Observation of Electron-Antineutrino Disappearance at Daya Bay

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On behalf of the Daya Bay Collaboration
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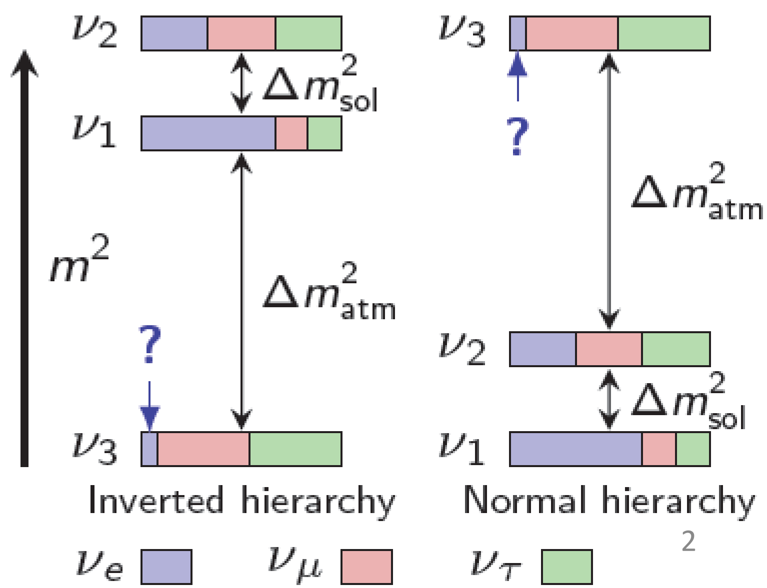
Three neutrino mixing

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

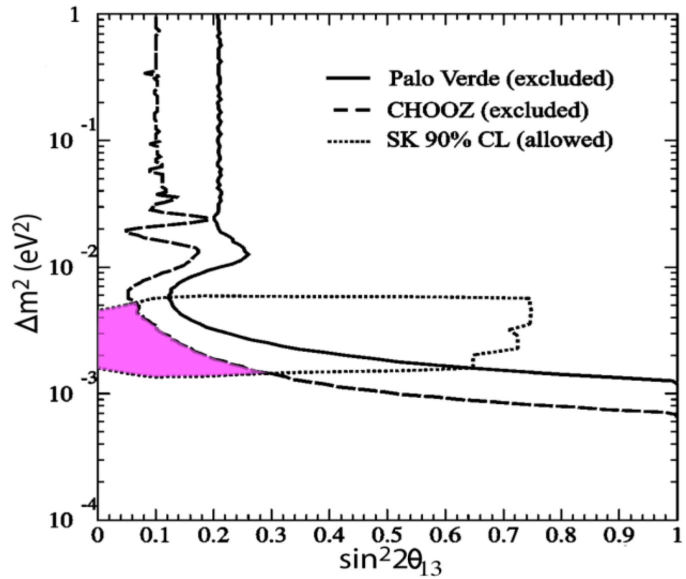
$\theta_{23} = 45^{o}$ Atmospheric Accelerator	$\theta_{13} = ?$ Reactor Accelerator	$\theta_{23} = 34^{o}$ Solar Reactor

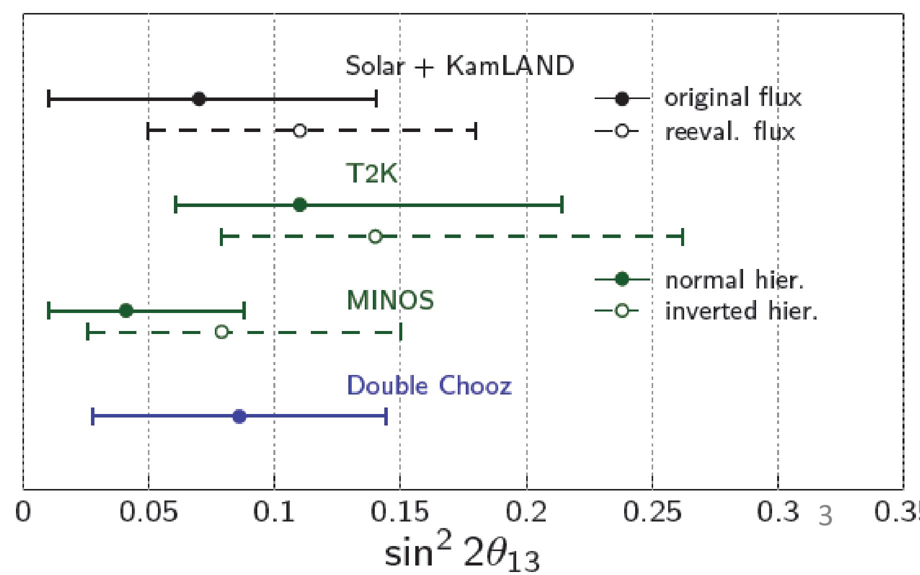
- θ_{13} is the only mixing angle unknown previously.
- Daya Bay experiment aimed to measure $\sin^2 2\theta_{13}$ to 0.01 or better at 90% C.L.



Past measurement of $\sin^2 2\theta_{13}$

- Palo Verde & CHOOZ: only upper limit.
- Global fit (solar + reactor) suggests $\sin^2 2\theta_{13} > 0$.
- T2K, MINOS, and Double Chooz indicate $\sin^2 2\theta_{13} > 0$.
- No results > 2.5σ for $\sin^2 2\theta_{13} > 0$ before Daya Bay.

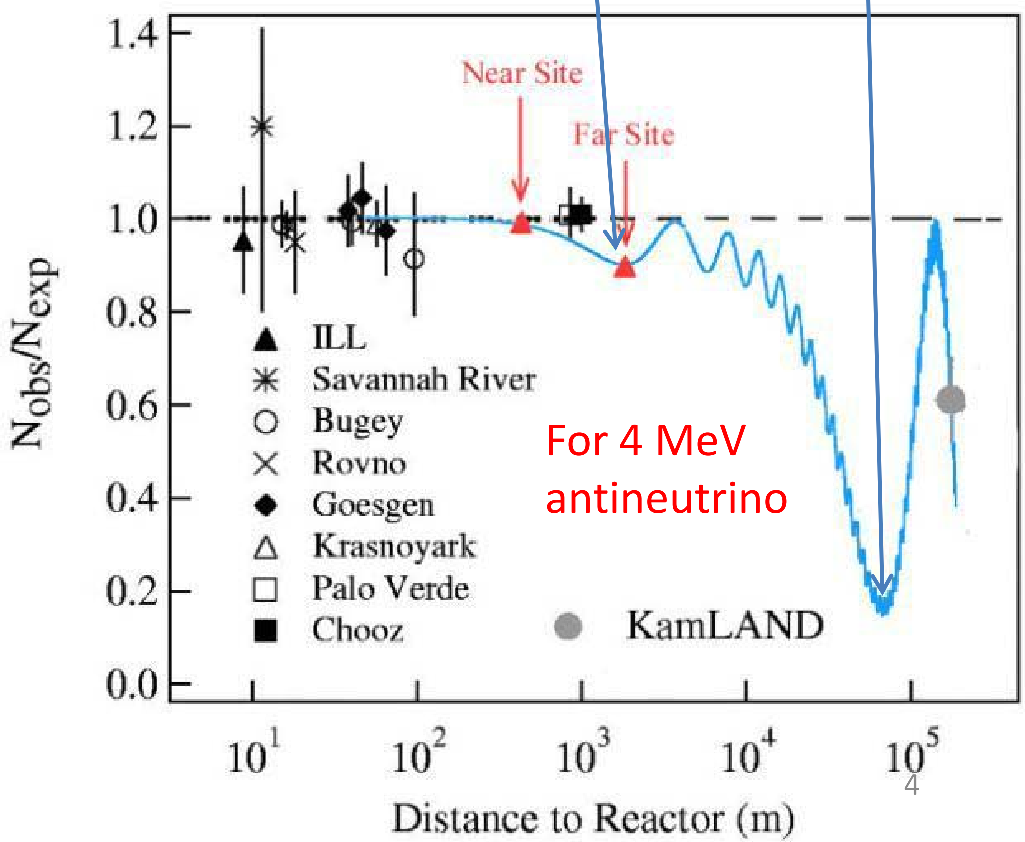




Precision measurement at reactors

- Benefits of reactor
  - Free and pure antineutrino source.
  - No relation with CP phase and matter effect.
- Uncertainties reduction
  - Near-far relative measurement to reduce reactor related errors.
  - 'Identical' and multiple detector modules to verify and reduce detector related errors.
  - Good shielding and enough overburden to reduce backgrounds.

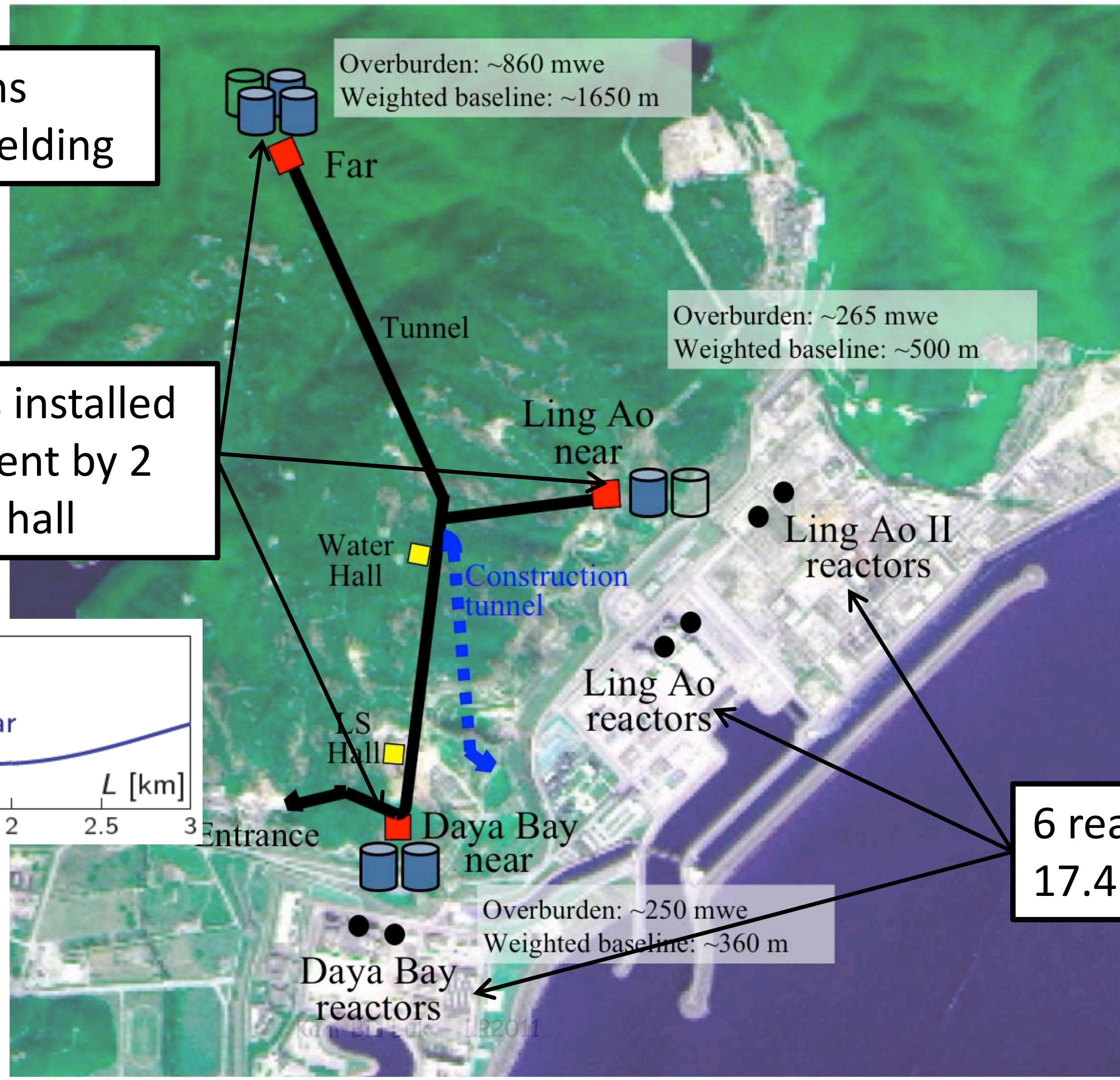
$$P_{\bar{\nu}_e \to \bar{\nu}_e} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\Delta m^2_{31} L / 4E\right) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2\left(\Delta m^2_{21} L / 4E\right)$$

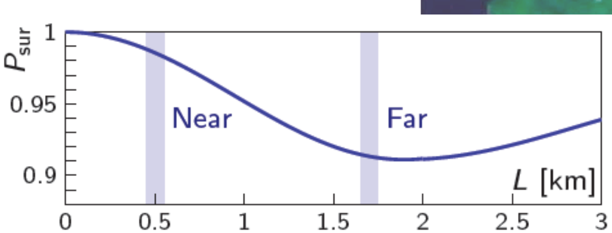


The Daya Bay experiment

Adjacent mountains provide cosmic shielding

6 detector modules installed
Relative measurement by 2 near halls and 1 far hall

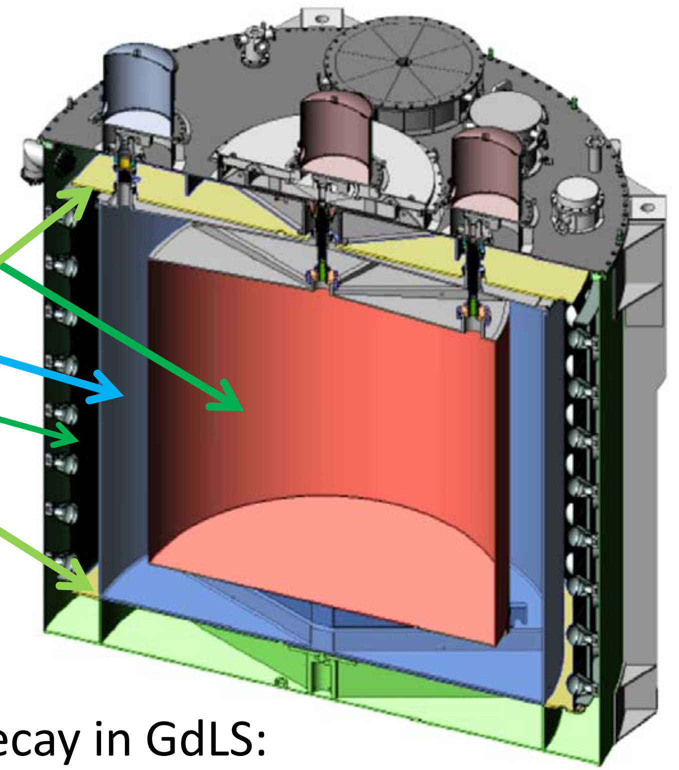


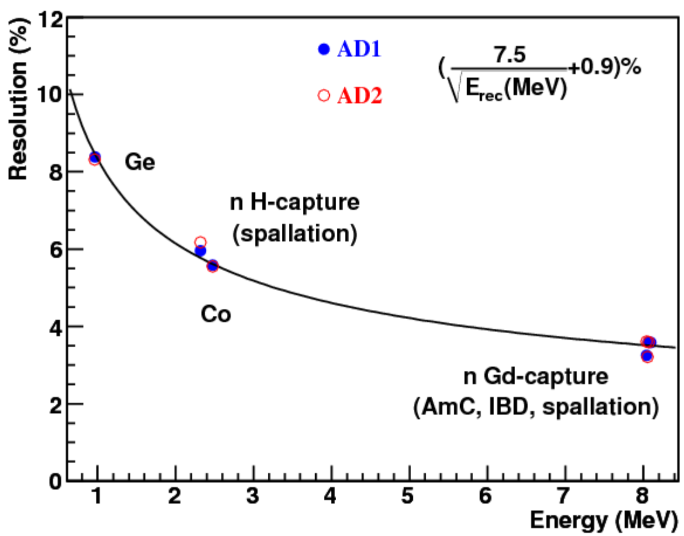


6 reactor cores
17.4 GW_{th} in total

Antineutrino detector

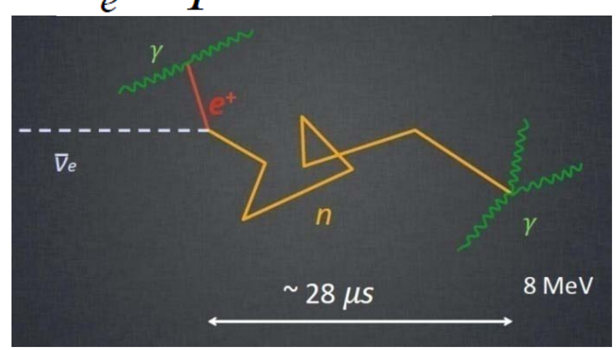
- Three zones structure:
  - Target: 20 t 0.1% Gd-loaded scintillator
  - γ-catcher: 20 t scintillator
  - Buffer shielding: mineral oil
- Top and bottom optical reflectors double the photon coverage.
- 192 8’’ PMTs collect ~163 p.e./MeV





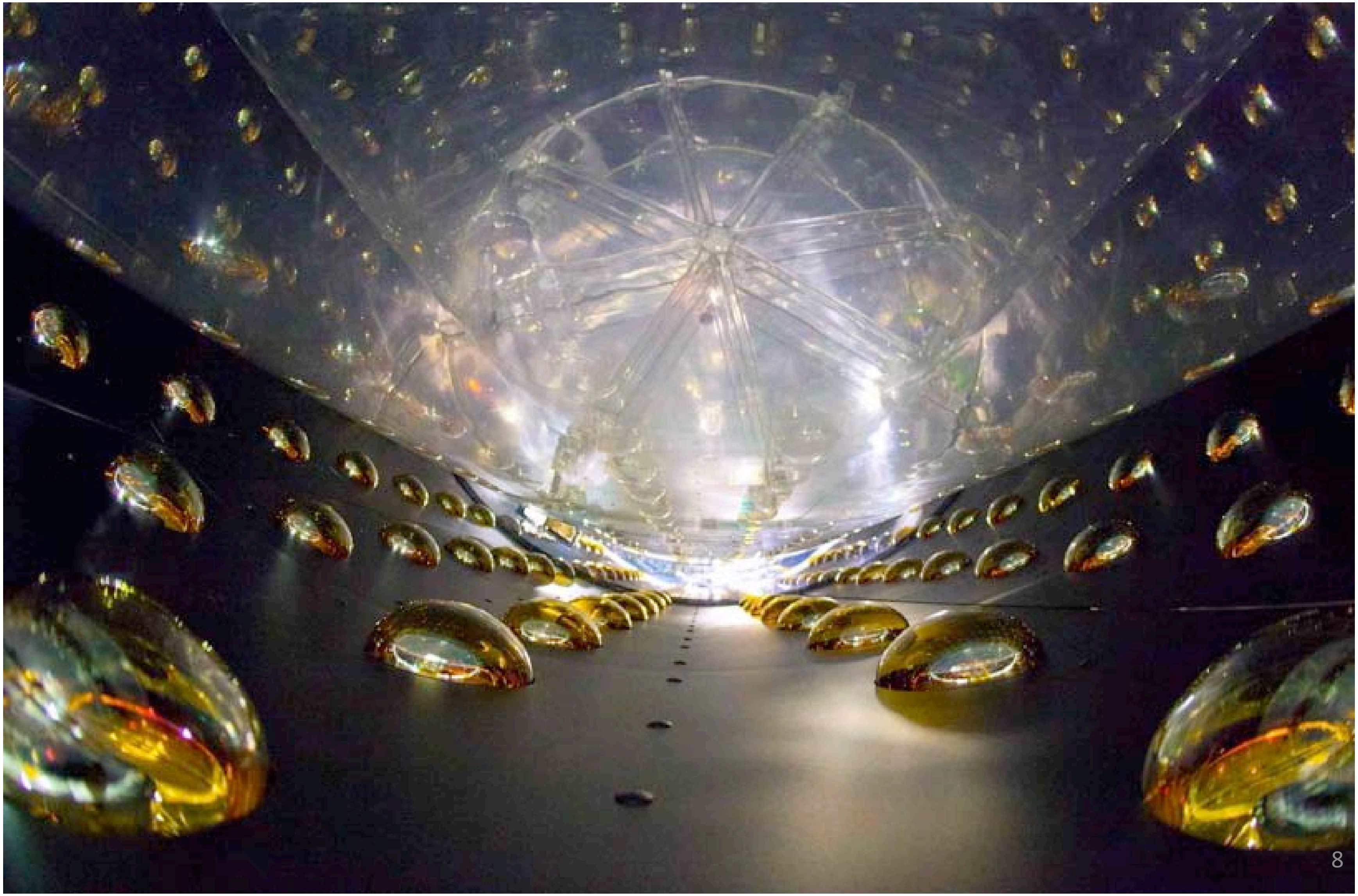
Inverse beta decay in GdLS:

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



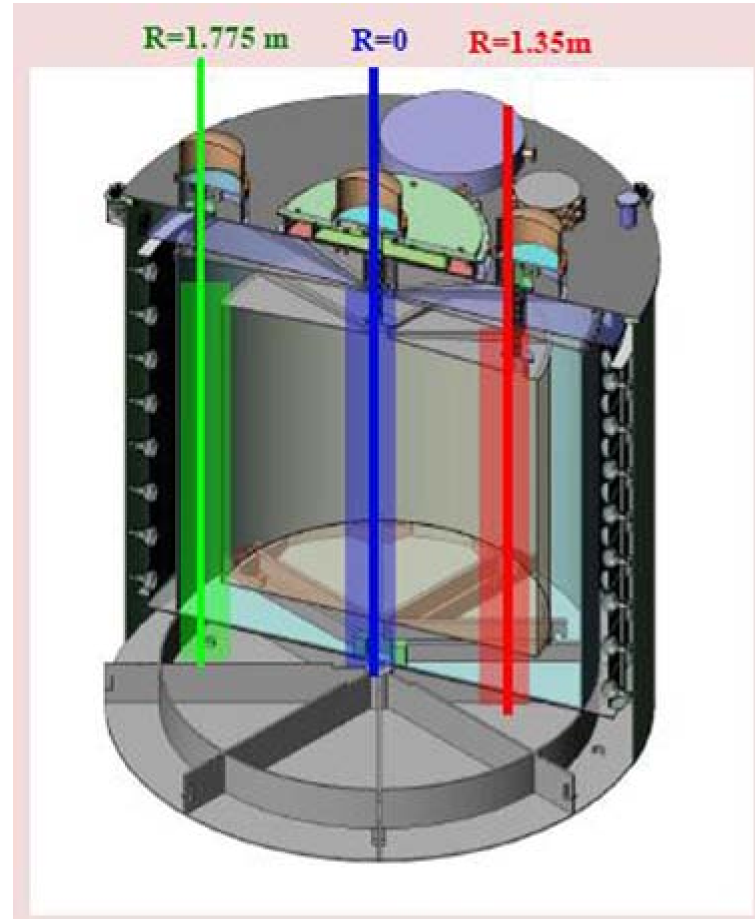
Assembly of antineutrino detector

Interior of antineutrino detector



Automatic calibration system

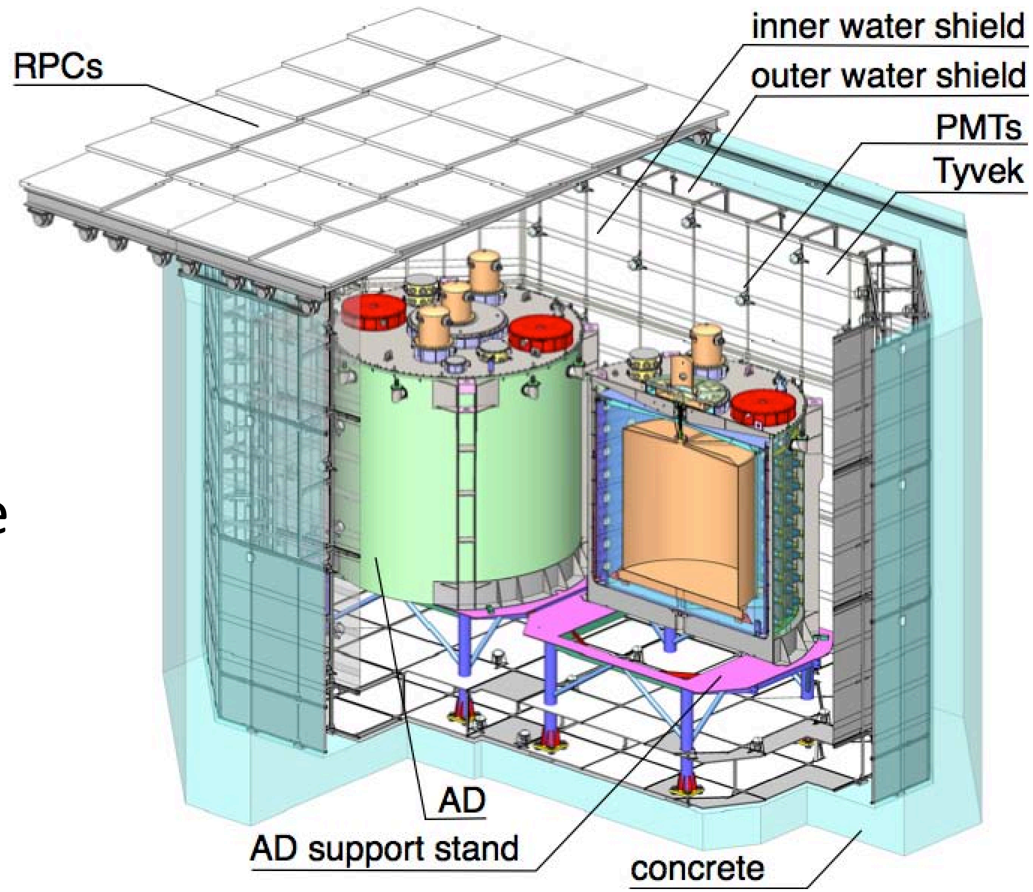
- Three z axis
  - At the center: time evolution, energy scale, non-linearity
  - At the edge: efficiency, spatial response
  - In the γ-catcher: efficiency, spatial response
- Three sources for each z axis
  - LED: PMT gain, relative QE and time offset
  - ^{68}Ge (2x0.511 MeV γs): positron threshold, non-linearity
  - ^{214}Am-^{13}C + ^{60}Co: neutron capture time, energy scale, response function
- Once every week
  - 3 axis, 5 points in Z, 3 sources



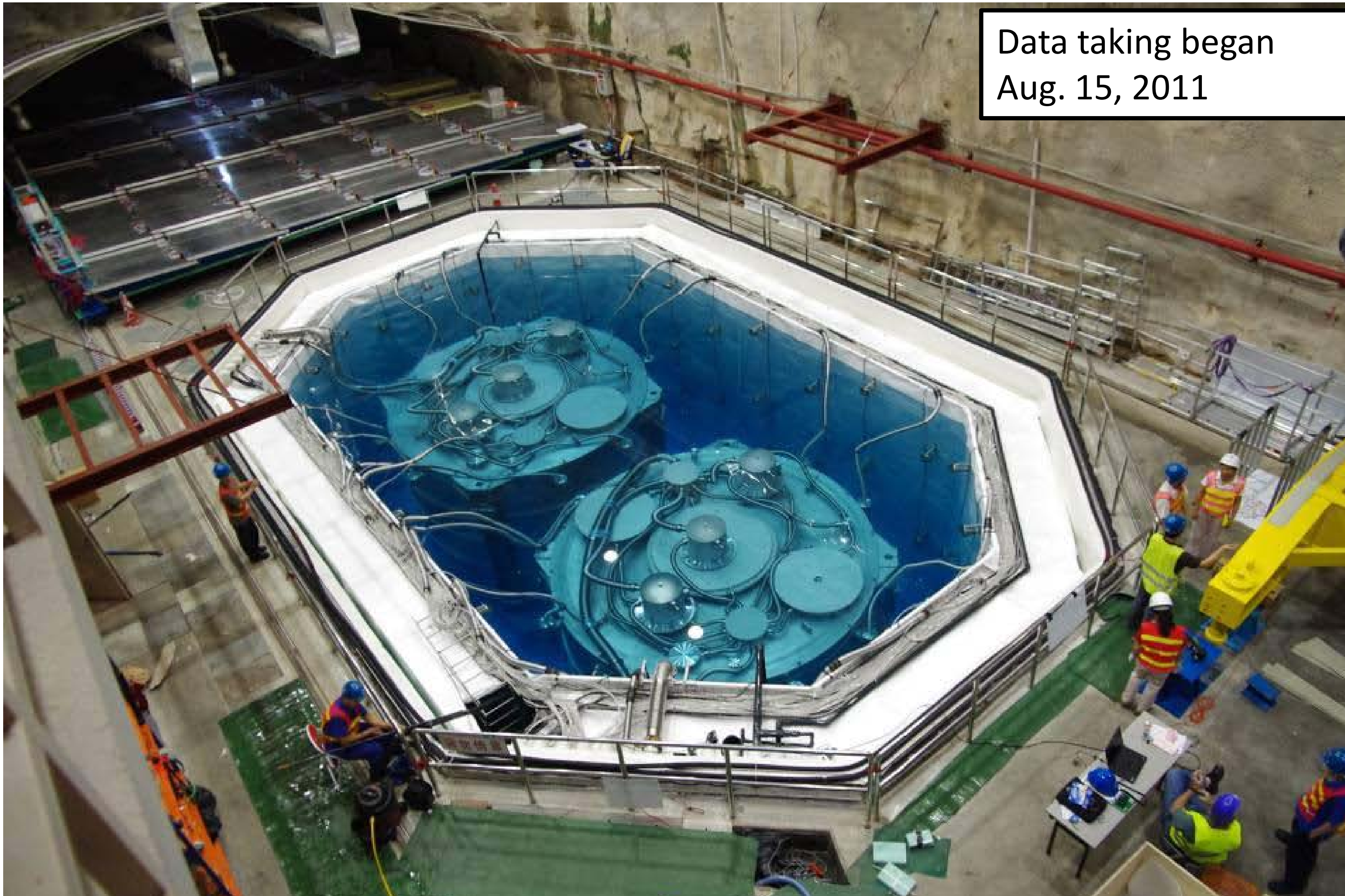
Key to understanding detector and reducing systematic error

Muon veto system

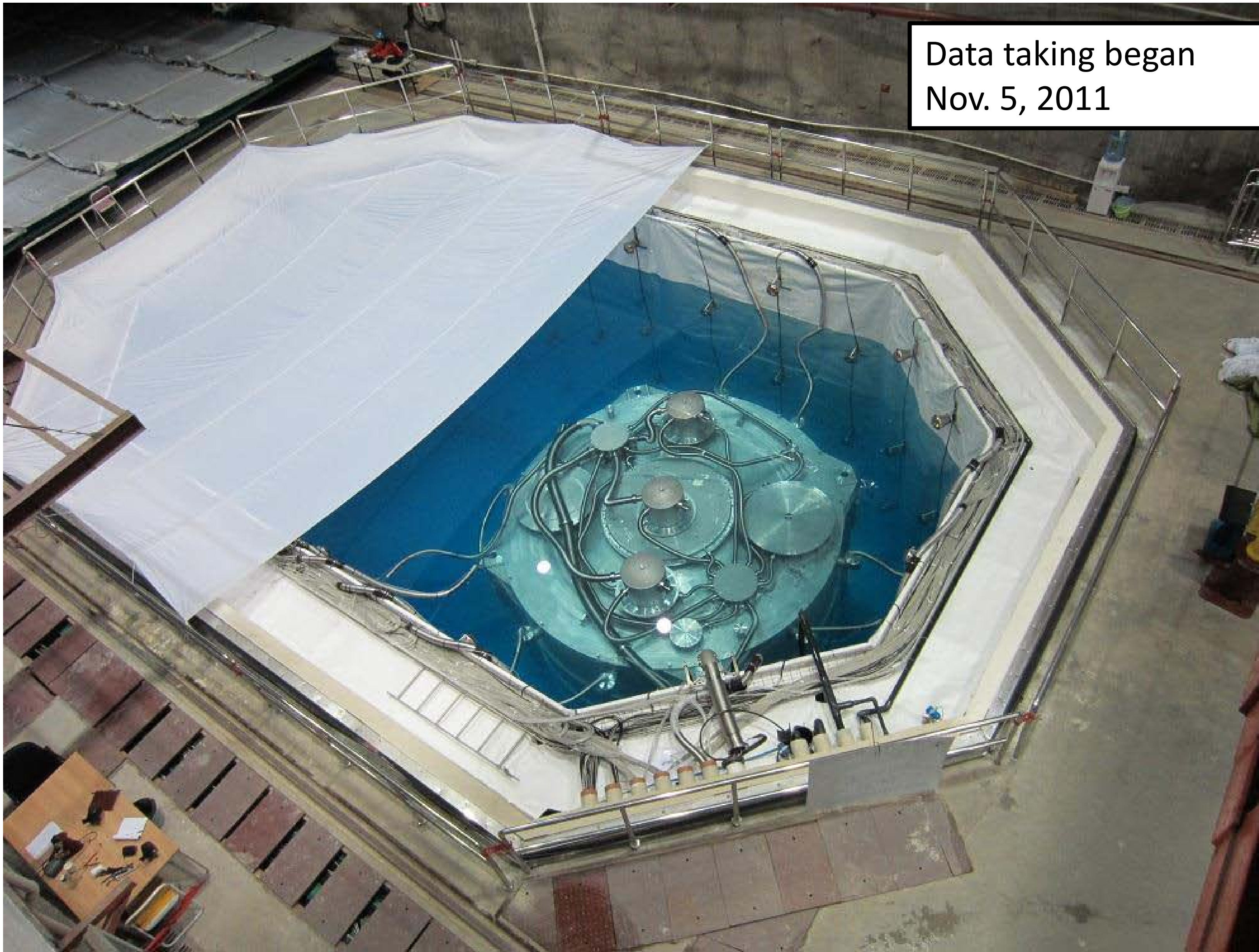
- Water Cerenkov detector
  - Two layers: inner (> 1.5m) and outer (1m) layers
  - Also for shielding
  - 288 8” PMTs in each near hall
  - 384 8” PMTs in Far Hall
- 4-layer RPC modules above pool
  - 54 modules in each near hall
  - 81 modules in Far Hall
  - 2 telescope modules/hall



Two ADs installed in Hall 1

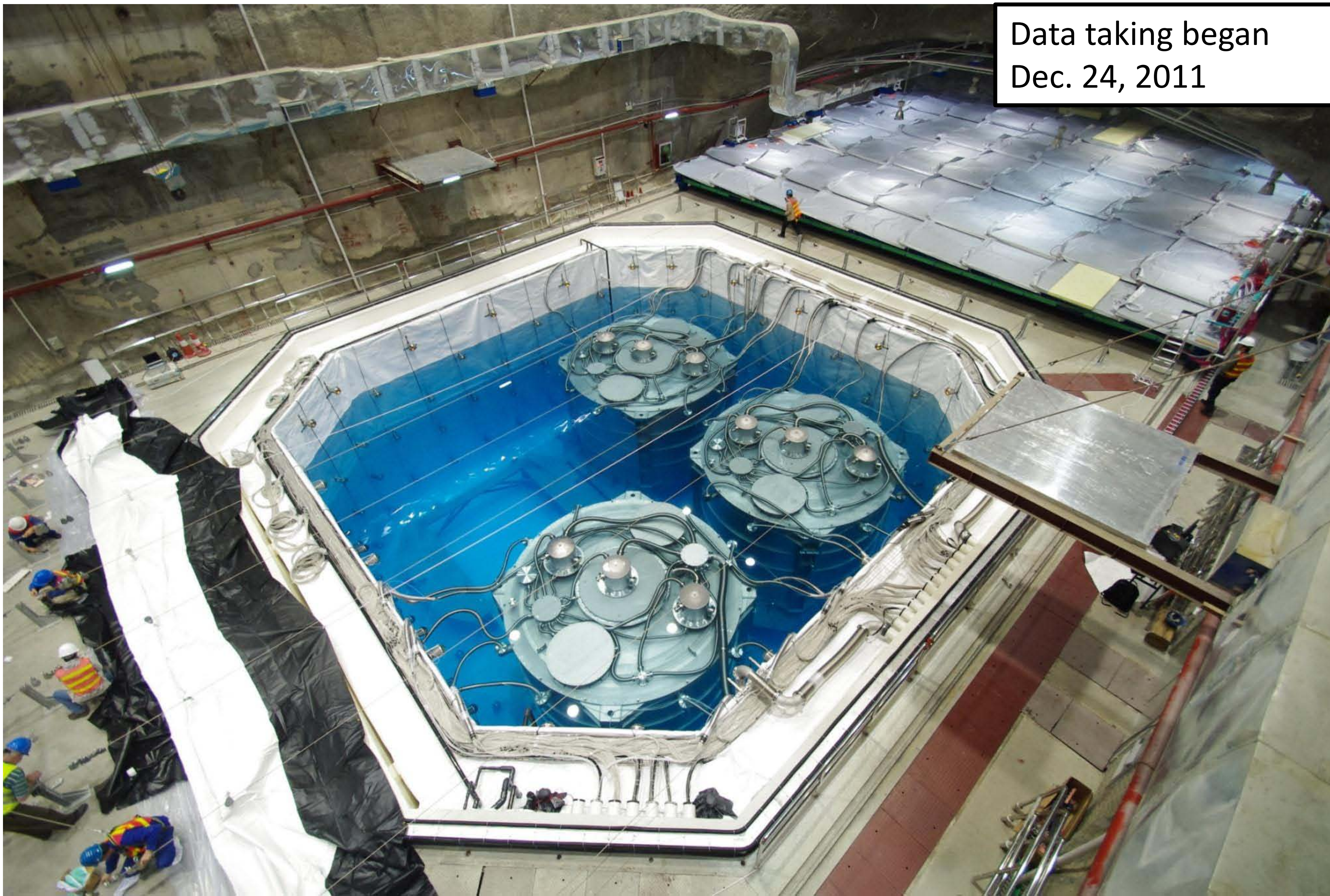


One AD installed in Hall 2



Data taking began
Nov. 5, 2011

Three ADs installed in Hall 3



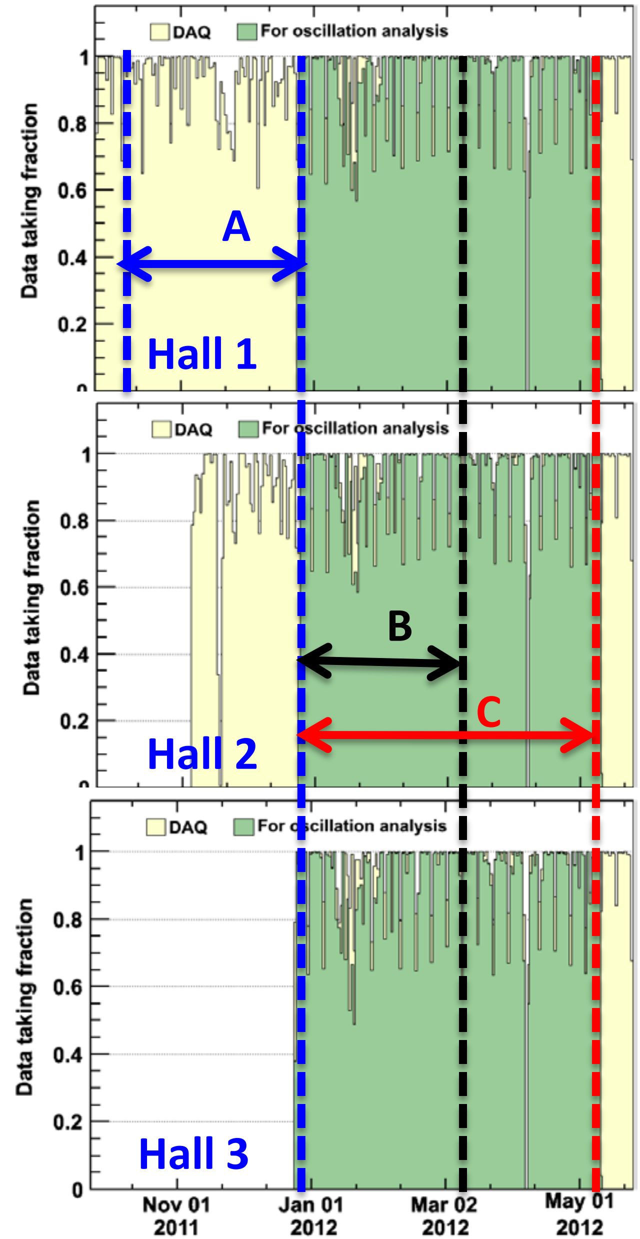
Data taking began
Dec. 24, 2011

Data Period

A. Two Detector Comparison: arXiv:1202:6181
- Sep. 23, 2011 – Dec. 23, 2011
- Side-by-side comparison of 2 detectors in Hall 1
- Demonstrated detector systematics better than requirements.
- Nucl. Inst. and Meth. A 685 (2012), pp. 78-97

B. First Oscillation Result: arXiv:1203:1669
- Dec. 24, 2011 – Feb. 17, 2012
- All 3 halls (6 ADs) operating
- First observation of $\bar{\nu}_e$ disappearance
- Phys. Rev. Lett. **108**, 171803 (2012)

C. Updated result:
- Dec. 24, 2011 – May 11, 2012
- More than 2.5x the previous data set
- To be submitted to Chinese Physics C

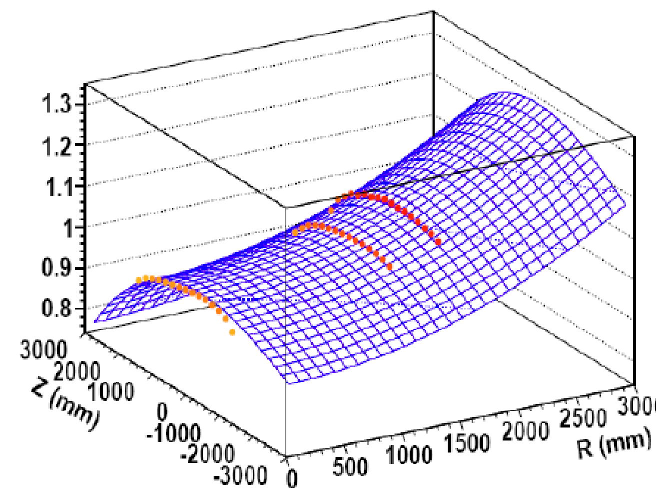


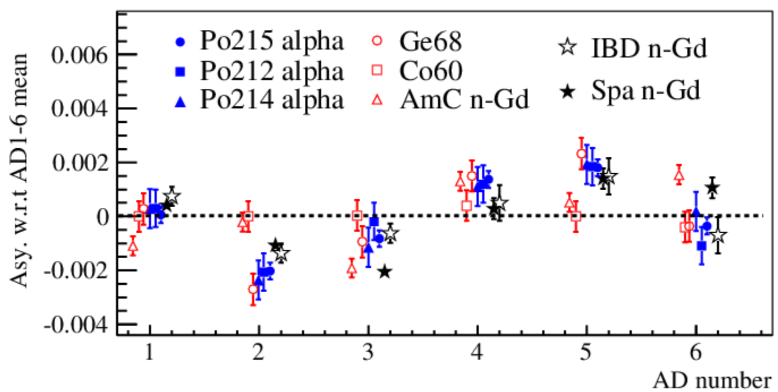
Energy calibration and reconstruction

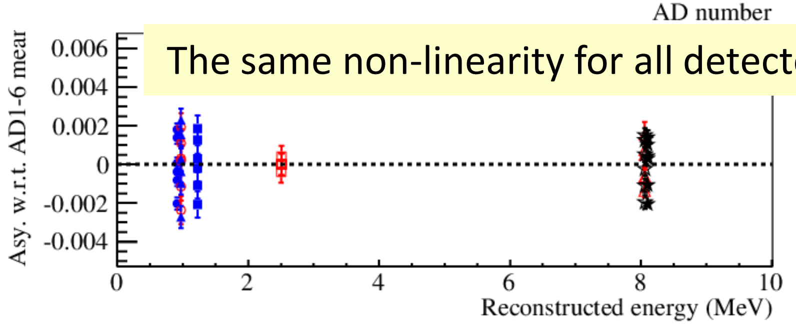
- Low-intensity LED ➔PMT gains are stable to 0.3%
- ^{60}Co at the detector center ➔raw energies
  - Correct small (0.2%) time dependence
- ^{60}Co at different positions in detector
  - Correct spatial dependence
- Calibrate energy scale using neutron capture peak

➔0.12% efficiency difference among detectors

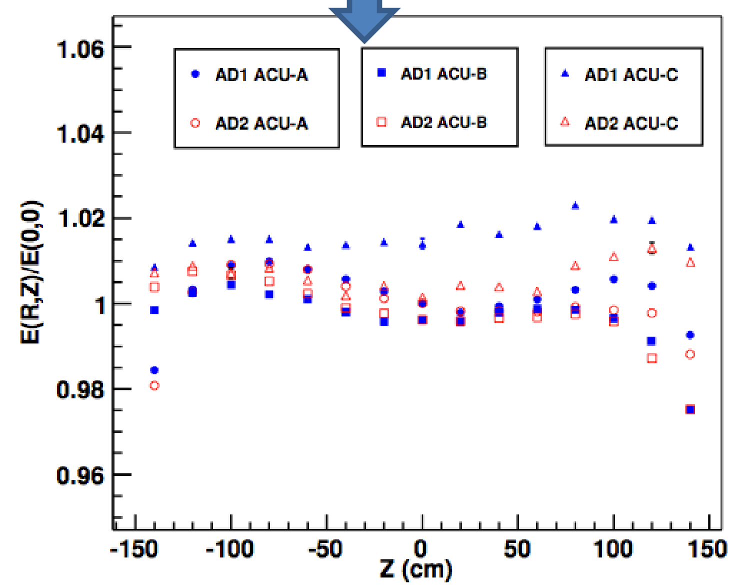
$f(R,Z) = f_1(R) * f_2(Z)$





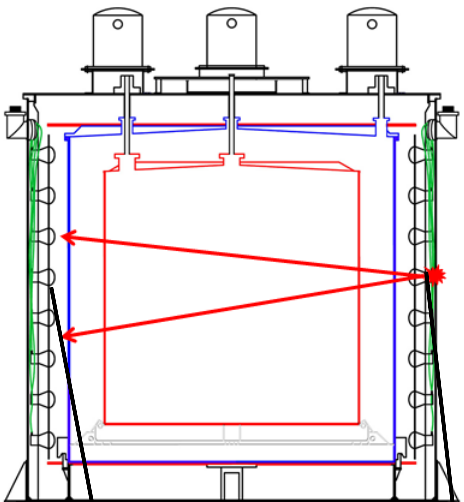


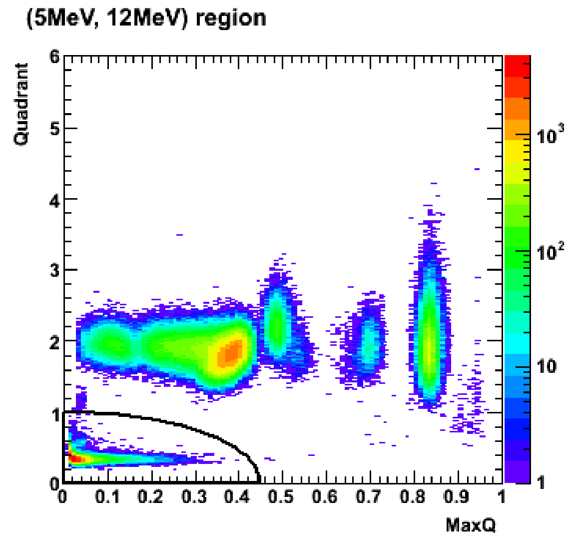
The same non-linearity for all detectors



PMT flashers

- PMT spontaneous light, rejected by hit pattern discriminator

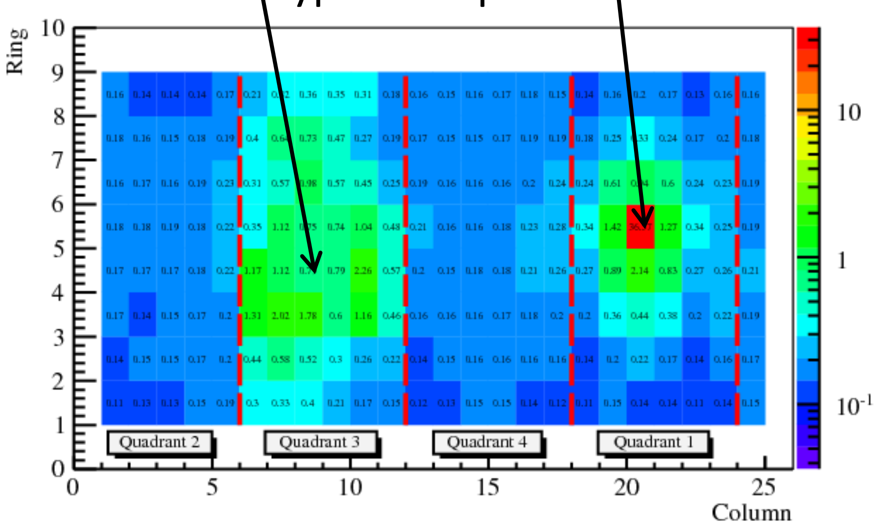


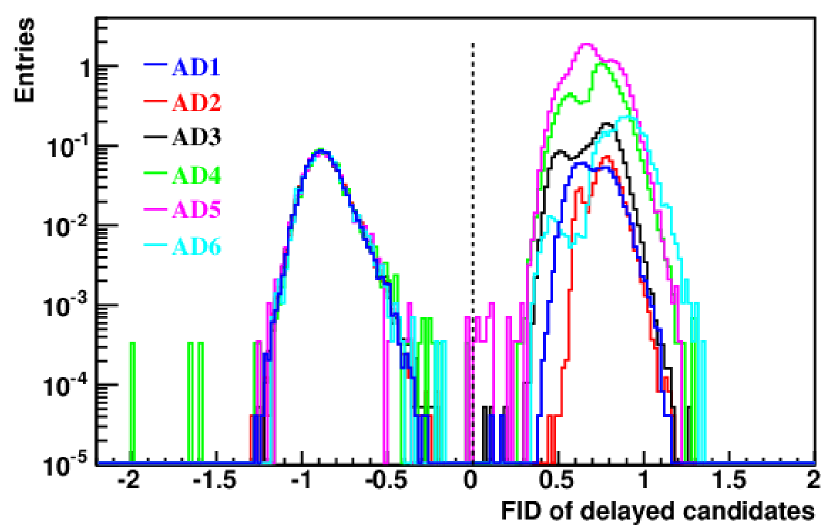


~5% PMTs and ~ 5% events.

Efficiency 99.98%
Uncertainty 0.01%

Typical hit pattern





Event signature and backgrounds

- Signature:
  - 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
- Five backgrounds identified
  - 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
    - ^{8}He/^{9}Li: prompt - β decay, delayed - n capture
    - Am-C source: prompt - γ rays, delayed - n capture
    - α -n: $^{13}C(\alpha,n)^{16}O$: prompt - ^{16}O de-excitation, delayed – n capture

Prompt signal

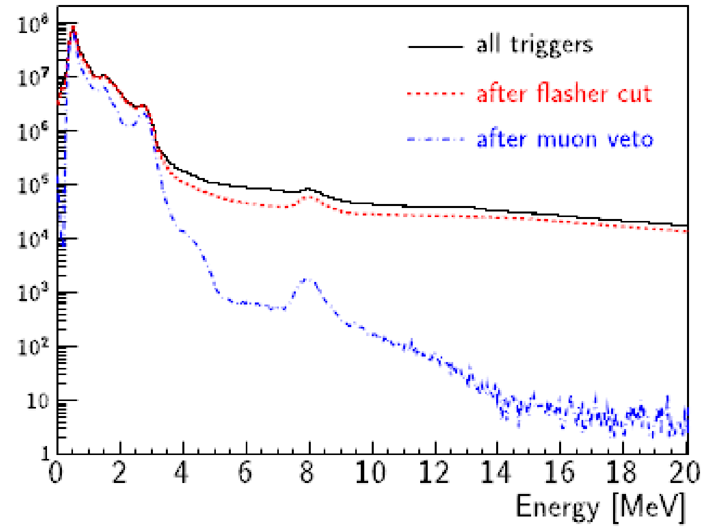
$$e^{+} + e^{-} \rightarrow 2\gamma$$

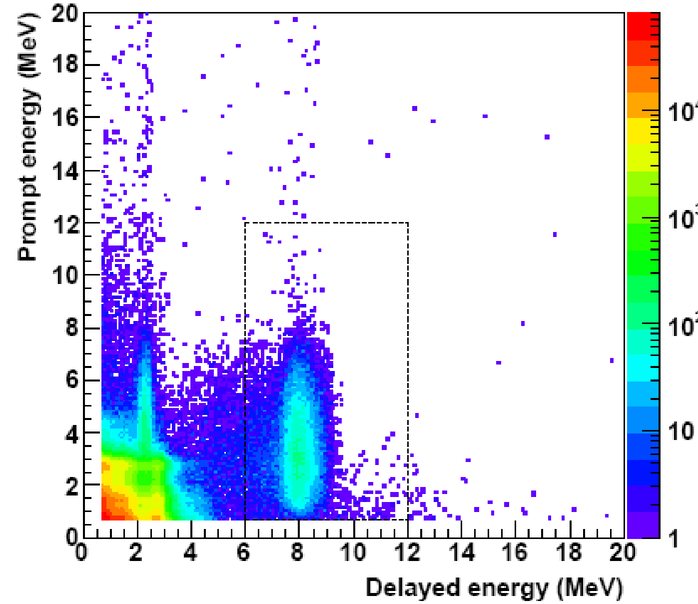
$$\bar{\nu}_e + p \rightarrow e^{+} + n$$

Delayed signal, Capture on H (2.2 MeV) or Gd (8 MeV), ~30μs

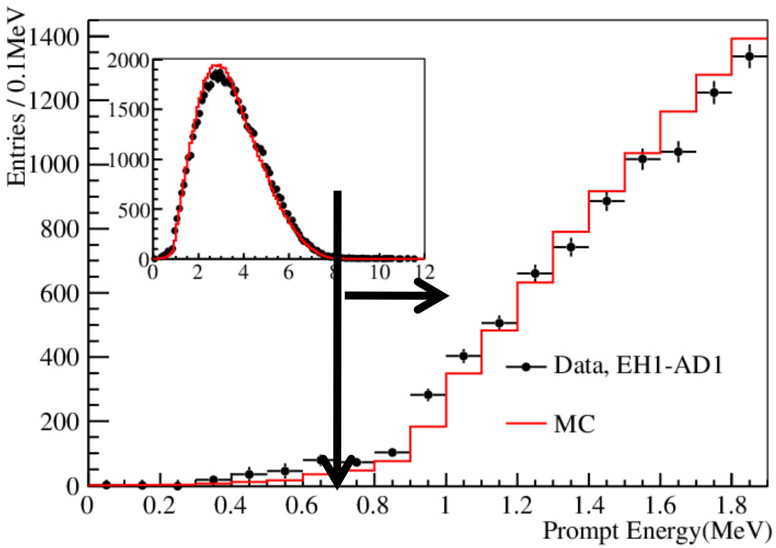
Antineutrino events selection

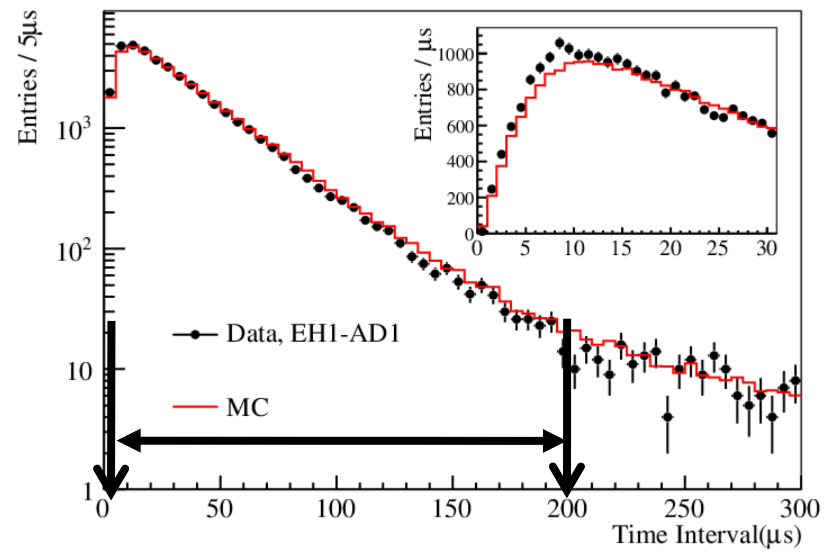
- Reject PMT flashers
- Prompt positron:
  - 0.7 MeV < E_p < 12.0 MeV
- Delayed neutron:
  - 6.0 MeV < E_d < 12.0 MeV
- Neutron capture time:
  - 1 μs < $\Delta t_{p\text{-}d}$ < 200 μs
- Muon veto
  - Water pool muon: reject 0.6 ms
  - AD tagged muon: reject 1 ms
  - AD shower muon: reject 1 s
- Multiplicity: no other signal > 0.7 MeV in -200 μs to 200 μs of IBD.

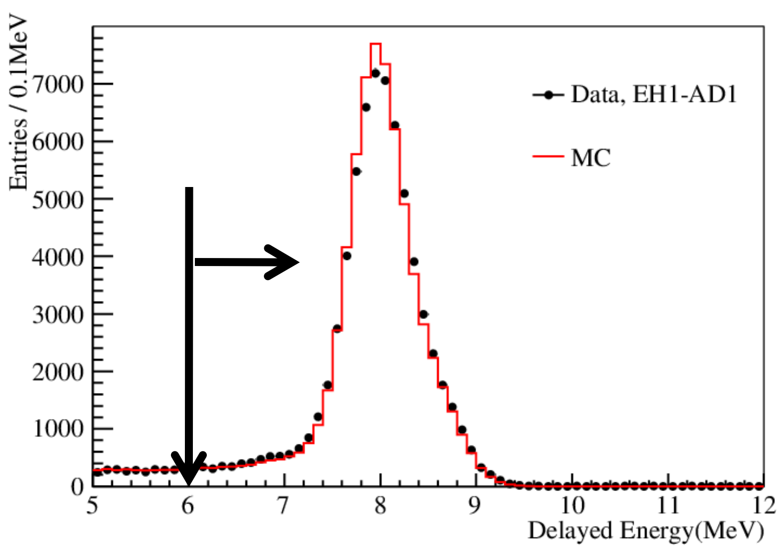




Energy and time cut efficiency







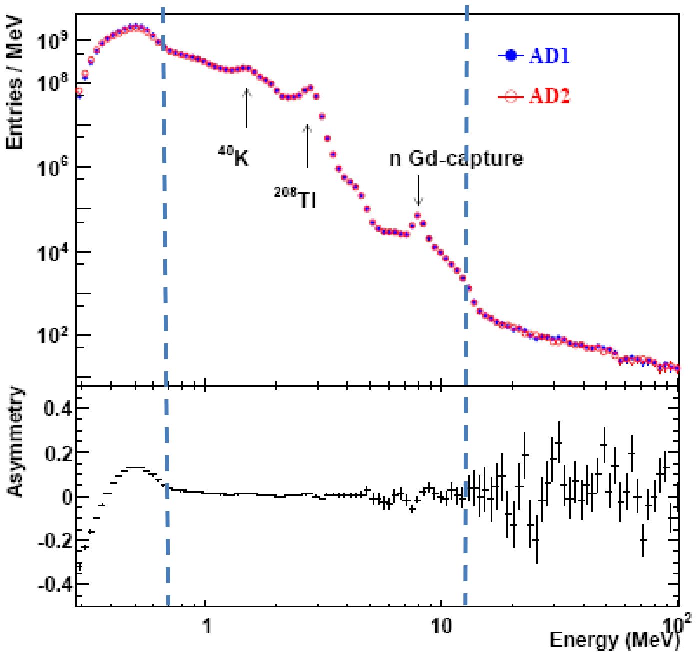
	Eff.	Corr.	Uncorr.
Prompt	90.9%	0.6%	0.12%
Delayed	99.88%	0.10%	0.01%
Capture time	98.6%	0.12%	0.01%

Systematic error studied by comparing MC and data, or AD identicality

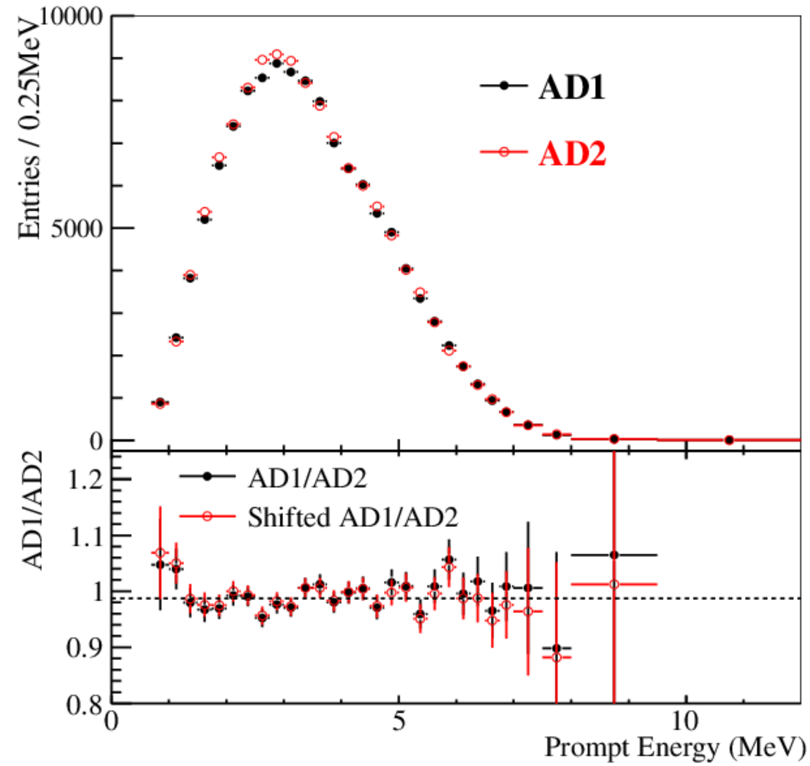
Side-by-side comparison

- Multiple detectors allow detailed comparison and cross-checks of systematic error

Two ADs in Hall 1 have functionally identical spectra and response in 0.7-12MeV

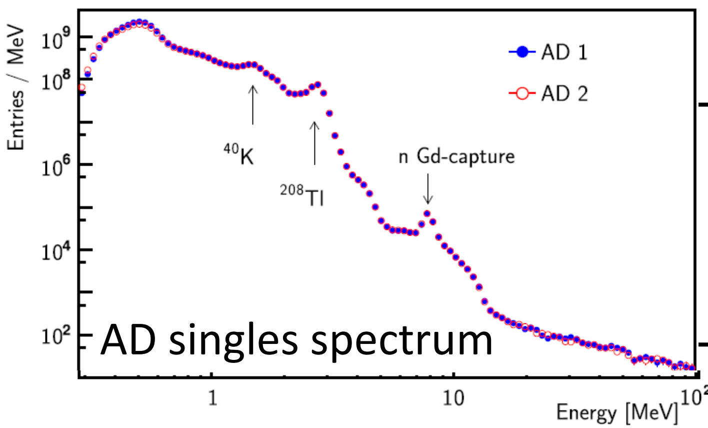


Expected rate ratio R(AD1/AD2) = 0.982 (not 1 due to different baseline and target mass)
Measured 0.987 ± 0.004(stat) ± 0.003(syst)



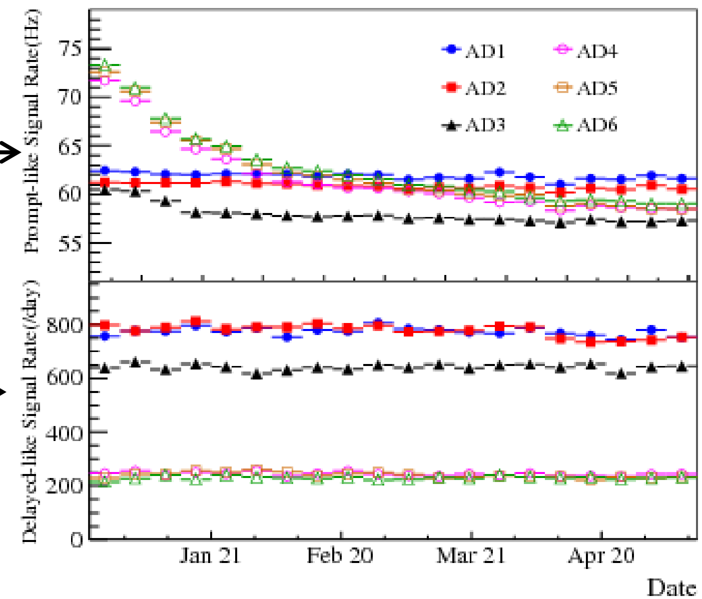
Backgrounds: accidentals

Accidental background rate calculated by coincidence probability, and rate of the prompt and delayed singles

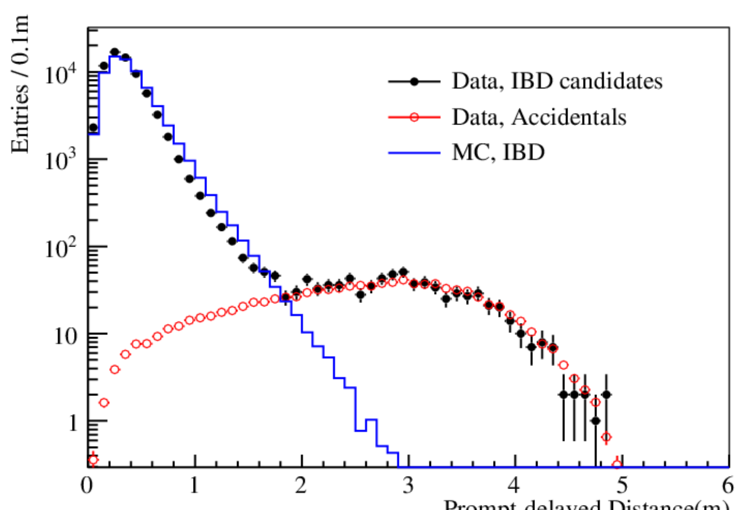


Prompt rate
0.7-12 MeV

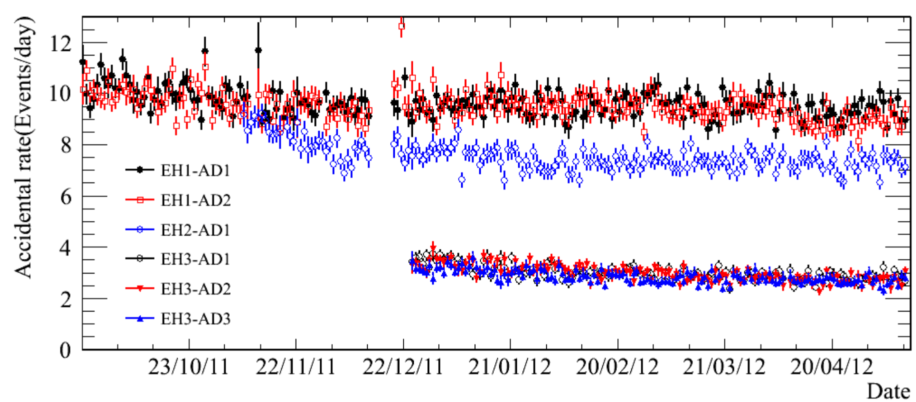
Delayed rate
6-12 MeV



Cross check using prompt-delayed distance, and off-window coincidence

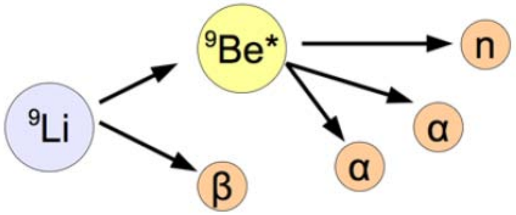


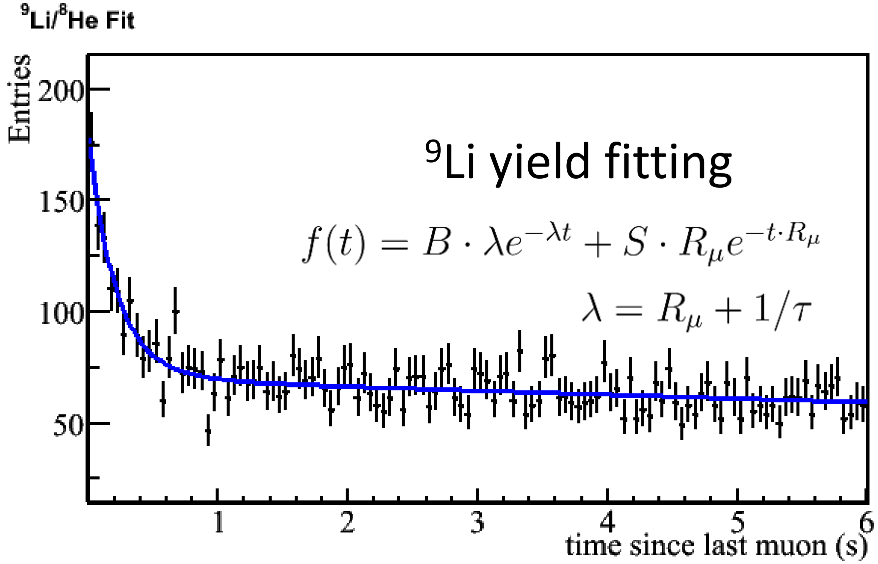
Accidental backgrounds rate

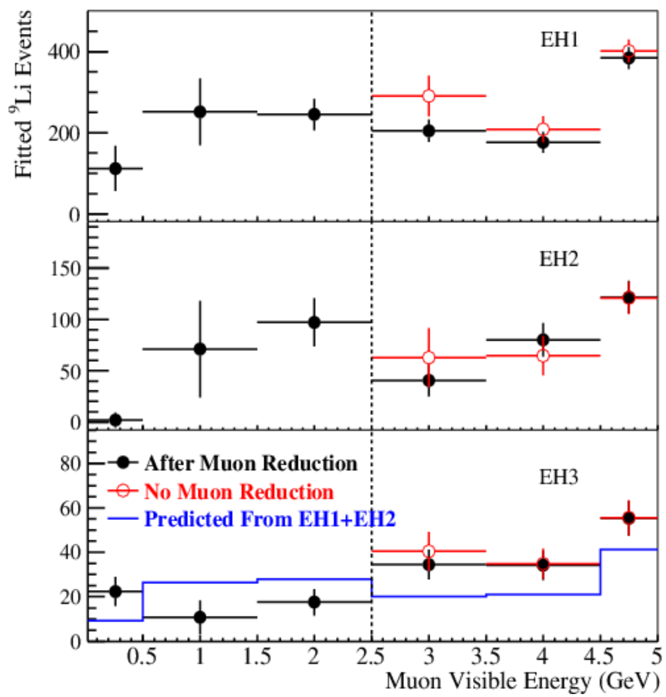


Backgrounds: $^9Li/^8He$

- Cosmic μ produces $^9Li/^8He$ in LS
  - β-decay + neutron emitter
- Measurement
  - Time-since-last-muon fit method
  - Improve the precision by preparing muon samples w/ and w/o followed neutrons



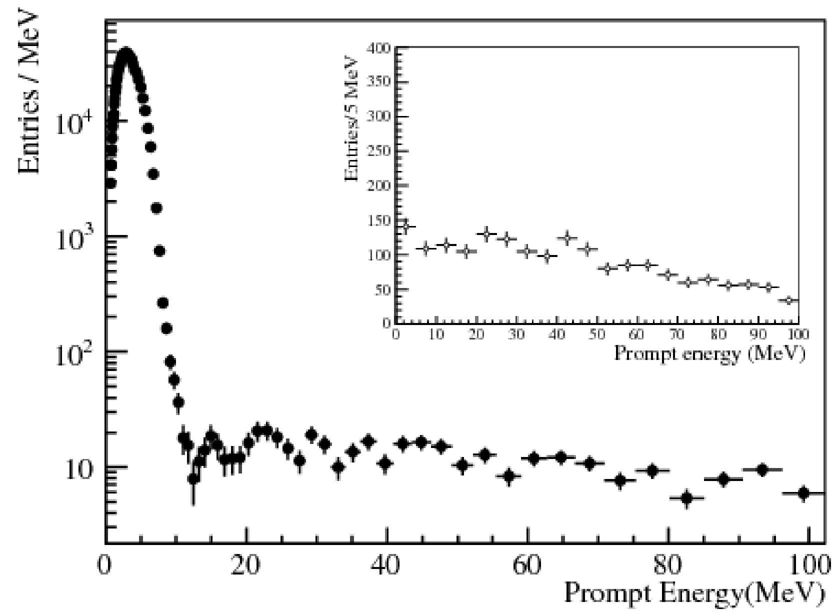




ΔB/B = 50%

Backgrounds: fast neutron

- Cosmic μ produces neutron
  - Prompt: recoiling proton
  - Delayed: neutron capture
- Method I
  - Extend prompt energy cut (E_p < 12 MeV) to 100 MeV.
  - Extrapolate the part in 12-100 MeV to 0.7-12 MeV.
- Method II
  - Extrapolate the tagged fast neutron to the untagged fast neutron using the muon veto inefficiency.



Two methods have consistent result

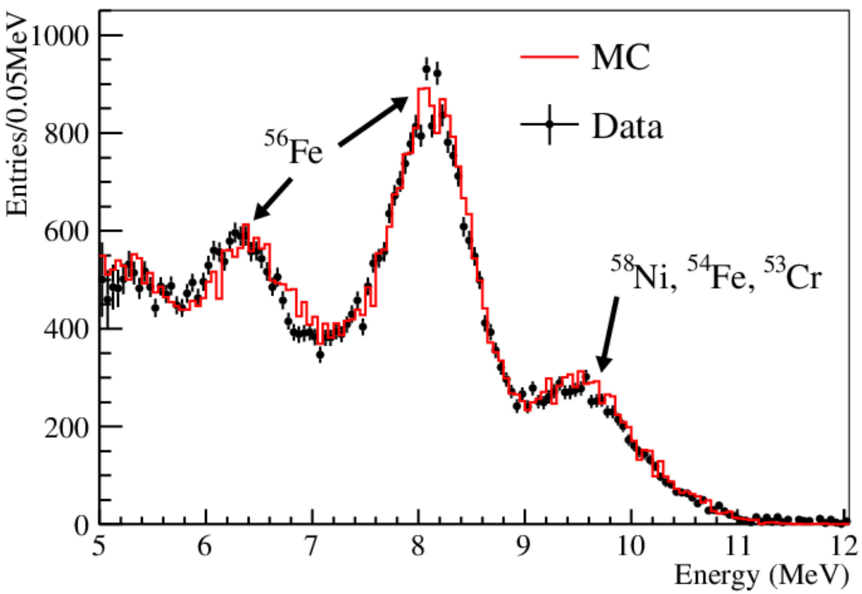
ΔB/B = 40%

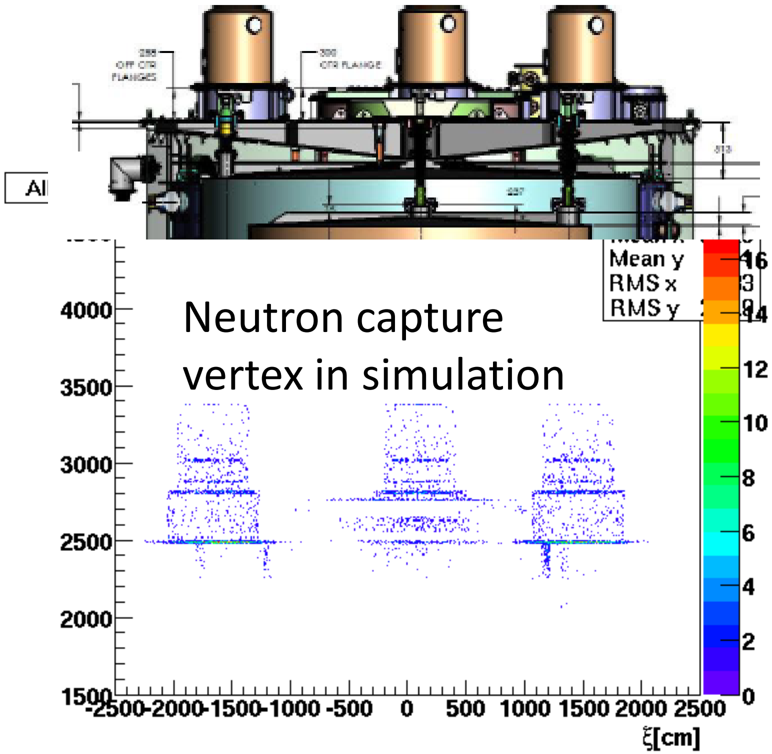
$$n_f = n_f^{iws} \cdot (1 - \epsilon_{iws}) + n_f^{ows} \cdot (1 - \epsilon_{ows}) + n_f^{rock}$$

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

- Correlated backgrounds from ^{241}Am-^{13}C source in ACUs.
  - Neutron inelastic scattering with ^{56}Fe + neutron capture on ^{57}Fe
  - Simulation shows that correlated backgrounds is 0.2 events/day/AD
  - $\Delta B/B$ = 100%

^{241}Am-^{13}C source activities constrained by MC/data comparison

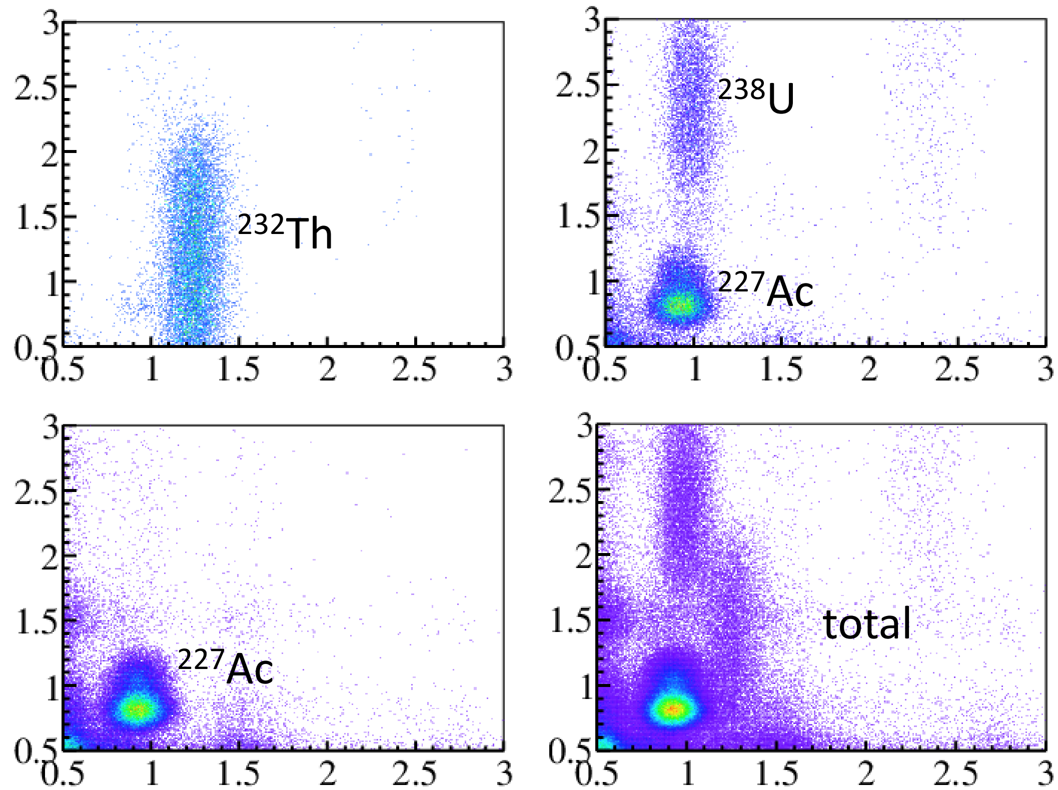




Backgrounds: $^{13}C(\alpha,n)^{16}O$

- Identify α sources (^{238}U, ^{232}Th, ^{227}Ac, ^{210}Po) and rates from cascade decays and spatial distribution
- Calculate backgrounds from α rate and (α,n) cross sections

Source	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	0.07 Bq	0.001/day
^{232}Th	1.2 Bq	0.01/day



Backgrounds summary

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

The background induced systematic errors of antineutrino rate are 0.21% for near halls and 0.37% for far hall

Event rate summary (to May 11, 2012)

	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	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					
$^{13}C(\alpha, n)^{16}O$ (/day)	0.08±0.04	0.07±0.0 4	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**

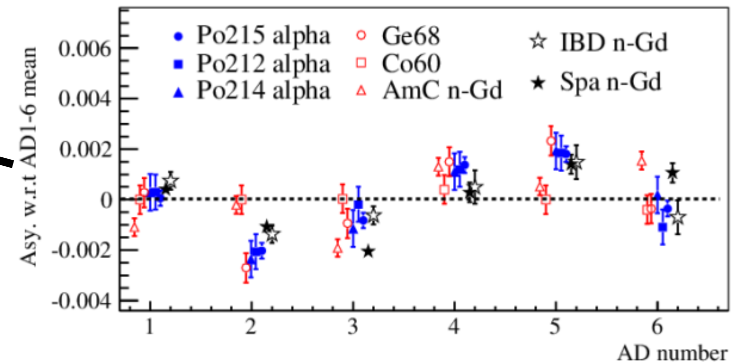
Current uncertainties dominated by statistics

Efficiency and uncertainties

Detector			
	Efficiency	Correlated	Uncorrelated
Target Protons		0.47%	0.03%
Flasher cut	99.98%	0.01%	0.01%
Delayed energy cut	90.9%	0.6%	0.12%
Prompt energy cut	99.88%	0.10%	0.01%
Multiplicity cut		0.02%	<0.01%
Capture time cut	98.6%	0.12%	0.01%
Gd capture ratio	83.8%	0.8%	<0.1%
Spill-in	105.0%	1.5%	0.02%
Livetime	100.0%	0.002%	<0.01%
Combined	78.8%	1.9%	0.2%

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

For near/far oscillation, only uncorrelated uncertainties are used.



Largest uncertainty studied by AD asymmetries

Reactor uncorrelated uncertainty can be reduced by near/far relative measurement (x1/20).

Reactor neutrino flux

- Reactor neutrino spectrum

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

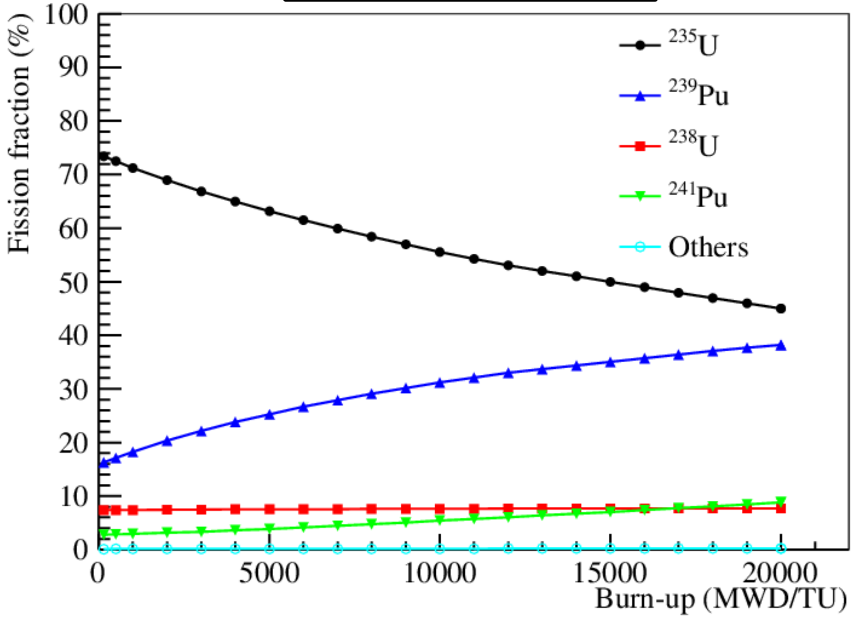
Thermal power $\mathbf{W_{th}}$ provided by reactor power plant

Fission energy $\mathbf{e_i}$

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)

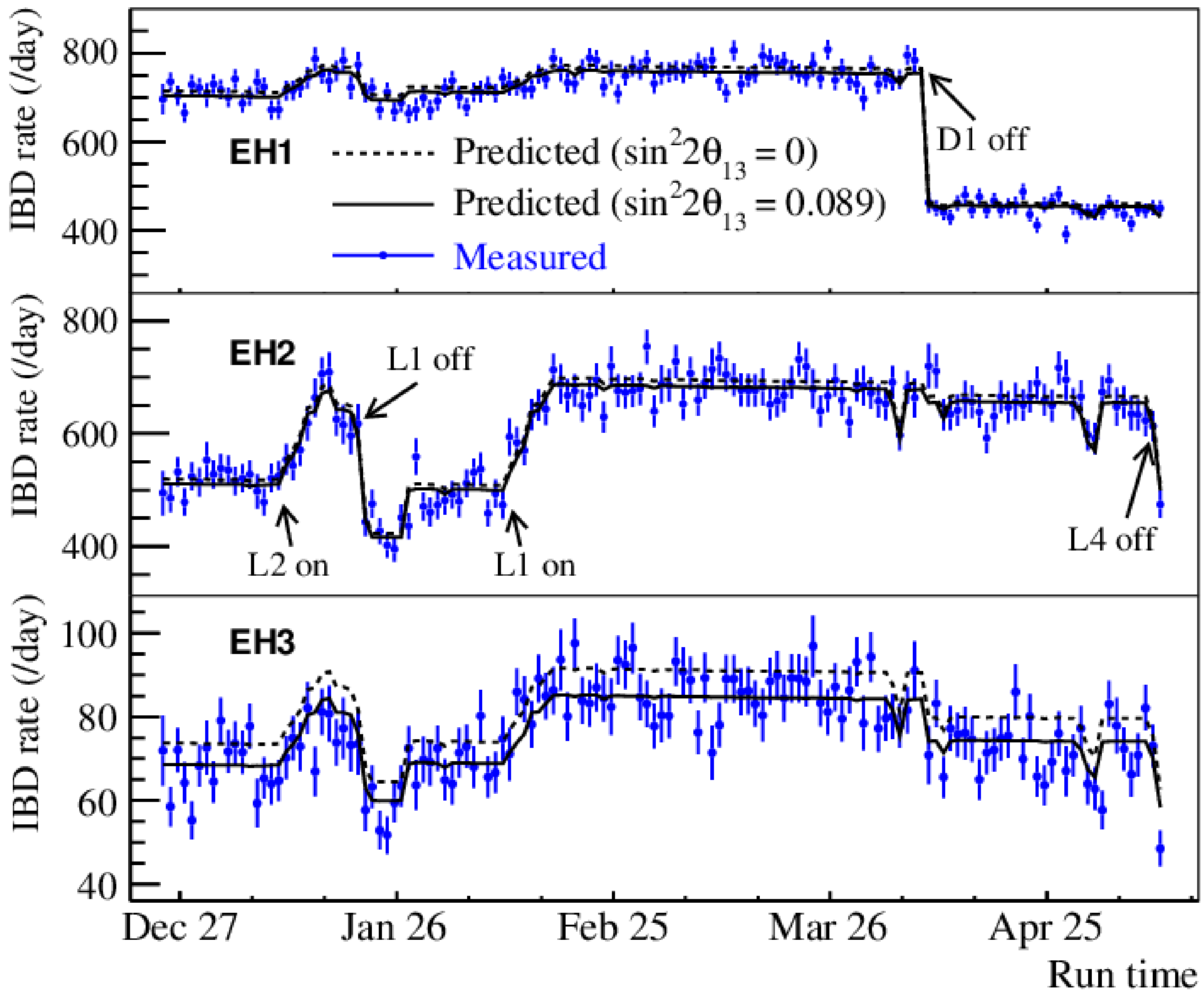
Fission fraction $\mathbf{f_i}$



Others < 0.3%

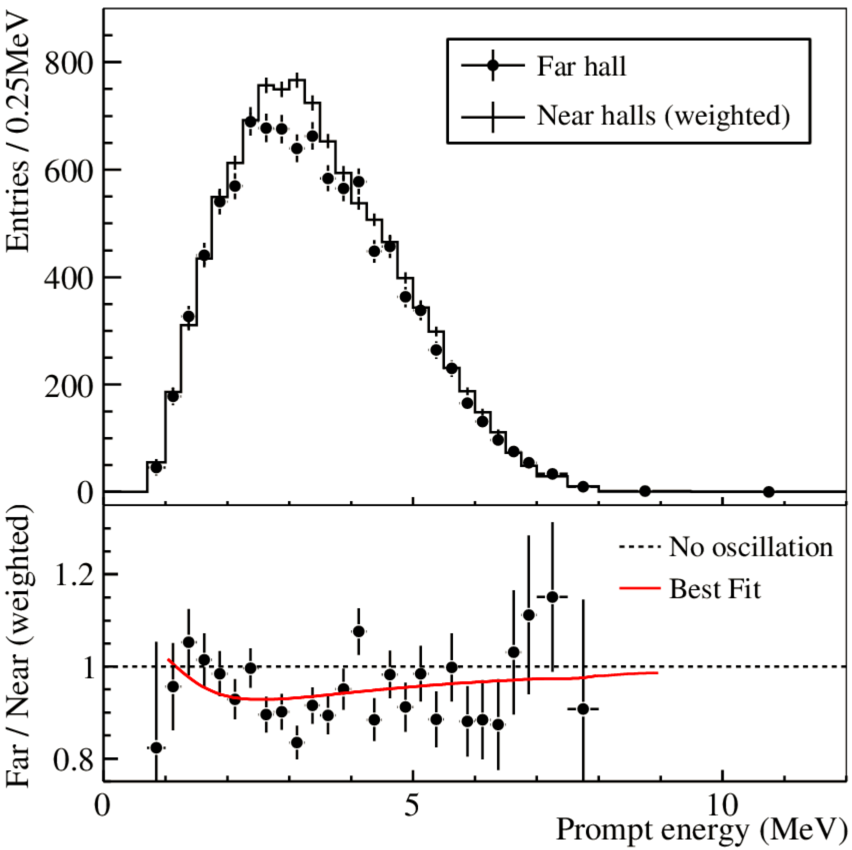
$\mathbf{S_i(E_\nu)}$: isotope spectra of ^{235}U, ^{239}Pu, ^{241}Pu from ILL measurement, ^{238}U from calculation.

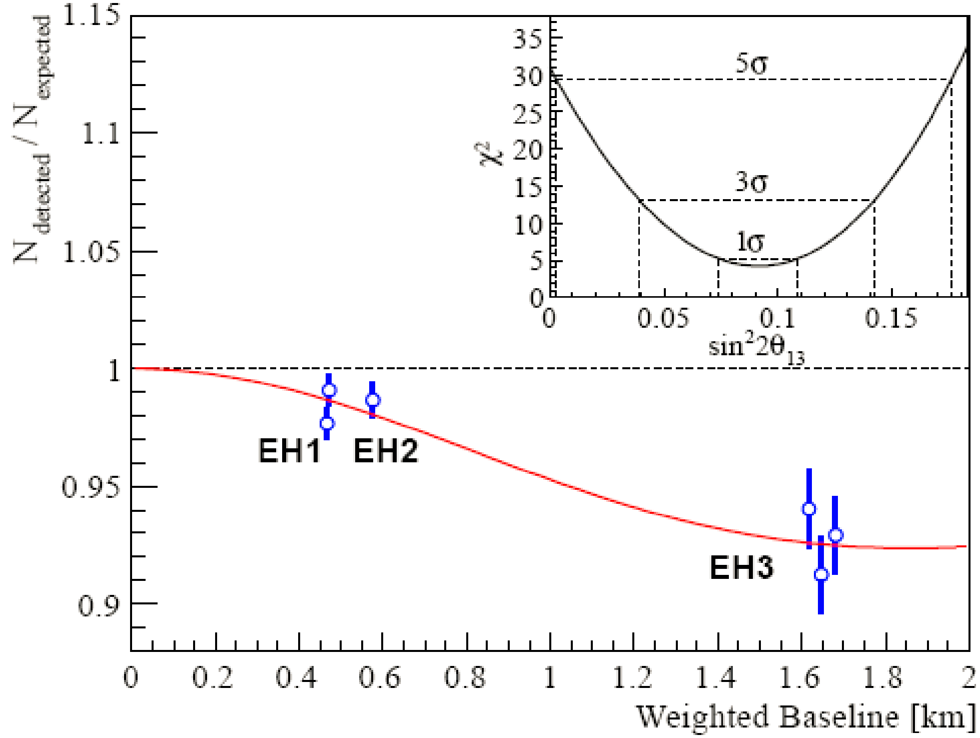
Daily rate



Obvious deficit for far site

Discovery of non-zero $\sin^2 2\theta_{13}$ (2012.3)



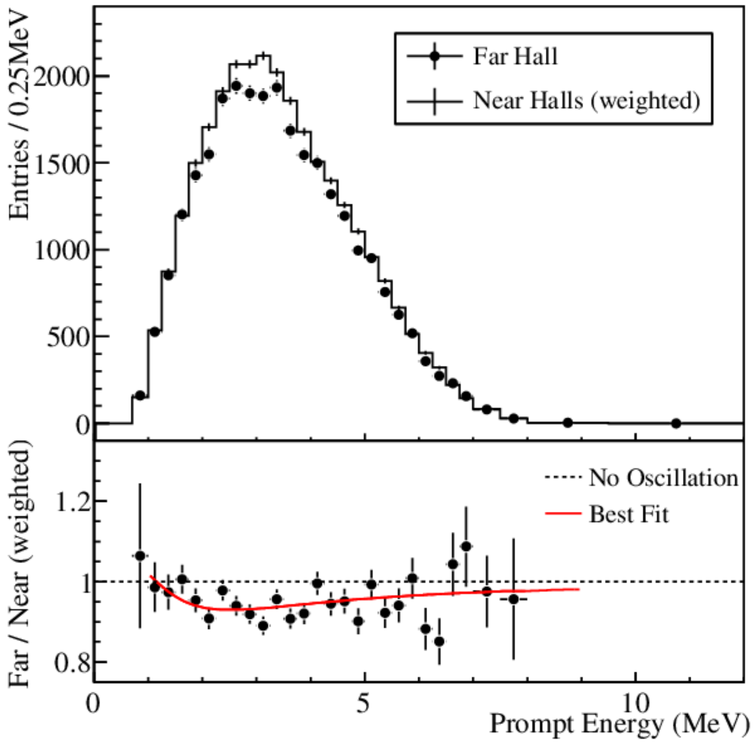


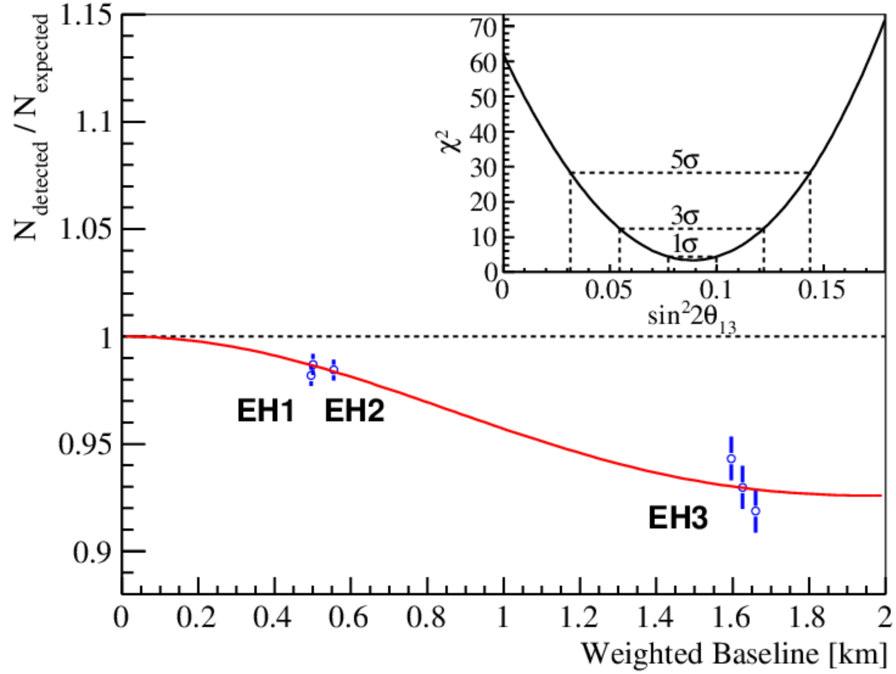
R = 0.940 ± 0.011 (stat) ± 0.004 (syst)

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

5.2σ for non-zero $\sin^2 2\theta_{13}$ with a 55-day data set

Improved Results (2012.6)





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}
7.7σ for non-zero $\sin^2 2\theta_{13}$

Summary

- Daya Bay has unambiguously observed reactor electron-antineutrino disappearance.

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

- In a 3-neutrino framework, the observed disappearance leads to mixing angle

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

- All 8 antineutrino detectors have been installed. Now conducting comprehensive calibration for spectral shape analysis.
- The estimated $\sin^2 2\theta_{13}$ precision is 5% after 3 years of Daya Bay data.
- Pursue other physics goals, such as precise reactor ν_e flux and spectrum, and measurement of Δm^2_{31} (~ 5% precision)

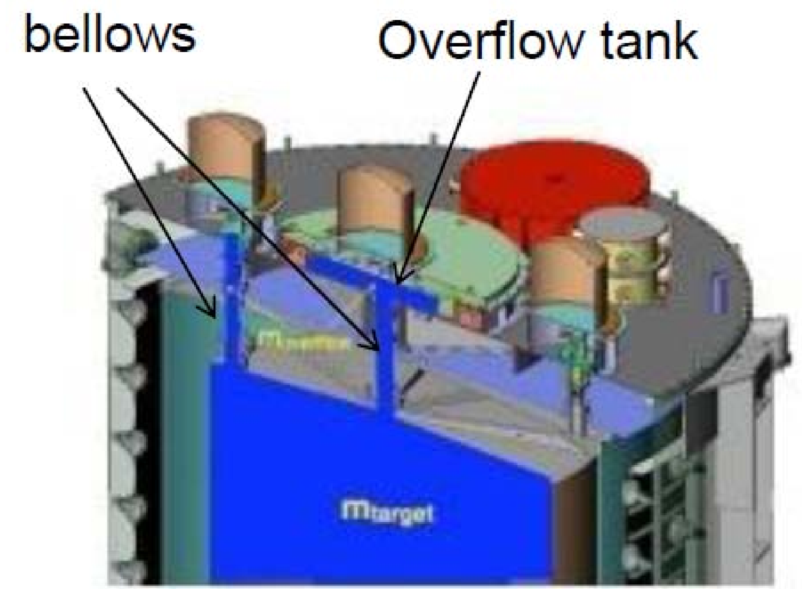
Backup slides

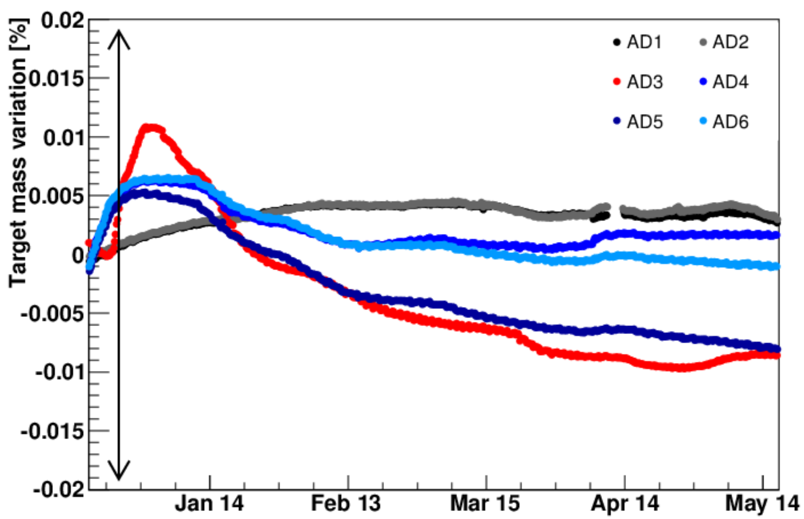
Target Mass & No. of Protons

- Target mass during the filling measured by the load cell, precision ~ 3kg→0.015%
- Cross 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





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 gravity from simulation
  - 2 cm horizontally
  - 20 cm vertically
- The combined baseline error is 35mm, corresponding to a negligible reactor flux uncertainty (<0.02%)