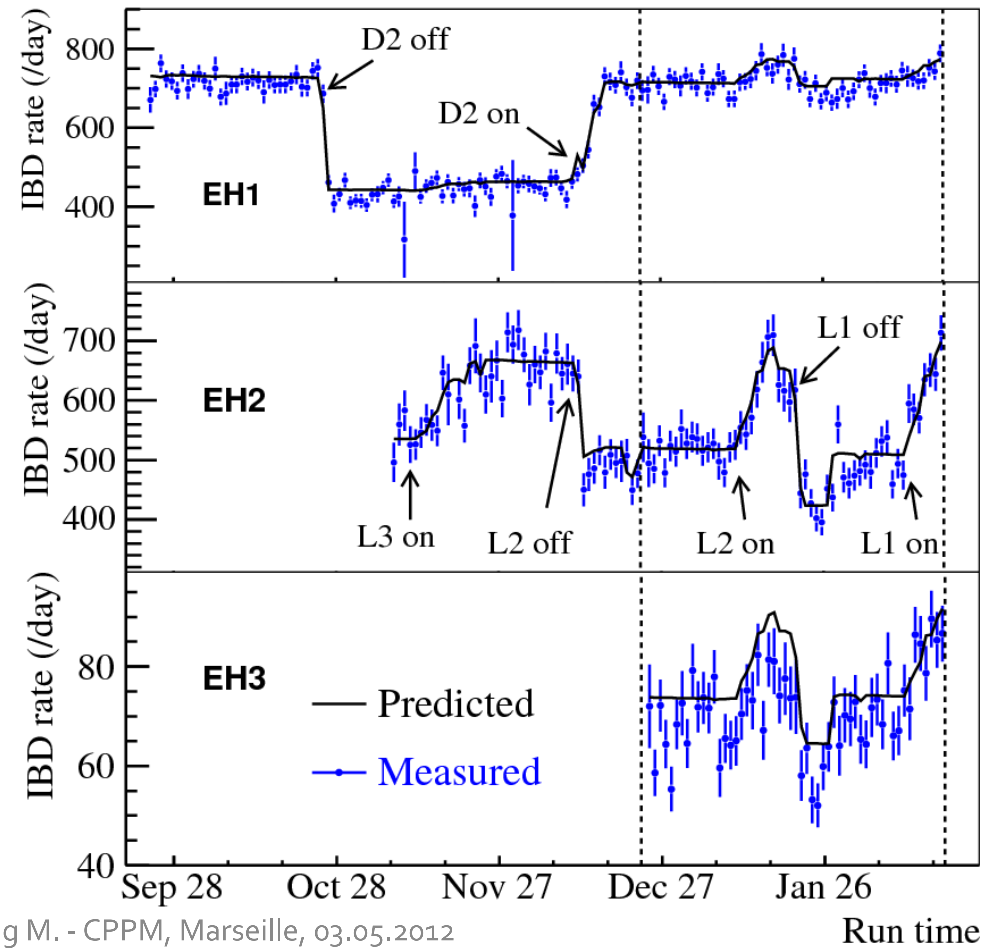
Kopeikin et al, Physics of Atomic Nuclei, Vol. 67, No. 10, 1892 (2004)

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 ➔ 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 & systematics

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%

TDR: (0.18 - 0.38) %

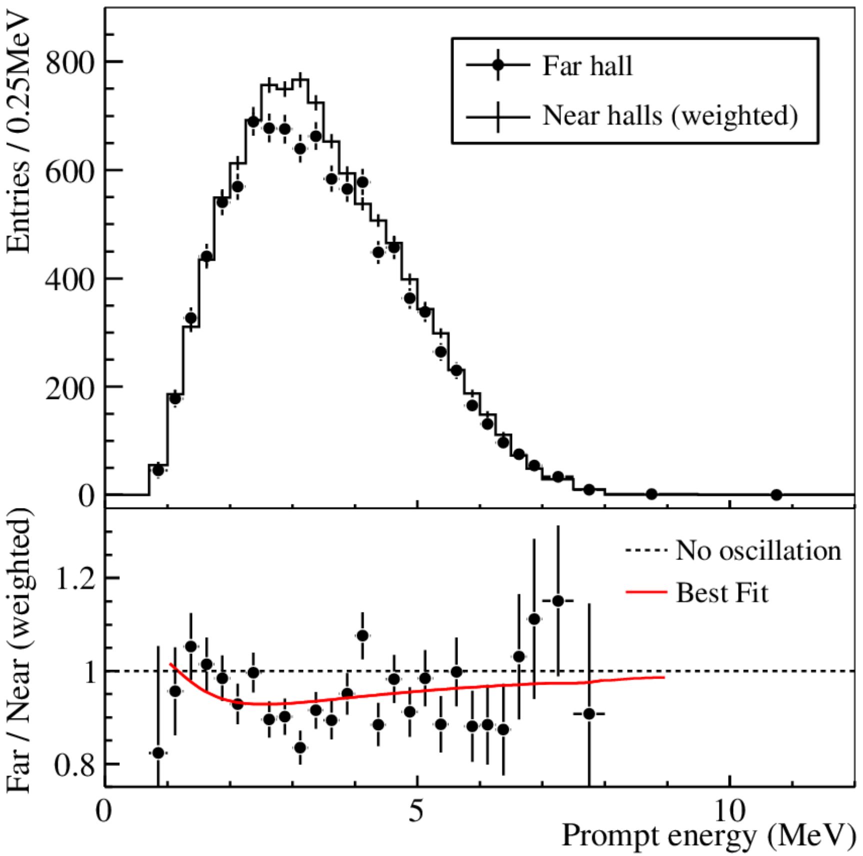
Reactor			
Correlated		Uncorrelated	
Energy/fission	0.2%	Power	0.5%
$\overline{\nu}_e$/fission	3%	Fission fraction	0.6%
		Spent fuel	0.3%
Combined	3%	Combined	0.8%

electron antineutrino 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_n: measured rates after background subtraction and efficiency correction
α_i, β_i: weights determined from baselines and reactor fluxes



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

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

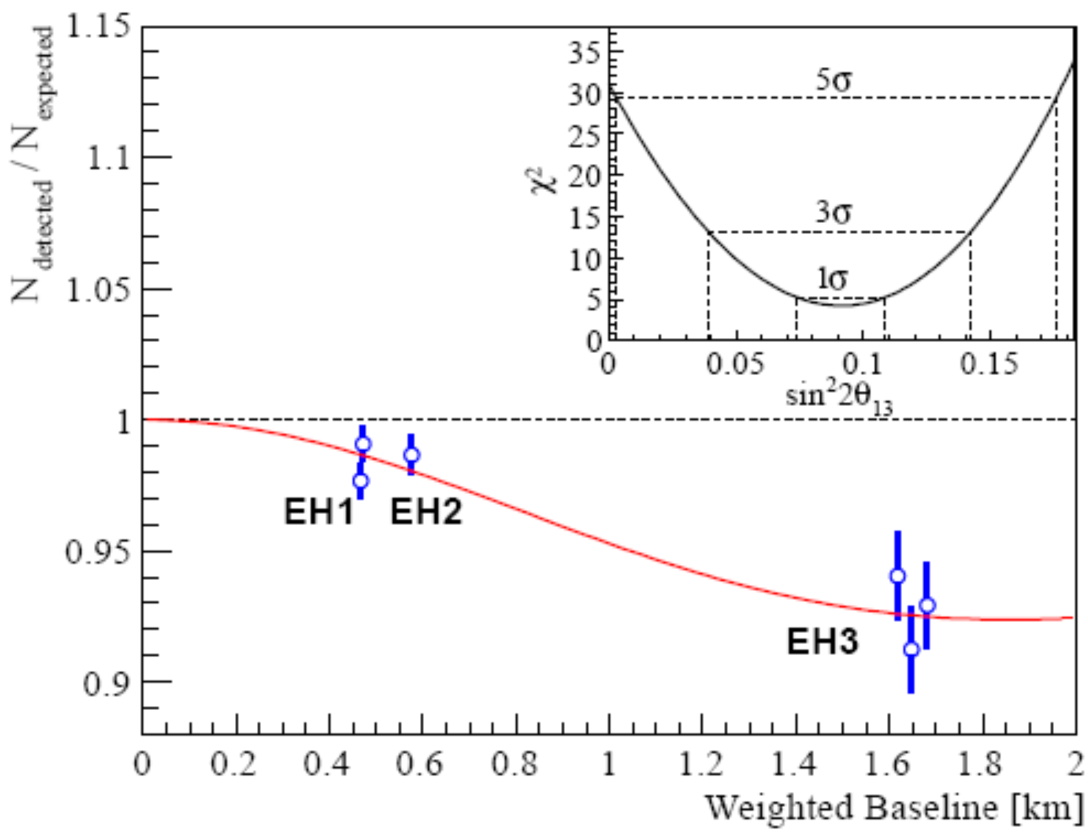
Spectral distortion consistent with oscillation

χ^2 analysis

$$\chi^2 = \min_{\gamma} \sum_{d=1}^{6} \frac{\left[M_d - T_d\left(1 + \sum_r \omega_r^d \epsilon_r + \epsilon + \epsilon_d\right) - B_d\left(1 + \eta_d\right)\right]^2}{M_d}$$

$$+ \sum_r \frac{\epsilon_r^2}{\sigma_r^2} + \sum_{d=1}^{6}\left[\frac{\epsilon_d^2}{\sigma_d^2} + \left(\frac{\eta_d}{\sigma_B^d}\right)^2\right] + \cancel{\frac{\epsilon^2}{\sigma^2}}$$

No constrain on absolute normalization. Fit on the near-far relative measurement.



the results

- Electron antineutrino disappearance is observed at Daya Bay,

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

together with a spectral distortion

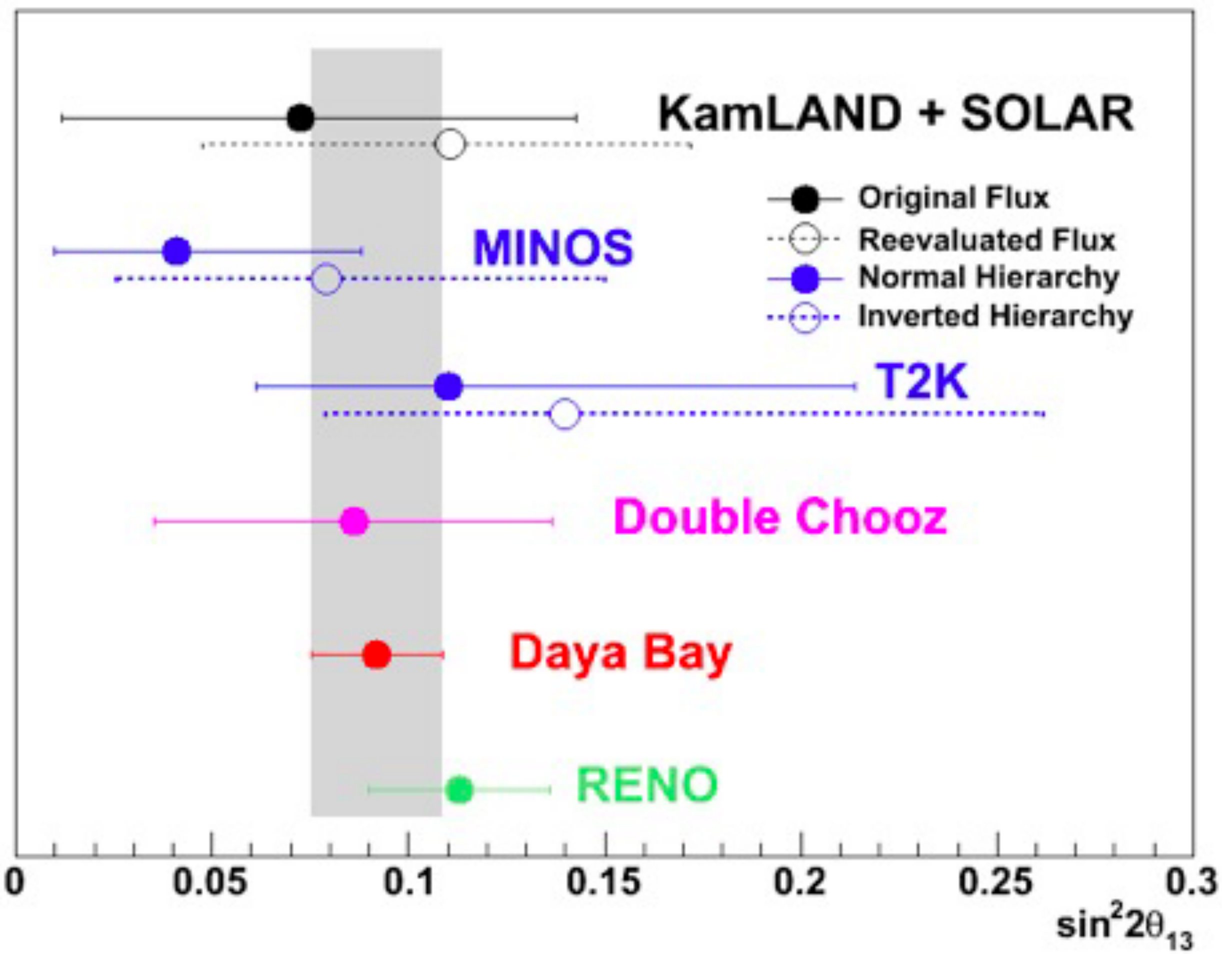
- A new type of neutrino oscillation is thus discovered

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

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

5.2 σ for non-zero θ_{13}

global status



RENO also released their results about one month later, arXiv:1204.0626v2

the future

- Improved analysis including spectrum information in progress.
- Assembly of the final pair of antineutrino detectors to be completed before summer.
- Current data taking will continue until the summer
- Summer activities:
  – Installation of AD7 & AD8
  – Detector calibration
- Re-start data taking after summer

merci

谢谢

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