Observation of Electron Anti-neutrino Disappearance at Daya Bay

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on behalf of the Daya Bay Collaboration

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Neutrino Oscillation

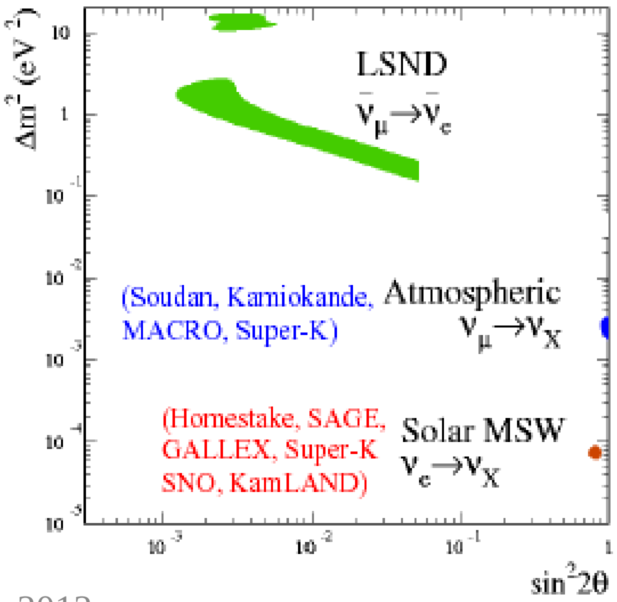
Neutrino Mixing: PMNS Matrix

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric,
K2K, MINOS, T2K,
etc.

Reactor
Accelerator
$\theta_{13} < 12^{o}$

Solar
KamLAND
$\theta_{12} \sim 30^{o}$



Known: $|\Delta m^2_{32}|$, $\sin^2 2\theta_{23}$, Δm^2_{21}, $\sin^2 2\theta_{12}$

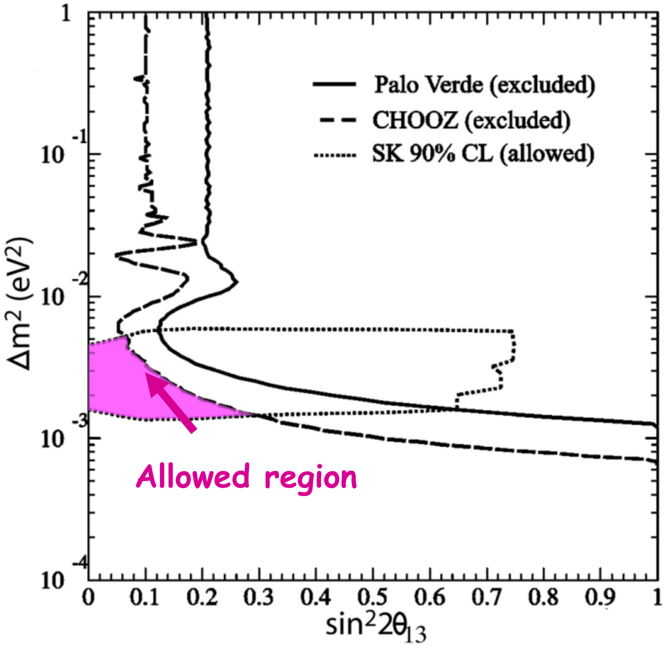
Unknown: $\sin^2 2\theta_{13}$, δ_{CP}, Sign of Δm^2_{32}

Daya Bay experiment is designed to measure $\sin^2 2\theta_{13}$ to 0.01 or better at 90% C.L. in a three-year run.

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

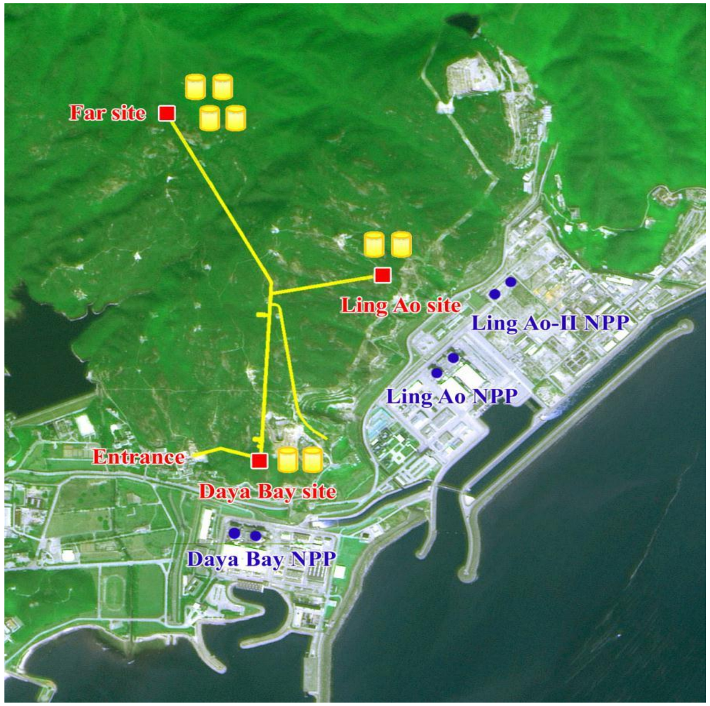
- **Double Chooz: 1.7 σ**

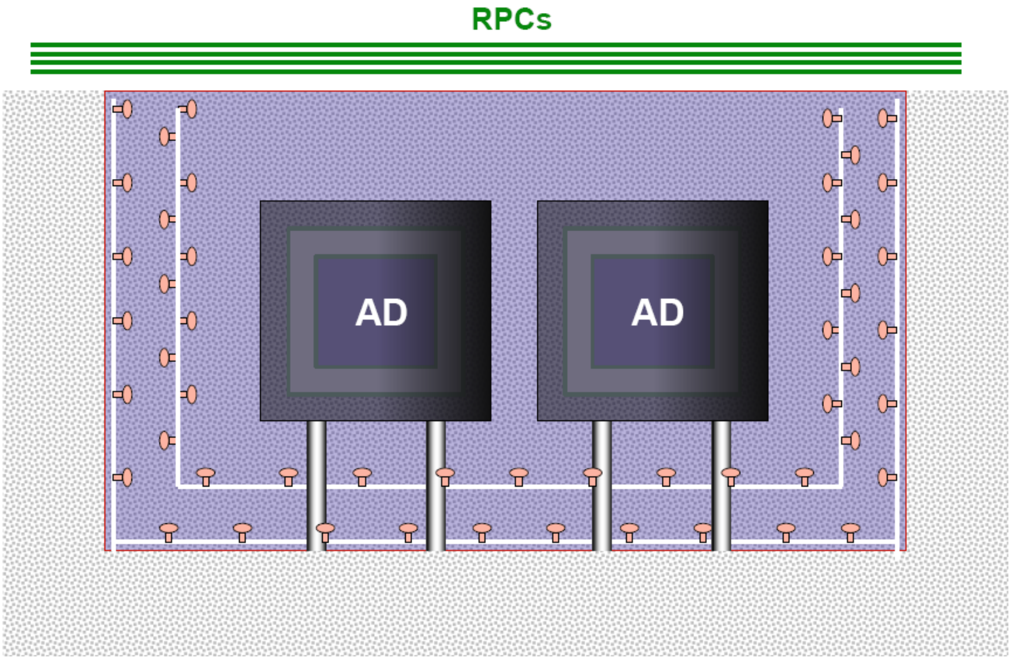
$\sin^2 2\theta_{13} = 0.086 \pm 0.041(\mathrm{stat}) \pm 0.030(\mathrm{sys})$

Global fit 3σ (Fogli et al)

No single exp. exceeds 3σ

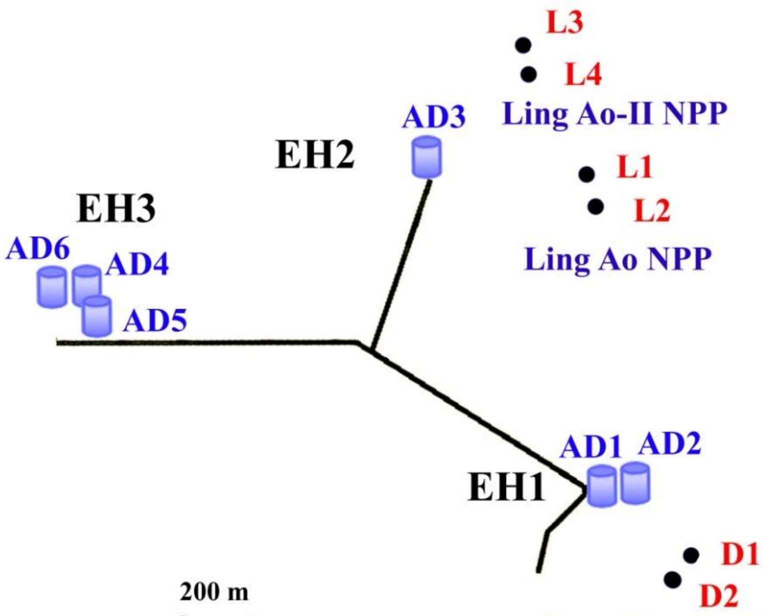
Daya Bay Experiment: Layout

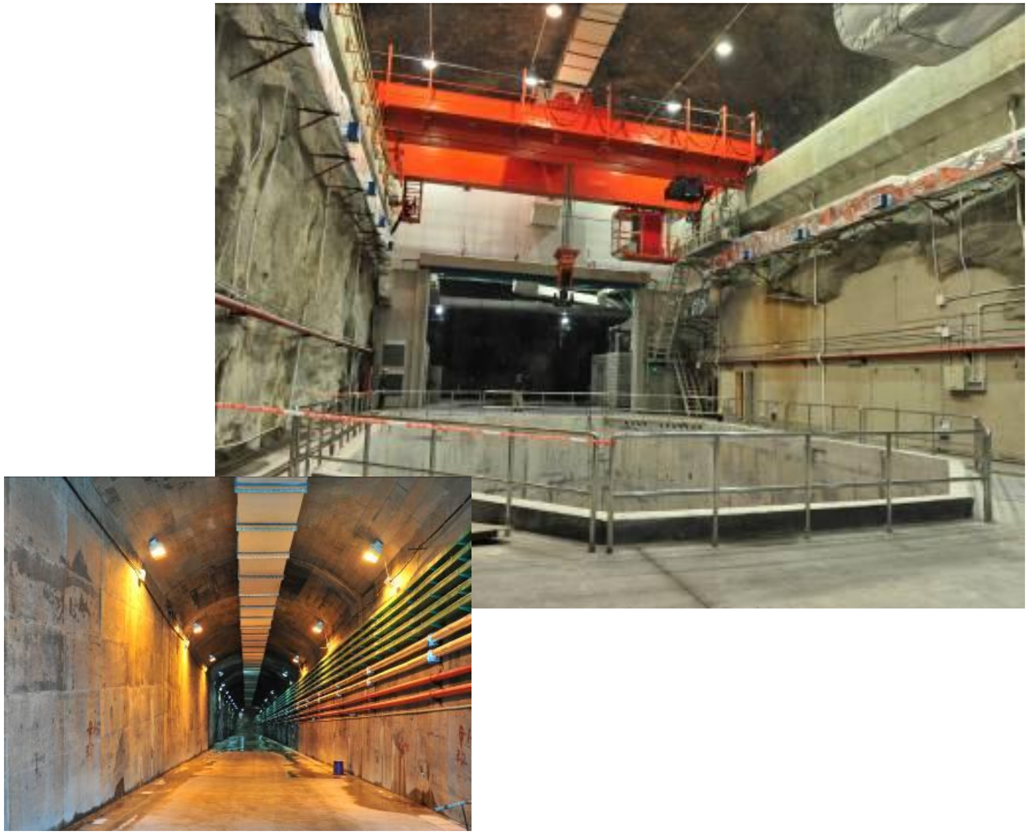




- Relative measurement to cancel Corr. Syst. Err.
  - ⇨ 2 near sites, 1 far site
- Multiple AD modules at each site to { verify Uncorr. syst. Err. / reduce Uncorr. Syst. Err.
  - ⇨ Far: 4 modules， near: 2 modules
- Multiple muon detectors to reduce veto eff. uncertainties
  - ⇨ Water Cherenkov： 2 layers
  - ⇨ RPC： 4 layers at the top + telescopes

Underground Labs

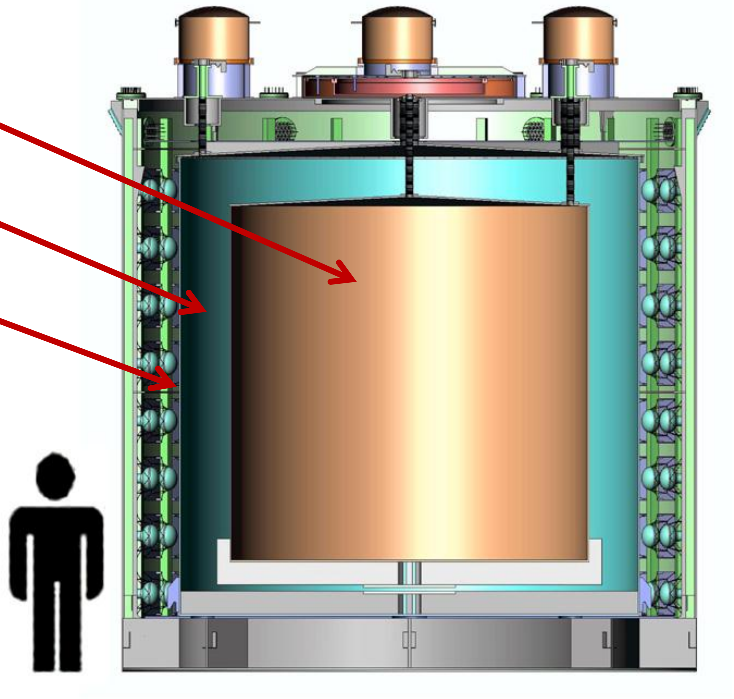


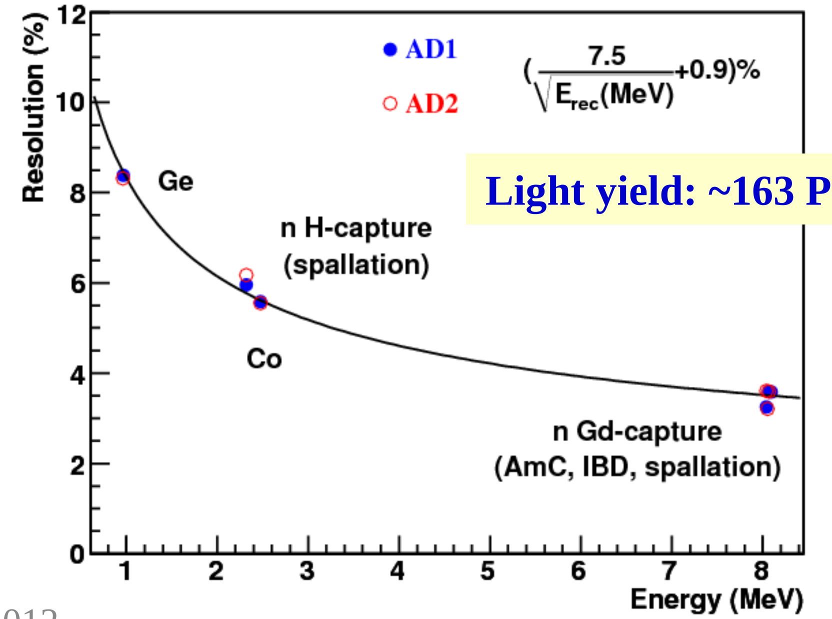


	Overburden （MWE）	R_μ （Hz/m^2）	E_μ （GeV）	D1,2 (m)	L1,2 (m)	L3,4 (m)
EH1	250	1.27	57	364	857	1307
EH2	265	0.95	58	1348	480	528
EH3	860	0.056	137	1912	1540	1548

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, doubled the photocathode coverage.





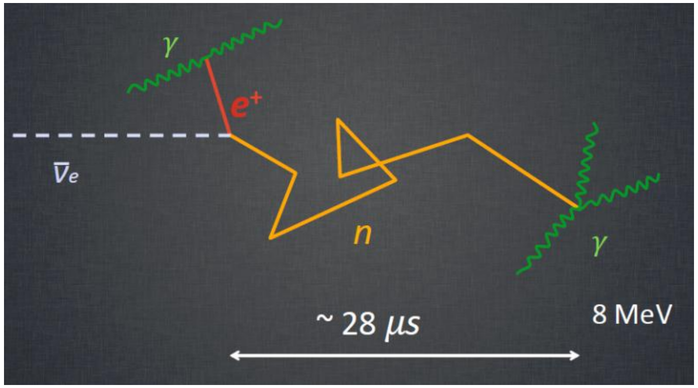
Light yield: ~163 PE/MeV

Target:	20 t,	1.55m
γ-catcher:	20 t,	45cm
Buffer:	40 t,	45cm

Total weight: ~110 t

Neutrino Detection: Gd-loaded Liquid Scintillator

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

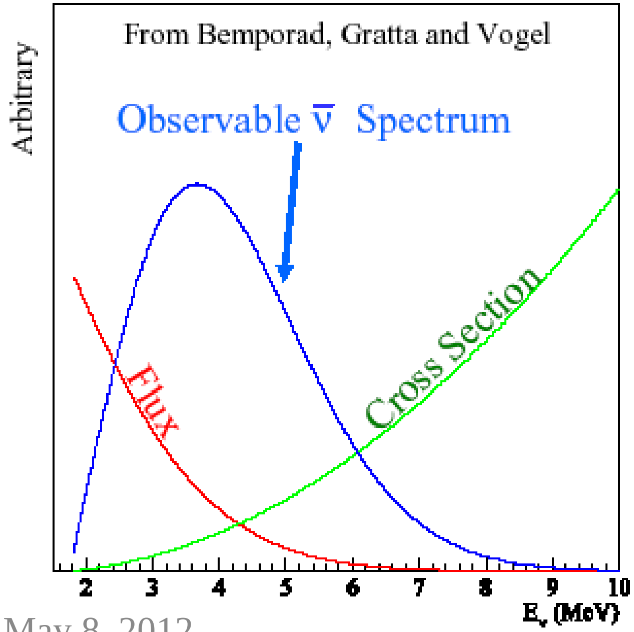


τ ≈ 28 μs(0.1% Gd)

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

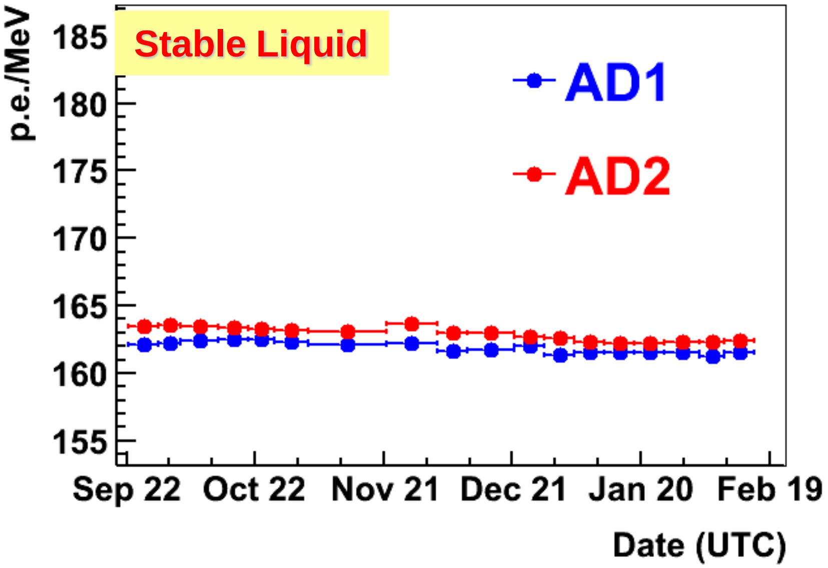
Neutrino energy:

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

Gd-loaded Liquid Scintillator

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

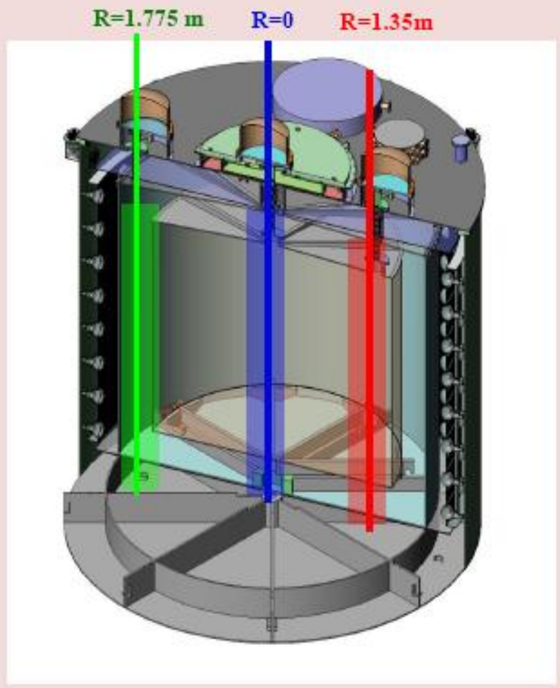
Liquid hall and mixing equipment



Stable Liquid

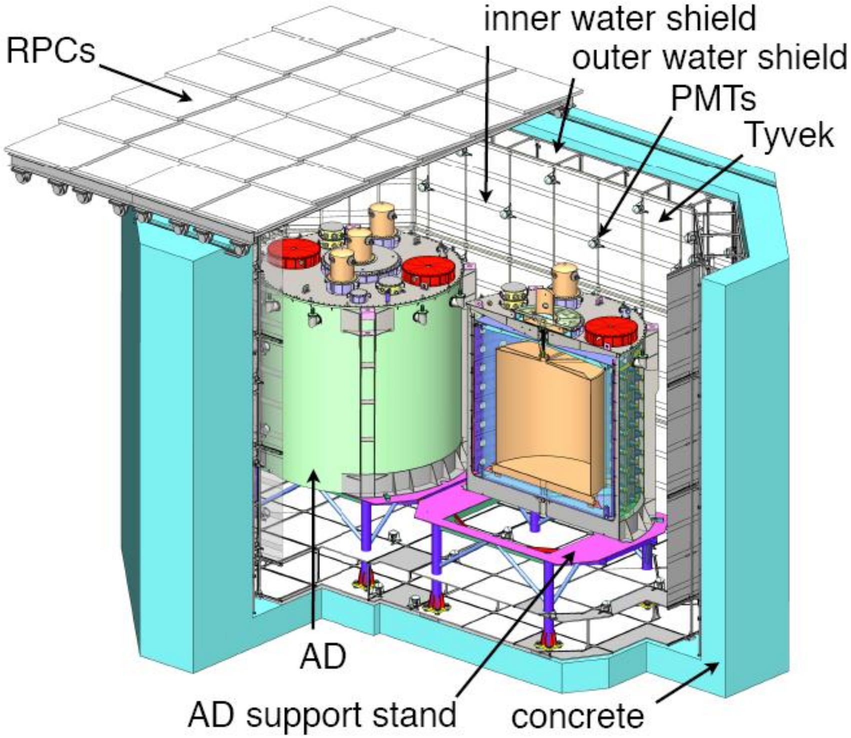
Automatic Calibration System

- **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

Muon Veto Detector

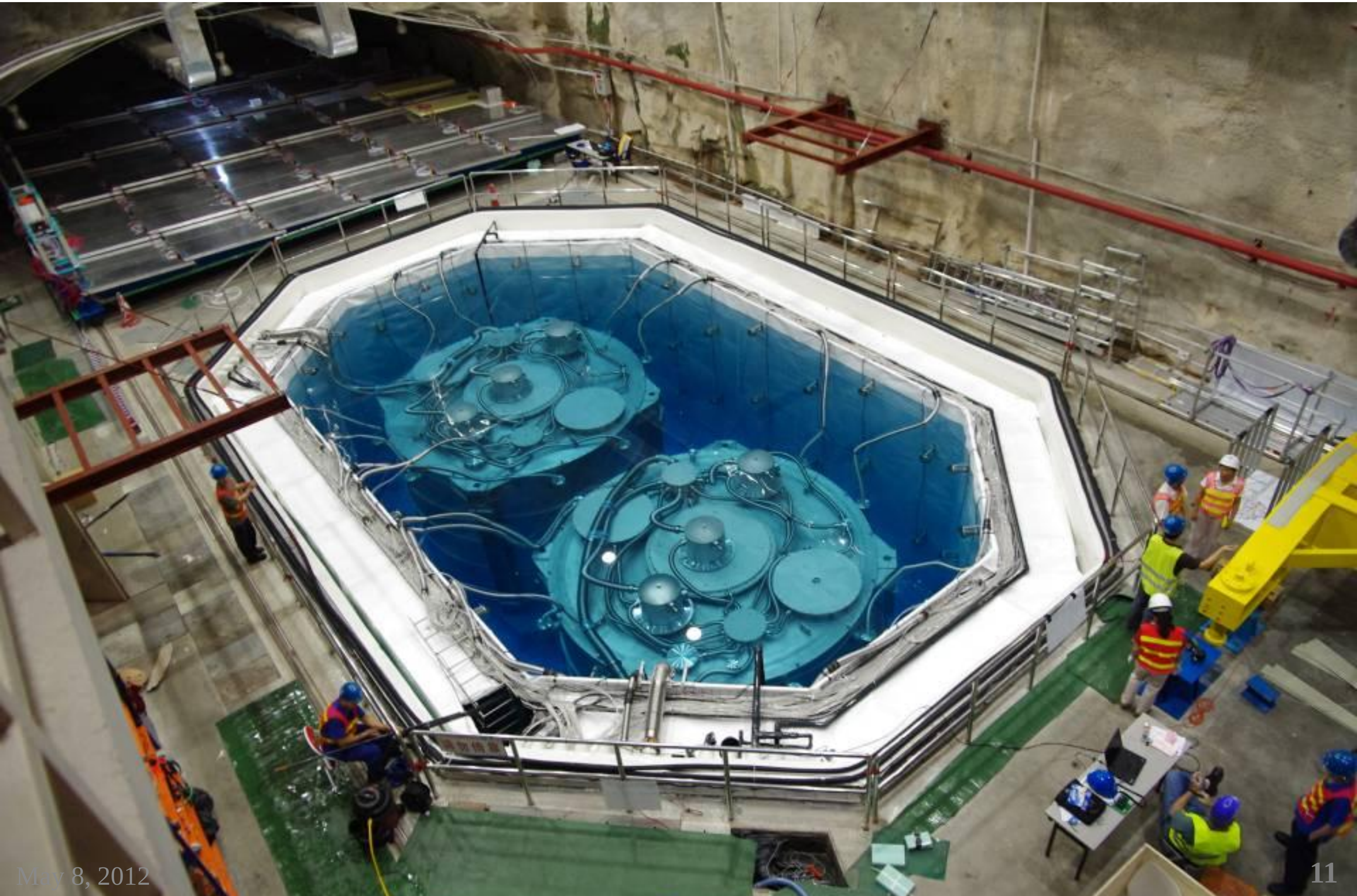


Two active cosmic-muon veto's

- **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**

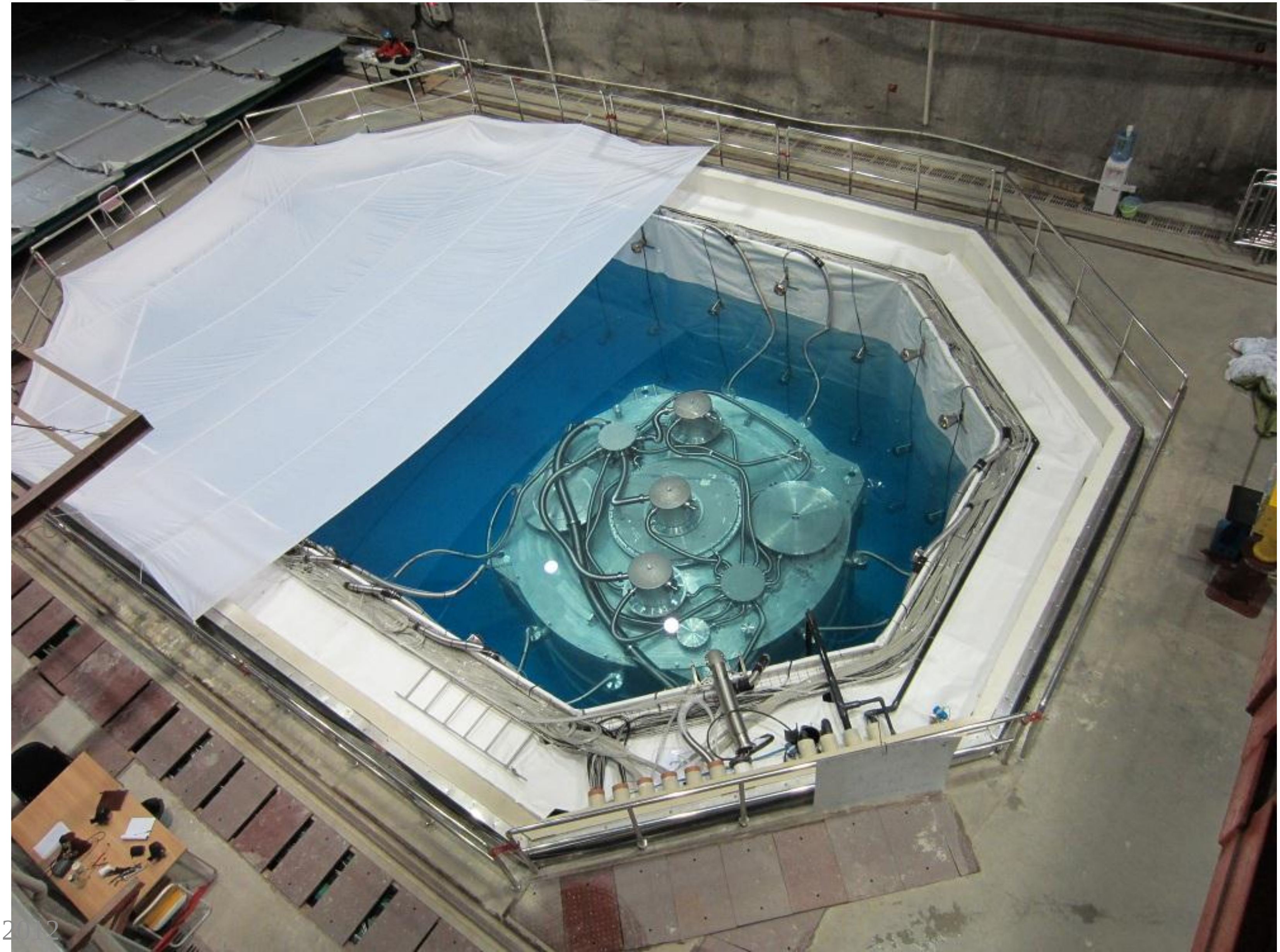
Two ADs Installed in Hall 1



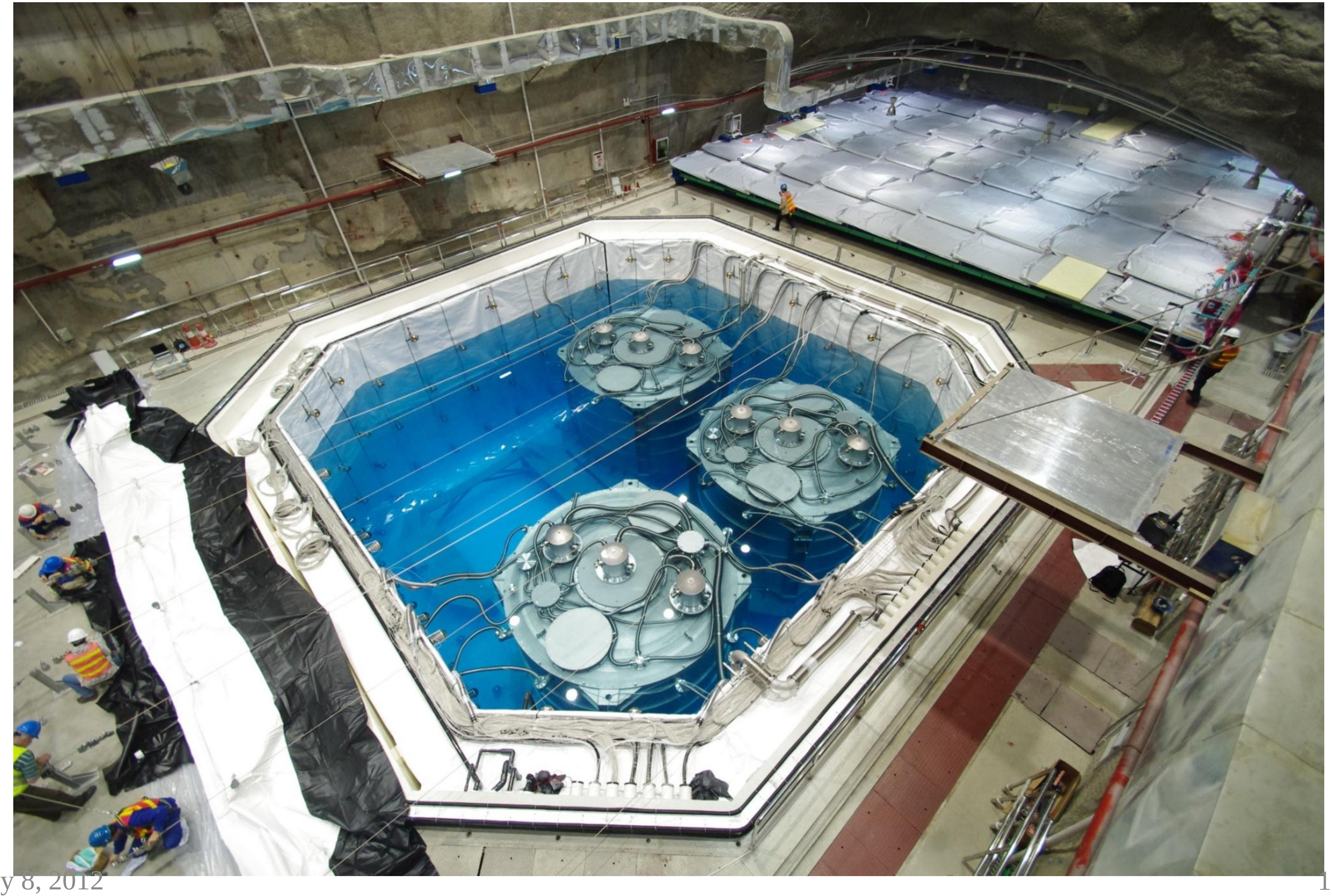
Hall 1 (2 ADs) Started the Operation on Aug.15, 2011

One AD insalled in Hall 2

Physics Data Taking Started on Nov.5, 2011

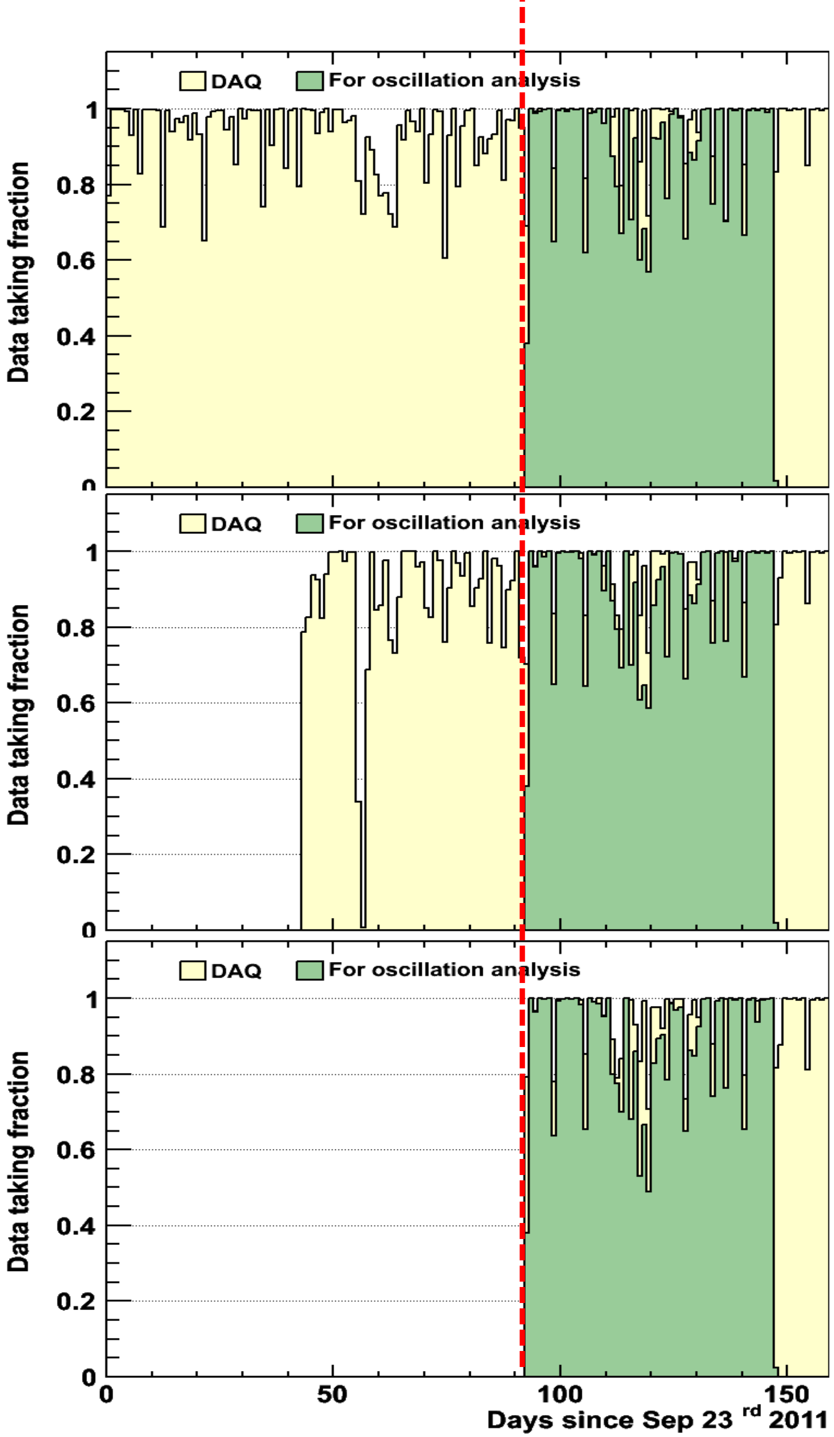


Three ADs insalled in Hall 3
Physics Data Taking Started on Dec.24, 2011

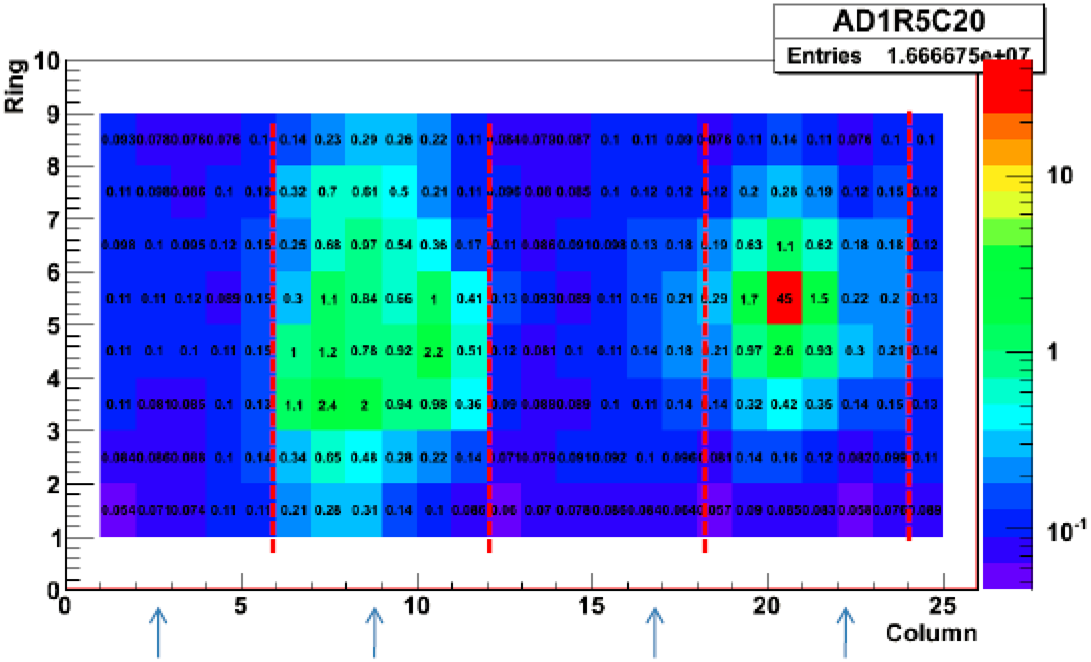


Data Set

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



Flashers: Imperfect PMTs

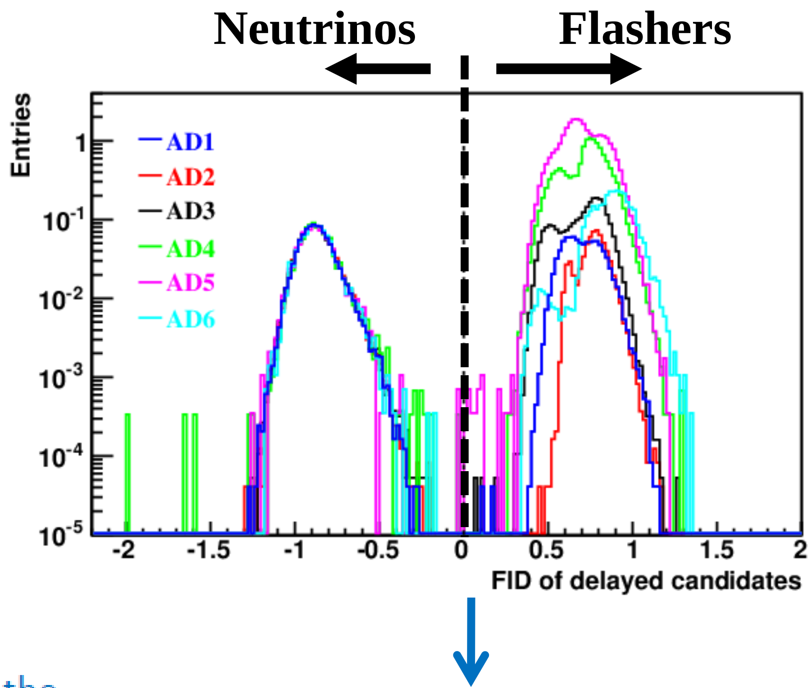


Quadrant 4

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:

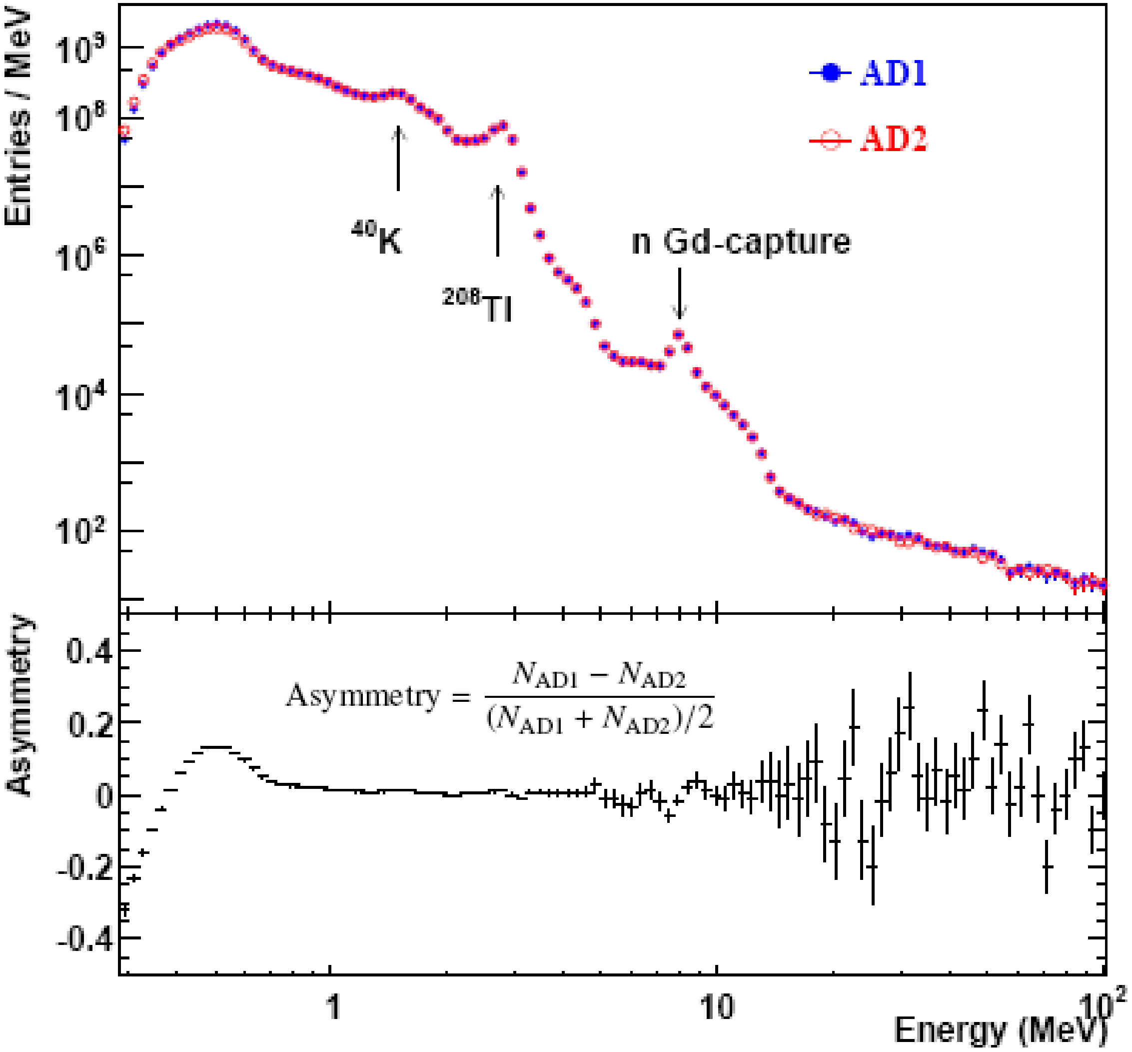
0.024% ± 0.006%(stat)

Contamination: < 0.01%

Single Rate: Understood

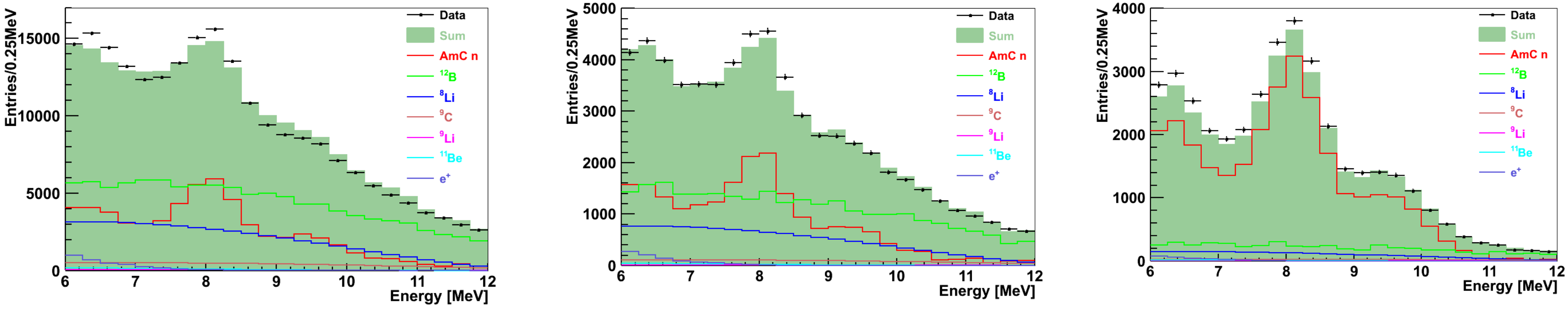
- **Design: ~50Hz above 1 MeV**
- **Data: ~60Hz above 0.7 MeV, ~40Hz above 1 MeV**

- **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**



Neutron-like Singles

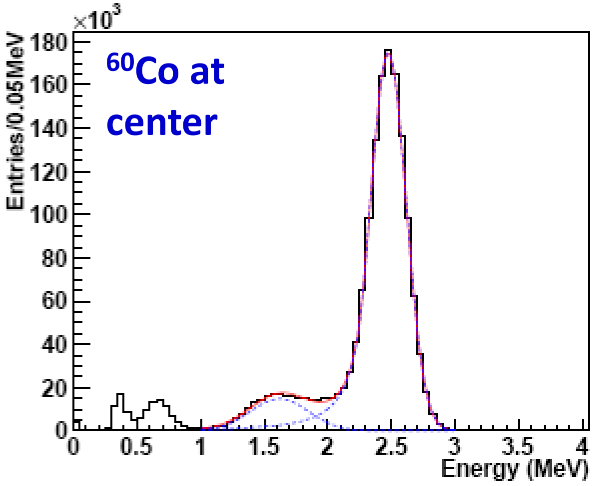
Sources	EH1		EH2		EH3	
	Rate (/day/AD)	Fraction	Rate (/day/AD)	Fraction	Rate (/day/AD)	Fraction
^{12}B/^{12}N	478+-13	46.4+-1.3%	354+-4	42.1+-0.5%	35+-2	12.7+-1.0%
^{8}Li/^{8}B	216+-18	21.0+-1.8%	155+-16	18.5+-1.9%	16+-5	5.8+-1.8%
^{9}C	40+-16	3.8+-1.6%	24+-9	2.9+-1.1%	4+-4	1.4+-1.4%
^{9}Li/^{8}He	4+-2	0.4+-0.2%	3+-2	0.4+-0.2%	< 1	< 0.4%
^{11}Be	7+-4	0.7+-0.4%	5+-3	0.6+-0.4%	< 1	< 0.4%
IBD e^{+} (n captured on H)	14+-1	1.4+-0.1%	12+-1	1.4+-0.1%	2+-1	0.7+-0.4%
AmC neutron	271+-10	26.3+-1.0	277+-7	33.0+-0.8	205+-11	74.3+-5.5%
Sum	1030+-29	100.0+-2.9%	830+-20	98.8+-2.4%	262+-13	94.9+-6.7%
All singles	1030+-7	-----	840+-3	-----	276+-14	-----



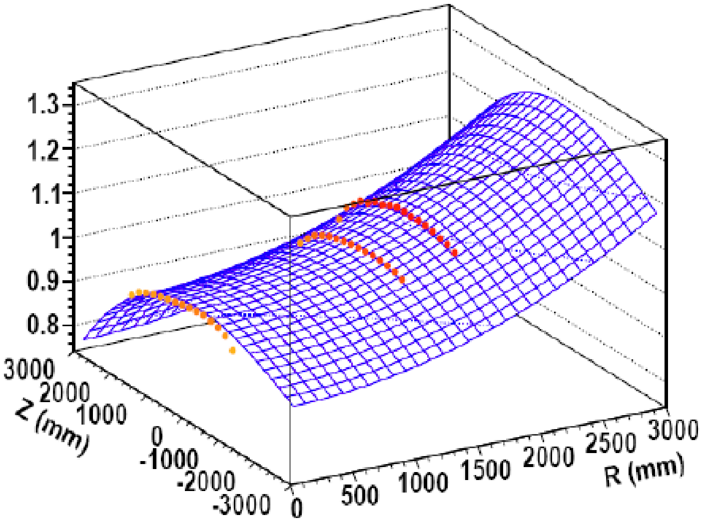
Event Reconstruction: Energy Calibration

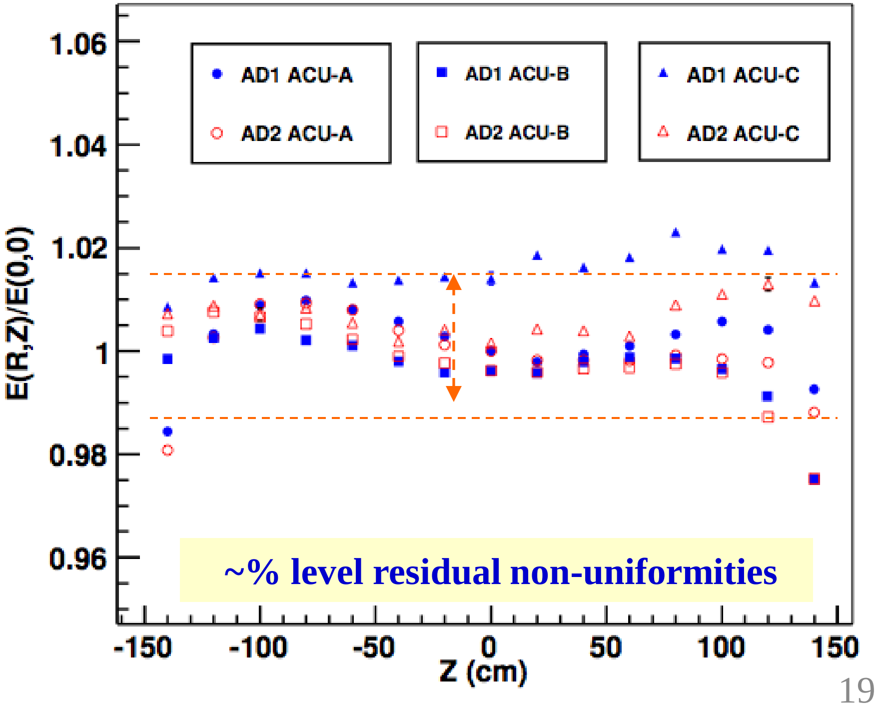
◆ **PMT gain calibration ➔ No. of PEs in an AD**

1. **^{60}Co at the center ➔ raw energies,**
   - ⇨ **time dependence corrected**
   - ⇨ **different for different ADs**
2. **^{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**
3. **A constant (0.988) correction: non-linearity between ^{60}Co and nGd.**



^{60}Co at center

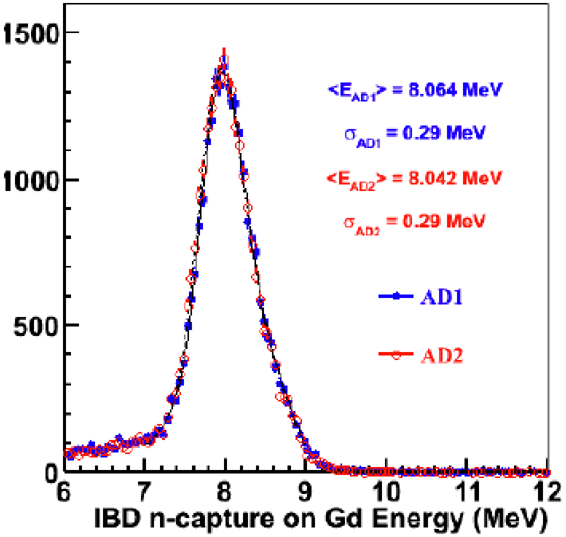




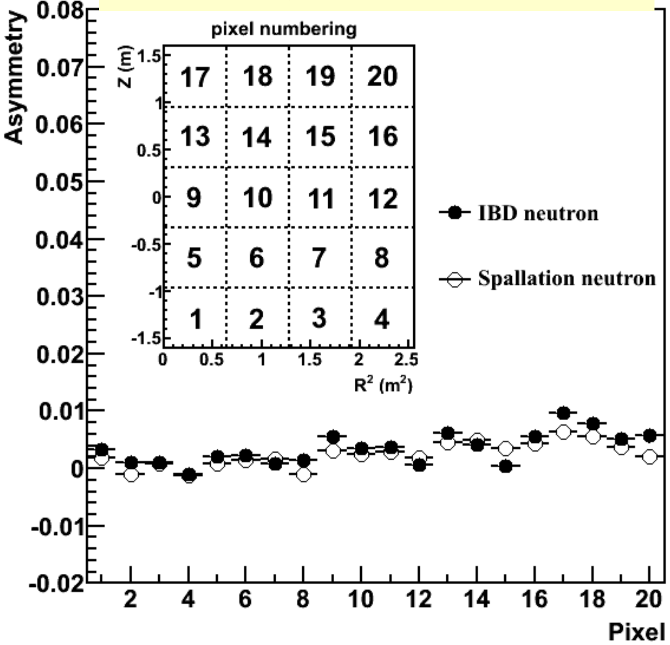
~% level residual non-uniformities

Event Reconstruction: Energy Calibration

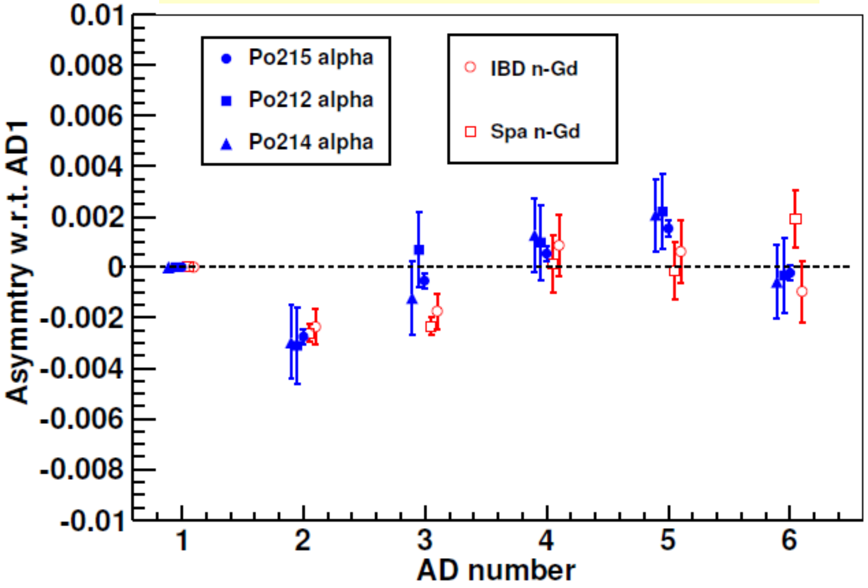
- **Energy uncertainty among 6 ADs (uncorrelated):**
  - ⇨ **Relative difference in reconstructed energy among ADs is better than 0.5%**
  - ⇨ **Systematic uncertainties from time-variation, non-linearity, non-uniformity… are also within 0.5%**



Uniformity at different location



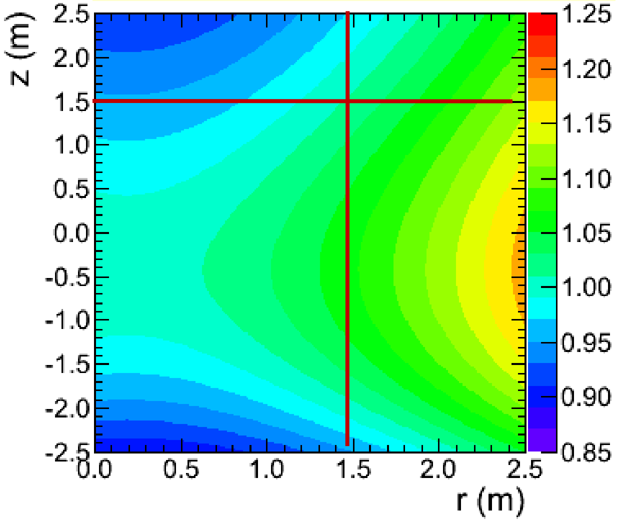
Peak energy of different sources



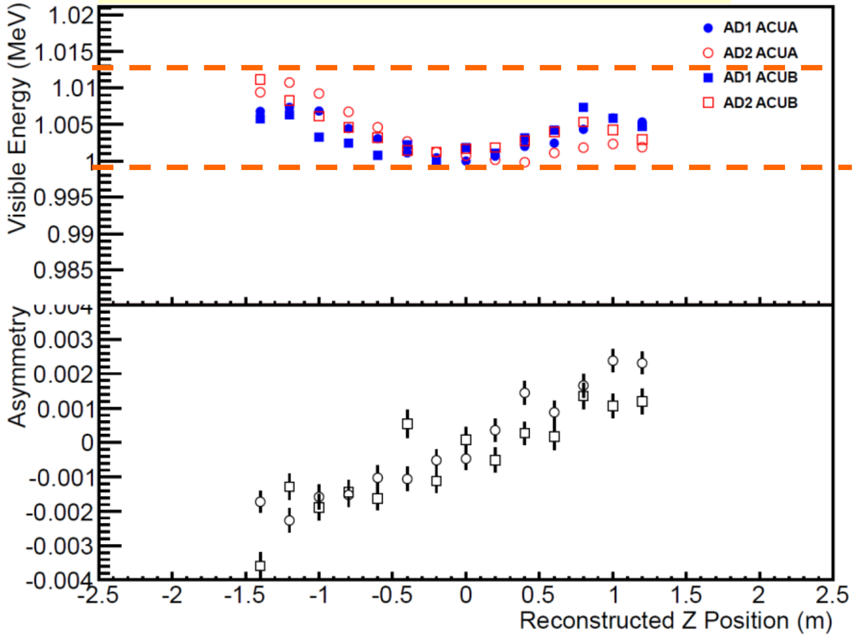
An Alternative Method

- 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%

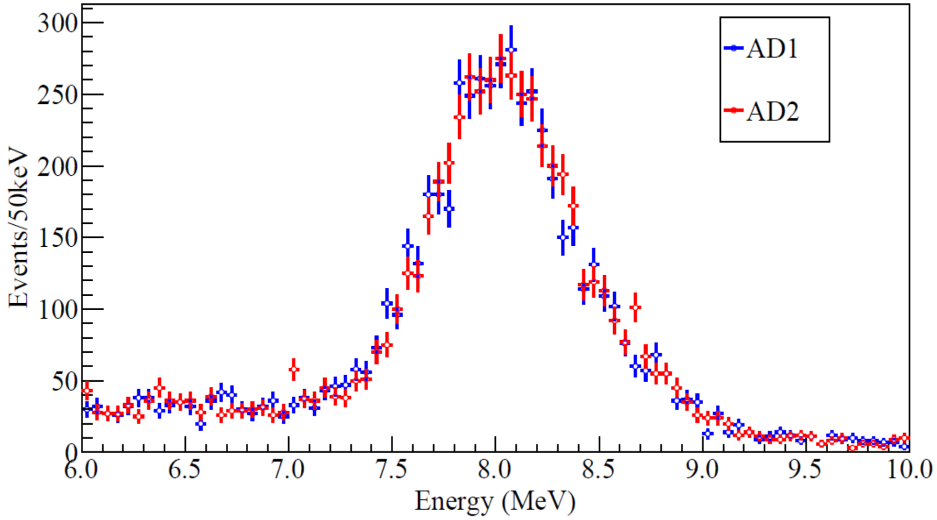
Uniformity of energy response



Residual non-uniformities

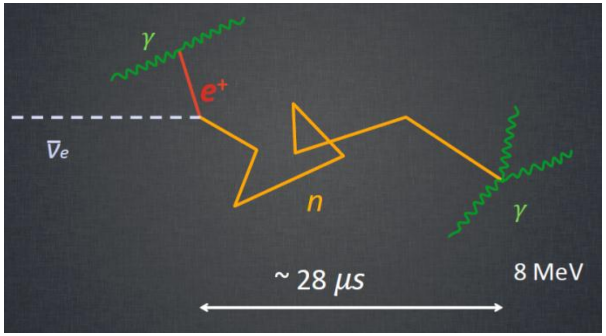


Energy of spallation neutron



Event Signature and Backgrounds

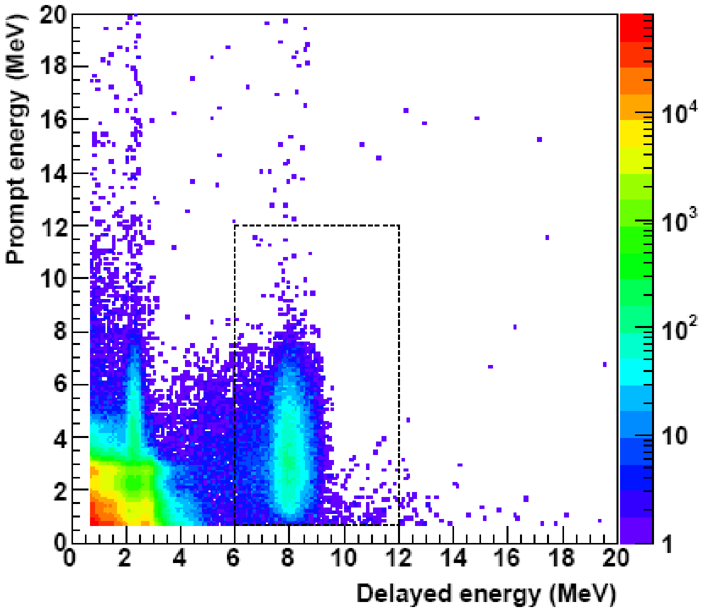
- **Signature:** $\bar{\nu}_e + p \rightarrow e^+ + n$
  - ⇨ **Prompt: e^+, E: 1-10 MeV,**
  - ⇨ **Delayed: n, E: 2.2 MeV@H, 8 MeV @ Gd**
  - ⇨ **Capture time: 28 μs in 0.1% Gd-LS**



- **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**
    - ✓ **8He/9Li: prompt—β decay, delayed—n capture**
    - ✓ **Am-C source: prompt—γ rays, delayed—n capture**
    - ✓ **α-n: ^{13}C(α,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
  - **$0.7\text{MeV} < E_{prompt} < 12.0\text{MeV}$**
  - **$6.0\text{MeV} < E_{delayed} < 12.0\text{MeV}$**
  - **$1\mu s < \Delta t_{e^+-n} < 200\mu s$**

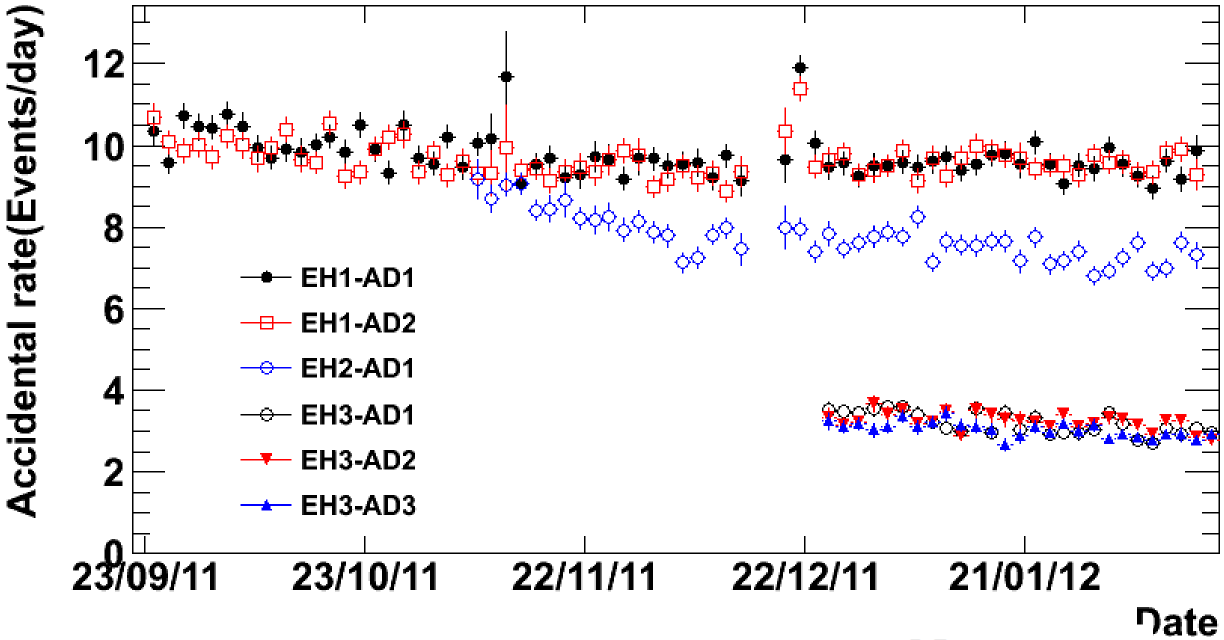


Accidental Backgrounds

- **Coincidence probability**

- **Off-window**
- **Distance between prompt-delay pair**

- **Consistent to 1%**

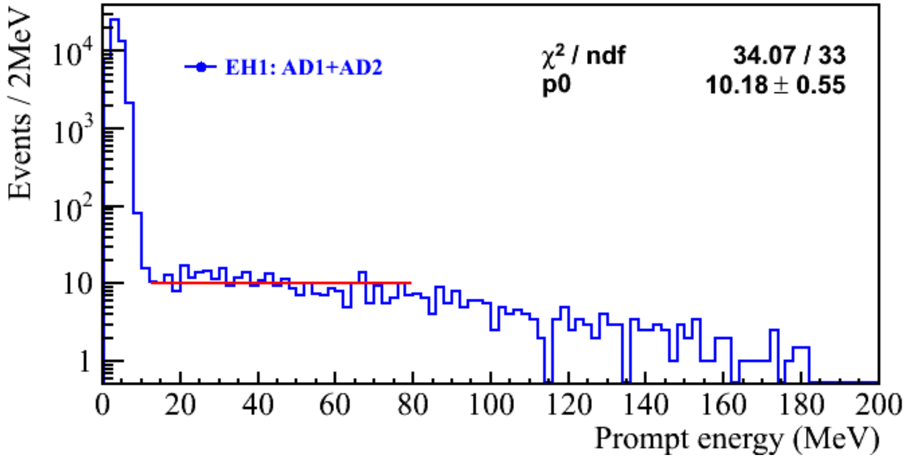


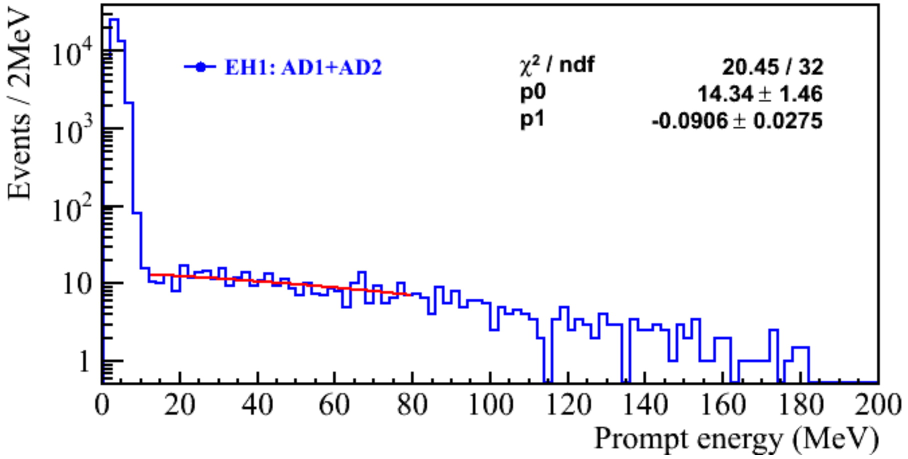
$$N_{\text{accBkg}} = \sum_i N^i_{\text{n-like singles}} \bullet \left(1 - e^{-R^i_{e^+\text{-like triggers}} \bullet 200\,\mu s}\right) \pm \frac{N_{\text{accBkg}}}{\sqrt{\sum_i N^i_{\text{n-like singles}}}}$$

	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%

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 checked by muon-tagged fast neutrons with projected muon eff.



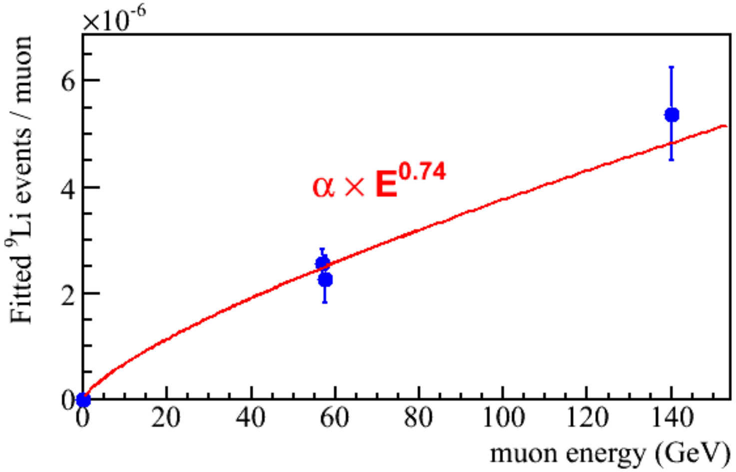


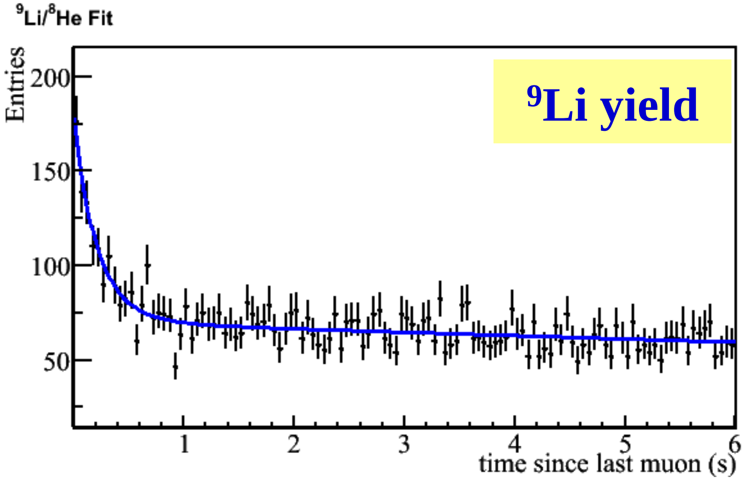
Backgrounds –^{8}He/^{9}Li

- **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**





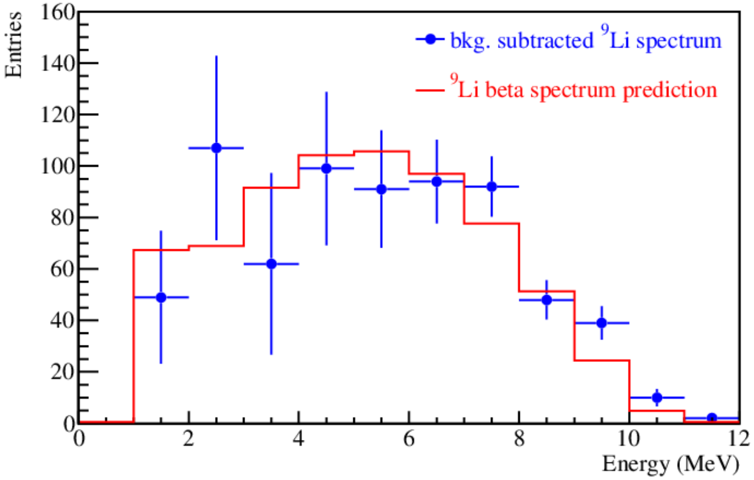
Error follows

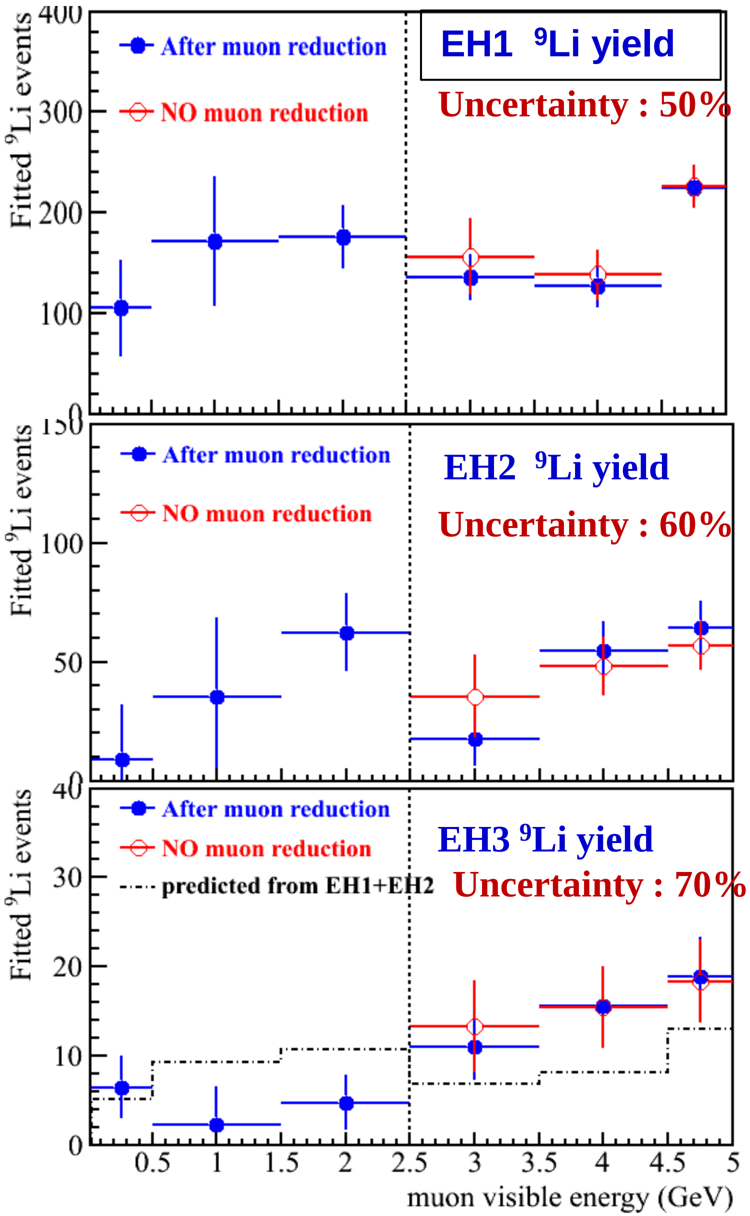
$$\boxed{\sigma_b = \frac{1}{N} \cdot \sqrt{(1+\tau R_\mu)^2 - 1}}$$

NIM A564 (2006)471

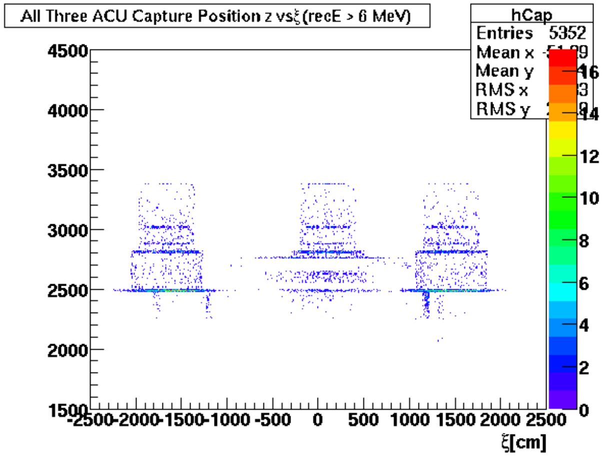
Measurement in EH1+EH2 & Prediction in EH3

- **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.**





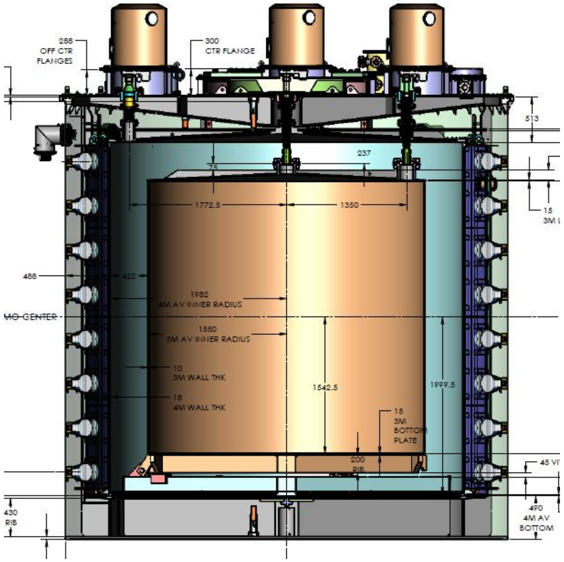
^{241}Am-^{13}C Backgrounds



- **Uncorrelated backgrounds:**

  R = 50 Hz × 200 μs × $R_{n\text{-like}}$ (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%) (will remove ACU-B/C)
  - ⇨ Measured together with all the other uncorrelated backgrounds

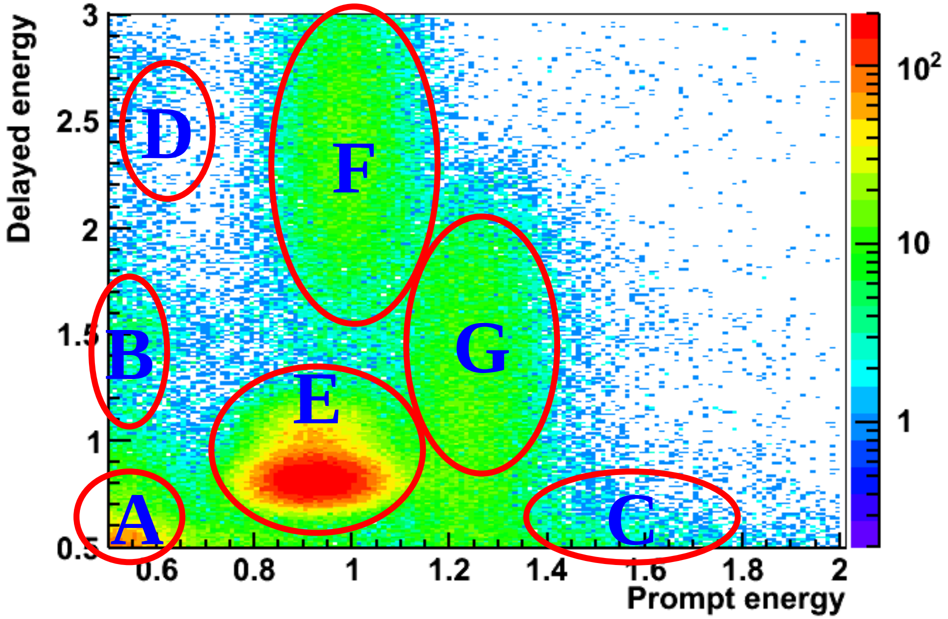


- **Correlated backgrounds:**
  - ⇨ Neutron inelastic scattering with ^{56}Fe + neutron capture on ^{57}Fe
  - ⇨ Simulation shows that correlated background is 0.2 events/day/AD, corresponding to a B/S ratio of 0.03% at near site, 0.3% at far site

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 α rate and (α,n) cross sections



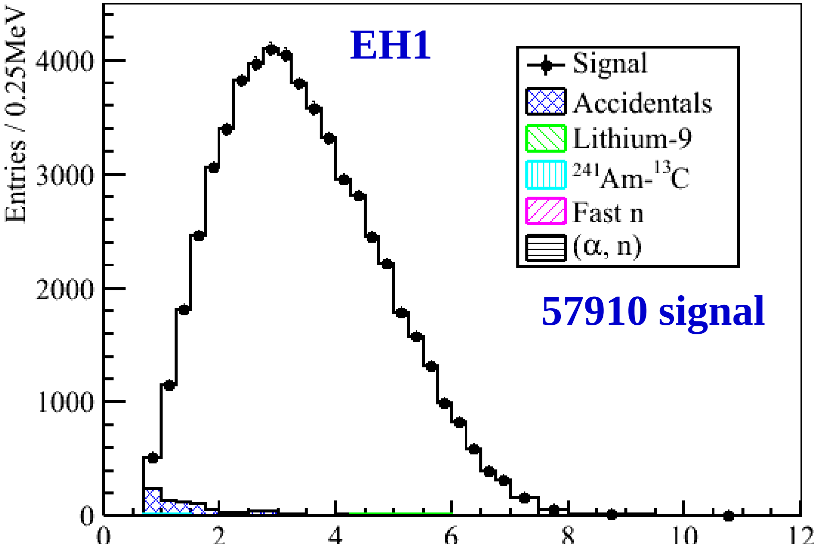
	Components	Total α rate	BG rate
Region A	Acc. Coincidence of ^{210}Po & ^{210}Po	^{210}Po: 10Hz at EH1 8Hz at EH2 6Hz at EH3	0.02/day at EH1 0.015/day at EH2 0.01/day at EH3
Region B	Acc. Coincidence of ^{210}Po & ^{40}K		
Region C	Acc. Coincidence of ^{40}K & ^{210}Po		
Region D	Acc. Coincidence of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

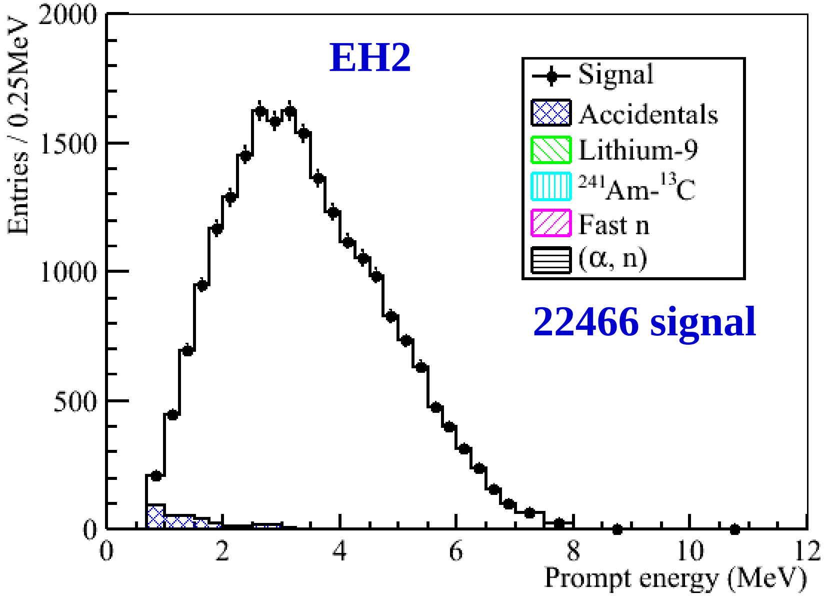
Uncertainty: 50%

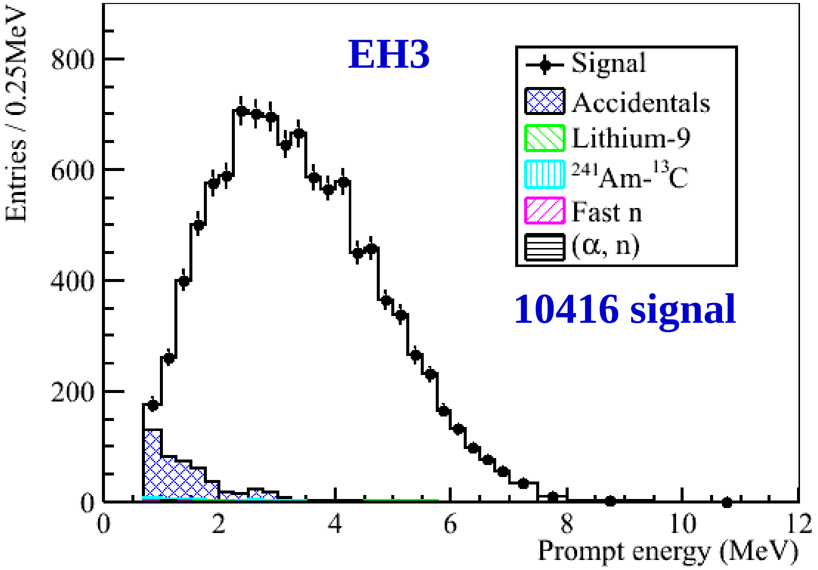
Signals and Backgrounds

	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	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(α, 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





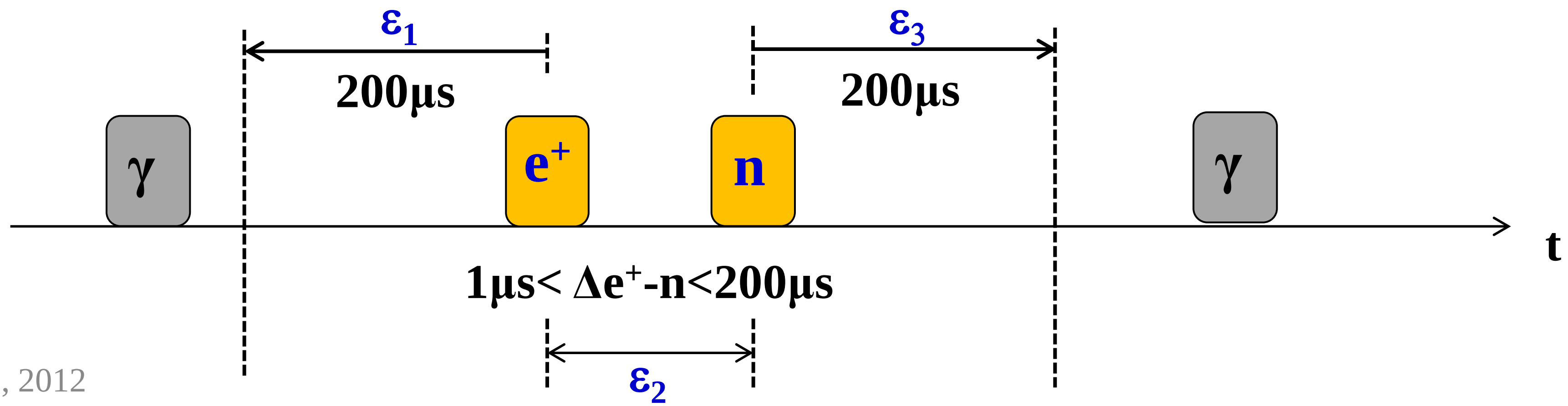


	B/S @EH1/2	B/S @EH3
Accidentals	~1.4%	~4.5%
Fast neutrons	~0.1%	~0.06%
^{8}He/^{9}Li	~0.4%	~0.2%
Am-C	~0.03%	~0.3%
α-n	~0.01%	~0.04%
Sum	2.0%	5.2%

Muon Veto and Multiplicity Cut

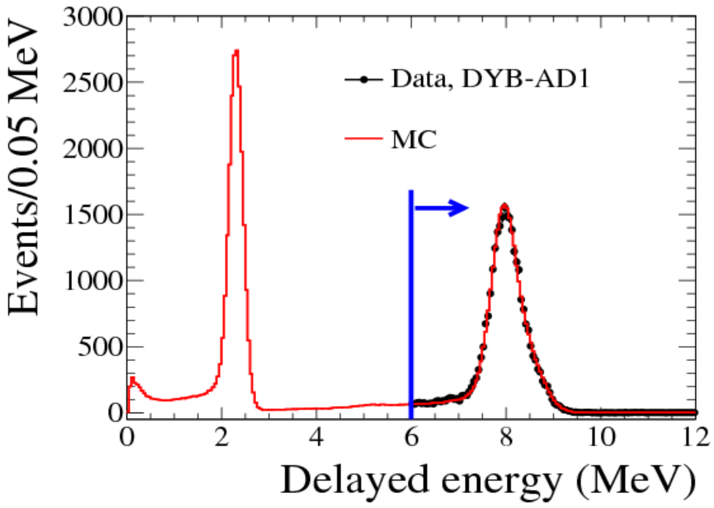
- The only eff. that correct for each AD.
- All other differences between the functionally identical ADs were not corrected, but taken as uncorrelated uncertainties.
- Muon veto
  - Total veto time is sum of individual veto time window of each muon
  - Temporal overlap is taken into account, to avoid repetitive calculation
- Multiplicity cut
  - Live time is segmented into isolated live windows by muon veto
  - Efficiency in each live window→ $\varepsilon_1 \times \varepsilon_2 \times \varepsilon_3$

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

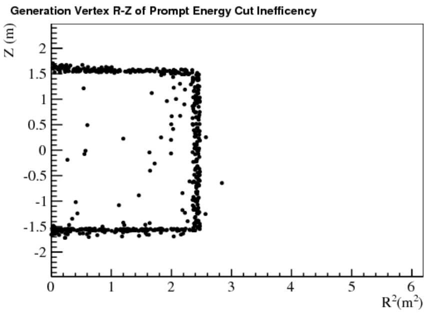


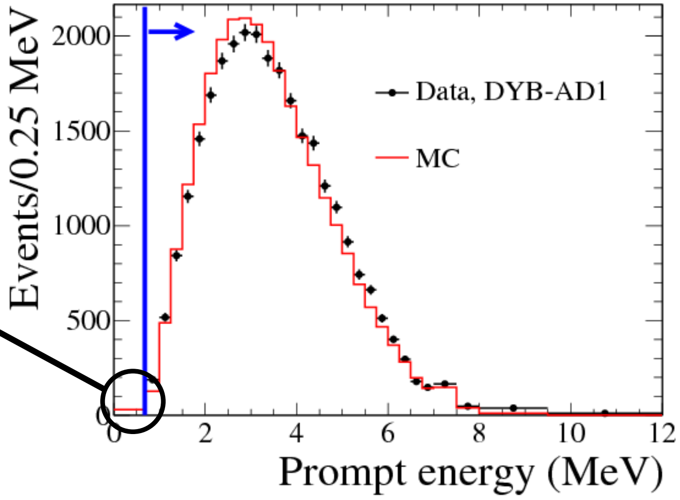
Energy Cuts Efficiency and Systematics

- **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



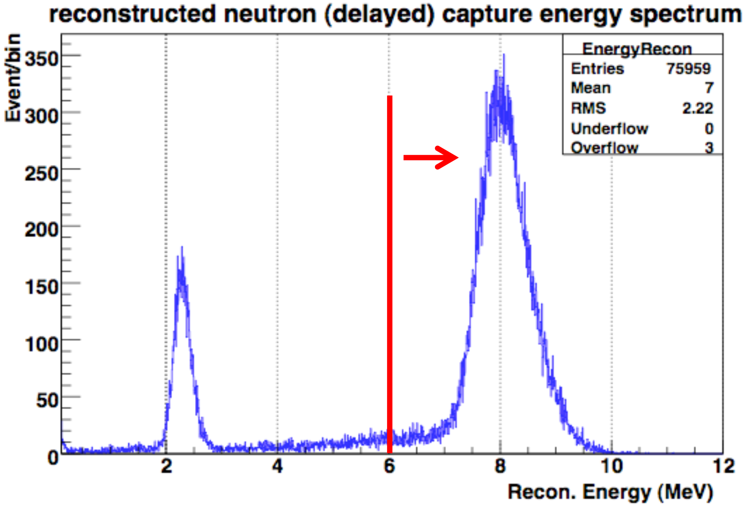
The inefficiency mainly comes from edges



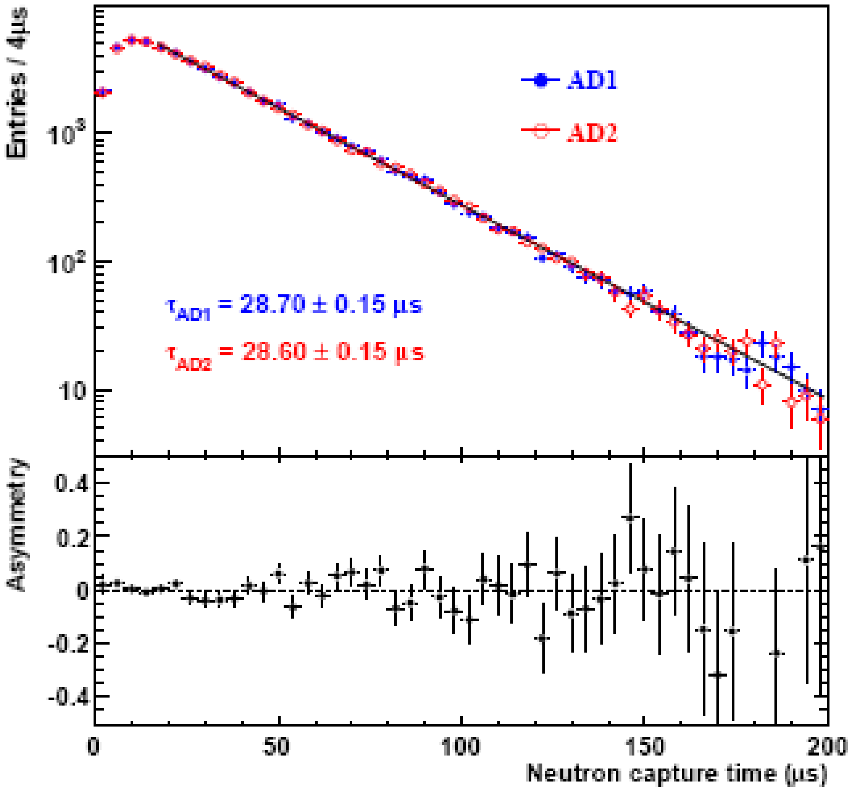


	Eff.	Corr.	Un-corr.
Delayed energy cut	90.9%	0.6%	0.12%
Prompt energy cut	99.88%	0.10%	0.01%

Gd Capture Fraction: H/Gd and Systematics



Neutron capture time from Am-C

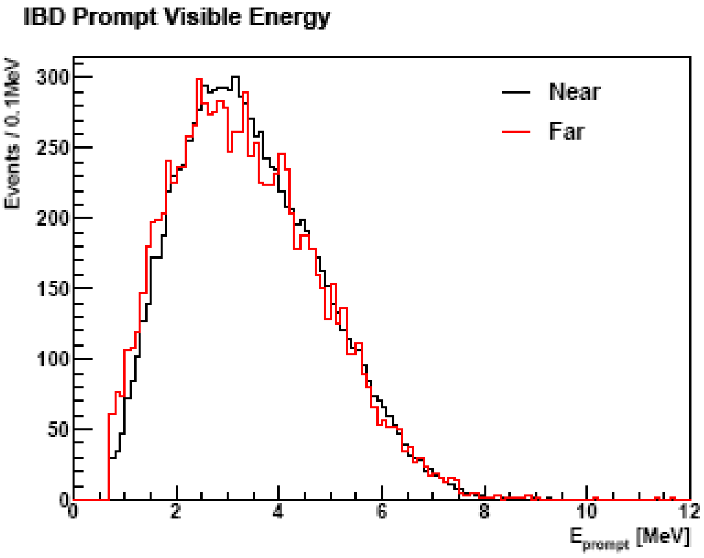


- **Uncertainties :**
  - **Relative Gd content variation 0.1% → evaluated from neutron capture time**
  - **Geometry effect on spill-in/out 0.02% → relative differences in acrylic vessel thickness and density and liquid density are modeled in MC**

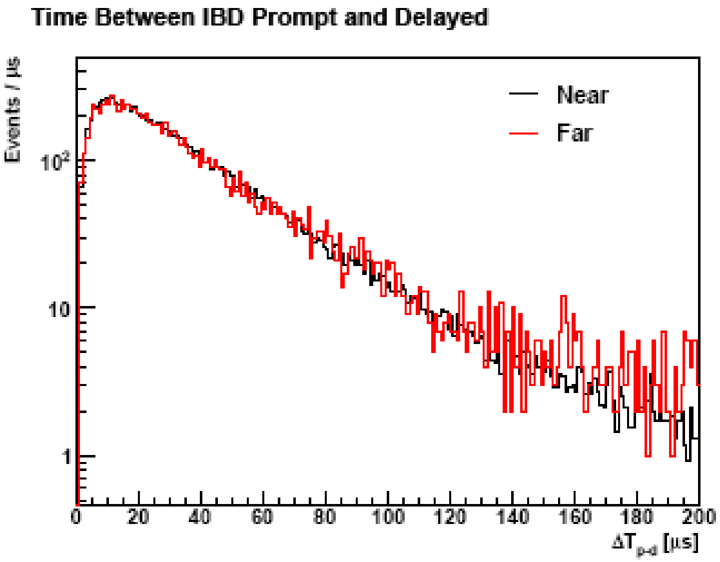
	Eff.	Corr.	Un-corr.
Gd capture ratio	83.8%	0.8%	<0.1%

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**



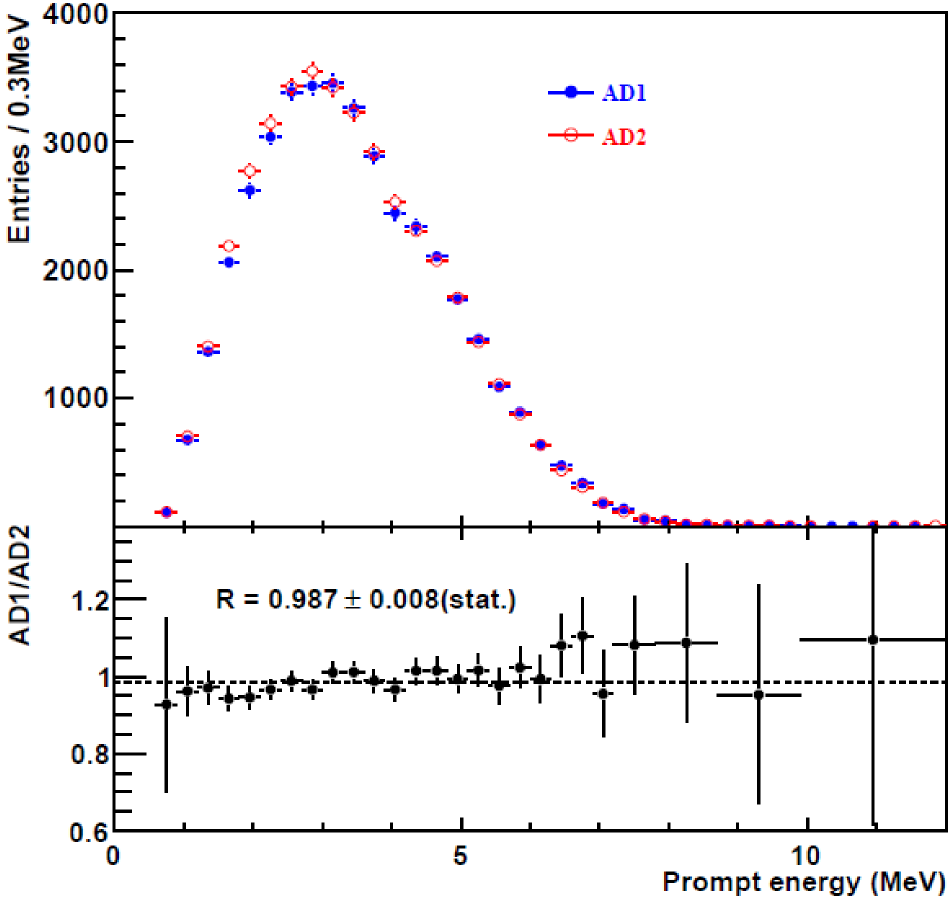
IBD Prompt Visible Energy



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 **baseline**
- This final check shows that systematic errors are under control

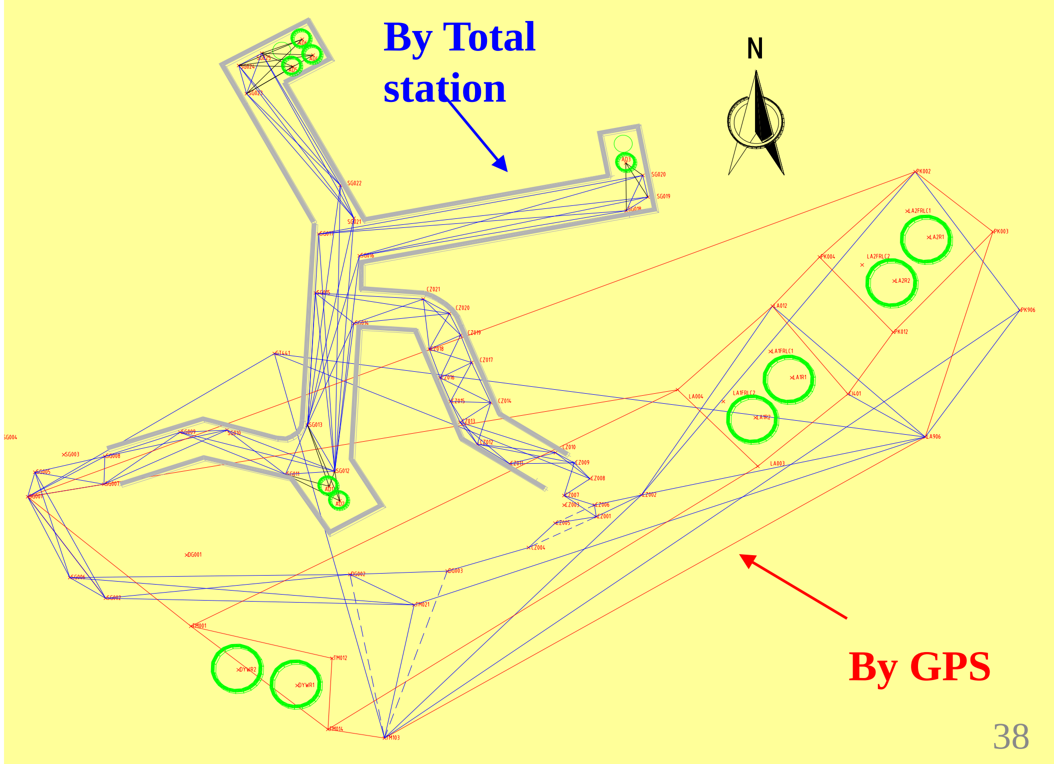
Predictions

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

- **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%)

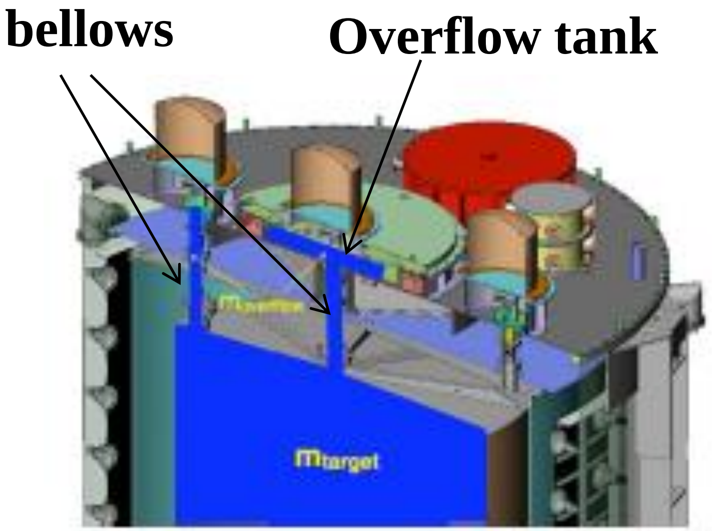


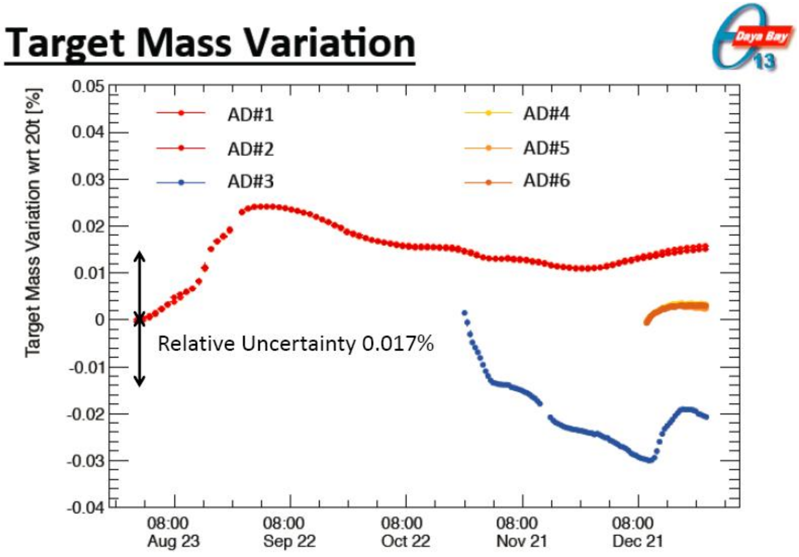
Target Mass & No. of Protons

- 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

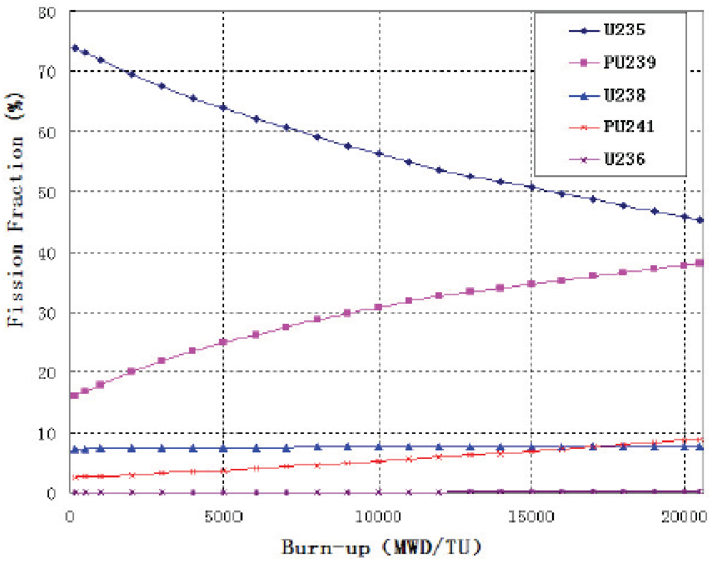
Quantity	Relative	Absolute
Free protons/Kg	neg.	0.47%
density	neg.	0.0002%
Total mass	0.015%	0.015%
Bellows	0.0025%	0.0025
Overflow tank	0.02%	0.02%
Total	0.03%	0.47%

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

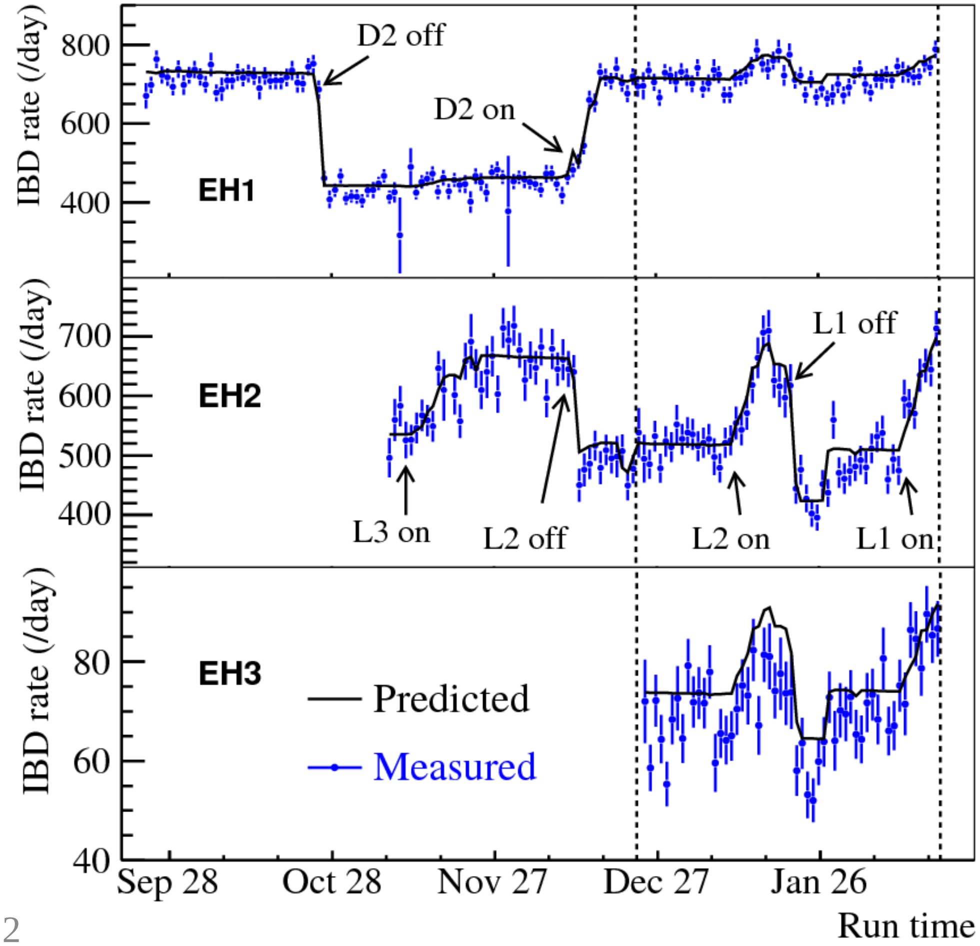
Reactor			
Correlated		Uncorrelated	
Energy/fission	0.2%	Power	0.5%
$\overline{\nu}_e$/fission	3%	Fission fraction	0.6%
		Spent fuel	0.3%
Combined	3%	Combined	0.8%

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

Relative measurement ➔ independent from the neutrino spectrum prediction

Daily Rate

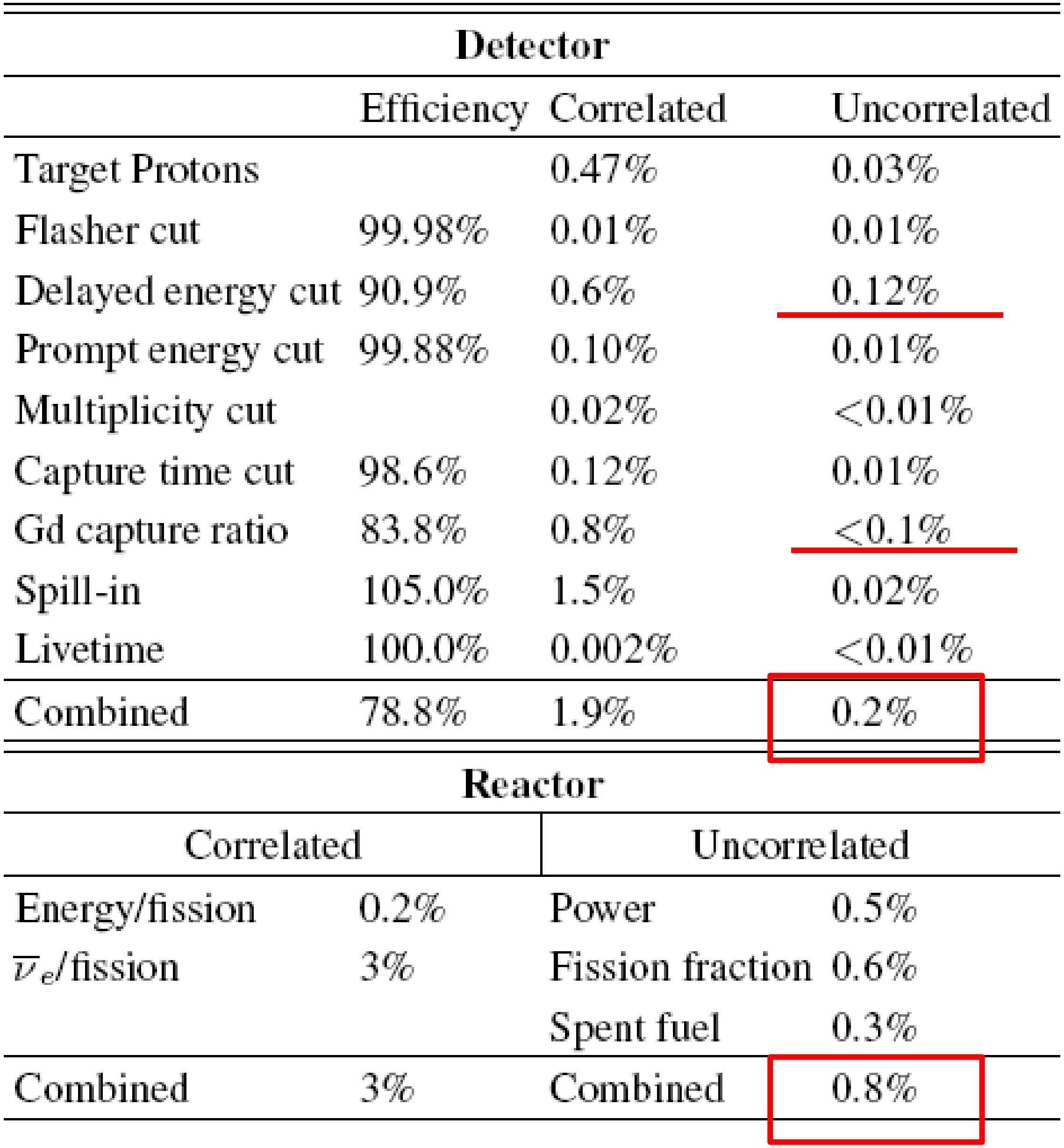
- Three halls taking data synchronously allows near-far cancellation of reactor related uncertainties
- Rate changes reflect the reactor on/off.



Prediction is relative plus a normalization correction.

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

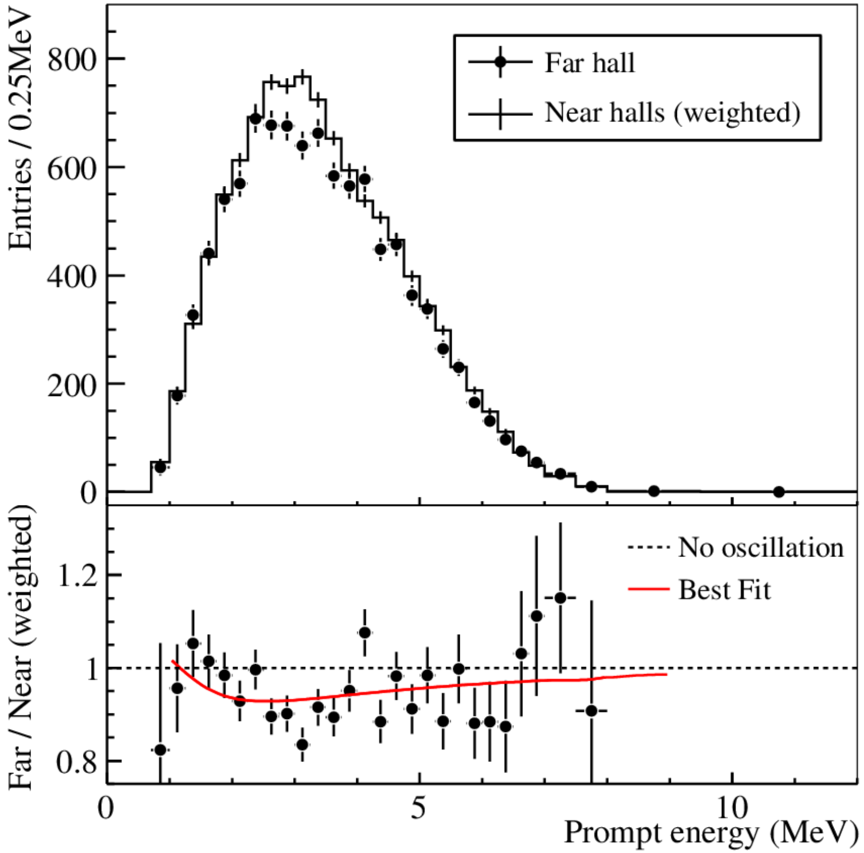
Using near to predict far

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

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

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

Spectral distortion
Consistent with oscillation

R = 0.940 ±0.011 (stat) ±0.004 (syst)

χ^2 Analysis

$$\chi^2 = \sum_{d=1}^{6} \frac{[M_d - T_d(1 + \boxed{\varepsilon} + \sum_r \omega_r^d \alpha_r + \varepsilon_d) + \eta_d]^2}{M_d + B_d} + \sum_r \frac{\alpha_r^2}{\sigma_r^2} + \sum_{d=1}^{6} \left(\frac{\varepsilon_d^2}{\sigma_d^2} + \frac{\eta_d^2}{\sigma_B^2} \right),$$

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

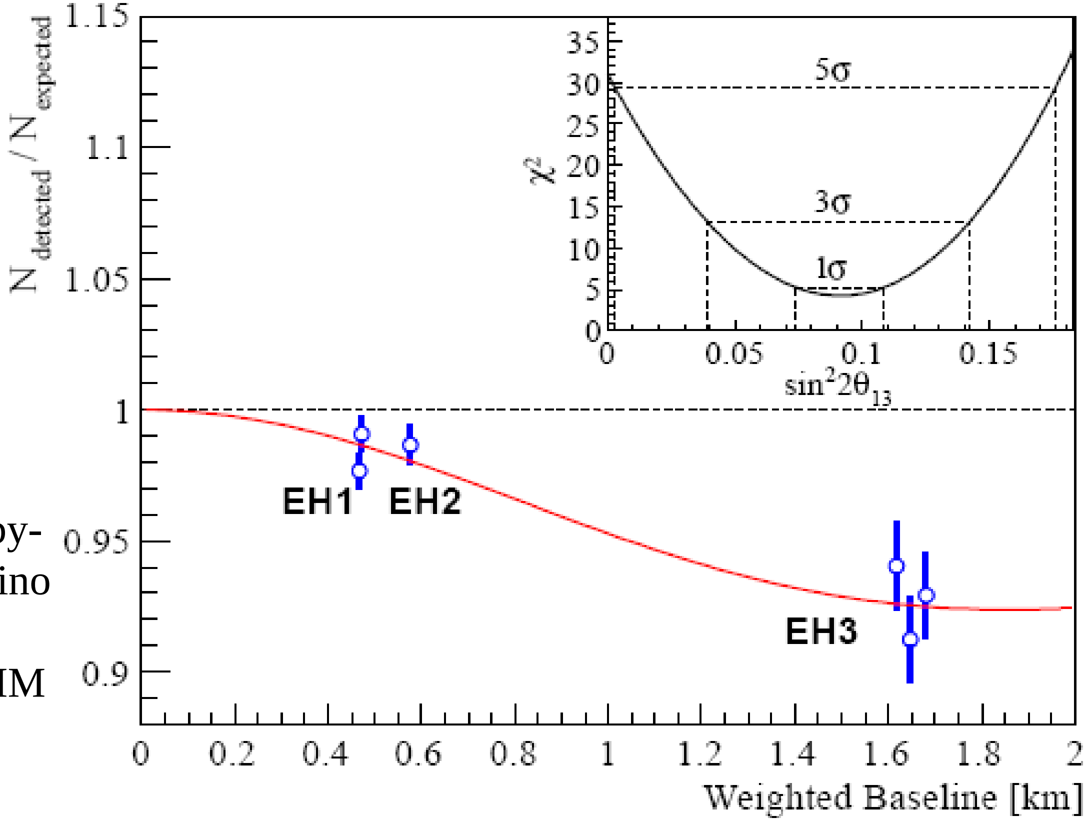
$\chi^2/\text{NDF} = 4.26/4$

5.2 σ for non-zero θ_{13}

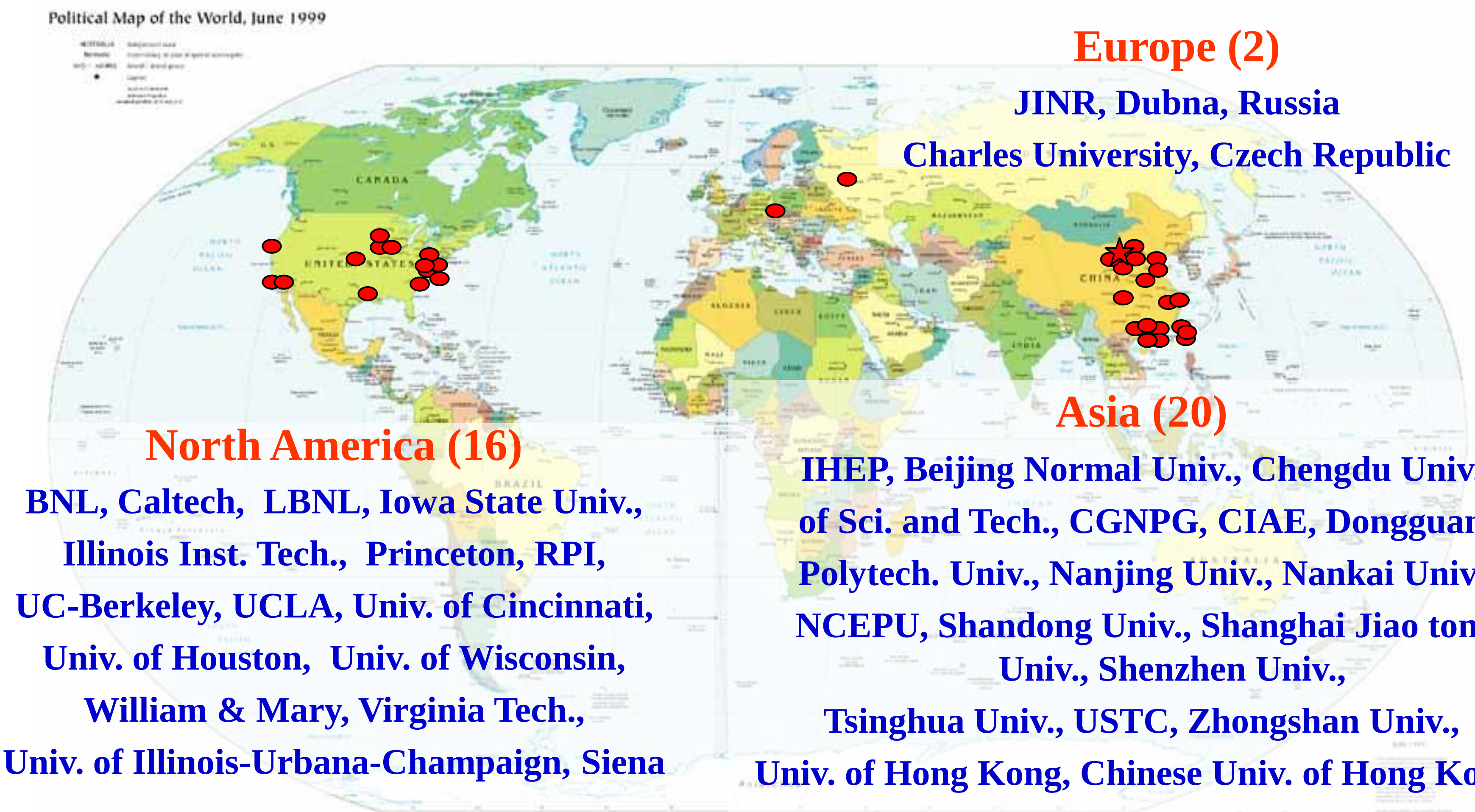
No constrain on absolute normalization. Fit on the near-far relative measurement.

F.P. An et al., Daya Bay Coll., PRL108, 171803 (2012)

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



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

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.

~250 Collaborators

Daya Bay Future plan

  - Assembly of AD7 and AD8, to be completed before summer
  - Continue the data taking until summer
- **Update result for *Neutrino* and *ICHEP* conferences with 2.5 times more statistics.**

  - Installation of AD7 & AD8 in summer
  - Detector calibration
  - Re-start data taking after summer
- **Full 6-AD data set with shape analysis.**

- **Three years' operation, reducing uncertainty from 20% to (4-5)%.**

Daya Bay-II

A 60km-baseline Reactor Experiment and Beyond

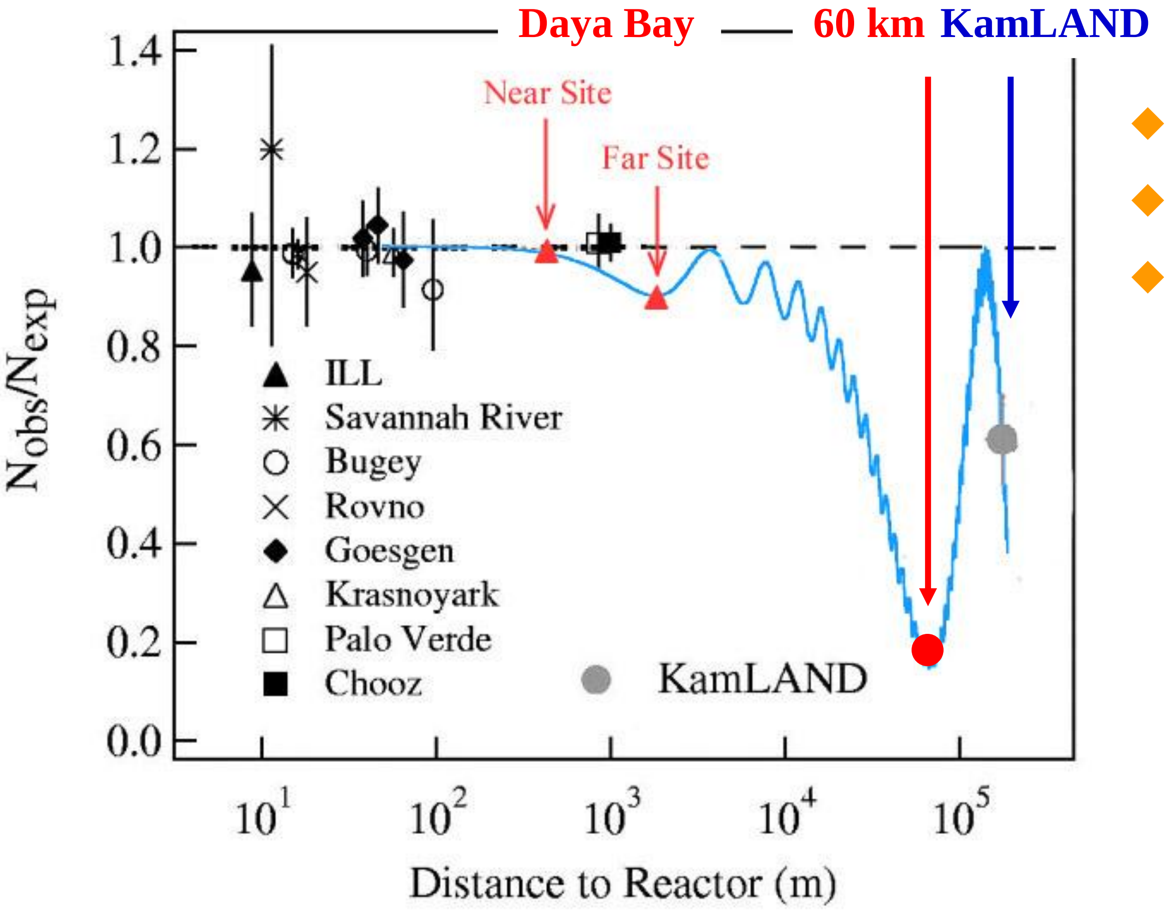
Jun Cao

Institute of High Energy Physics, CAS

nuTURN2012 - Neutrino at the Turning Point, Gran Sasso, May 8-10, 2012

Daya Bay-II Experiment

Giant Detector located at 60 km from Daya Bay reactors, the 1st maximum of θ_{12} oscillation.



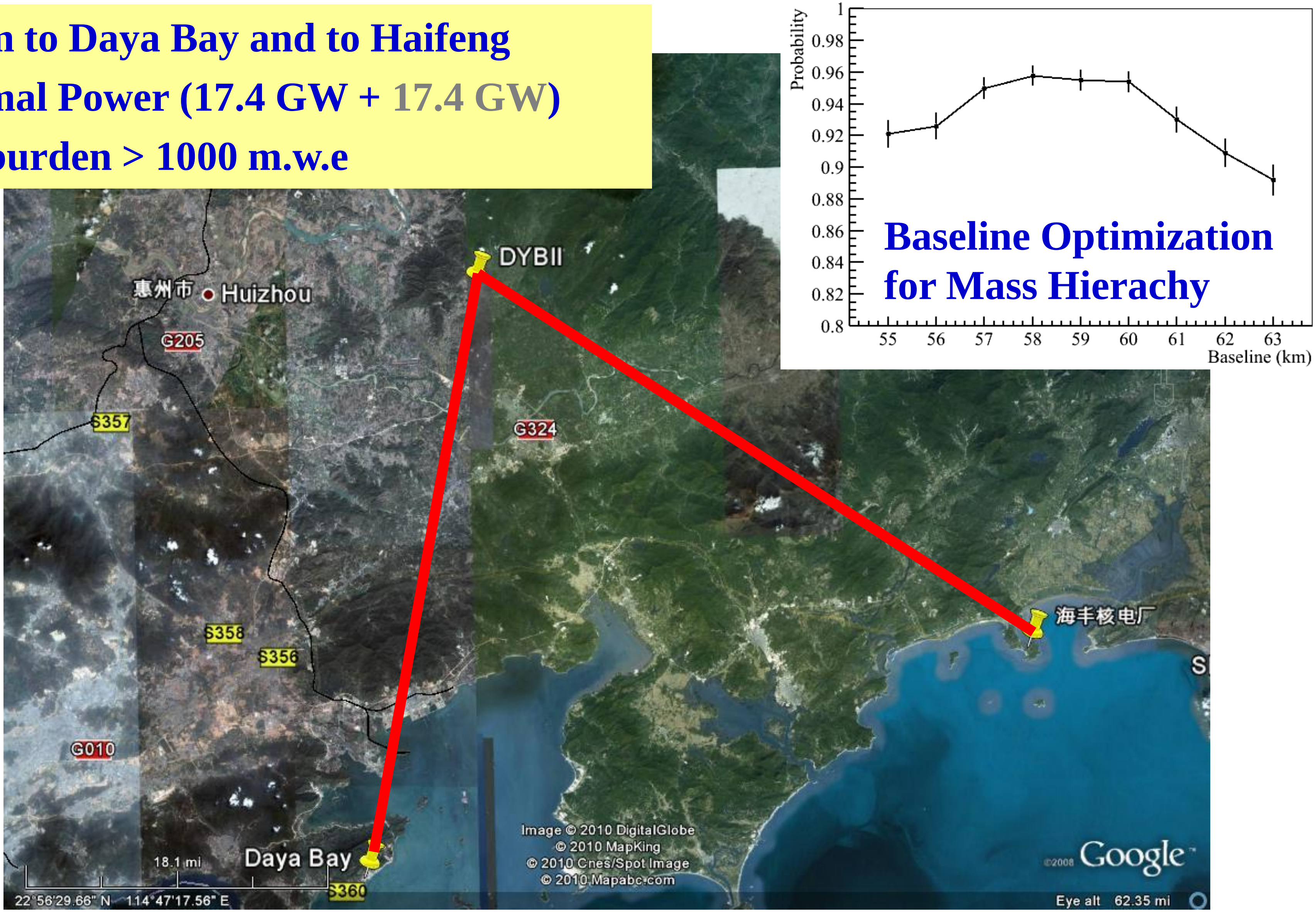
- **20 kton detector**
- **3% energy resolution**
- Rich physics possibilities
  - **Mass hierarchy**
  - **Precision measurement of 4 mixing parameters**
  - **Supernovae neutrino**
  - **Geoneutrino**
  - **Sterile neutrino**
  - **Abnormal magnetic moment**
  - **Possible CPV**

Site Investigation

~60km to Daya Bay and to Haifeng

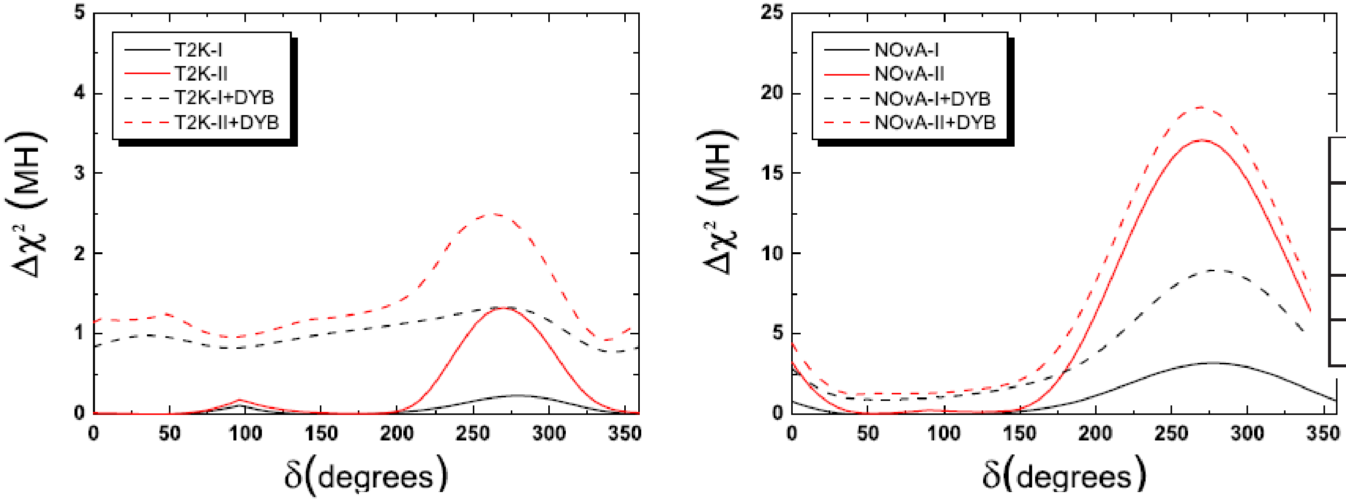
Thermal Power (17.4 GW + 17.4 GW)

Overburden > 1000 m.w.e

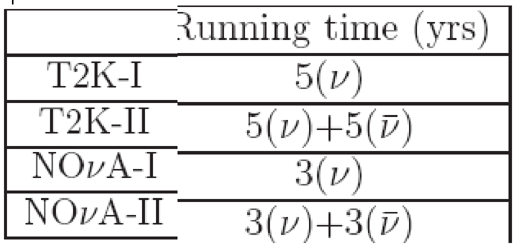


Baseline Optimization for Mass Hierachy

MH: Accelerator Exp.

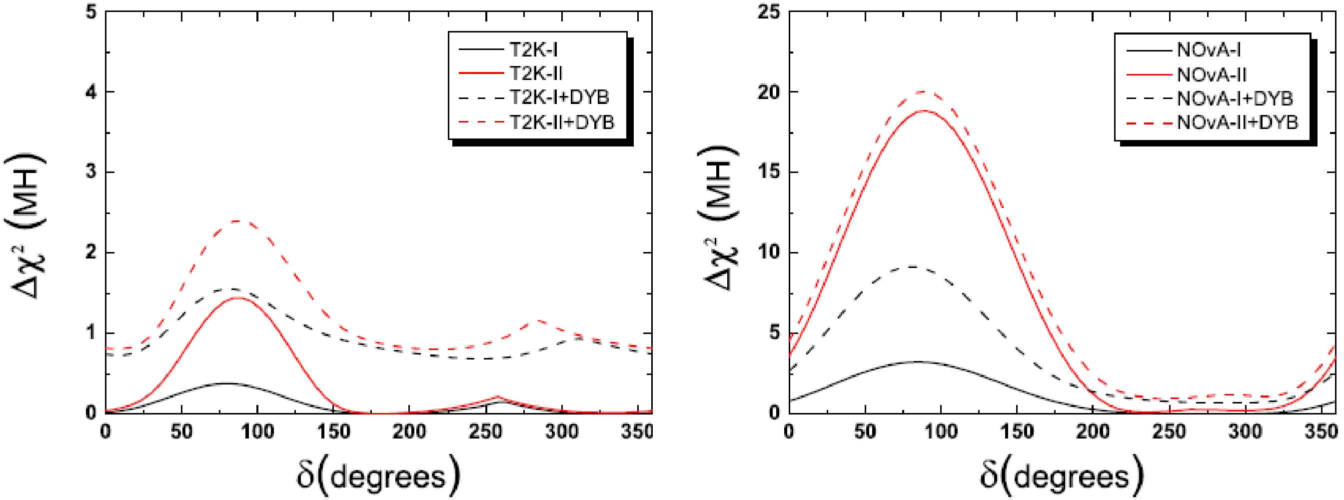


30% chance



	Running time (yrs)
T2K-I	$5(\nu)$
T2K-II	$5(\nu)+5(\bar{\nu})$
NOνA-I	$3(\nu)$
NOνA-II	$3(\nu)+3(\bar{\nu})$

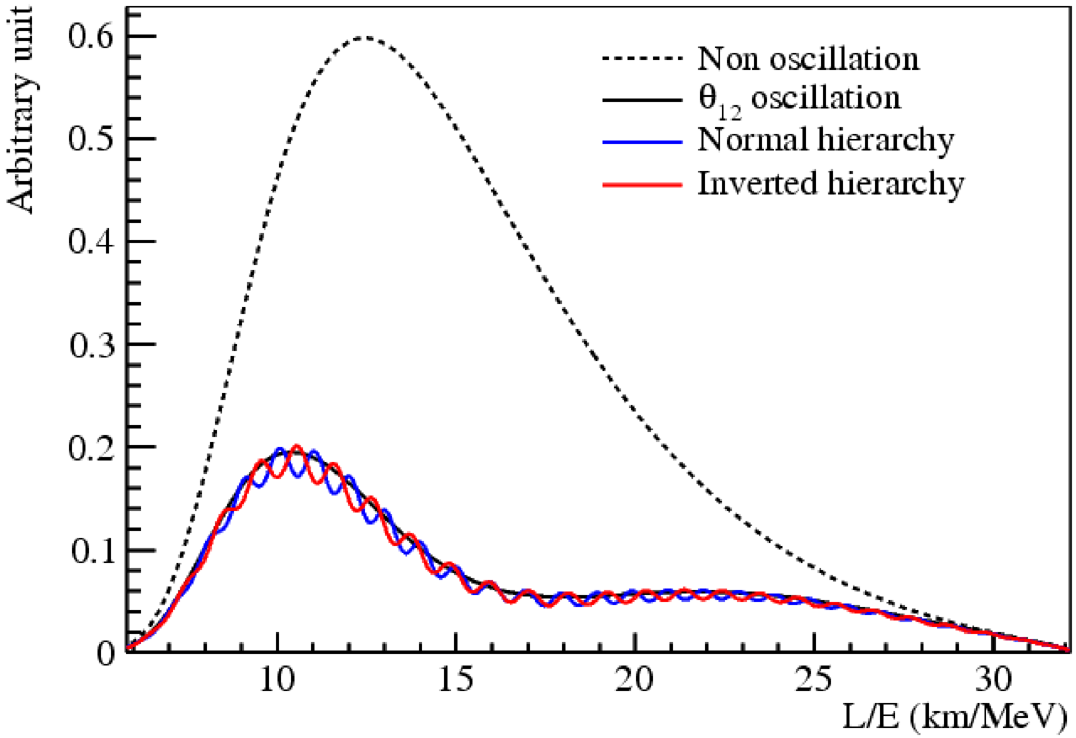
Figure 1: The power to and the combinations of l is assumed in the simulat



by Y.F. Li

Figure 2: The power to discriminate the mass hierarchy (MH) with LBL experiments and the combinations of beam and Daya-Bay experiments where an inverted mass hierarchy is assumed in the simulation.

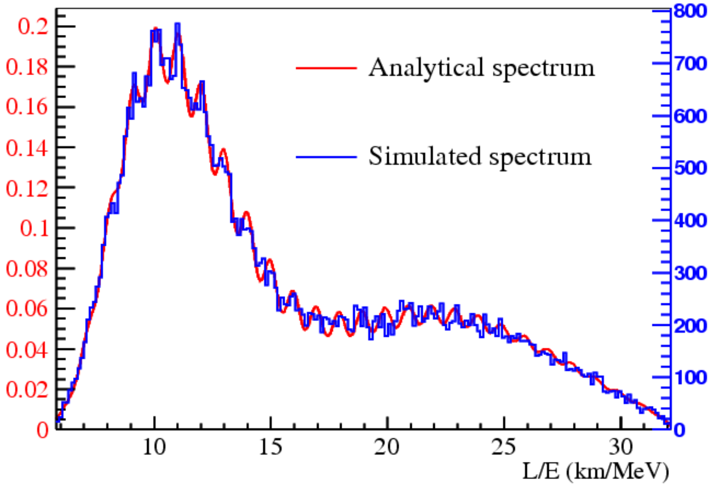
Reactor Exp. to determine MH



S.T. Petcov et al., PLB533(2002)94
S.Choubey et al., PRD68(2003)113006
J. Learned et al., hep-ex/0612022

L. Zhan, Y. Wang, J. Cao, L. Wen,
PRD78:111103, 2008
PRD79:073007, 2009

$$
\begin{aligned}
P_{ee}(L/E) &= 1 - P_{21} - P_{31} - P_{32} \\
P_{21} &= \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21}) \\
P_{31} &= \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31}) \\
P_{32} &= \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32})
\end{aligned}
$$

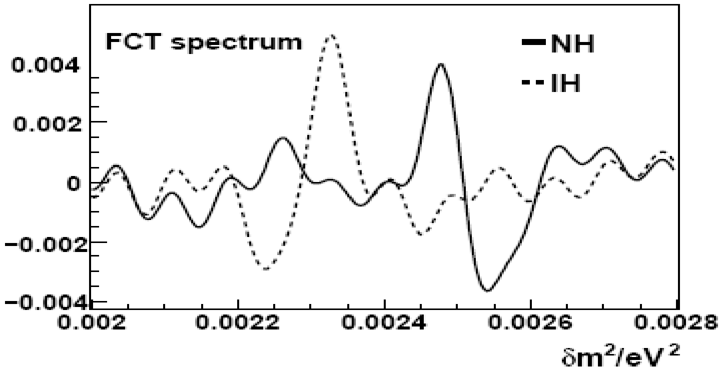


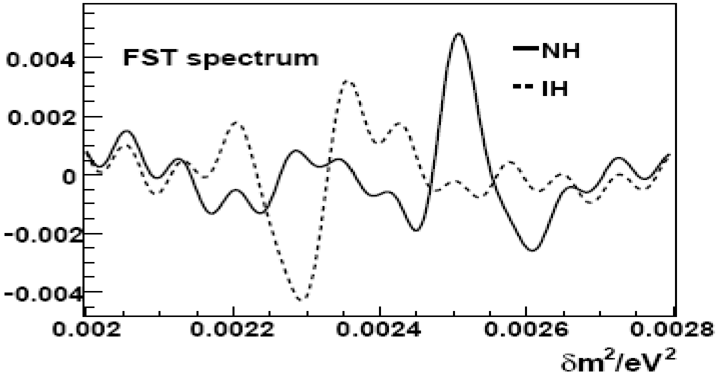
Features of Hierarchy

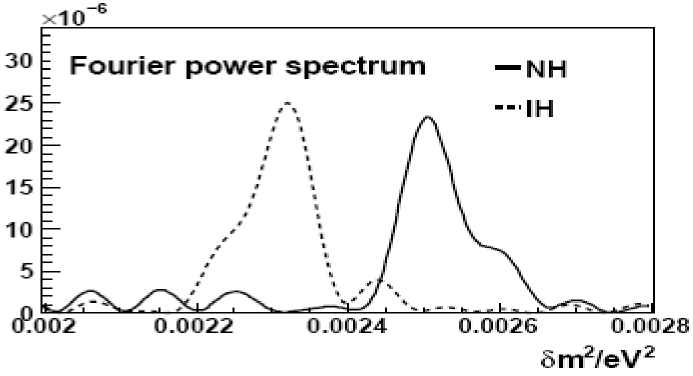
$$FST(\omega) = \int_{t_{min}}^{t_{max}} F(t)\sin(\omega t)\mathrm{d}t$$

$$FCT(\omega) = \int_{t_{min}}^{t_{max}} F(t)\cos(\omega t)\mathrm{d}t$$

- **Clear distinctive features:**
  - **FCT:**
    - ✓ **NH: peak before valley**
    - ✓ **IH: valley before peak**
  - **FST:**
    - ✓ **NH: prominent peak**
    - ✓ **IH: prominent valley**
- **Better than power spectrum**
- **No pre-condition of Δm^2_{23}**





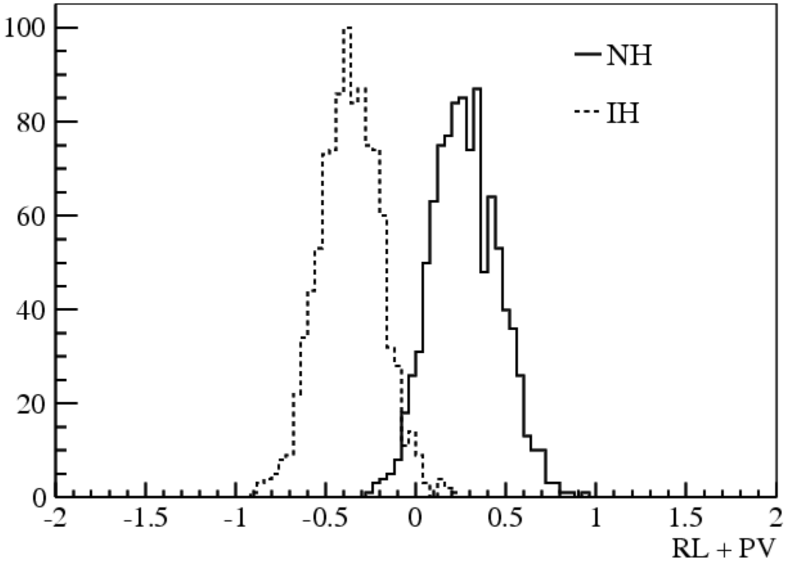


Discrimination Power

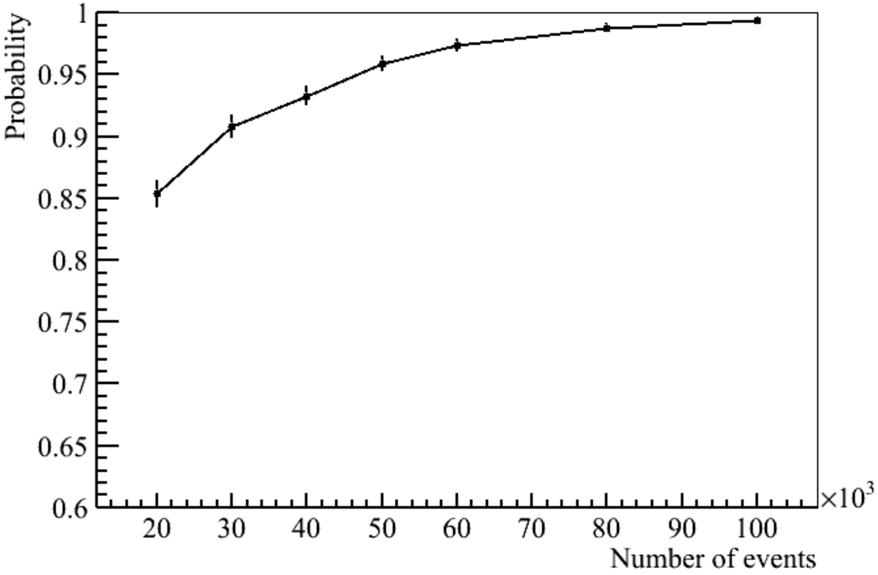
$$\sin^2 2\theta_{13} = 0.092$$
$$\sin^2 2\theta_{12} = 0.861$$
$$\sin^2 2\theta_{23} = 1$$
$$\Delta m^2_{21} = 7.59 \times 10^{-5} eV^2$$
$$\Delta m^2_{32} = 2.43 \times 10^{-3} eV^2$$

Energy resolution	3%/sqrt(E)
Baseline	58 km
Thermal Power	35 GW

50k events =20k tons X 3 years



50k events: 96% probability



100k events: 3 σ

Mixing parameters

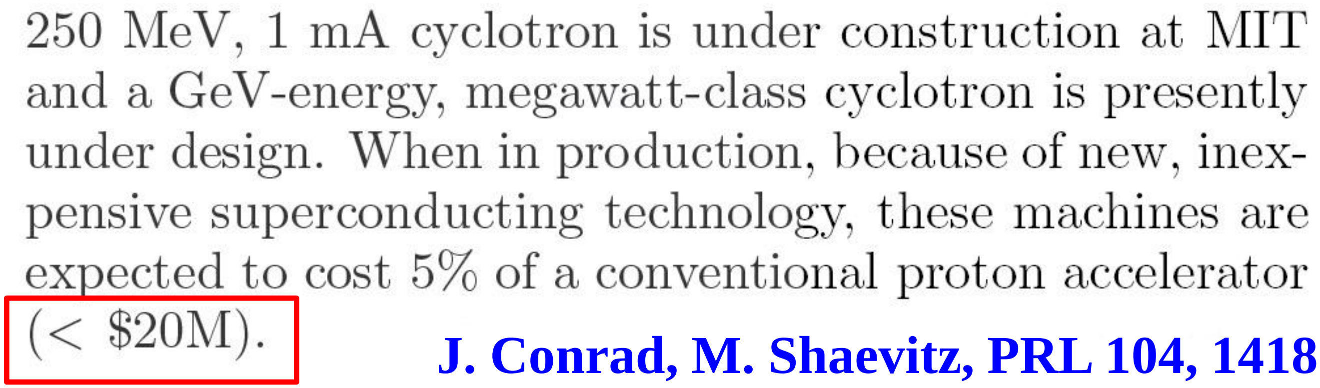
- Uncertainties of mixing parameters

	Current	Daya Bay II
Δm^2_{12}	3%	$< 1\%$
Δm^2_{23}	5%	$< 1\%$
$\sin^2\theta_{12}$	6%	$< 1\%$
$\sin^2\theta_{23}$	20%	-
$\sin^2\theta_{13}$	20% (5%)	cross check to 5%

To be elaborated

- Check the unitary of the mixing matrix to 1% (need $\sin^2\theta_{23}$, CPV)

It is possible to measure everything

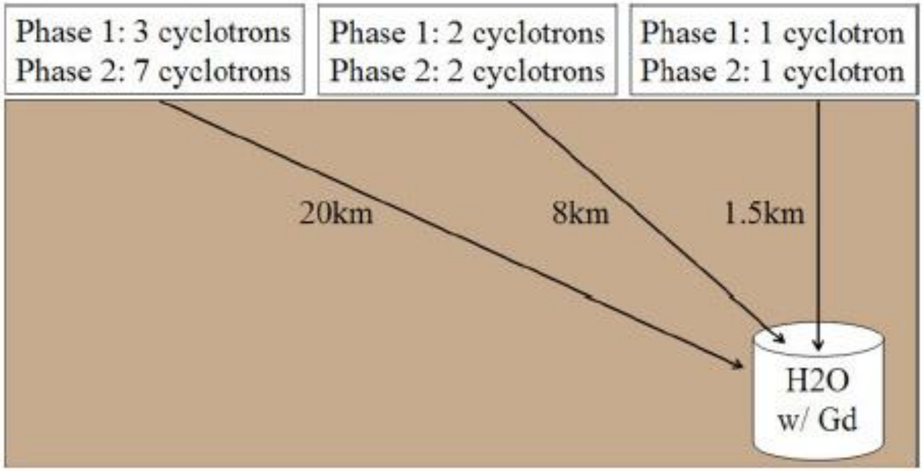


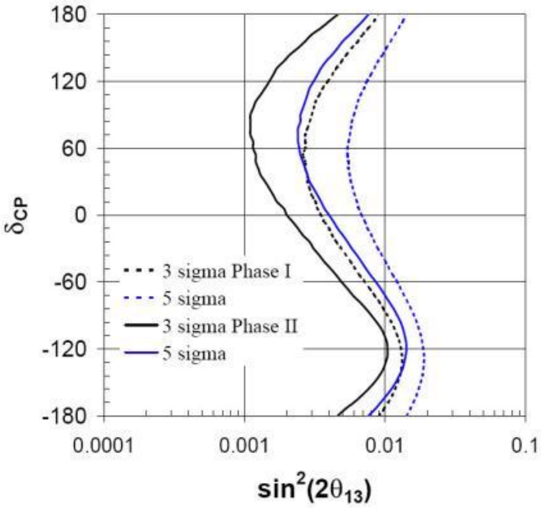
250 MeV, 1 mA cyclotron is under construction at MIT and a GeV-energy, megawatt-class cyclotron is presently under design. When in production, because of new, inexpensive superconducting technology, these machines are expected to cost 5% of a conventional proton accelerator (< \$20M).

Cyclotron

Pion decay at rest

J. Conrad, M. Shaevitz, PRL 104, 141802





Supernova

- Less than 20 events observed so far (2002 Noble prize)
- Assumptions:
  - Distance: 10 kpc (our Galaxy center)
  - Energy: 3×10^{53} erg
  - L_ν the same for all types
  - Tem. & energy

$T(\underline{\nu}_e)$ = 3.5 MeV, $<E(\underline{\nu}_e)>$ = 11 MeV

$T(\nu_e)$ = 5 MeV, $<E(\nu_e)>$ = 16 MeV

$T(\nu_x)$ = 8 MeV, $<E(\nu_x)>$ = 25 MeV

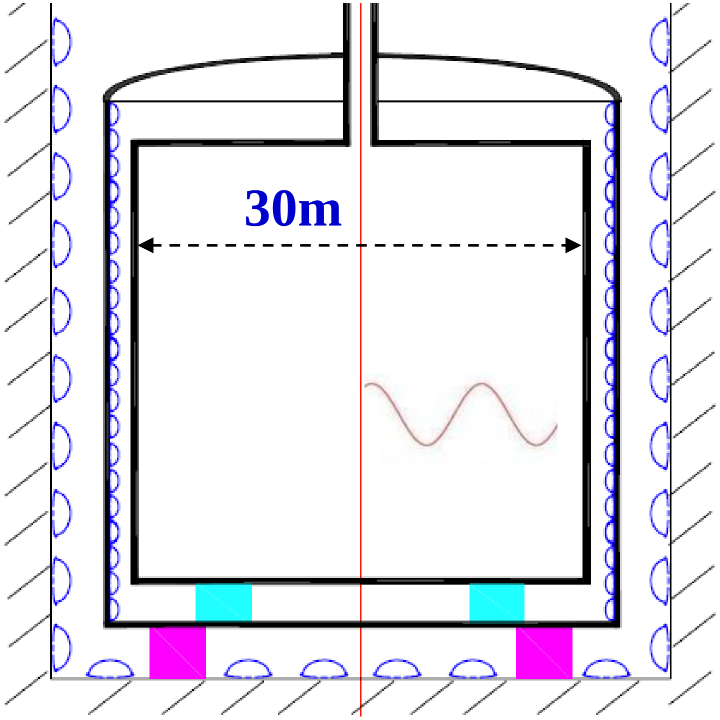
- Many types of events:
  - $\nu_e + p \rightarrow n + e^+$, ~ 3000 correlated events
  - $\bar{\nu}_e + {}^{12}C \rightarrow {}^{13}B^* + e^+$, ~ 10-100 correlated events
  - $\bar{\nu}_e + {}^{12}C \rightarrow {}^{11}N^* + e^-$, ~ 10-100 correlated events
  - $\nu_x + {}^{12}C \rightarrow \nu_x + {}^{12}C^*$, ~ 600 correlated events
  - $\nu_x + p \rightarrow \nu_x + p$, single events
  - $\nu_e + e^- \rightarrow \nu_e + e^-$, single events
  - $\nu_x + e^- \rightarrow \nu_x + e^-$, single events

SuperK can not see these correlated events

Detector Concept

- **Neutrino target: ~20kt LS, LAB based**

  30m(D)×30m(H)
- **Oil buffer: 6kt**
- **Water buffer: 10kt**
- **PMT: 15000 20”**



- **Strong Source: Sterile neutrino, abnormal magnetic moment**
- **Geoneutrino**

Thanks!