Observation of Electron-antineutrino Disappearance at Daya Bay

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For Daya Bay Collaboration

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Outline

- Introduction
- Construction of Daya Bay Experiment
- Data Analysis
  - Calibrations
  - IBD Selections
  - Background
  - Oscillation Analysis

Inside Daya Bay Anti-neutrino Detector

Inside of Outer Water Shield

Daya Bay: for a New Type of Oscillation

- **Neutrino mixing matrix(PMNS):**

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

Atmospheric+Accelerator | Reactor+Accelerator | Solar+Reactor | $0\nu\beta\beta$

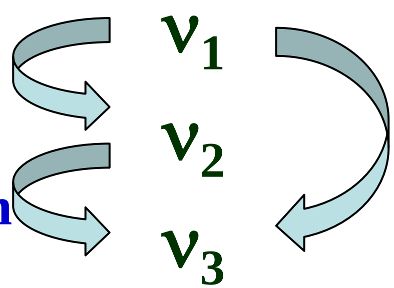
Unknown mixing parameters: θ_{13}, δ + 2 Majorana phases

Sizable θ_{13} could open the door to answer the questions of CP violation, matter and anti-matter asymmetry, neutrino mass hierarchy

- **Goal: search for a new oscillation mode θ_{13} ?**

θ_{12} solar neutrino oscillation

θ_{23} atmospheric neutrino oscillation



θ_{13} ?

Ongoing programs:

Reactor: Daya Bay Double-Chooz, Reno

Accelerator: NOVA, T2K

Indications of nonzero θ_{13} in 2011, Observation in 2012

2011 has given many hints:

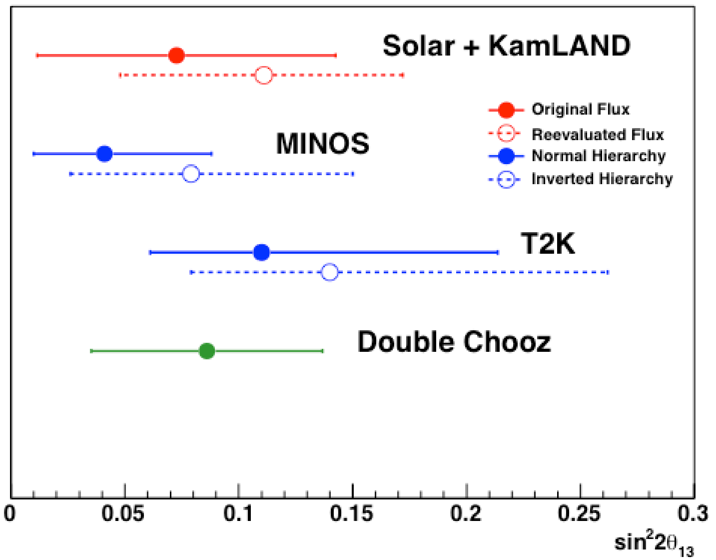
Solar + KamLAND: G.L.Fogli *et al.*, PRD 84, 053007 (2011)

MINOS: P. Adamson *et al.*, PRL. 107, 181802 (2011)

T2K: K. Abe *et al.*, PRL. 107 041801 (2011)

Double CHOOZ: Y. Abe *et al.*, PRL. 108, 131801 (2012)

No result >2.5σ from $\theta_{13} = 0$



Daya Bay excludes θ_{13}= 0 at 5.2σ – Mar. 8

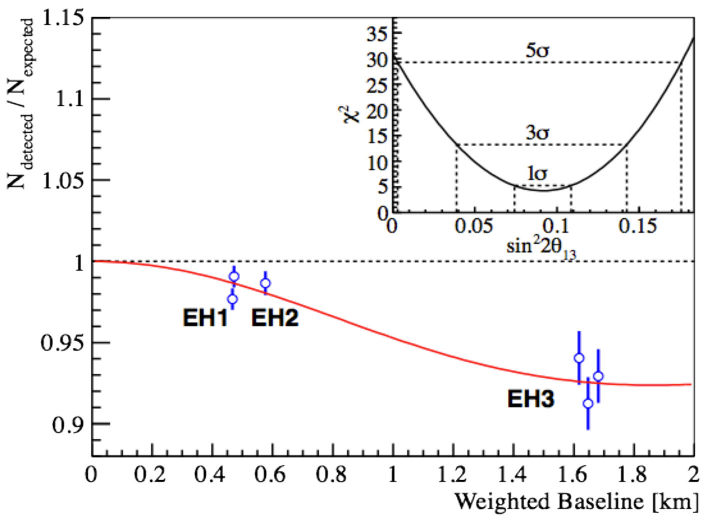
$\sin^2 2\theta_{13} = 0.092 \pm 0.016$ (stat) ± 0.005 (syst)

Phys.Rev.Lett. 108 (2012) 171803

Reno confirms – Apr. 3

$\sin^2 2\theta_{13} = 0.113 \pm 0.013$ (stat) ± 0.019 (syst)

Phys.Rev.Lett. 108 (2012) 191802



Why measure θ_{13} with Reactor Experiments?

reactor

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

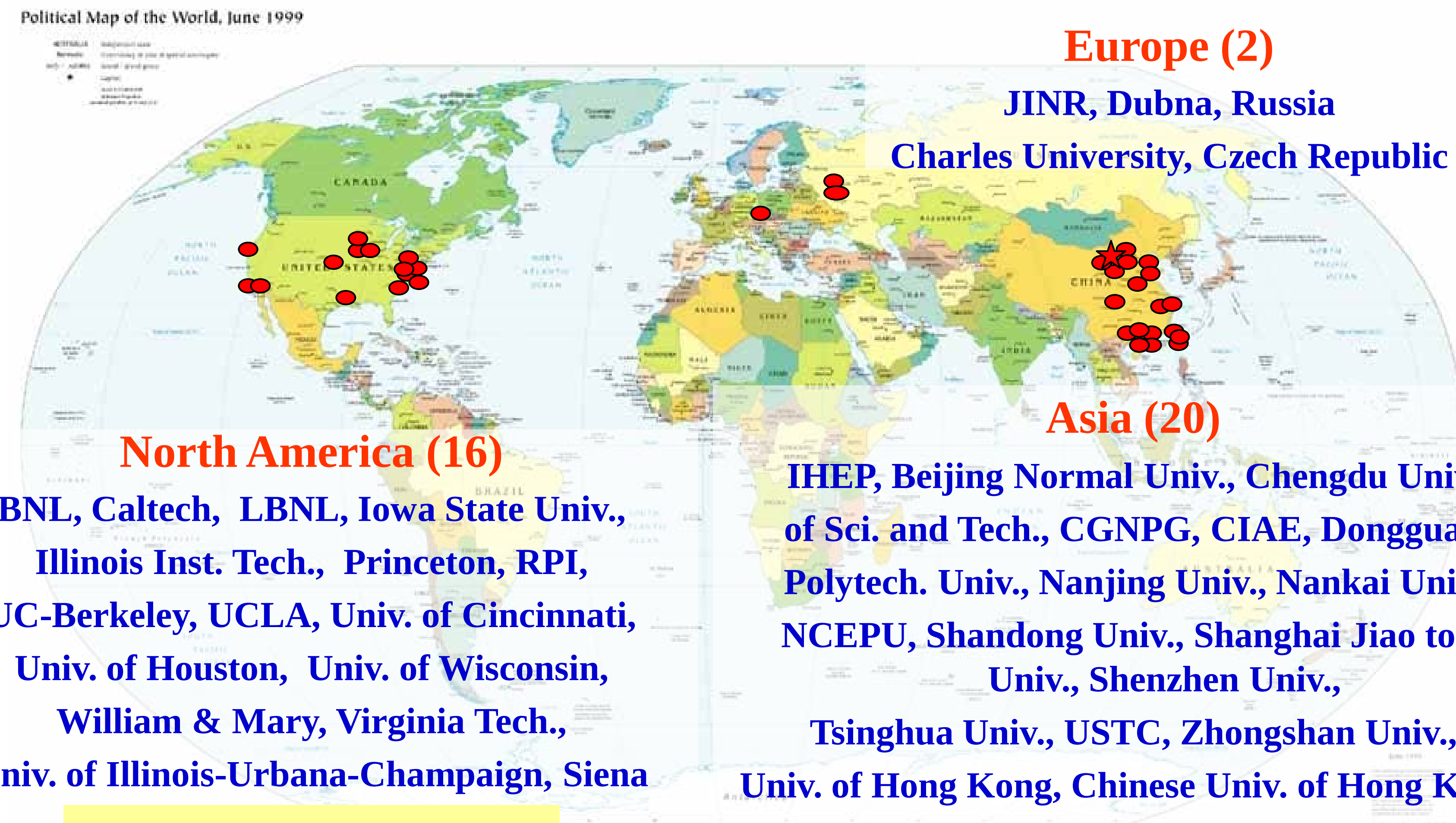
- Disappearance measurement
- Clean measurement of θ_{13}
- No matter effects

accelerator

mass hierarchy
CP violation
matter

$$\begin{aligned} P(\nu_\mu \to \nu_e) = & \; 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2\Delta_{31} \\ & + 8c_{13}^2 s_{13} s_{23} c_{23} s_{12} c_{12} \sin\Delta_{31}[\cos\Delta_{32}\cos\delta - \sin\Delta_{32}\sin\delta]\sin\Delta_{21} \\ & - 8c_{13}^2 s_{13}^2 s_{23}^2 s_{12}^2 \cos\Delta_{32}\sin\Delta_{31}\sin\Delta_{21} \\ & + 4c_{13}^2 s_{12}^2[c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta]\sin^2\Delta_{21} \\ & - 8c_{13}^2 s_{13}^2 s_{23}^2(1 - 2s_{13}^2)\frac{aL}{4E_\nu}\sin\Delta_{31}\left[\cos\Delta_{32} - \frac{\sin\Delta_{31}}{\Delta_{31}}\right] . \end{aligned}$$

The Daya Bay Collaboration



Europe (2)

JINR, Dubna, Russia

Charles University, Czech Republic

North America (16)

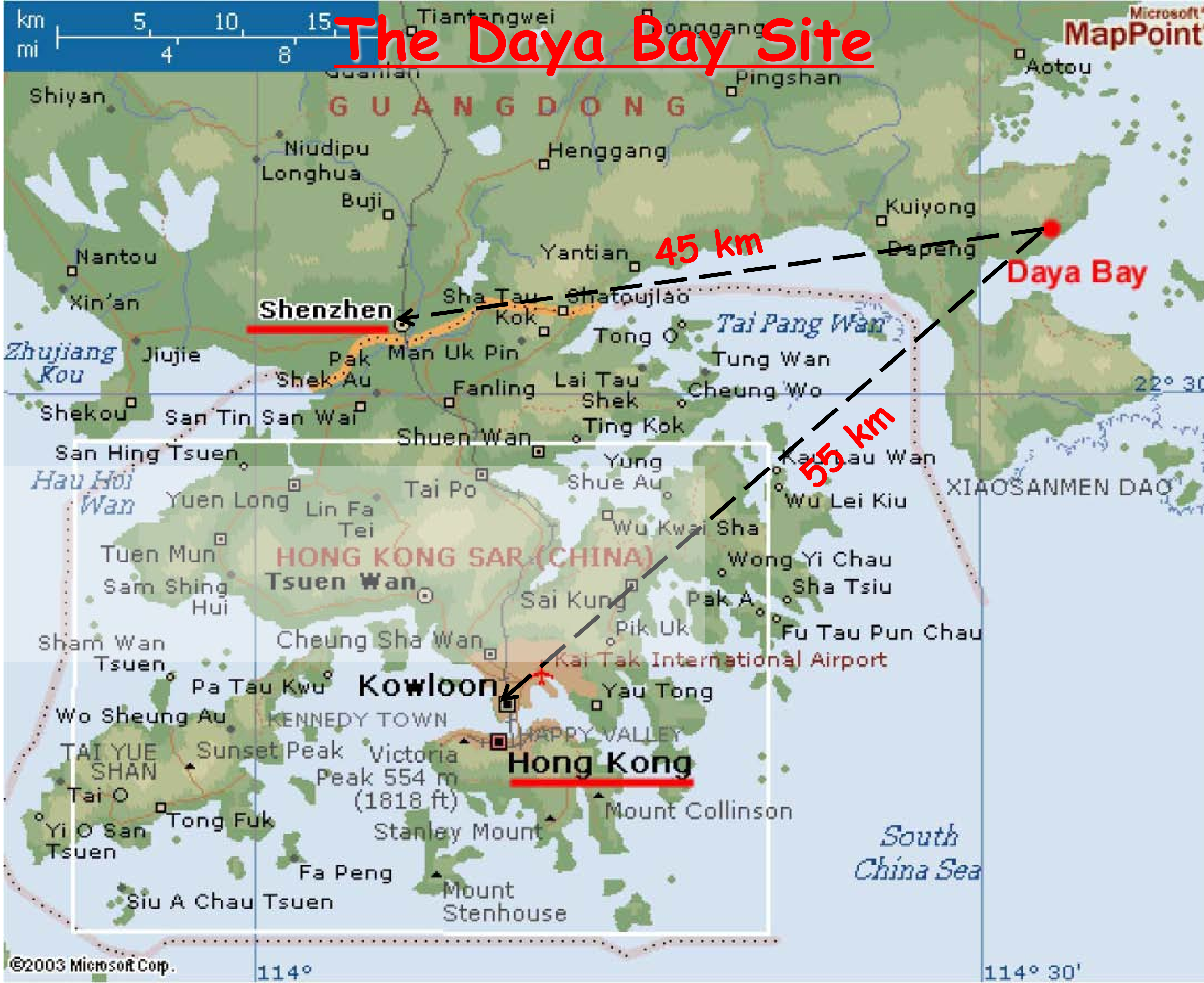
BNL, Caltech, LBNL, Iowa State Univ., Illinois Inst. Tech., Princeton, RPI, UC-Berkeley, UCLA, Univ. of Cincinnati, Univ. of Houston, Univ. of Wisconsin, William & Mary, Virginia Tech., Univ. of Illinois-Urbana-Champaign, Siena

~250 Collaborators

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.

The Daya Bay Site



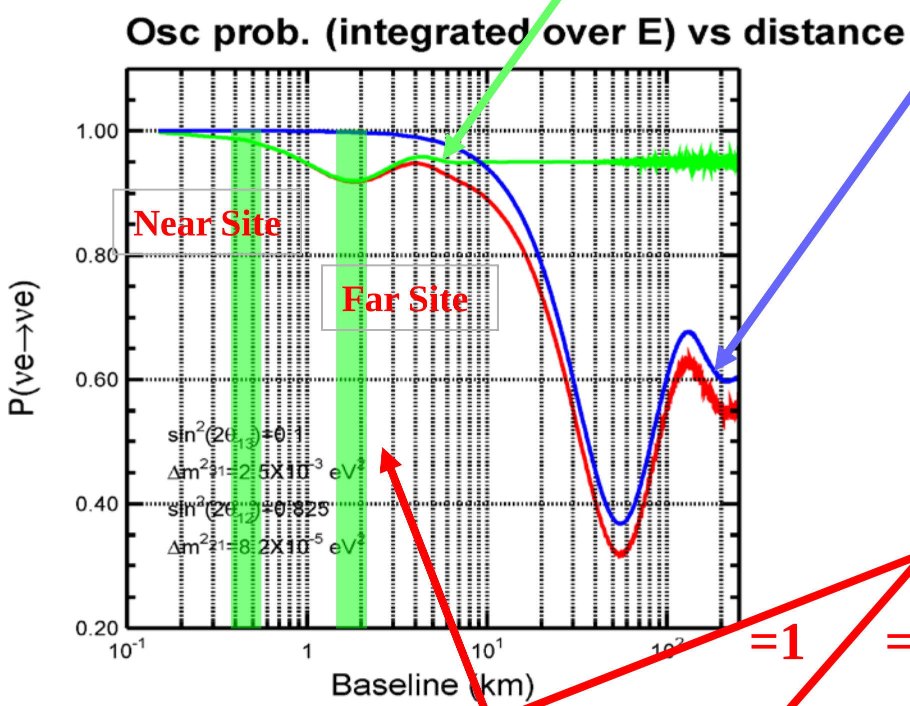
Daya Bay Nuclear Power Complex

- Three-pair reactor cores: 2.95 × 6=17.7GWth
- Each core produces 6×10^{20} anti-ν_e's/s
- Mountains near by

Determining θ_{13} With Reactor ν_e

Looking for non-$1/r^2$ behavior of $\overline{\nu}_e$ interaction rate

$$\frac{N_{obs}}{N_{\exp}} = 1 - \sin^2 2\theta_{13} \sin^2(1.27\Delta m_{13}^2 \frac{L}{E}) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2(1.27\Delta m_{12}^2 \frac{L}{E})$$



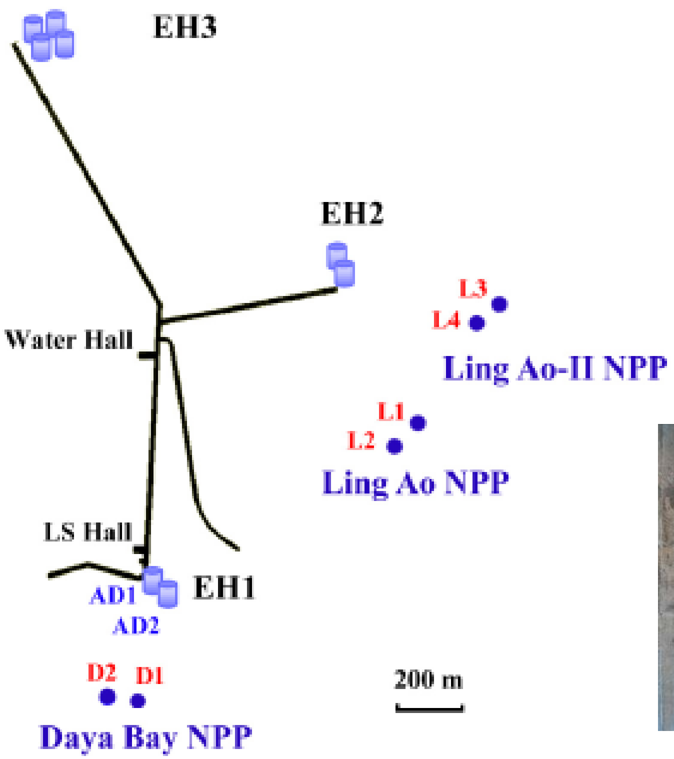
- **Absolute reactor flux is the largest uncertainty in previous measurements**
- **Relative measurement removes absolute uncertainties!**
  First proposed by L. A. Mikaelyan and V.V. Sinev, Phys. Atomic Nucl. 63 1002 (2000)
- **Identical near and far detector**

=1 **=1**

$$\frac{N_f}{N_n} = \left(\frac{N_{p,f}}{N_{p,n}}\right)\left(\frac{L_n}{L_f}\right)^2\left(\frac{\varepsilon_f}{\varepsilon_n}\right)\frac{P_{survival}(E, L_f)}{P_{survival}(E, L_n)} \Rightarrow \sin^2 2\theta_{13}$$

far/near $\overline{\nu}_e$ ratio **target mass** **distances** **efficiency** **oscillation deficit**

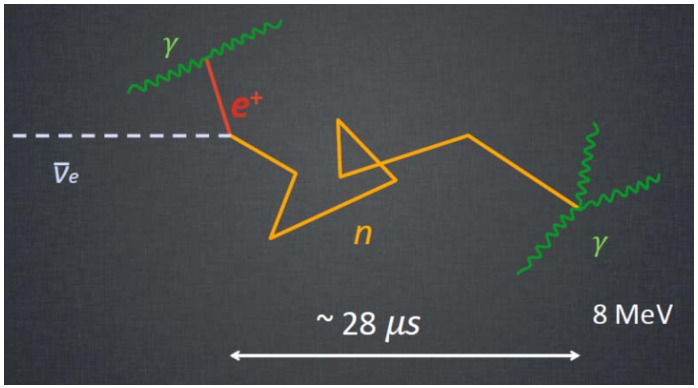
Underground Labs



	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

Neutrino Detection: Gd-loaded Liquid Scintillator

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

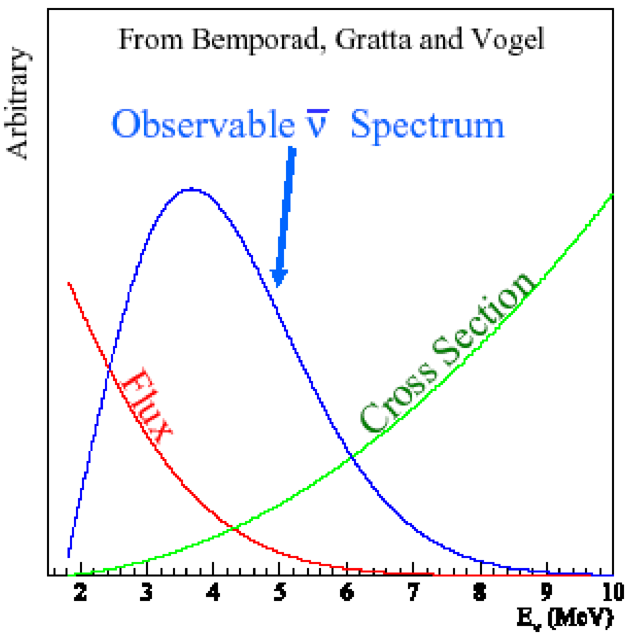


$\tau \approx 28\ \mu s$ (0.1% Gd)

n + p → d + γ (2.2 MeV)

n + Gd → Gd* + γ (8 MeV)

Neutrino Event: coincidence in time, space and energy



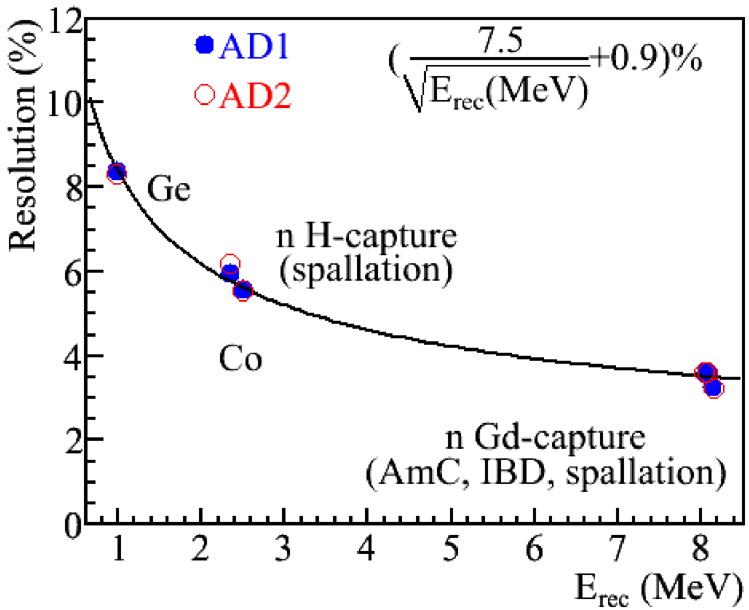
Neutrino energy:

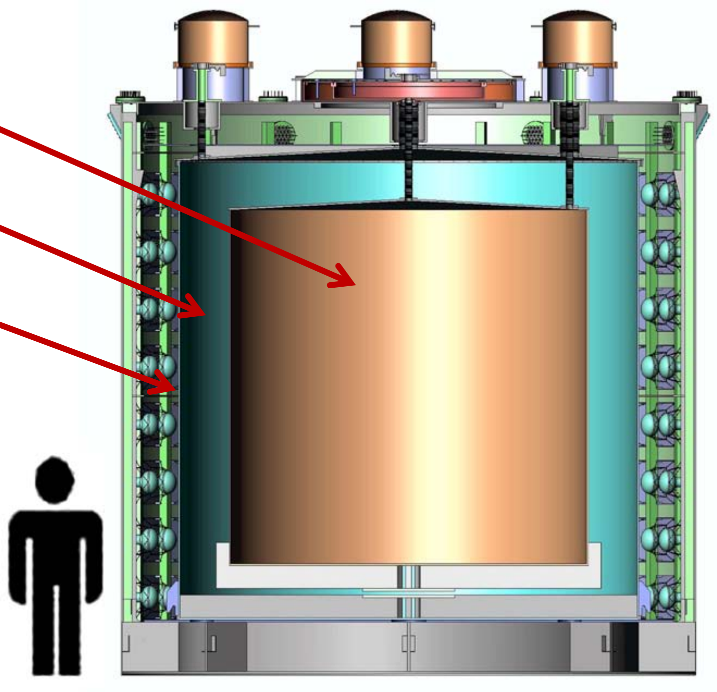
$$E_{\overline{\nu}} \cong T_{e^+} + T_n + (M_n - M_p) + m_{e^+}$$

10-40 keV *1.8 MeV:* **Threshold**

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, Photocathode coverage increased from 5.6% to 12%**





Target: 20 t, 1.6m

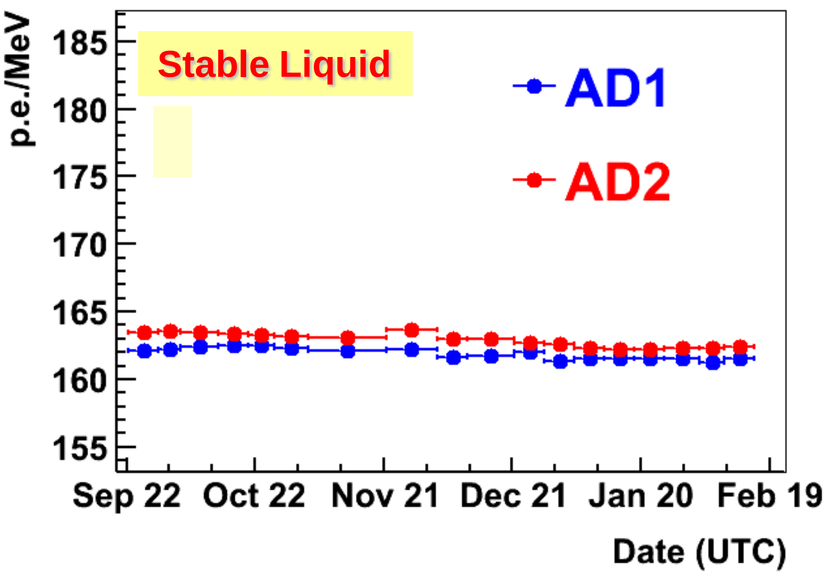
γ-catcher: 20t, 45cm

Buffer: 40t, 45cm

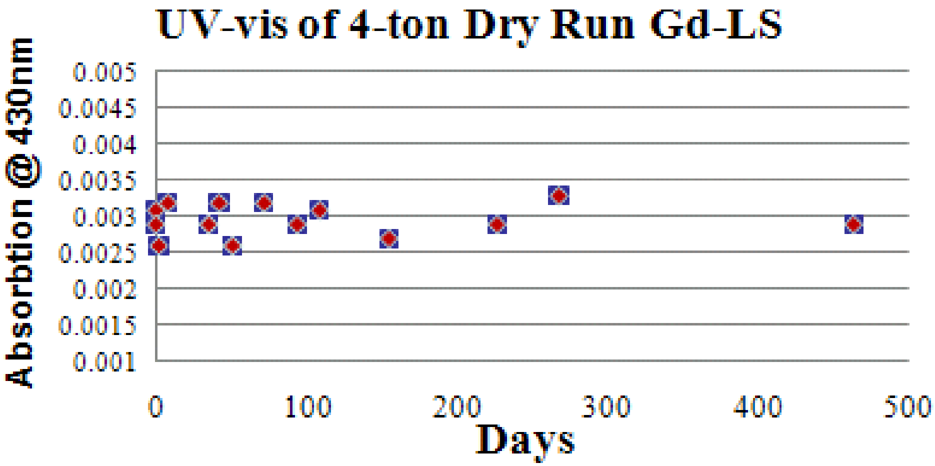
Total weight: ~110 t

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

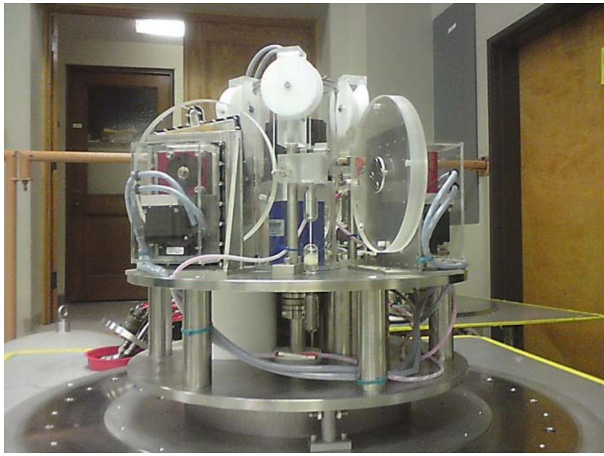


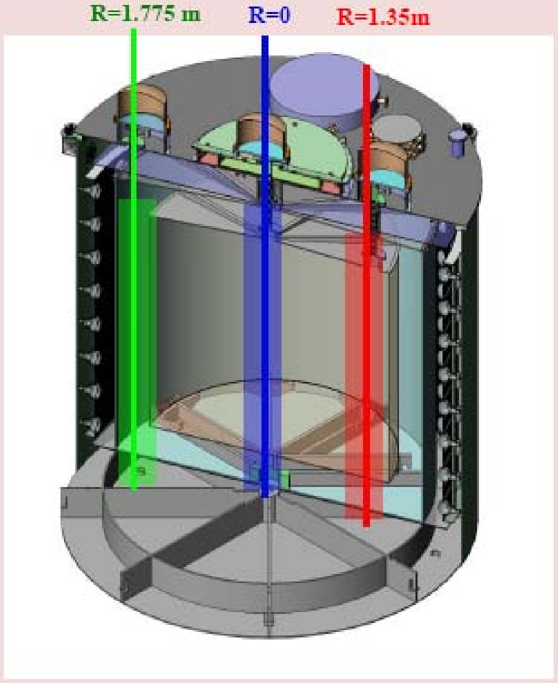
Liquid hall: LS production and filling



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

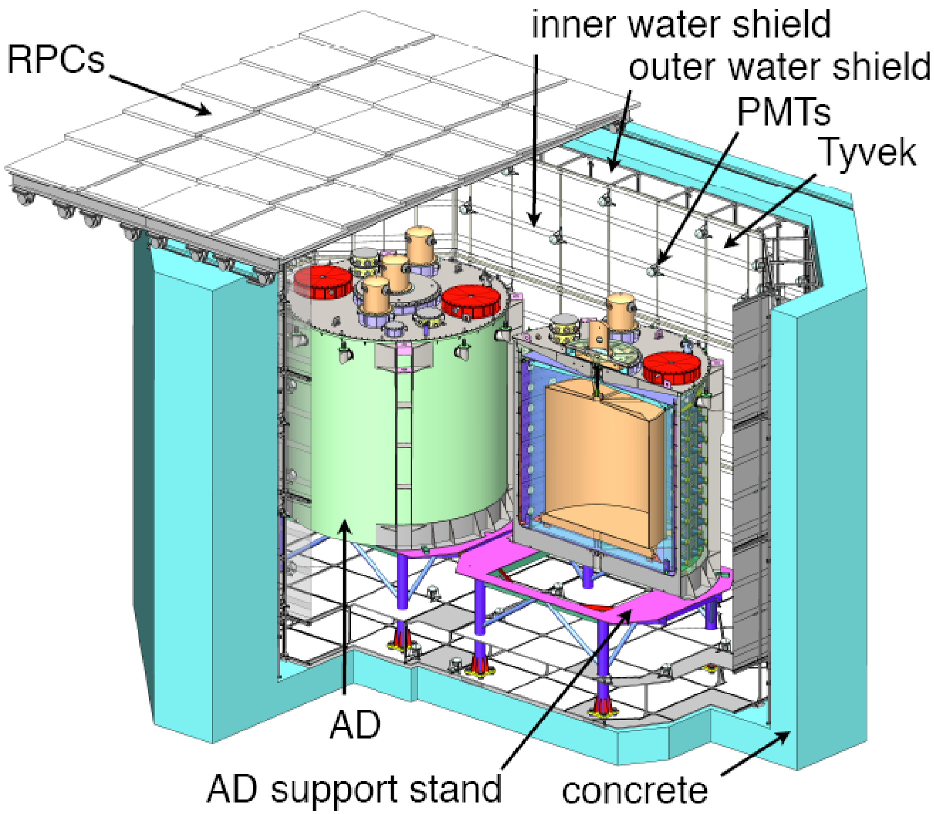




Automated Calibration

Muon Veto Detector

Dual tagging systems: 2.5 meter thick two-section water shield and RPCs

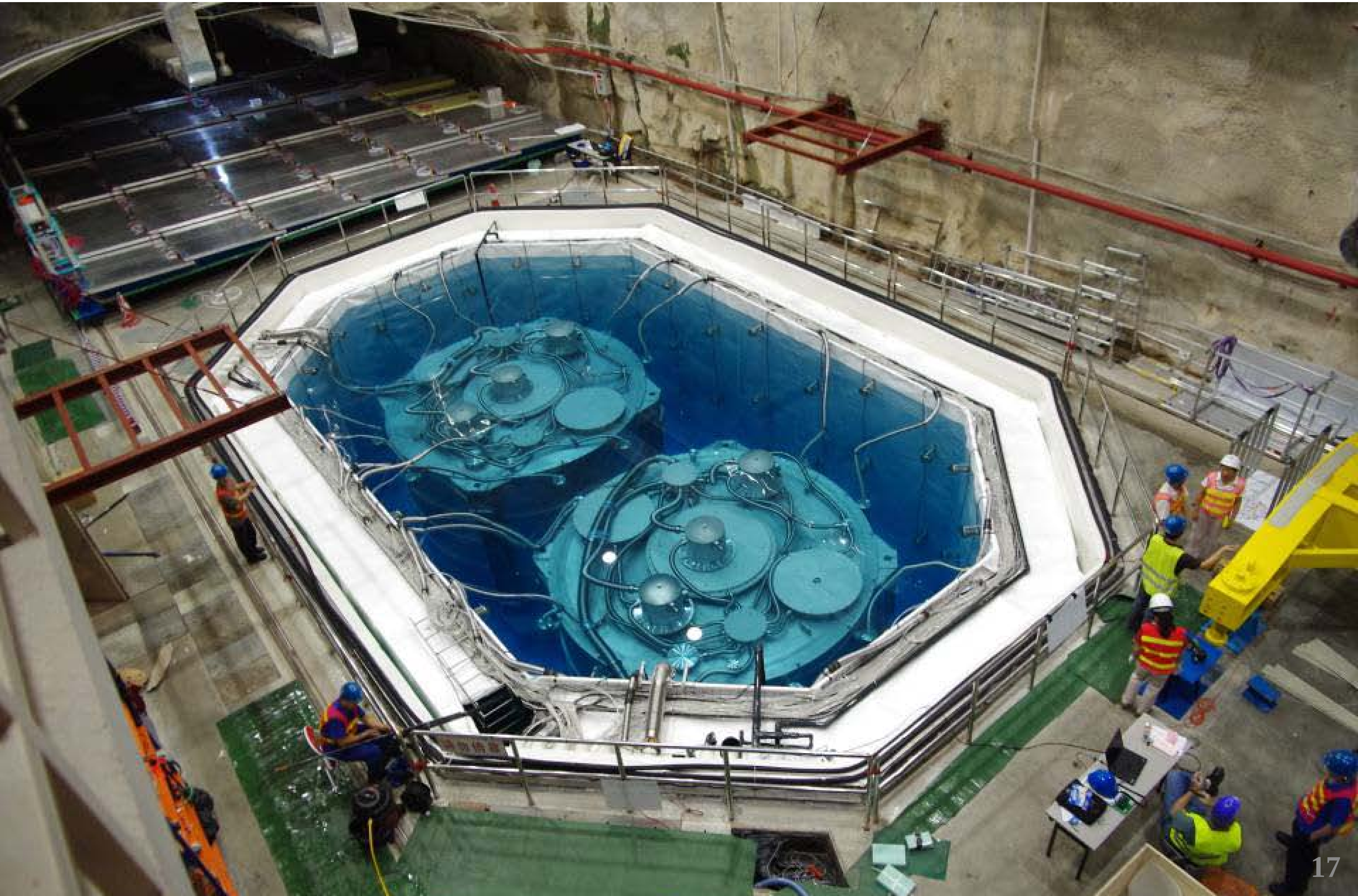


Goal efficiency: > 99.5% with <0.25% uncertainty

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

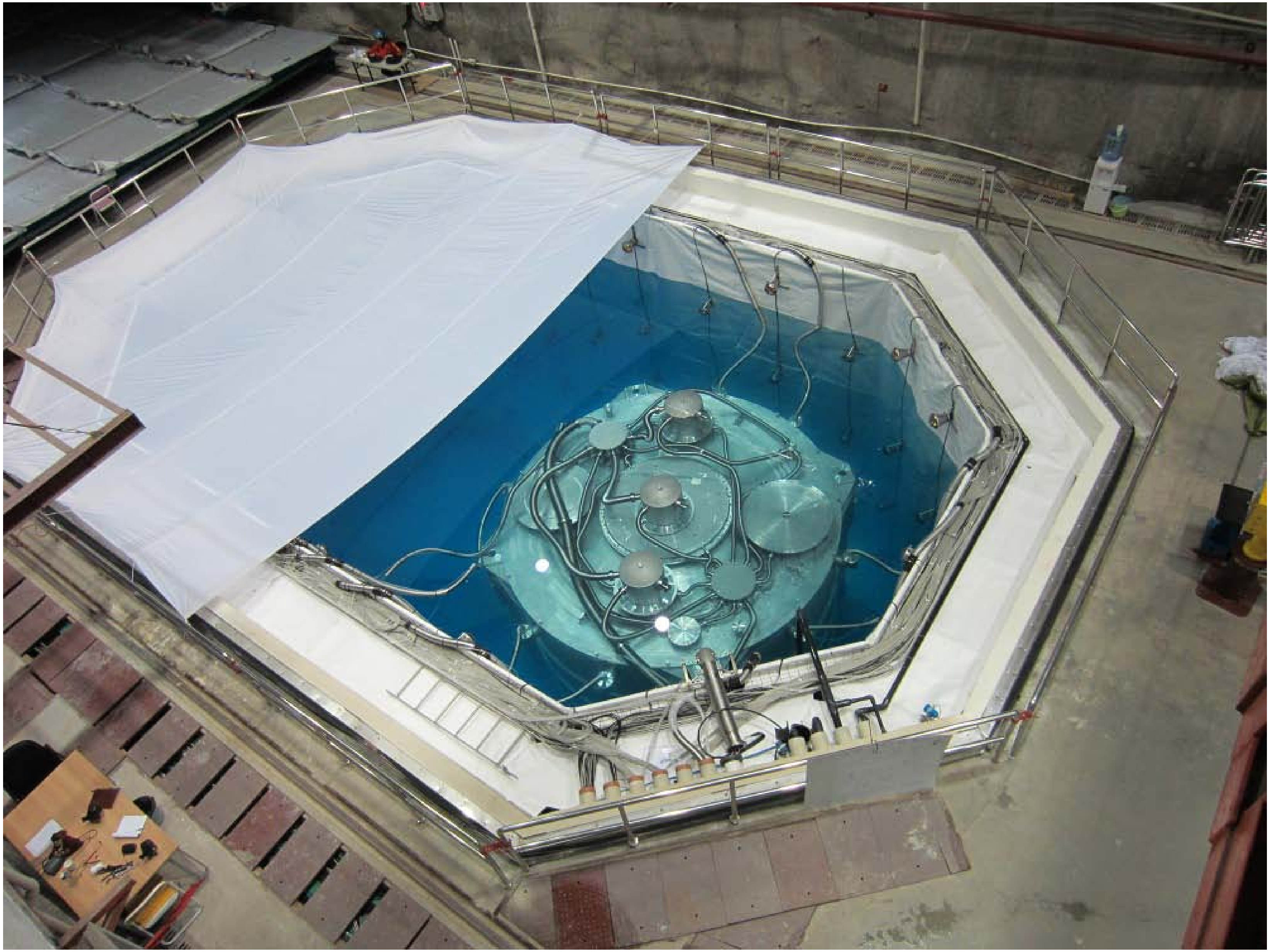
Installation

Two ADs Installed in Hall 1

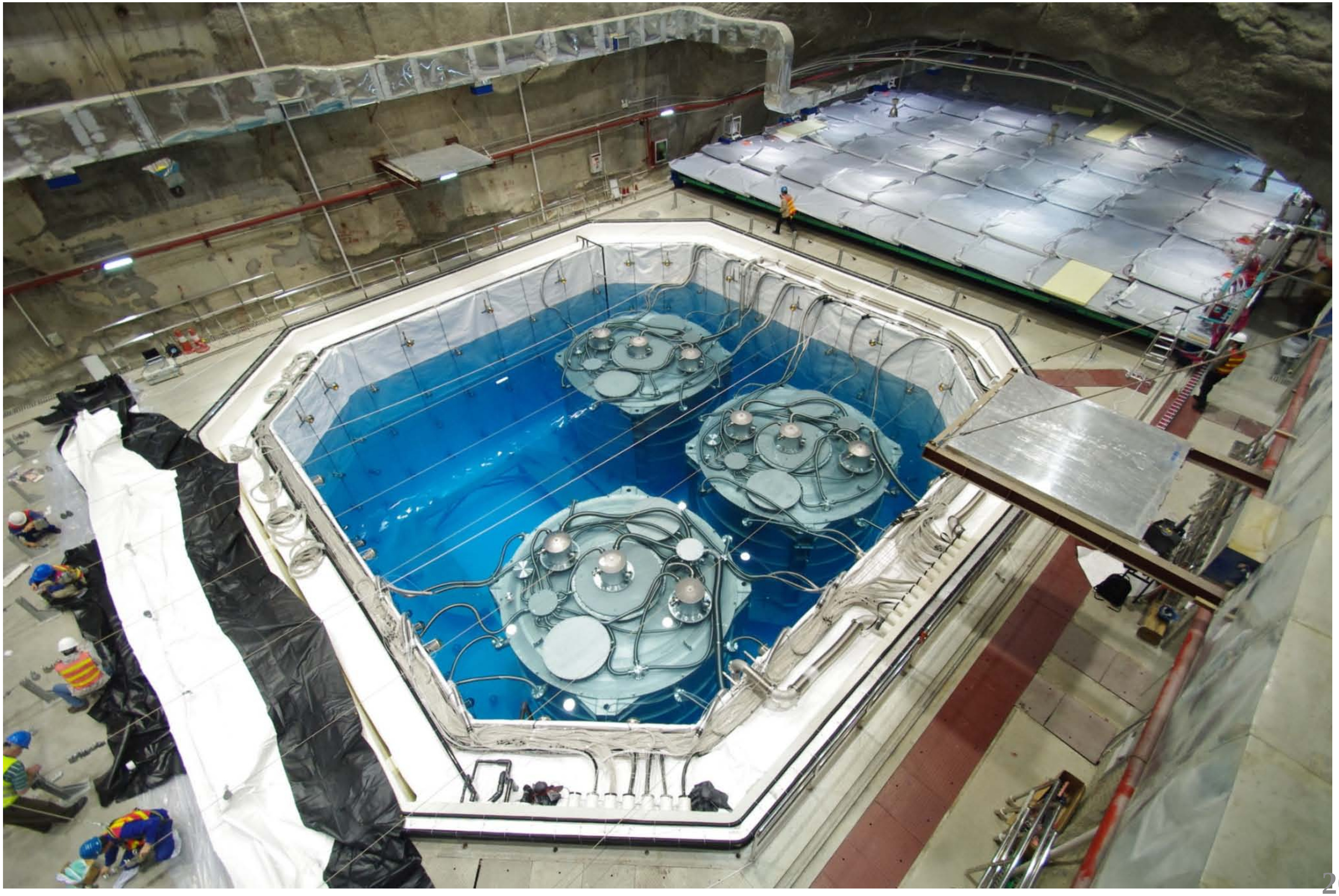


Hall 1(two ADs) Started the Operation on Aug. 15, 2011

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



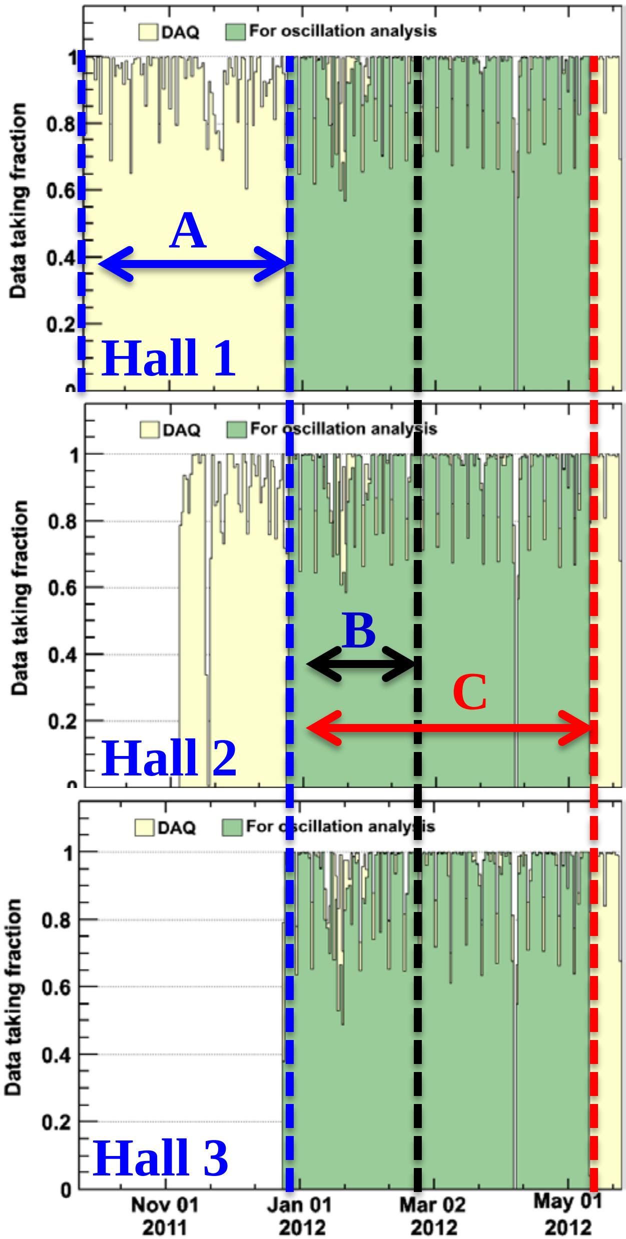
Data Periods

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.
- Soon published in Nucl. Inst. and Meth.

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)

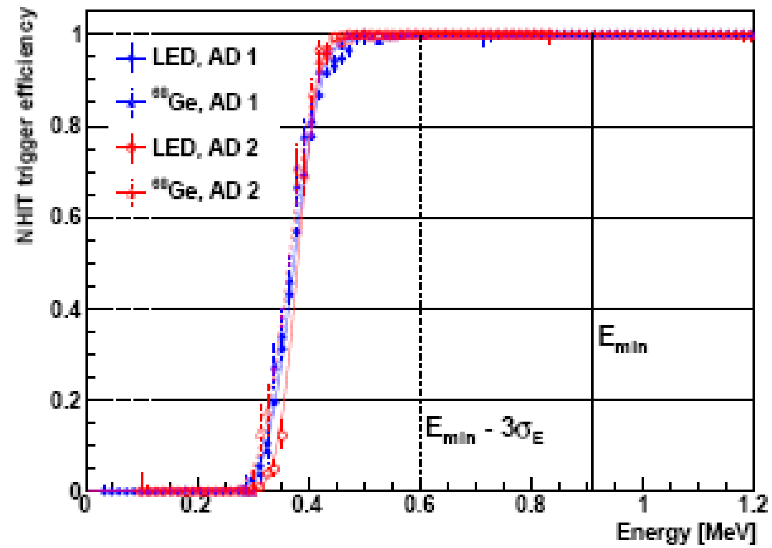
C. June Oscillation Result Update:

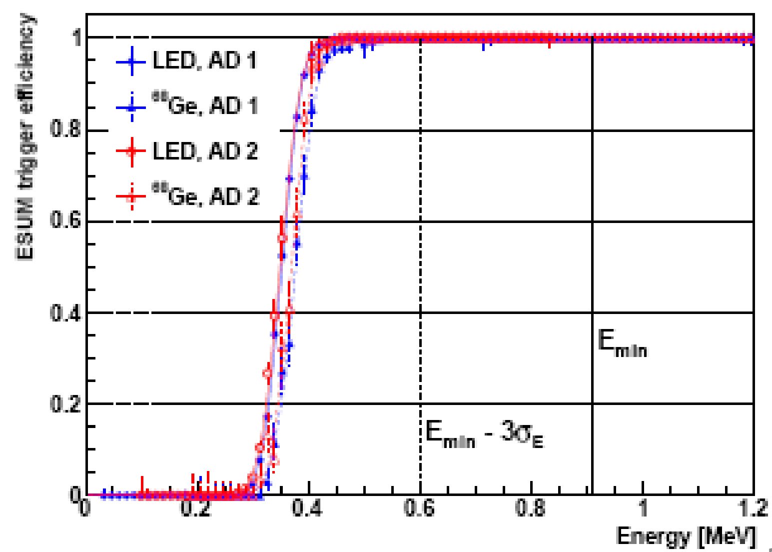
Neutrino 2012
- Dec. 24, 2011 – May 11, 2012
- More than 2.5 x the previous data set



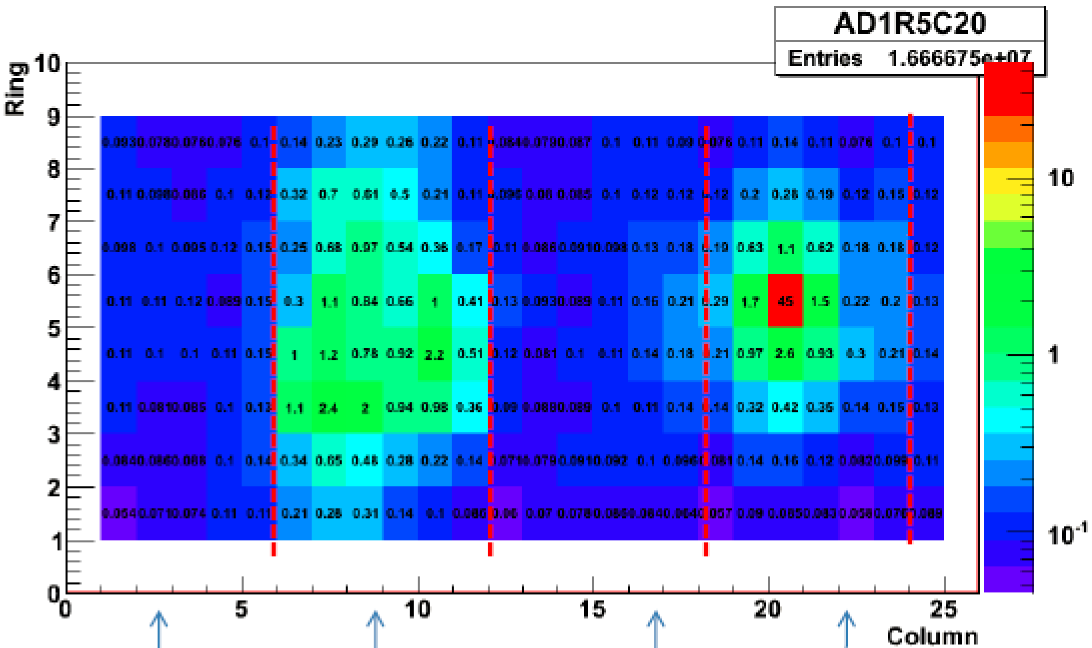
Trigger Performance

- **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**

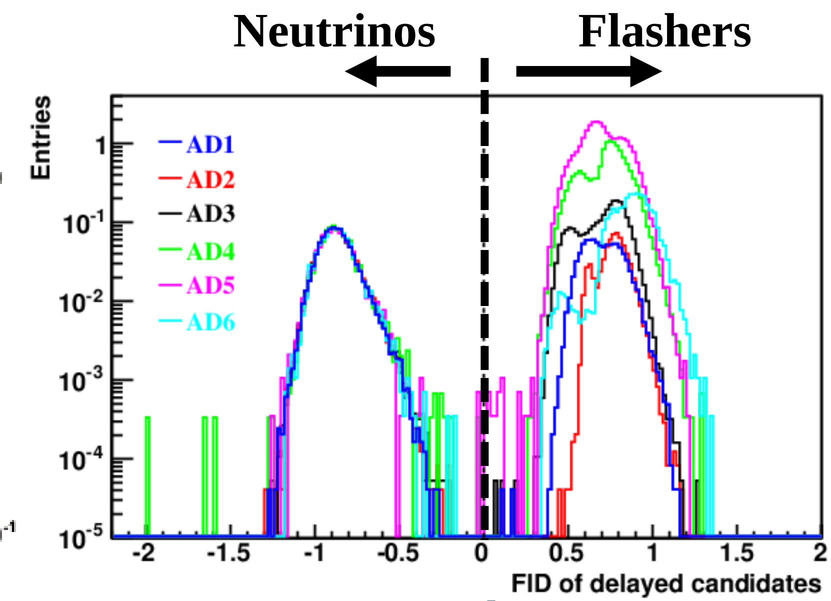




Flashers: Imperfect PMTs



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



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

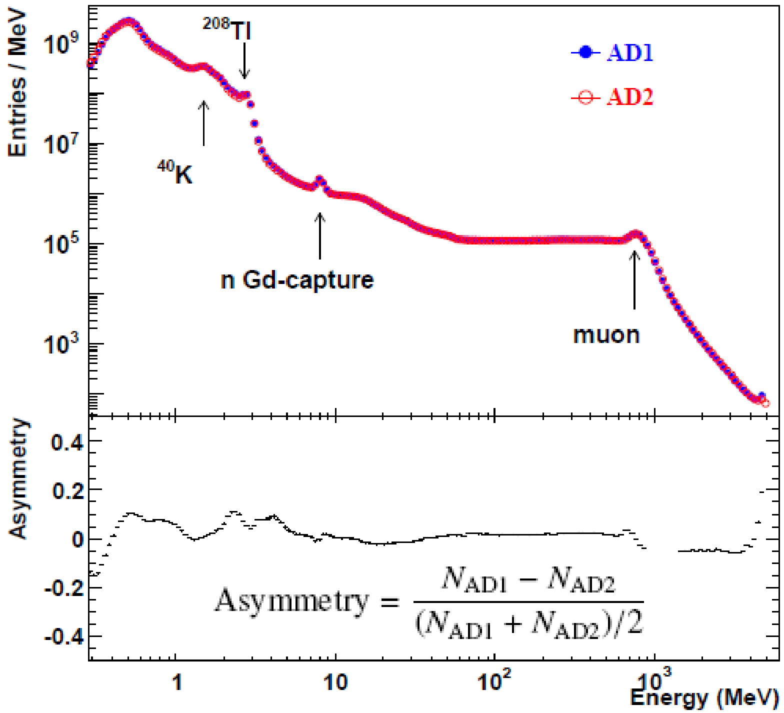
Quadrant = Q3/(Q2+Q4)

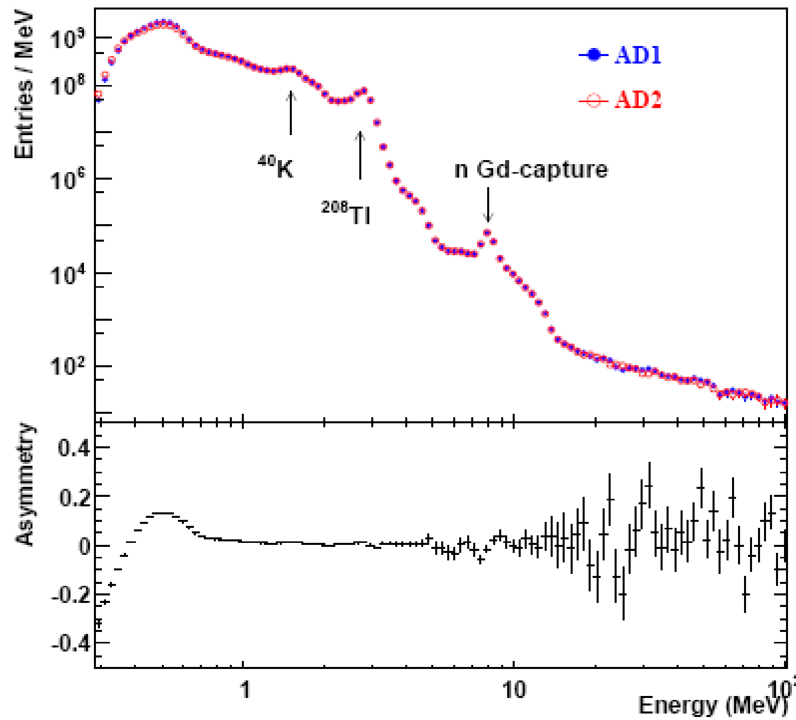
MaxQ = maxQ/sumQ

- **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





After PMT flasher remove

Muon remove with:

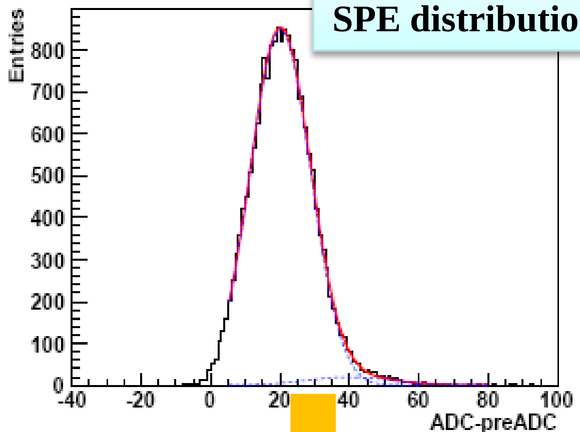
1μs < Pool muon <200μs

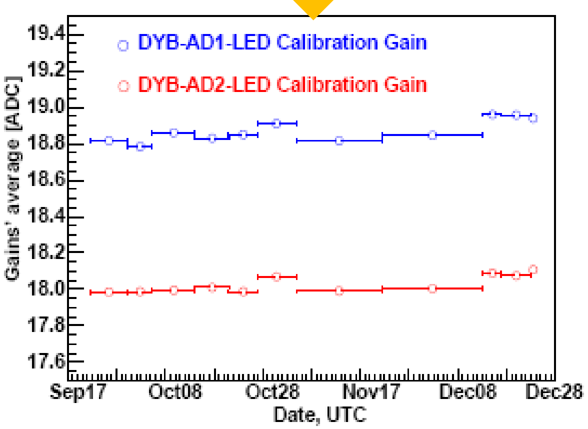
- **Single rate contribution:**
  - **~ 5 Hz from SSV**
  - **~ 10 Hz from LS**
  - **~ 25 Hz from PMT**
  - **~ 5 Hz from rock**

PMT Calibration:

PMT gain stability

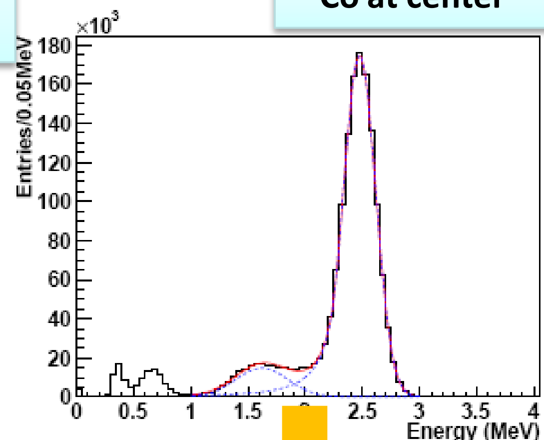
Fit to one PMT SPE distribution

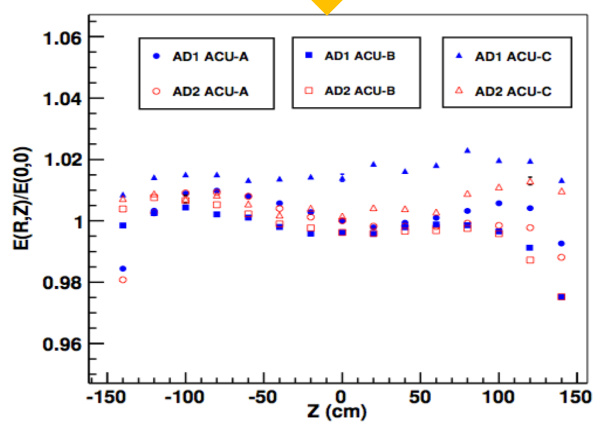




Energy calibration

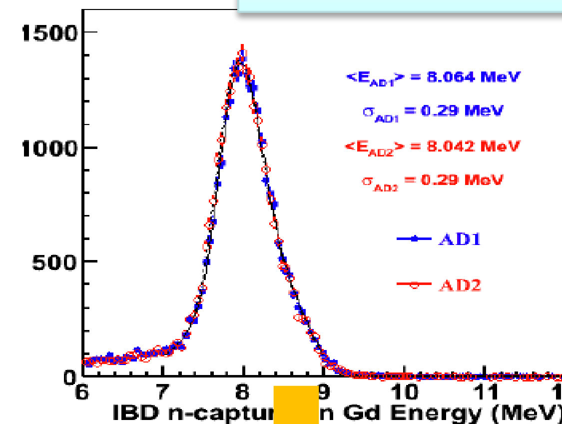
^{60}Co at center

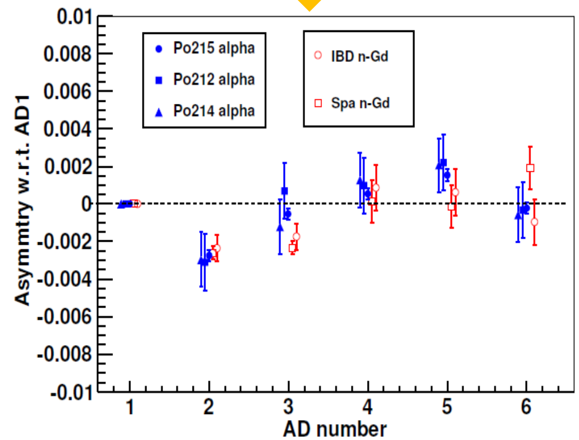




Energy in different ADs

neutron capture

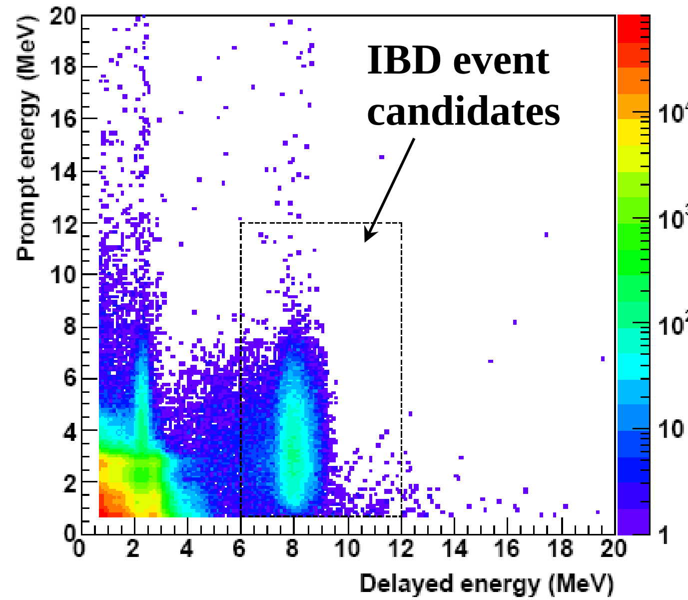


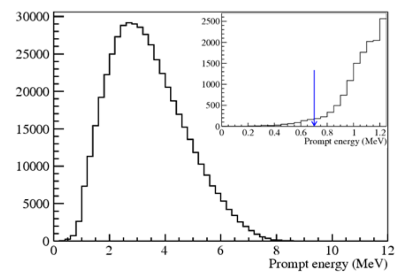


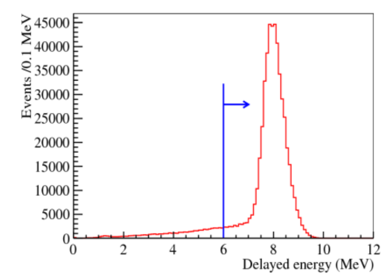
IBD event selection

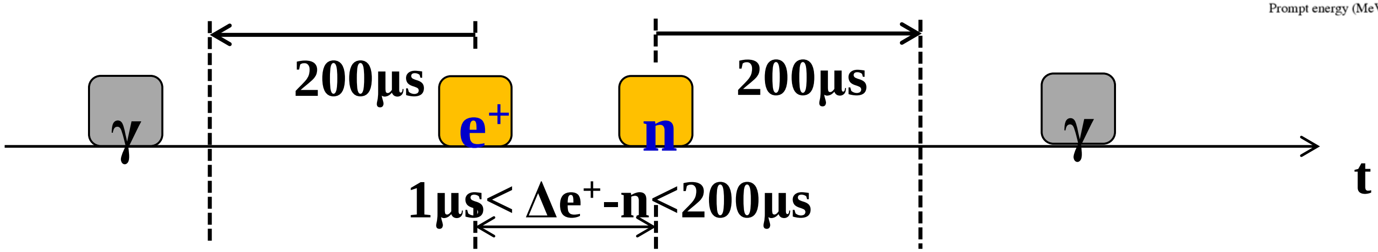
Prompt + Delayed Selection $\overline{\nu}_e + p \rightarrow e^+ + n$

- Reject Flashers
- Muon Veto:
  - Pool Muon: Reject 0.6ms
  - AD Muon (>20 MeV): Reject 1ms
  - AD Shower Muon (>2.5GeV): Reject 1s
- Multiplicity:
  - No other signal > 0.7 MeV in -200 μs to 200 μs of IBD.
- Prompt Positron: 0.7 MeV < E_p < 12 MeV
- Delayed Neutron: 6.0 MeV < E_d < 12 MeV
- Capture time: 1 μs < Δt < 200 μs





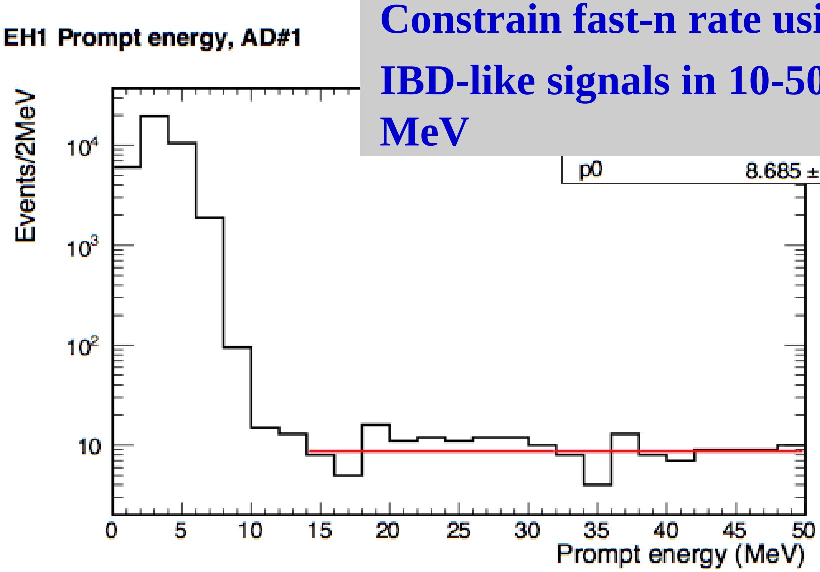




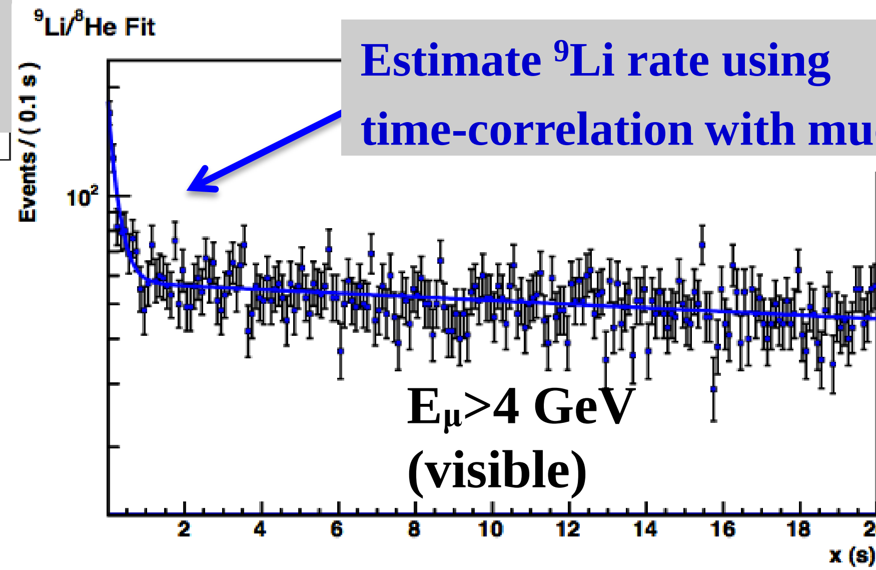
Backgrounds

- **Low background experiment**
  - Total backgrounds are 5% (2%) in far(near) halls
  - Background uncertainties are 0.3% (0.2%) in far (near) halls
- **The backgrounds are all estimated using data-driven methods:**
  - The largest source of background can be measured to ~1%

	Near Halls		Far Hall	
	B/S %	$\sigma_{B/S}$ %	B/S %	$\sigma_{B/S}$ %
Accidentals	1.5	0.02	4.0	0.05
Fast neutrons	0.12	0.05	0.07	0.03
^{9}Li/^{8}He	0.4	0.2	0.3	0.2
^{241}Am-^{13}C	0.03	0.03	0.3	0.3
^{13}C(α, n)^{16}O	0.01	0.006	0.05	0.03



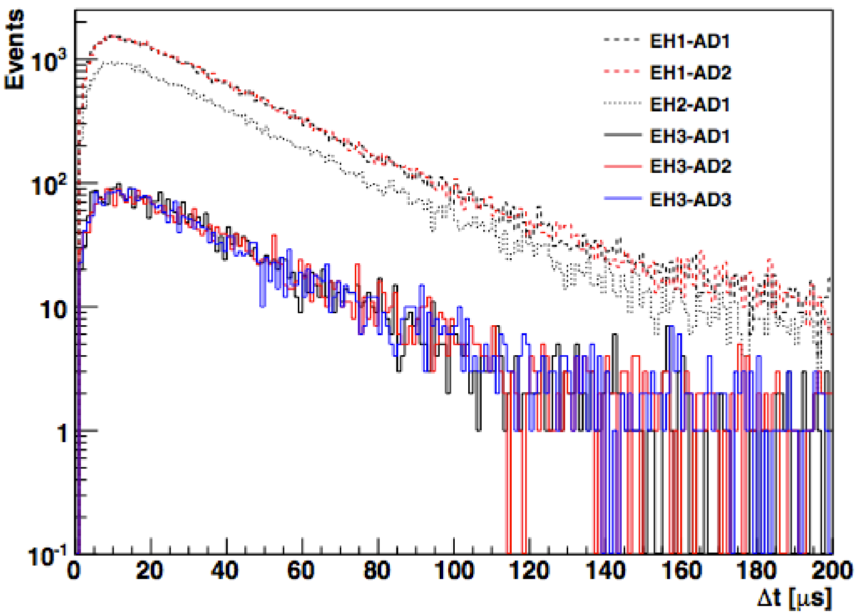
Constrain fast-n rate using IBD-like signals in 10-50 MeV



Estimate ^{9}Li rate using time-correlation with muon

Neutron Capture Time

Consistent IBD capture time measured in all detectors

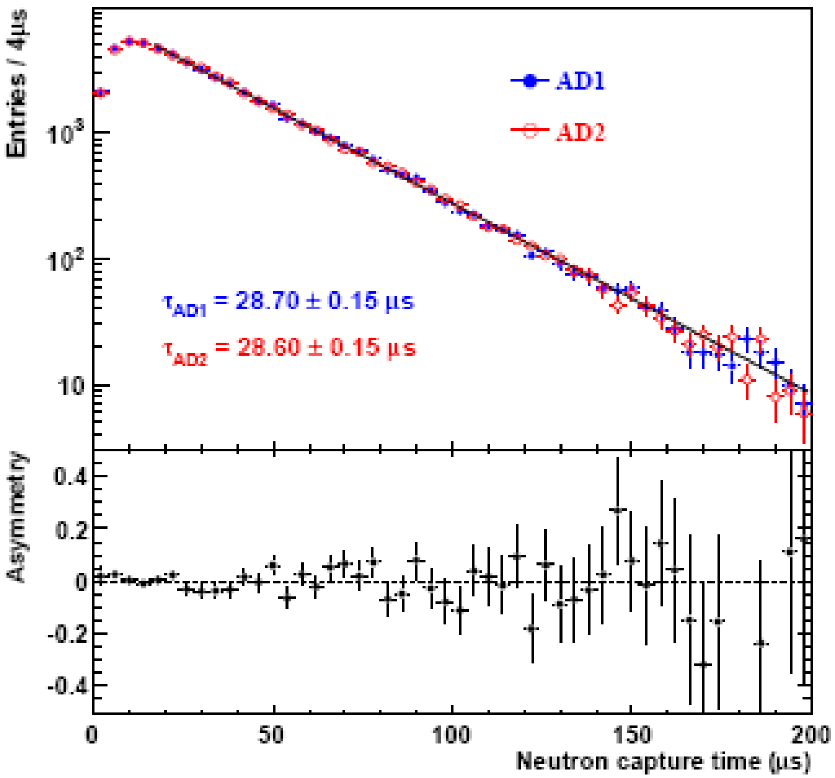


Capture time cut:

1μs to 200μs

Relative detector efficiency estimated within 0.01% by considering possible variations in Gd concentration.

Capture time in each detector constrains H/Gd capture ratio



Measurement of Am-C source neutron capture time distributions constrain uncertainty in relative H/Gd capture efficiency to < 0.1% between detectors.

Daya Bay Data Set Summary

~ four months

~200k near and ~30k far detector antineutrino interactions

	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±0.04	0.05±0.03	0.04±0.02	0.04±0.02	0.04±0.02
Antineutrino rate (/day)	**662.47 ±3.00**	**670.87 ±3.01**	**613.53 ±2.69**	**77.57 ±0.85**	**76.62 ±0.85**	**74.97 ±0.84**

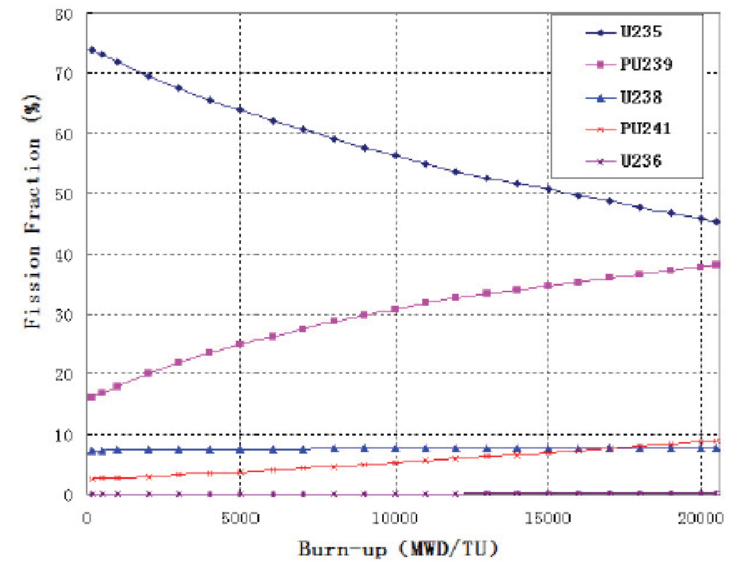
Uncertainty still dominated by statistics

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

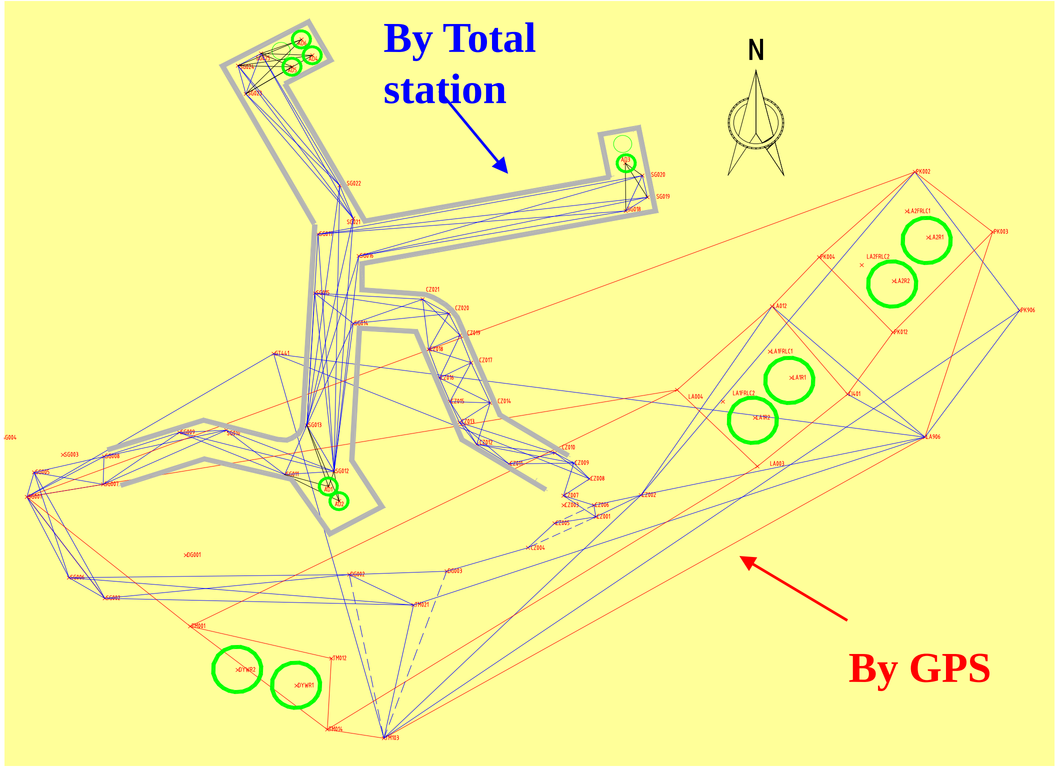
Reactor			
Correlated		Uncorrelated	
Energy/fission	0.2%	Power	0.5%
$\overline{\nu}_e$/fission	3%	Fission fraction	0.6%
		Spent fuel	0.3%
Combined	3%	Combined	0.8%

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

Relative measurement ➔ independent from the neutrino spectrum prediction

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 Summary

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%

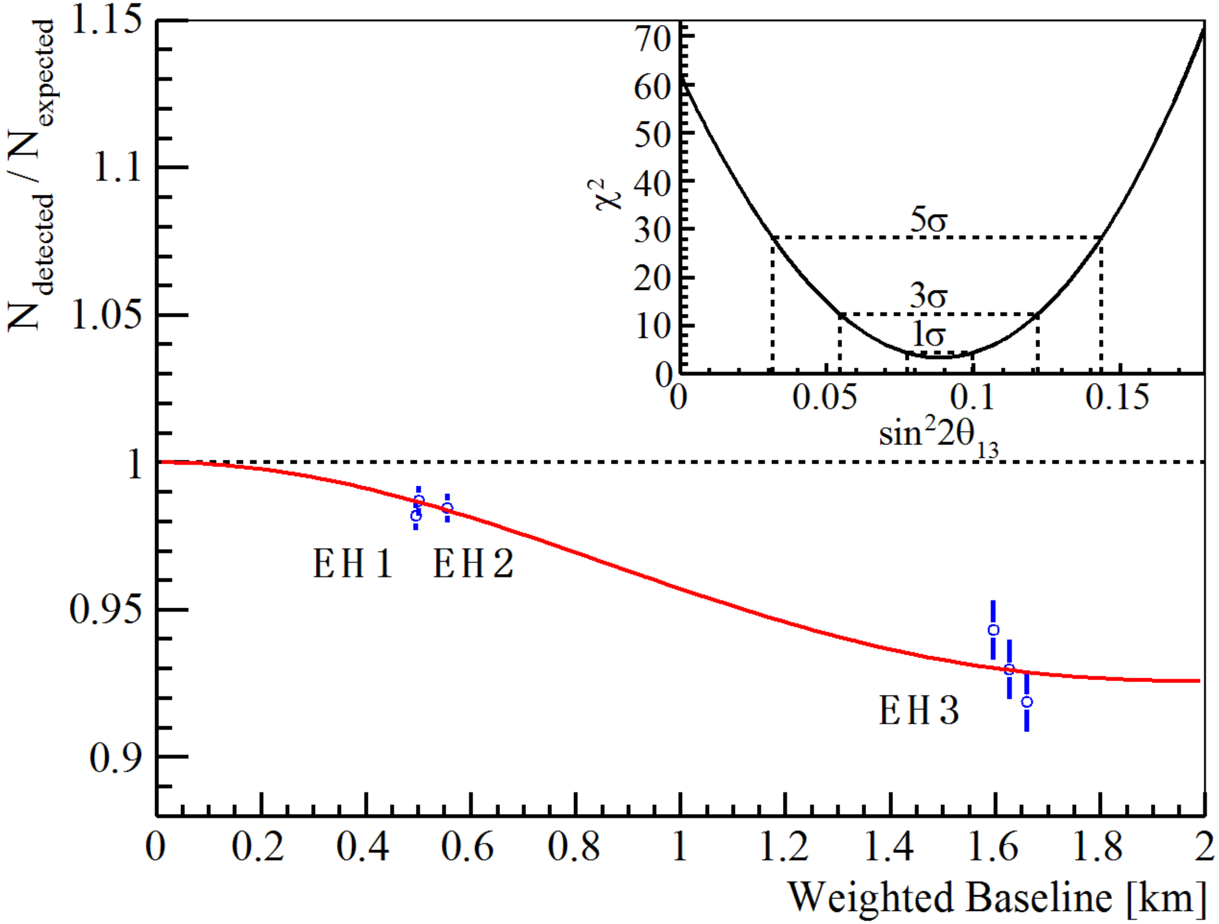
For near/far oscillation, only uncorrelated uncertainties are used.

Largest systematics are smaller than far site statistics (~1%)

Influence of uncorrelated reactor systematics (0.8%) is reduced to 0.04% detector systematics uncertainty by far vs near measurement.

Rate Only Oscillation Analysis

Estimate θ_{13} using measured rates in each detector.



Uses standard χ^2 approach.

Far vs. near relative measurement.

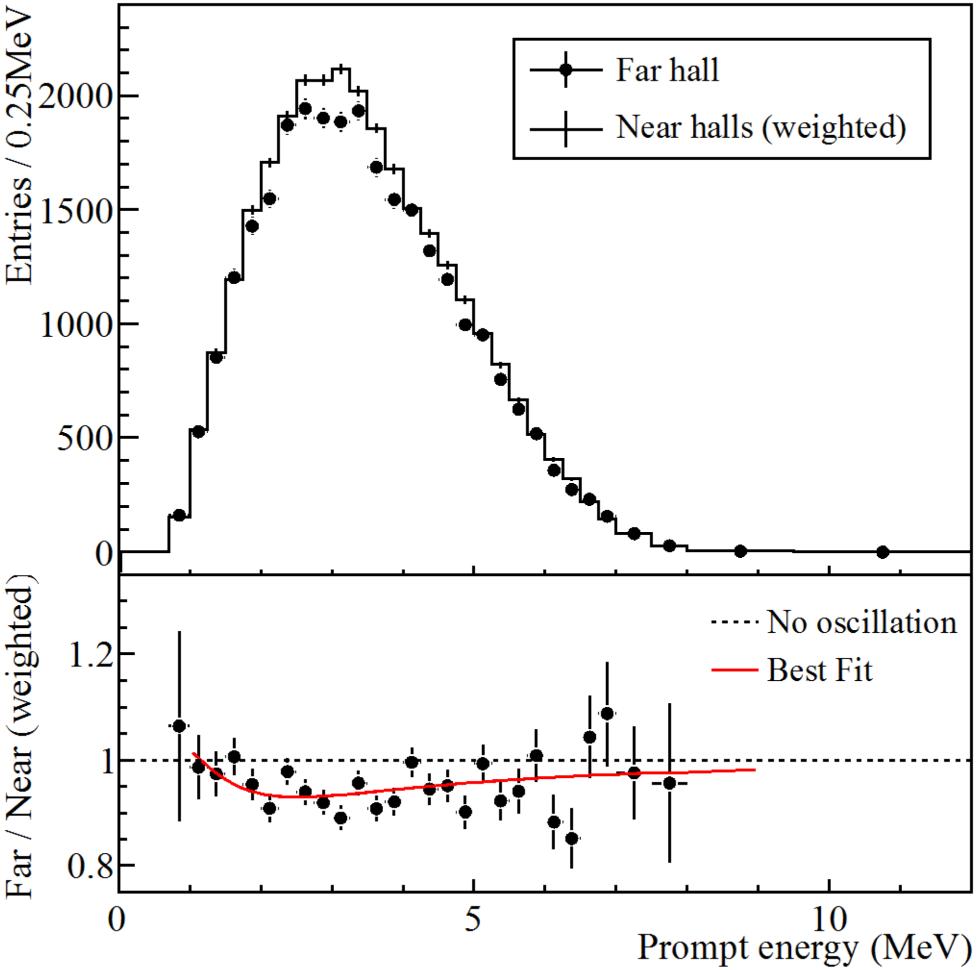
[Absolute rate is not constrained.]

Most precise measurement of $\sin^2 2\theta_{13}$ to date.

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

Spectrum Shape

Compare the far/near measured rates and spectra



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

M_n are the measured rates in each detector. Weights α_i,β_i are determined from baselines and reactor fluxes.

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

Clear observation of far site deficit.

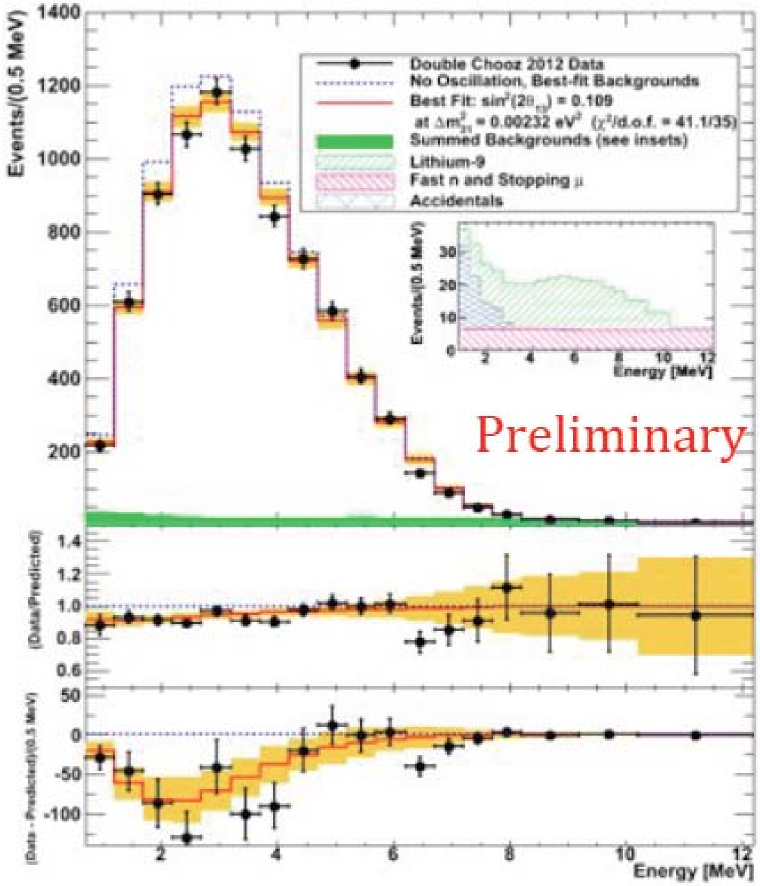
Spectral distortion consistent with oscillation.*

*** Caveat: Spectral systematics not fully studied; θ_{13} value from shape analysis is not recommended.**

Global θ_{13} Situation

Double Chooz update

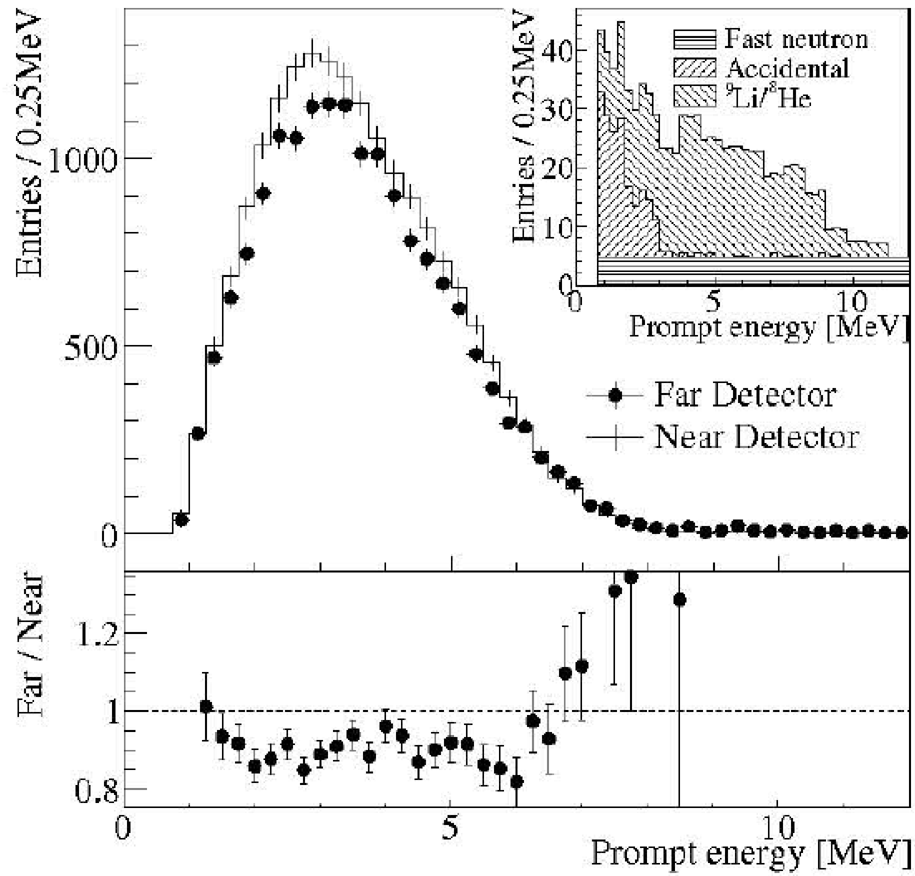
M. Ishitsuka Neutrino 2012



Rate only: $\sin^2 2\theta_{13} = 0.170 \pm 0.035(stat) \pm 0.040(syst)$

Rate+Shape: $\sin^2 2\theta_{13} = 0.109 \pm 0.030(stat) \pm 0.025(syst)$

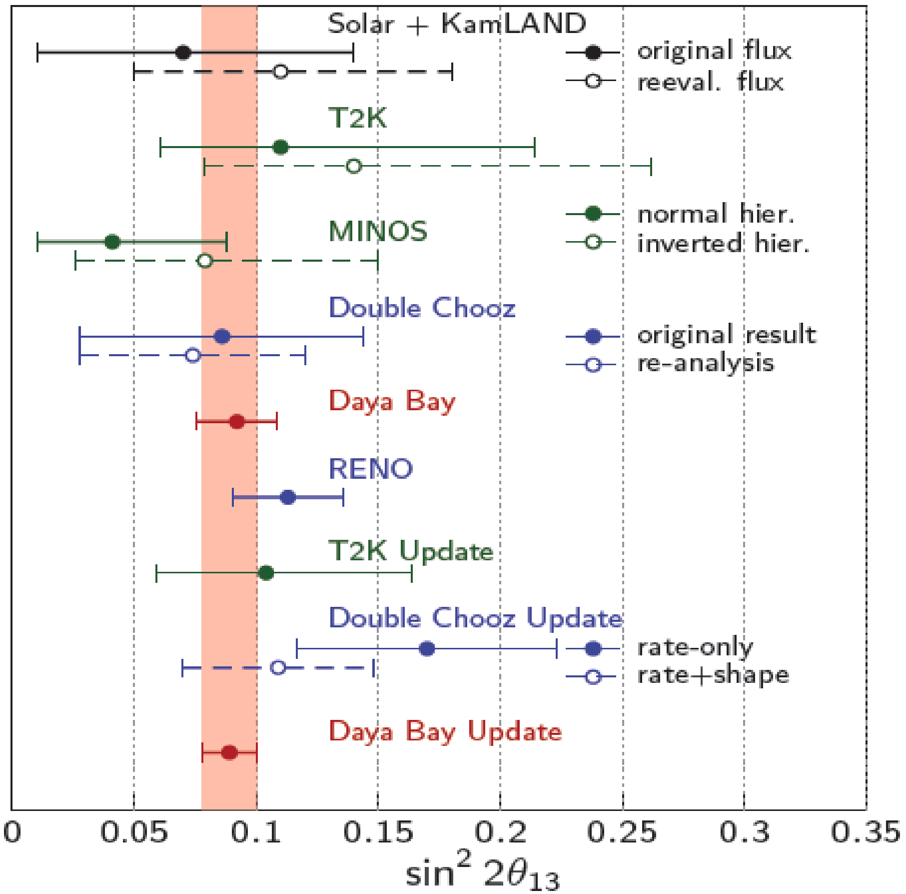
Reno



$$\sin^2 2\theta_{13} = 0.113 \pm 0.013(stat.) \pm 0.019(syst.)$$

World Measurement of θ_{13}

S.Jetter



Measurement of θ13 opens an exciting future.

Daya Bay Summary

Daya Bay has made an unambiguous observation of electron-antineutrino disappearance at ~2km and measured a far/near ratio of

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

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

Interpretation of disappearance as neutrino oscillation

rules out $\sin^2 2\theta_{13} = 0$ at 7.7σ

Daya Bay precision surpasses all existing measurements.

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

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

Last two detectors will be installed this year

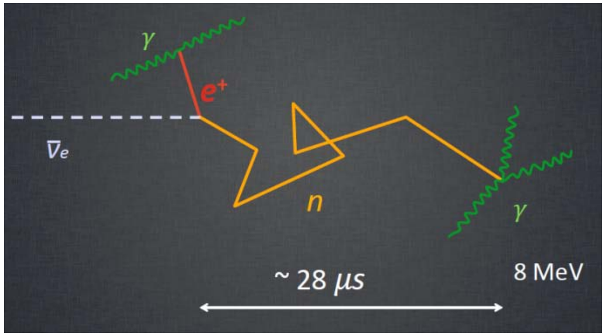
Expect more statistics and improvements in analysis.

Daya Bay will continue to have the best sensitivity to θ_{13} among all the other experiments in operation or in construction.

Backup

Event Signature and Backgrounds

- **Signature:** $\overline{\nu}_e + p \rightarrow e^+ + n$
  - ⇨ **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**



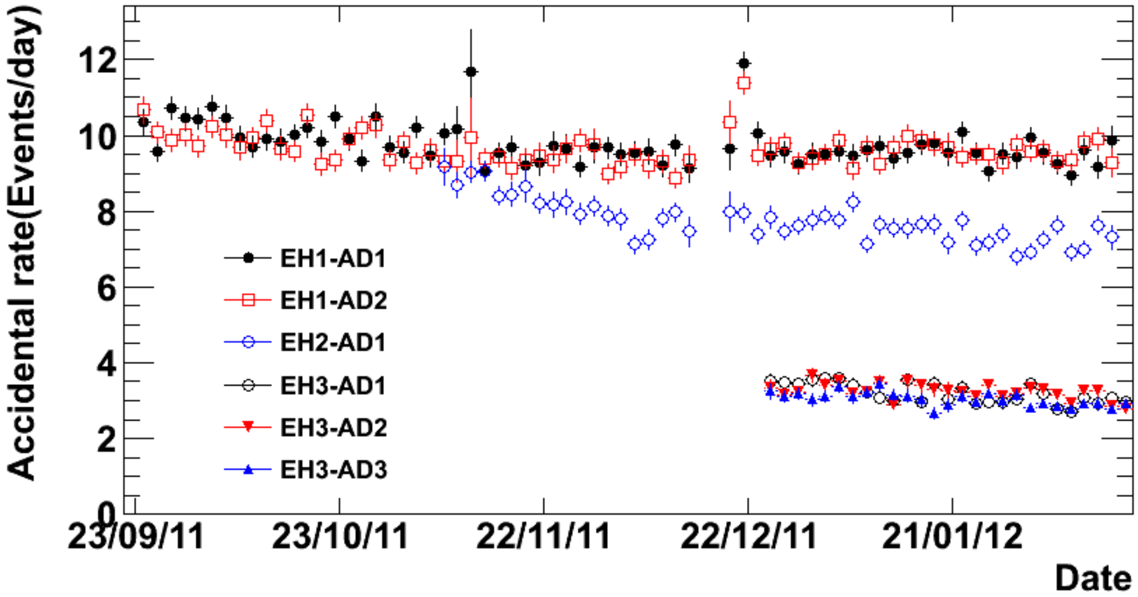
- **Backgrounds**
  - ⇨ **Uncorrelated: random coincidence of γγ, γn & nn**
    - ✓ **γ from U/Th/K/Rn/Co… in LS, SS, PMT, Rock, …**
    - ✓ **n from α-n, μ-capture, μ-spallation in LS, water & rock**
  - ⇨ **Correlated:**
    - ✓ **Fast neutrons: prompt—n scattering, delayed—n capture**
    - ✓ **8He/9Li: prompt—β decay, delayed—n capture**
    - ✓ **Am-C source: prompt—γ rays, delayed—n capture**
    - ✓ **α-n: $^{13}C(\alpha,n)^{16}O$**

Background: Accidentals

Accidentals: Two uncorrelated events 'accidentally' passing the cuts and mimic IBD event.

Rate and spectrum can be accurately predicted from singles data.

Multiple analyses/methods estimate consistent rates.



	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%

Background: Fast neutrons

Correlated events mimic IBD events

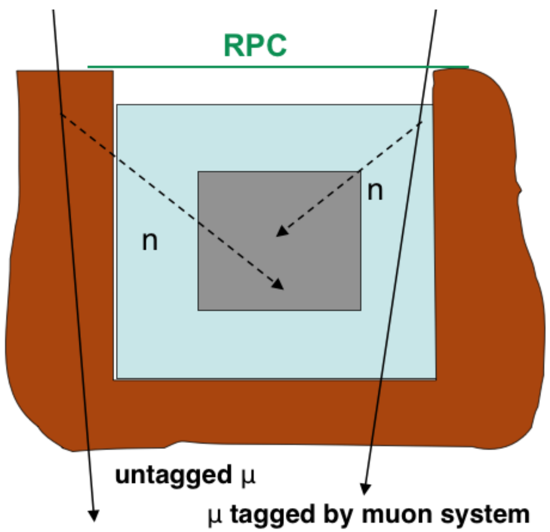
Fast Neutrons

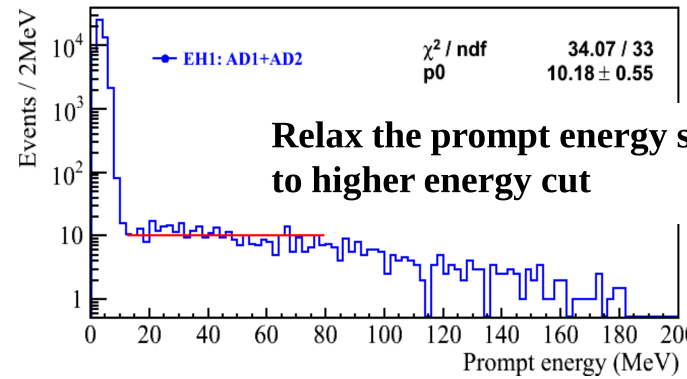
Energetic neutrons produced by cosmic rays (inside and outside of muon veto system)

Mimics antineutrino (IBD) signal

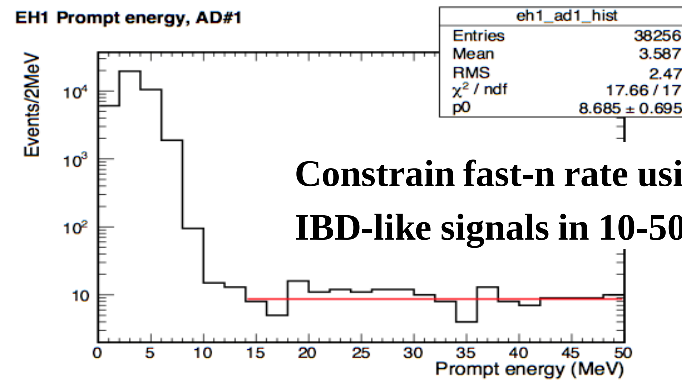
Prompt: Neutron collides/stops in target

Delayed: Neutron captures on Gd

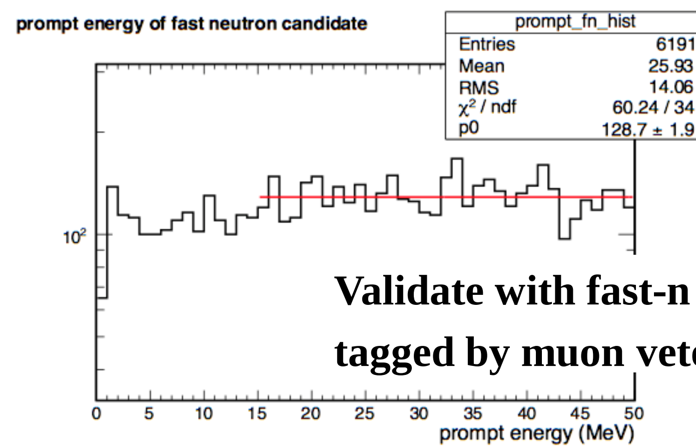




Relax the prompt energy spectrum to higher energy cut



Constrain fast-n rate using IBD-like signals in 10-50 MeV



Validate with fast-n events tagged by muon veto.

Projected errors - assuming 1/√N– rate only