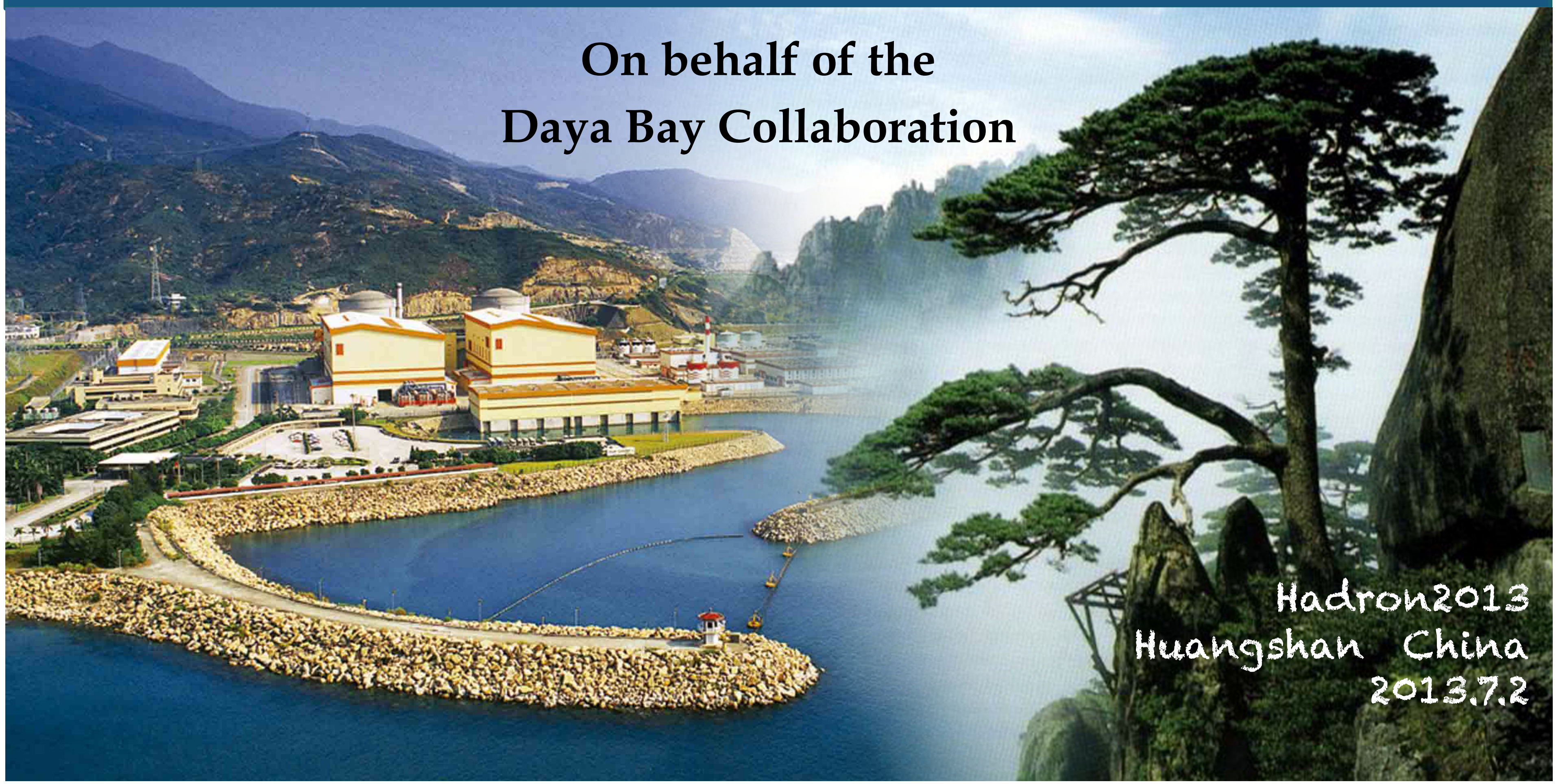
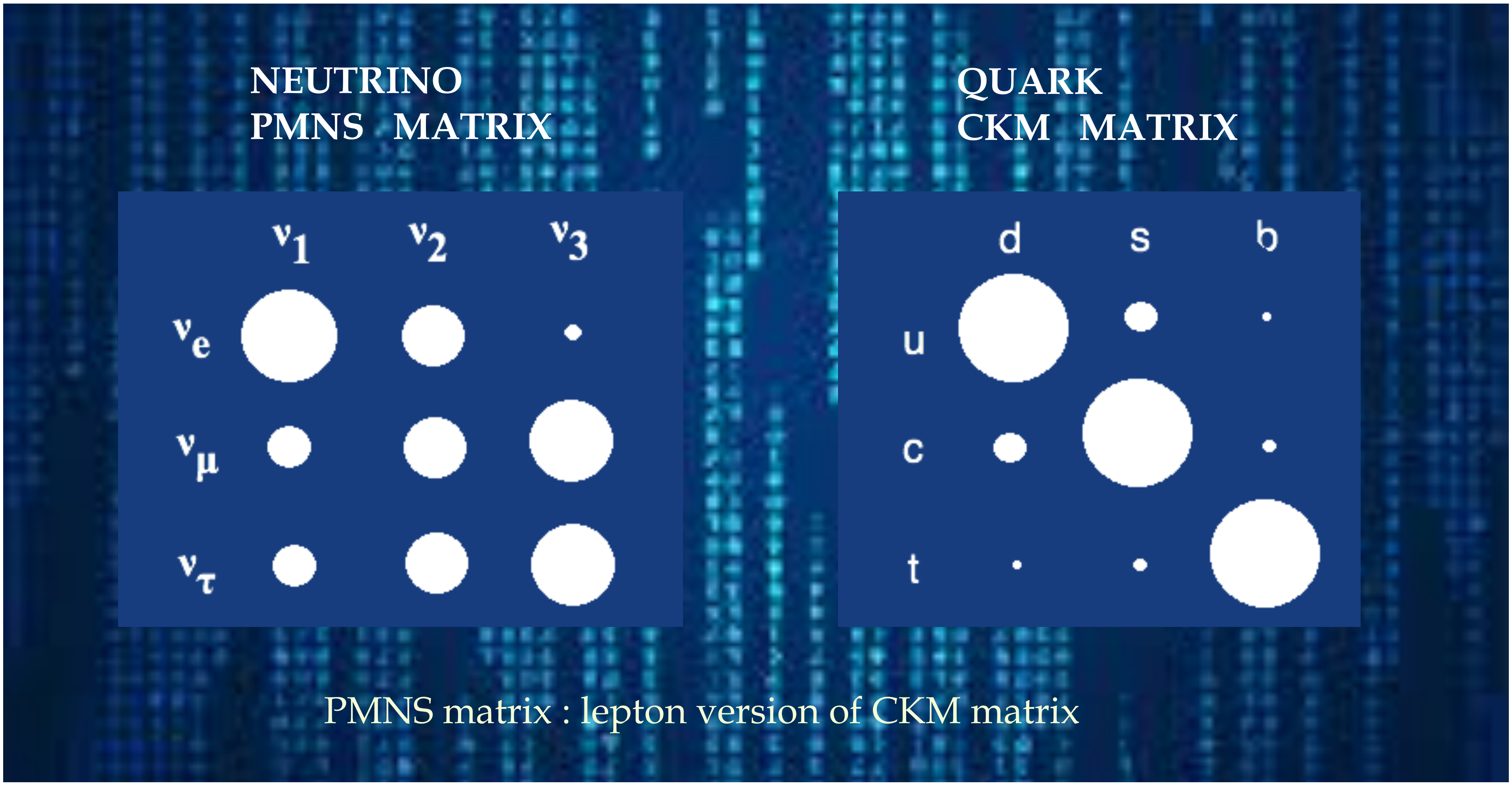
DAYA BAY REACTOR ANTINEUTRINO EXPERIMENT

钟玮丽 Weili Zhong IHEP

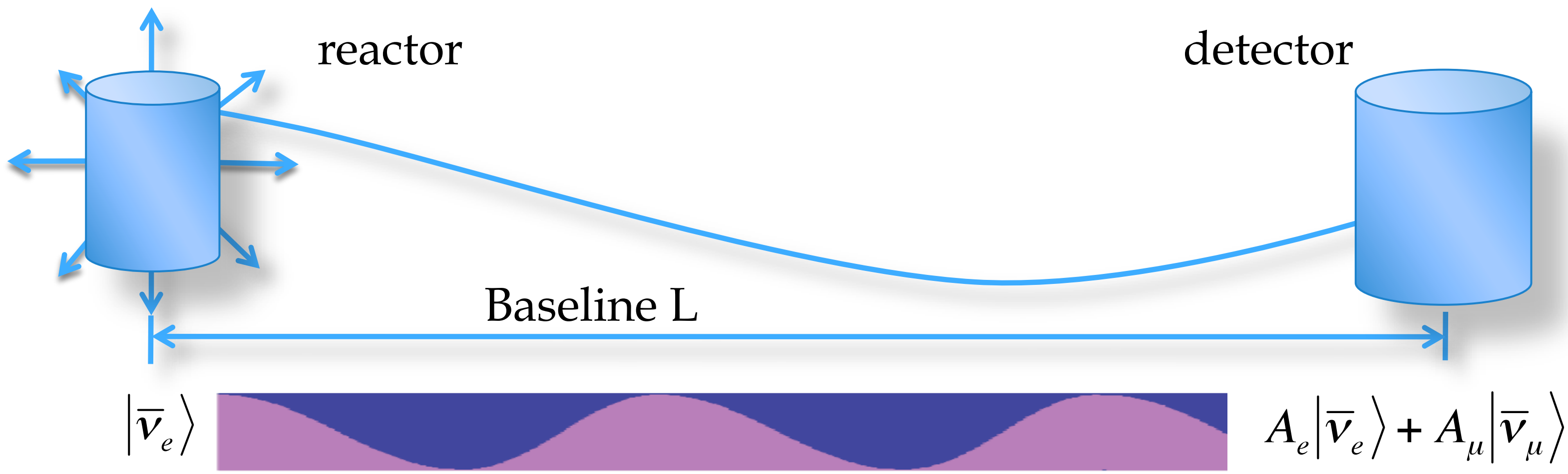


Flavor mixing

Mass eigenstate $\neq$ weak interaction eigenstate



Neutrino Mass and Mixing



$|\overline{\nu}_e\rangle$ $\quad A_e|\overline{\nu}_e\rangle + A_\mu|\overline{\nu}_\mu\rangle$

$$|\overline{\nu}_e\rangle = \cos\theta|\overline{\nu}_1\rangle + \sin\theta|\overline{\nu}_2\rangle \qquad P(\nu_e \to \nu_e) = |A_e^2| = 1 - \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Mass eigenstates: $\overline{\nu}_1 \quad \overline{\nu}_2$

Mass squared difference: $\Delta m^2 = m_1^2 - m_2^2$

Neutrino oscillation requires that neutrinos have:

1. Flavor mixing
2. Finite non-degenerate mass

Neutrino oscillation

- PMNS matrix:

θ_{23} and $|\Delta m^2_{32}|$ θ_{13} θ_{12} and Δm^2_{21}

$$U=\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\times\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix}\times\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\times\begin{pmatrix}e^{i\alpha_1/2} & 0 & 0\\ 0 & e^{i\alpha_2/2} & 0\\ 0 & 0 & 1\end{pmatrix}$$

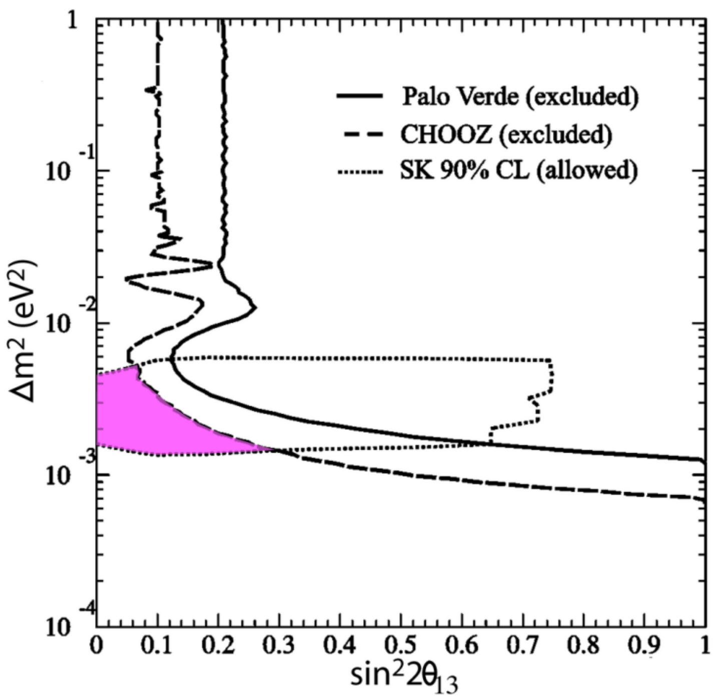
Atmospheric $\theta \sim 45°$ | Cross-Mixing | Solar $\theta \sim 34°$ | Majorana CPV phases $0\nu\beta\beta$

- θ_{13} was the last unknown mixing angle.

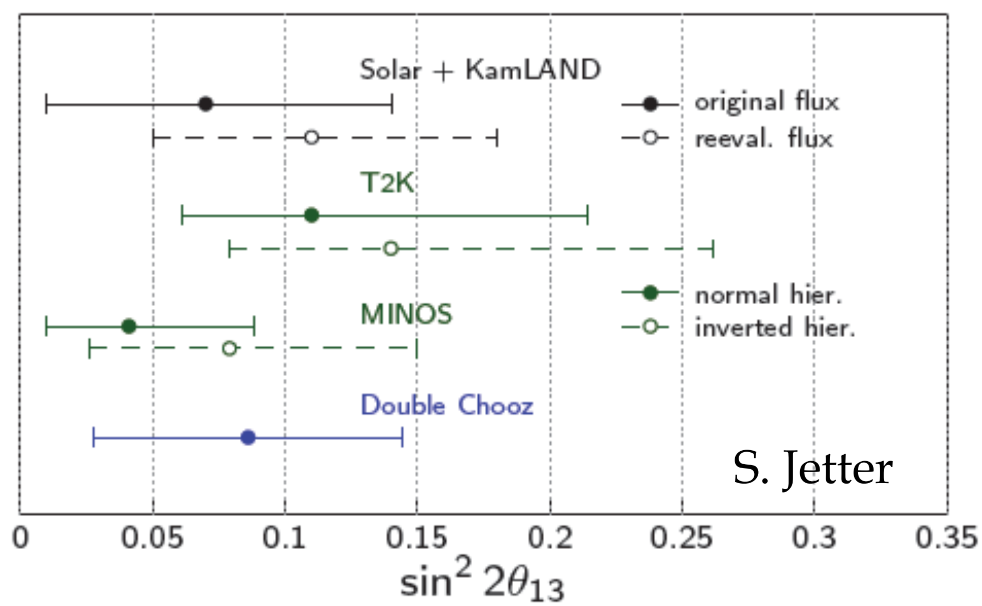
- θ_{13} is the gate way to δ_{CP} measurement.

Direct Measurement of θ_{13}

- Before the Daya Bay experiment was proposed(2003), the best limit was given by Chooz.



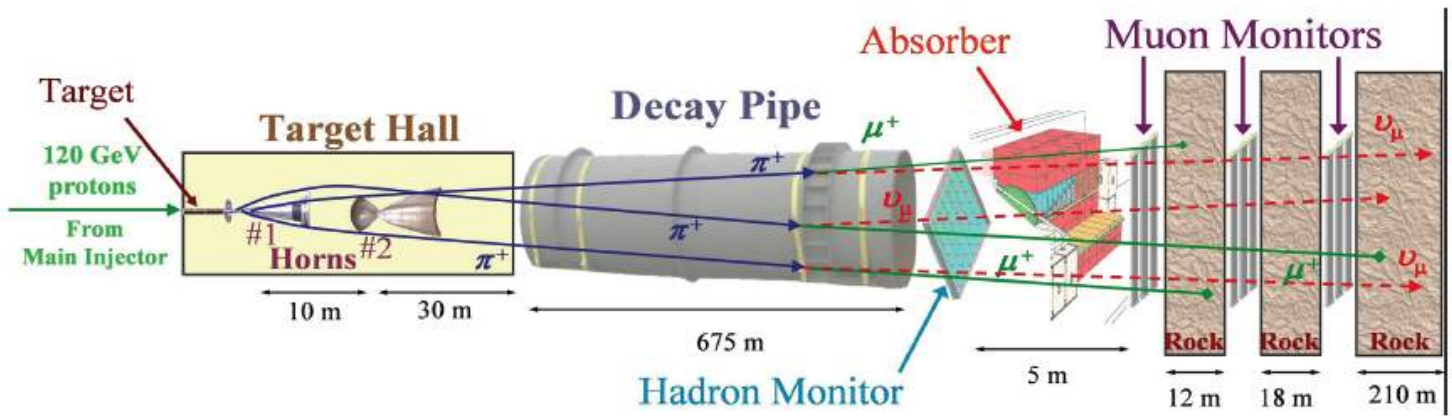
$\sin^2 2\theta_{13} < 0.12$ @ 90%C.L.
if $\Delta M^2_{23} = 0.0024\ eV^2$



- In 2011, there were hints of a non-zero $\theta_{13,}$ but no more than 2.5 σ from zero.

Approaches of θ_{13} Measurements

- Accelerator neutrino appearance experiment

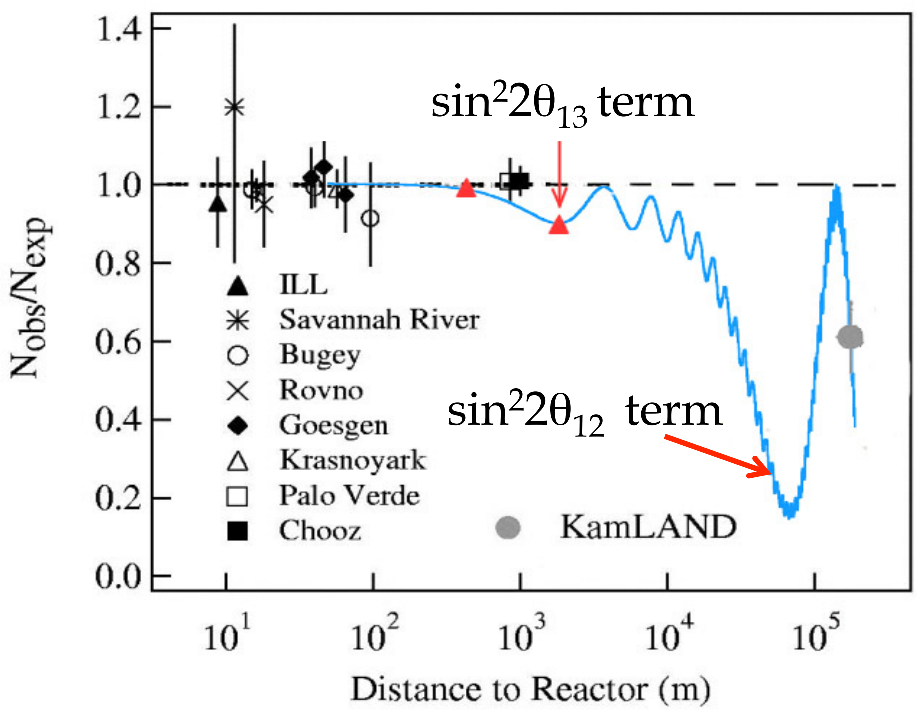


- Neutrino sources: more than one flavor
- Signal: ν_e CC, with ν_α NC, CC background
- Oscillation probability:

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta_{13} \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{31} L}{4E_\nu}\right) + \boxed{terms(\delta, \Delta m^2_{32}, \text{matter effect})}$$

Approaches of θ_{13} Measurements

- Reactor neutrino disappearance experiment

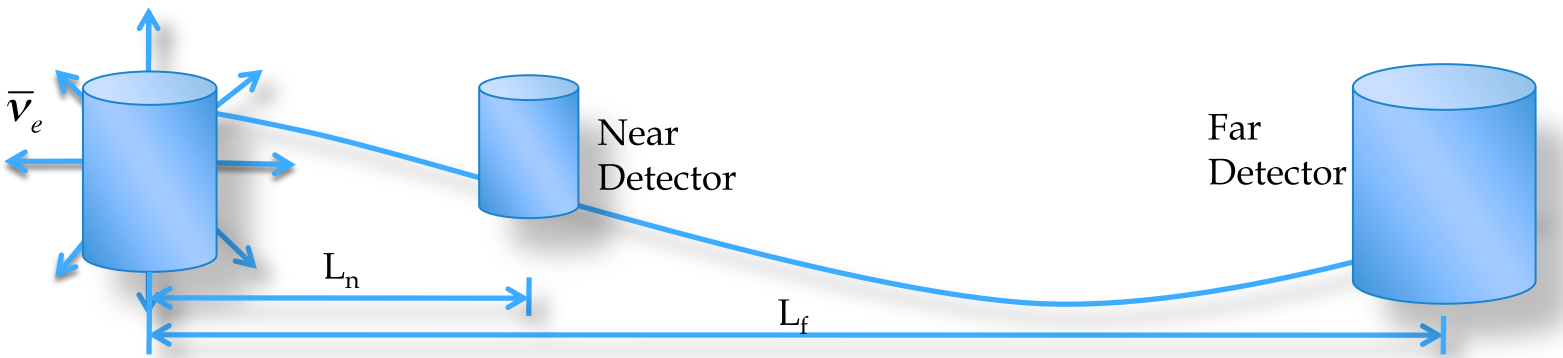


- Neutrino sources: pure electron antineutrinos
- Signal: inverse beta-decay
- Oscillation probability: only $\sin^2 2\theta_{13}$ was previously unknown

$$P(\nu_e \to \nu_e) \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E_\nu}\right) + \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}^2 L}{4E_\nu}\right)$$

Precise Measurement of θ_{13} at Reactors

- Reactor flux: largest uncertainty source in previous reactor experiments.
- Near/Far relative measurement



$$\frac{N_f}{N_n} = \left(\frac{N_{P,f}}{N_{P,n}}\right)\left(\frac{L_n}{L_f}\right)^2\left(\frac{\varepsilon_f}{\varepsilon_n}\right)\left(\frac{P_{sur}(E,L_f)}{P_{sur}(E,L_n)}\right)$$

Ratio of Measured Rates

Ratio of proton Number

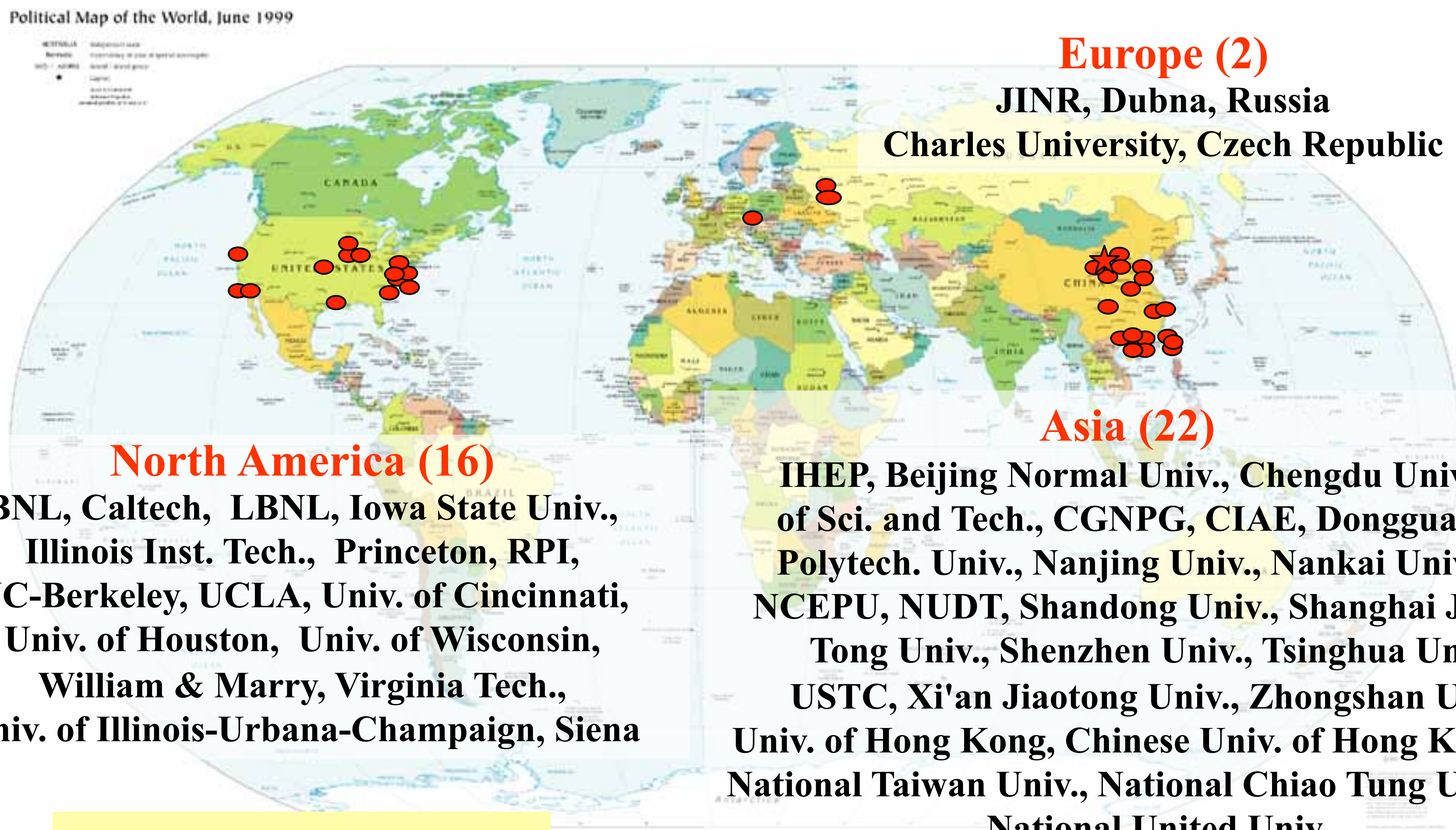
Ratio of Detector Efficiency

↑ $\sin^2 2\theta_{13}$

Near/far relative measurement: Mikaelyan and Sinev, Hep-ex/9908047

Proposed Reactor Experiments

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 & Marry, Virginia Tech., Univ. of Illinois-Urbana-Champaign, Siena

Asia (22)

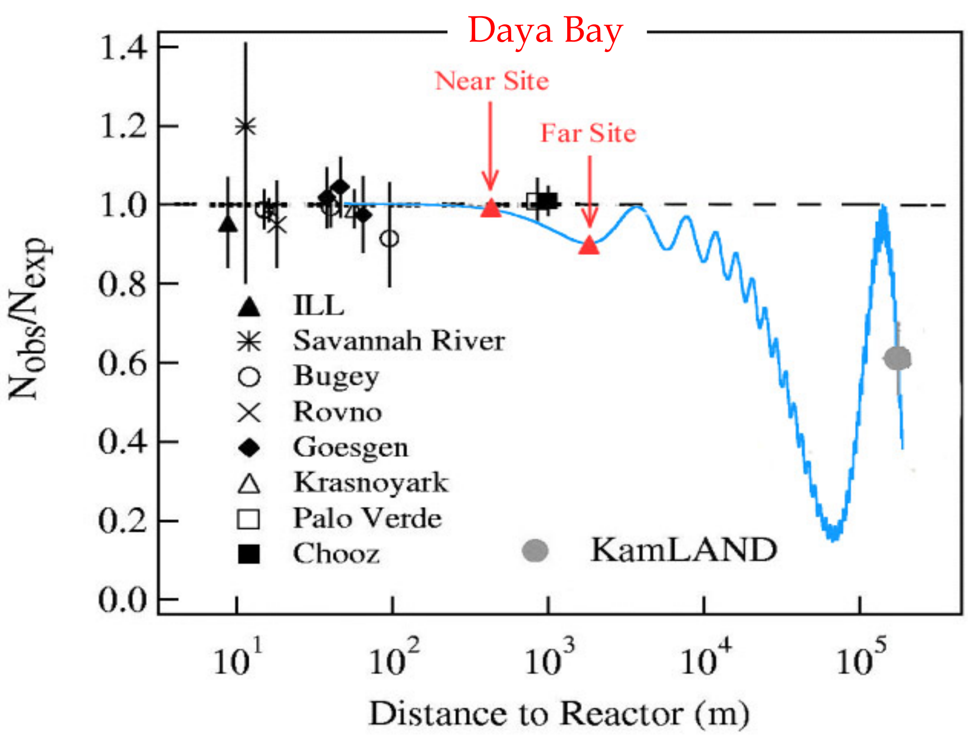
IHEP, Beijing Normal Univ., Chengdu Univ. of Sci. and Tech., CGNPG, CIAE, Dongguan Polytech. Univ., Nanjing Univ., Nankai Univ., NCEPU, NUDT, Shandong Univ., Shanghai Jiao Tong Univ., Shenzhen Univ., Tsinghua Univ., USTC, Xi'an Jiaotong Univ., Zhongshan Univ., Univ. of Hong Kong, Chinese Univ. of Hong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

~230 Collaborators

Daya Bay Experiment Design

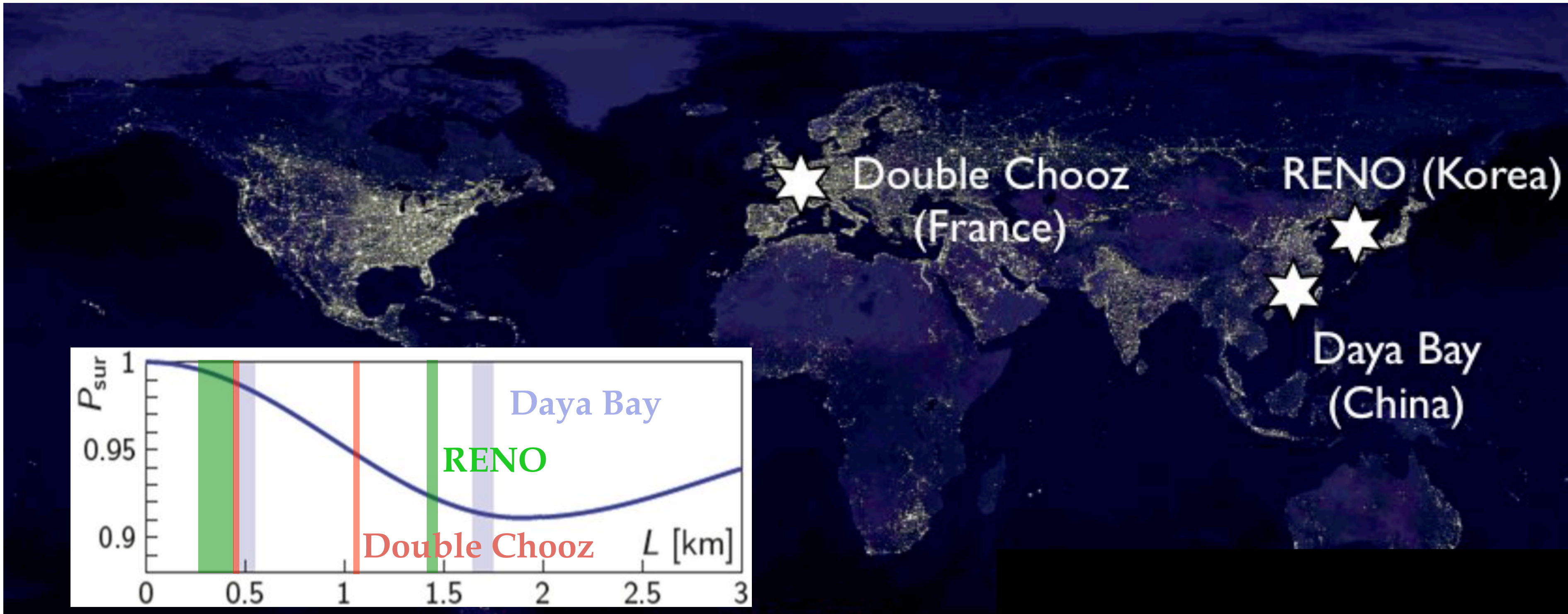
- High statistics: 6 reactor cores, 17.6GW$_{th}$
- Strong cosmic ray suppression: good mountain shielding

Daya Bay Experiment Design



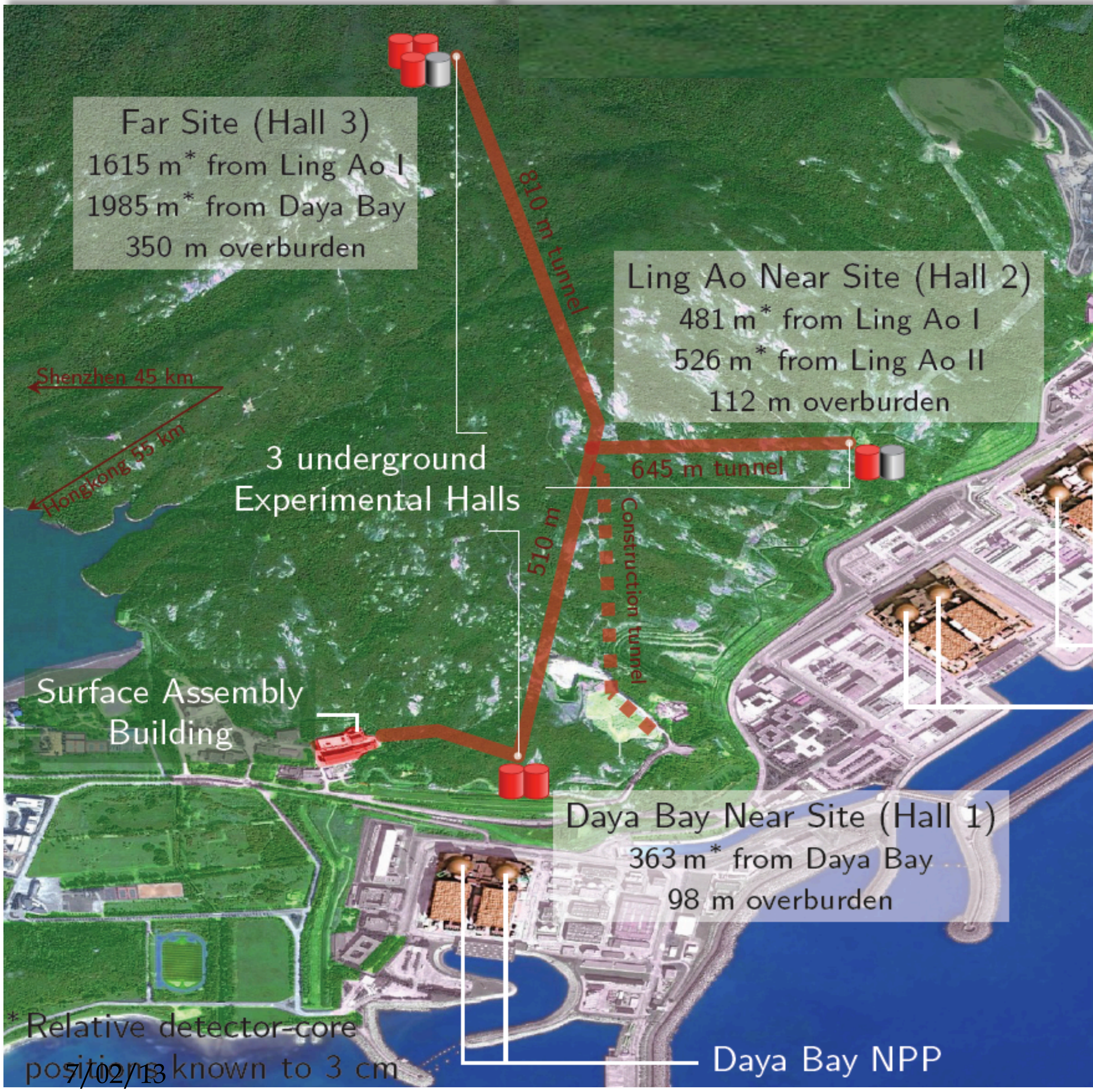
$$\frac{N_f}{N_n} = \left(\frac{N_{P,f}}{N_{P,n}}\right)\left(\frac{L_n}{L_f}\right)^2\left(\frac{\varepsilon_f}{\varepsilon_n}\right)\left(\frac{P_{sur}(E,L_f)}{P_{sur}(E,L_n)}\right)$$

- Baseline optimization: P_f/P_n
  - Near site detector location: a few hundred meters; almost no oscillation.
  - Far site detector location: oscillation maximum (~1.8km) due to $\sin^2 2\theta_{13}$ term.
- $\varepsilon_f/\varepsilon_n$: functionally 'identical' detectors
- L_n/L_f: baseline uncertainty is negligible. Precise survey (<0.02%).
- $N_{p,f}/N_{p,n}$: detector target materials produced in the same batch (<0.015%).



	Thermal Power (GW)	Mass (Tons)	Near		Far		$\sigma_{sys.}$
			Distance (m)	Depth (m.w.e.)	Distance (m)	Depth (m.w.e.)	
Double Chooz	8.5	2x8	400	120	1050	300	0.025
RENO	16.5	2x16	290	120	1380	450	0.019
Daya Bay	17.4	8(6)×20	363 &481	250 &265	1985 &1615	860	0.005

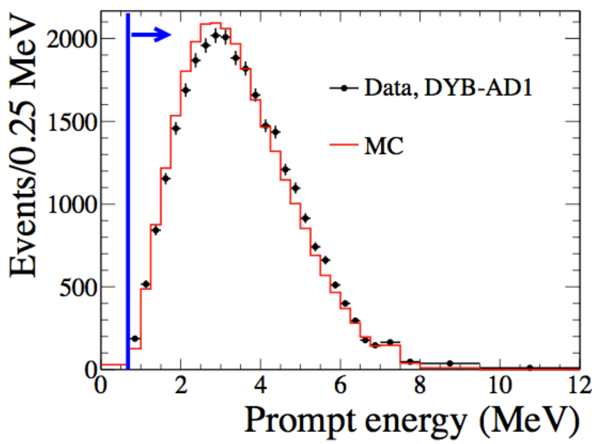
Experiment Layout

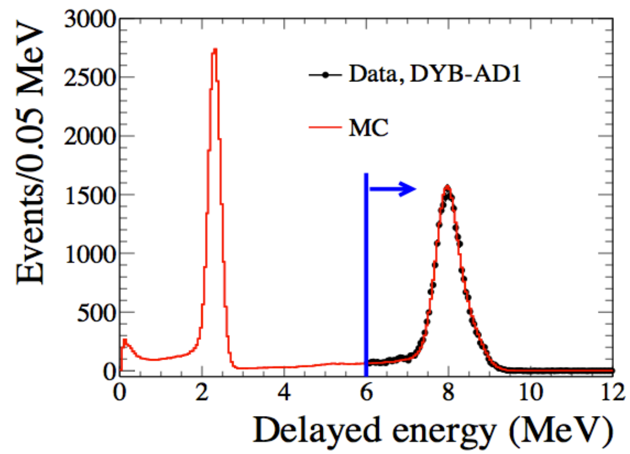


Hall 1: 2
Hall 2: 1 + 1
Hall 3: 3 + 1
Phase 1: 6 detectors
Phase 2: 8 detectors

Antineutrino Detection

- Inverse **beta decay** interaction (IBD)
  - In Gd-doped Liquid Scintillator (Gd-LS) Detector





$\bar{\nu}_e + p \rightarrow e^+ + n$ **(prompt signal)**

Energy and Time coincidence!

~180μs

$\rightarrow + p \rightarrow D + \gamma$ (2.2 MeV) (delayed signal)

$\rightarrow + Gd \rightarrow Gd^*$

~30μs
for 0.1% Gd

$\rightarrow Gd + \gamma's$ (8 MeV) **(delayed signal)**

$E_\nu \approx T_{e+} + T_n + (m_n - m_p) + m_{e+} \approx T_{e+} + 1.8$ MeV

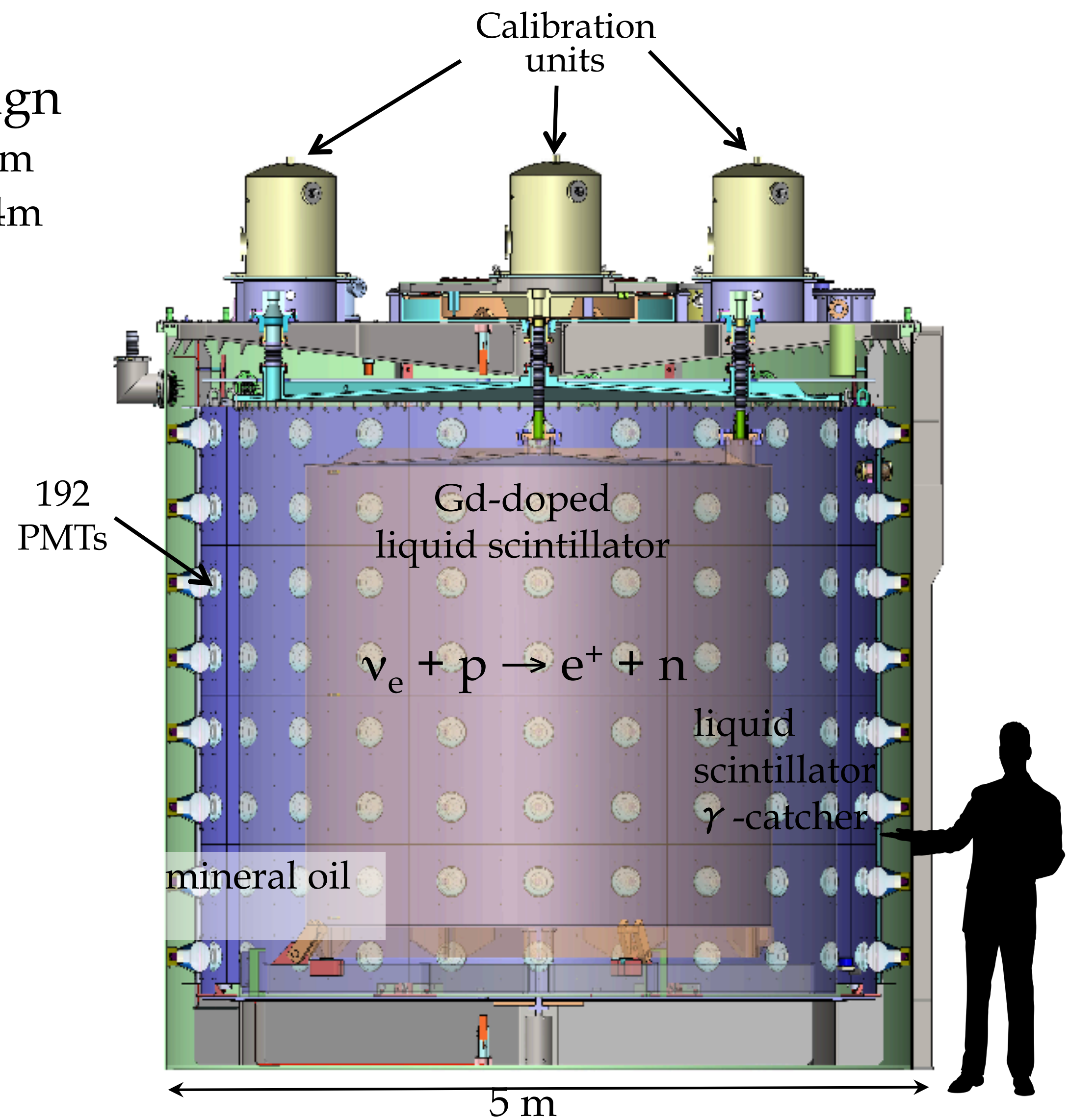
T_n: ~10-40 keV

Antineutrino Detector

- Three-zone cylindrical design
  - Inner acrylic vessel: Φ3m×H3m
  - Outer acrylic vessel: Φ4m×H4m
  - Steel vessel: Φ5m×H5m

Zone	Mass	Liquid	Purpose
Inner acrylic vessel	20 t	Gd-doped liquid scintillator	Anti-neutrino target
Outer acrylic vessel	20 t	Liquid scintillator	Gamma catcher (from target zone)
Stainless steel vessel	40 t	Mineral Oil	Radiation shielding

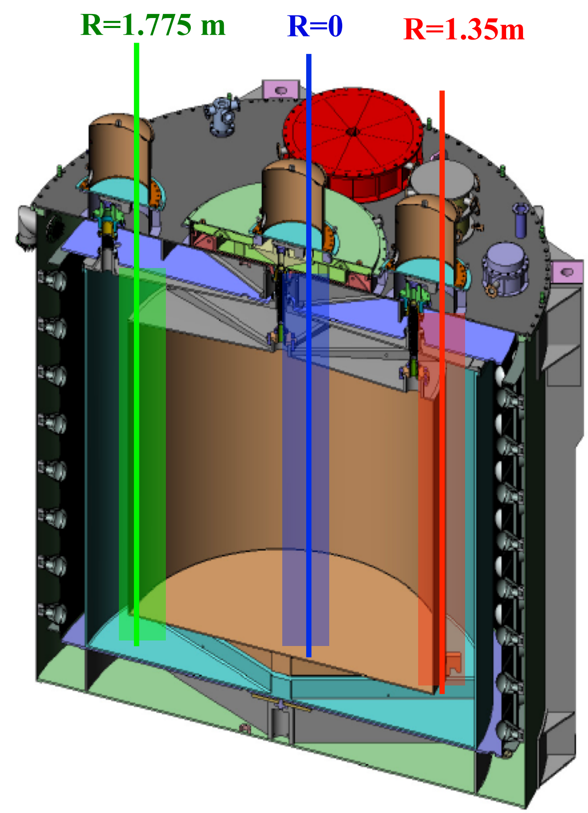
- Top and bottom reflectors
  - Increase light coverage
- Energy resolution
  - $\sigma_E/E \sim 7.5\%/\sqrt{E}$



Calibration Units

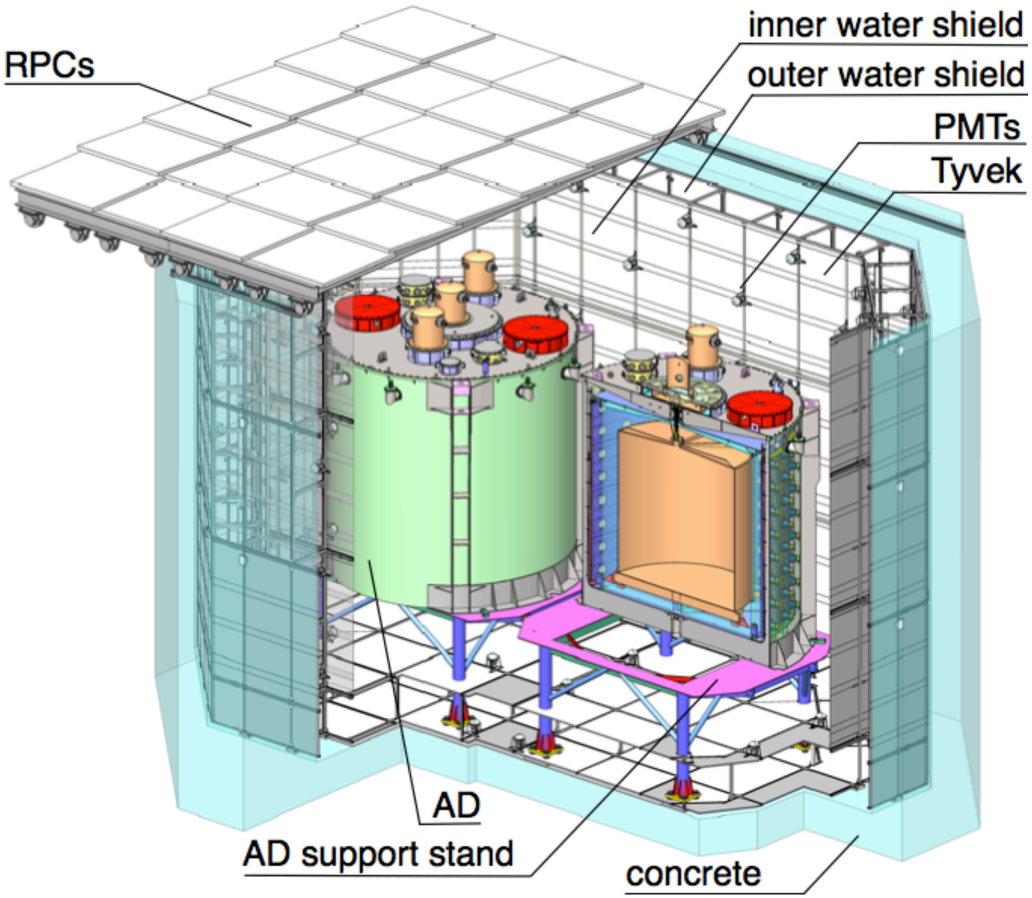
- Key to reduce detector-related systematic uncertainties ('identical' detectors)
- Three sources for each Z-axis on a turntable
  - 10 Hz ^{68}Ge
  - 0.5Hz ^{241}Am-^{13}C + 100Hz ^{60}Co
  - LED diffuser ball → PMT calibration

  (Energy calibration (energy scale, linearity, uniformity etc.) for the three radioactive sources)
- Also use spallation neutrons and αs in detectors
  - Uniformity, etc.



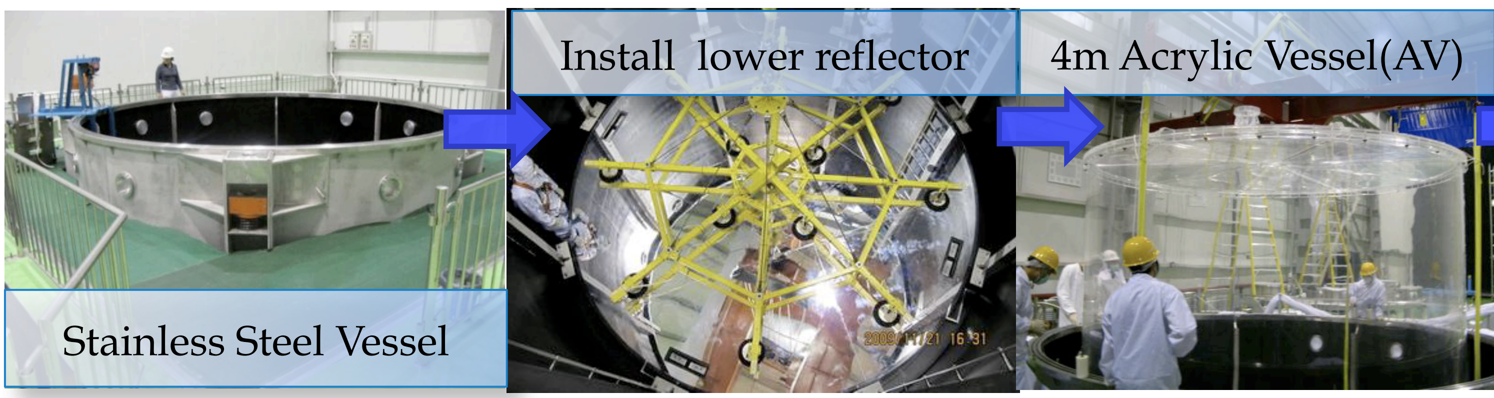
Automated Calibration Units (ACU)

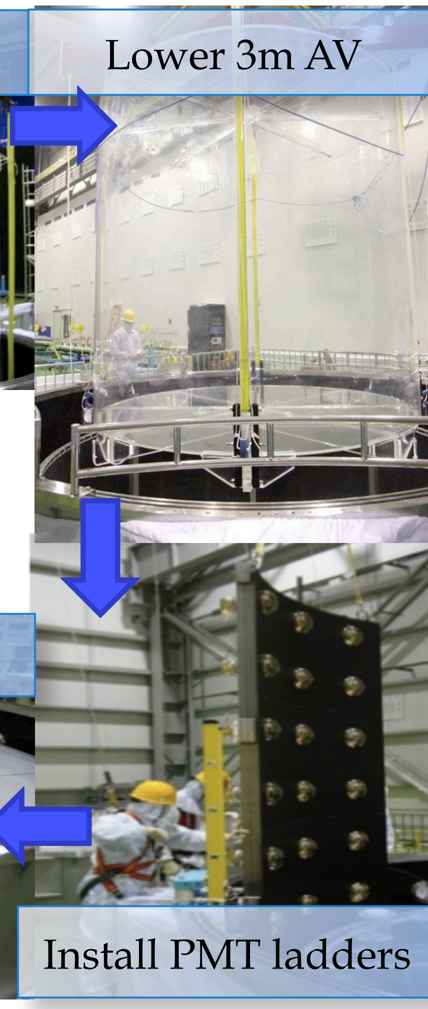
Muon Detector



- Redundant design
  - Passive shielding
    - ≥ 2.5m water
  - Active muon tagging
    - Surrounding two-layer Water Cherenkov detector
    - Top: 4-layer RPC detector
- Efficiency
  - Water Cherenkov: >97%
  - RPC: >88%
- Water system
  - Hall4: water production
  - Re-circulation and purification

Antineutrino Detector Assembly





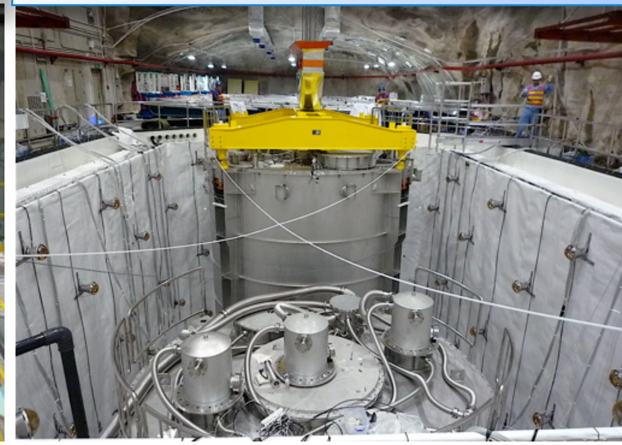
The assembly chain is processed in the clean room, which holds one pair of ADs to be assembled at the same time.

Detector Filling and Installation

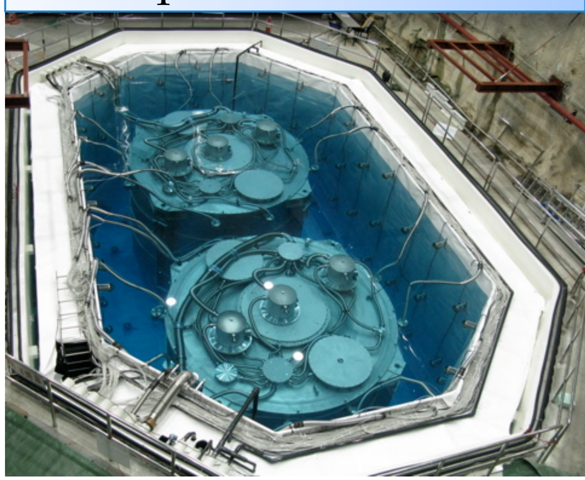
Transport assembled AD to LS Hall from SAB

Fill Gd-LS, LS and Mineral oil into AD in LS Hall

Install filled AD into water pool after testing

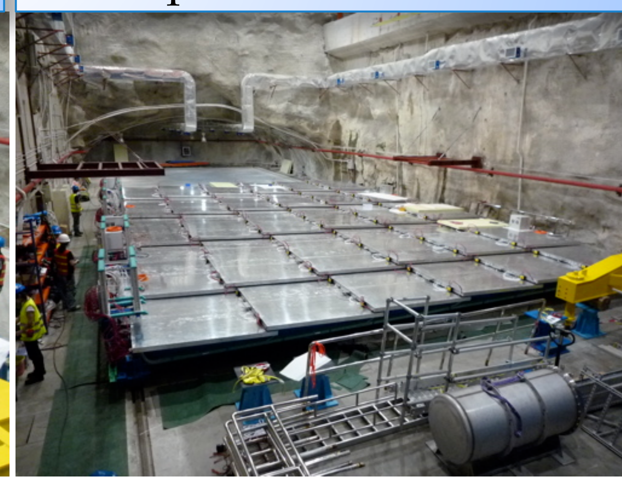


Fill purified water into water pool

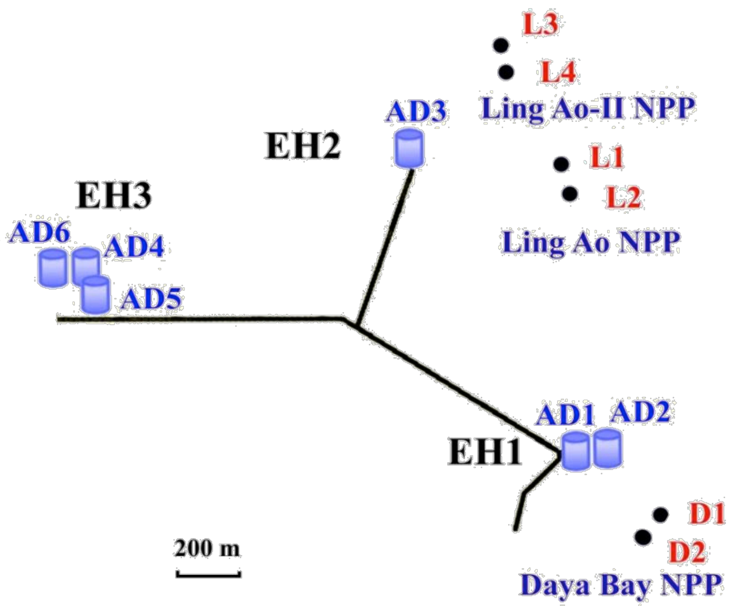


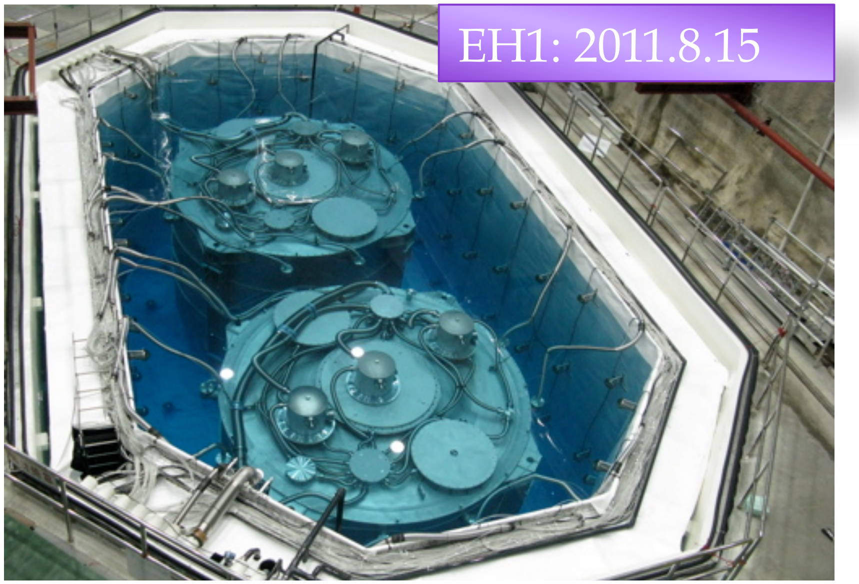
Install pool cover

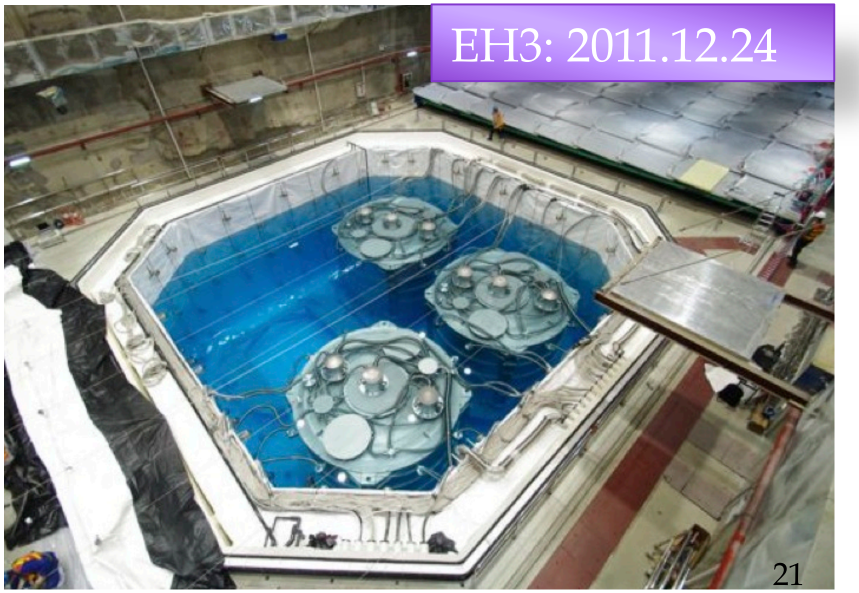
Pull RPC detector onto top of the pool



Phase 1: 6 ADs at 3 Halls







Data Set

- I: *2011.9.23 – 2011.12.23*
  - Side-by-side comparison of two ADs in EH1

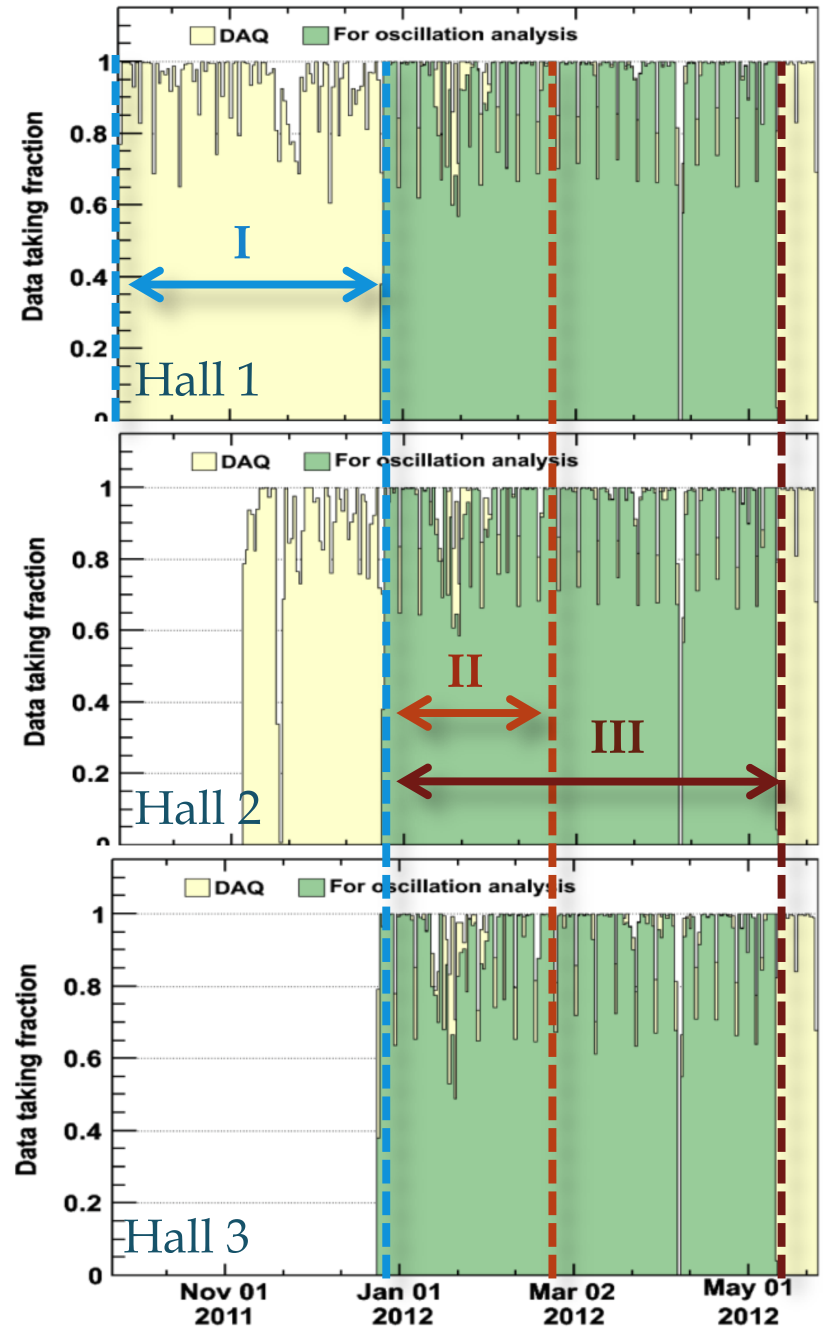
  Nucl. Inst. And Meth. A 685. 78 (2012)

- II: *2011.12.24 – 2012.2.17*
  - First measurement of θ_{13}

  Phys. Rev. Lett. 108, 171803 (2012)

- III: *2012.12.24 – 2012.5.11*
  - Improved measurement of θ_{13}

  Chinese Phys. C37, 011001 (2013)

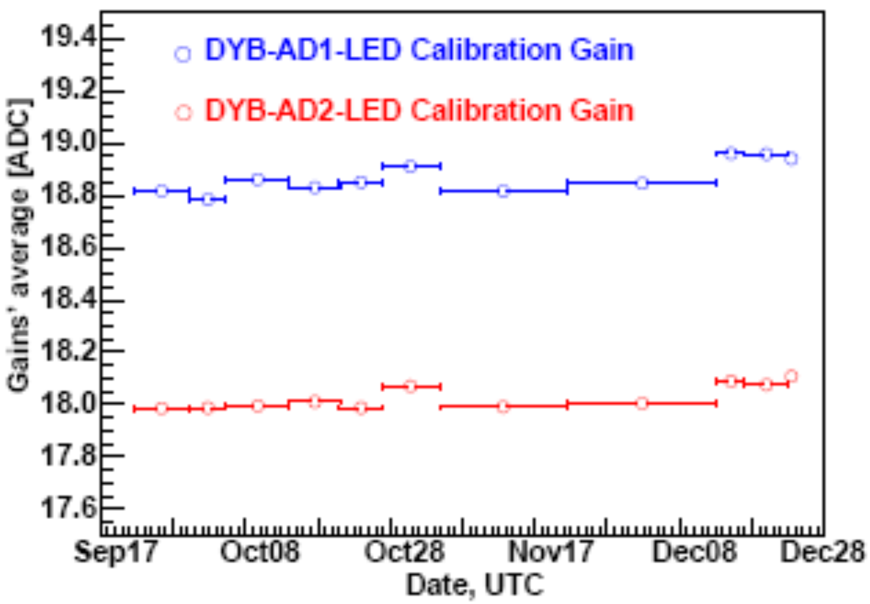


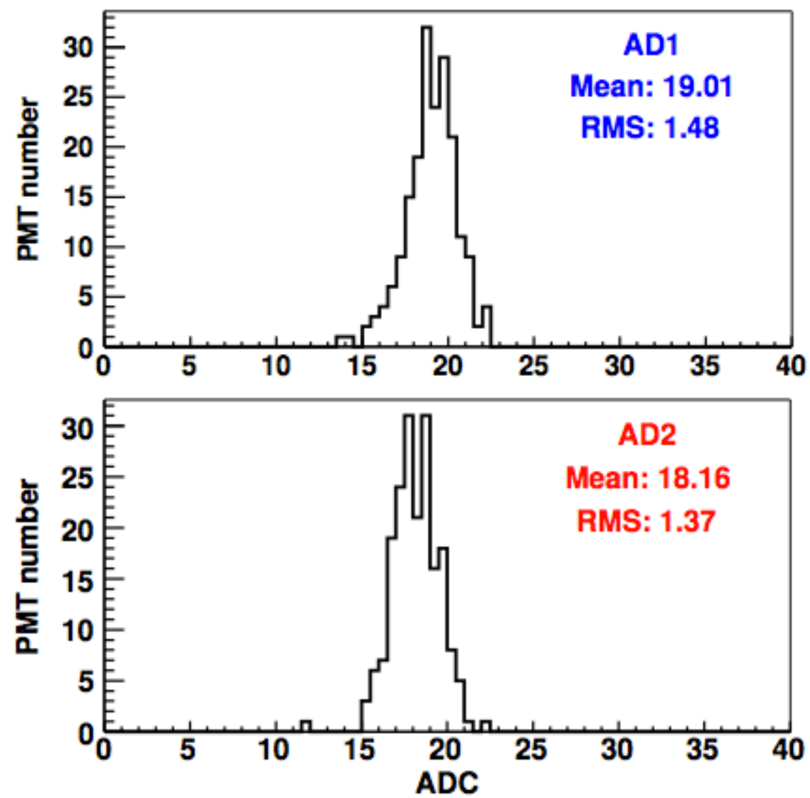
Analysis Strategy

- **Blind** analysis
  - Reactor flux
  - Baseline
  - Target mass
- **Multiple** analyses to cross check
- Differences of multiple analysis
  - Calibration and reconstruction
  - Inverse Beta Decay (IBD) event selection
  - Backgrounds
  - Antineutrino flux prediction
  - Fit methods of $\sin^2 2\theta_{13}$

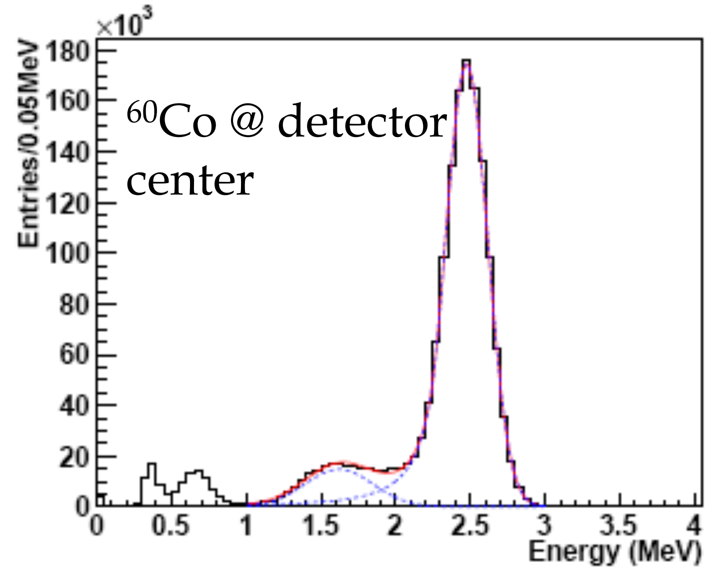
Calibration & Reconstruction

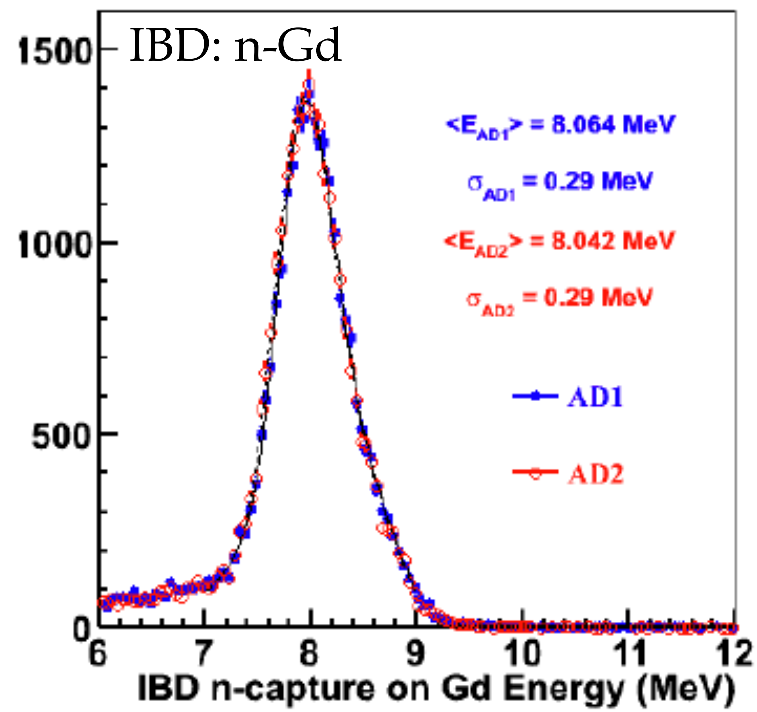
- PMT Gain calibration: Low intensity **LEDs**
  - HV is set for a gain @ 1×10^7, fit s.p.e. spectrum
  - Stability: Gain VS time, depends on Temperature.





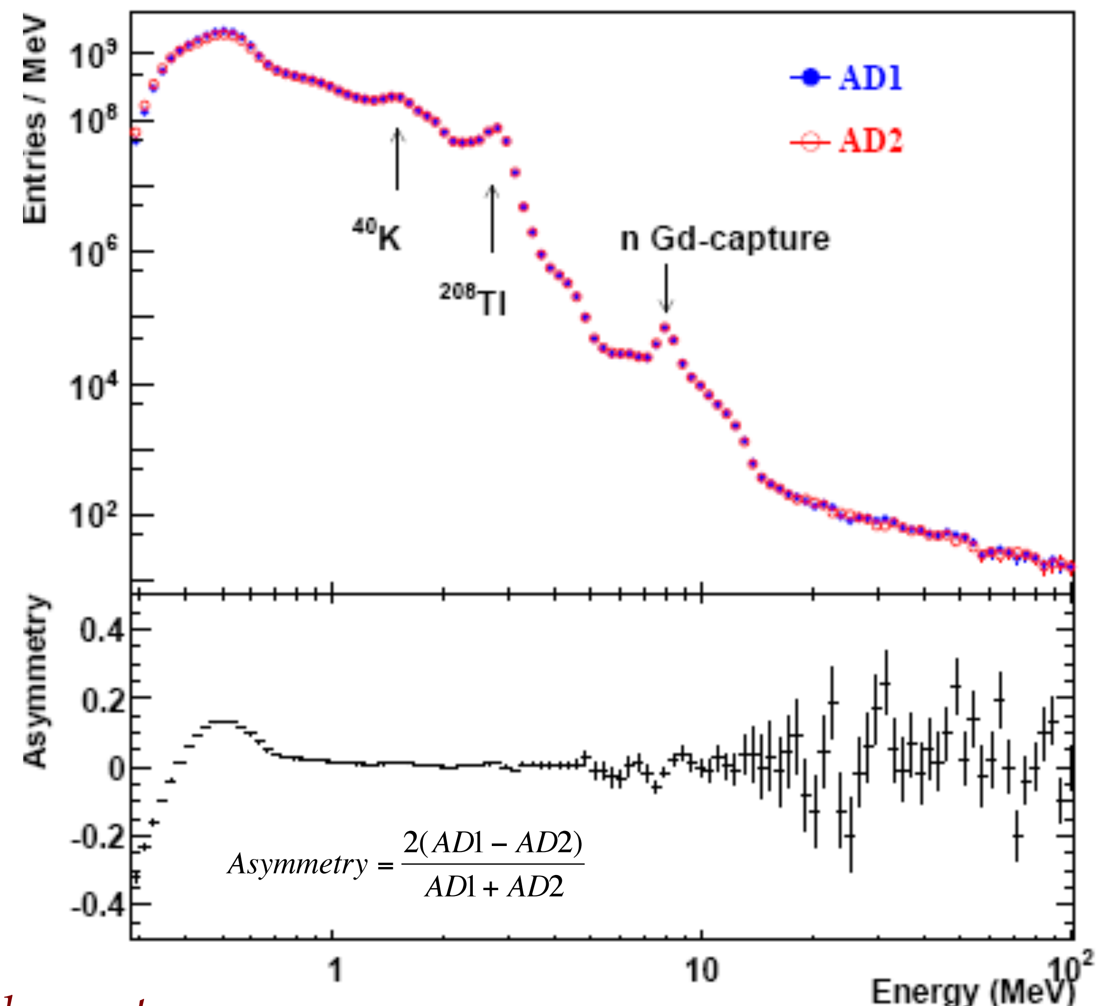
- Energy scale calibration:
  - ^{60}Co at detector **center**
    - p.e./MeV
  - ^{60}Co at different **(R, Z)**
    - Space dependence correction
- Nonlinearity correction
  - Energy scale is normalized to neutron capture peak
- Energy scale uncertainty
  - Reconstructed energy: Differences in ADs <0.5%
  - Non-uniformity, non-linearity, time variation: differences in ADs <0.5%





Singles Rate

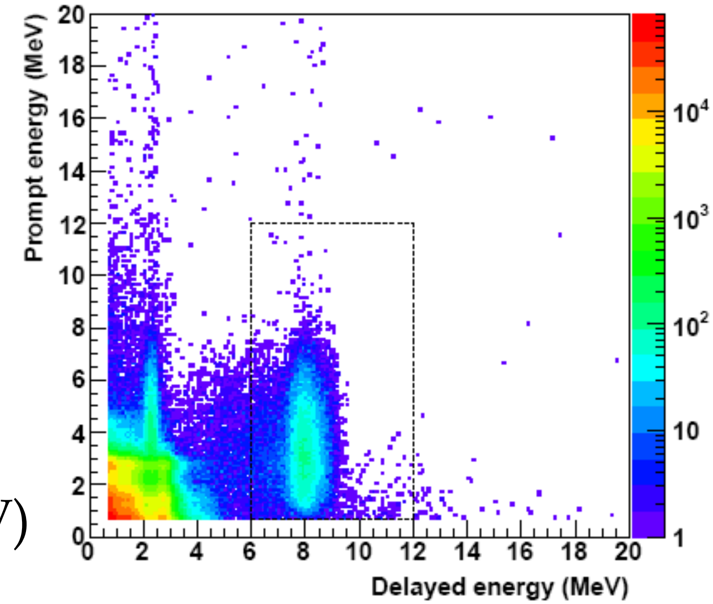
- Singles:
  - Trigger on events that >45PMT | | >0.4MeV
- Measured rates:
  - ~60Hz (>0.7MeV)
  - ~40Hz (>1MeV)
- Rates from simulation:
  - ~5Hz from SSV
  - ~10Hz from LS
  - ~25Hz from PMT
  - ~5Hz from rock

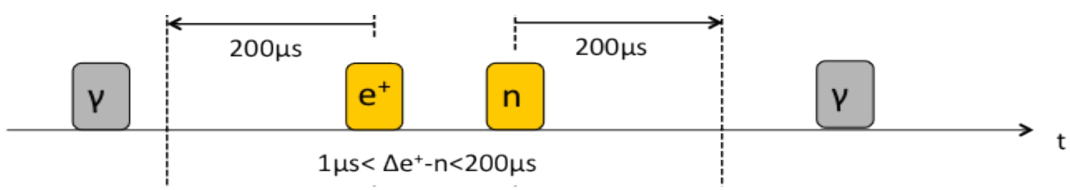


Select IBD events out from the single events

IBD Selection

- Pre-selection:
  - Reject flashers (imperfect PMT, flashing)
  - Reject triggers within (-2 μ s, 200 μ s) of a muon tagged by a water pool
- **IBD events selection:**
  - $0.7MeV < E_{prompt} < 12.0MeV$
  - $6.0MeV < E_{delayed} < 12.0MeV$
  - $1\mu s < \Delta t_{e+-n} < 200\mu s$
  - **Muon veto:**
    - 0.6ms after a water pool muon
    - 1ms after an AD muon (20MeV)
    - 1s after an AD shower muon (2.5GeV)
  - **Multiplicity cut**



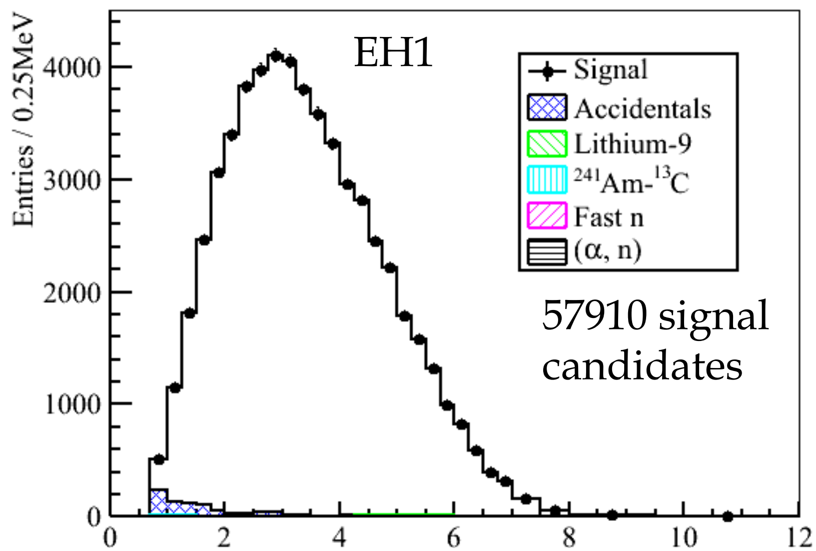


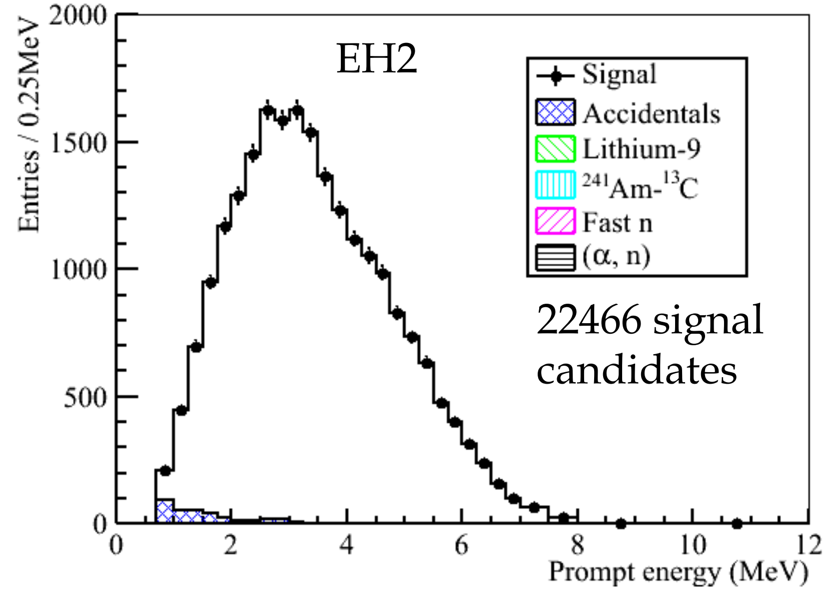
No E>0.7MeV signal before and after Prompt-Delayed pair

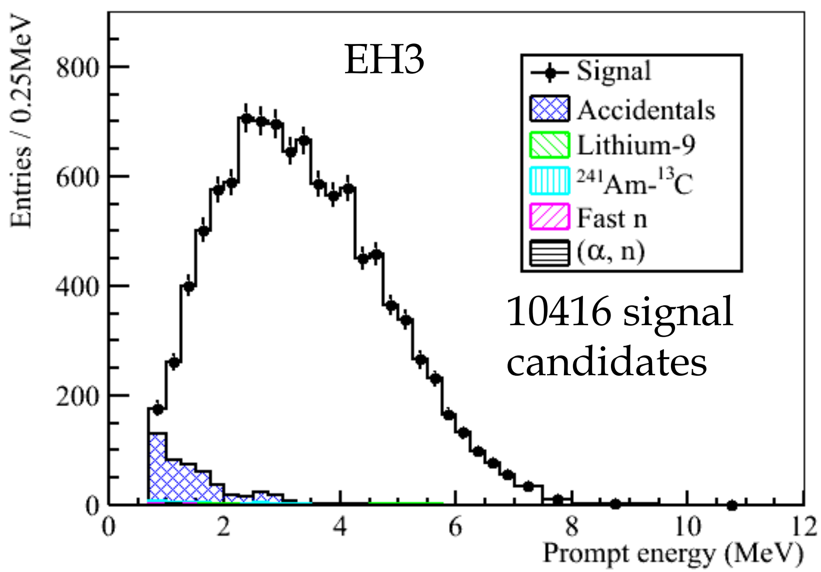
Backgrounds

- **Uncorrelated** background: prompt and delay signals from different sources
  - Accidentals (γ-γ, γ-n, n-n, from radioactivity and cosmic muon interactions with rock, water, AD materials)
  - The largest source of background
- **Correlated** background: prompt and delay signals from one source
  - Fast neutron (p recoil-n)
  - $^{9}Li/^{8}He$ (β-n)
  - ^{241}Am-^{13}C (γ-n)
  - α-n: $^{13}C(\alpha,n)^{16}O$

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%
a-n	~0.01%	~0.04%
Sum	**1.5%**	**4.7%**

Antineutrino Flux Prediction

- Flux calculation with:

Reactor part

$$S_d(E_\nu) = \sum_r \frac{1}{4\pi L_r^2} \cdot \boxed{\frac{W_{th}^r}{\sum_i f_i^r e_i} \cdot \sum_i f_i^r S_i(E_\nu)} \cdot \varepsilon_d \cdot N_d \cdot \sigma(E_\nu)$$

- From nuclear power plant:
  - Thermal power $\mathbf{W_{th}}$
  - Isotope fission fraction $\mathbf{f_i}$
- Energy release per fission $\mathbf{e_i}$:
  - V. Kopeikin, 2004

Table 7: Energy release per fission

Fissile isotopes	E_{eff} (MeV)	E_f[10] (MeV)	E_f (MeV)
^{235}U	193.68± 0.33	201.92±0.46	202.25±0.39
^{238}U	195.01± 0.46	205.52±0.96	205.87±0.55
^{239}Pu	200.16±0.14	210.99±0.60	211.41±0.32
^{241}Pu	202.84±0.21	213.60±0.65	214.47±0.36
		Kopeikin	Our results

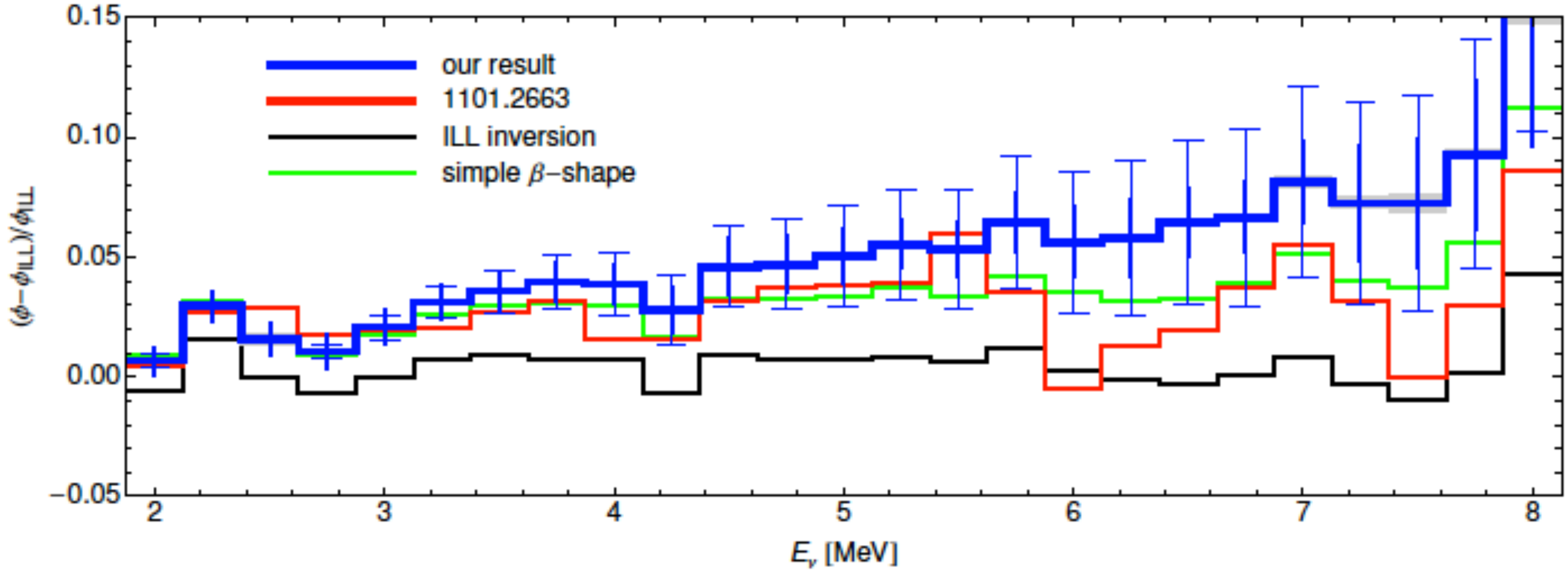
Update results by X.B. Ma et. al. (accepted by Phys. Rev. C recently)

Antineutrino Flux Prediction

- Isotope spectrum $S_i(E)$

^{235}U spectrum differences from different models : ~3%

P. Huber



Different flux models have a negligible effect on near/far relative oscillation measurement

Systematic Uncertainties

Detector uncorrelated uncertainty: 0.2%

Reactor uncorrelated uncertainty: 0.8%

Only uncorrelated uncertainties have impact on near/far relative measurement

Total correlated uncertainty: 3.6%

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%

Rate Comparison

- Assume no oscillation, use near to predict far, and then compare measured rate and predicted rate of far site:

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

Mn : measured IBD rate, with subtraction of background, in each detector

α i and β i are determined by baselines and reactor fluxes: Assuming R=1, minimize the residual reactor uncertainty

R = 0.944 ± 0.007(stat.) ± 0.003(syst.)

Chinese Phys. C37, 011001 (2013)

Rate Analysis

- χ^2 analysis

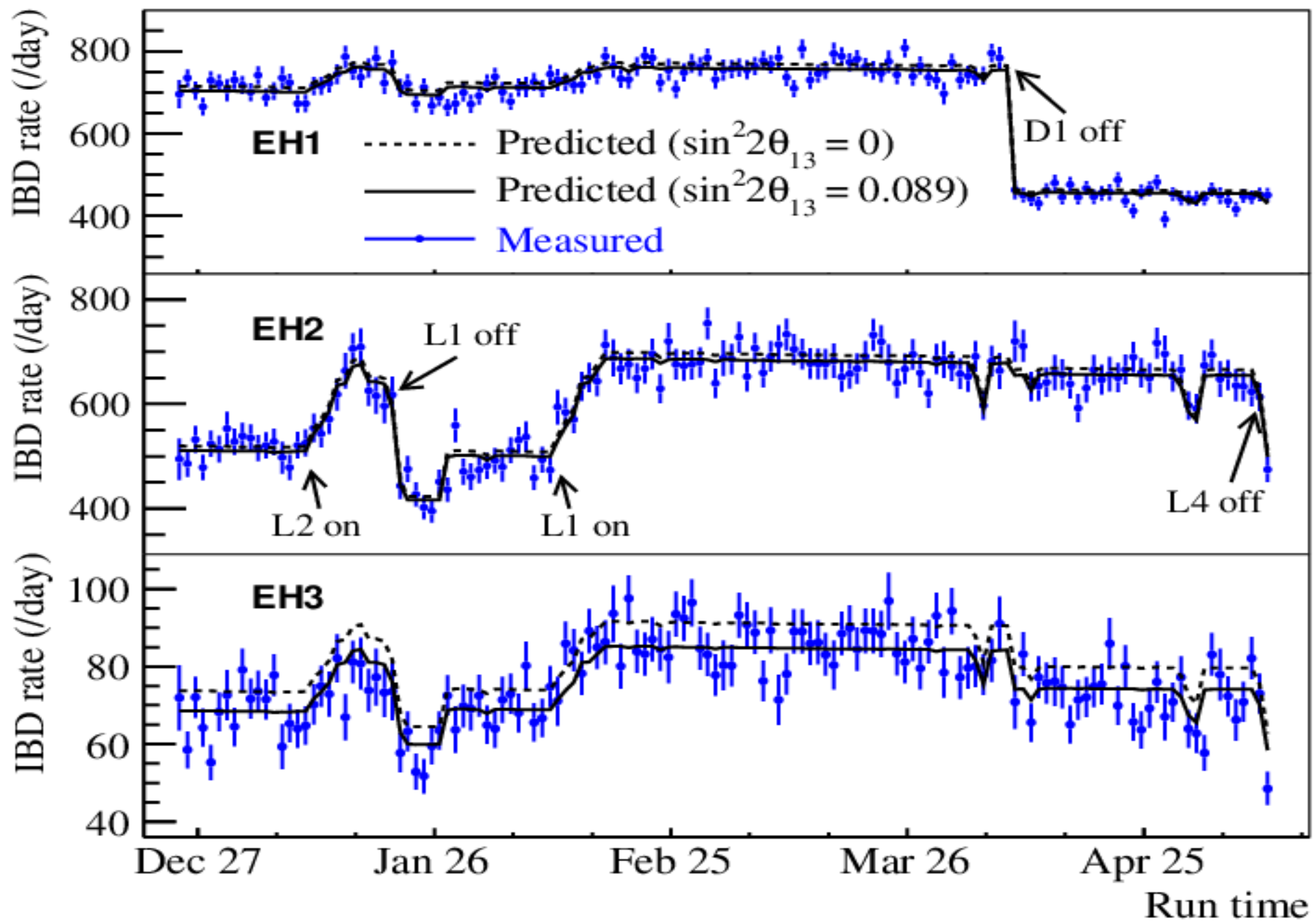
$$\chi^2 = \sum_{d=1}^{6} \frac{\left[M_d - T_d(1 + \sum_r \omega_r^d \varepsilon_r + \varepsilon + \varepsilon_d) - B_d(1 + \eta_d)\right]^2}{M_d}$$

$$+ \sum_r \frac{\varepsilon_r^2}{\sigma_r^2} + \sum_{d=1}^{6} \left[\frac{\varepsilon_d^2}{\sigma_d^2} + \left(\frac{\eta_d}{\sigma_B^d} \right)^2 \right] + \frac{\varepsilon^2}{\sigma^2}$$

No constraint on the absolute normalization factor ε, which is used to reduce the bias from the absolute reactor flux uncertainty and absolute detector efficiency uncertainty

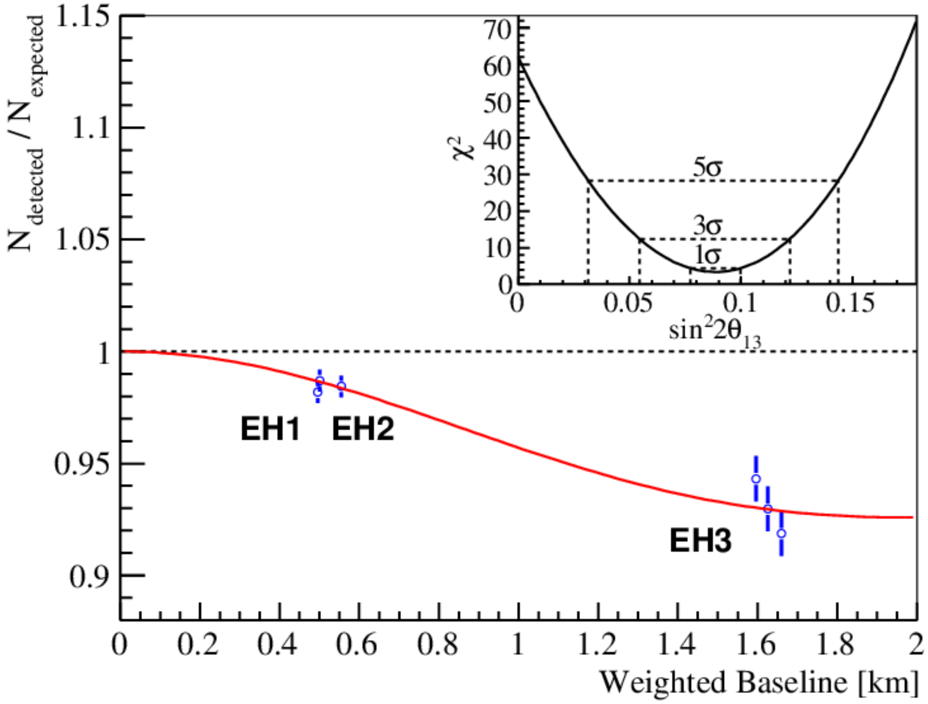
- σ_r: reactor uncorrelated uncertainty
- σ_d: detector uncorrelated uncertainty
- σ_B: background uncertainty
- Reactor- and detector-correlated uncertainty are not included

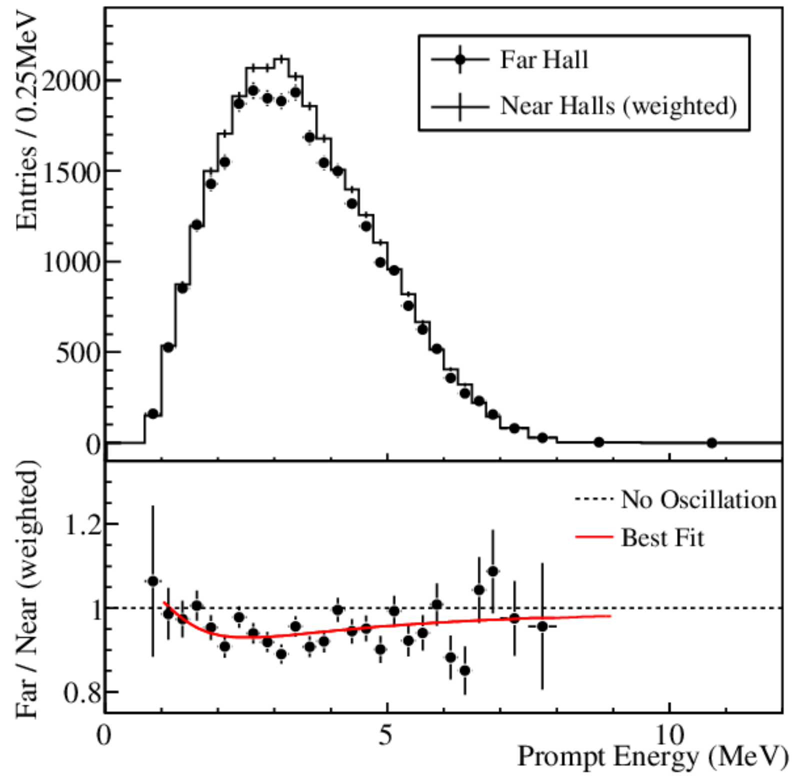
Daily Rate v.s. Time



- Predicted rates and measurements track very closely.
- The prediction is multiplied by the absolute normalization factor. Absolute normalization is within a few percent of expectation.

Observation of $\bar{\nu}_e$ Disappearance



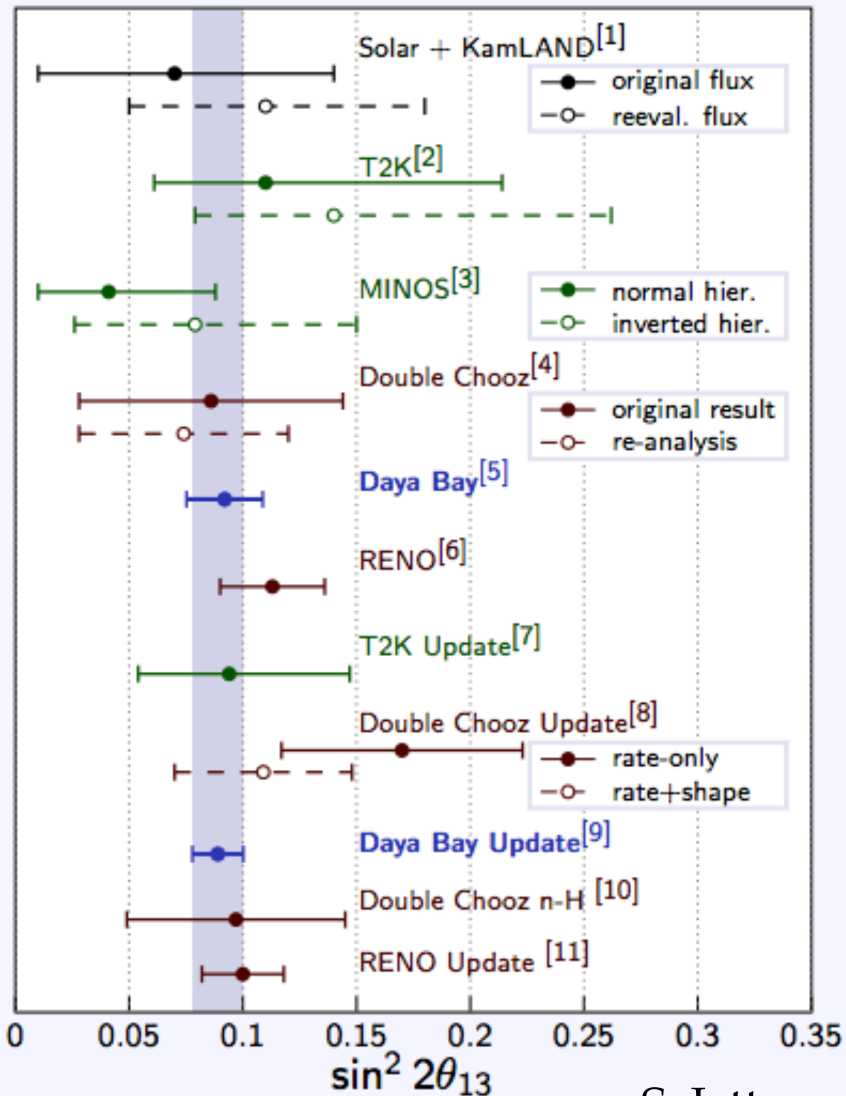


$\mathrm{Sin}^2 2\theta_{13}$ = 0.089 ± 0.010 (stat) ± 0.005 (syst) **R = 0.944 ± 0.007 (stat) ± 0.003 (syst)**

With 2.5x more statistics, an improved measurement to θ_{13}
7.7 σ exclusion of θ_{13}=0

Chinese Phys. C37, 011001 (2013)

Global Measurement of θ_{13}

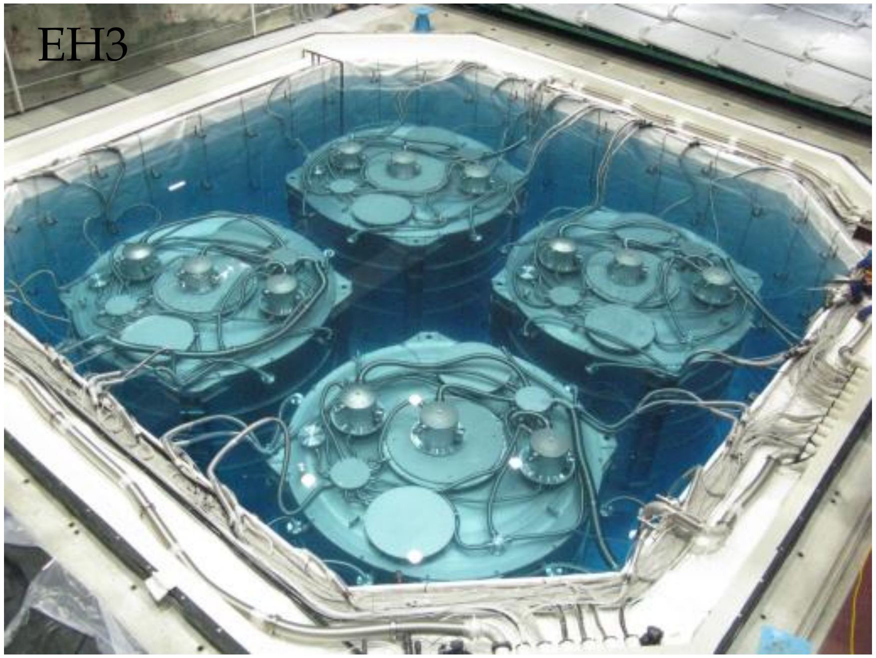


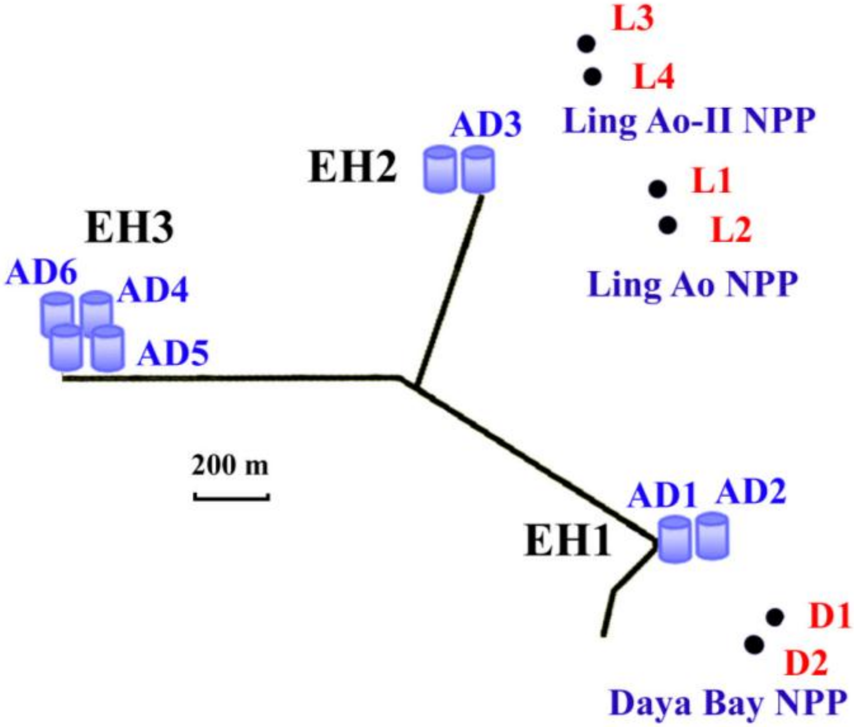
S. Jetter

1. G.L. Fogli *et al.*, "Evidence of $\theta_{13} > 0$ from global neutrino data analysis," Phys. Rev. **D 84** (2011) 053007 arXiv:1106.6028
2. K. Abe *et al.*, "Indication of Electron Neutrino Appearance from an Accelerator-Produced Off-Axis Muon Neutrino Beam," Phys. Rev. Lett. **107** (2011) 041801, arXiv:1106.2822
3. P. Adamson *et al.*, "Improved Search for Muon-Neutrino to Electron-Neutrino Oscillations in MINOS," Phys. Rev. Lett. **107** (2011) 181802, arXiv:1108.0015
4. Y. Abe *et al.*, "Indication of Reactor $\bar{\nu}_e$ Disappearance in the Double Chooz Experiment," Phys. Rev. Lett. **108** (2012), 131801, arXiv:1112.6353
5. F. P. An *et al.* "Observation of electron-antineutrino disappearance at Daya Bay," Phys. Rev. Lett. **108** (2012), 171803, arXiv:1203.1669
6. J. K. Ahn *et al.* "Observation of Reactor Electron Antineutrinos Disappearance in the RENO Experiment," Phys. Rev. Lett. **108** (2012) 191802, arXiv:1204.0626
7. K. Sakashita, "Results from T2K," presented at ICHEP 2012 in Melbourne. Available at T2K.org
8. Y. Abe *et al.* "Reactor electron antineutrino disappearance in the Double Chooz experiment," Phys. Rev. **D86** (2012) 052008, arXiv:1207.6632
9. F. P. An *et al.* "Improved measurement of electron antineutrino disappearance at Daya Bay," Chinese Phys. **C37** (2013) 011001 arXiv:1210.6327
10. Y. Abe *et al.* "First Measurement of θ_{13} from Delayed Neutron Capture on Hydrogen in the Double Chooz Experiment," Phys.Lett. **B723** (2013) 66-70 arXiv:1301.2948
11. S.-H. Seo, "New Results from RENO", presented at NuTel 2013 in Venice. Available at NuTel2013

Phase II: 8 ADs, Full Operation

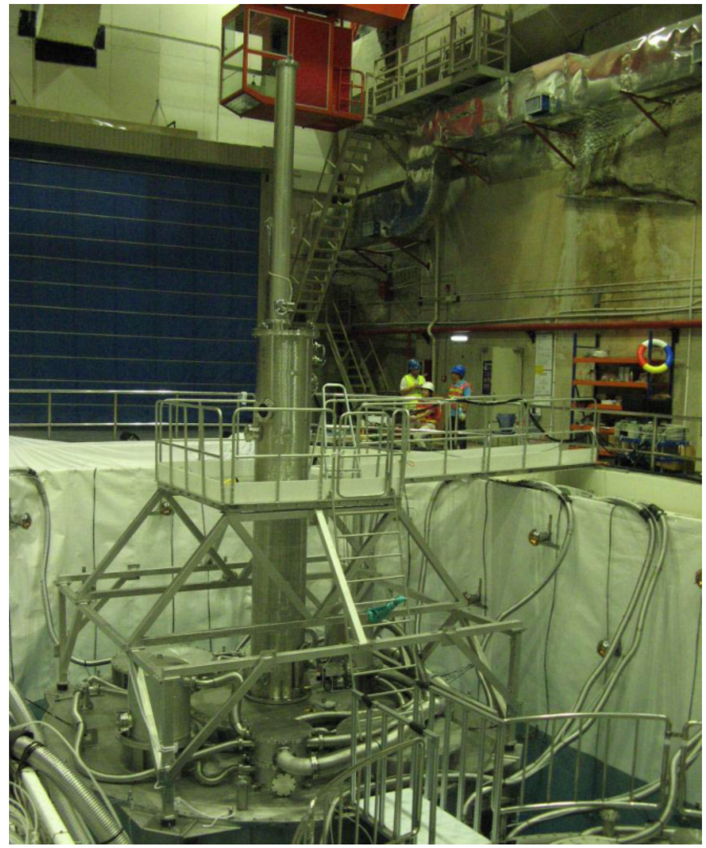
- 8ADs started data taking 2012.10.19



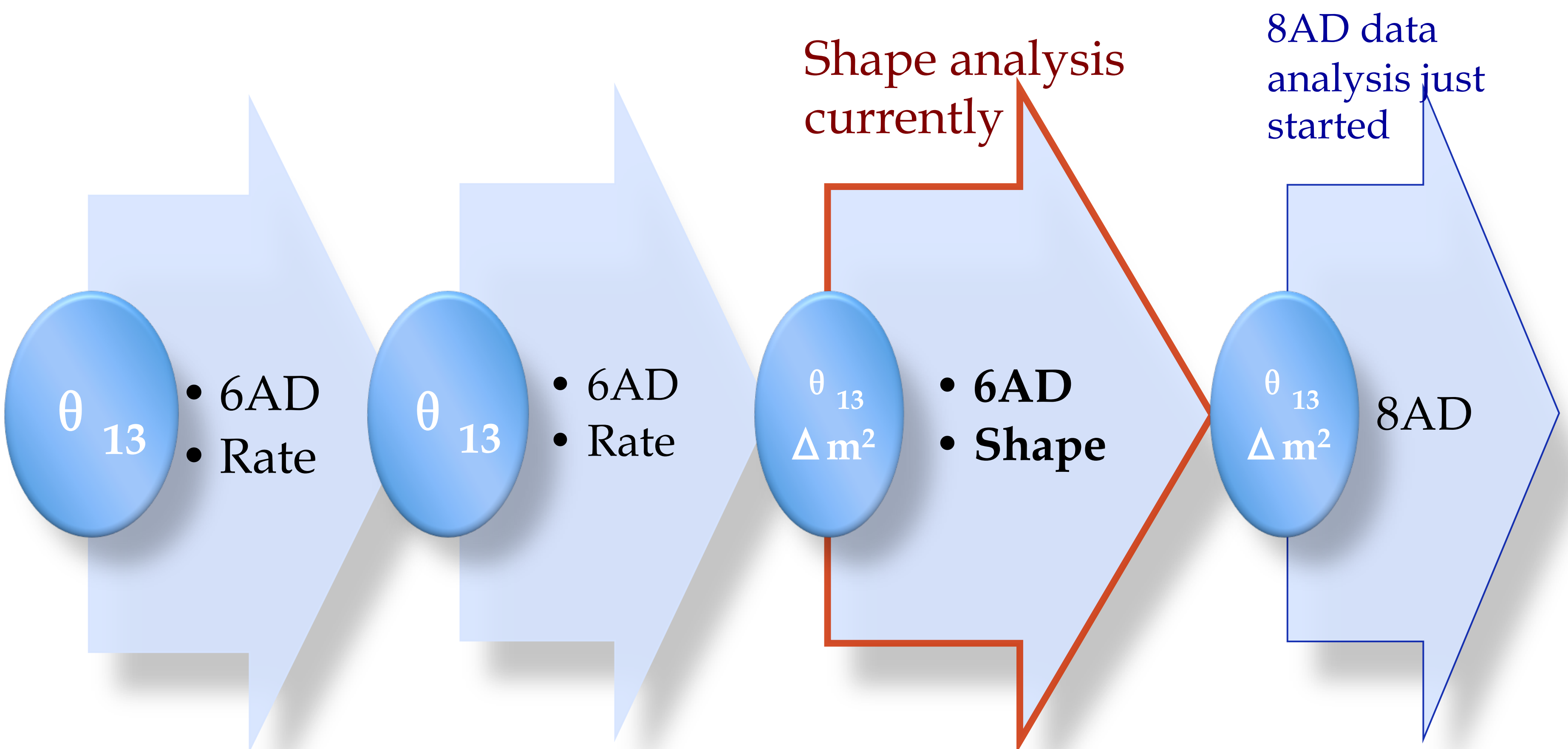


Special and Manual Calibration

- Special ACU
  - Cs, Mn, K, Am-Be, Pu-C and Am-C, Co
  - Detector Non-linearity calibration
- Manual Calibration system
  - 4π calibration
  - Pu-C(4% 6MeV γ)



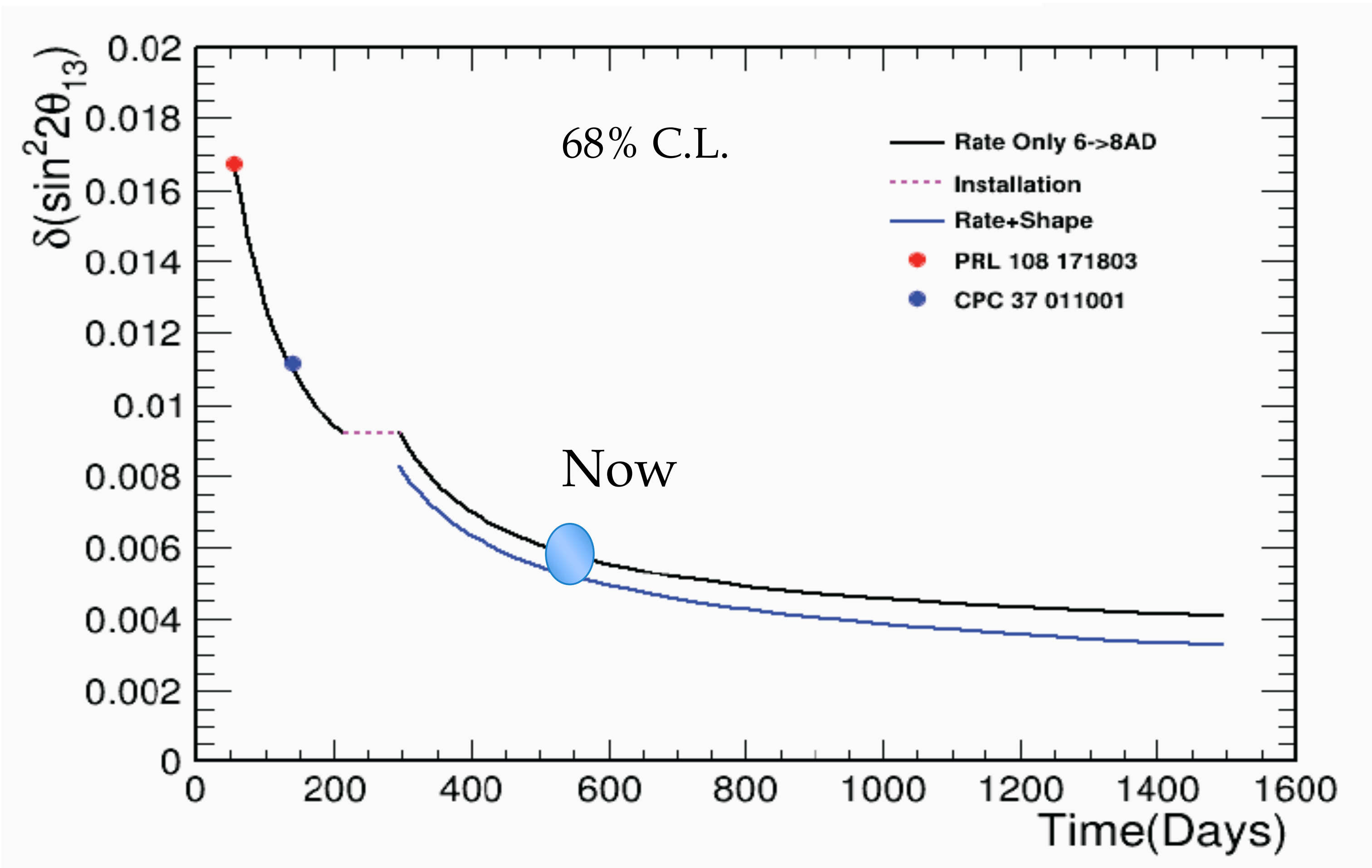
Current Status



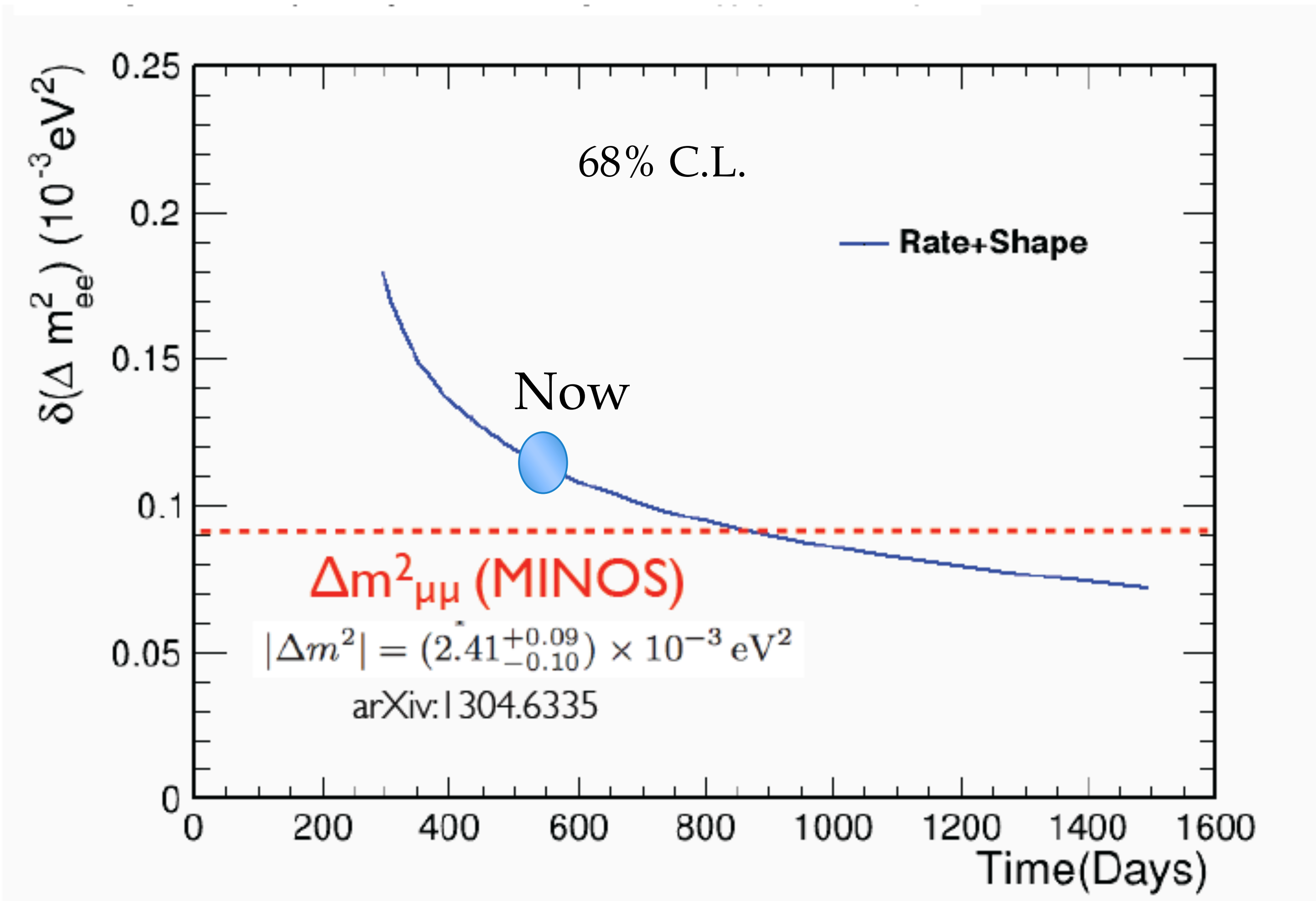
Other topics:

- Supernova search
- Cosmogenic neutrons and isotopes measurement
- Reactor antineutrino spectrum measurement

Future Sensitivity of $\sin^2 2\theta_{13}$

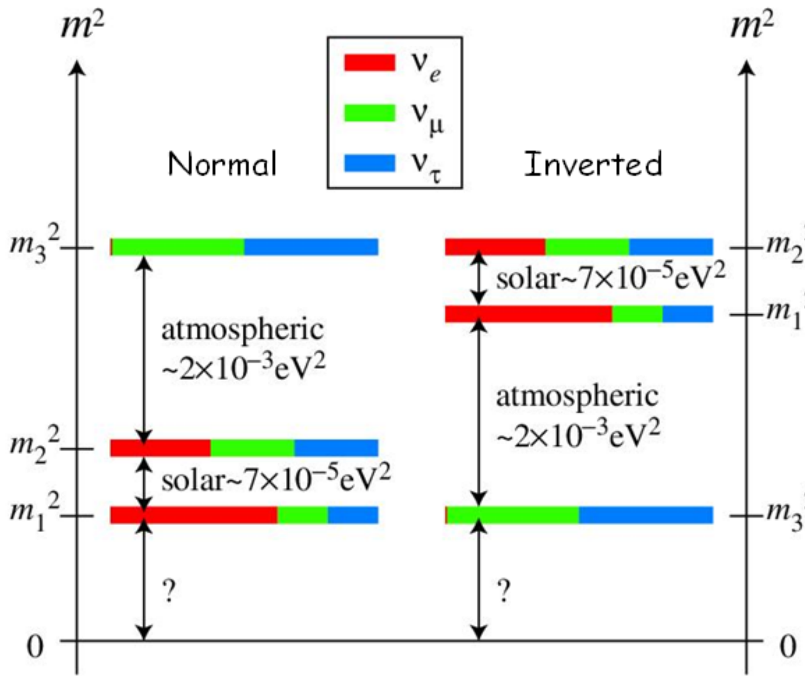


Expected Sensitivity of Δm^2_{ee}

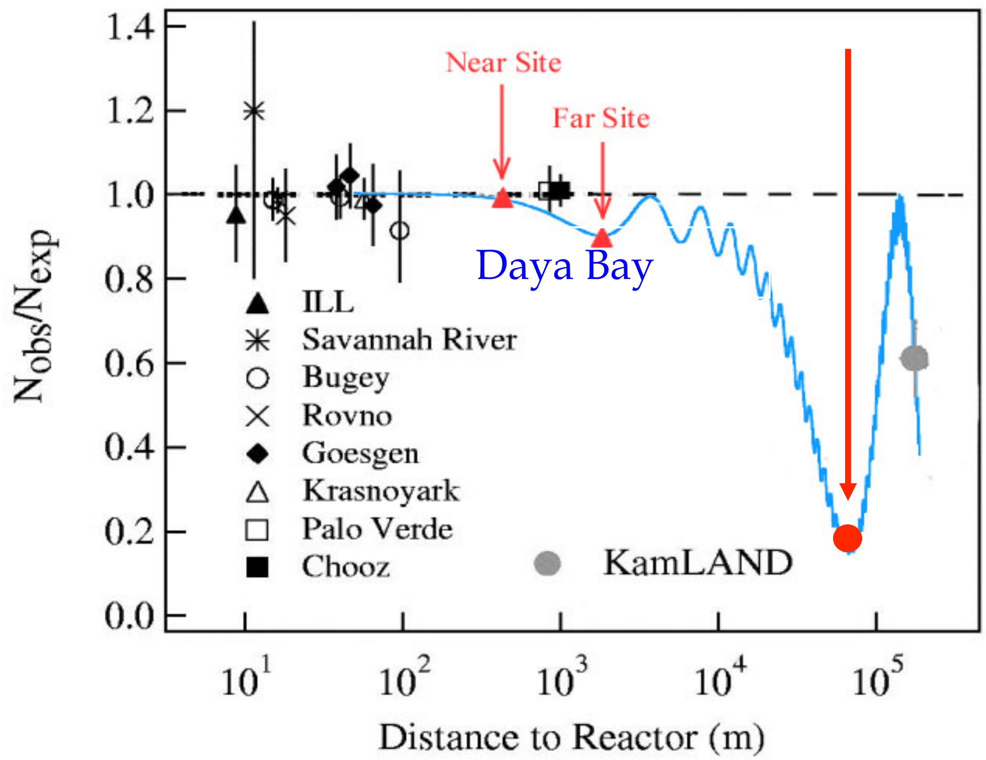


another unknown…

Which mass hierarchy?



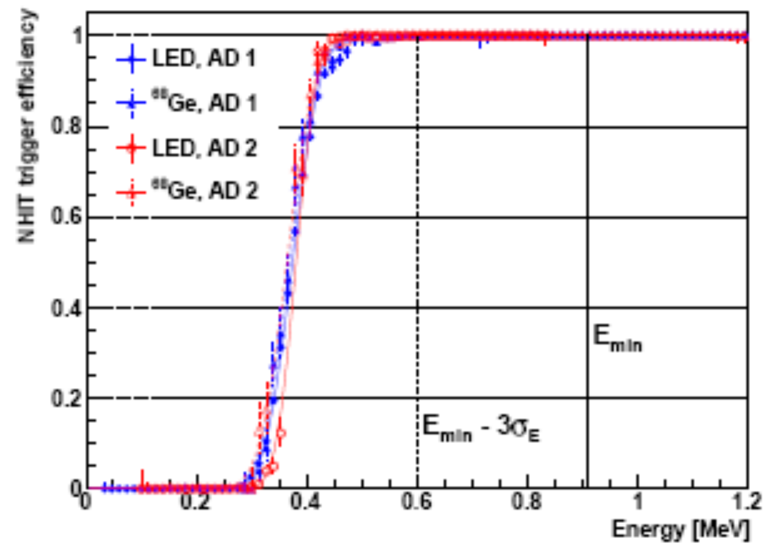
Daya Bay II

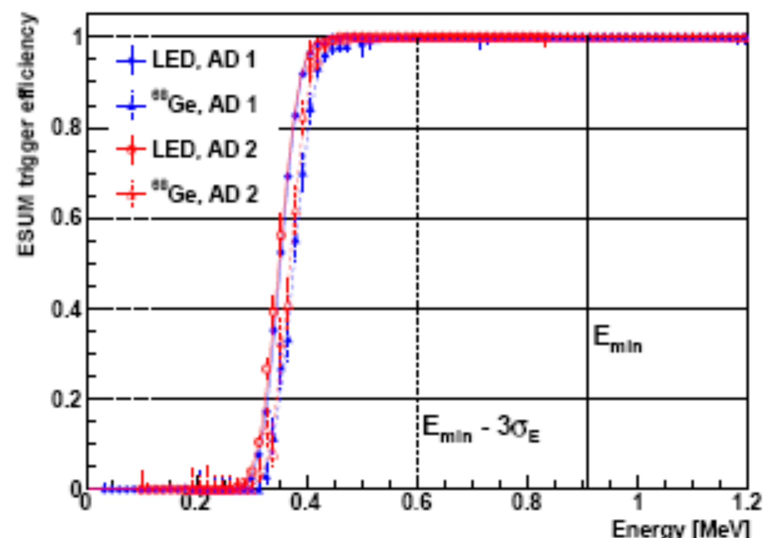


Backup

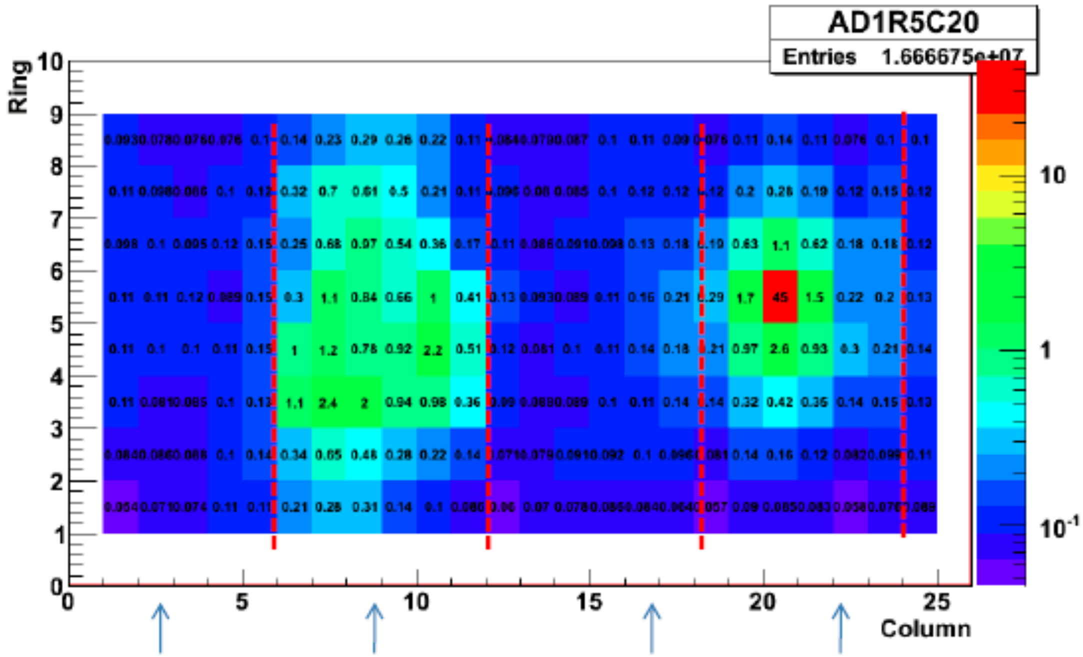
Trigger Performance

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

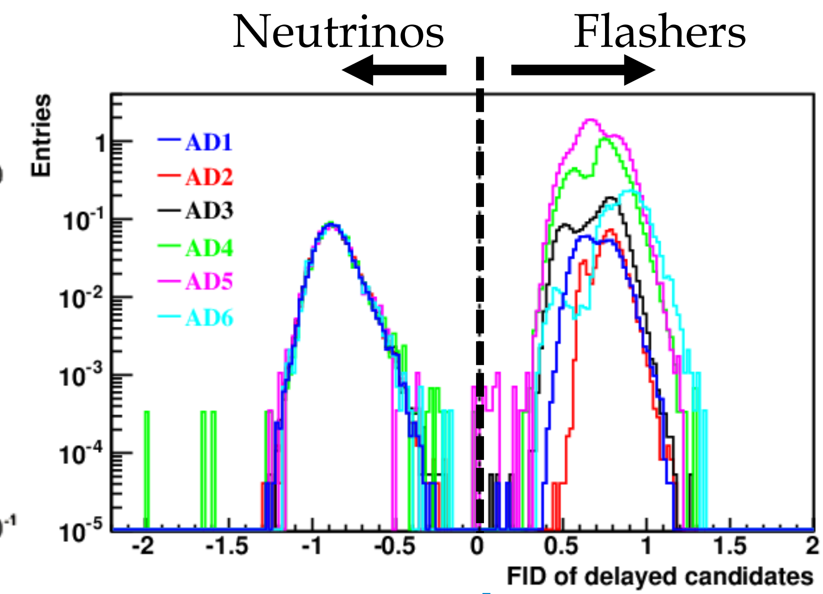




Flashers



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



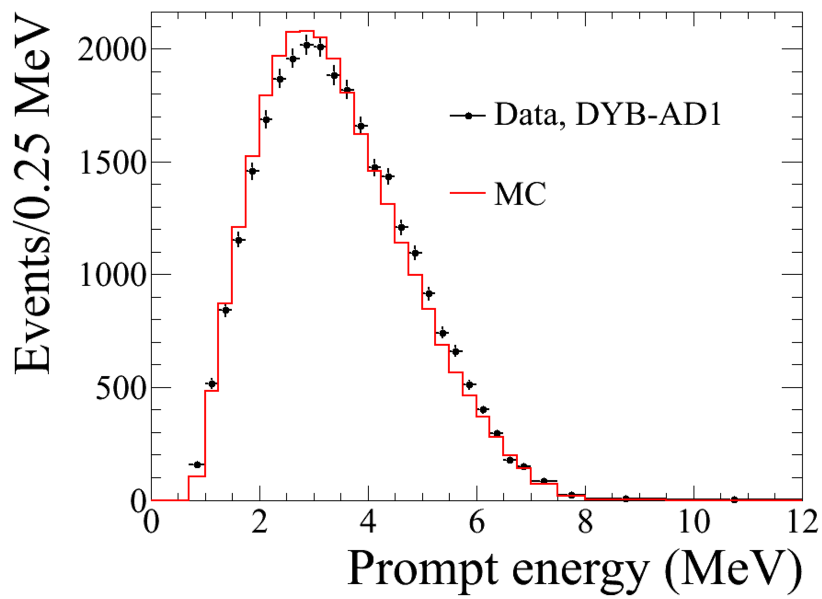
$$\log_{10}\left(\left(\frac{Quadrant}{1.}\right)^2 + \left(\frac{MaxQ}{0.45}\right)^2\right) < 0$$

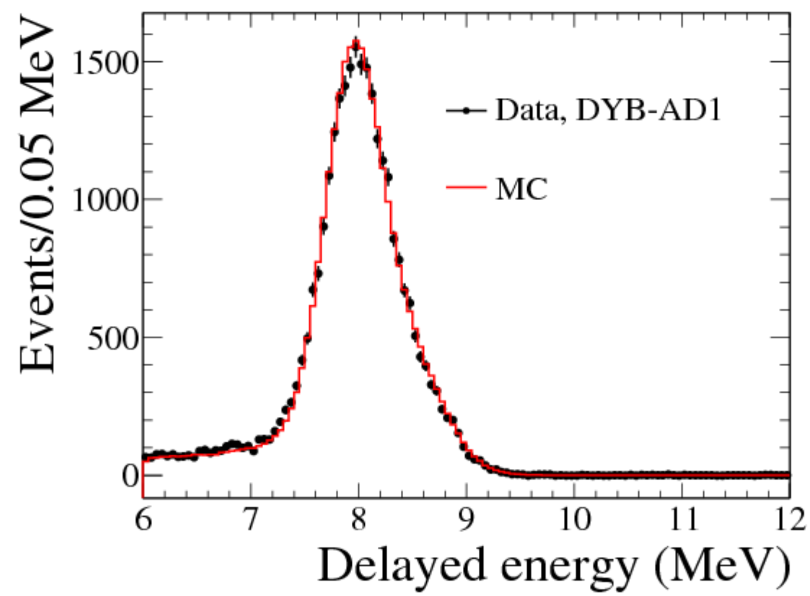
Quadrant = Q3/(Q2+Q4)
MaxQ = maxQ/sumQ

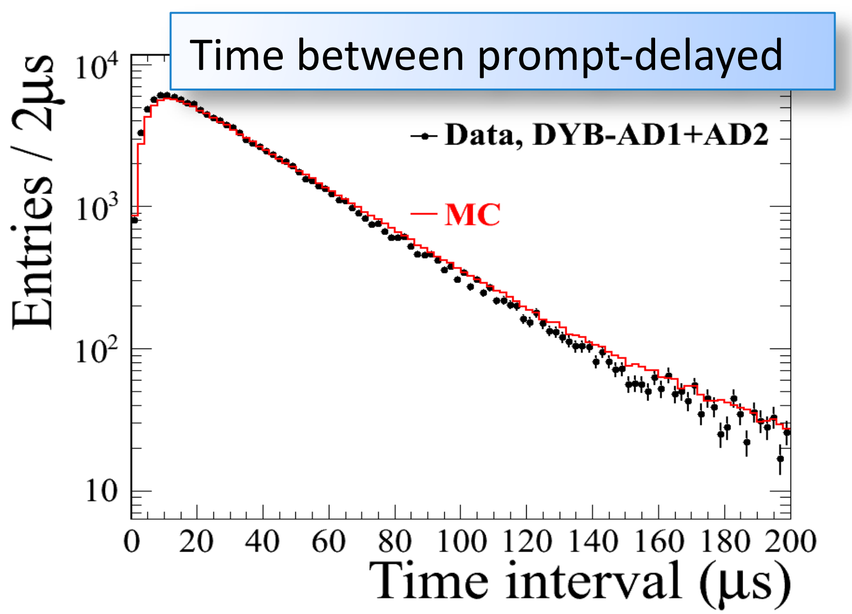
- Spontaneous light emission by PMT
- Topology: a hot PMT + near-by PMTs and opposite PMTs
- ~ 5% of PMT, 5% of event
- Rejection: pattern of fired PMTs

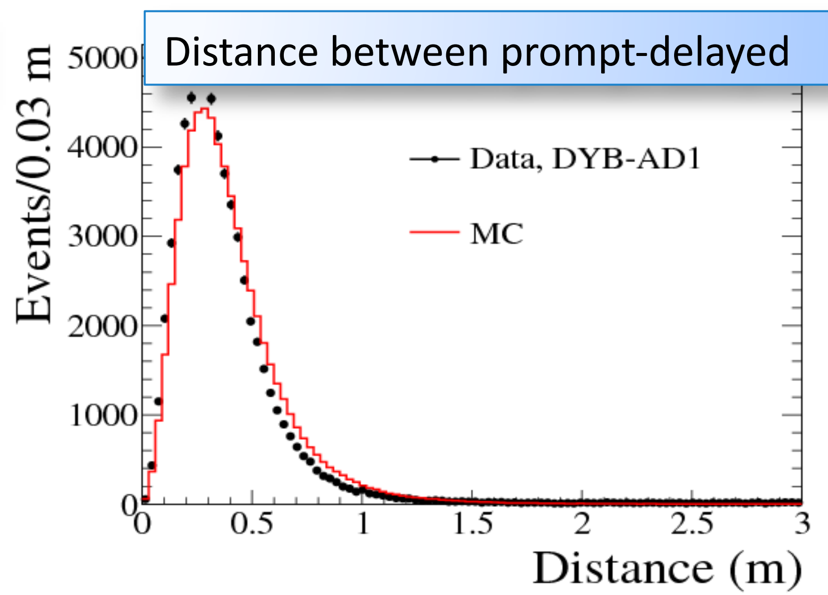
Inefficiency to neutrinos:
0.024% ± 0.006%(stat)
Contamination: < 0.01%

IBD Events Compared with MC



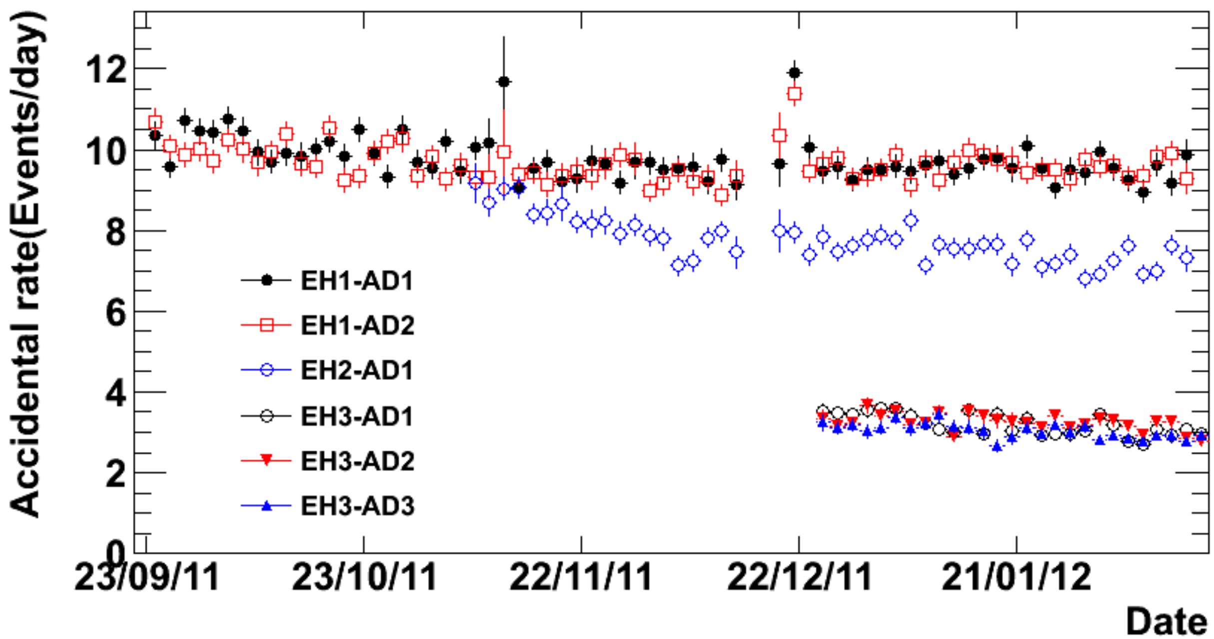






Accidentals

- Largest source of background is well-known

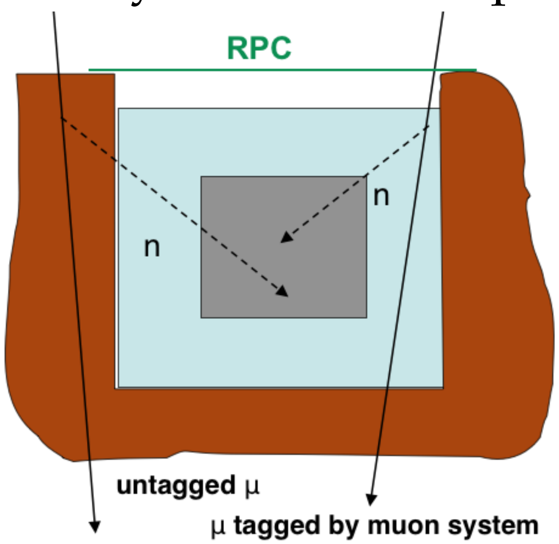


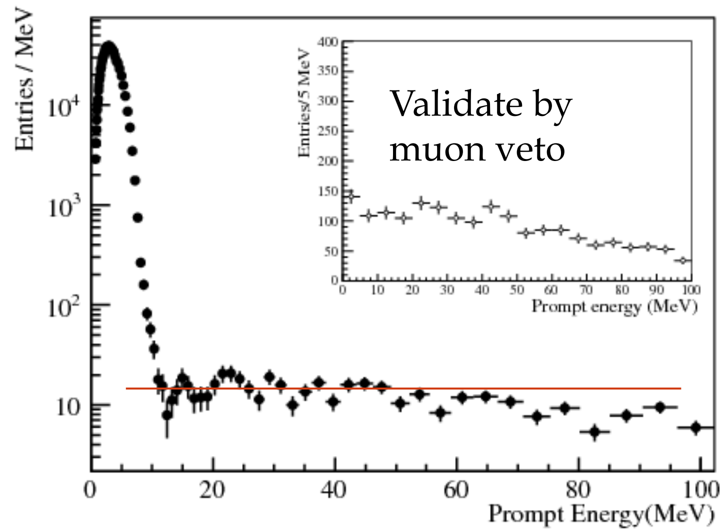
Δ B/B<1%

	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

- energetic neutrons produced by cosmic rays
  - Prompt: proton recoil
  - Delayed: neutron capture on Gd





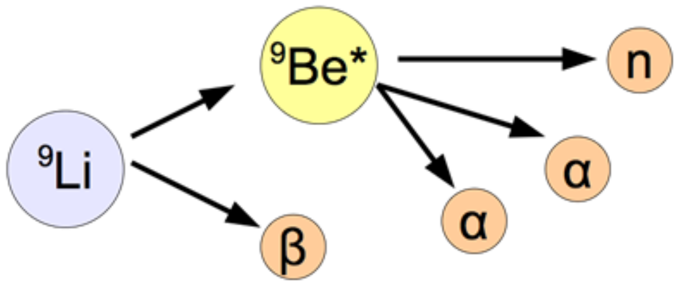
B/S @ EH1/2 ~ 0.12%, B/S @ EH3 ~ 0.07%

ΔB/B ~ 40%

- Extend prompt signal energy spectrum to high energy
  - Fit energy spectrum [20-100]MeV range
  - Estimate background at [0.7-12]MeV range

^{9}Li/^{8}He

- Cosmic muon interaction with LS



Prompt: β decay

Delayed: neutron capture

$\tau(^8He/^9Li) = 171.7ms/257.2ms$

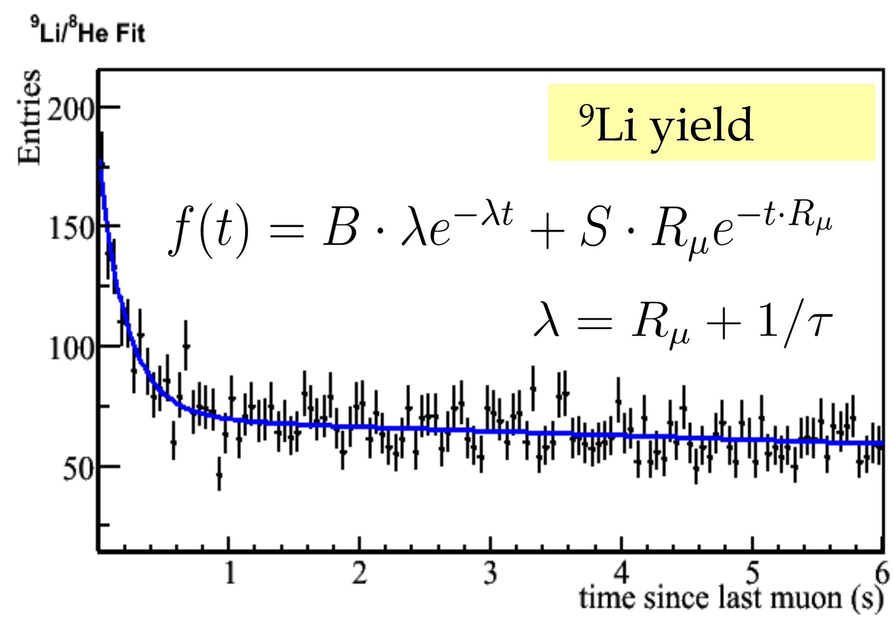
^{8}He/^{9}Li, Br(n) = 12%/48%, ^{9}Li dominant

- Fit time-since-last-muon spectrum
- Improve precision by reducing muon rate (dE>1.8GeV in [10 μ s, 200 μ s] window)

ΔB/B ~ 50%

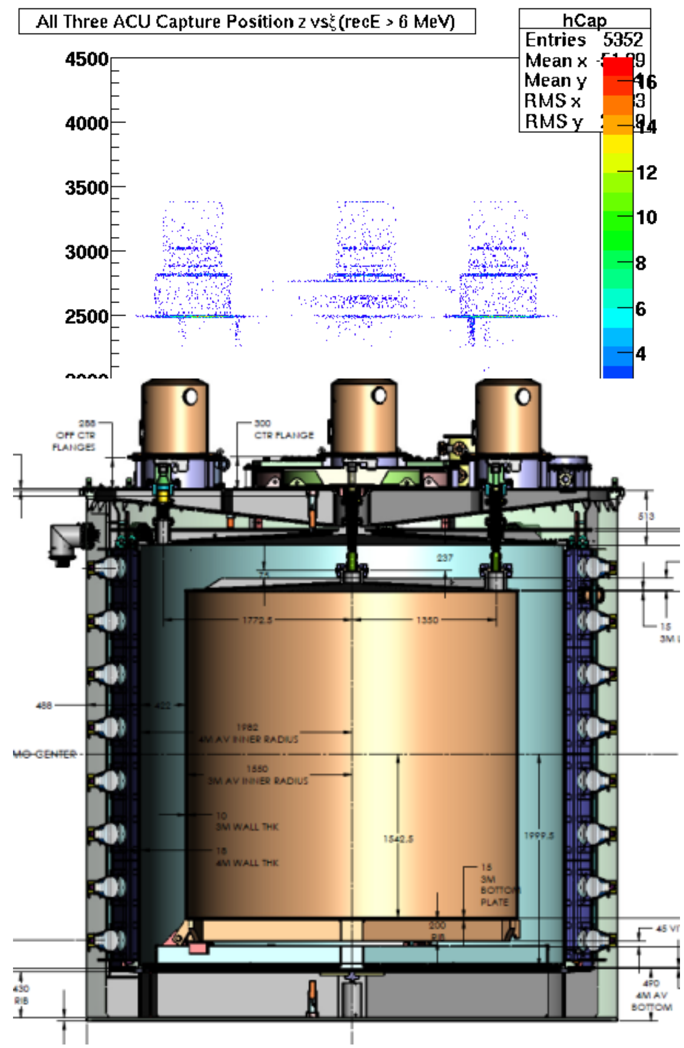
B/S @ EH3 ~ 0.3%

B/S @ EH1/2 ~ 0.4%



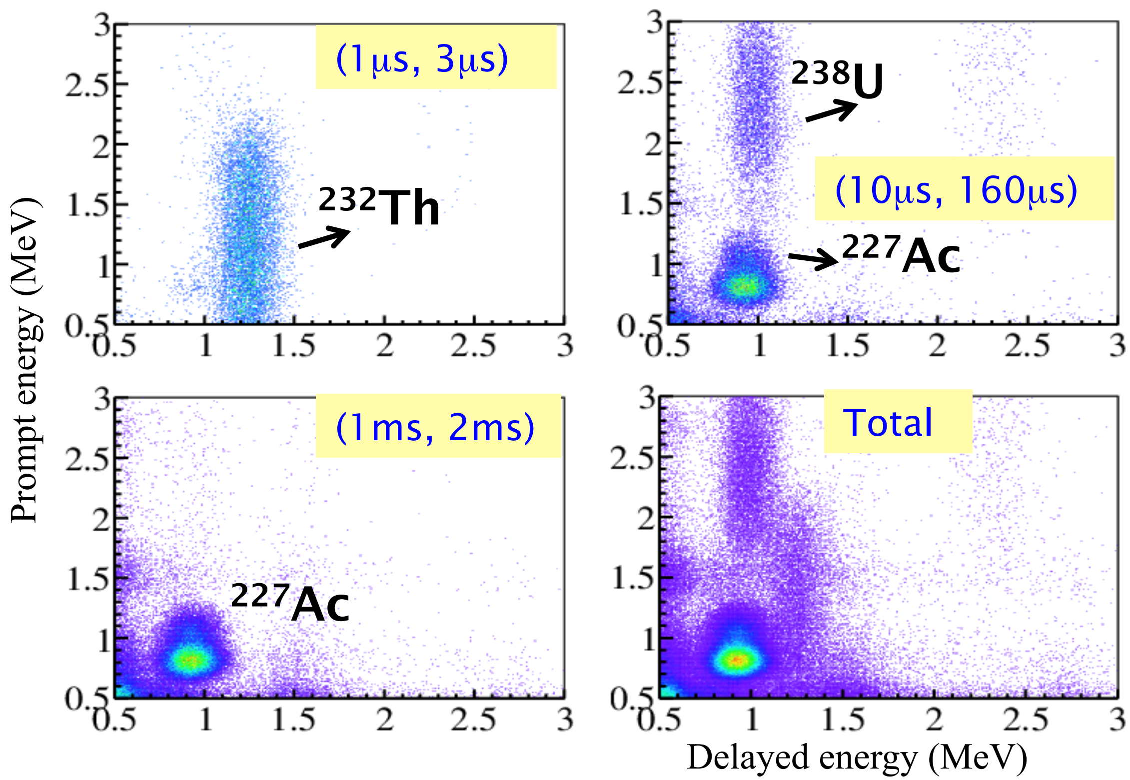
^{241}Am-^{13}C

- Calibration source in ACUs
  - Prompt: neutron inelastic scattering with ^{56}Fe
  - Delayed: neutron capture on ^{57}Fe
- Simulation:
  - 0.2events/day/AD
  - B/S: 0.03%(near), 0.3%(far)
  - ΔB/B: 100%



α-n: $^{13}C(\alpha,n)^{16}O$

- α sources: (^{238}U, ^{232}Th, ^{227}Ac, ^{210}Po)
- α rate: cascade decays
- Background rate: (α,n) cross section × α rate



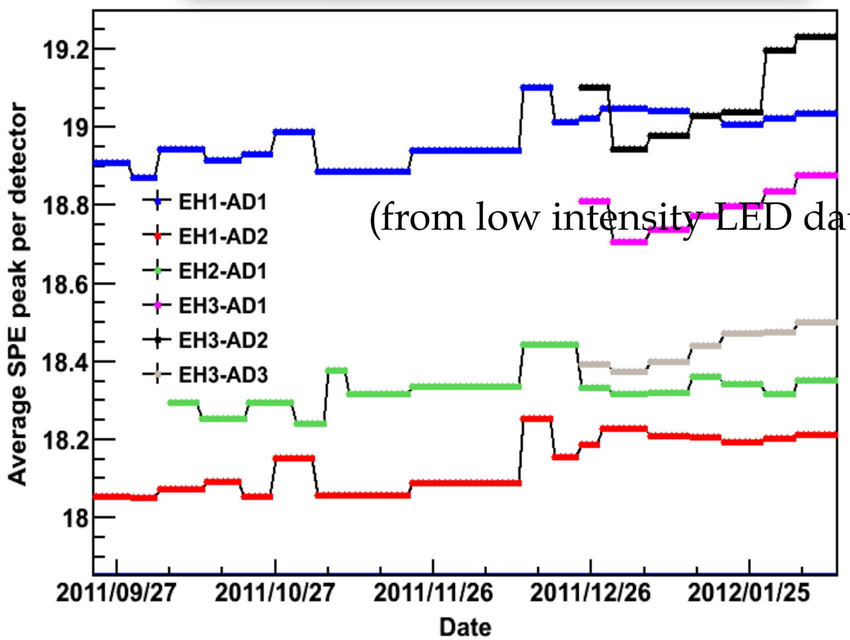
B/S @ EH1/2 ~ 0.01%,

B/S @ EH3 ~ 0.05%,

ΔB/B ~ 50%

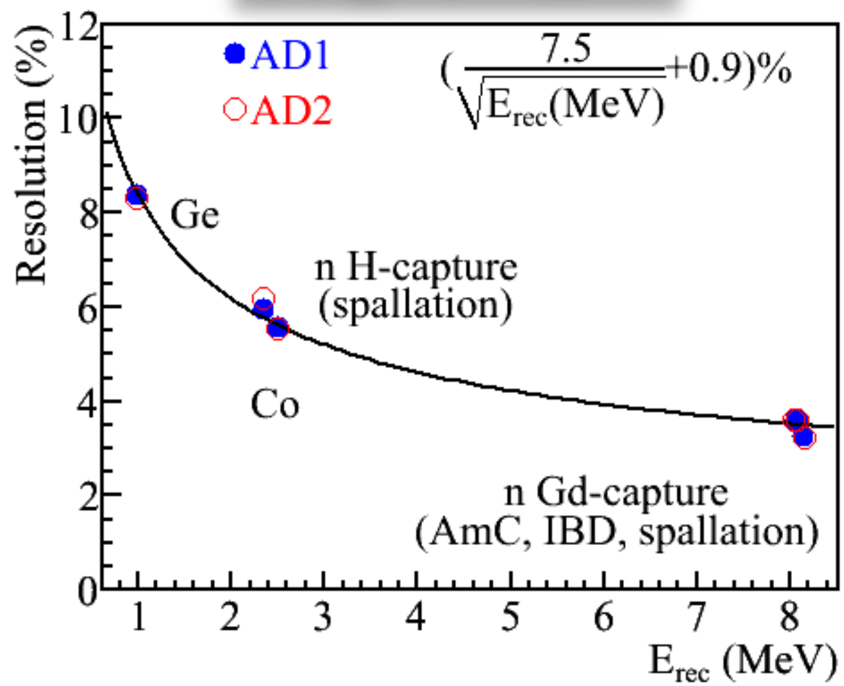
Energy Calibration

Average PMT Gain vs. time



(from low intensity LED data)

Energy Resolution

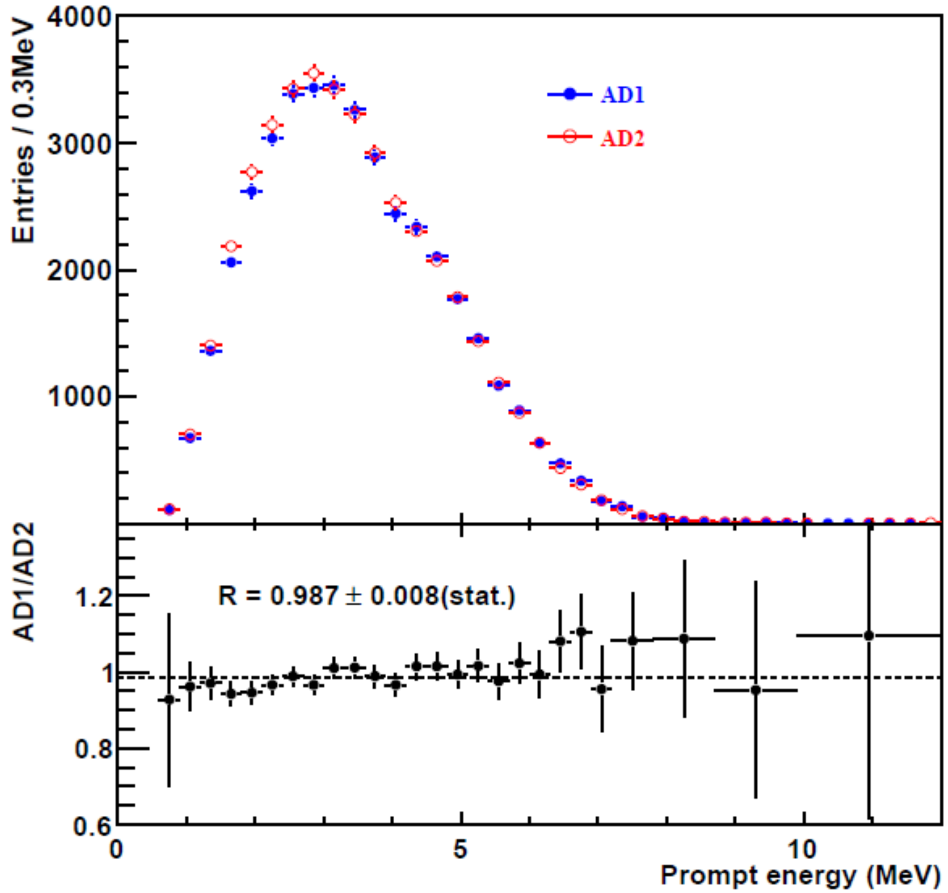


Signals and Backgrounds

	AD1	AD2	AD3	AD4	AD5	AD6
Neutrino candidates	28935	28975	22466	3528	3436	3452
DAQ live time (day)	49.5530		49.4971	48.9473		
Veto time (day)	8.7418	8.9109	7.0389	0.8785	0. 8800	0.8952
Efficiency $\varepsilon_\mu * \varepsilon_m$	0.8019	0.7989	0.8363	0.9547	0.9543	0.9538
Accidentals (/day)	9.82±0.06	9.88±0.06	7.67±0.05	3.29±0.03	3.33±0.03	3.12±0.03
Fast neutron (/day)	0.84±0.28	0.84±0.28	0.74±0.44	0.04±0.04	0.04±0.04	0.04±0.04
$^{8}He/^{9}Li$ (/day)	3.1±1.6		1.8±1.1	0.16±0.11		
Am-C corr. (/day)	0.2±0.2					
$^{13}C(\alpha, n)^{16}O$ background (/day)	0.04±0.02	0.04±0.02	0.035 ±0.02	0.03±0.02	0.03±0.02	0.03±0.02
Neutrino rate (/day)	714.17 ±4.58	717.86 ±4.60	532.29 ±3.82	71.78 ±1.29	69.80 ±1.28	70.39 ±1.28

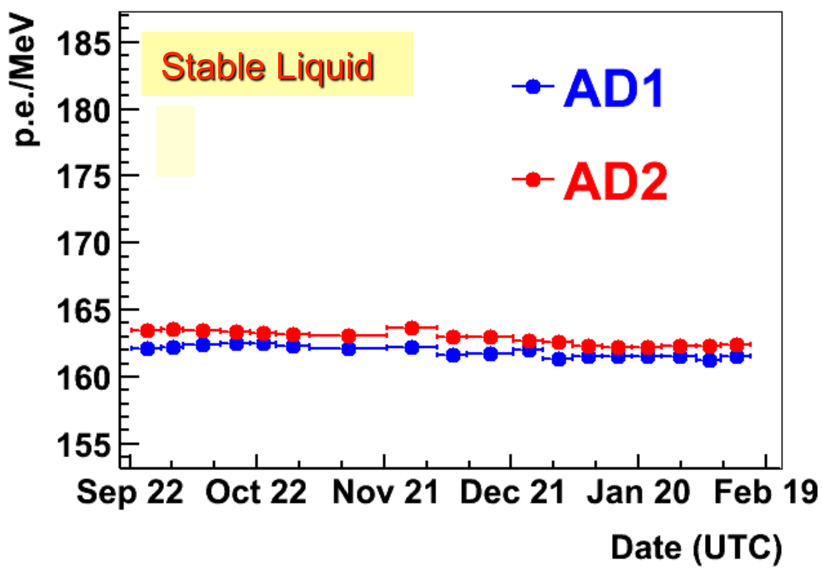
Side-by-side Comparison

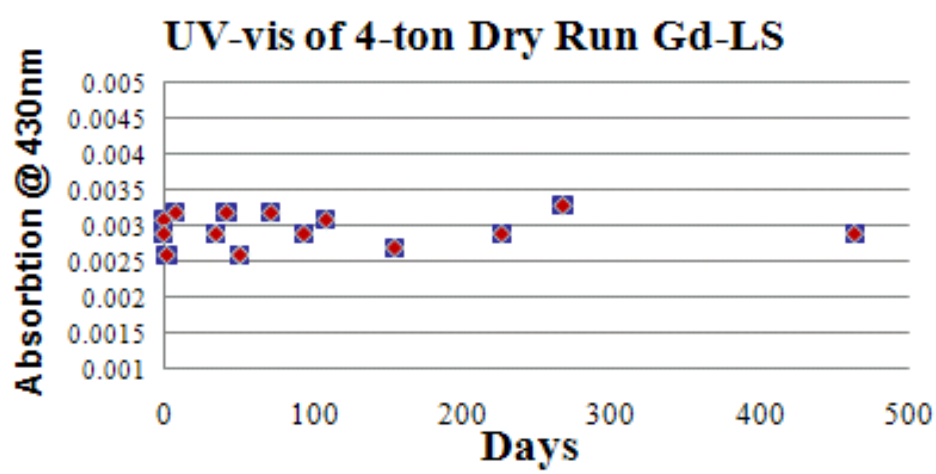
- Expected ratio of neutrino events from AD1 and AD2: 0.981
- Measured ratio: 0.987 ± 0.008(stat) ± 0.003
- The ratio is not 1 because of target mass, baseline, etc.
- This final check shows that systematic errors are under control



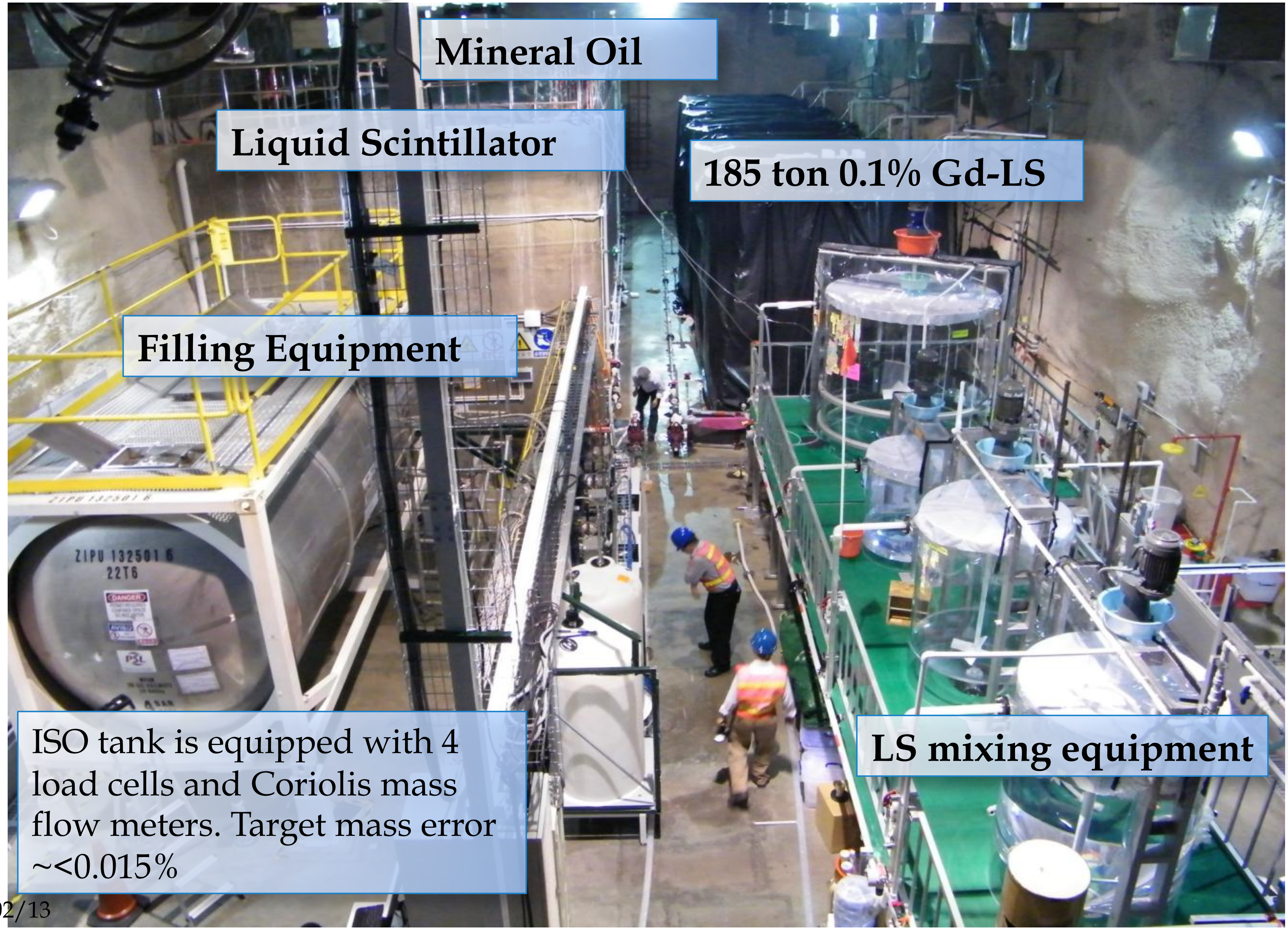
Gd-loaded Liquid Scintillator

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



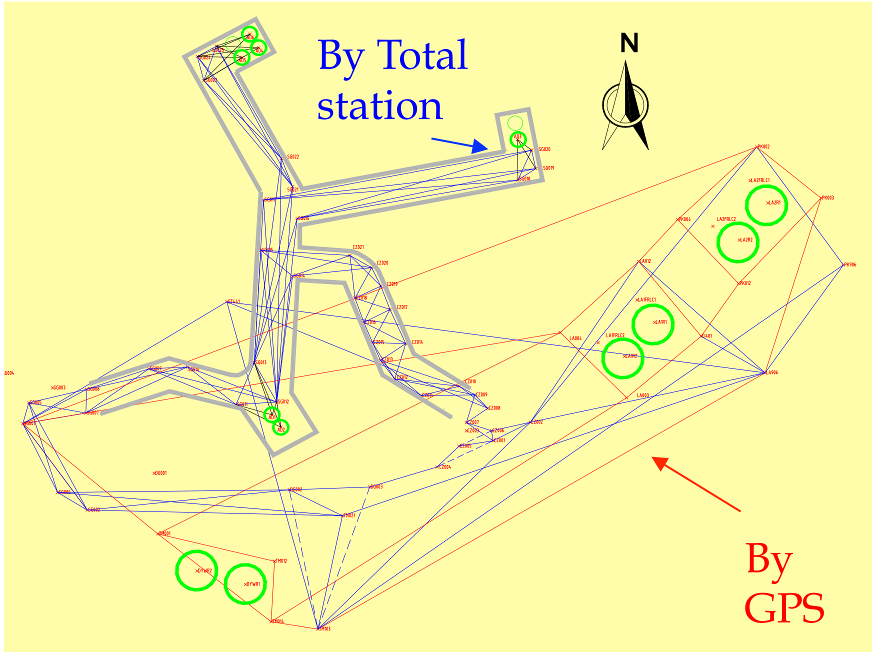


Liquid Scintillator Hall



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%)

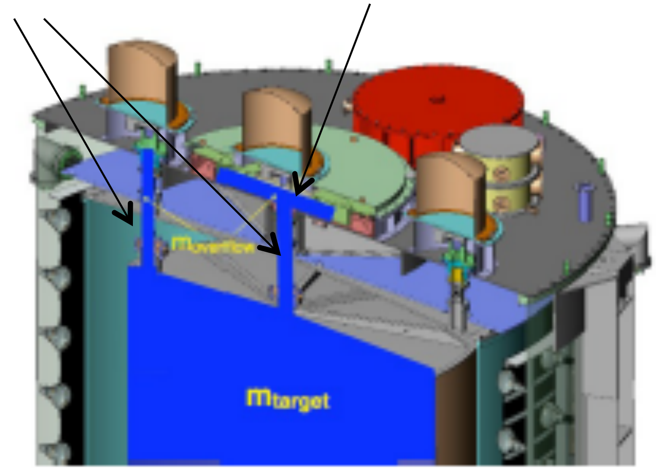


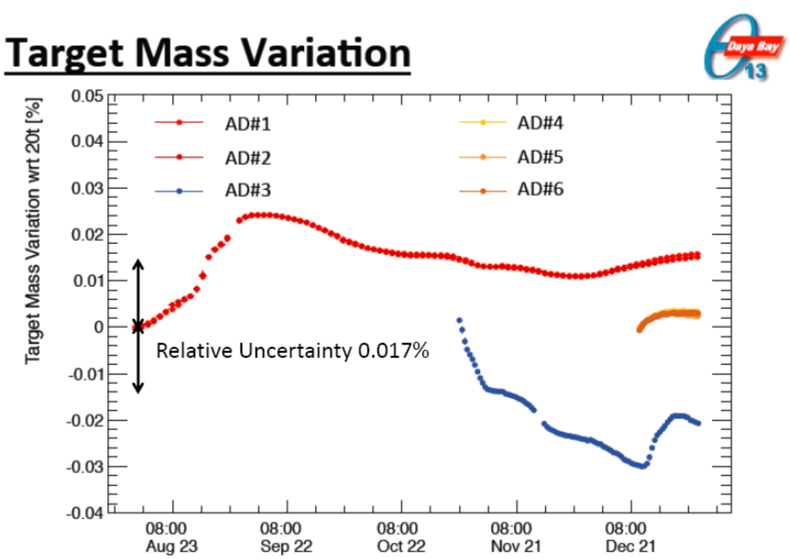
Target Mass & No. of Protons

- 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%

Near site installation