An Improved Measurement of Electron Antineutrino Disappearance at Daya Bay

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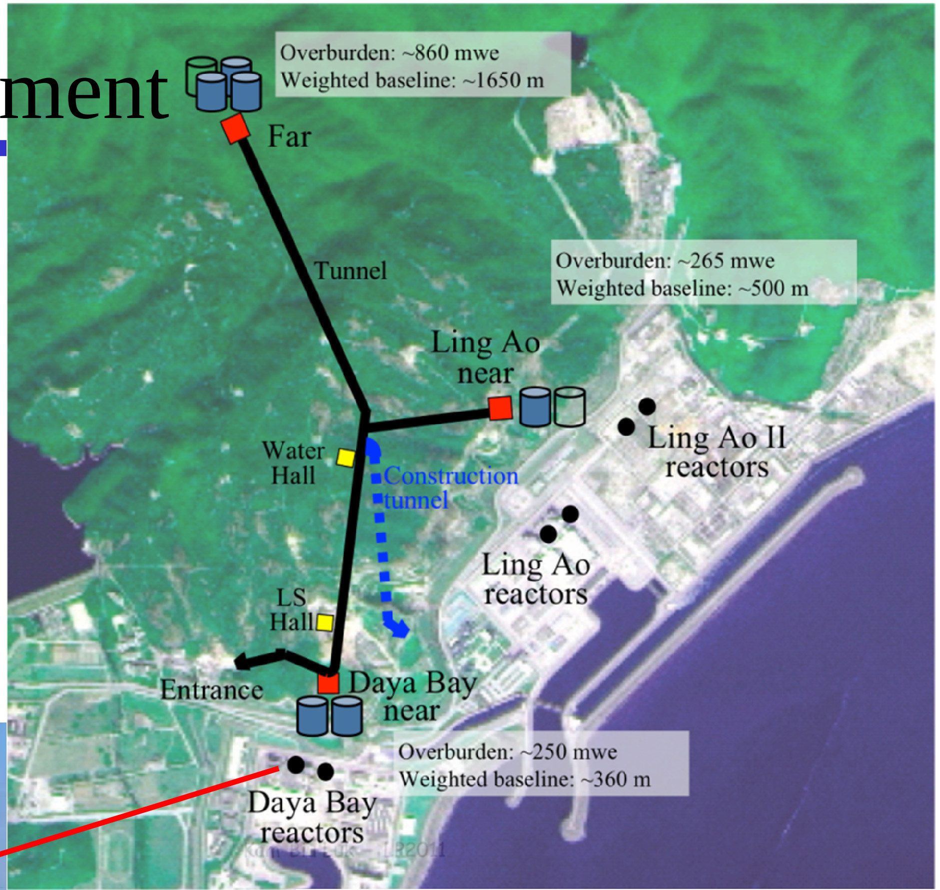
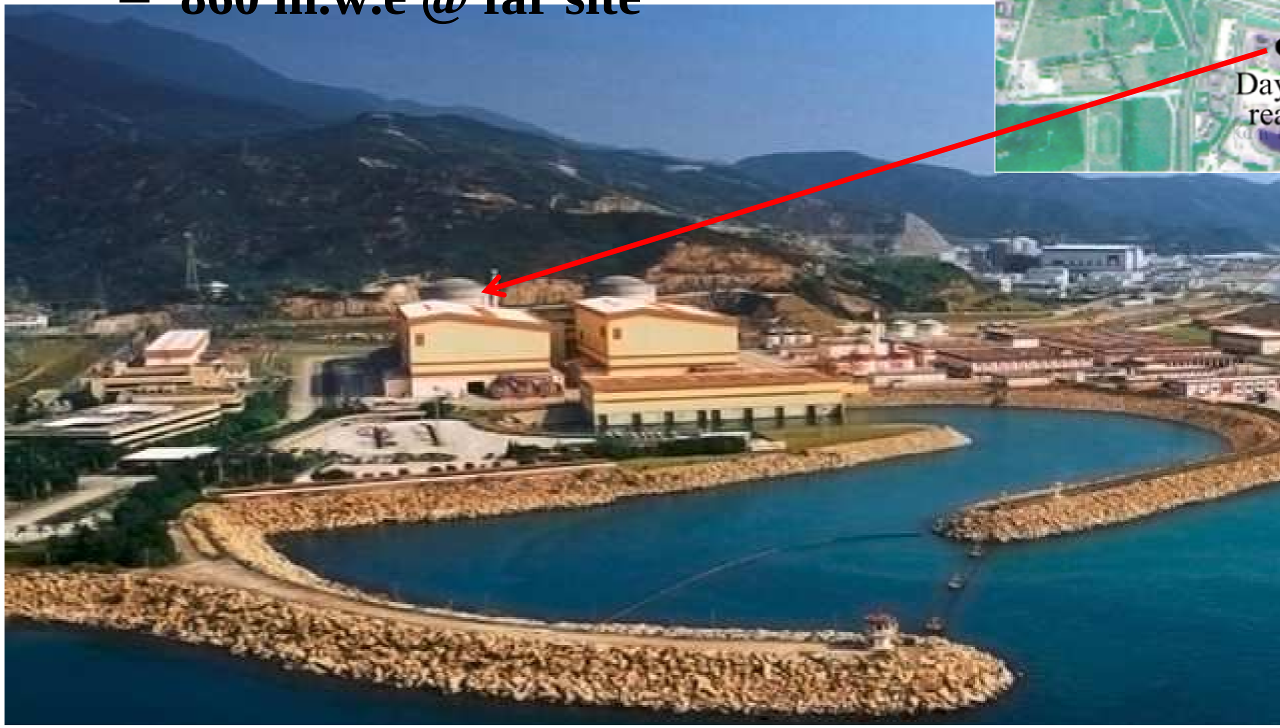
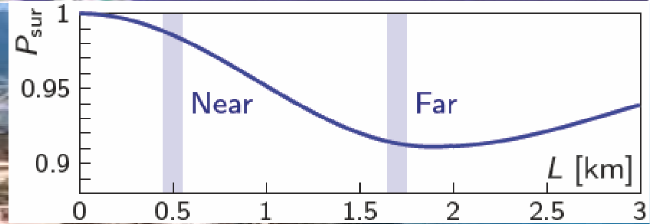
On behalf of Daya Bay Collaboration

The Daya Bay Experiment

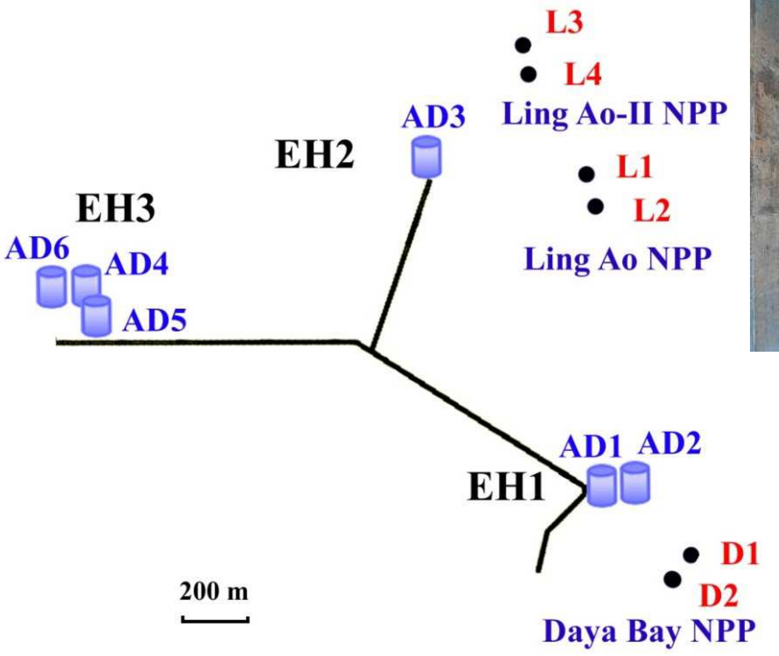
- **6 reactor cores, 17.4 GW_{th} total power**
- **Relative measurement**
  - **2 near sites, 1 far site**
- **Multiple detector modules**
- **Good cosmic shielding**
  - **250 m.w.e @ Daya Bay near**
  - **860 m.w.e @ far site**

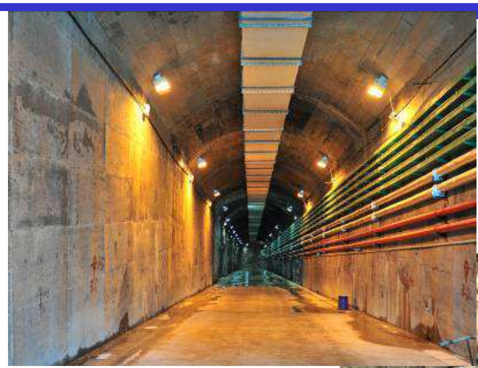






Underground Labs





	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)

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

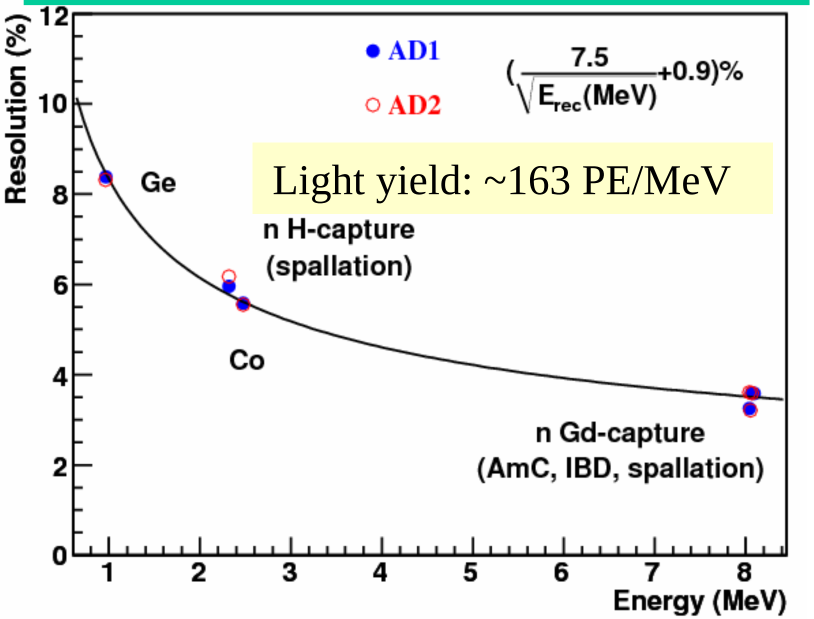
$$\downarrow$$

$$n + {}^{x}Gd \rightarrow {}^{x+1}Gd + \gamma$$

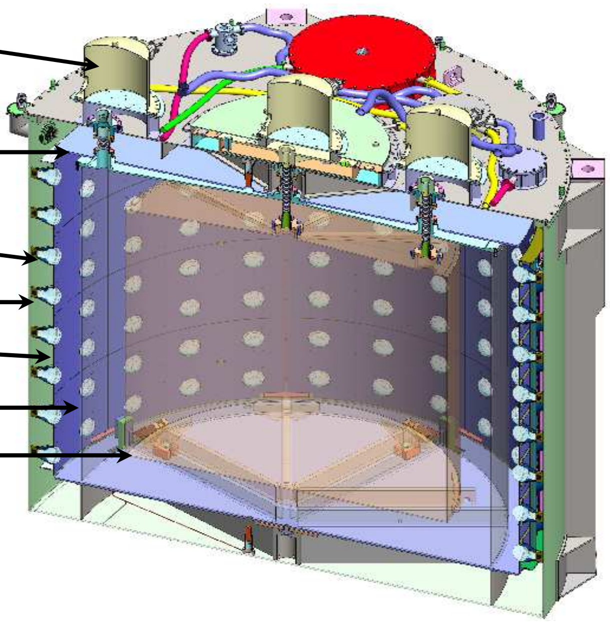
Neutrino Event

coincidence in time, space and energy

"functionally identical" detectors reduces systematic uncertainties



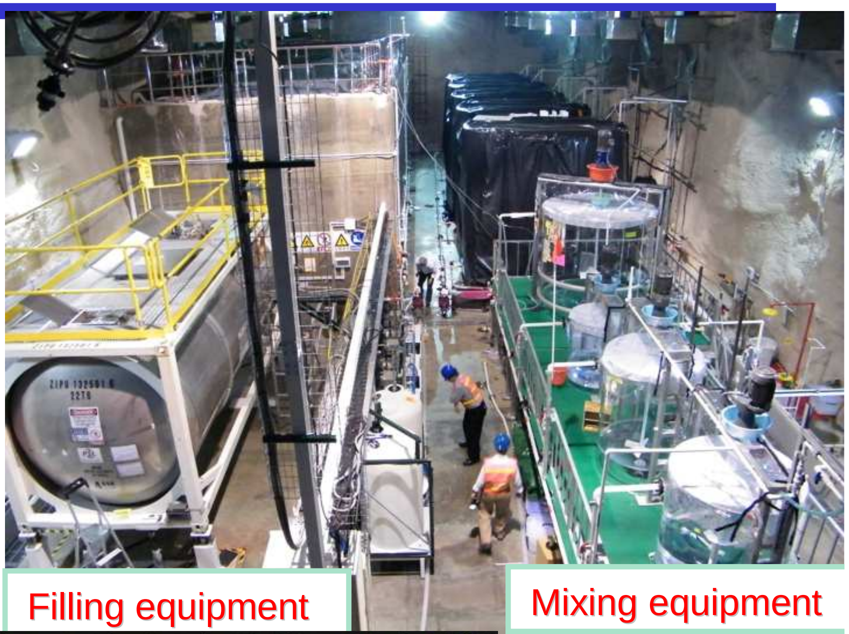
- Automated calibration system
- Reflectors at top/bottom of cylinder
- Photomultipliers
- Steel tank
- Radial shield
- Outer acrylic tank
- Inner acrylic tank

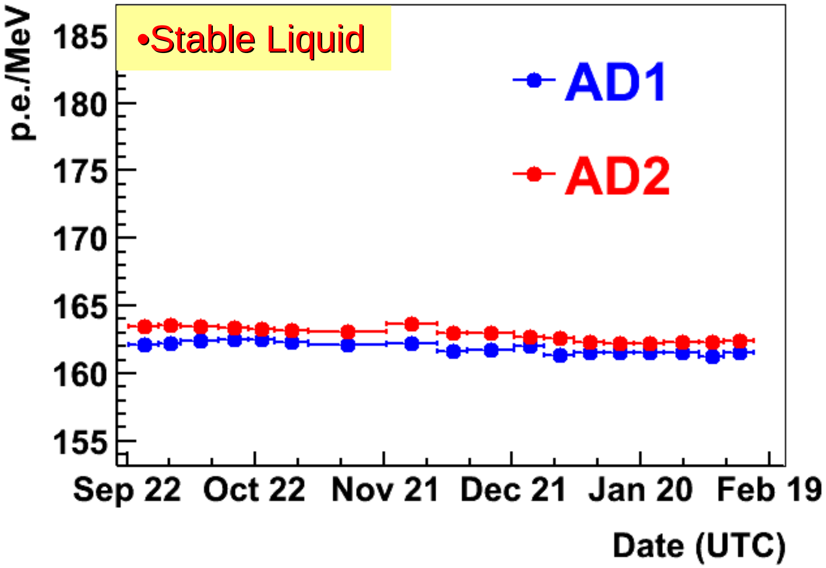


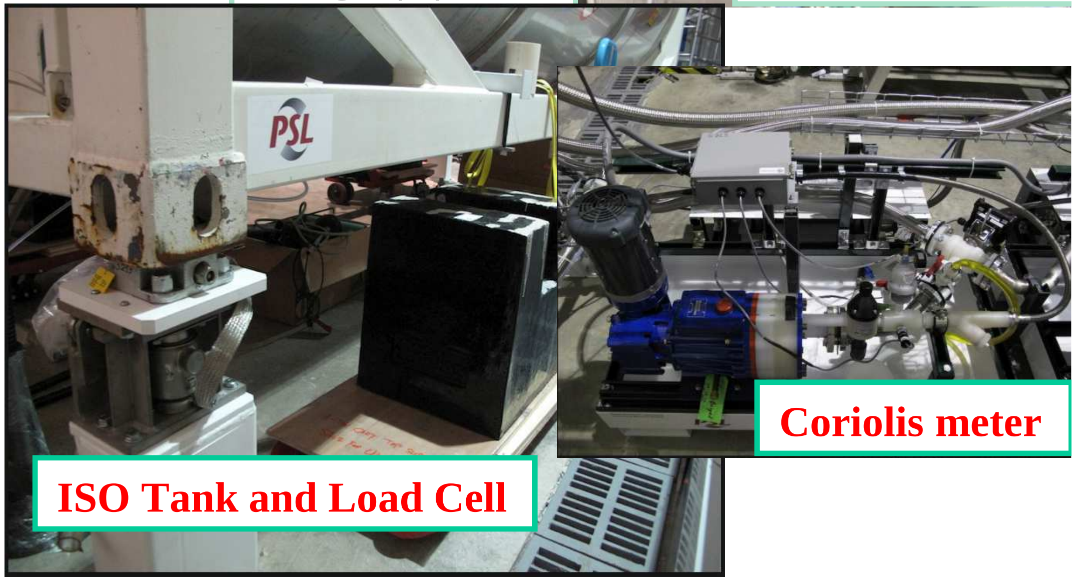
- Three zones modular structure:
  - target: Gd-loaded scintillator, 20t, 1.55m
  - γ-catcher: normal scintillator, 20t, 45cm
  - buffer shielding: mineral oil, 40t, 45cm
  - Total weight: 110t
- 192 8" PMTs/module
- Two optical reflectors at the top and the bottom, doubled the photocathode coverage

Gd-loaded Liquid Scintillator

- Home made liquid:
  - **185t Gd-LS, ~200t LS, ~320t oil**
- LAB-based+PPO+BisMSB
- $Gd(TMHA)_3$
- 3 liquids filled simultaneously
- Stable over time
  - IHEP prototype (600L) since 2007
  - 4-ton dry run since Mar. 2009
  - 185t production completed in Jan. 2011

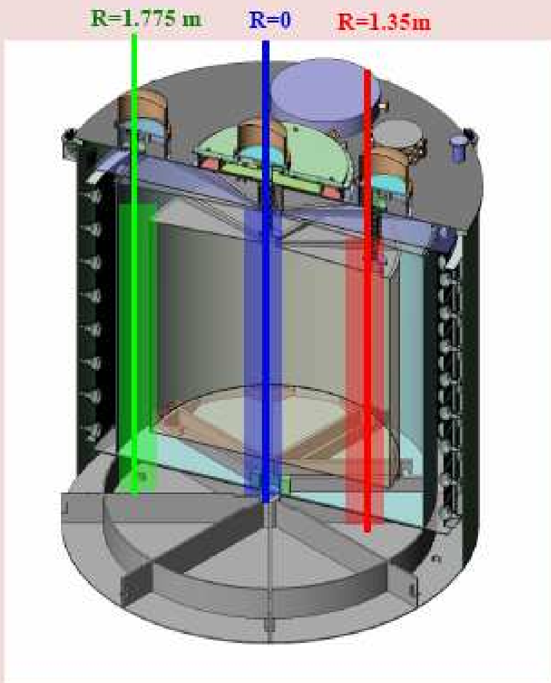






Automated Calibration System (ACU)

- 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**

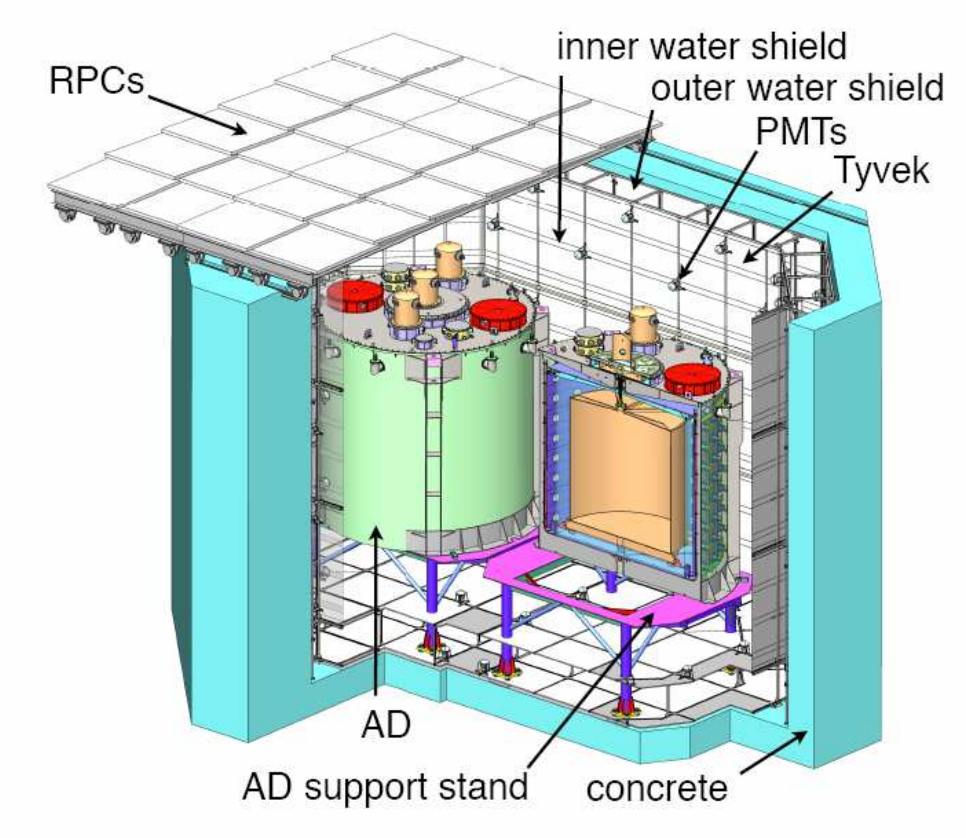


Automated Calibration


Interior of an Antineutrino Detector


Stainless Steel Vessel
Bottom Reflector
3m/4m Acrylic Vessel
SSV Lid and ACU
Top Reflector
PMT Ladder
AD Transportation
AD Filling

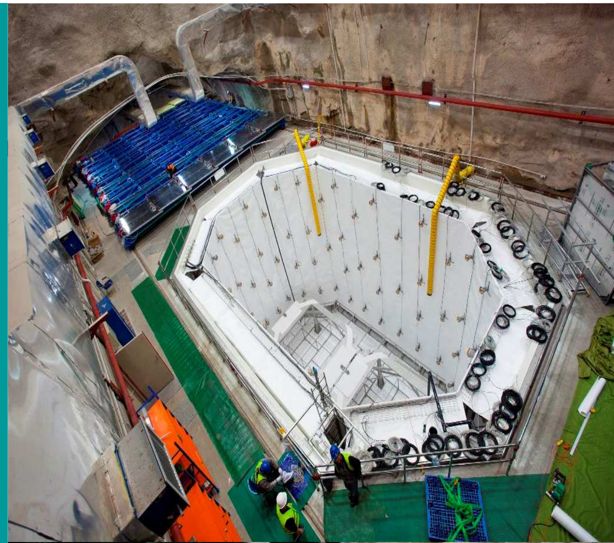
Muon Veto Detector

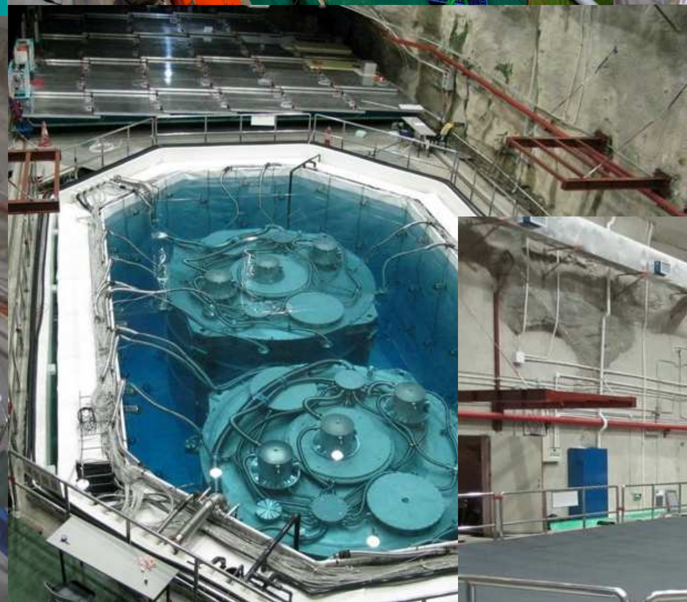


Two active cosmic-muon veto's

- Water Cerenkov: Eff.>99.7% (long track muon)
- RPC Muon tracker: Eff. > 88%

- Water Pool
  - **High purity de-ionized water in pools also for shielding (2.5m)**
  - **First stage water production in hall 4**
  - **Local water re-circulation & purification**
- Water Cerenkov detector
  - **Two layers, separated by Tyvek/PE/Tyvek film**
  - **288 8" PMTs for near halls**
  - **384 8" PMTs for the far hall**
- RPCs
  - **4 layers/module**
  - **54 modules/near hall, 81 modules/far hall**
  - **2 telescope modules/hall**

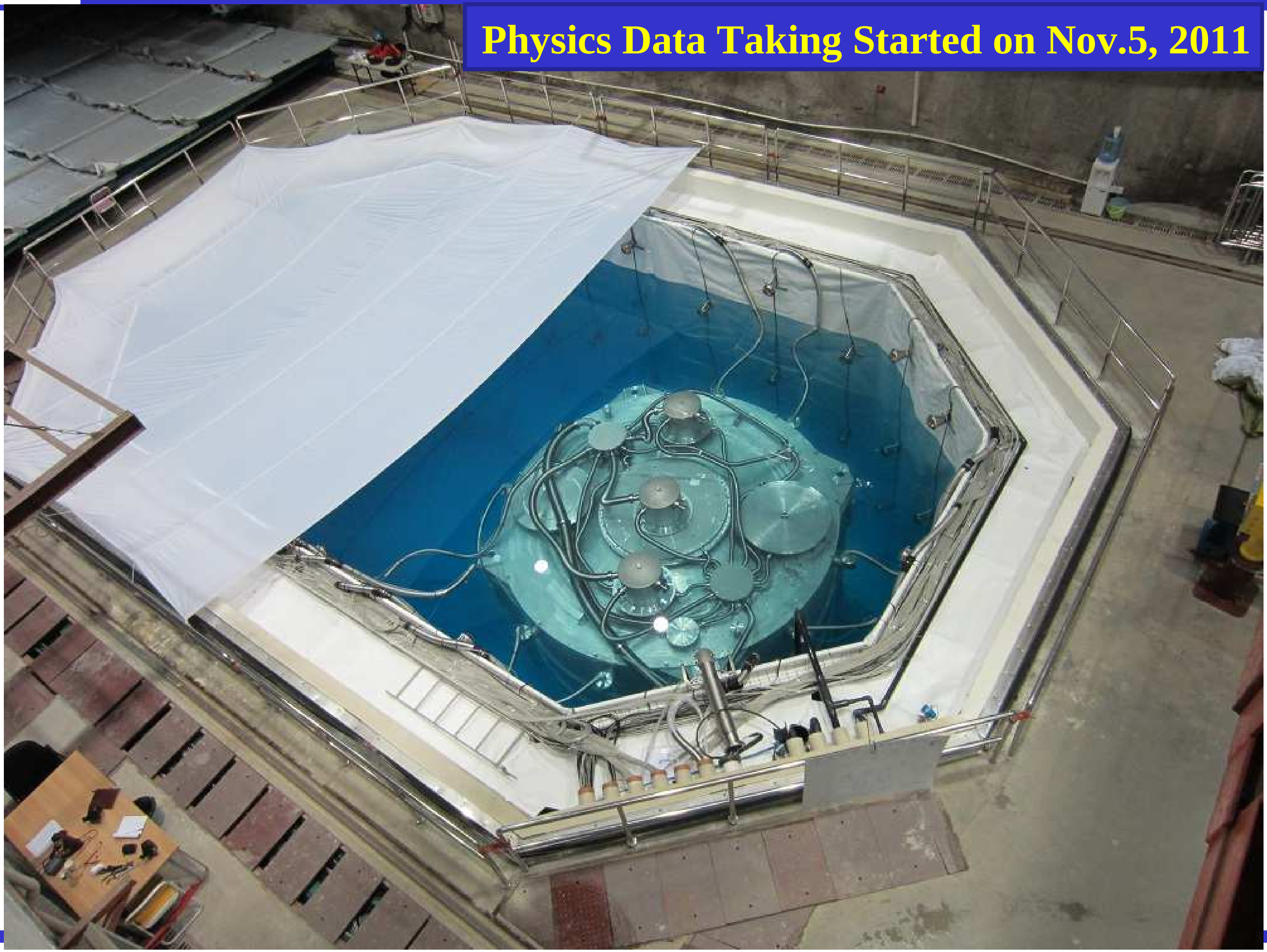




EH1 Water Pool Installation

Hall 1 (2 ADs) after Installation

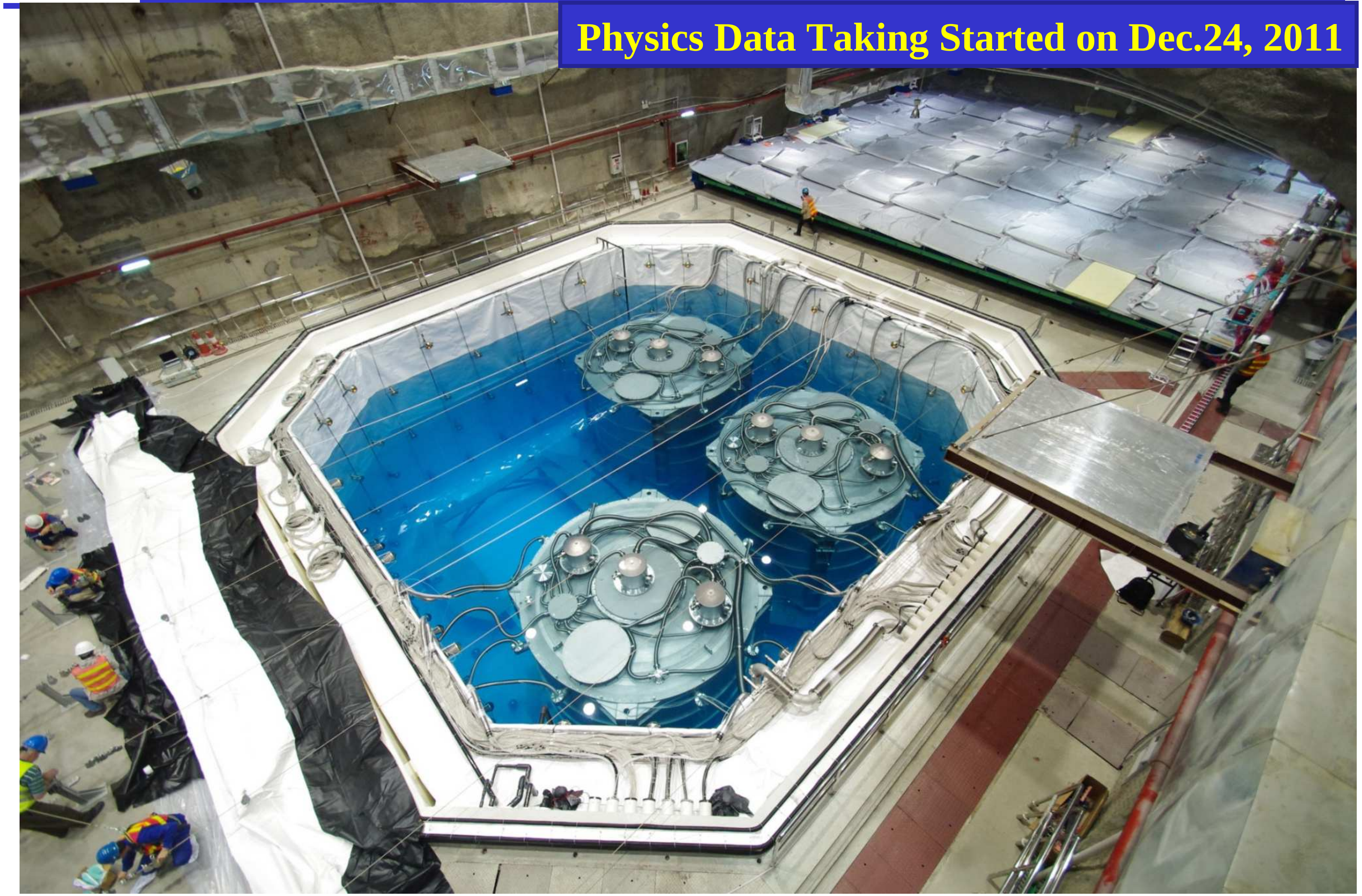
One AD Installed in Hall 2

Physics Data Taking Started on Nov.5, 2011



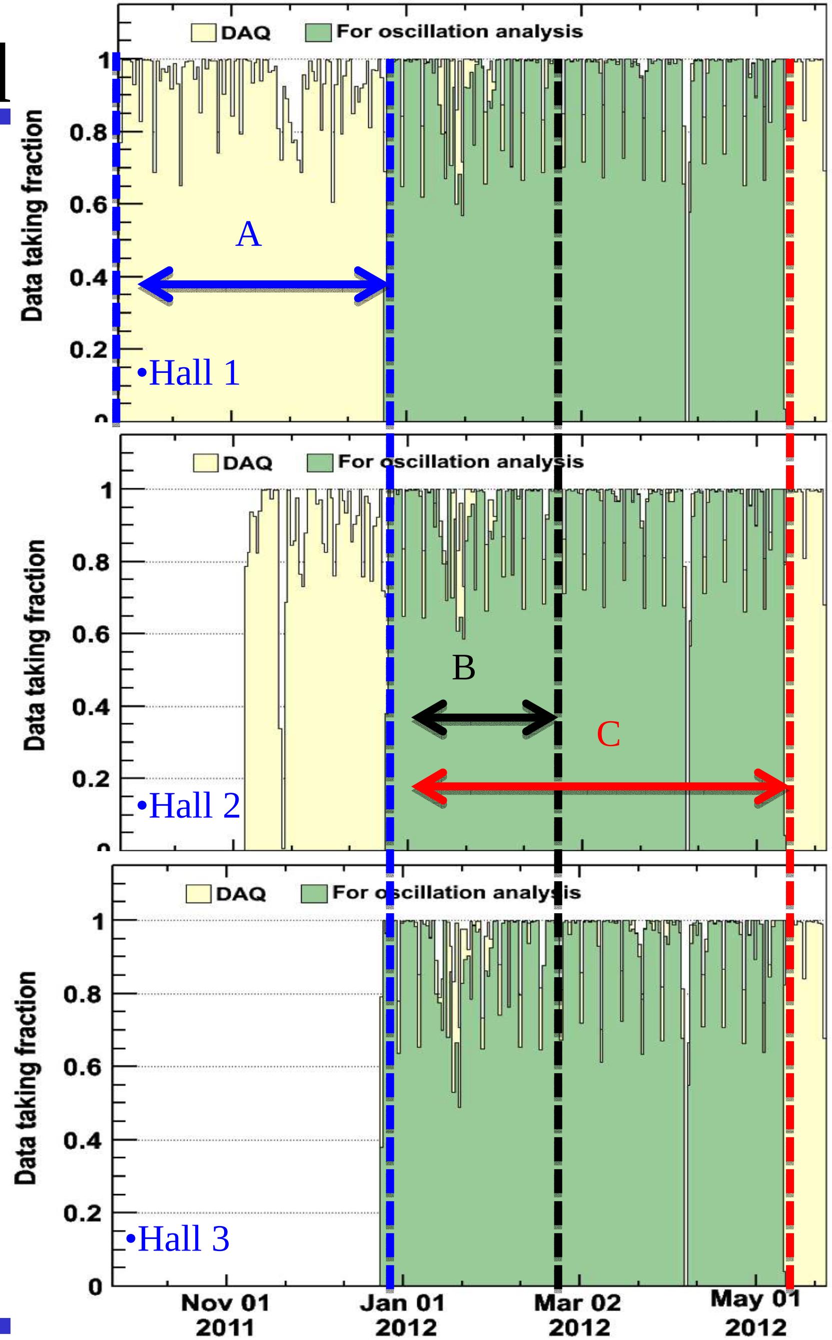
Three ADs installed in Hall 3

Physics Data Taking Started on Dec.24, 2011



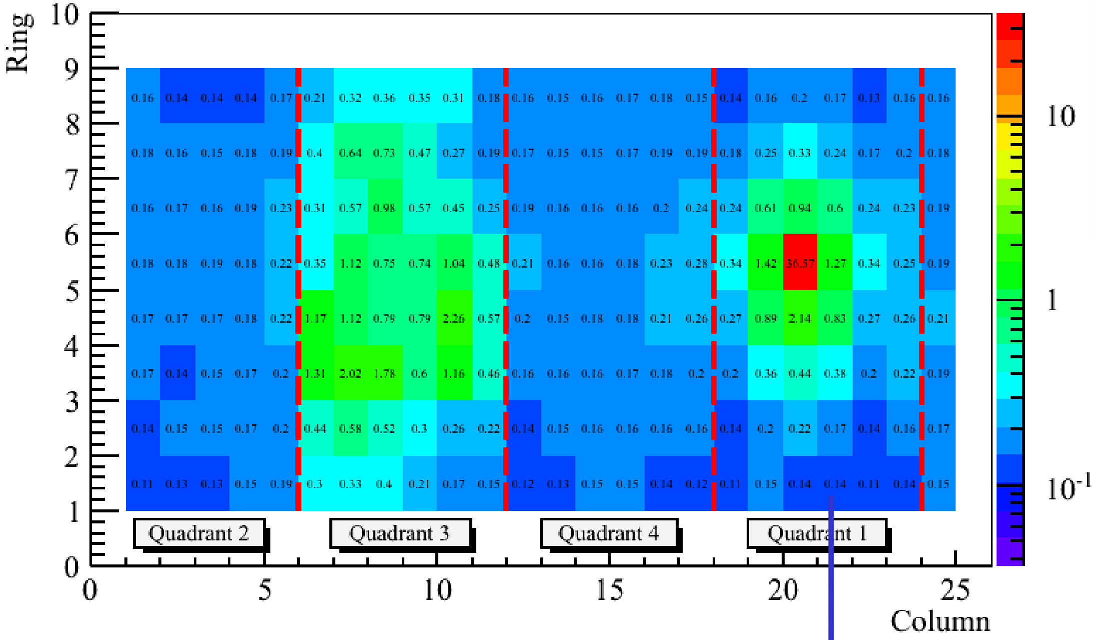
Data Period

- 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%

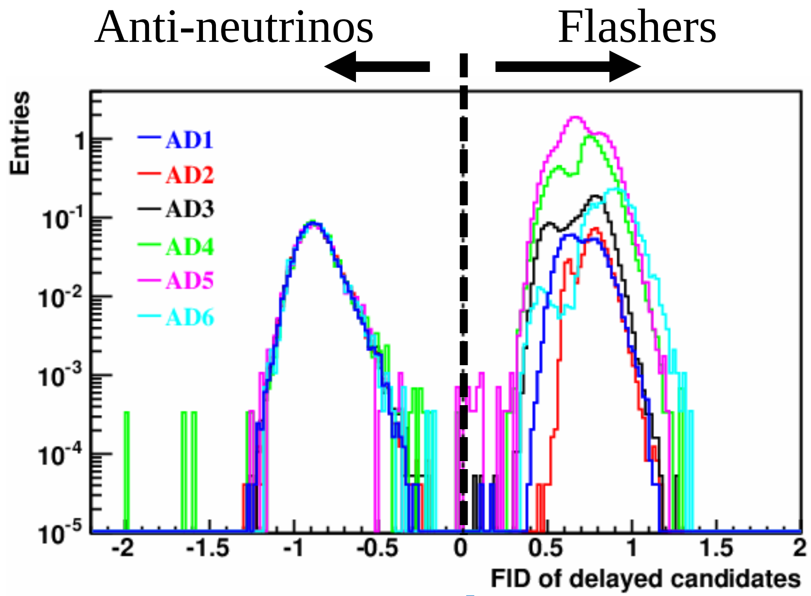


Flashers: Imperfect PMTs

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



Contain the hottest PMT



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

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

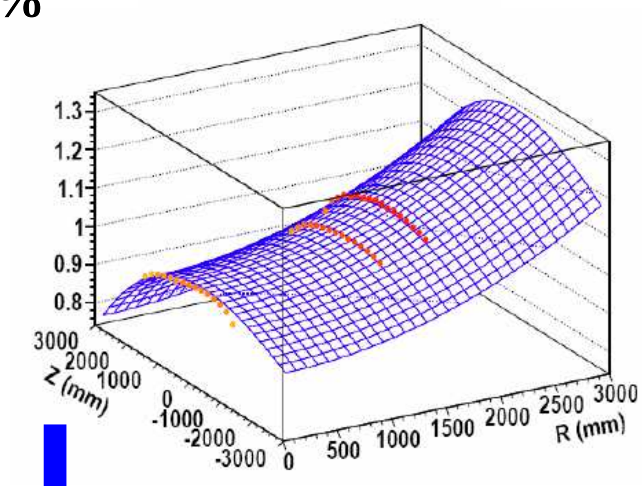
$$d_{max} = Q_{max}/Q_{sum}$$

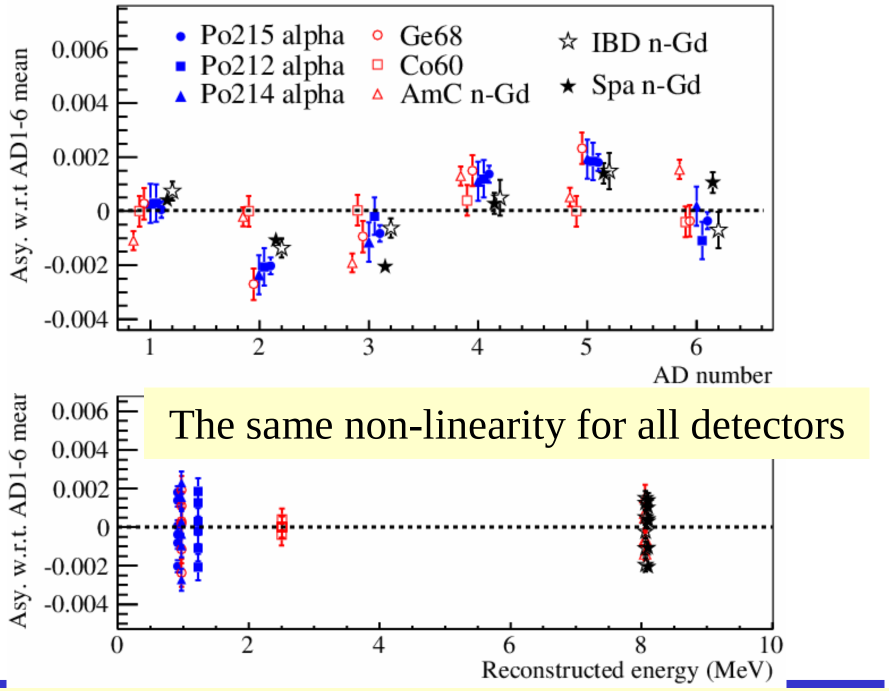
- **Inefficiency to neutrinos:**
- **0.024% ± 0.006%(stat)**
- **Contamination: < 0.01%**

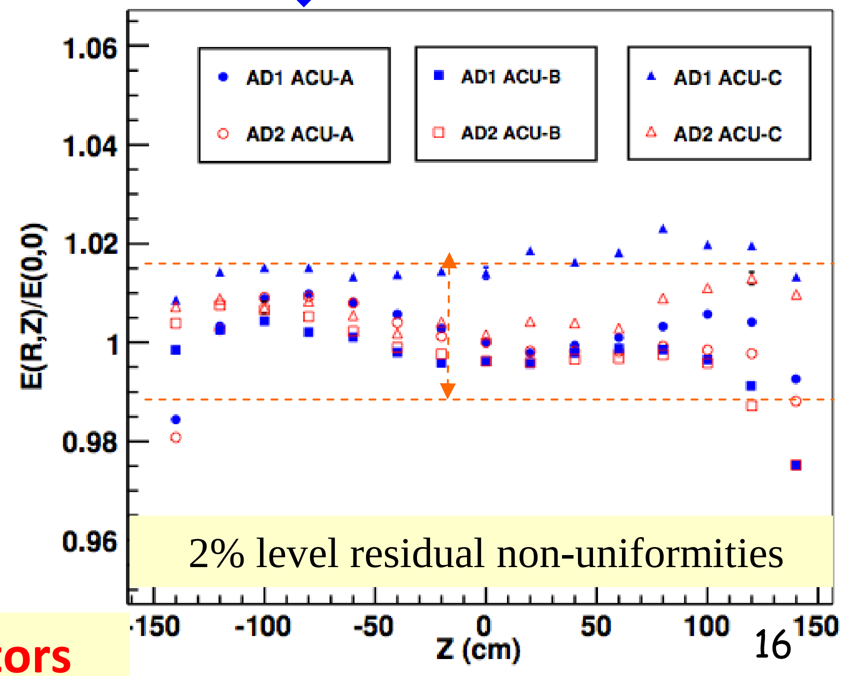
Energy calibration & reconstruction

- **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**
  - **Same correction for all the ADs**
- **Calibrate energy scale using neutron capture peak**

$f(R,Z) = f_1(R) * f_2(Z)$



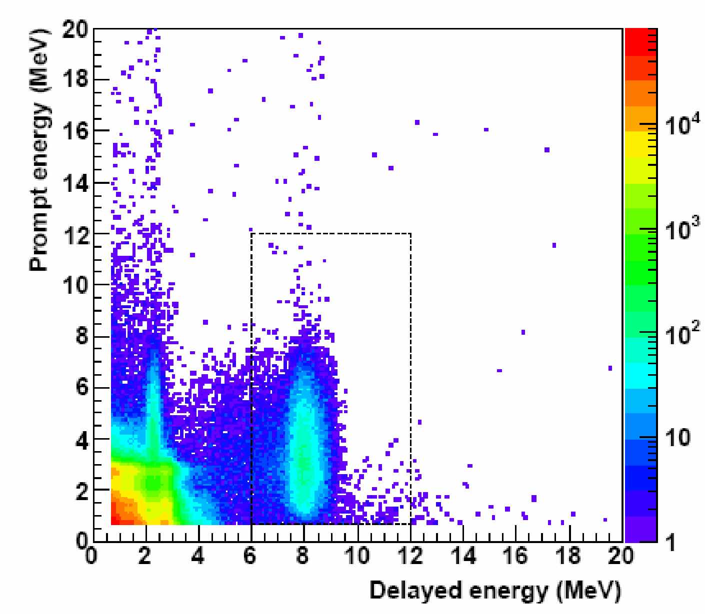




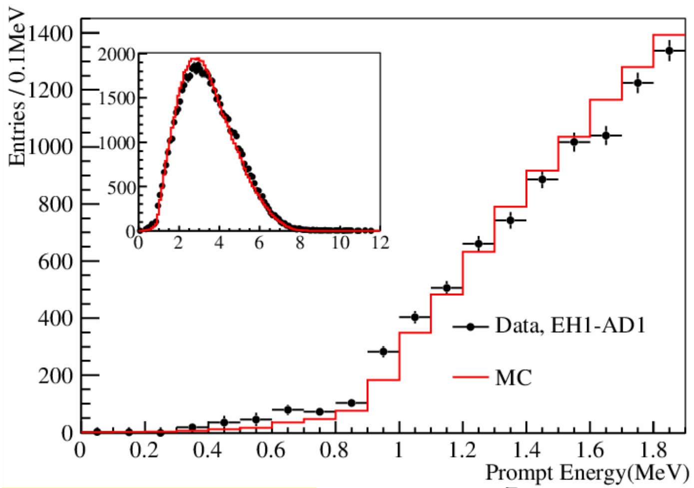
→ 0.12% efficiency difference among detectors

Anti-neutrino Events Selection

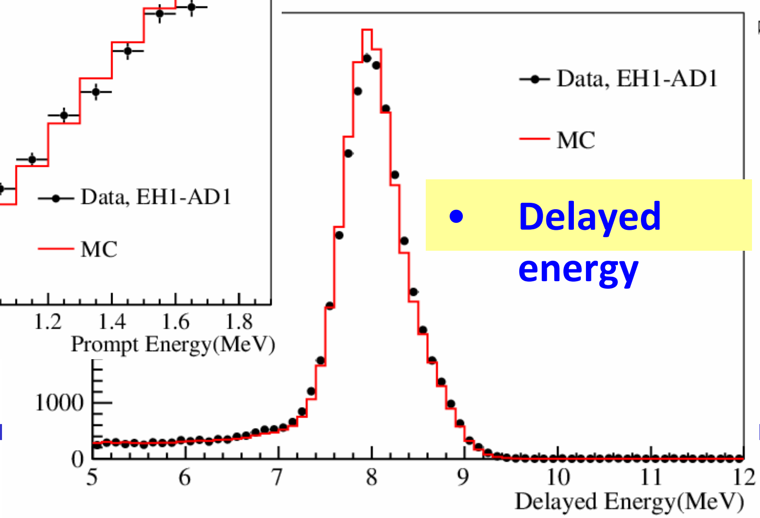
- Anti-neutrino event selection
  - 0.7 MeV < E_p < 12.0 MeV
  - 6.0 MeV < E_d < 12.0 MeV
  - 1 μs < $\Delta t_{p\text{-}d}$ < 200 μs
  - Muon Veto:
    - 0.6 ms after a Pool muon (reject fast neutron),
    - 1 ms after an AD muon (reject double neutron),
    - 1 s after an AD shower muon (reject $^{9}Li/^{8}He$)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



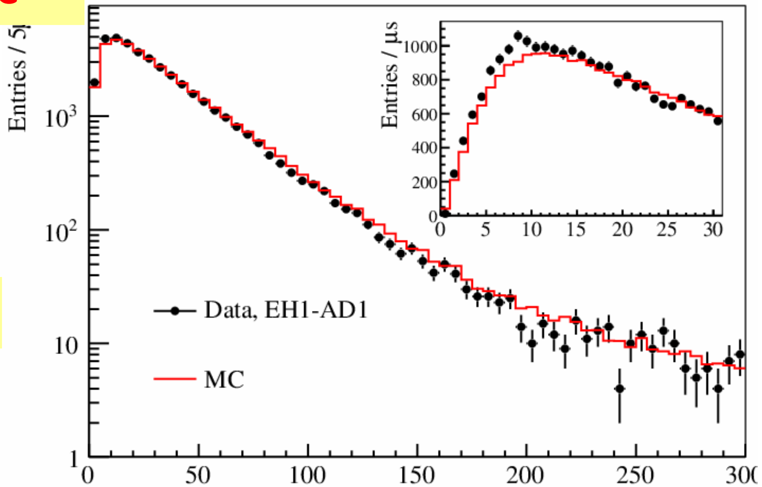
Good agreement with MC



- **Prompt energy**



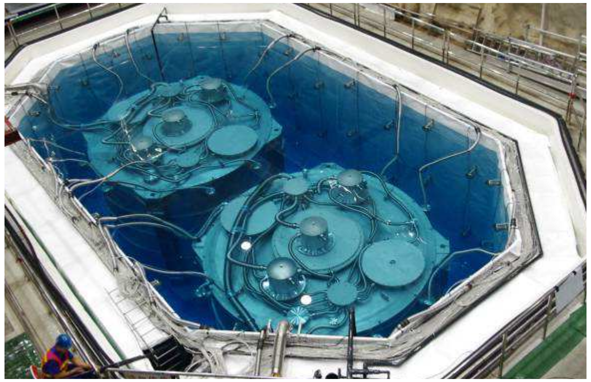
- **Delayed energy**

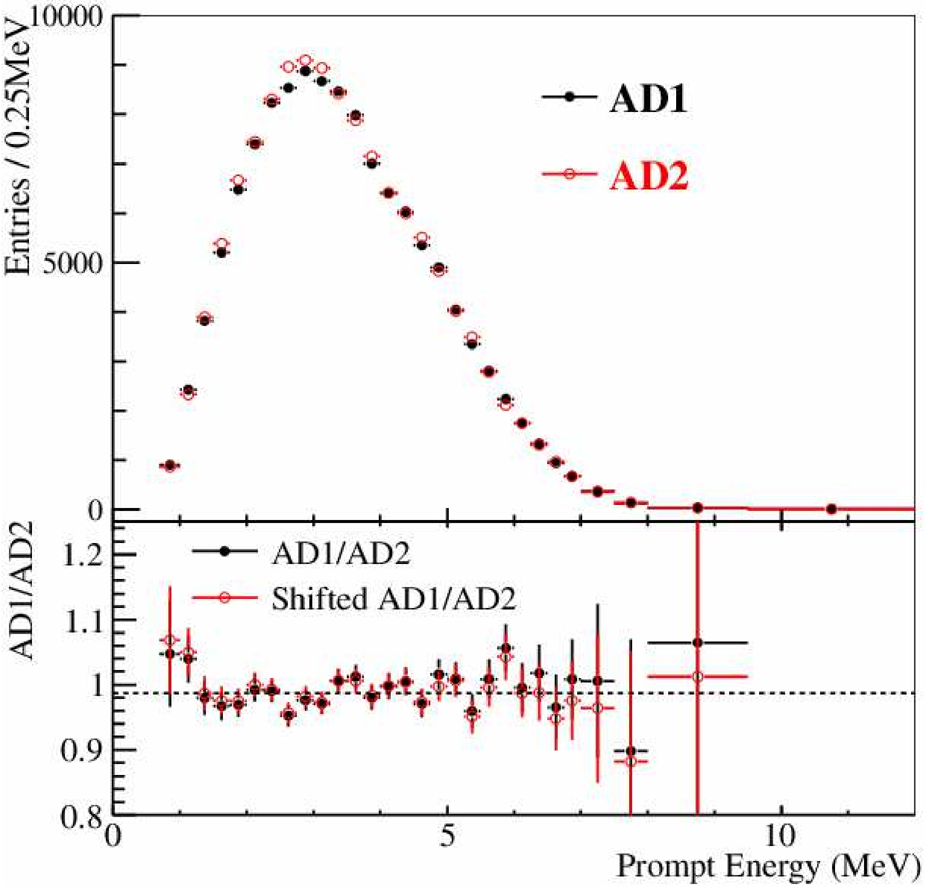


- **Time between prompt-delayed**

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)

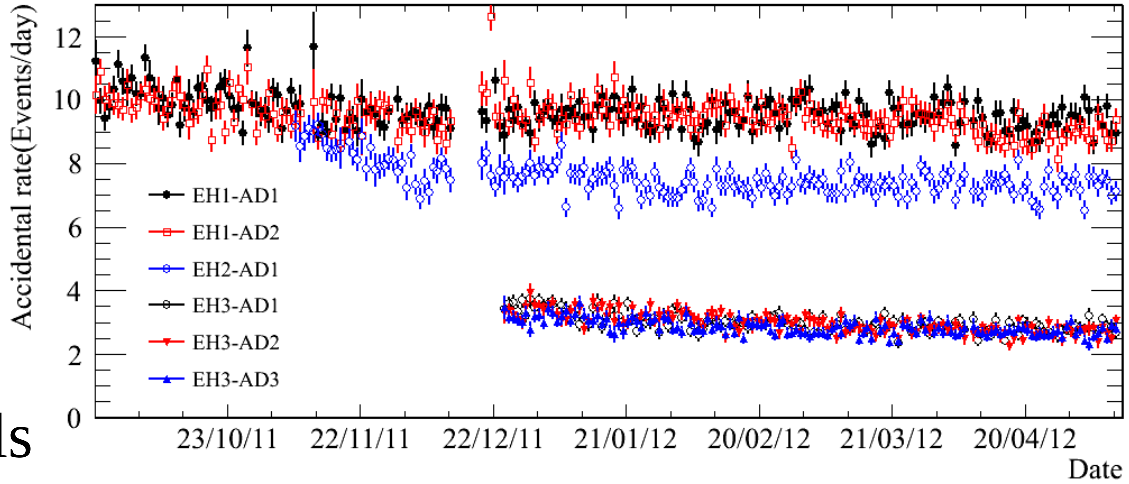




This check shows that systematic errors are under control, and will determine the final systematic error

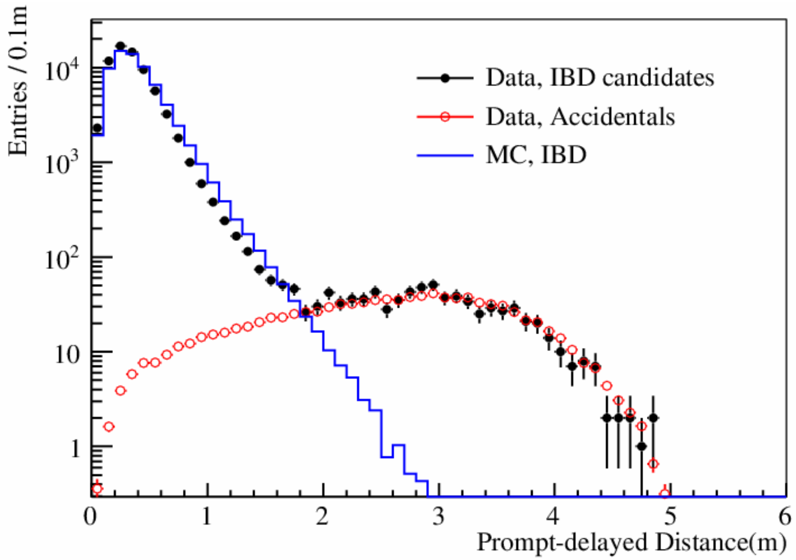
Backgrounds: Accidentals

- 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**

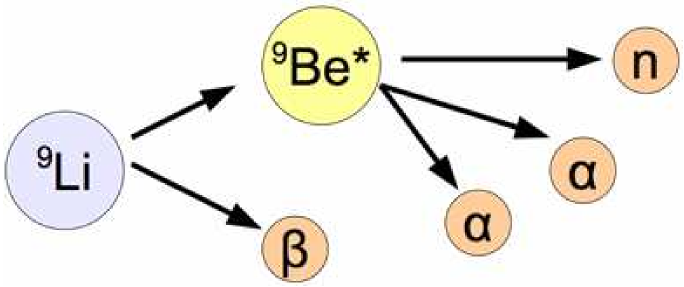


➢**B/S @ EH1/2 ~ 1.4%, B/S @ EH3 ~ 4.0% , ΔB/B ~ 1%**

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

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

β-decay + neutron emitter

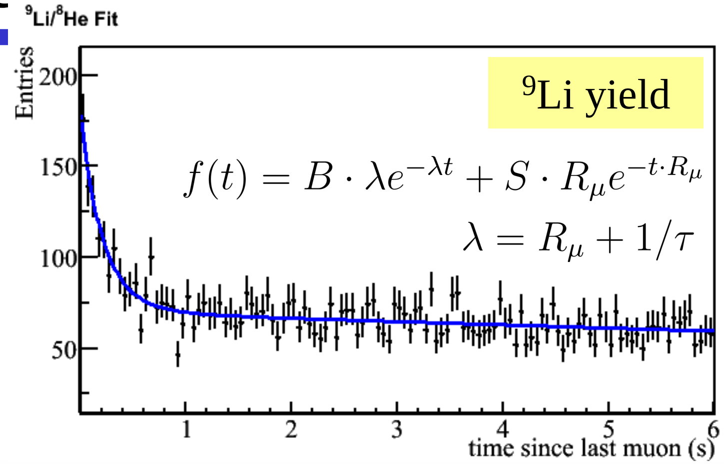


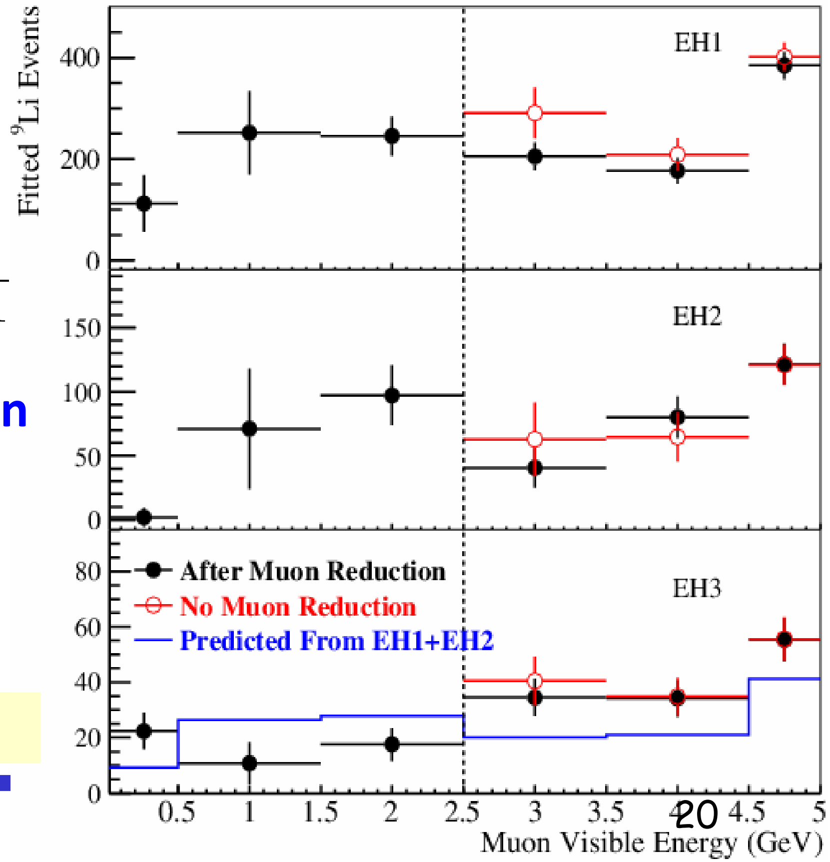
- Measurement:
  - **Time-since-last-muon fit method**

•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**
  - **EH3 is predicted from EH1+EH2, and consistent with measurement**

B/S @ EH1/2 ~ 0.4%, B/S @ EH3 ~ 0.3%, ΔB/B ~ 50%

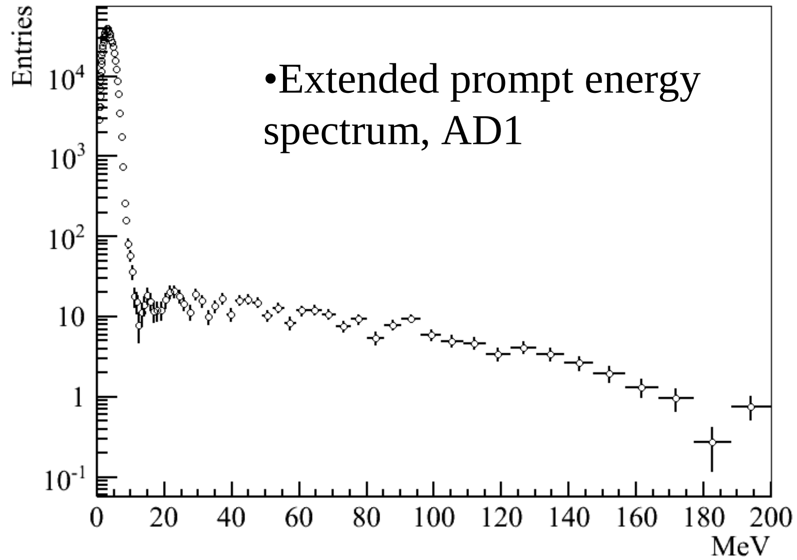




Backgrounds: Fast neutrons

- **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.



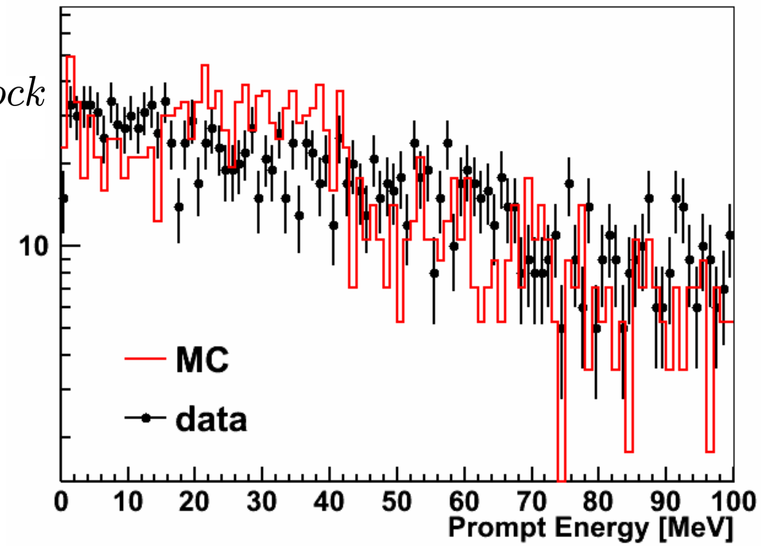
- **Method II:**

  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



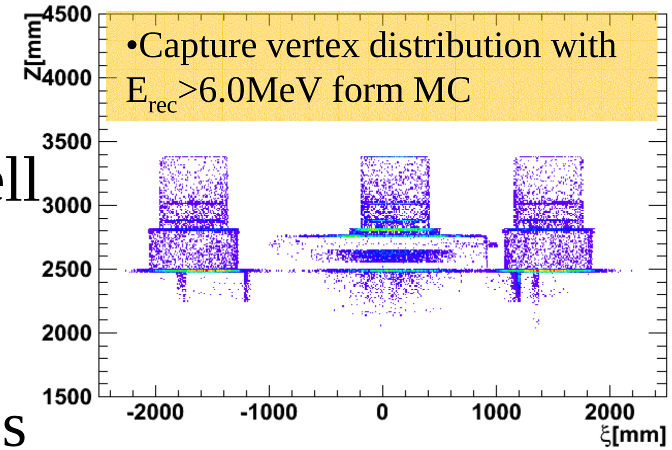
•Results are consistent

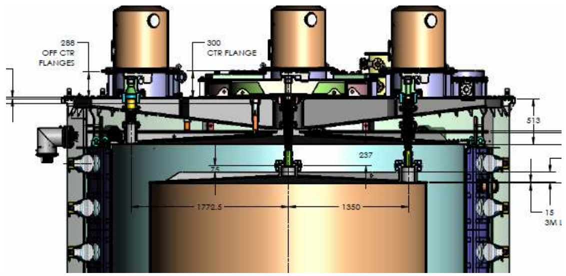
B/S @ EH1/2 ~ 0.12%, B/S @ EH3 ~ 0.07%, ΔB/B ~ 40%

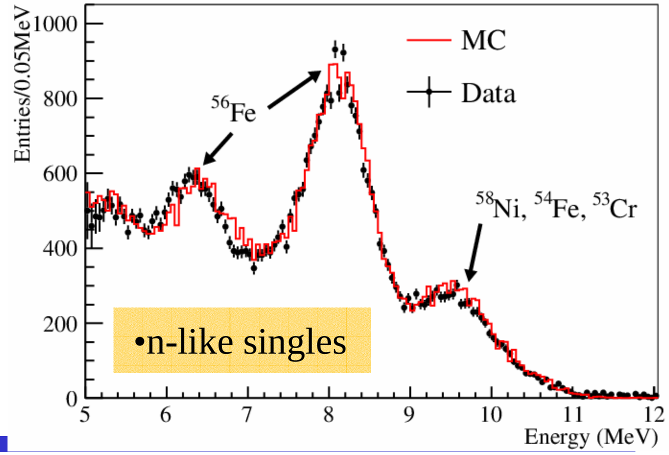
Backgrounds: ^{241}Am-^{13}C source

- 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%

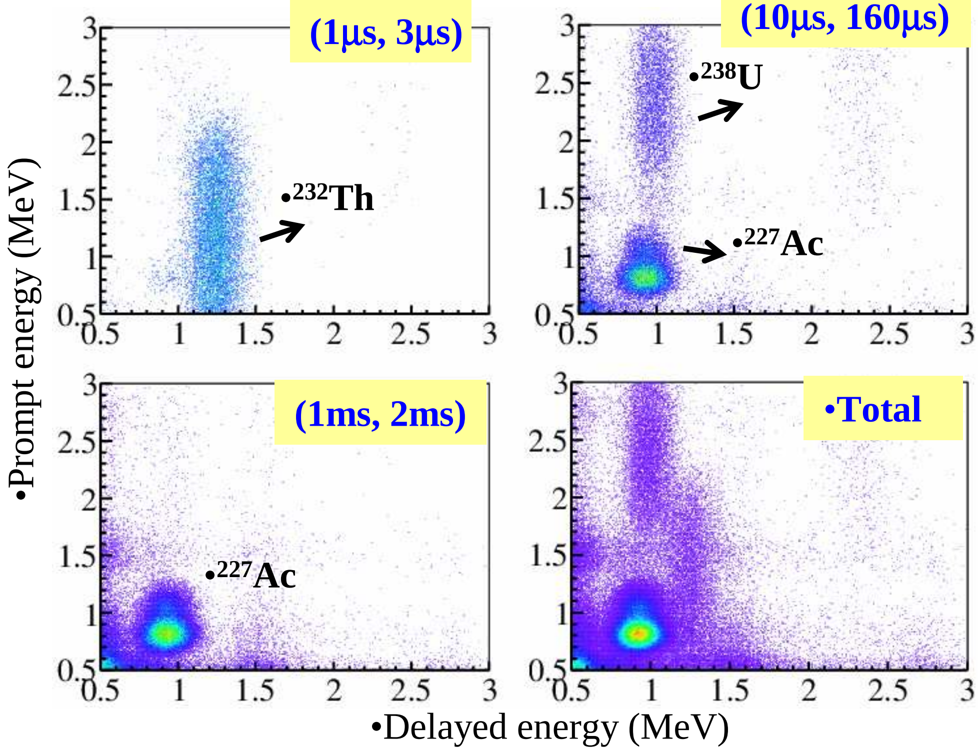




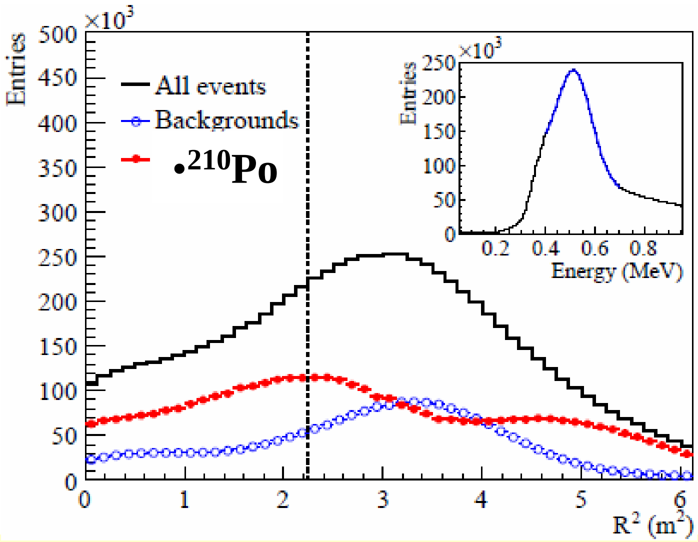


Backgrounds: $^{13}C(\alpha,n)^{16}O$

- 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



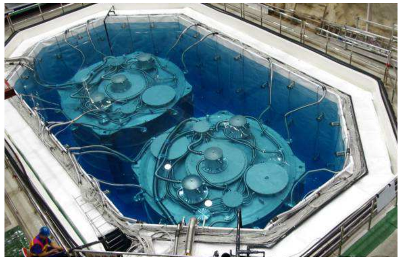
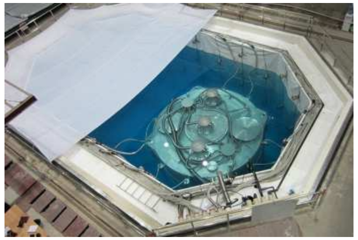
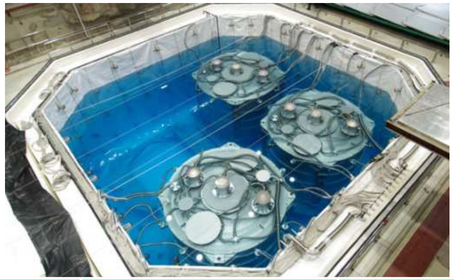
- Time correlations of the cascade decay



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

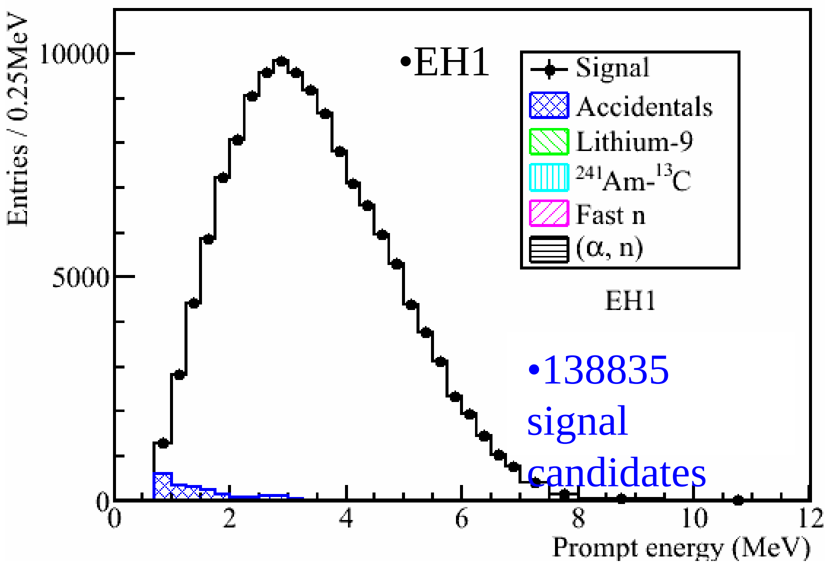
α source	Total α rate	BG rate
^{210}Po	22Hz at EH1 14Hz at EH2 5Hz at EH3	0.06/day at EH1 0.04/day at EH2 0.02/day at EH3
^{227}Ac	1.4 Bq	0.01/day
^{238}U	0.07Bq	0.001/day
^{232}Th	1.2Bq	0.01/day

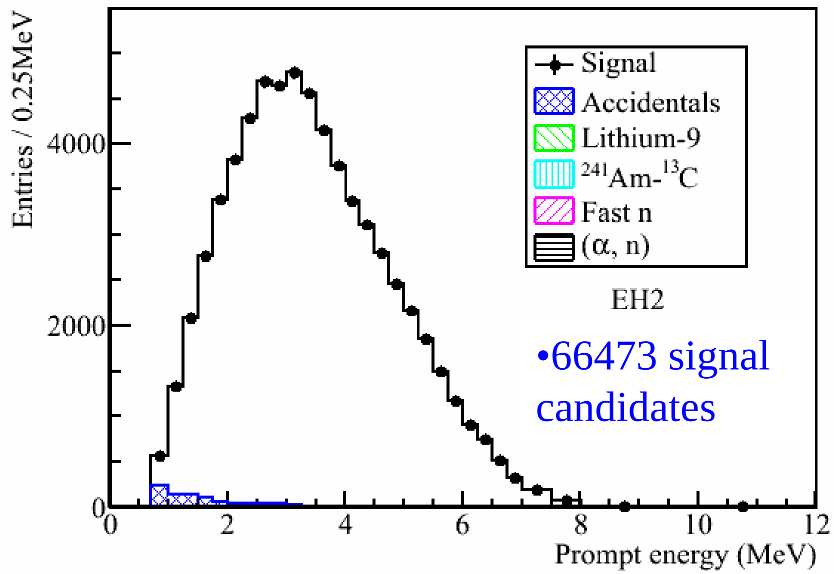
Signals and Backgrounds

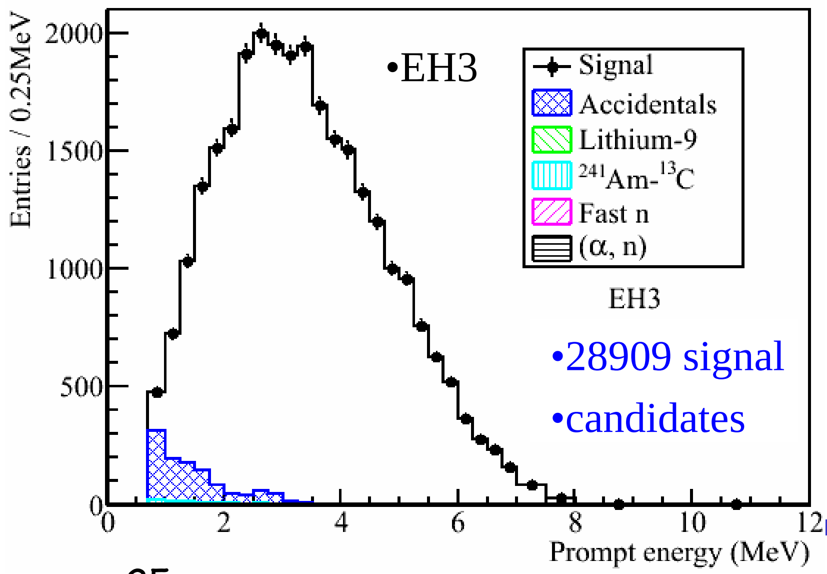




	AD1	AD2	AD3	AD4	AD5	AD6
Antineutrino candidates	69121	69714	66473	9788	9669	9452
DAQ live time (day)	127.5470		127.3763	126.2646		
Efficiency $\varepsilon_\mu * \varepsilon_m$	0.8015	0.7986	0.8364	0.9555	0.9552	0.9547
Accidentals (/day)	9.73±0.10	9.61±0.10	7.55±0.08	3.05±0.04	3.04±0.04	2.93±0.03
Fast 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+Background Spectrum







	Near Halls		Far Hall		
	B/S %	σ B/S %	B/S %	σ 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
$^{13}C(\alpha$,	0.01	0.006	0.05	0.03	~50%

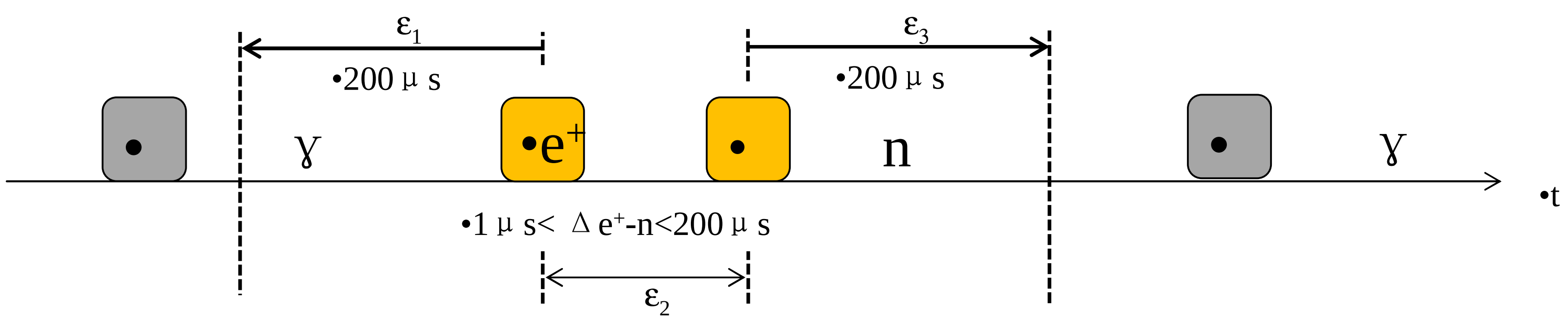
Muon Veto and Multiplicity Cut

- Muon veto
  - Total veto time is the sum of all the veto time windows
  - Temporal overlap is taken into account
- Multiplicity cut
  - Efficiency = $\varepsilon_1 \times \varepsilon_2 \times \varepsilon_3$
- The only eff. that is corrected for each AD.
- All other differences between the functionally identical ADs were not corrected, but taken as uncorrelated uncertainties.

> ➢ *1s* after an AD shower mu
> ➢ *1ms* after an AD mu
> ➢ *0.6ms* after an WP mu

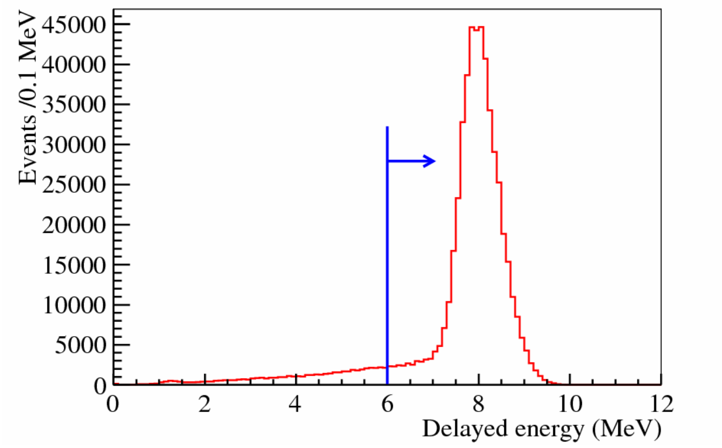
> ➢
> rompt-delayed pairs within 200 μs
> ➢
> o triggers before the prompt and after the delayed signal by 200 μs

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

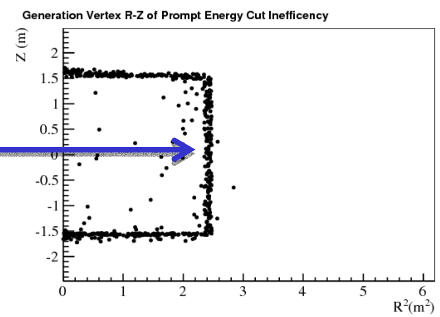


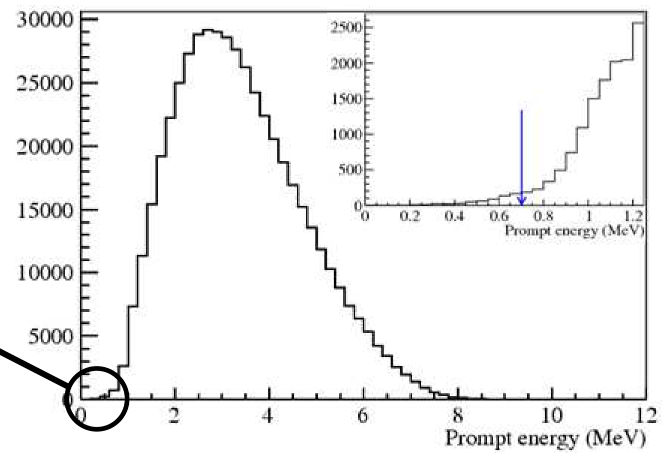
Energy Cuts Efficiency and Systematics

- 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%



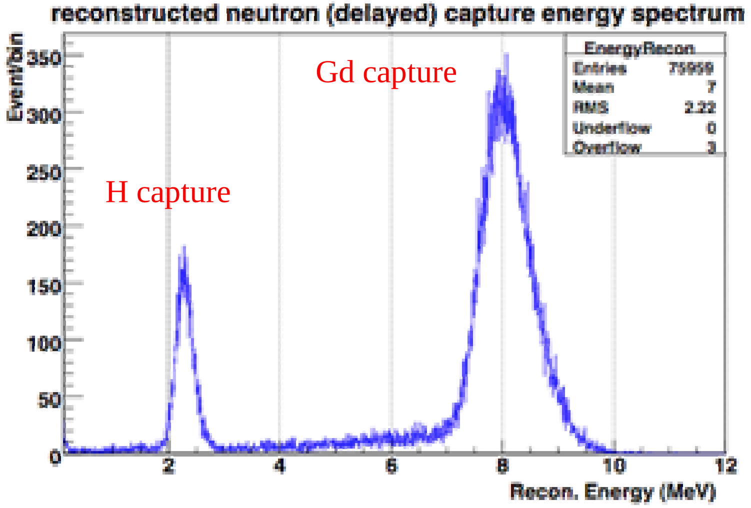
The inefficiency mainly comes from edges





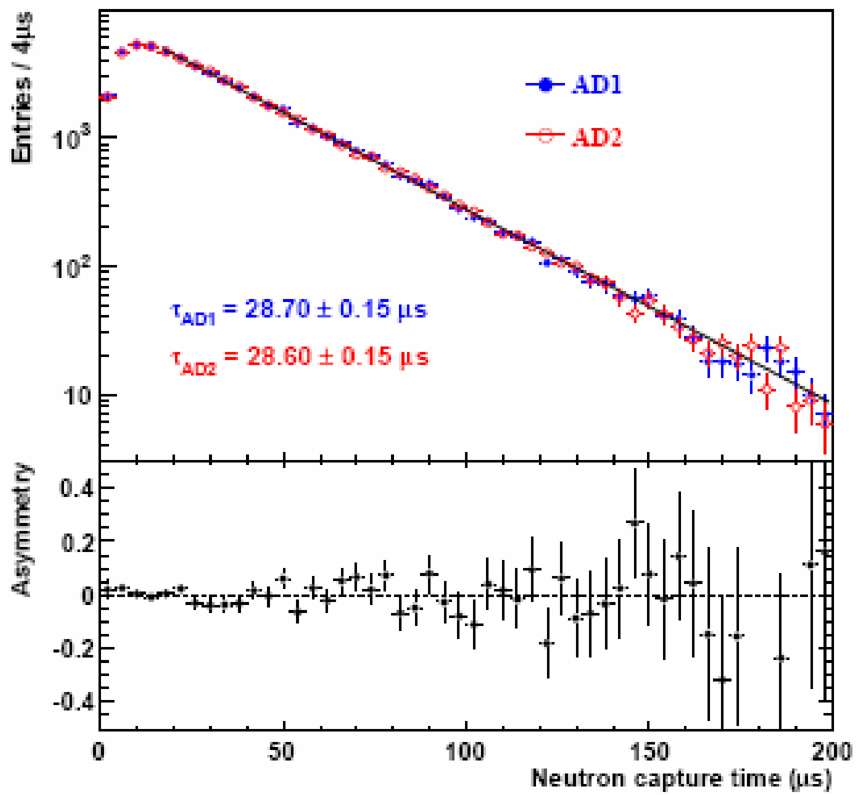
	Eff.	Corr.	Un-corr.
Delayed energy cut	**90.9%**	**0.6%**	**0.12%**
Prompt energy cut	**99.88%**	**0.10%**	**0.01%**

Gd Capture Fraction: H/Gd and Systematics



- 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

Neutron capture time from Am-C



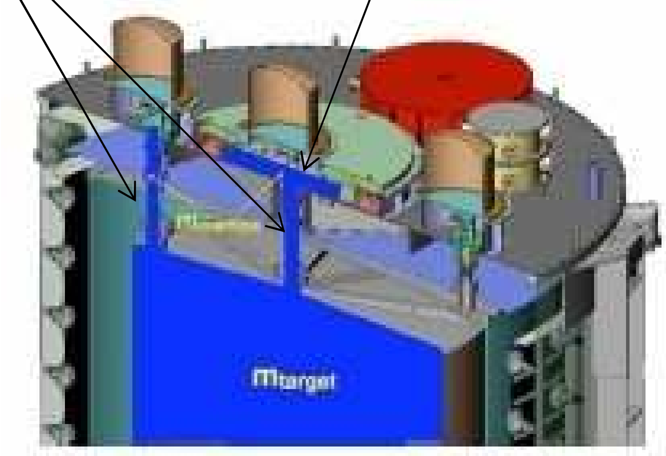
	Eff.	Corr.	Un-corr.
Gd capture ratio	83.8%	0.8%	<0.1%

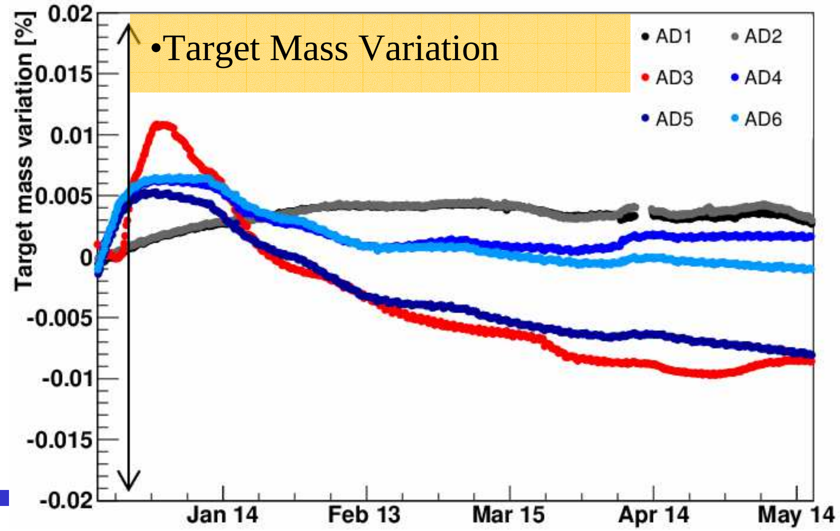
Target Mass & No. of Protons

- 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



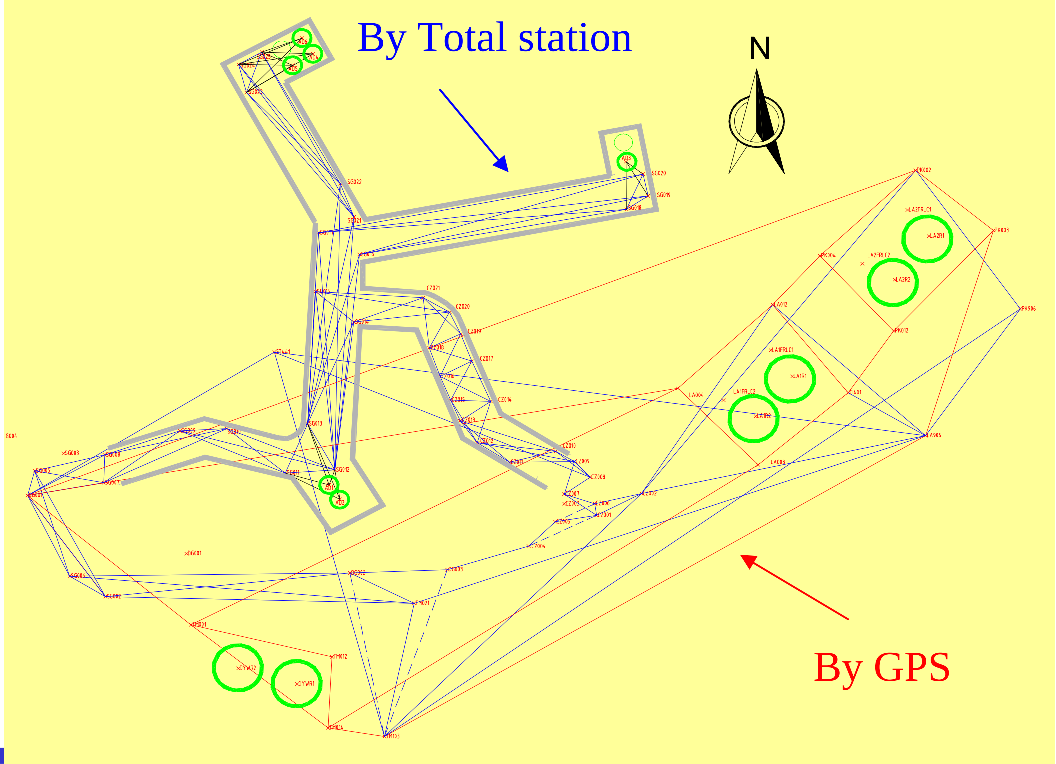


•One batch LAB

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%**

Baseline Survey

- 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%)



- **Reactor neutrino spectrum**

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

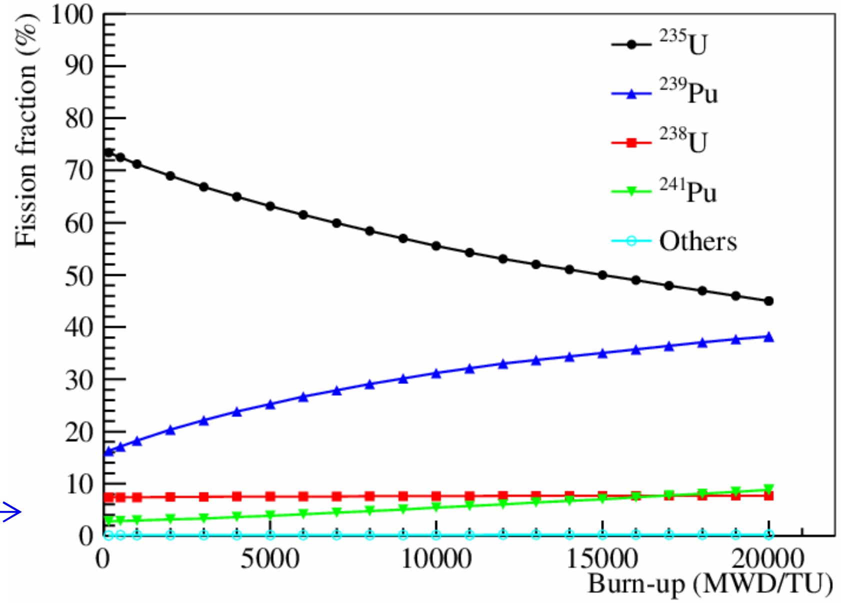
•neutrino spectra per fission of each isotope ($S_i(E)$)

•simulated fission rate (F_i)

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

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%

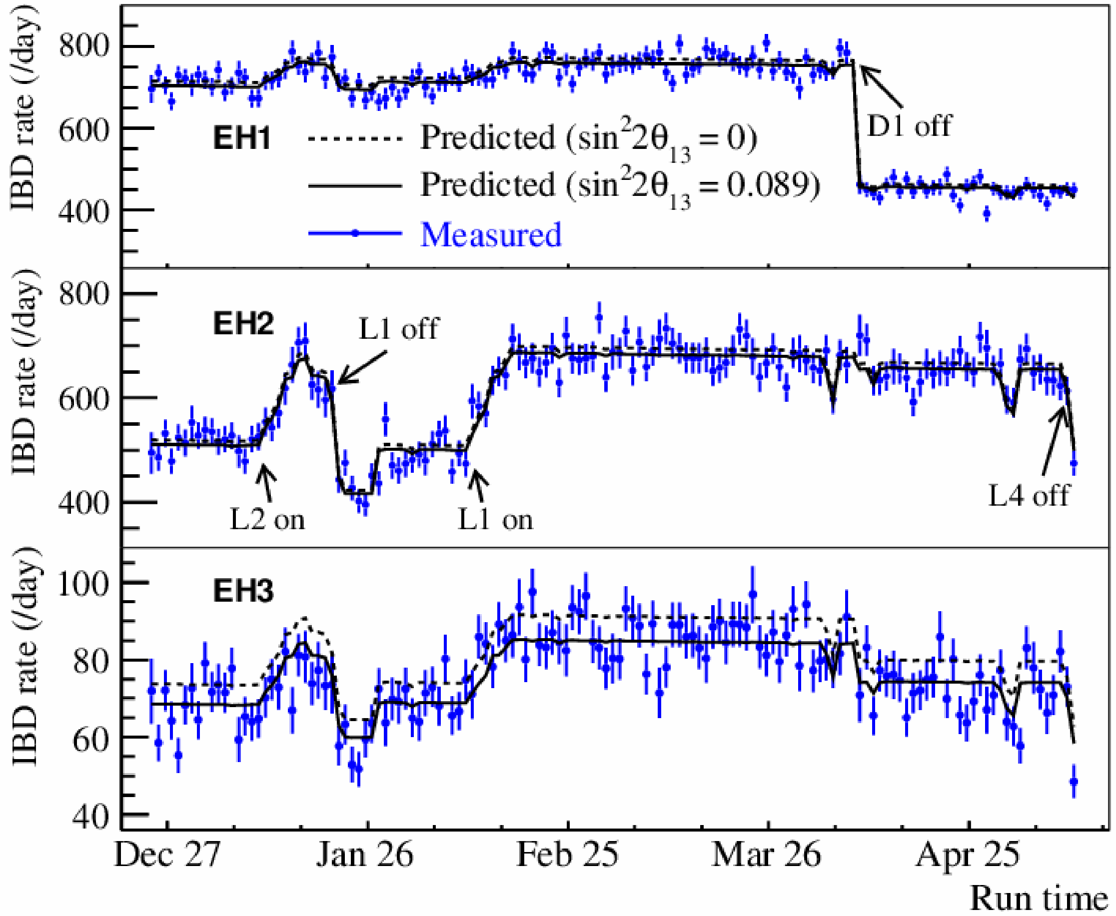
Reactor			
Correlated		Uncorrelated	
Energy/fission	0.2%	Power	0.5%
$\overline{\nu}_e$/fission	3%	Fission fraction	0.6%
		Spent fuel	0.3%
Combined	3%	Combined	0.8%

Other Approach

- Analysis was cross checked by the alternative
  - Using an alternative energy calibration algorithm based on spallation neutron peak
  - Different neutrino selection criteria
- The results are consistent within statistical errors
- Blind analysis
  - The reactor neutrino flux, baseline and target mass are blinded before we fix our analysis cut and procedure.

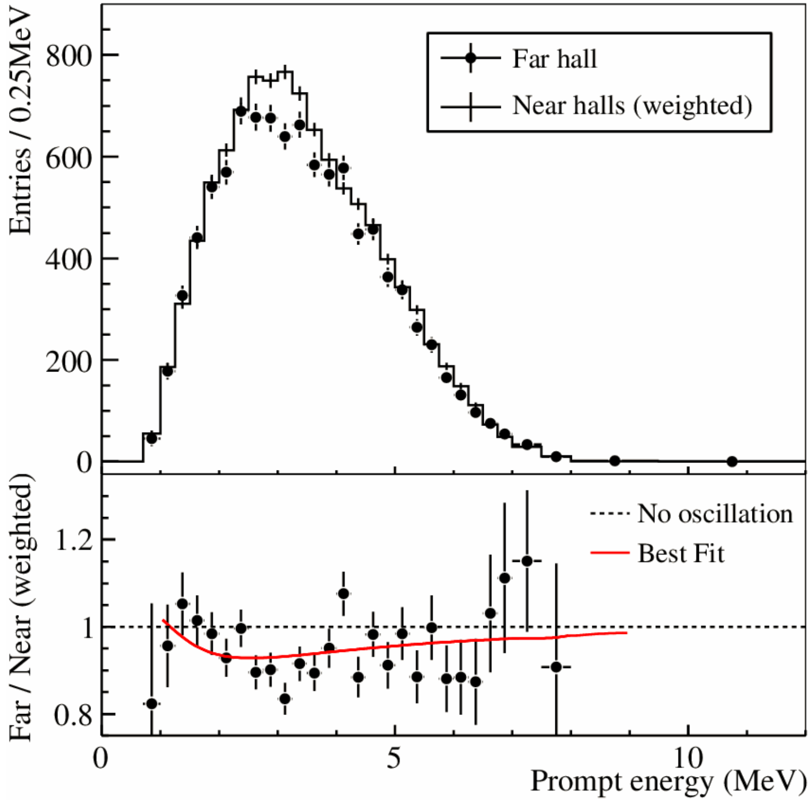
Daily Anti-neutrino Rate

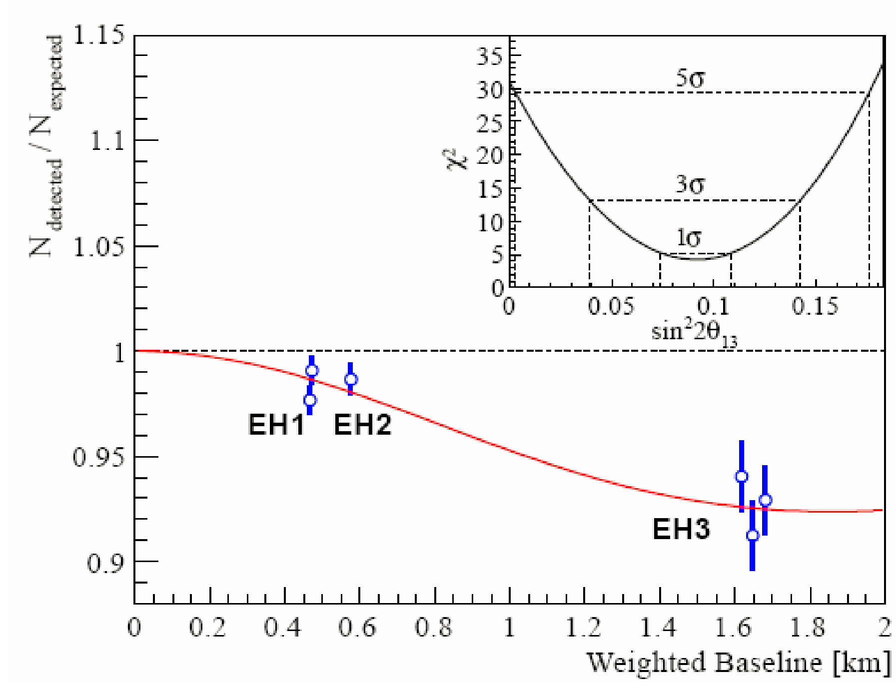
- Three halls taking data synchronously allows near-far cancellation of reactor related uncertainties
- Rate changes reflect the reactor on/off.



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

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



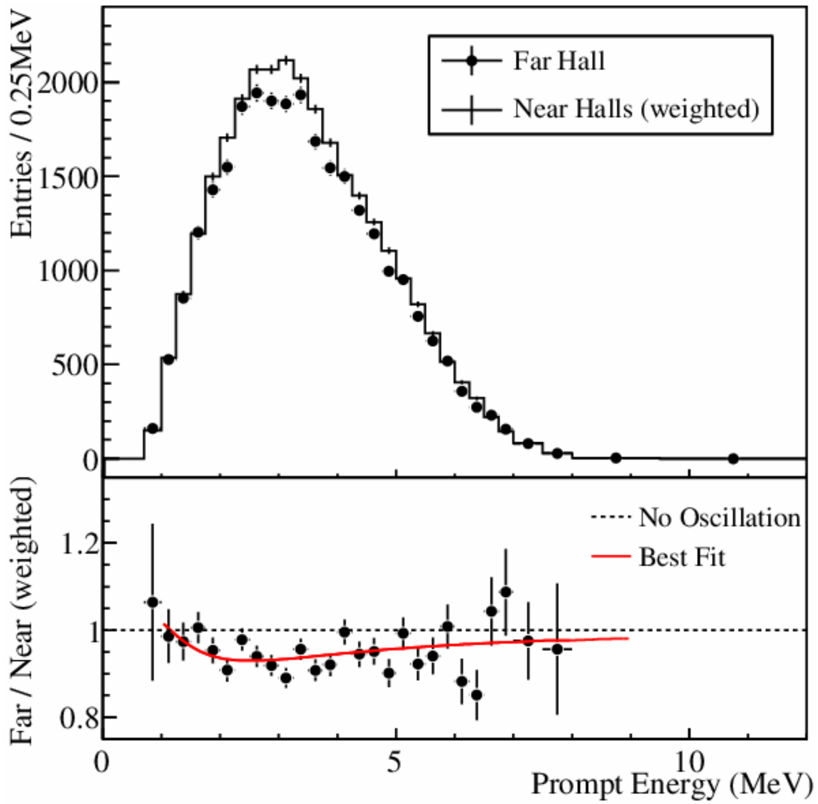


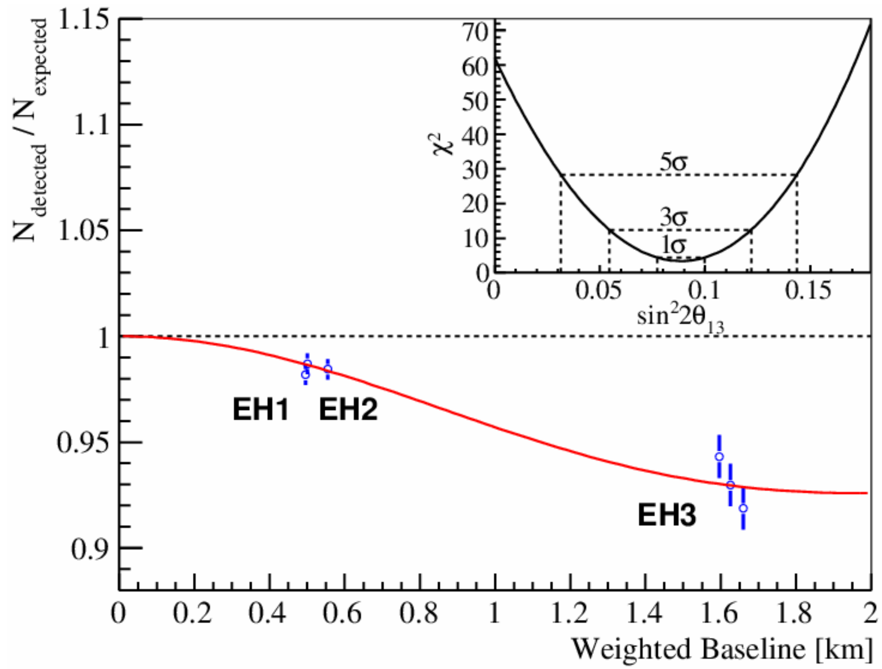
$R = 0.940 \pm 0.011$ (stat) $\pm$ 0.004 (syst)

$\sin^2 2\theta_{13} = 0.092 \pm 0.016$(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.**

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

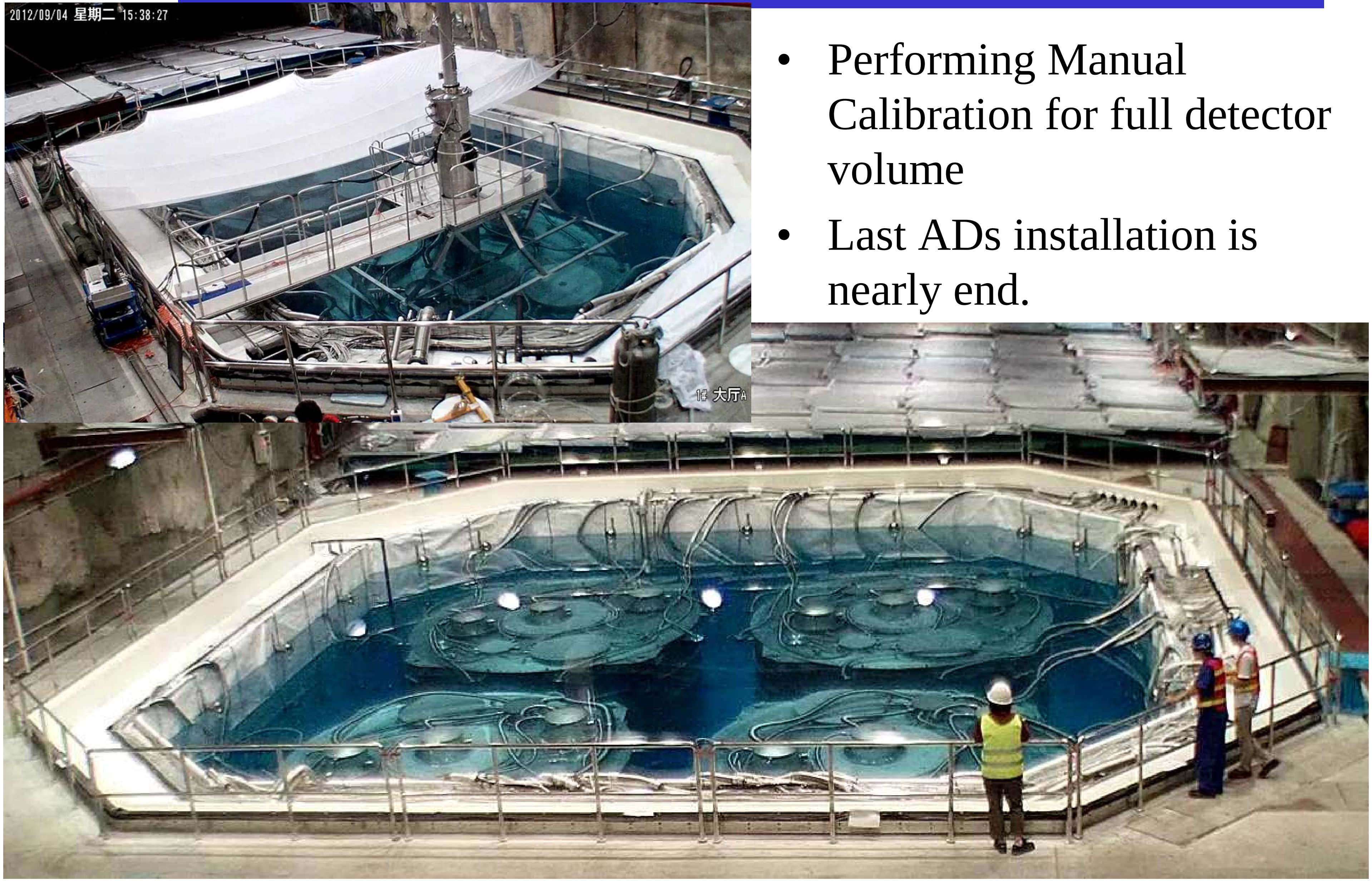
$R = 0.944 \pm 0.007$ (stat) ± 0.003 (syst)

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

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

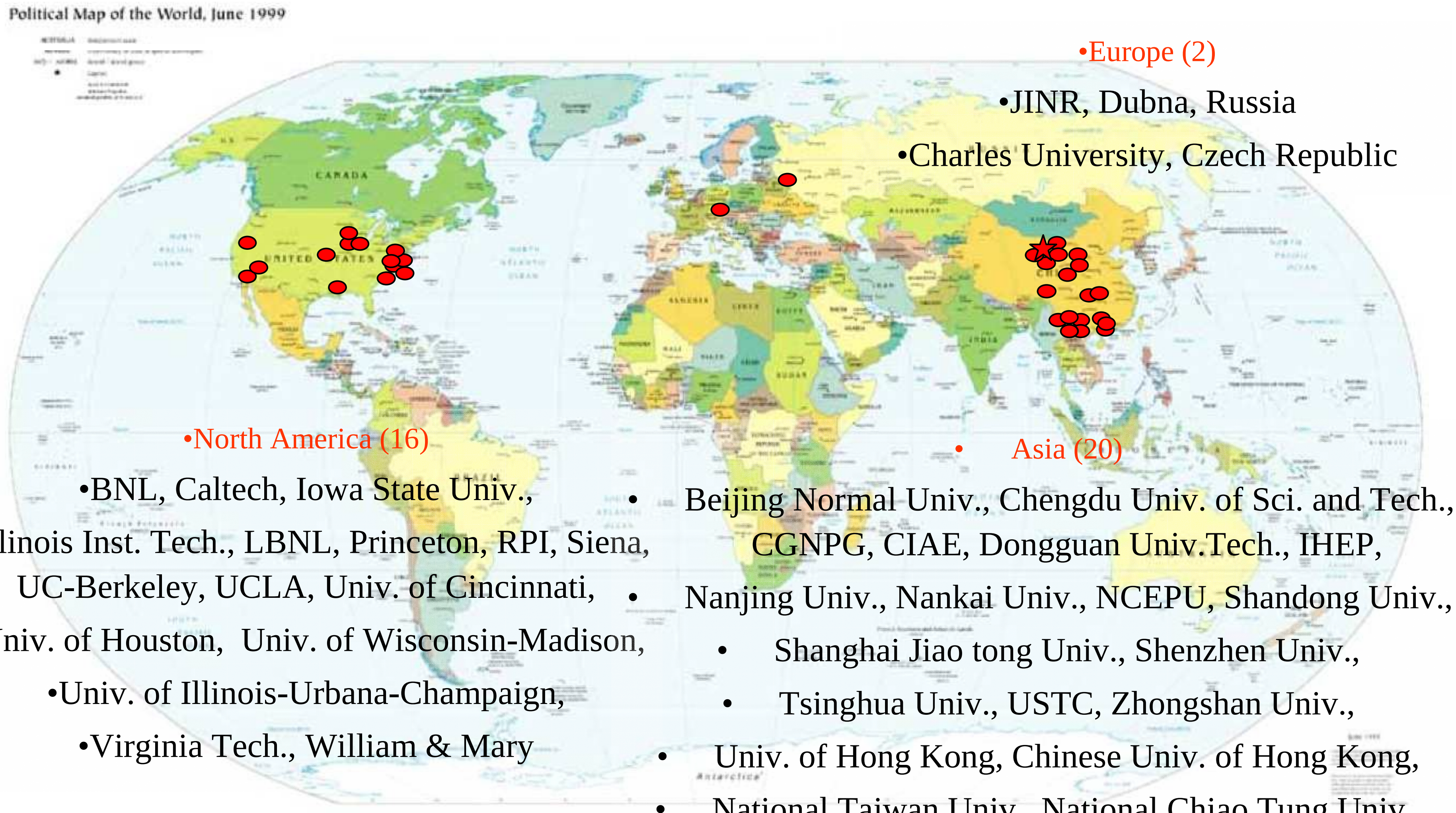
- Install the last two antineutrino detectors, resume 8 ADs operation in October, measure $\sin^2 2\theta_{13}$ to ~5% precision
- Pursue other physics, such as precise reactor ν_e flux and spectrum, and measurement of Δm^2_{31} (~5% precision)
- Liang Zhan, Daya Bay II, Parallel session II, Friday

Present Installation Status



- Performing Manual Calibration for full detector volume
- Last ADs installation is nearly end.

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

Thanks