

Observation of Reactor Antineutrino Disappearance at RENO

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KNRC, Seoul National University

(presented at Fermilab on April 11, 2012)



Outline

- Introduction
- Experimental setup & detector
- Data-taking & data set
- Calibration
- Event selection
- Efficiency & Background
- Reactor antineutrino prediction
- Systematic uncertainties
- Results
- Summary

Fermilab Today Friday, April 6, 2012

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Calendar

[Have a safe day!](#)

Friday, April 6
3:30 p.m.
DIRECTOR'S COFFEE
BREAK - 2nd Flr X-Over
4 p.m.
[Joint Experiment
Theoretical Physics
Seminar](#) - One West
Speaker: Brendan Kiburg,
University of Washington
Title: Muon Capture on
the Proton: Final Results
from the MuCap
Experiment

Monday, April 9
THERE WILL BE NO
PARTICLE
ASTROPHYSICS

From symmetry breaking

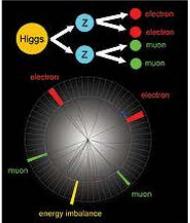
Korean experiment confirms groundbreaking neutrino measurement



Hot on the heels of the Daya Bay experiment's completion of one of the most difficult measurements in neutrino physics, a Korean experiment has produced its own measurement confirming the earlier results.

Physics in a Nutshell

Subatomic CSI



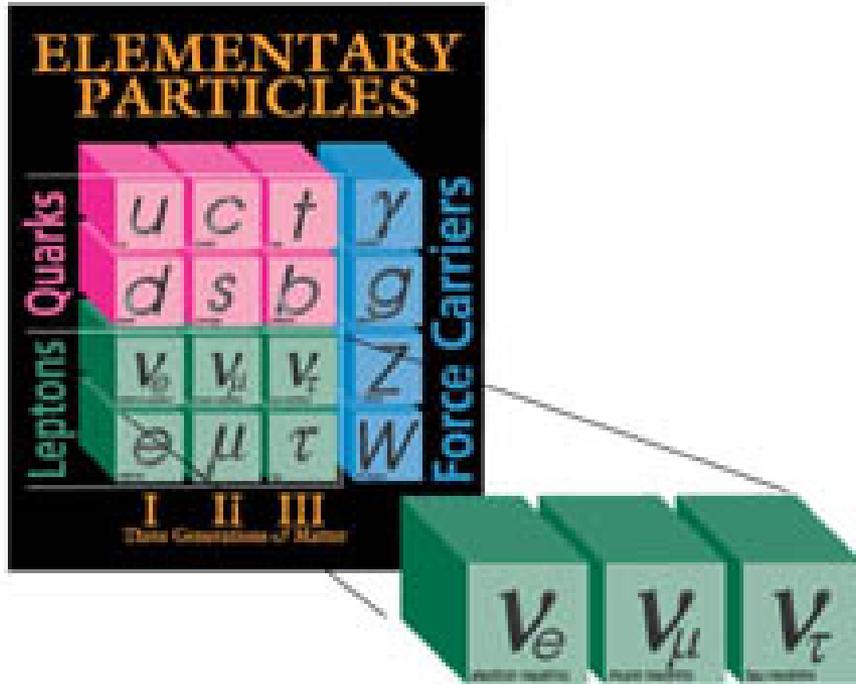
This 0Z0 event is not thought to have come from a Higgs boson, but an event in which a Higgs boson decayed into a pair of Z bosons would look very similar.

If we find the Higgs boson, we won't

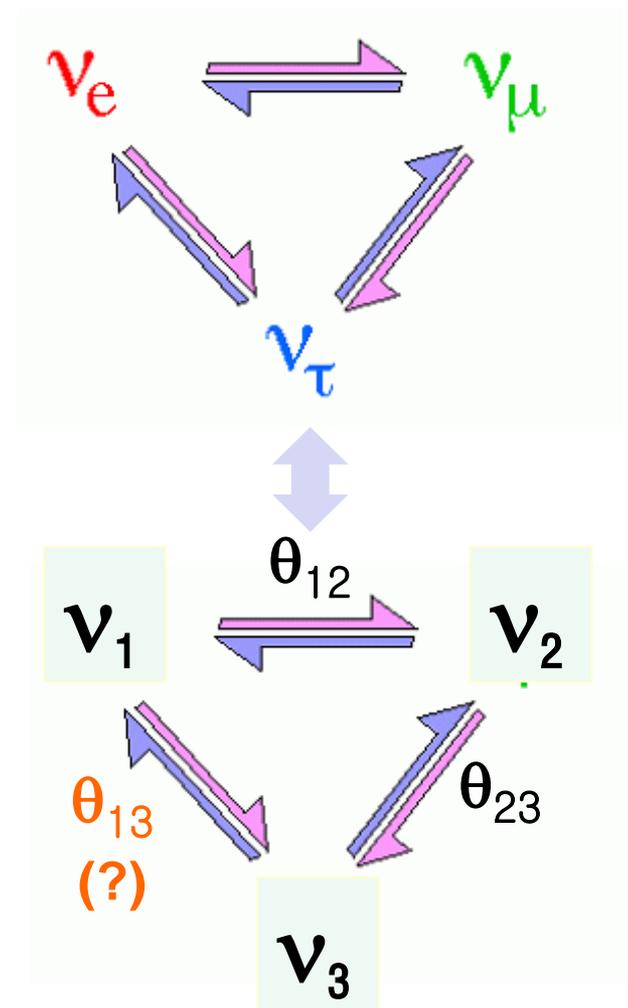
YongGwang (靈光) :



Neutrino Oscillation



PMNS Neutrino Mixing Angles and CP Violation



Reactor Antineutrino Oscillation

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2 \left(\frac{1.27 \Delta m_{31}^2 L}{E_\nu} \right)$$

Past Efforts for Finding θ_{13}

- Chooz (2003) & Palo Verde (2000): No signal

$$\sin^2(2\theta_{13}) < 0.12 \text{ at 90\% C.L.}$$

- T2K : 2.5 σ excess (2011)

$$0.03 < \sin^2(2\theta_{13}) < 0.28 \text{ at 90\% C.L. for N.H.}$$

$$0.04 < \sin^2(2\theta_{13}) < 0.34 \text{ at 90\% C.L. for I.H.}$$

- MINOS : 1.7 σ excess (2011)

$$0 < \sin^2(2\theta_{13}) < 0.12 \text{ at 90\% C.L. for N.H.}$$

$$0.04 < \sin^2(2\theta_{13}) < 0.19 \text{ at 90\% C.L. for I.H.}$$

- Double Chooz : 1.7 σ measurement (2011)

$$\sin^2(2\theta_{13}) = 0.086 \pm 0.041(\text{stat.}) \pm 0.030(\text{syst.})$$

- Daya Bay (03. 08. 2012)

5.2 σ observation

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

March Madness to RENO

- After unexpected Daya Bay's releasing result on March 8th, our entire schedule was changed.....
- The RENO was the first reactor neutrino experiments to search for θ_{13} with both near & far detectors running, from the early August 2011.
- The RENO started to see a signal of reactor neutrino disappearance from the late 2011.
- According to reported schedules of the other experiments, RENO was thought to present a result first soon. We planned to publish our first results in April without a hurry and to present them in the Neutrino 2012.

RENO Collaboration



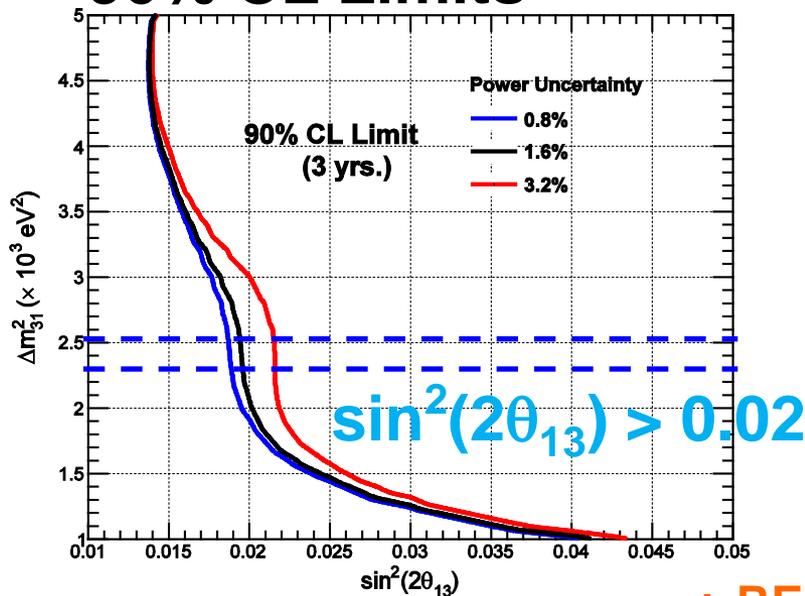
- (12 institutions and 40 physicists)
 - Chonbuk National University
 - Chonnam National University
 - Chung-Ang University
 - Dongshin University
 - Gyeongsang National University
 - Kyungpook National University
 - Pusan National University
 - Sejong University
 - Seokyeong University
 - Seoul National University
 - Seoyeong University
 - Sungkyunkwan University
- Total cost : \$10M
 - Start of project : 2006
 - The first experiment running with both near & far detectors from Aug. 2011



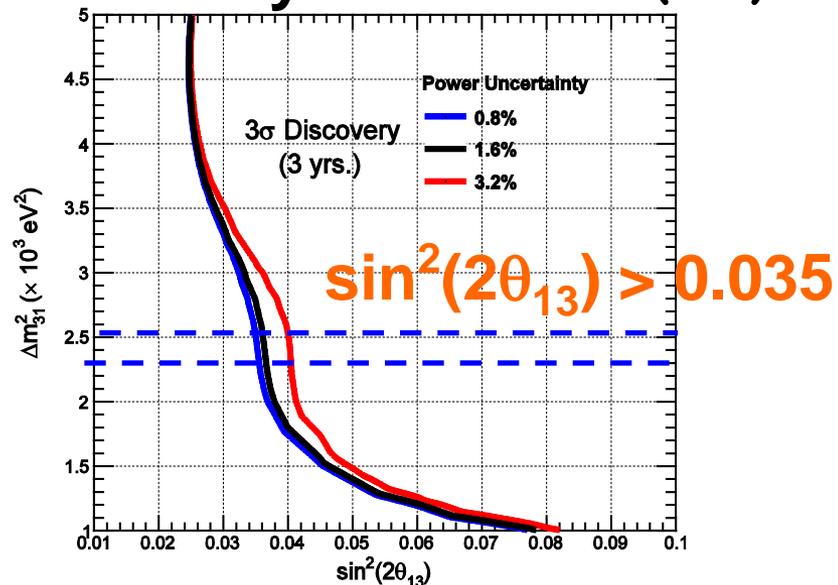
서울대 김수봉 교수가 이끄는 RENO 실험팀. 30여년간 관측에 실패한 마지막 중성미자 변환상수를 밝히기 위해 프랑스 중국과 치열한 경주를 벌이고 있다.

RENO Expected Sensitivity

90% CL Limits

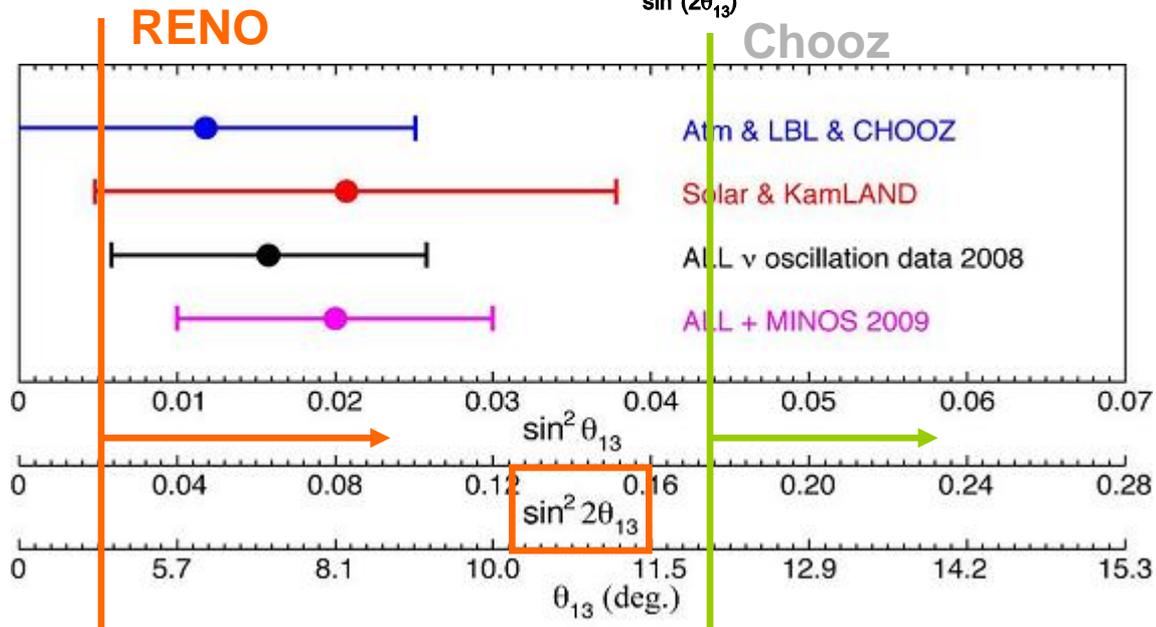


Discovery Potential" (3σ)

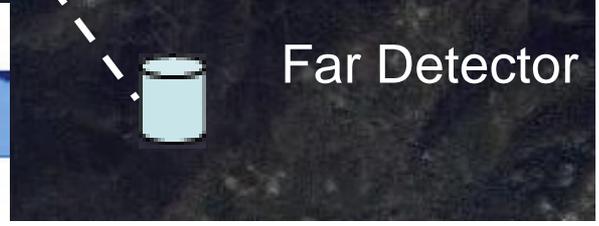
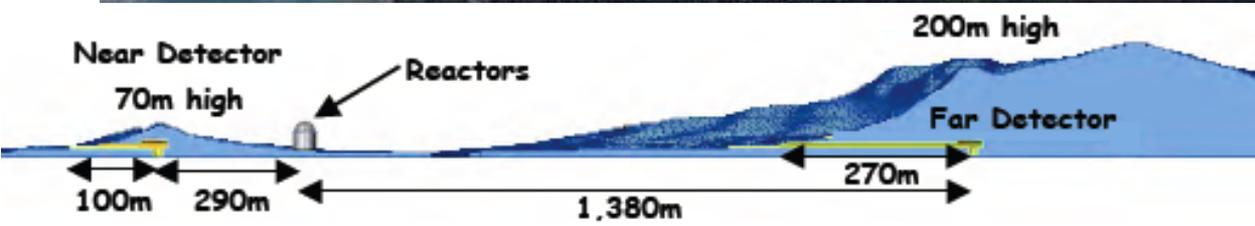
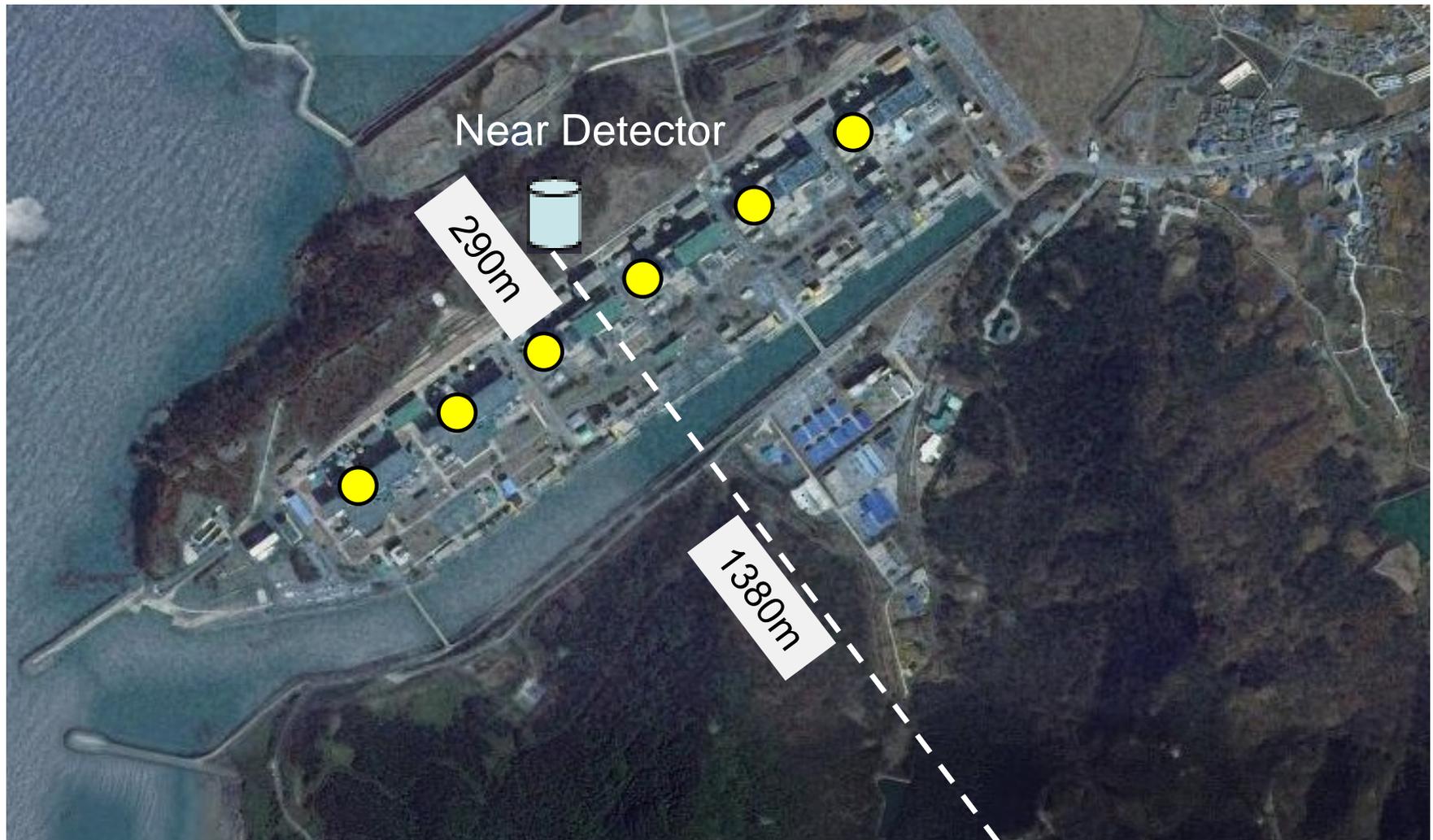


- 10 times better sensitivity than the current limit

G. Fogli *et al.*
(2009)



RENO Experimental Setup

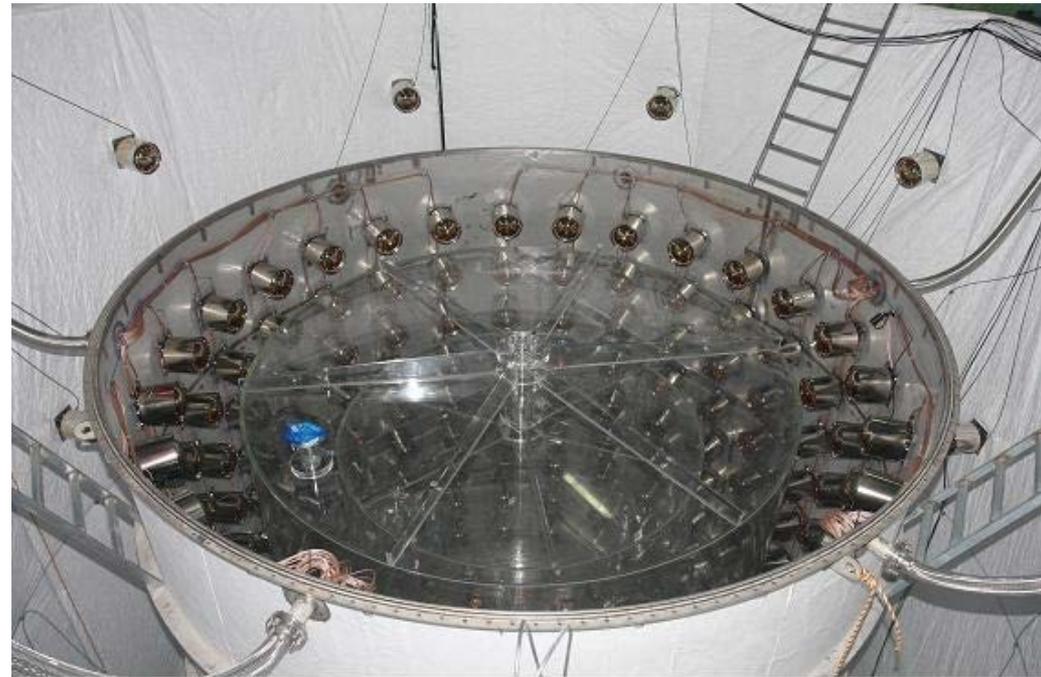
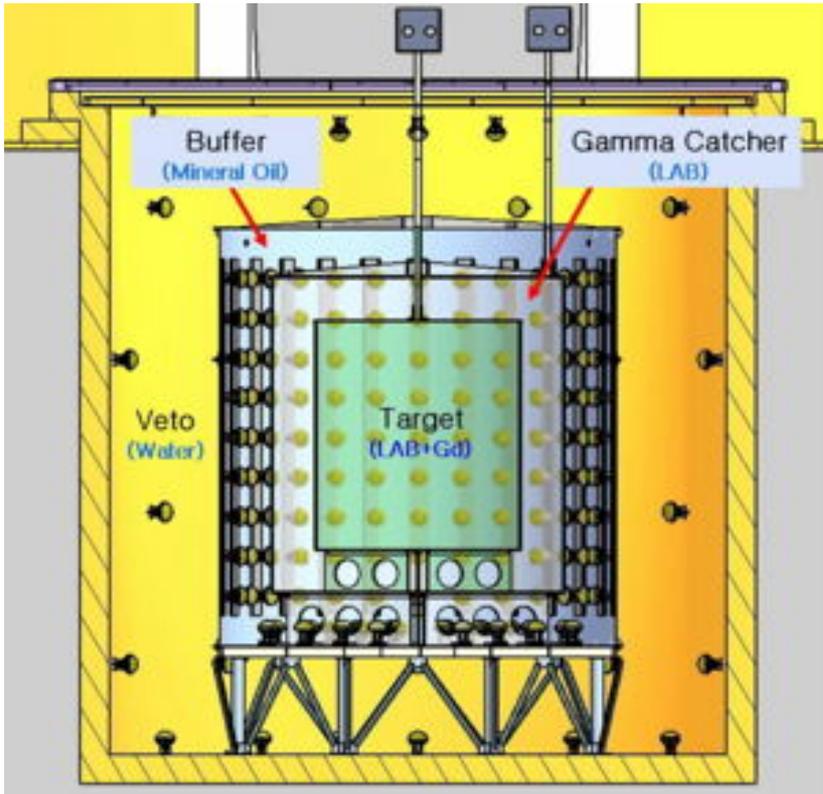


Contribution of Reactor to Neutrino Flux at Near & Far Detectors

Reactor #	Far (%)	Near (%)
1	13.73	6.78
2	15.74	14.93
3	18.09	34.19
4	18.56	27.01
5	17.80	11.50
6	16.08	5.58

- Accurate measurement of baseline distances to a precision of 10 cm using GPS and total station
- Accurate determination of reduction in the reactor neutrino fluxes after a baseline distance, much better than 0.1%

RENO Detector



- 354 ID +67 OD 10" PMTs
- Target : 16.5 ton Gd-LS, R=1.4m, H=3.2m
- Gamma Catcher : 30 ton LS, R=2.0m, H=4.4m
- Buffer : 65 ton mineral oil, R=2.7m, H=5.8m
- Veto : 350 ton water, R=4.2m, H=8.8m



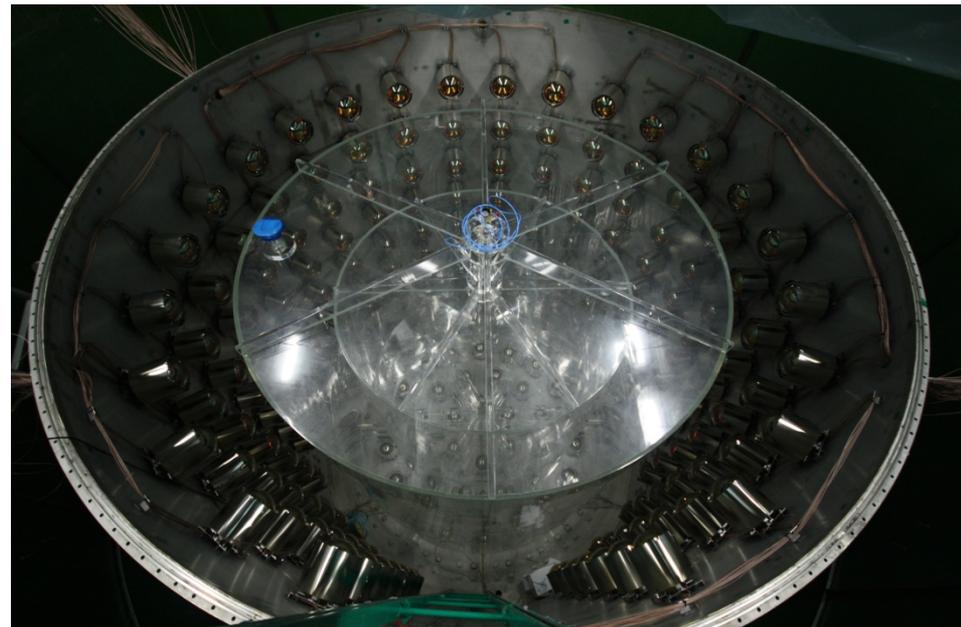
Summary of Detector Construction

- 2006. 03 : Start of the RENO project
- 2008. 06 ~ 2009. 03 : Civil construction including tunnel excavation
- 2008. 12 ~ 2009. 11 : Detector structure & buffer steel tanks completed
- 2010. 06 : Acrylic containers installed
- 2010. 06 ~ 2010. 12 : PMT test & installation
- 2011. 01 : Detector closing/ Electronics hut & control room built
- 2011. 02 : Installation of DAQ electronics and HV & cabling
- 2011. 03 ~ 06 : Dry run & DAQ debugging
- 2011. 05 ~ 07 : Liquid scintillator production & filling
- 2011. 07 : Detector operation & commissioning
- 2011. 08 : Start data-taking

PMT Mounting (2010. 8~10)



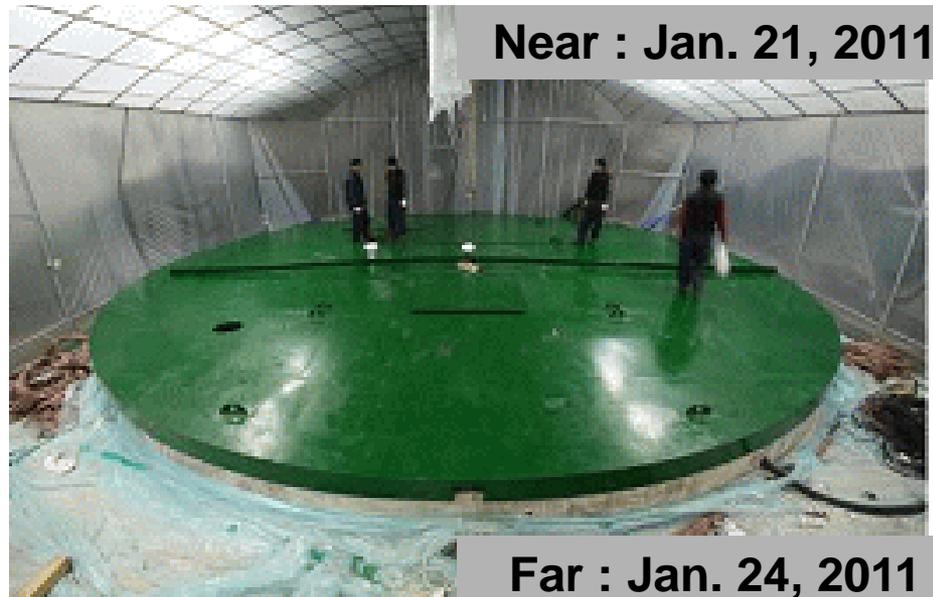
PMT Mounting (2010. 8~10)



Detector Closing (2011. 1)

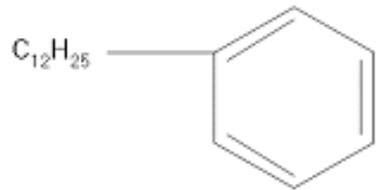
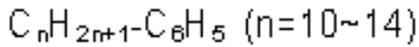


Near : Jan. 21, 2011

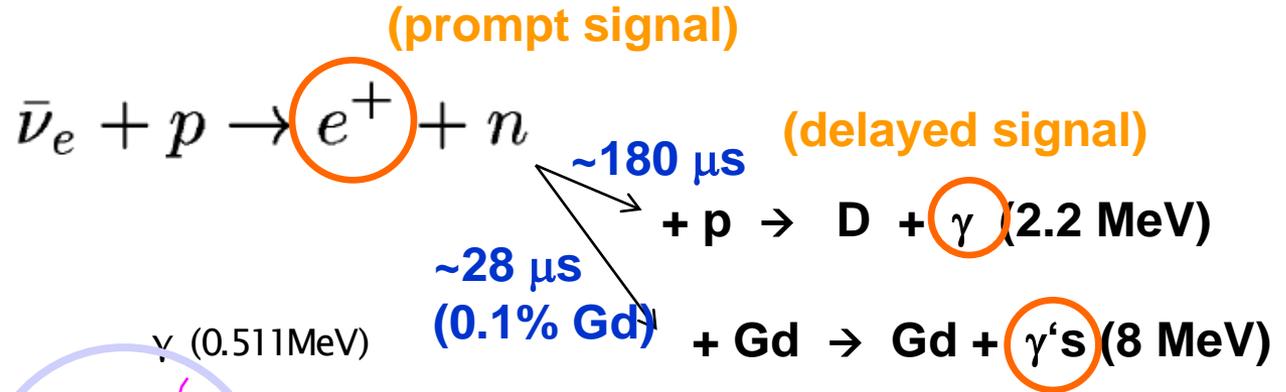


Far : Jan. 24, 2011

Detection of Reactor Antineutrinos



Linear Alkyl Benzene (LAB)

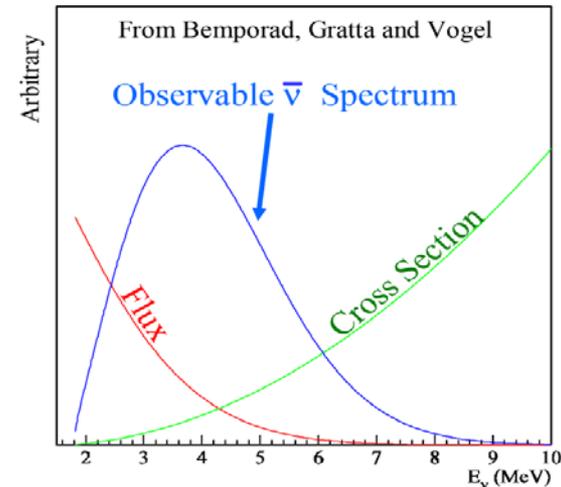
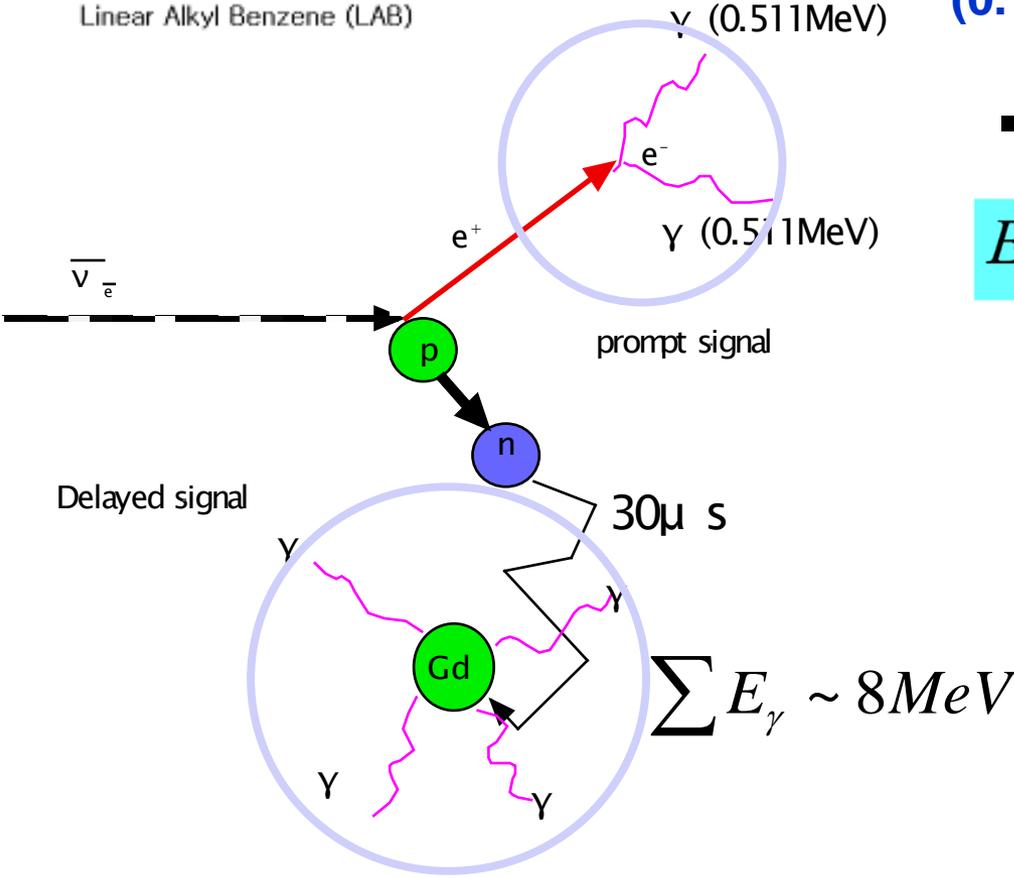


▪ Neutrino energy measurement

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

10-40 keV

1.8 MeV

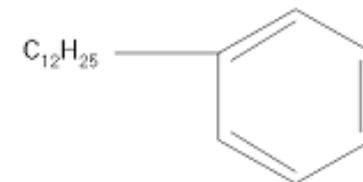
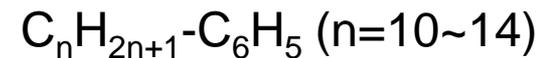


Gd Loaded Liquid Scintillator

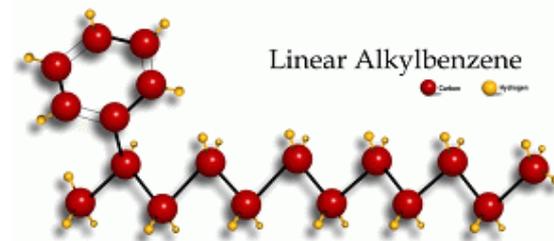
□ Recipe of Liquid Scintillator

Aromatic Solvent & Flour	WLS	Gd-compound
LAB	PPO + Bis-MSB	0.1% Gd+(TMHA) ³ (trimethylhexanoic acid)

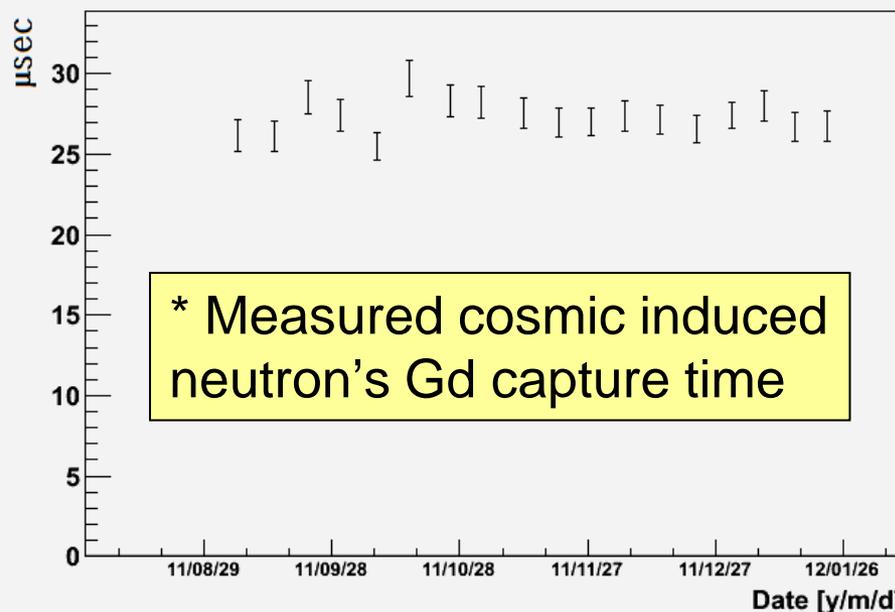
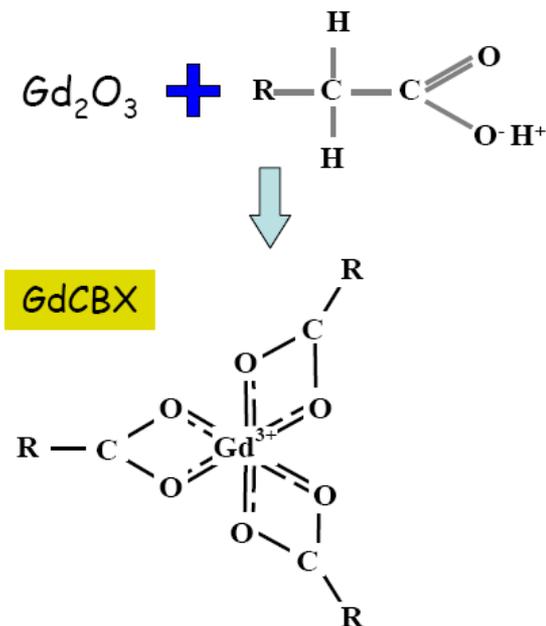
* Stable light yield over the time period : ~250 pe/MeV



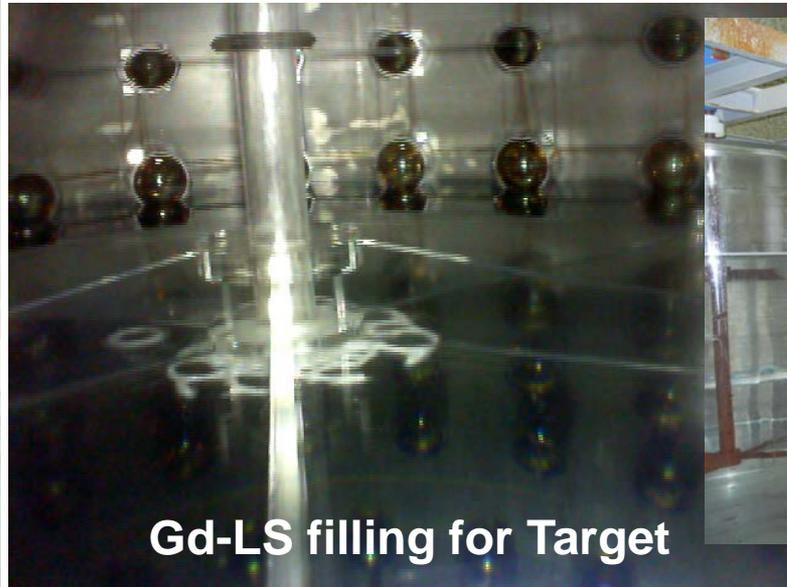
Linear Alkyl Benzene (LAB)



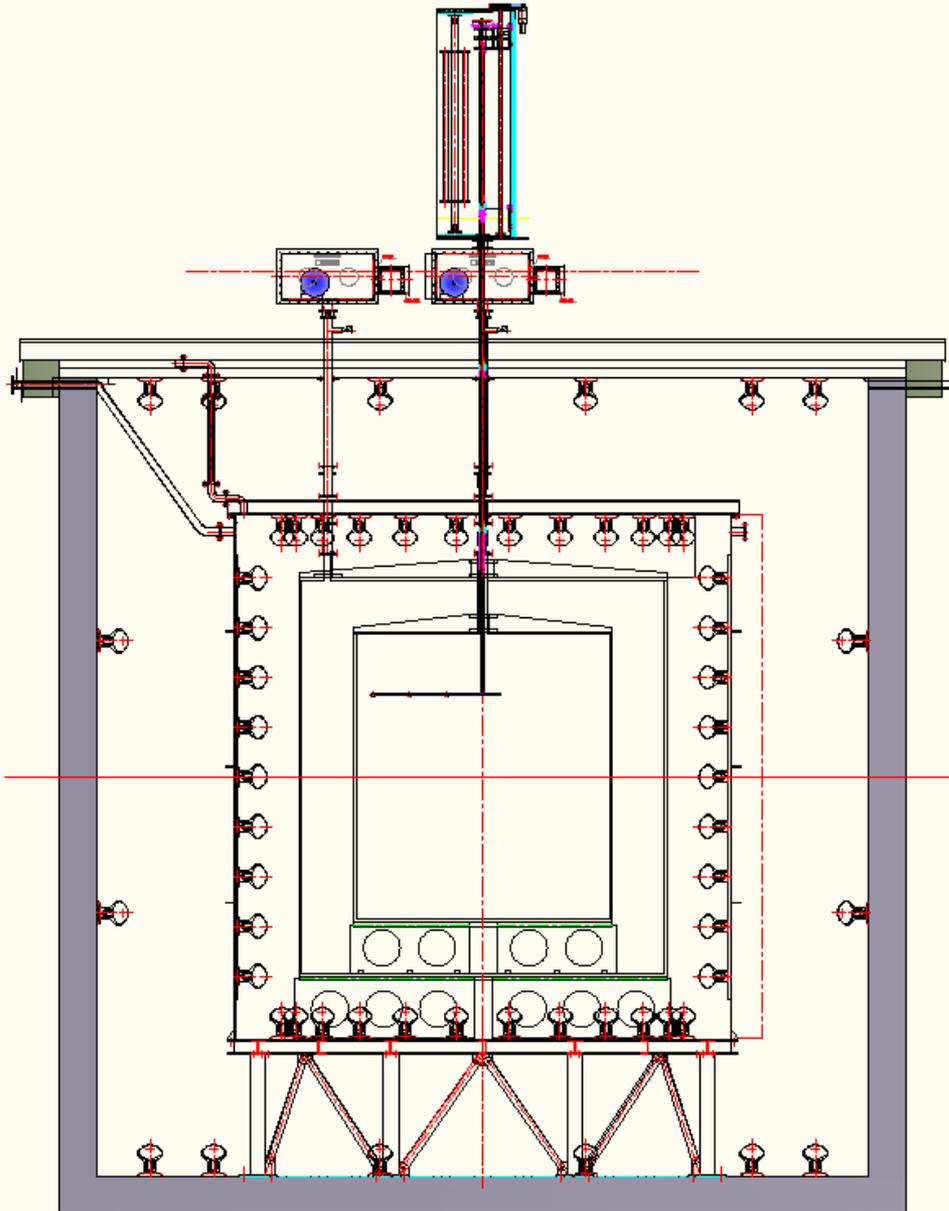
Carboxylic acids



Liquid(Gd-LS/LS/MO/Water) Production & Filling (May-July 2011)

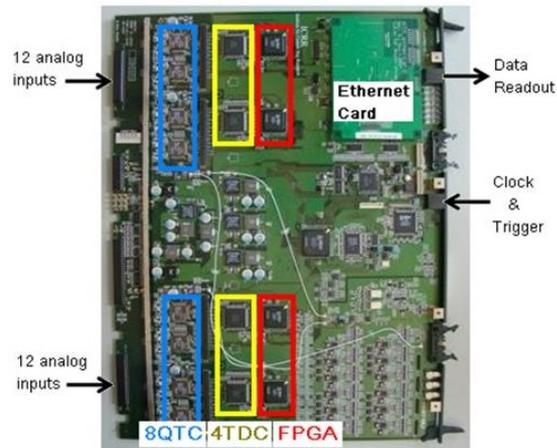


1D/3D Calibration System

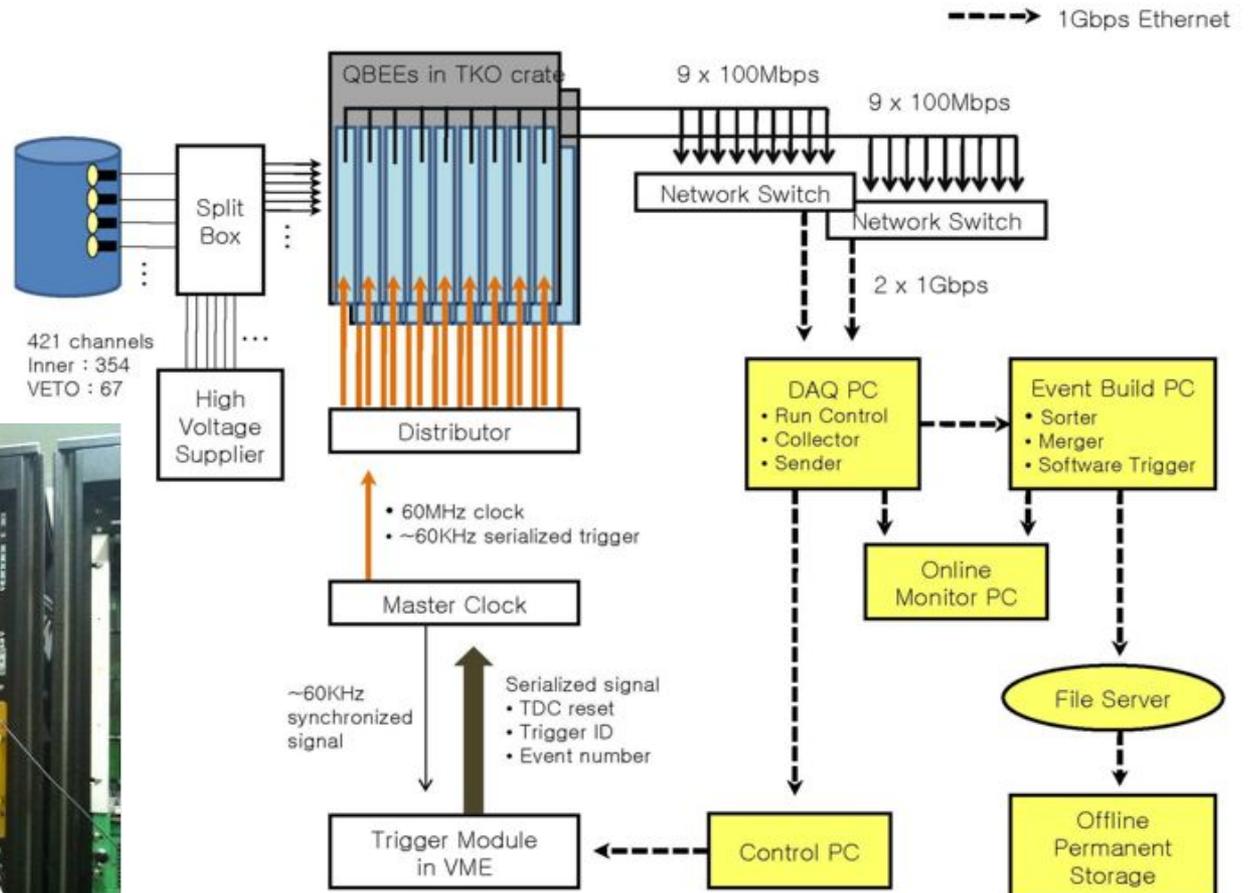


- ❑ Calibration system to deploy radioactive sources in 1D & 3D directions
- ❑ Radioactive sources :
 ^{137}Cs , ^{68}Ge , ^{60}Co , ^{252}Cf
- ❑ Laser injectors

Data Acquisition System



- 24 channel PMT input to ADC/TDC
- 0.1pC, 0.52nsec resolution
- ~2500pC/ch large dynamic range
- No dead time (w/o hardware trigger)
- Fast data transfer via Ethernet R/W



Data-Taking & Data Set

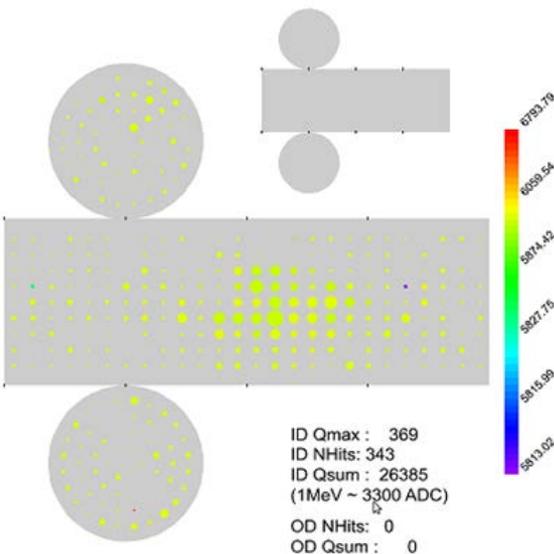
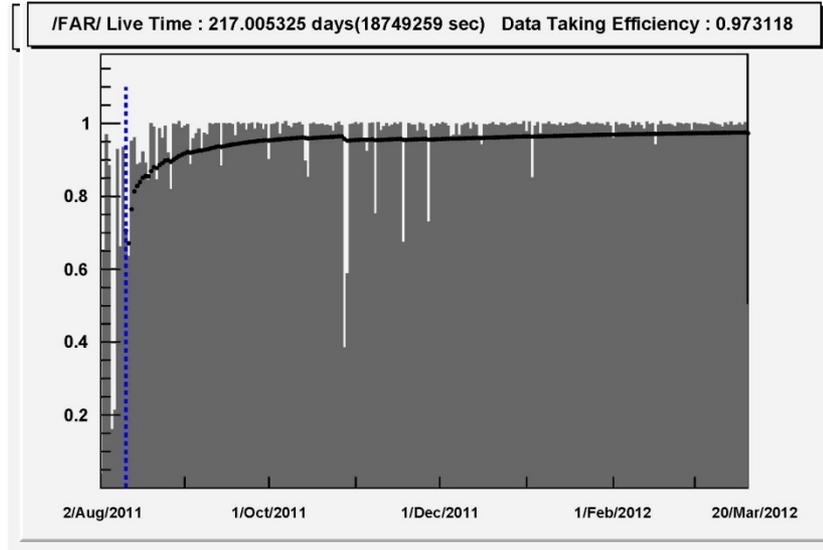
- Data taking began on Aug. 1, 2011 with both near and far detectors.

- Data-taking efficiency > 90%.

- Trigger rate at the threshold energy of 0.5~0.6 MeV : 80 Hz

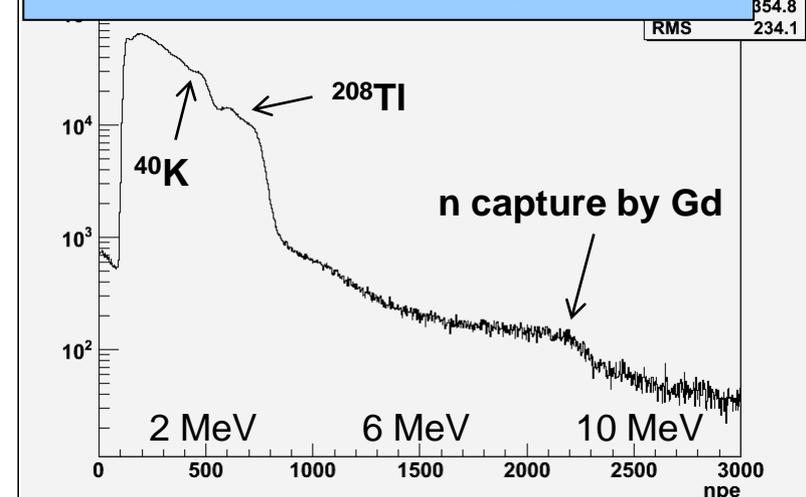
- Data-taking period : 228 days
Aug. 11, 2011 ~ Mar. 25, 2012

▪ Data-taking efficiency



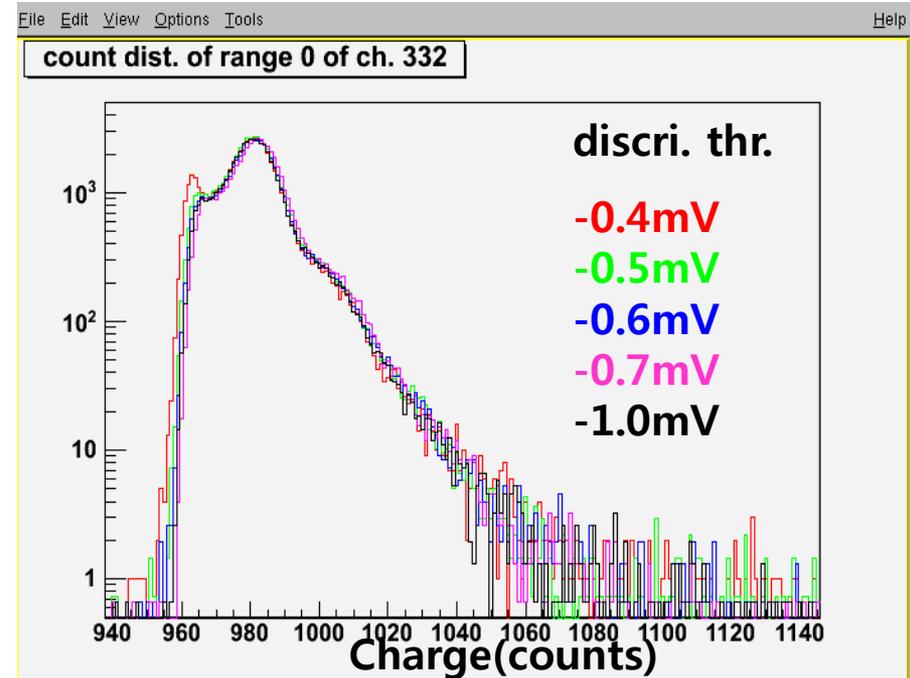
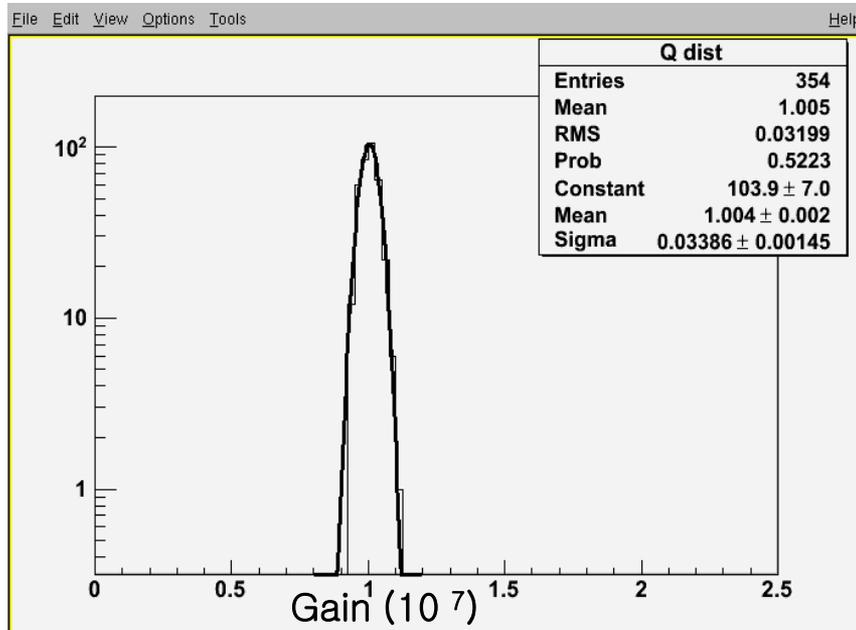
A candidate for a neutron capture by Gd

Event rate before reduction



PMT Threshold & Gain Matching

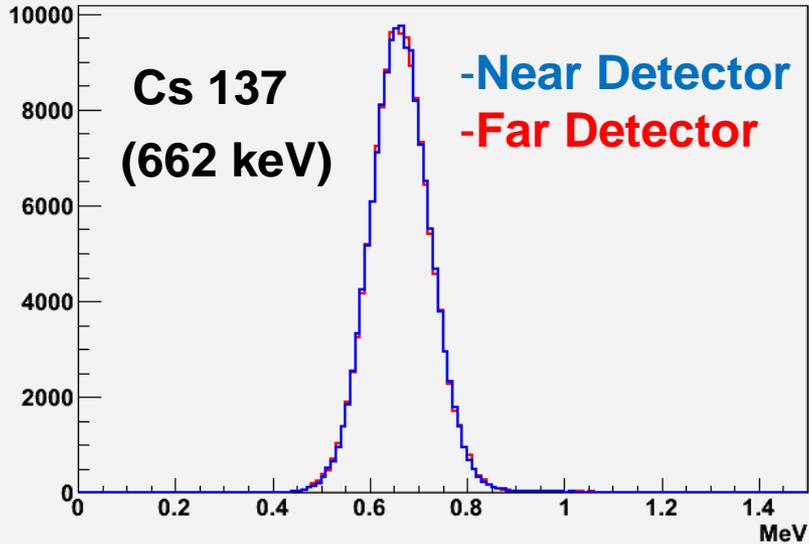
- PMT gain : set 1.0×10^7 using a Cs source at center
- Gain variation among PMTs : 3% for both detectors.



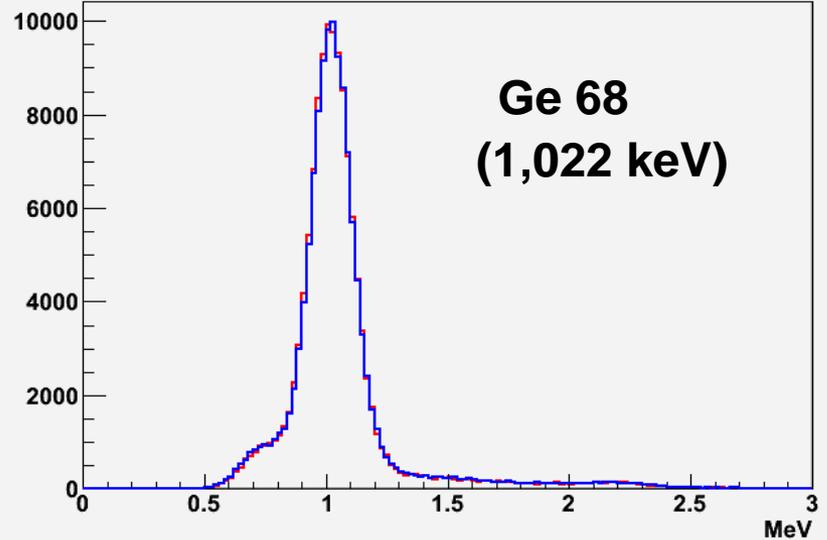
- PMT threshold : determined by a single photoelectron response using a Cs source at the center

Energy Calibration

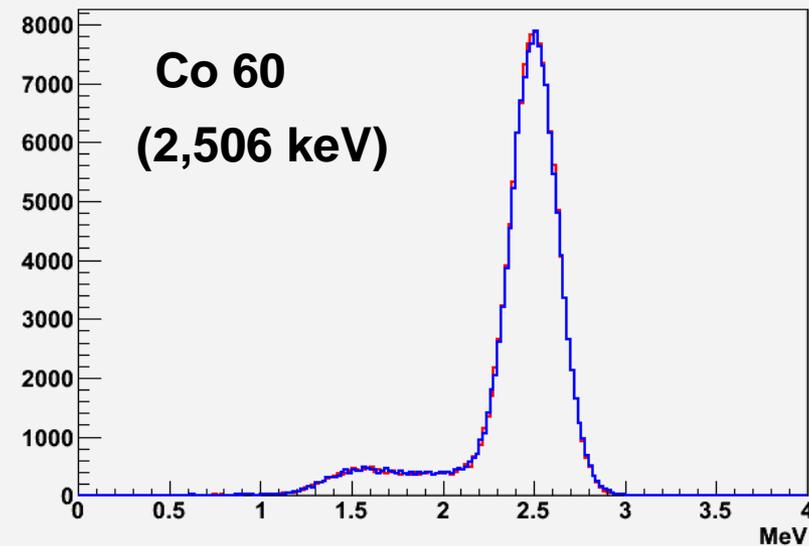
Energy Distribution(Cs)



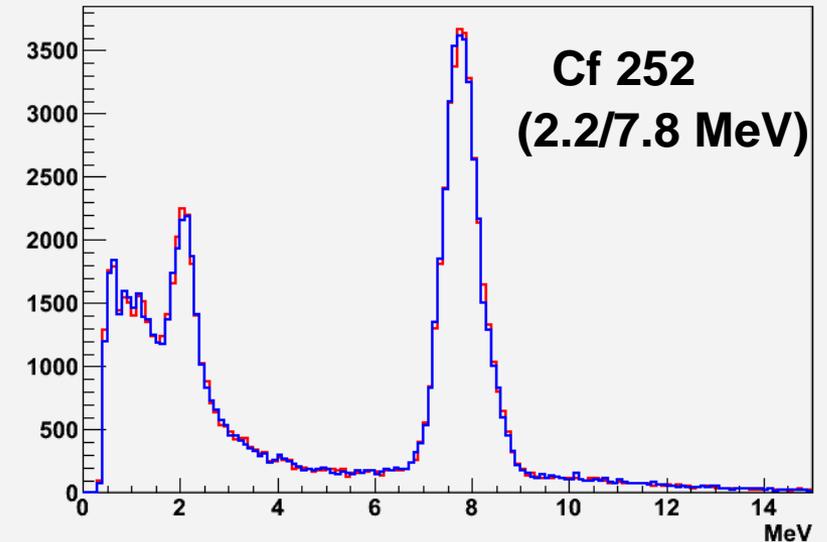
Energy Distribution(Ge)



Energy Distribution(Co)

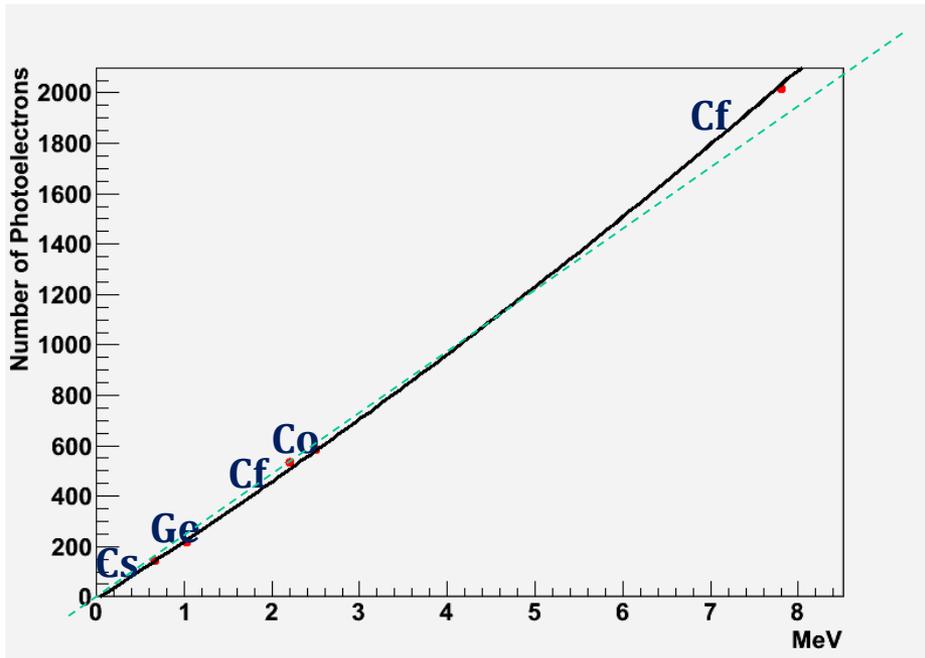


Energy Distribution(Cf)

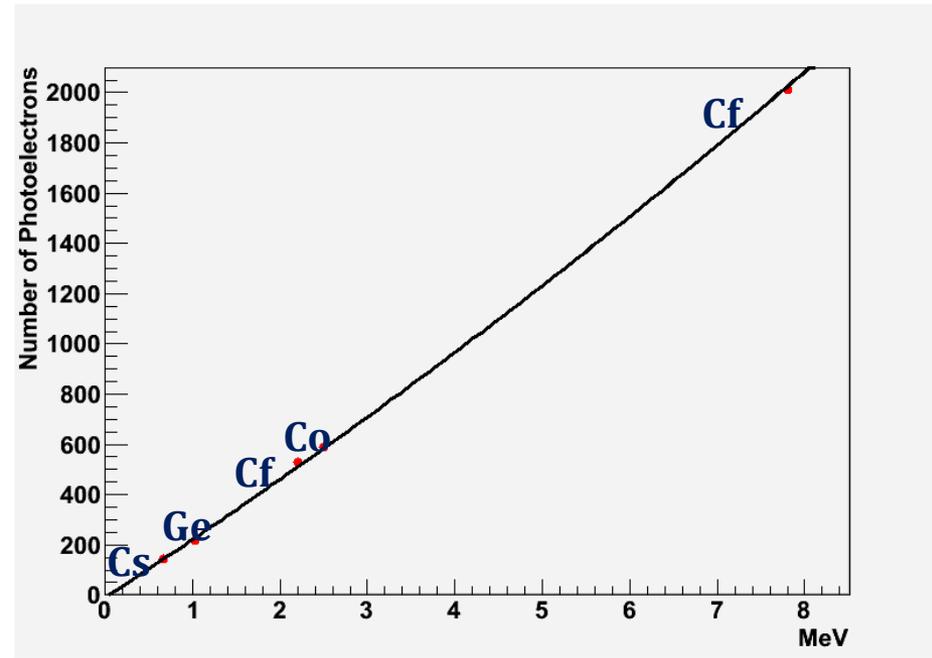


Energy Scale Calibration

Near Detector



Far Detector

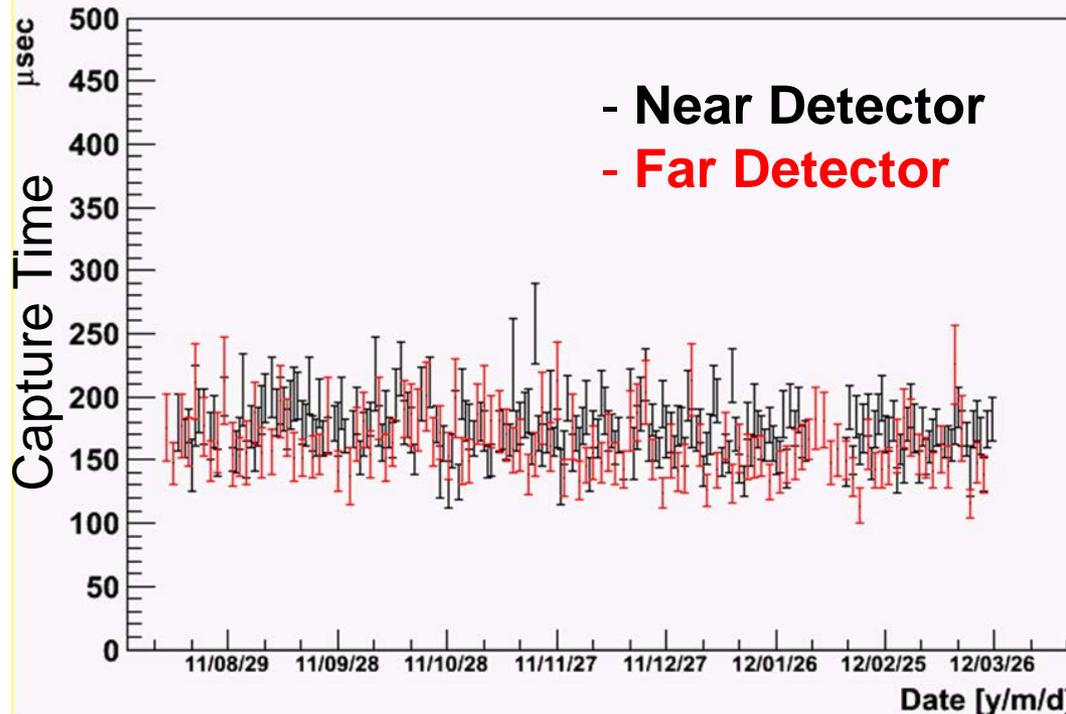


$$\delta E = \frac{5.9\%}{\sqrt{E(\text{MeV})}} + 1.1\%$$

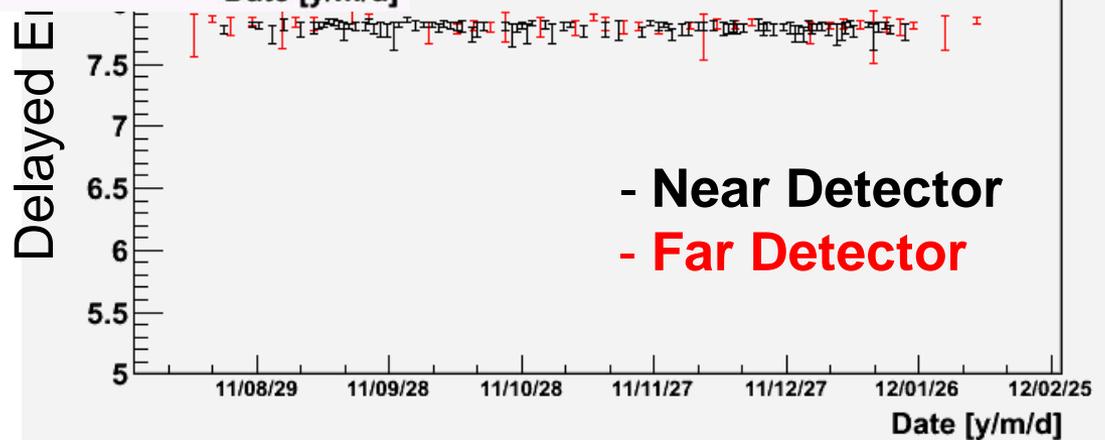
- ~ 250 pe/MeV (sources at center)
- Identical energy response (< 0.1%) of ND & FD
- Slight non-linearity observed

Detector Stability & Identity

- Cosmic muon induced neutron's capture by H

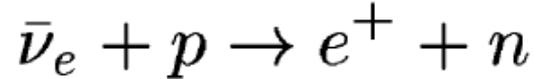


delayed signals (capture on Gd)

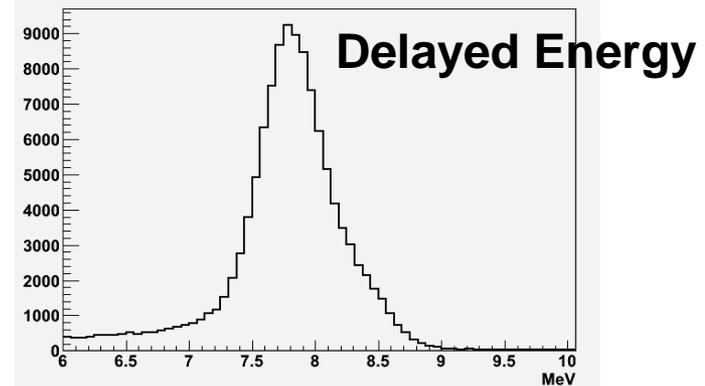
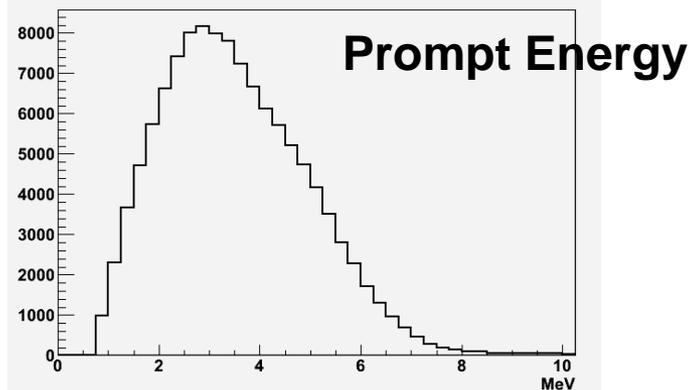


IBD Event Signature and Backgrounds

IBD Event Signature



- Prompt signal (e^+) : 1 MeV 2γ 's + e^+ kinetic energy ($E = 1\sim 10$ MeV)
- Delayed signal (n) : 8 MeV γ 's from neutron's capture by Gd
 $\sim 28 \mu\text{s}$ (0.1% Gd) in LS



Backgrounds

- Random coincidence between prompt and delayed signals (uncorrelated)
- ${}^9\text{Li}/{}^8\text{He}$ β -n followers produced by cosmic muon spallation
- Fast neutrons produced by muons, from surrounding rocks and inside detector (n scattering : prompt, n capture : delayed)

IBD Event Selection

- ❑ **Reject flashers and external gamma rays** : $Q_{\max}/Q_{\text{tot}} < 0.03$
- ❑ **Muon veto cuts** : reject events after the following muons
 - (1) 1 ms after an ID muon with $E > 70$ MeV, or with $20 < E < 70$ MeV and OD NHIT > 50
 - (2) 10 ms after an ID muon with $E > 1.5$ GeV
- ❑ **Coincidence** between prompt and delayed signals in $100 \mu\text{s}$
 - $E_{\text{prompt}} : 0.7 \sim 12.0$ MeV, $E_{\text{delayed}} : 6.0 \sim 12.0$ MeV
 - coincidence : $2 \mu\text{s} < \Delta t_{e+n} < 100 \mu\text{s}$
- ❑ **Multiplicity cut** : reject pairs if there is a trigger in the preceding 100 ms window

Random Coincidence Backgrounds

□ Calculation of accidental coincidence

$$N_{accidental} = N_{delayed} \times \left(1 - \exp^{-R_{prompt}(\text{Hz}) \times \Delta T(\text{s})}\right) \pm \frac{N_{accidental}}{\sqrt{N_{delayed}}}$$

▪ $\Delta T = 100 \mu\text{s}$ time window

▪ Near detector :

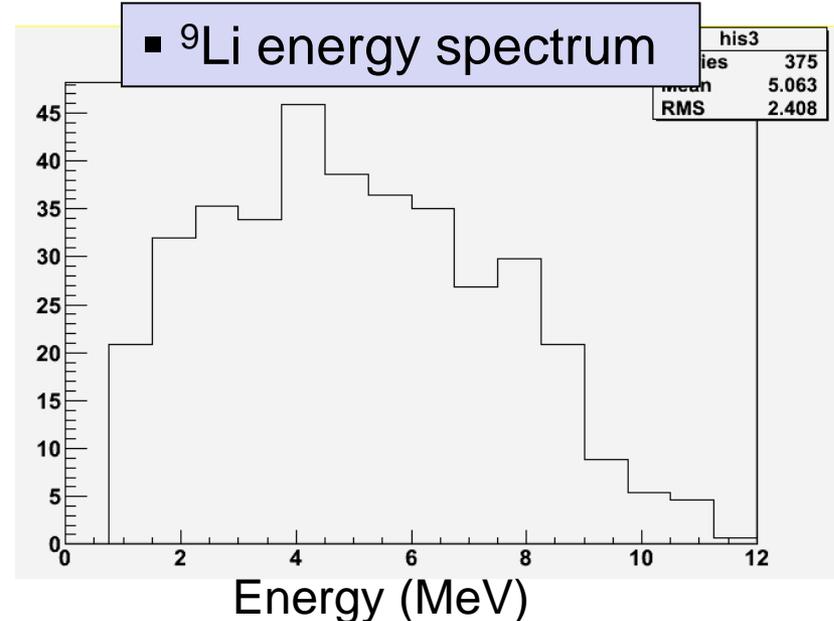
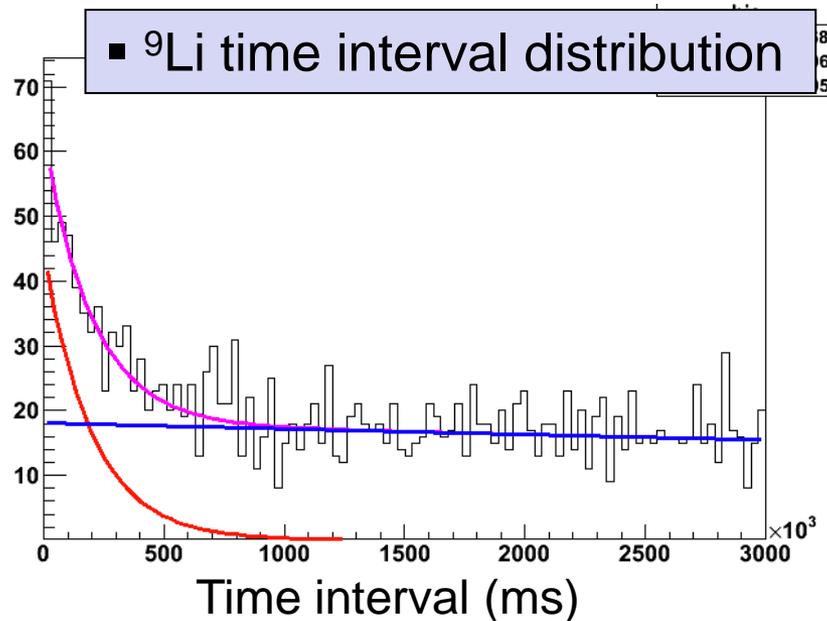
$$R_{prompt} = 8.8 \text{ Hz}, N_{delay} = 4884/\text{day} \rightarrow BG_{accidental}^{near} = 4.30 \pm 0.06 / \text{day}$$

▪ Far detector :

$$R_{prompt} = 10.6 \text{ Hz}, N_{delay} = 643/\text{day} \rightarrow BG_{accidental}^{far} = 0.68 \pm 0.03 / \text{day}$$

${}^9\text{Li}/{}^8\text{He}$ β -n Backgrounds

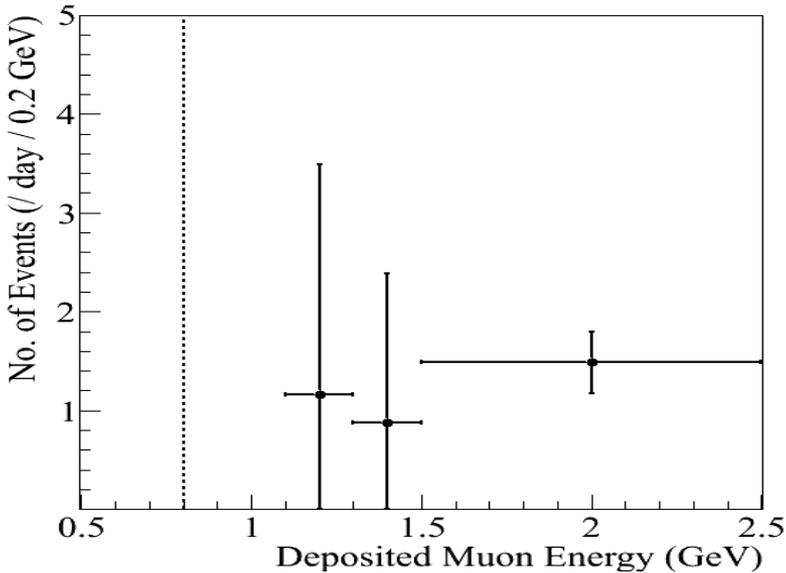
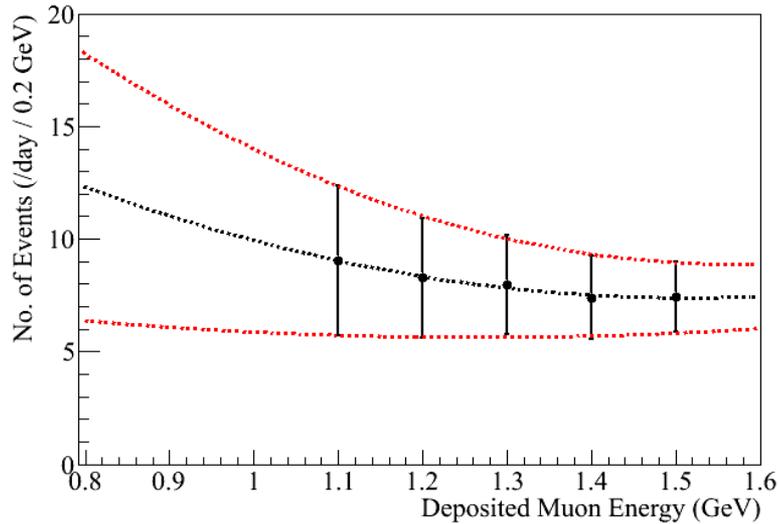
- Find prompt-delay pairs after muons, and obtain their time interval distribution with respect to the preceding muon.



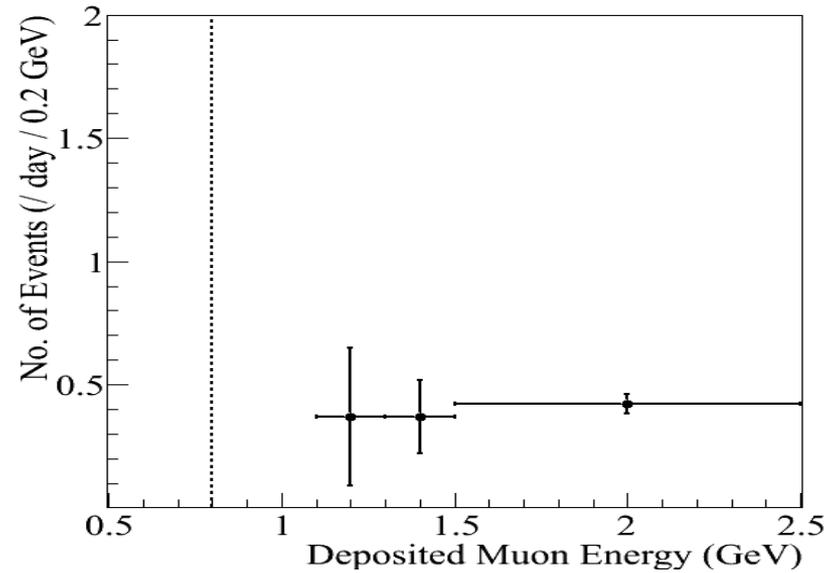
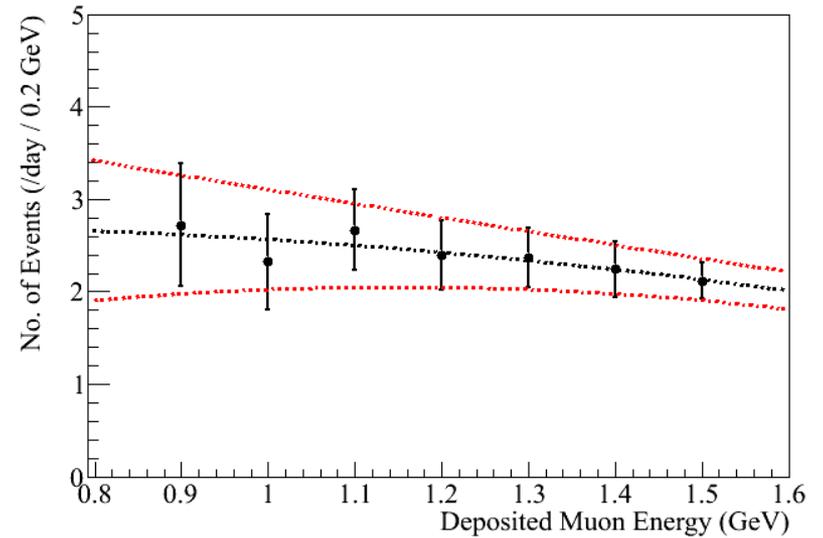
- Near detector : $BG_{Li/He}^{near} = 12.45 \pm 5.93 / day$
- Far detector : $BG_{Li/He}^{far} = 2.59 \pm 0.75 / day$

${}^9\text{Li}/{}^8\text{He}$ β -n Backgrounds

■ ${}^9\text{Li}$ production at near detector

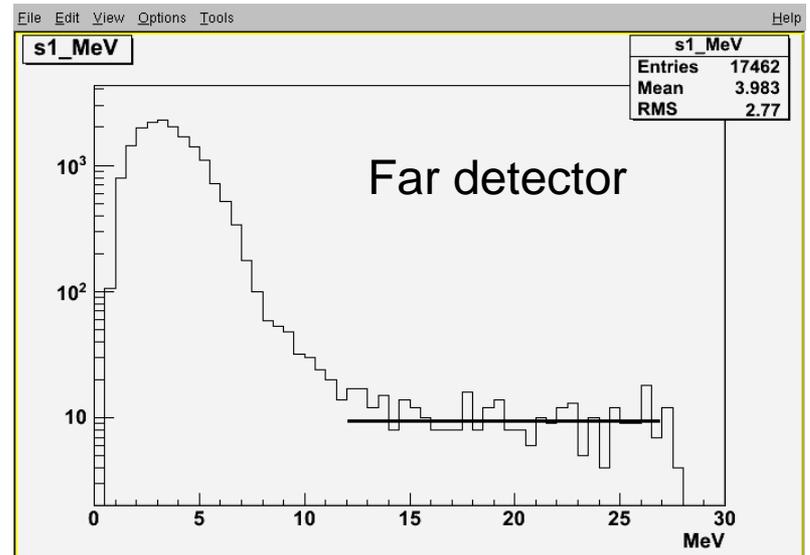
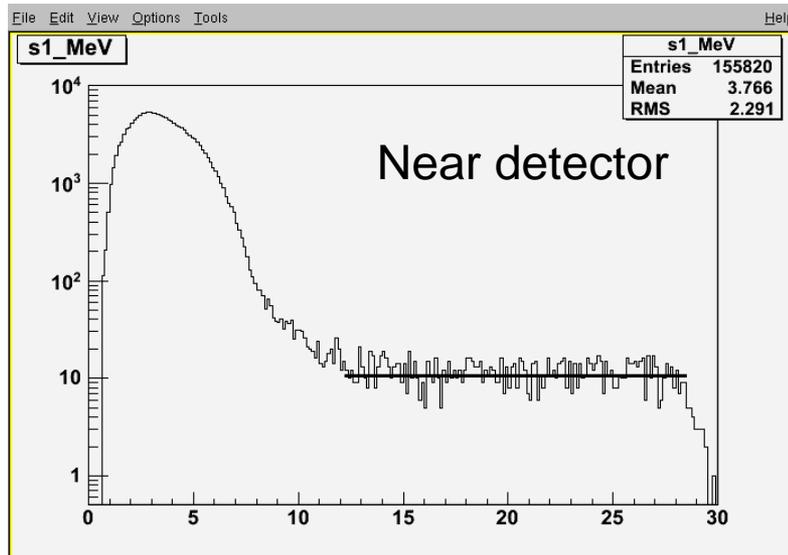


■ ${}^9\text{Li}$ production at far detector



Fast Neutron Backgrounds

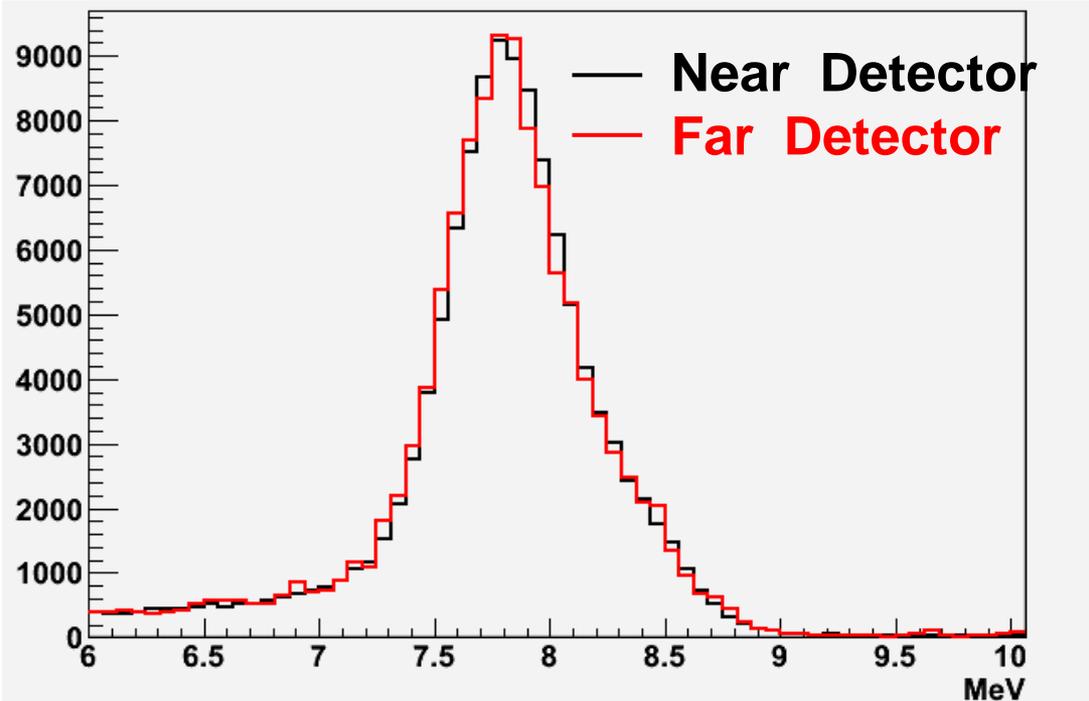
- ❑ Obtain a flat spectrum of fast neutron's scattering with proton, above that of the prompt signal.



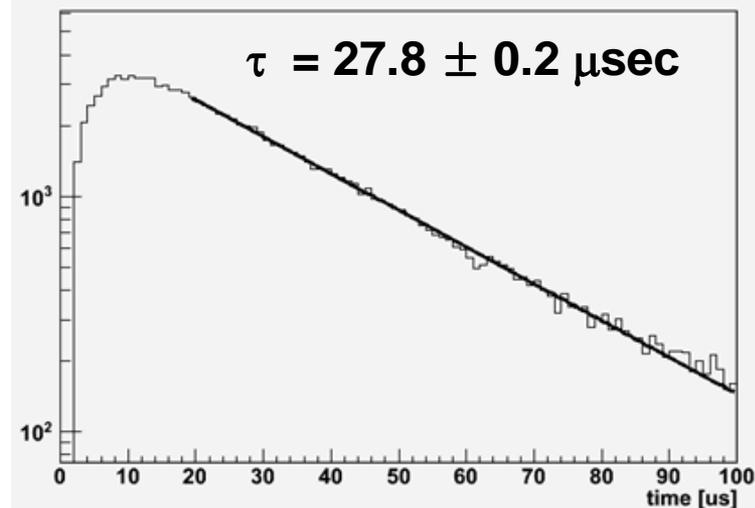
- Near detector : $BG_{neutron}^{near} = 5.00 \pm 0.13 / day$
- Far detector : $BG_{neutron}^{far} = 0.97 \pm 0.06 / day$

Spectra & Capture Time of Delayed Signals

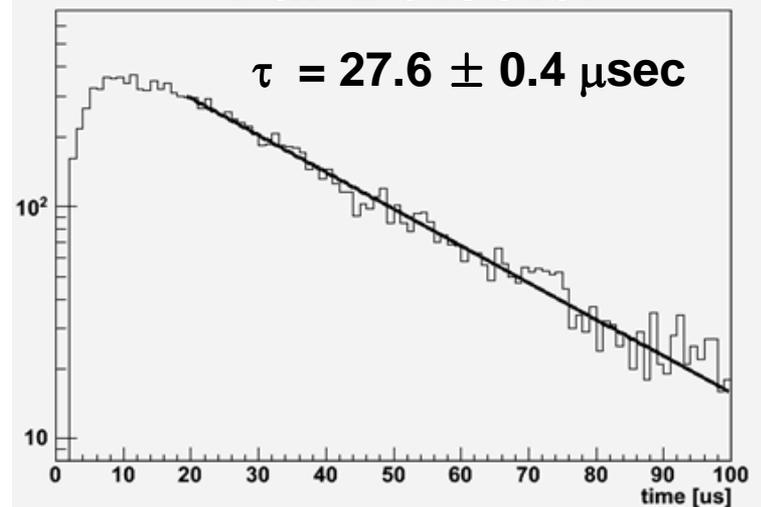
□ Observed spectra of IBD delayed signals



Near Detector



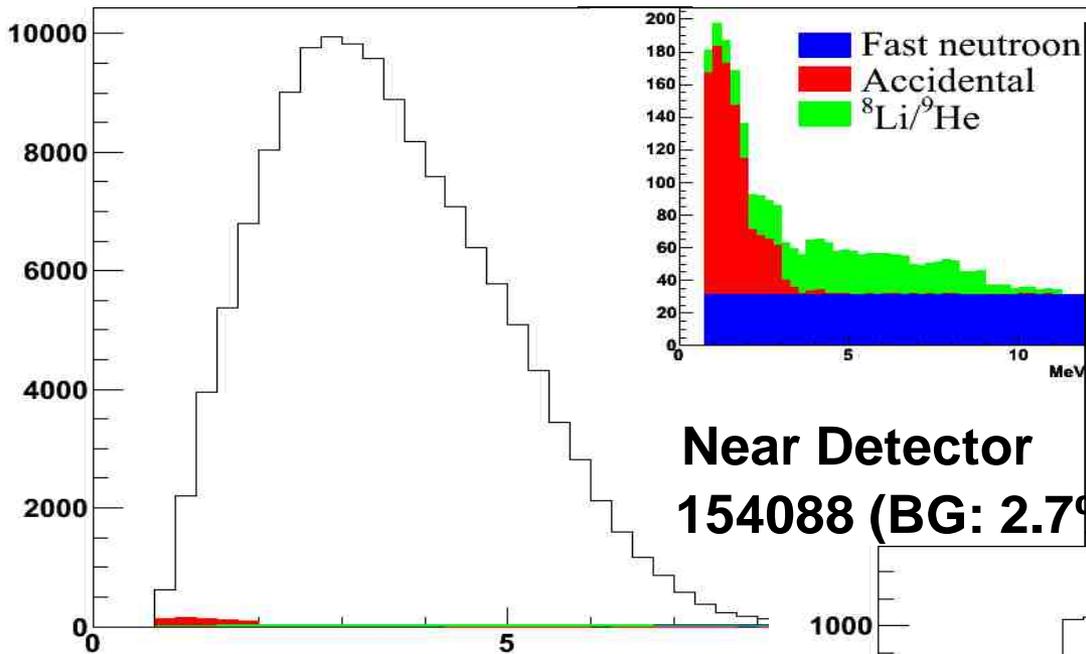
Far Detector



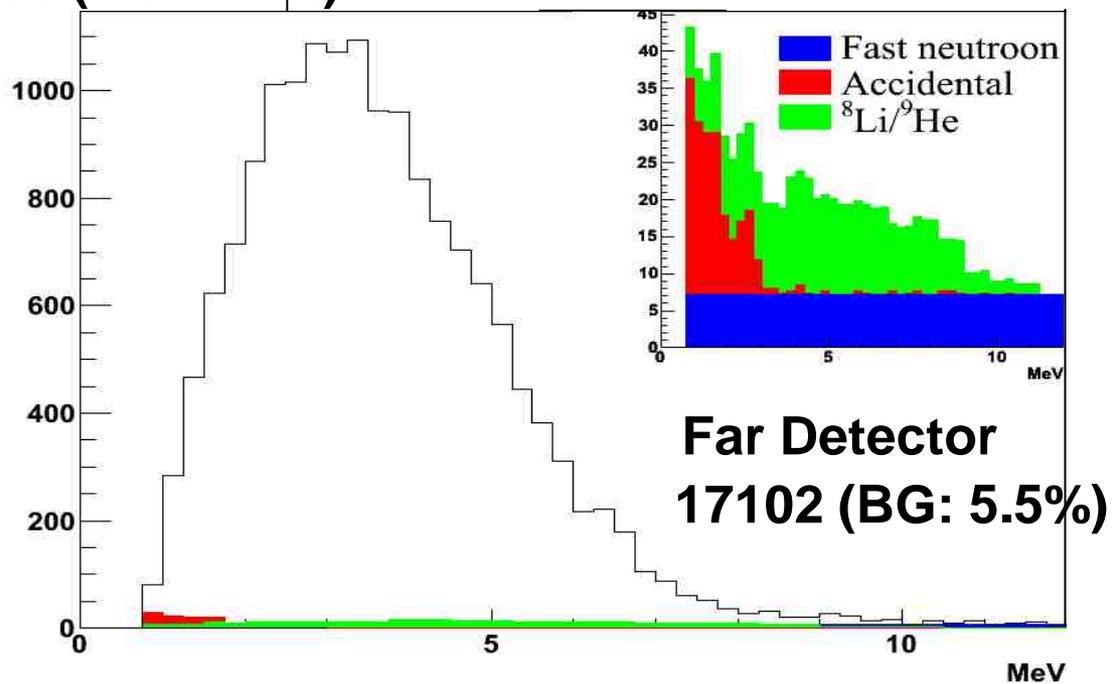
Summary of Final Data Sample

Detector	Near	Far
Selected events	154088	17102
Total background rate (per day)	21.75 ± 5.93	4.24 ± 0.75
IBD rate after background subtraction (per day)	779.05 ± 6.26	72.78 ± 0.95
DAQ Live time (days)	192.42	222.06
Detection efficiency (ϵ)	0.647 ± 0.014	0.745 ± 0.014
Accidental rate (per day)	4.30 ± 0.06	0.68 ± 0.03
${}^9\text{Li}/{}^8\text{He}$ rate (per day)	12.45 ± 5.93	2.59 ± 0.75
Fast neutron rate (per day)	5.00 ± 0.13	0.97 ± 0.06

Measured Spectra of IBD Prompt Signal



Near Detector
154088 (BG: 2.7%)



Far Detector
17102 (BG: 5.5%)

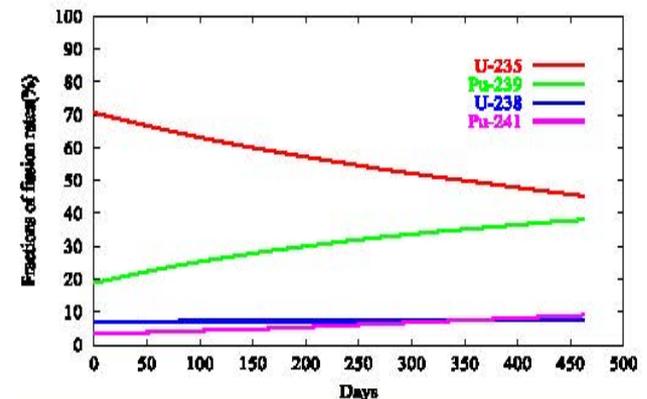
Expected Reactor Antineutrino Fluxes

- Reactor neutrino flux

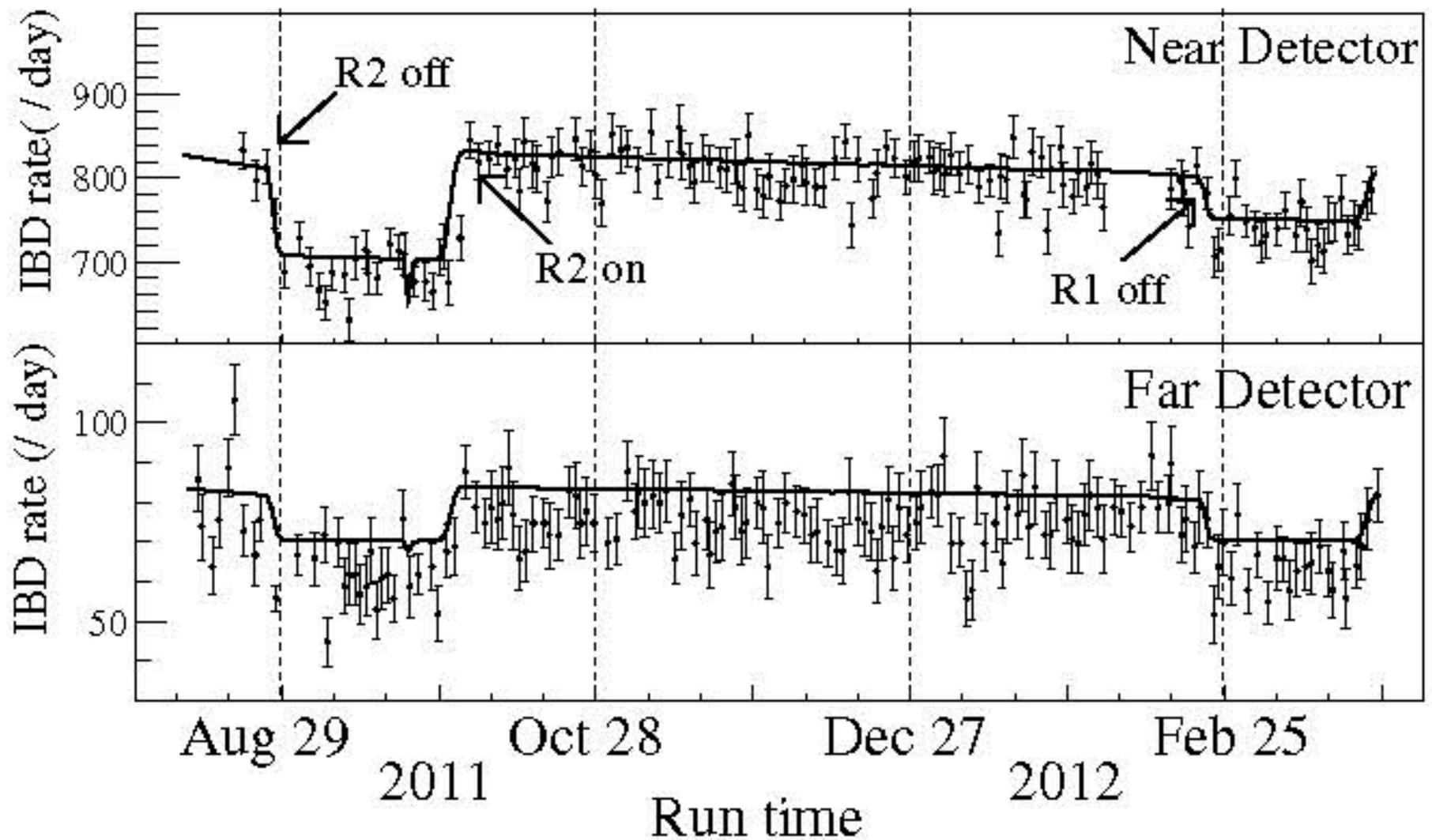
$$\Phi(E_\nu) = \frac{P_{th}}{\sum_i f_i \cdot E_i} \sum_i^{isotopes} f_i \cdot \phi_i(E_\nu)$$

- P_{th} : Reactor thermal power provided by the YG nuclear power plant
- f_i : Fission fraction of each isotope determined by reactor core simulation of Westinghouse ANC
- $\phi_i(E_\nu)$: Neutrino spectrum of each fission isotope
 [* P. Huber, Phys. Rev. C84, 024617 (2011)
 T. Mueller *et al.*, Phys. Rev. C83, 054615 (2011)]
- E_i : Energy released per fission
 [* V. Kopeikin *et al.*, Phys. Atom. Nucl. 67, 1982 (2004)]

Isotopes	James	Kopeikin
^{235}U	201.7±0.6	201.92±0.46
^{238}U	205.0±0.9	205.52±0.96
^{239}Pu	210.0±0.9	209.99±0.60
^{241}Pu	212.4±1.0	213.60±0.65



Observed Daily Averaged IBD Rate



Reduction of Systematic Uncertainties

- **Detector related :**
 - “Identical” near and far detectors
 - Careful calibration

- **Reactor related :**
 - Relative measurements with near and far detectors

$$\frac{N_{far}^{\nu}}{N_{near}^{\nu}} = \left(\frac{L_{near}}{L_{far}} \right)^2 \left(\frac{N_{far}^P}{N_{near}^P} \right) \left(\frac{\epsilon_{far}}{\epsilon_{near}} \right) \left[\frac{P(\bar{\nu}_e \rightarrow \bar{\nu}_e; E, L_{far})}{P(\bar{\nu}_e \rightarrow \bar{\nu}_e; E, L_{near})} \right]$$

Neutrino
events

$1/r^2$

Number
of
protons

Detection
efficiency

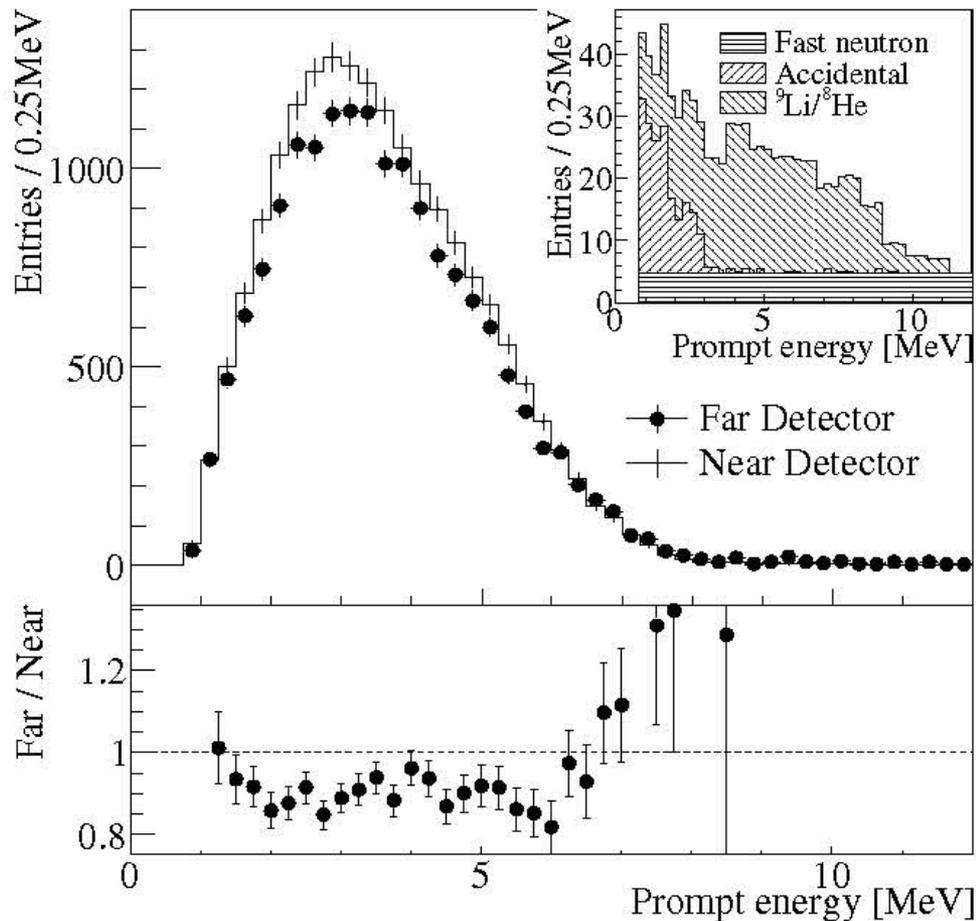
Yield of $\sin^2(2\theta_{13})$

Efficiency & Systematic Uncertainties

		Reactor		
		Uncorrelated	Correlated	
		Thermal power	0.5%	–
		Fission fraction	0.7%	–
Prompt energy cut		Fission reaction cross section	–	1.9%
Flasher cut		Reference energy spectra	–	0.5%
Gd capture fraction		Energy per fission	–	0.2%
Delayed energy cut		Combined	0.9%	2.0%
Time coincidence cut		Detection		
Spill-in		Uncorrelated	Correlated	
Common		IBD cross section	–	0.2%
		Target protons	0.1%	0.5%
		Prompt energy cut	0.01%	0.1%
Muon veto loss ($\delta_{\mu-veto}$)	(11.	Flasher cut	0.01%	0.1%
Multiplicity cut loss (δ_{multi})	(4.	Gd capture ratio	0.1%	0.7%
Total	(6.	Delayed energy cut	0.1%	0.5%
		Time coincidence cut	0.01%	0.5%
		Spill-in	0.03%	1.0%
		Muon veto cut	0.02%	0.02%
		Multiplicity cut	0.04%	0.06%
		Combined (total)	0.2%	1.5%

Reactor Antineutrino Disappearance

$$R = \frac{\Phi_{\text{observed}}^{\text{Far}}}{\Phi_{\text{expected}}^{\text{Far}}} = 0.920 \pm 0.009(\text{stat.}) \pm 0.014(\text{syst.})$$



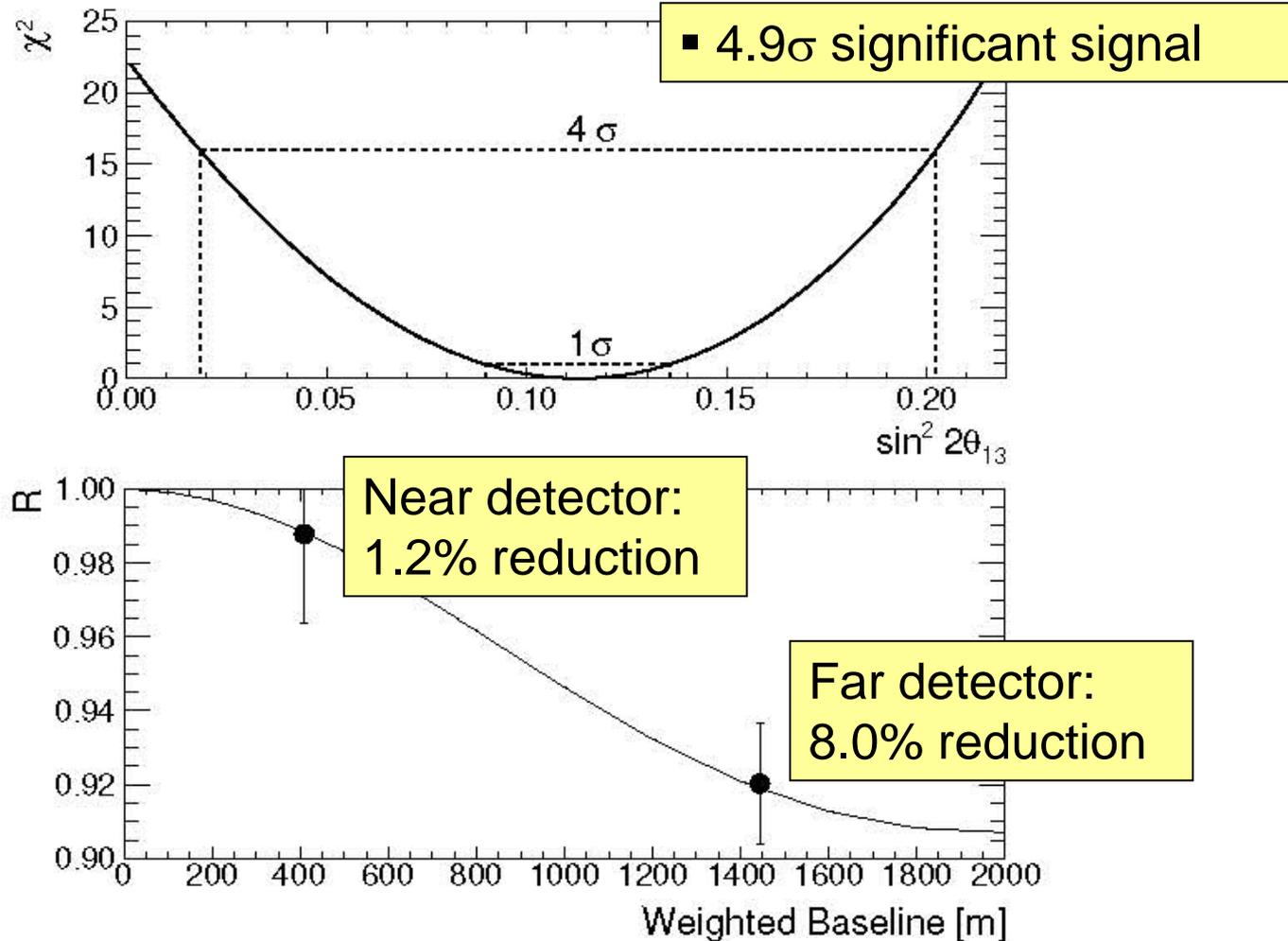
- A clear deficit in rate (8.0% reduction)
- Consistent with neutrino oscillation in the spectral distortion

χ^2 Fit with Pulls

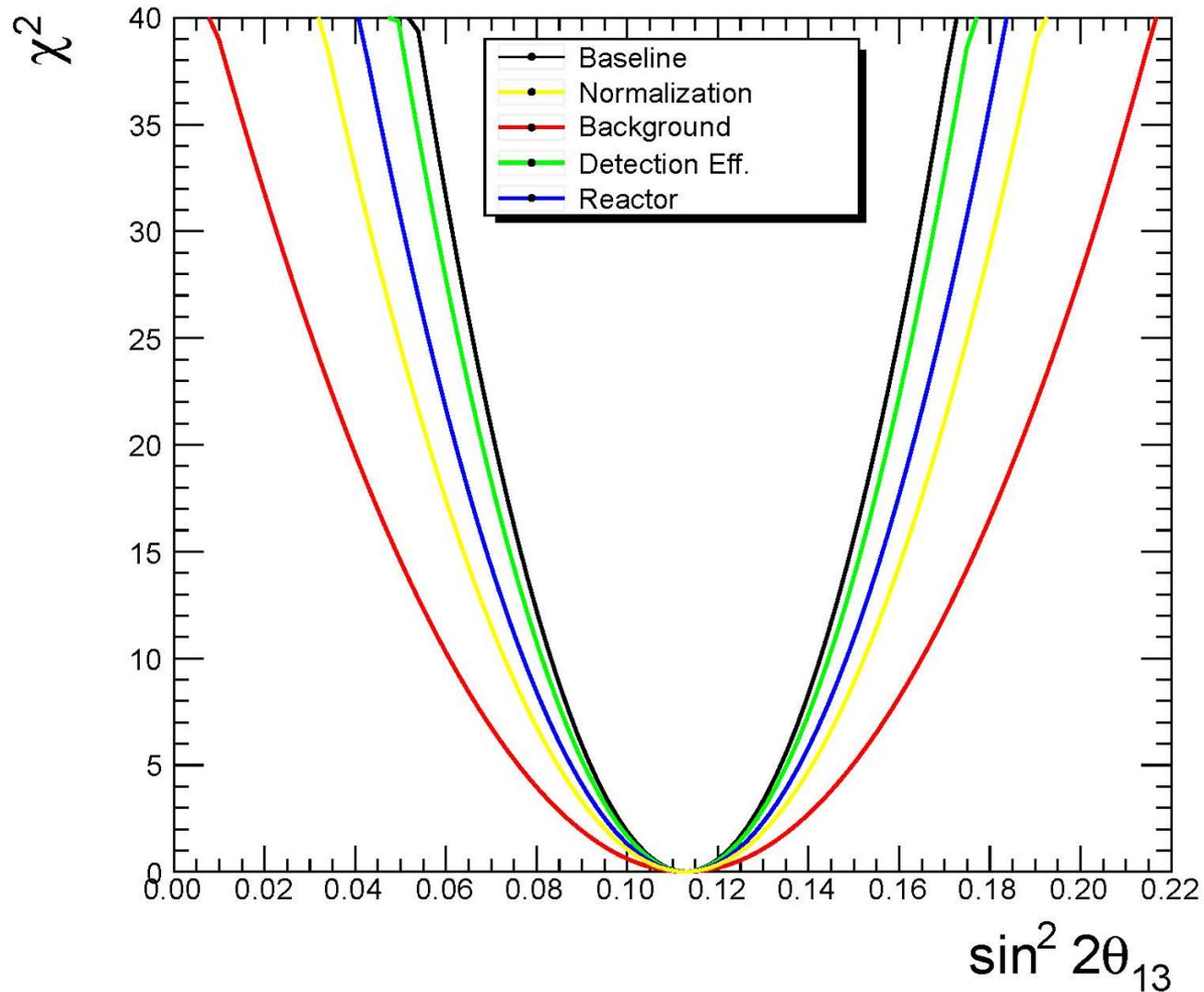
$$\chi^2 = \sum_{d=N,F} \frac{\left[N_{obs}^d + b_d - (1 + a + \xi_d) \sum_{r=1}^6 (1 + f_r) N_{exp}^{d,r} \right]^2}{N_{obs}^d} + \sum_{d=N,F} \left(\frac{\xi_d^2}{\sigma_d^{\xi^2}} + \frac{b_d^2}{\sigma_d^{b^2}} \right) + \sum_{r=1}^6 \left(\frac{f_r}{\sigma_r} \right)^2$$

Definitive Measurement of θ_{13}

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



χ^2 Distributions for Uncertainties



Future Efforts for Precision Measurement of θ_{13}

RENO

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

Daya
Bay

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

- Contributions of the systematic errors :
 - Background uncertainties : 0.0165
(far : $5.5\% \times 17.7\% = 0.97\%$, near : $2.7\% \times 27.3\% = 0.74\%$)
 - Reactor uncertainty (0.9%) : 0.0100
 - Detection efficiency uncertainty (0.2%) : 0.0103
 - Absolute normalization uncertainty (2.5%) : 0.0104



- Remove the backgrounds !
- Spectral shape analysis

Summary

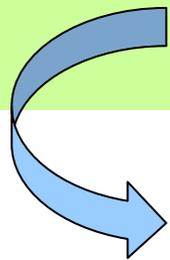
- RENO was the first experiment to take data with both near and far detectors, from August 1, 2011.

- RENO observed a clear disappearance of reactor antineutrinos.

$$R = 0.920 \pm 0.009(\text{stat.}) \pm 0.014(\text{syst.})$$

- RENO measured the last, smallest mixing angle θ_{13} unambiguously that was the most elusive puzzle of neutrino oscillations

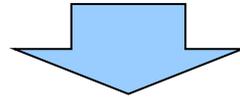
$$\sin^2 2\theta_{13} = 0.113 \pm 0.013(\text{stat.}) \pm 0.019(\text{syst.})$$



- Surprisingly large !!! (a big gift to RENO[^])
→ A plenty of tasks ahead for neutrino physicists

Prospective Future

- A surprisingly large value of θ_{13} :
(Save a lot of dollars for the future neutrino experiments which may need reconsideration of their designs!!)
- (1) Provides a complete picture of neutrino oscillations
(2) Open a bright window of understanding why there is much more matter than antimatter in the Universe today



A prospective future for neutrino physics due to a large value of θ_{13} !!!

- Our measurement will strongly promote the next round of neutrino experiments to find the CP phase.
- Complimentary measurements between accelerator experiments and reactor experiments will provide significant information on the CP phase.