Observation of Reactor Antineutrino Disappearance at RENO

Soo-Bong Kim for the RENO Collaboration

KNRC, Seoul National University

(presented at BNL on April 13, 2012)

RENO ν θ_{13}

ν_e ν_μ ν_τ KNRC Korea Neutrino Research Center

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.

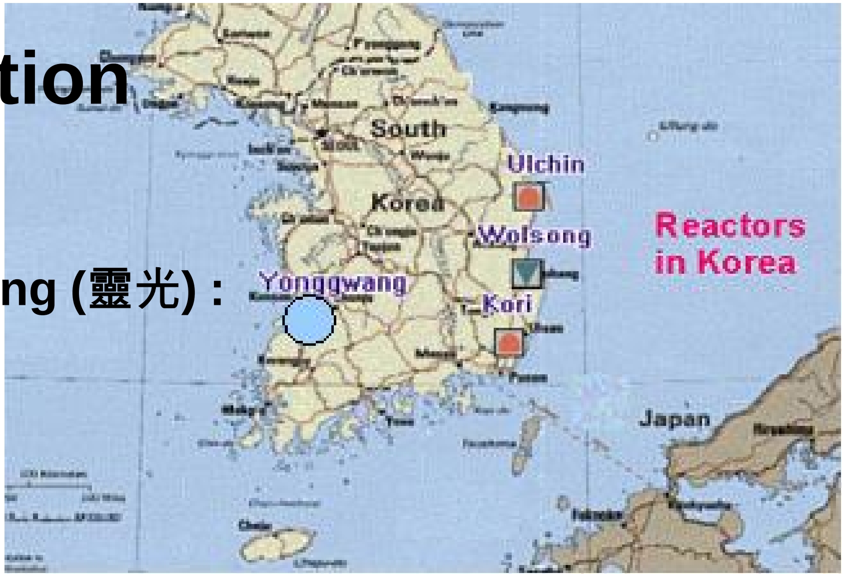
Physics in a Nutshell

Subatomic CSI

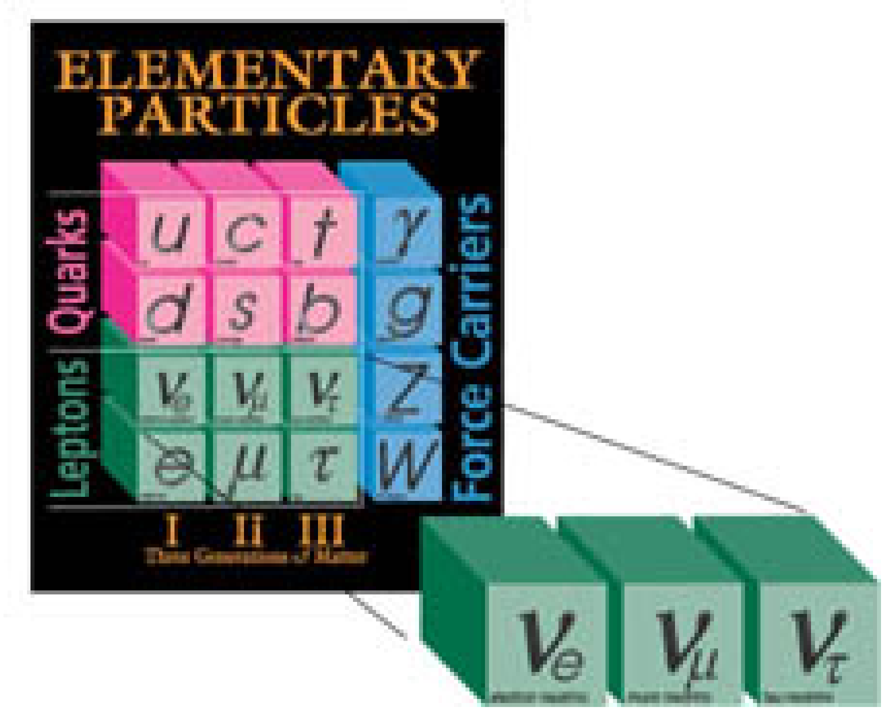
This DZero event is not thought to have come from a Higgs boson, but an event in which a Higgs boson decayed into a pair of Z bosons would look very similar.

If we find the Higgs boson, we won't

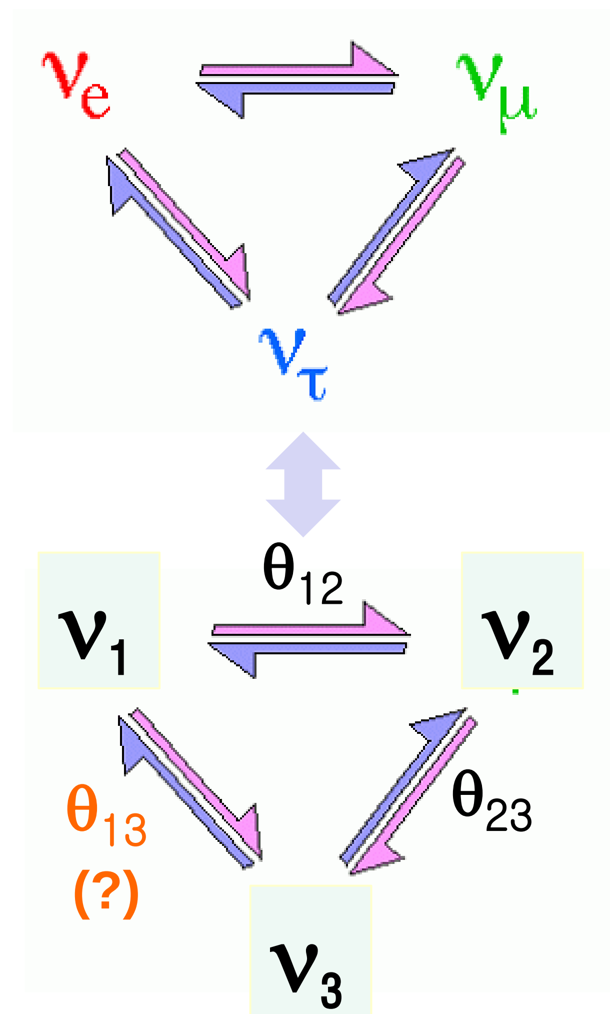
YongGwang (靈光) :



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

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

- T2K : 2.5 σ excess (2011)

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

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

- MINOS : 1.7 σ excess (2011)

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

$0.04 < \sin^2(2\theta_{13}) < 0.19$ 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)

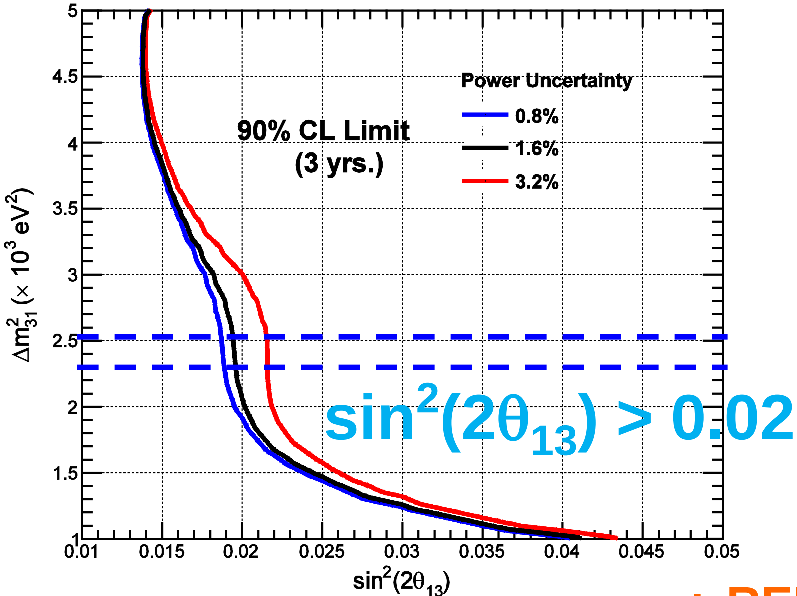
- Chonbuk National University
- Chonnam National University
- Chung-Ang University
- Dongshin University
- Gyeongsang National University
- Kyungpook National University
- Pusan National University
- Sejong University
- Seokyeong University
- Seoul National University
- Seoyeong University
- Sungkyunkwan University

- Total cost : $10M
- Start of project : 2006
- The first experiment running with both near & far detectors from Aug. 2011

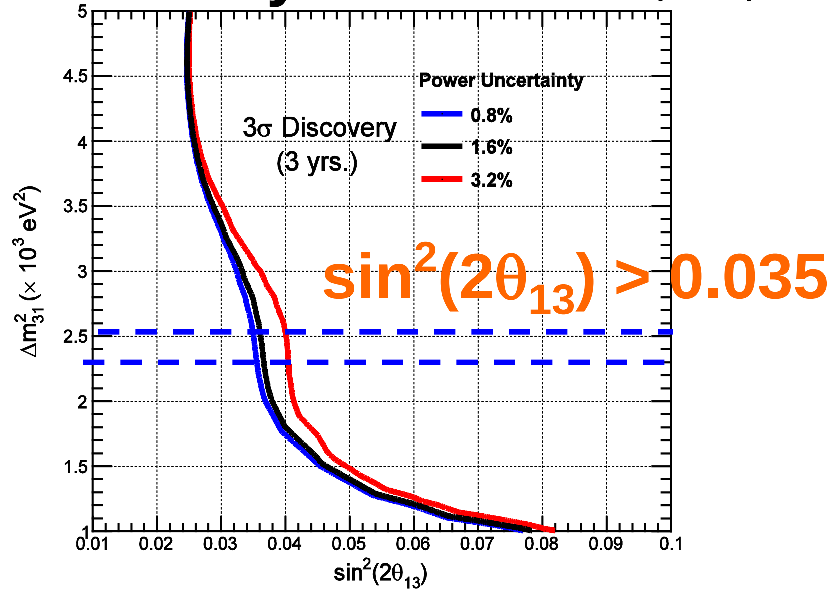
서울대 김수봉 교수가 이끄는 RENO 실험팀. 30여년간 관측에 실패한 마지막 중성미자 변환상수를 밝히기 위해 프랑스 중국과 치열한 경주를 벌이고 있다.

RENO Expected Sensivity

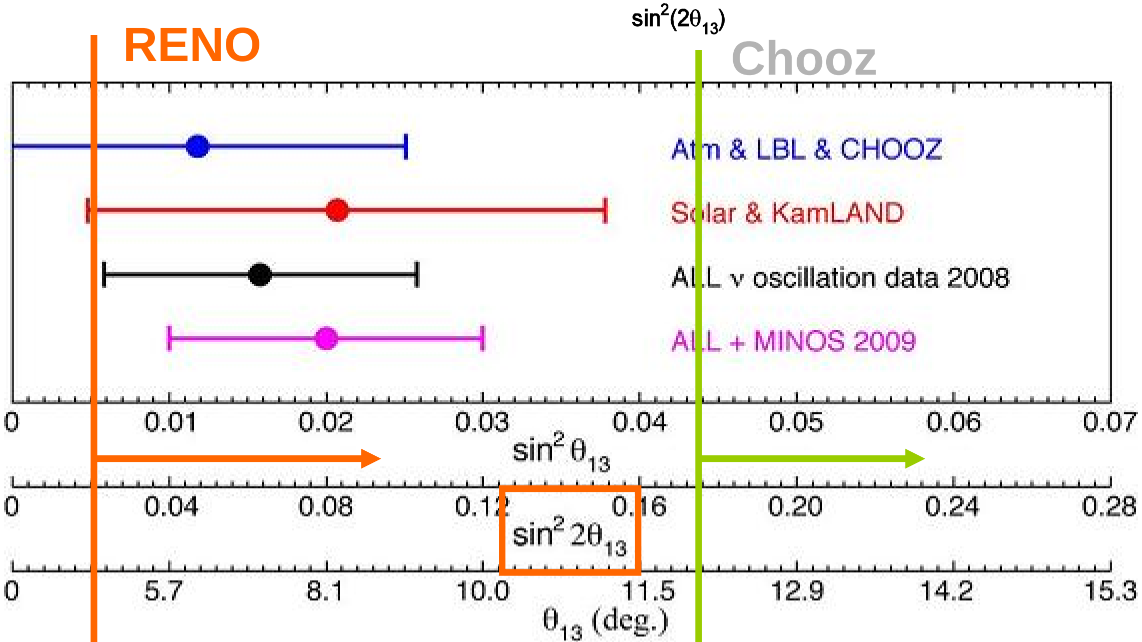
90% CL Limits



Discovery Potential" (3σ)

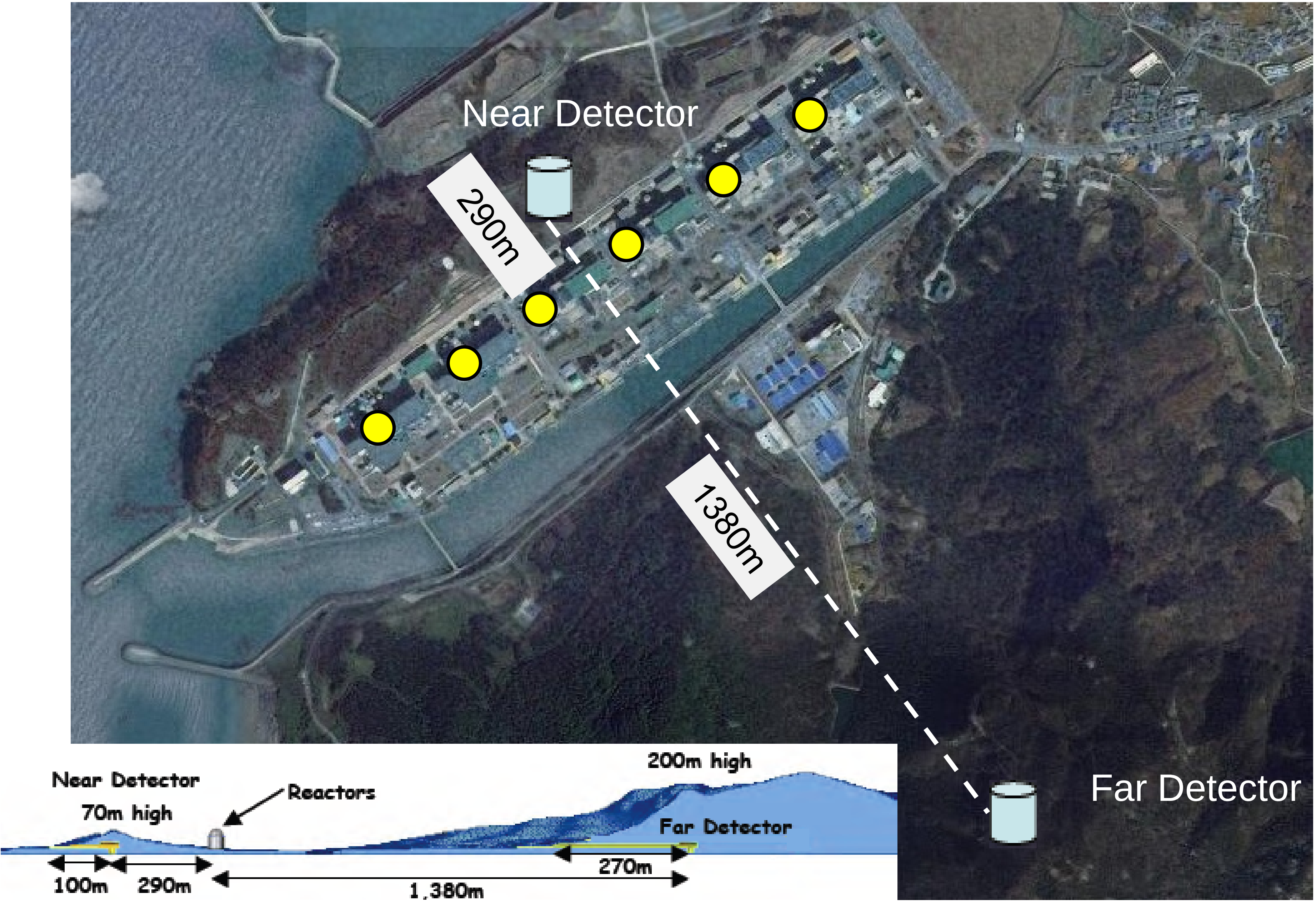


- **10 times better sensitivity than the current limit**



G. Fogli *et al.* (2009)

RENO Experimental Setup

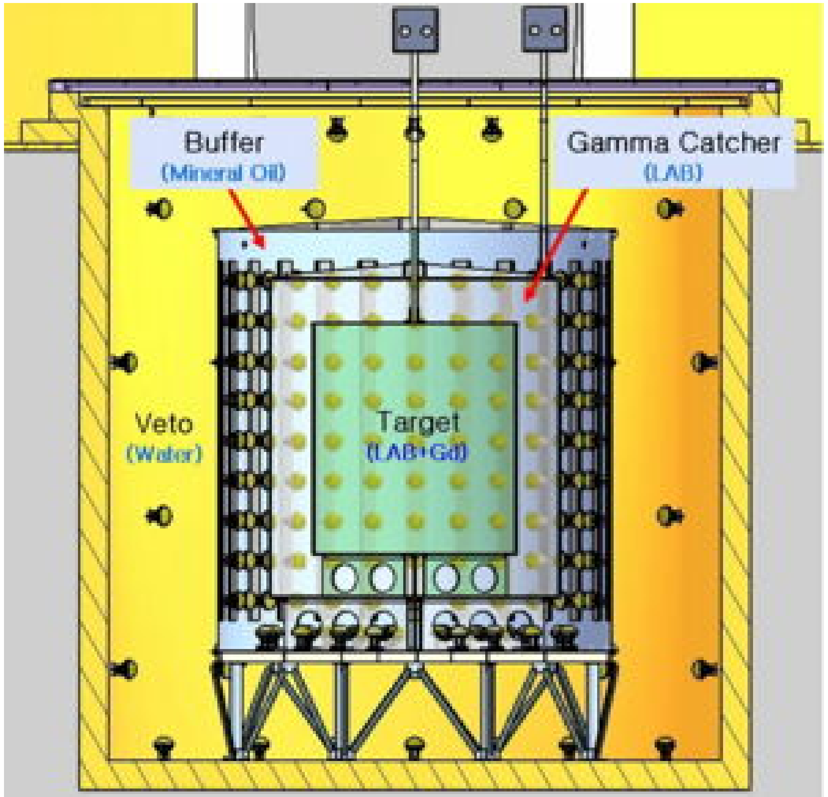


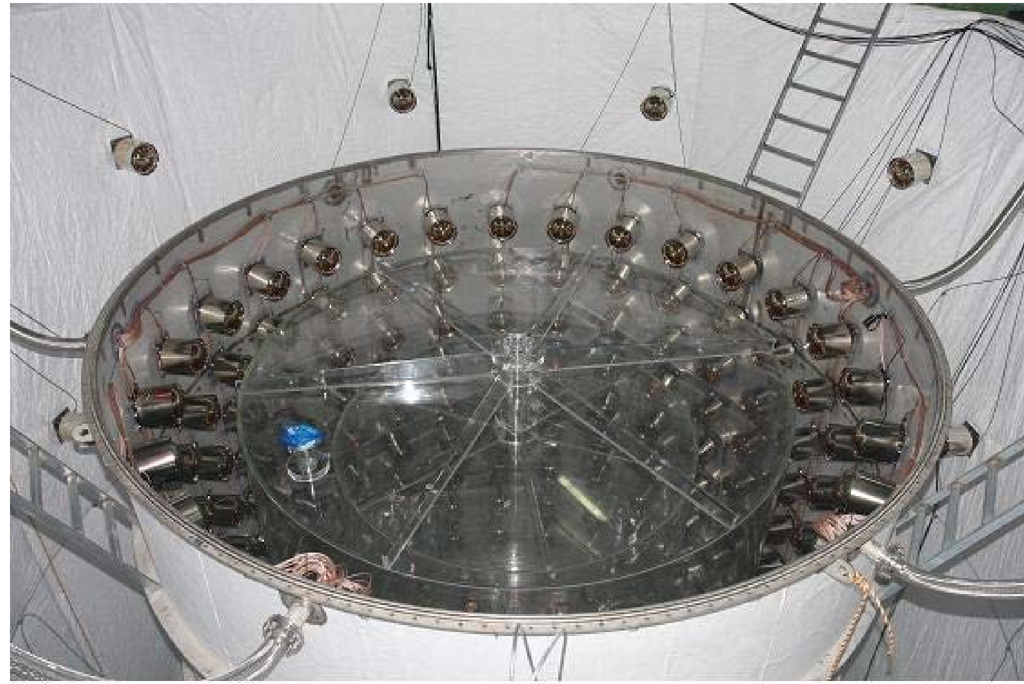
Contribution of Reactor to Neutrino Flux at Near & Far Detectors

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



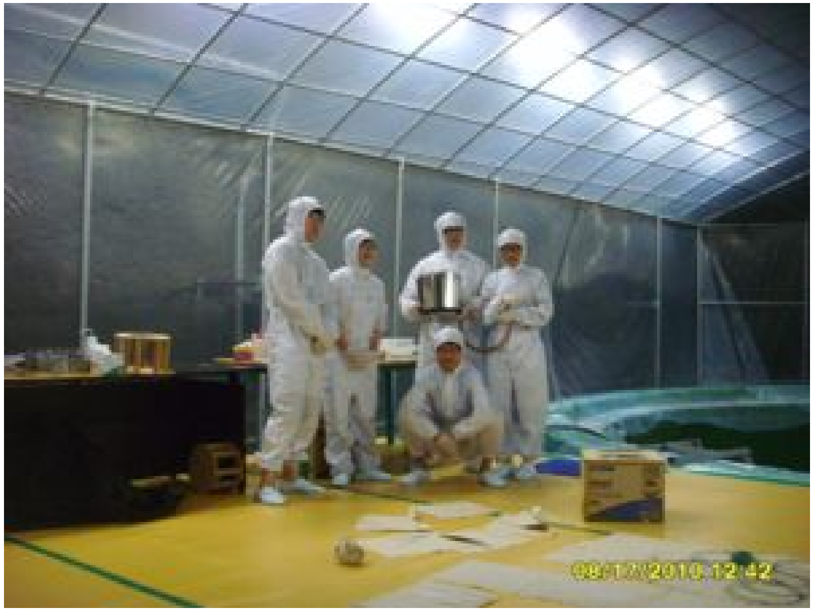


- 354 ID +67 OD 10” PMTs
- Target : 16.5 ton Gd-LS,   R=1.4m, H=3.2m
- Gamma Catcher : 30 ton LS,   R=2.0m, H=4.4m
- Buffer : 65 ton mineral oil,   R=2.7m, H=5.8m
- Veto : 350 ton water,   R=4.2m, H=8.8m

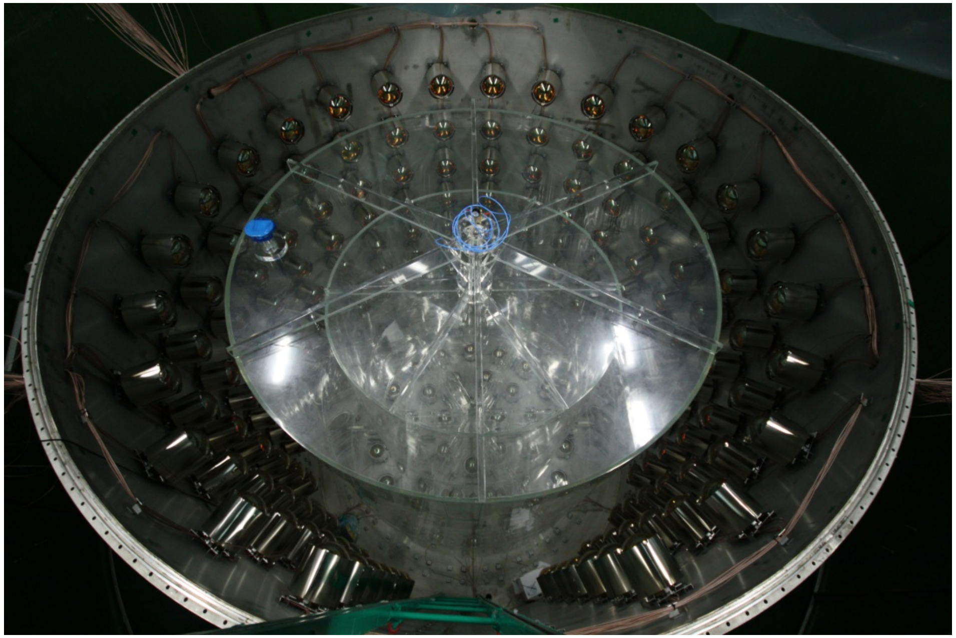
Summary of Detector Construction

- 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

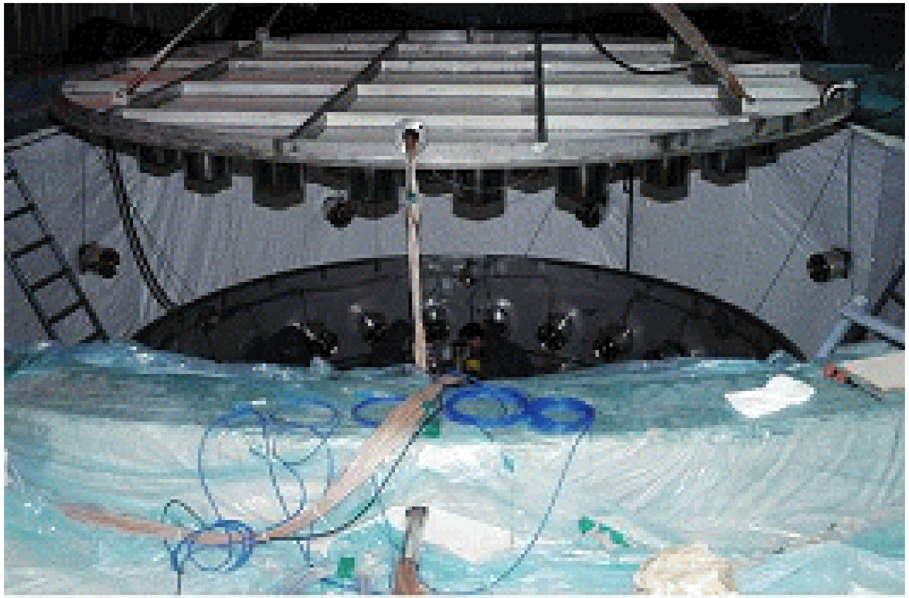
PMT Mounting (2010. 8~10)

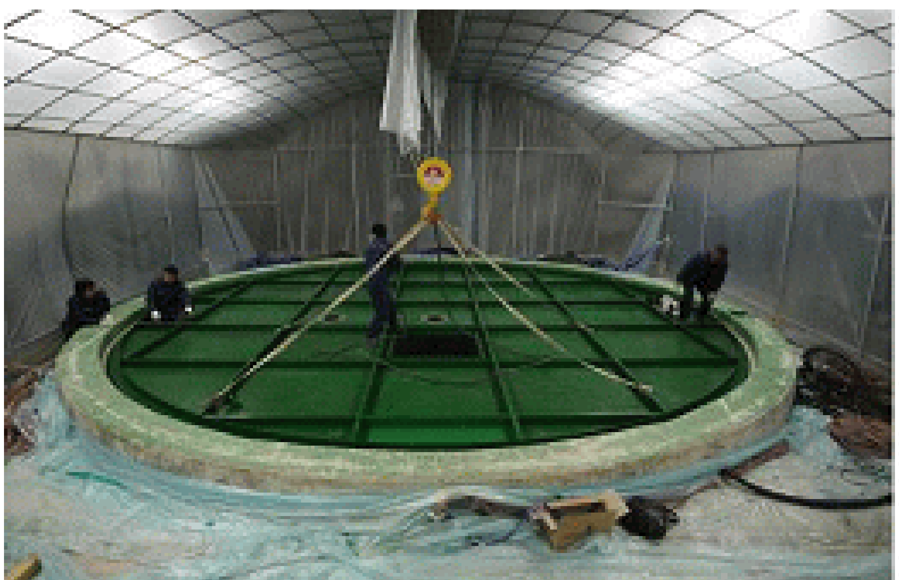


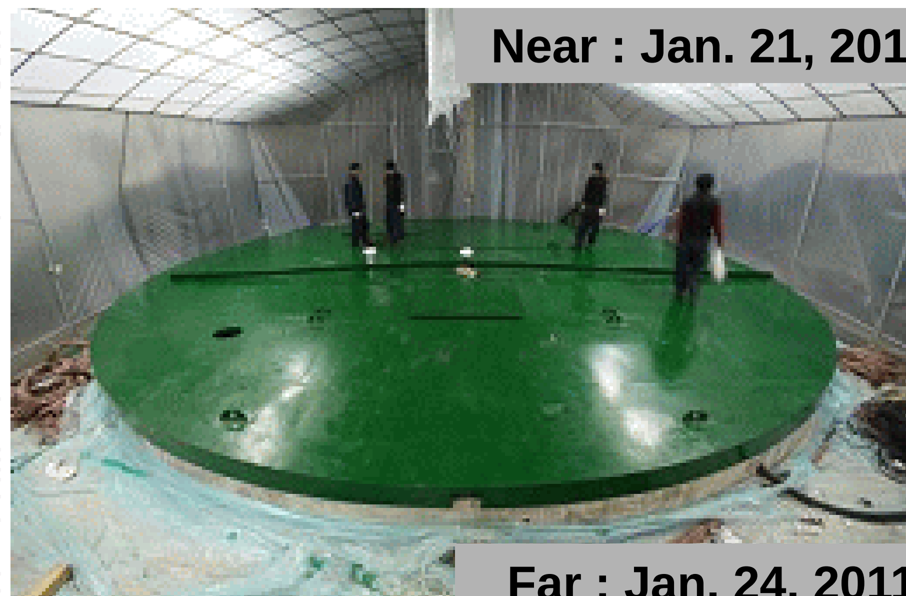
PMT Mounting (2010. 8~10)



Detector Closing (2011. 1)





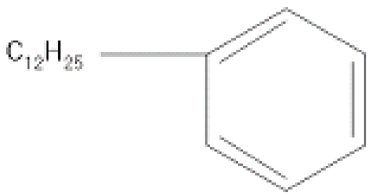


Near : Jan. 21, 2011

Far : Jan. 24, 2011

Detection of Reactor Antineutrinos

C_nH_{2n+1}-C_6H_5 (n=10~14)



Linear Alkyl Benzene (LAB)

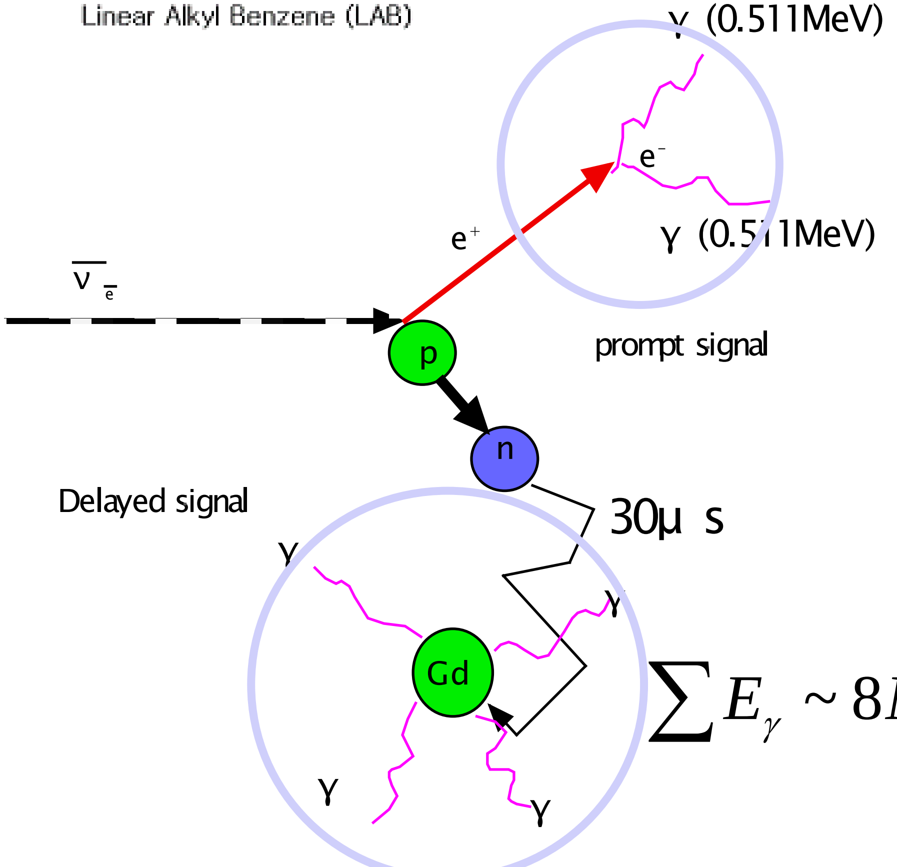
(prompt signal)

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

(delayed signal)

~180 μs $+ p \rightarrow D + \gamma$ (2.2 MeV)

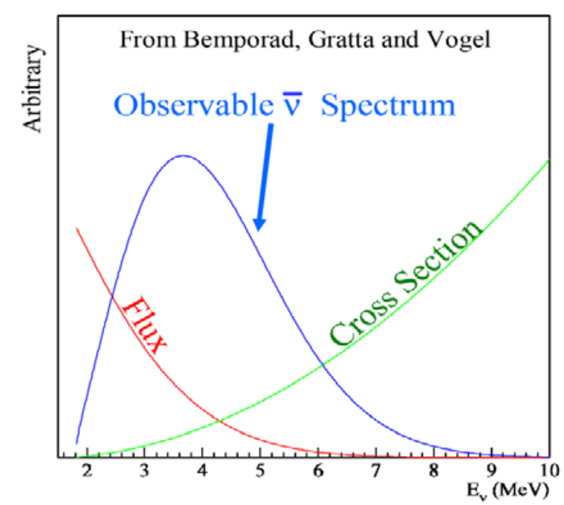
~28 μs (0.1% Gd) $+ Gd \rightarrow Gd + \gamma$'s (8 MeV)



$$\sum E_\gamma \sim 8MeV$$

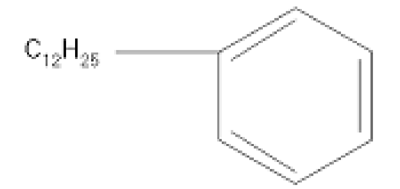
- **Neutrino energy measurement**

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



Gd Loaded Liquid Scintillator

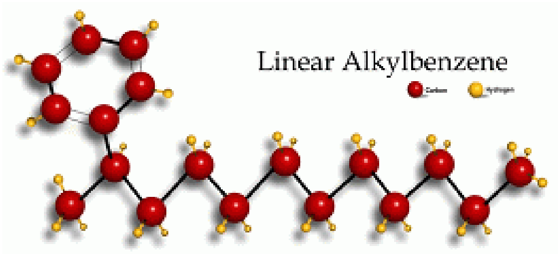
C_nH_{2n+1}-C_6H_5 (n=10~14)



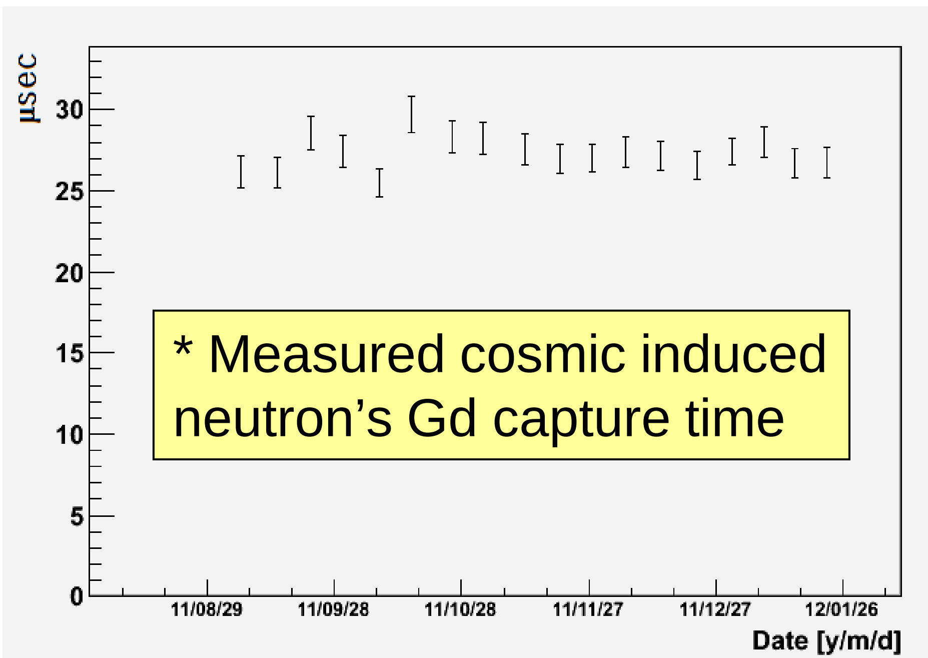
Linear Alkyl Benzene (LAB)

❑ Recipe of Liquid Scintillator

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

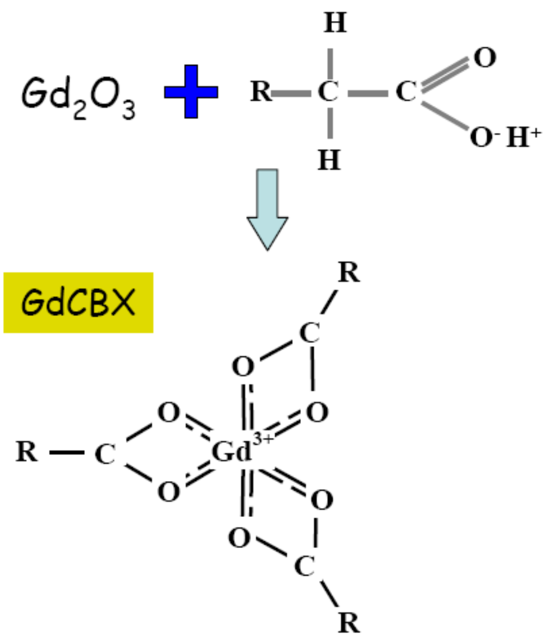


* Stable light yield over the time period : ~250 pe/MeV



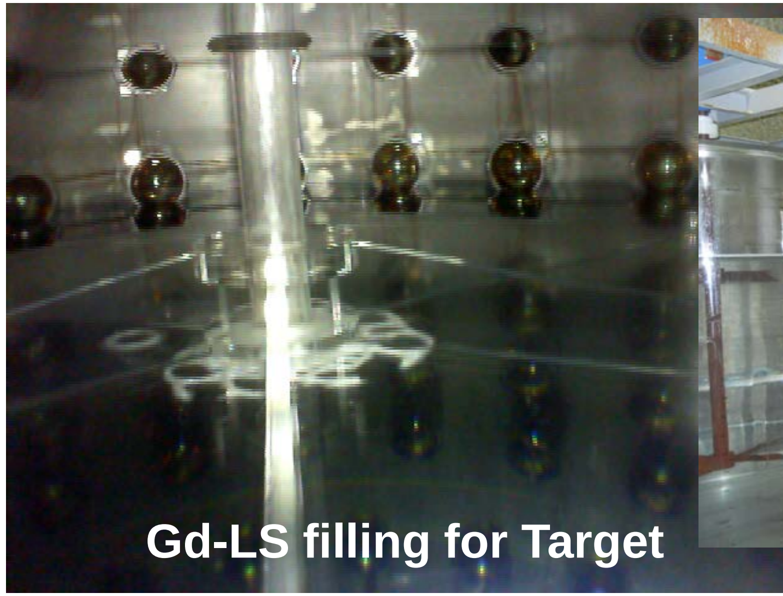
* Measured cosmic induced neutron's Gd capture time

Carboxylic acids



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

Gd Loaded Liquid Scintillator

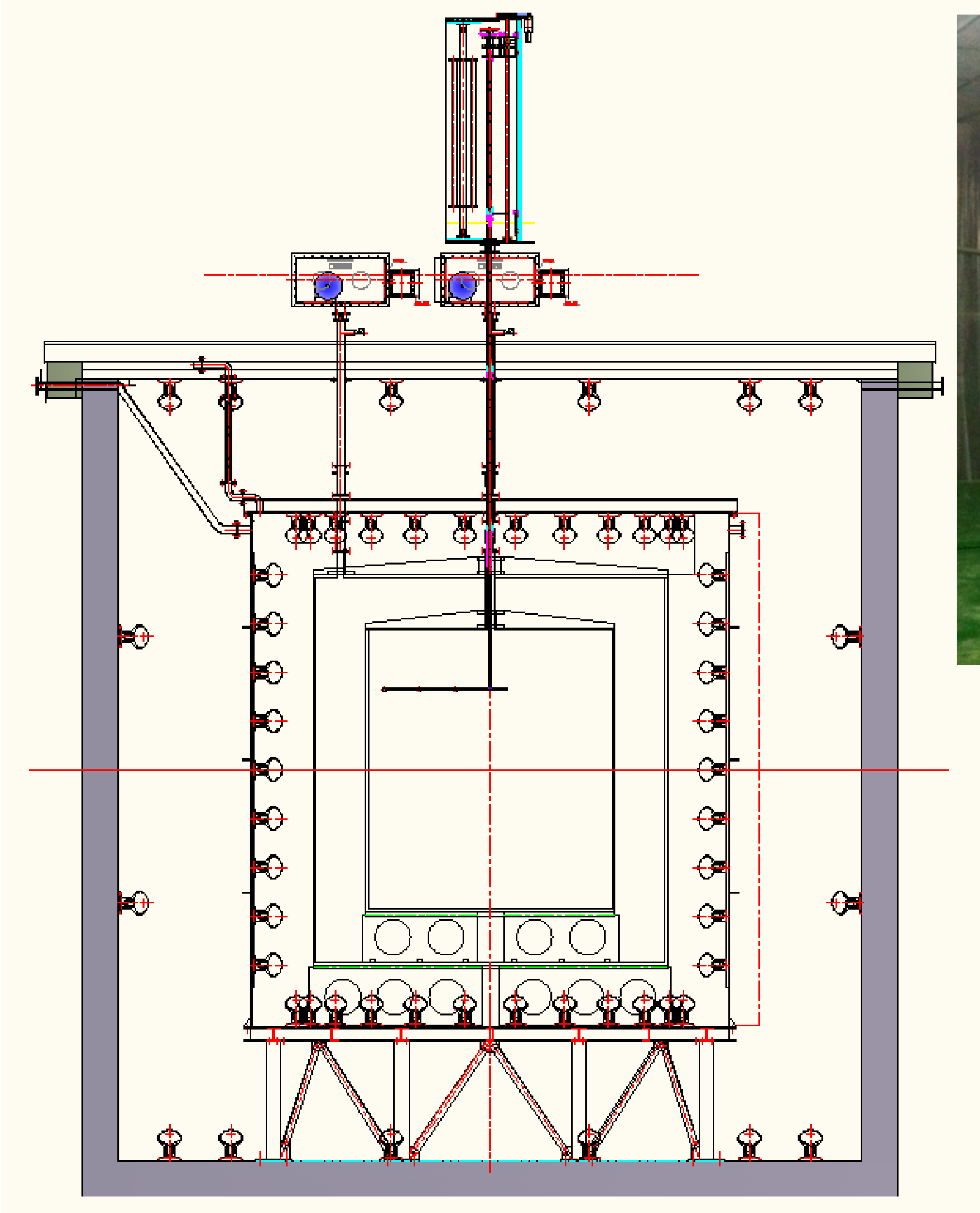


Gd-LS filling for Target

Water filling for Veto

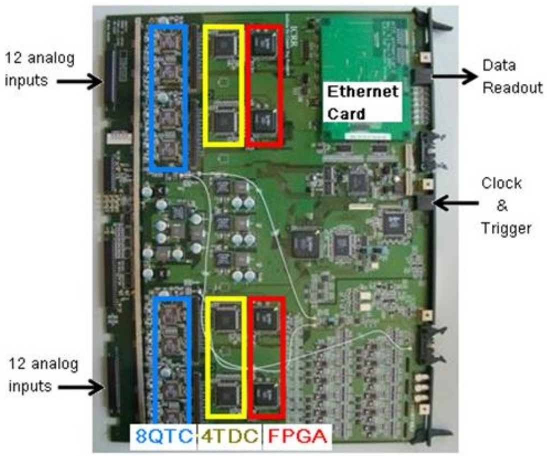
LS filling for Gamma Catcher

1D/3D Calibration System

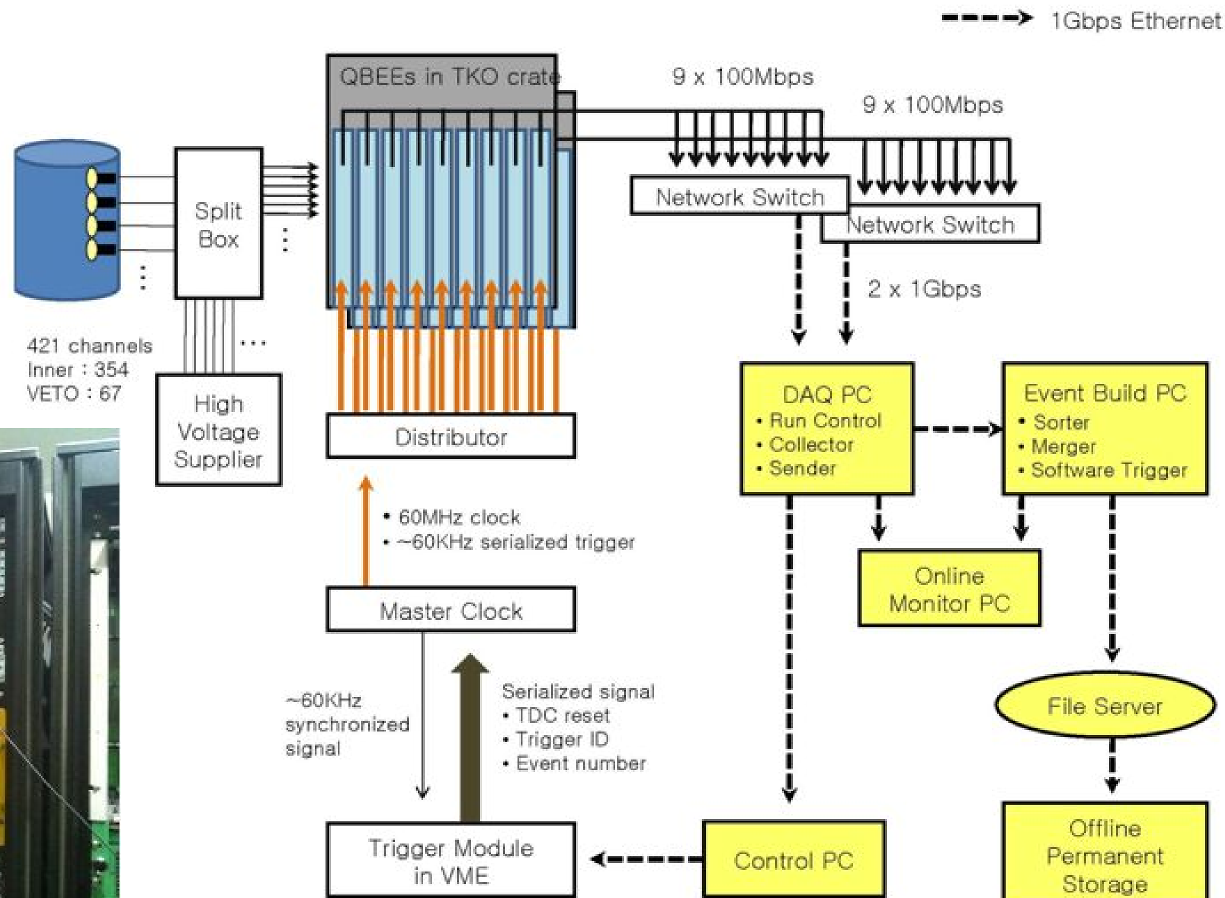


- ❑ Calibration system to deploy radioactive sources in 1D & 3D directions
- ❑ Radioactive sources : ^{137}Cs, ^{68}Ge, ^{60}Co, ^{252}Cf
- ❑ Laser injectors

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

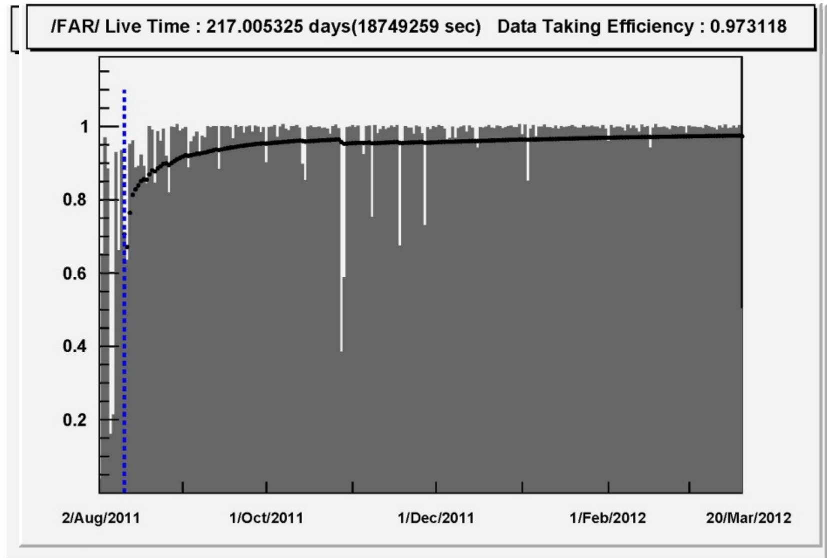
- Data taking began on Aug. 1, 2011 with both near and far detectors.

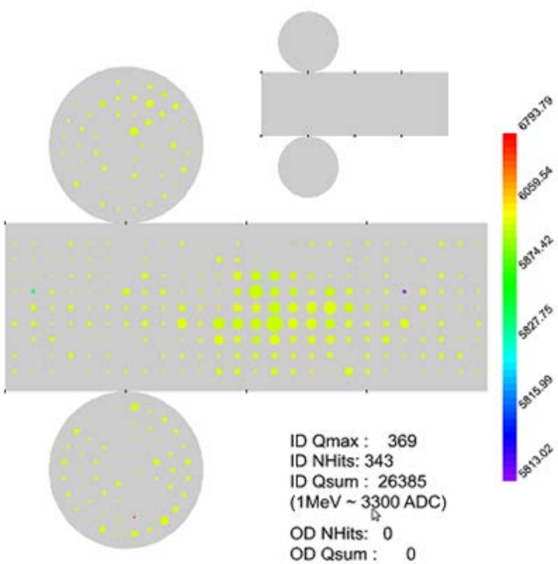
- Data-taking efficiency > 90%.

- 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

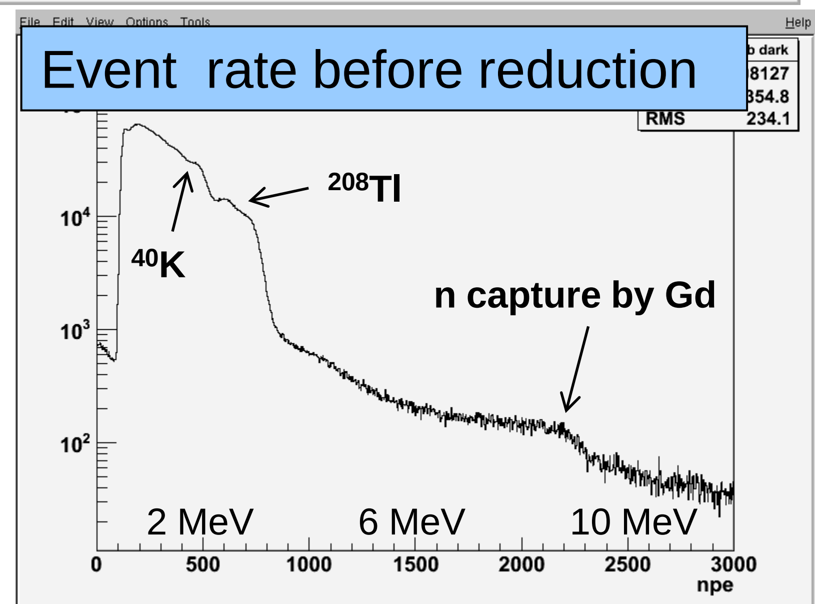
- Data-taking efficiency





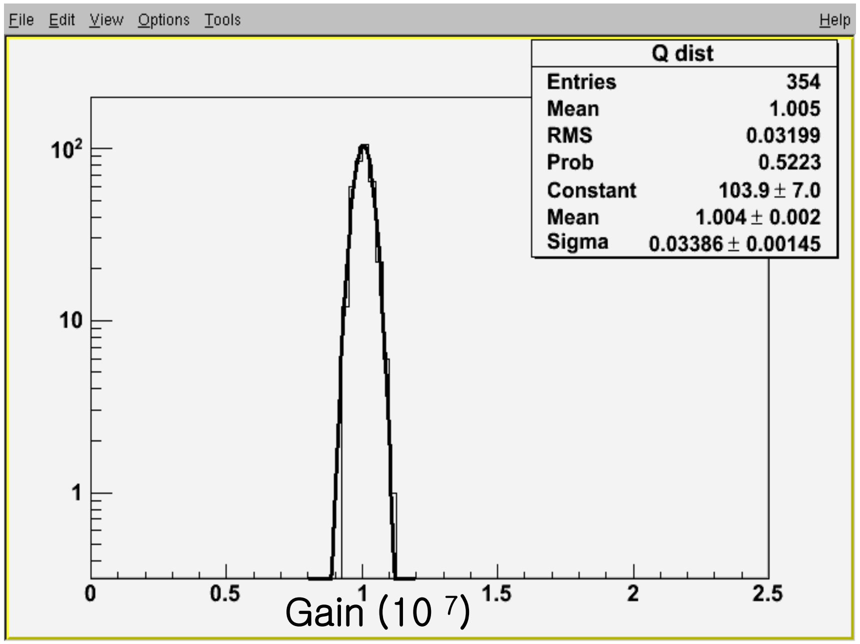
A candidate for a neutron capture by Gd

Event rate before reduction

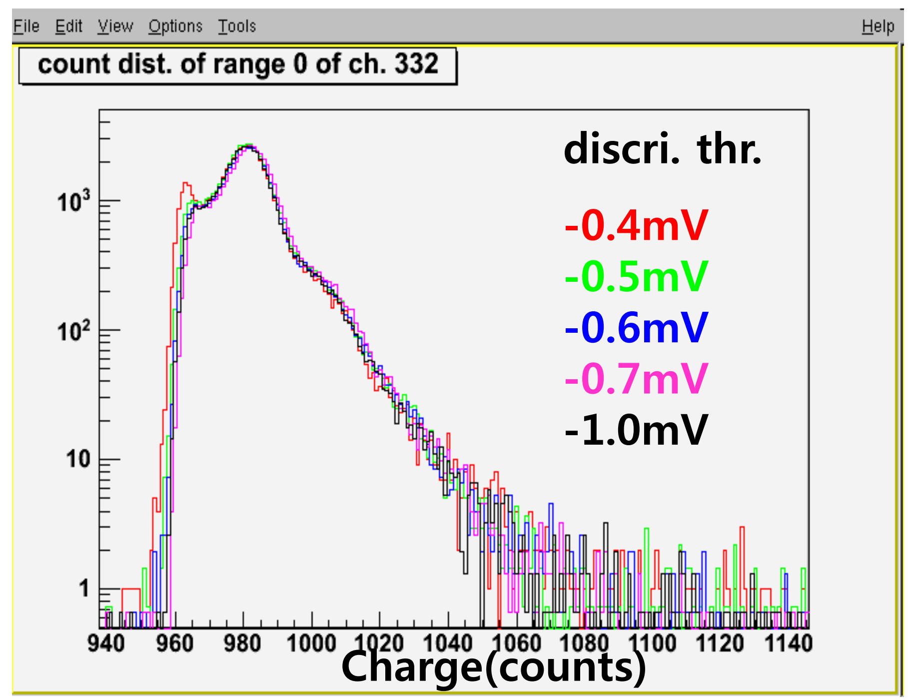


PMT Threshold & Gain Matching

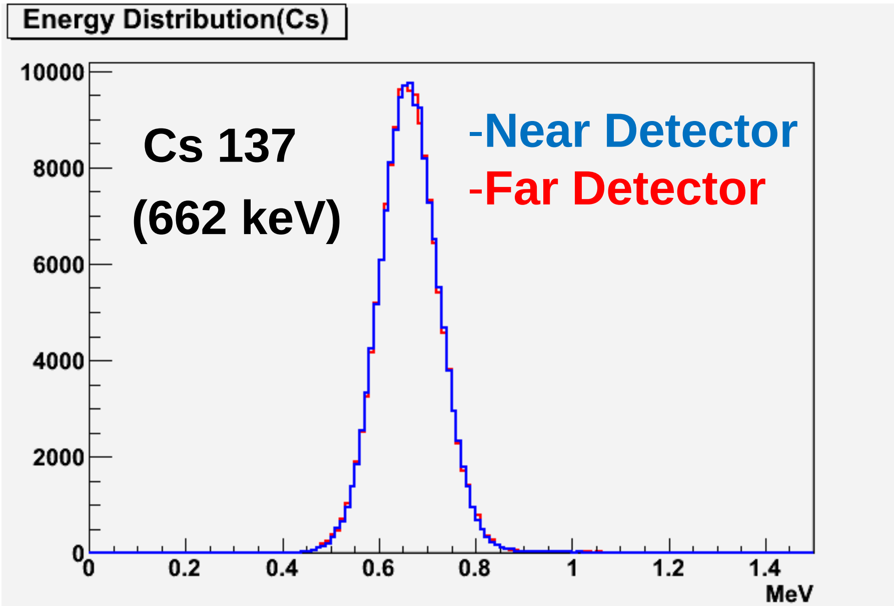
- PMT gain : set 1.0×10^7 using a Cs source at center
- Gain variation among PMTs : 3% for both detectors.

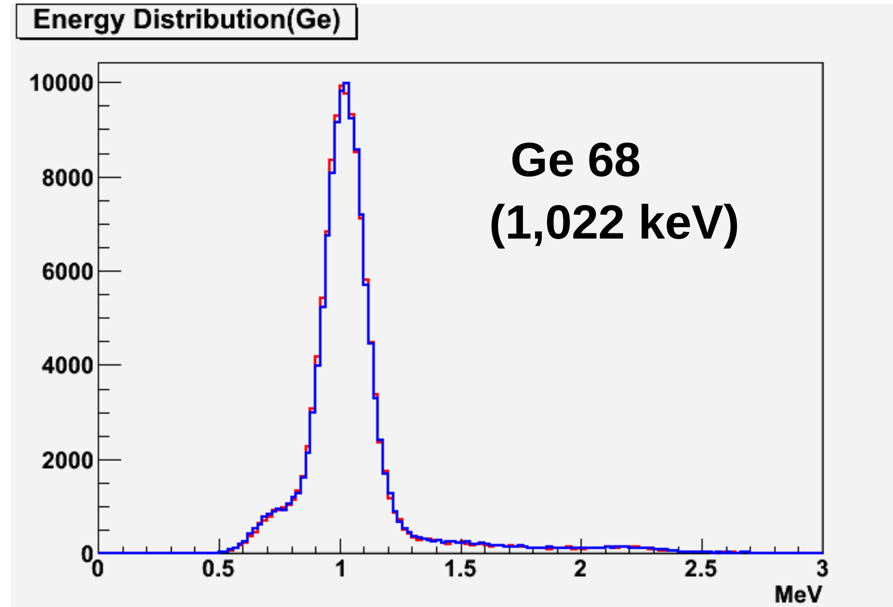


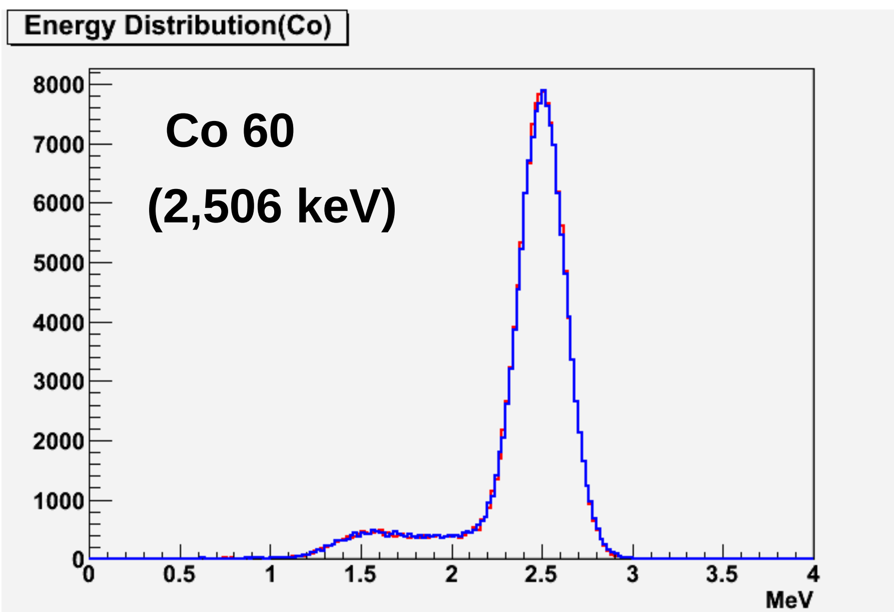
- PMT threshold : determined by a single photoelectron response using a Cs source at the center

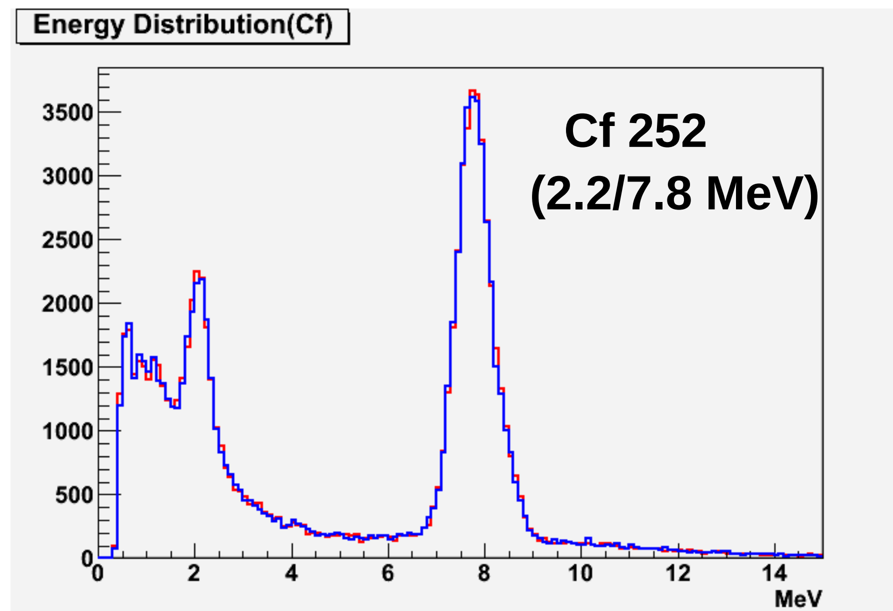


Energy Calibration



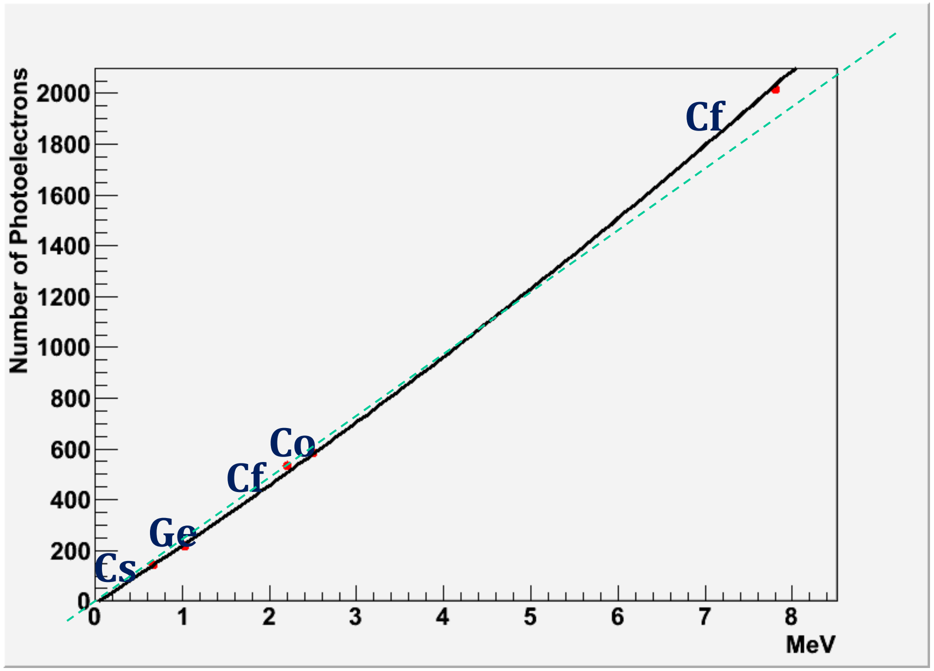




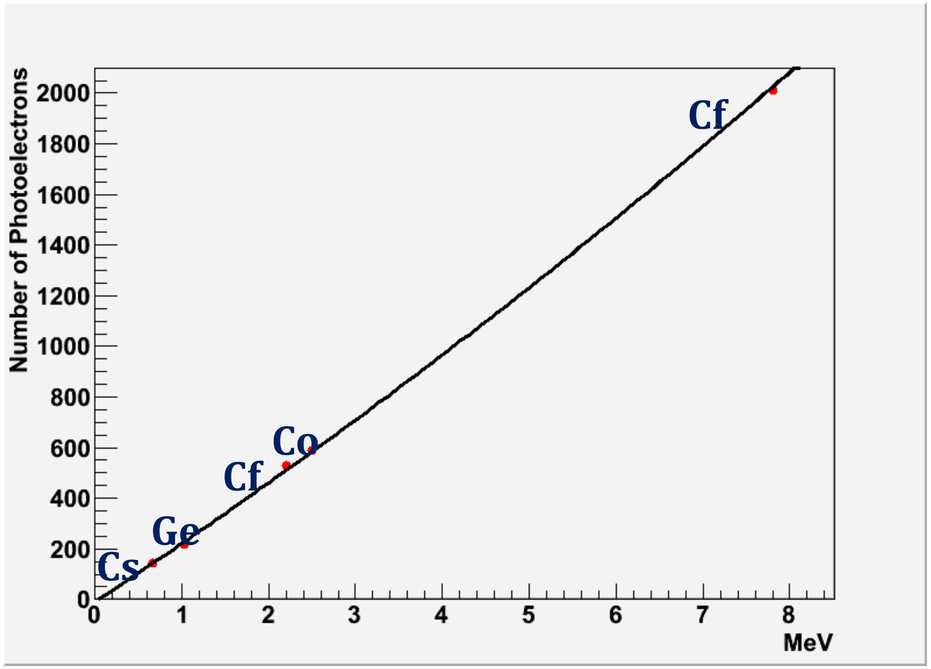


Energy Scale Calibration

Near Detector



Far Detector

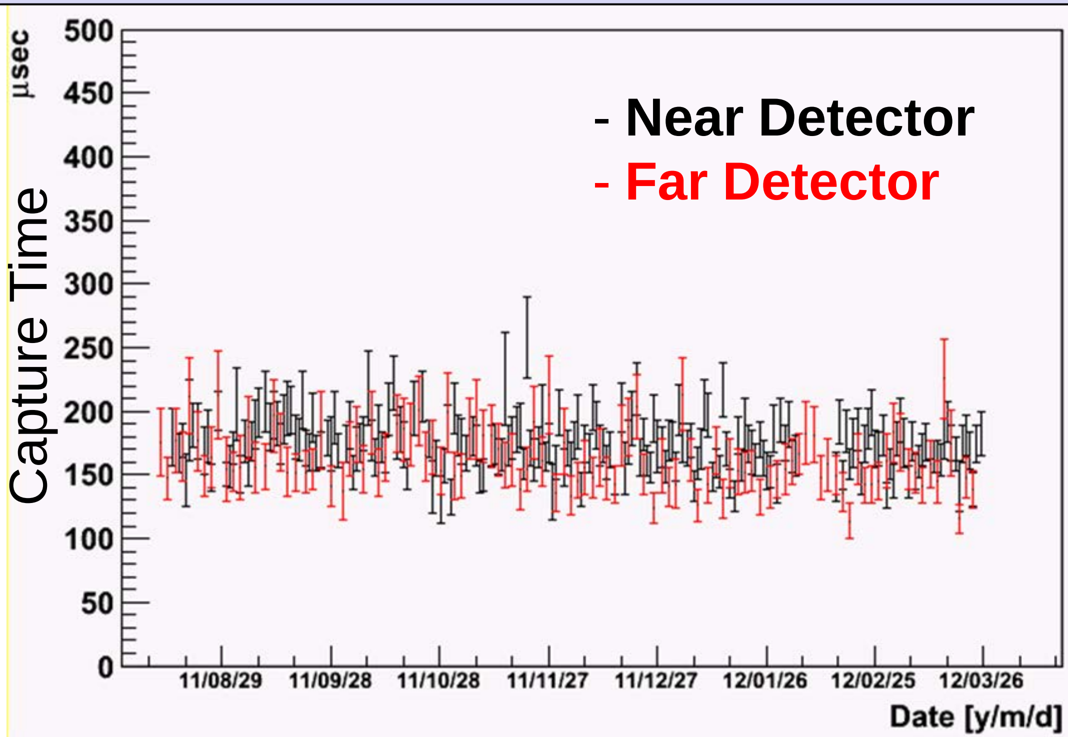


$$\delta E = \frac{5.9\%}{\sqrt{E(MeV)}} + 1.1\%$$

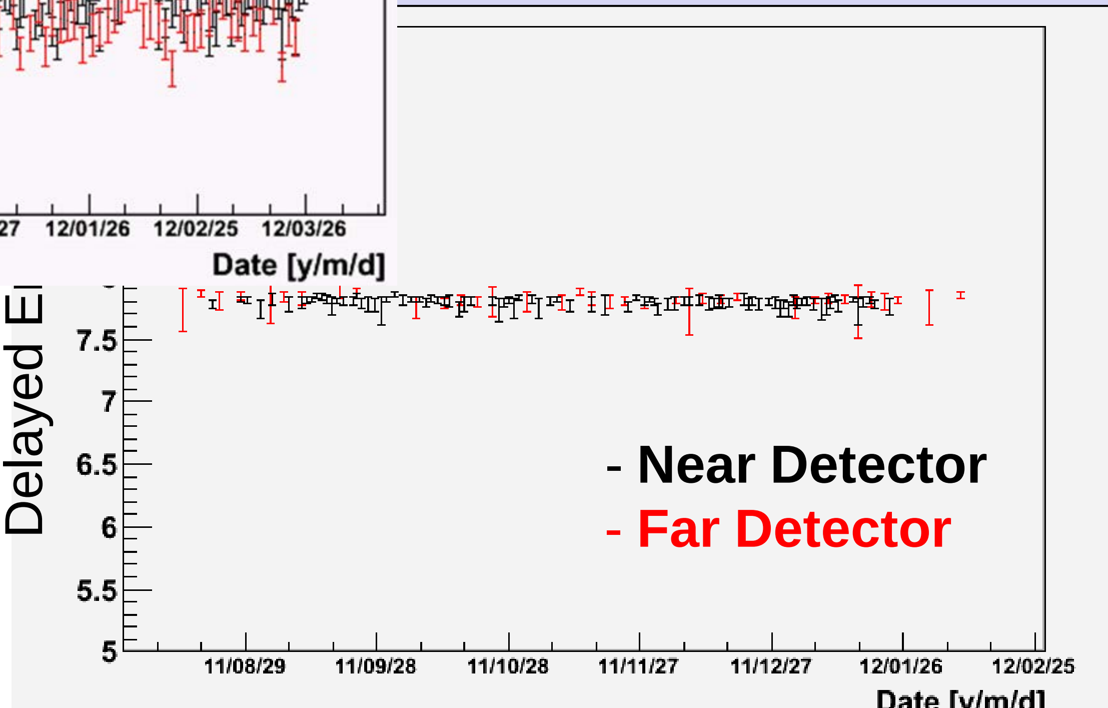
- ~ 250 pe/MeV (sources at center)
- Identical energy response (< 0.1%) of ND & FD
- Slight non-linearity observed

Detector Stability & Identity

- Cosmic muon induced neutron's capture by H



delayed signals (capture on Gd)

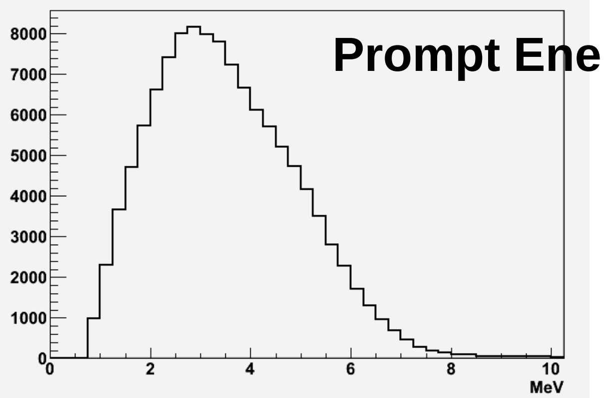


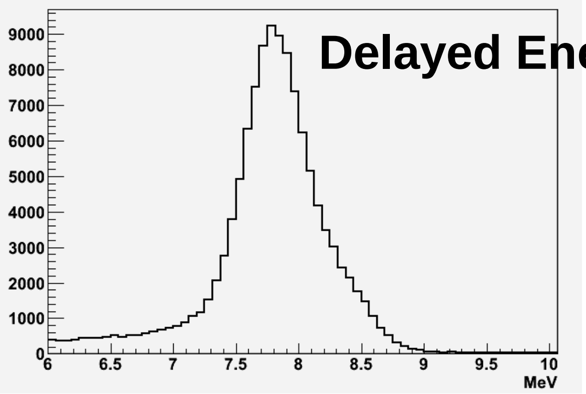
IBD Event Signature and Backgrounds

❑ IBD Event Signature

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

- Prompt signal (e^+) : 1 MeV 2γ's + e^+ kinetic energy (E = 1~10 MeV)
- Delayed signal (n) : 8 MeV γ's from neutron's capture by Gd
  ~28 μs (0.1% Gd) in LS





❑ Backgrounds

- Random coincidence between prompt and delayed signals (uncorrelated)
- ^{9}Li/^{8}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 : $Q_{max}/Q_{tot} < 0.03$
- ❑ 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 μs
  - E_{prompt} : 0.7 ~ 12.0 MeV, $E_{delayed}$: 6.0 ~ 12.0 MeV
  - coincidence : 2 μs < Δt_{e+n} < 100 μs
- ❑ Multiplicity cut : reject pairs if there is a trigger in the preceding 100 ms window

Random Coincidence Backgrounds

❑ Calculation of accidental coincidence

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

- ΔT = 100 μs time window
- Near detector :

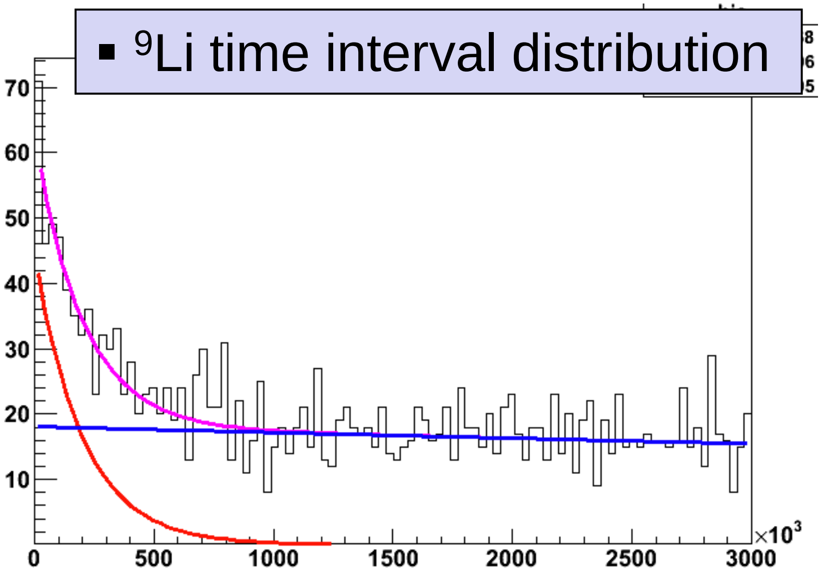
  R_{prompt} = 8.8 Hz, N_{delay} = 4884/day $\rightarrow$ $BG^{near}_{accidental} = 4.30 \pm 0.06 / day$
- Far detector :

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

$^{9}Li/^{8}He$ β-n Backgrounds

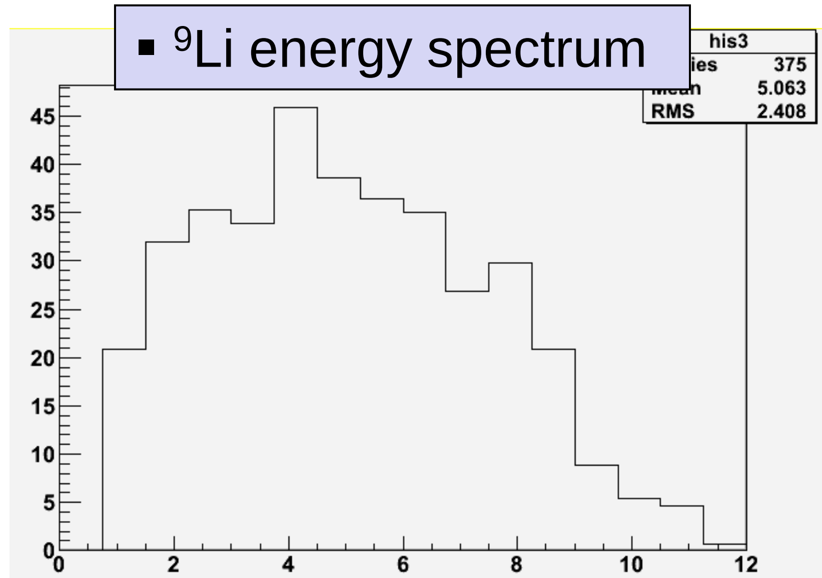
❑ Find prompt-delay pairs after muons, and obtain their time interval distribution with respect to the preceding muon.

▪ ^{9}Li time interval distribution



Time interval (ms)

▪ ^{9}Li energy spectrum



Energy (MeV)

▪ Near detector :

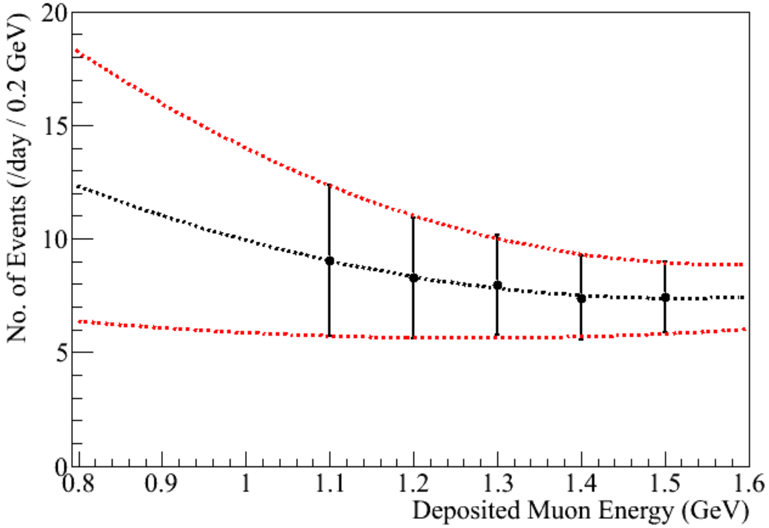
$$BG^{near}_{Li/He} = 12.45 \pm 5.93 / day$$

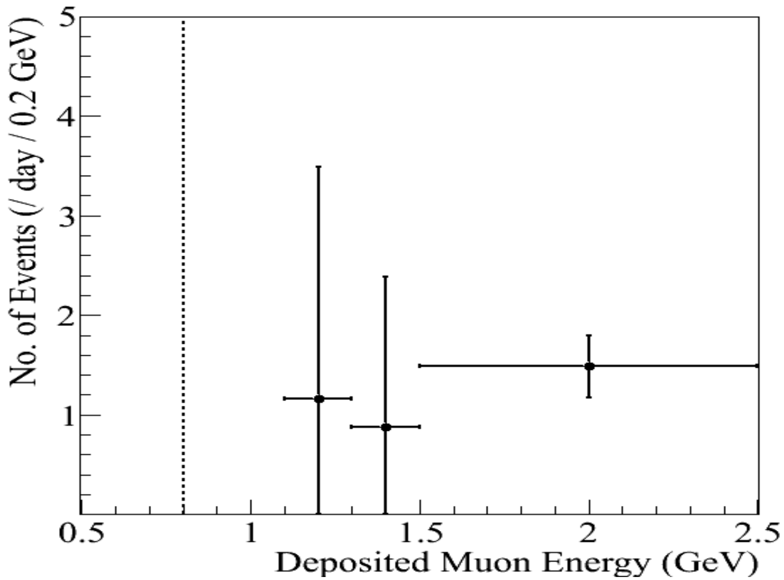
▪ Far detector :

$$BG^{far}_{Li/He} = 2.59 \pm 0.75 \ / day$$

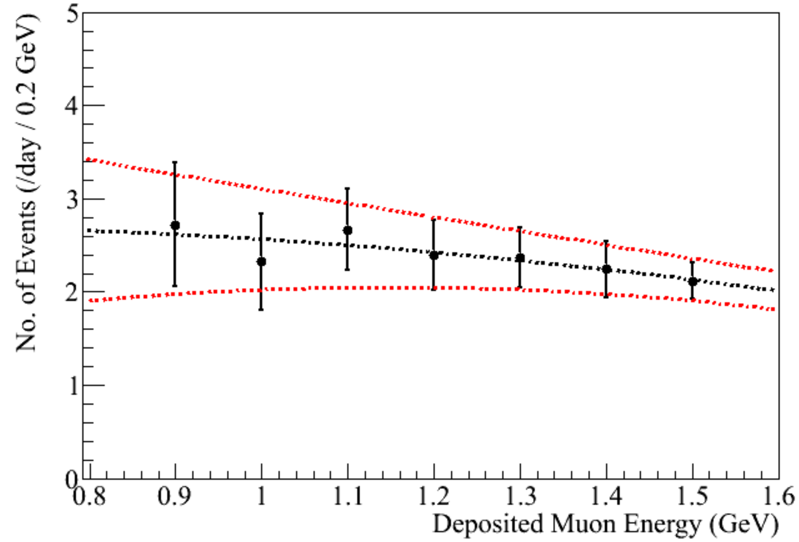
$^{9}Li/^{8}He$ β-n Backgrounds

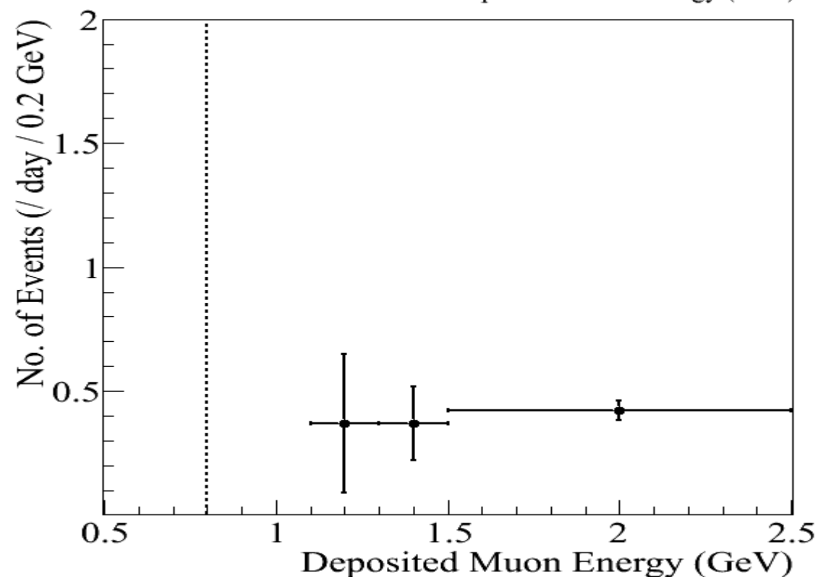
- ^{9}Li production at near detector





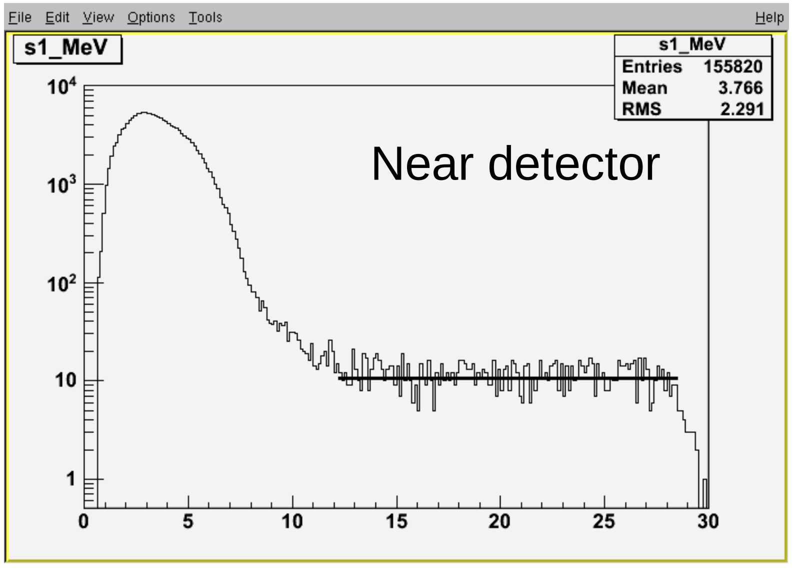
- ^{9}Li production at far detector

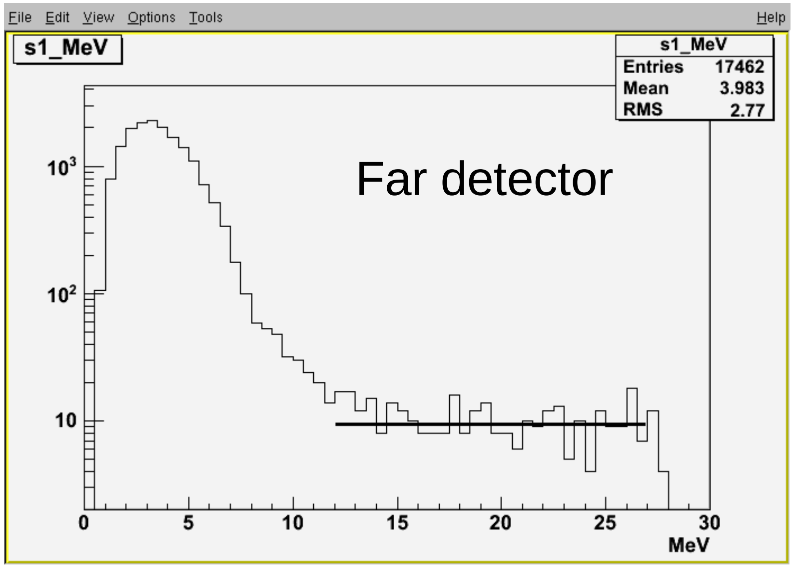




Fast Neutron Backgrounds

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

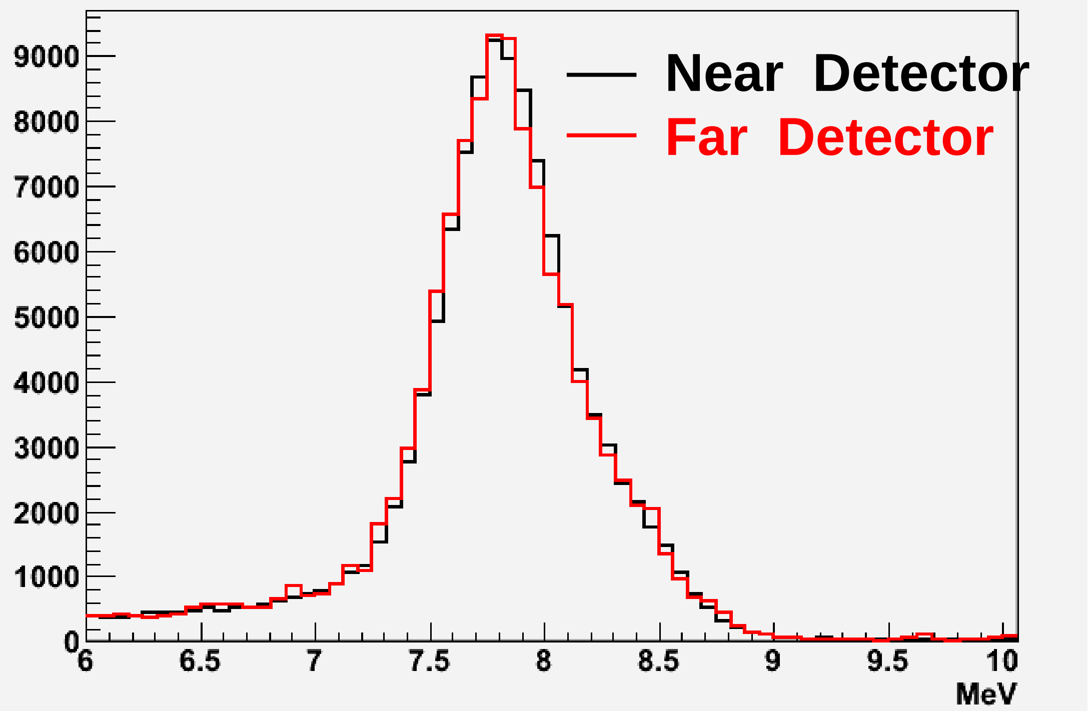




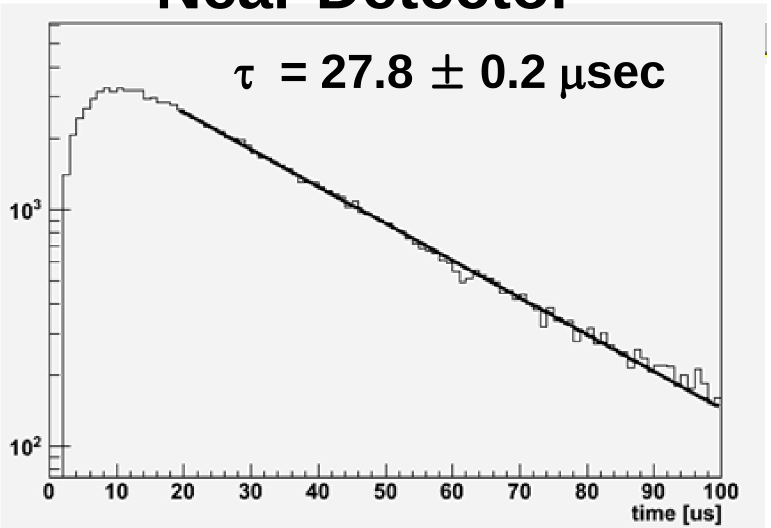
- Near detector : $BG^{near}_{neutron} = 5.00 \pm 0.13 \quad / \, day$
- Far detector : $BG^{far}_{neutron} = 0.97 \pm 0.06 \quad / \, day$

Spectra & Capture Time of Delayed Signals

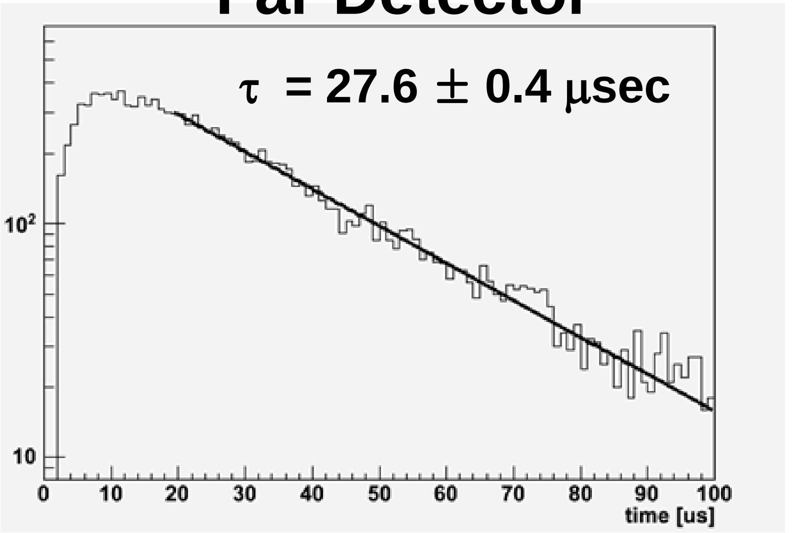
❑ Observed spectra of IBD delayed signals



Near Detector



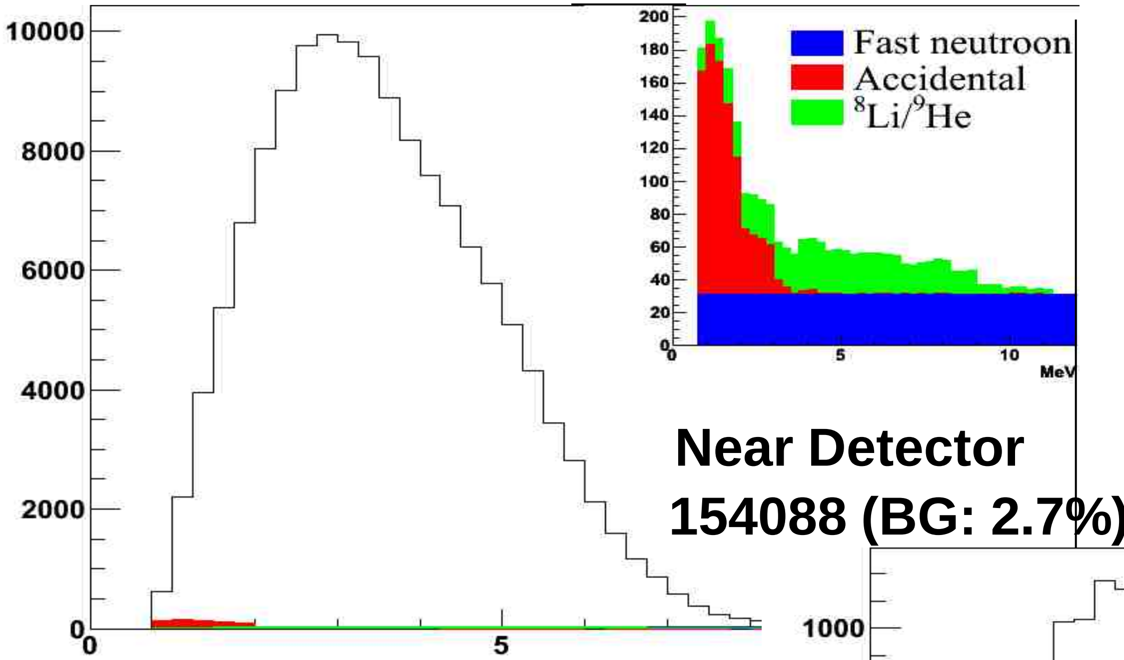
Far Detector

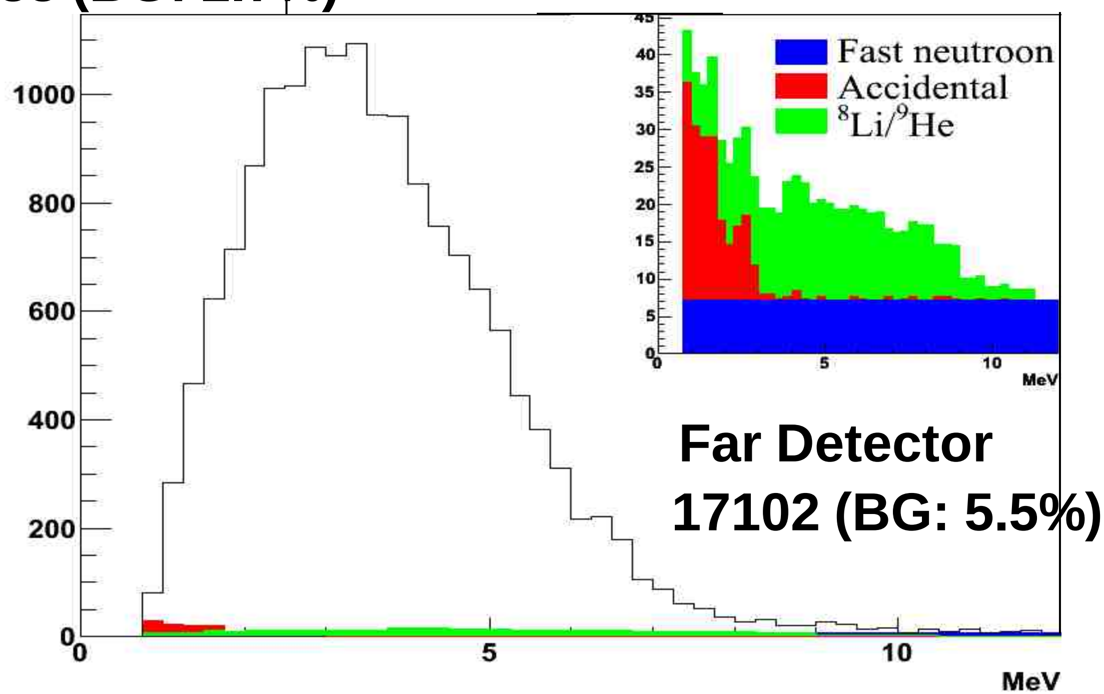


Summary of Final Data Sample

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}Li/^{8}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





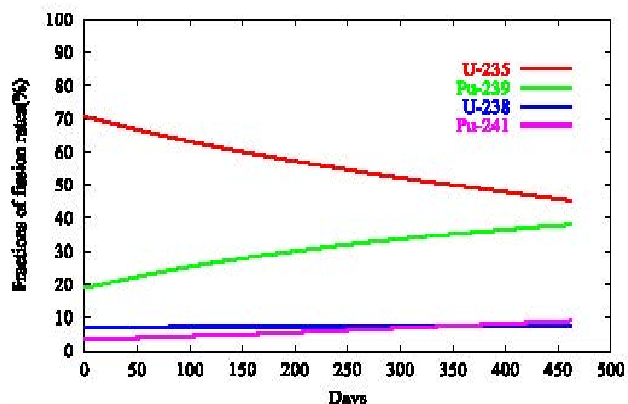
Expected Reactor Antineutrino Fluxes

- Reactor neutrino flux

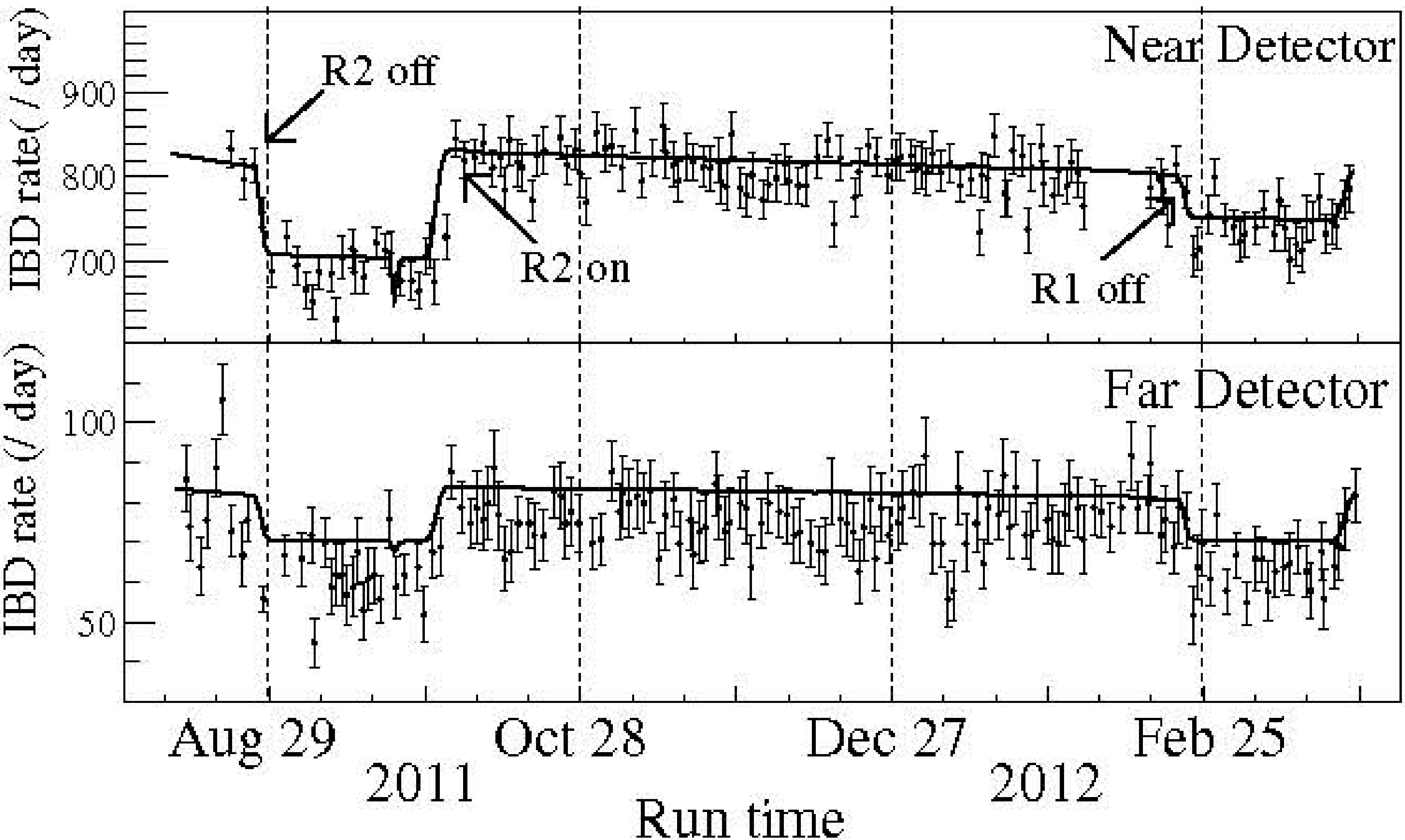
$$\Phi(E_\nu) = \frac{P_{th}}{\sum_i^{isotopes} f_i \cdot E_i} \sum_i^{isotopes} f_i \cdot \phi_i(E_\nu)$$

- 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**

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

Neutrino events	$1/r^2$	Number of protons	Detection efficiency	Yield of $\sin^2(2\theta_{13})$

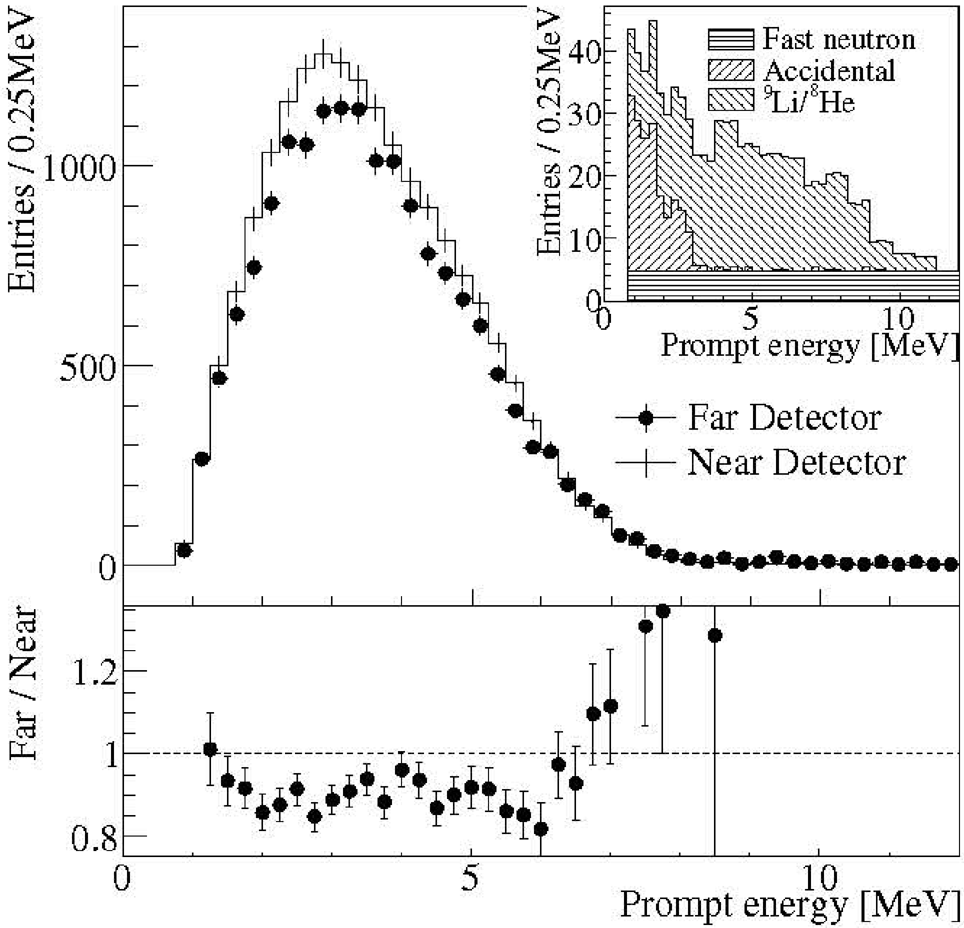
Efficiency & Systematic Uncertainties

Prompt energy cut	
Flasher cut	
Gd capture fraction	
Delayed energy cut	
Time coincidence cut	
Spill-in	
Common	
Muon veto loss ($\delta_{\mu-veto}$)	(11.
Multiplicity cut loss (δ_{multi})	(4.
Total	((

Reactor		
	Uncorrelated	Correlated
Thermal power	0.5%	—
Fission fraction	0.7%	—
Fission reaction cross section	—	1.9%
Reference energy spectra	—	0.5%
Energy per fission	—	0.2%
Combined	0.9%	2.0%
Detection		
	Uncorrelated	Correlated
IBD cross section	—	0.2%
Target protons	0.1%	0.5%
Prompt energy cut	0.01%	0.1%
Flasher cut	0.01%	0.1%
Gd capture ratio	0.1%	0.7%
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

$$R = \frac{\Phi^{Far}_{observed}}{\Phi^{Far}_{\exp ected}} = 0.920 \pm 0.009(stat.) \pm 0.014(syst.)$$



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

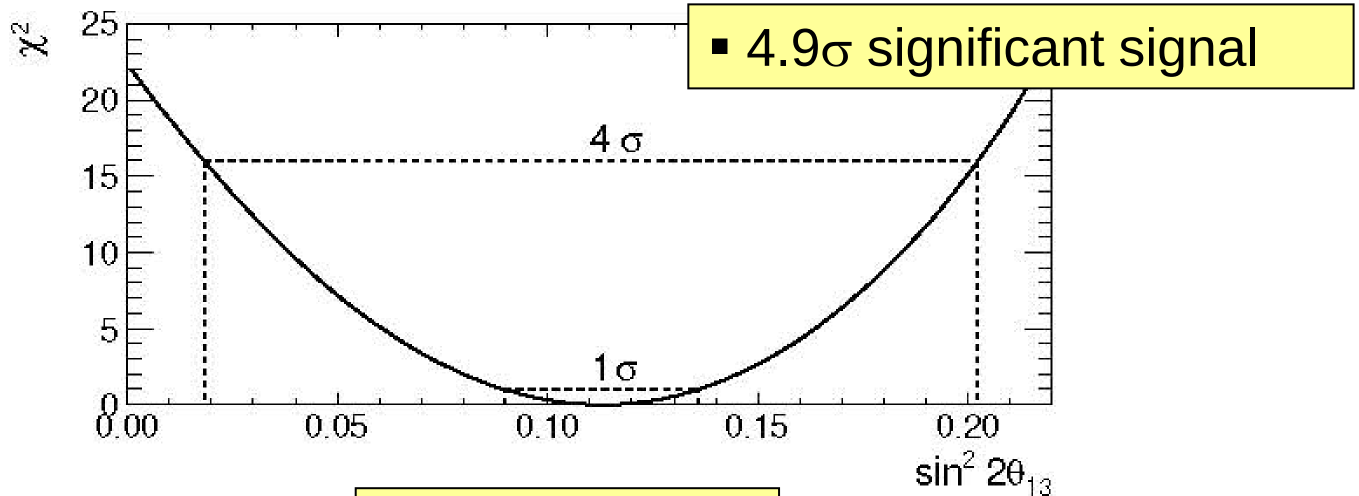
χ^2 Fit with Pulls

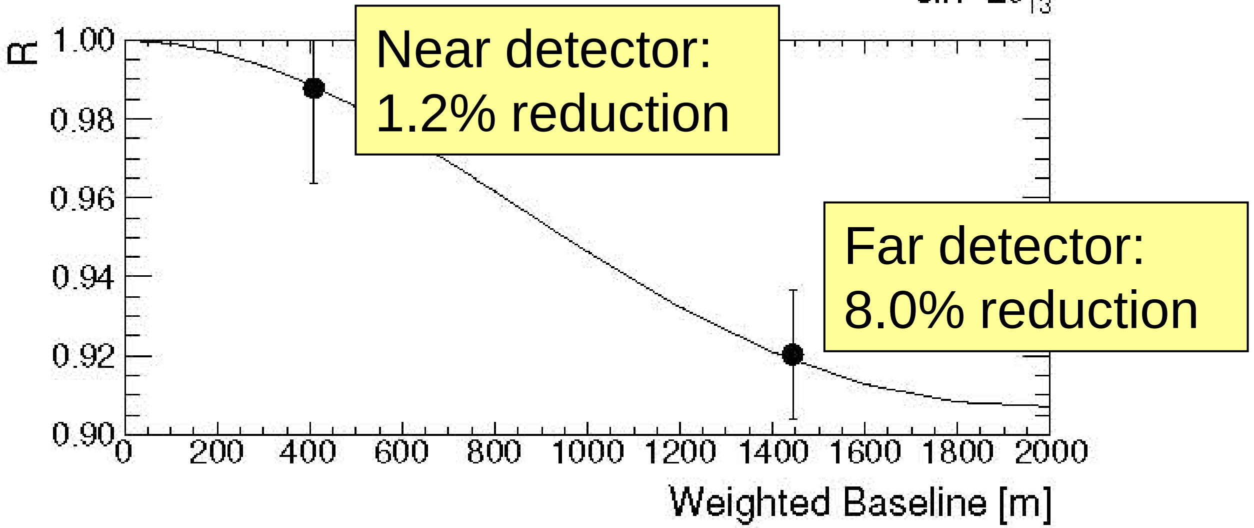
$$\chi^2 = \sum_{d=N,F} \frac{\left[N_{obs}^{d} + b_d - (1 + a + \xi_d)\sum_{r=1}^{6}(1 + f_r)N_{\exp}^{d,r}\right]^2}{N_{obs}^{d}}$$

$$+ \sum_{d=N,F}\left(\frac{\xi_d^2}{\sigma_d^{\xi\,2}} + \frac{b_d^2}{\sigma_d^{b\,2}}\right) + \sum_{r=1}^{6}\left(\frac{f_r}{\sigma_r}\right)^2$$

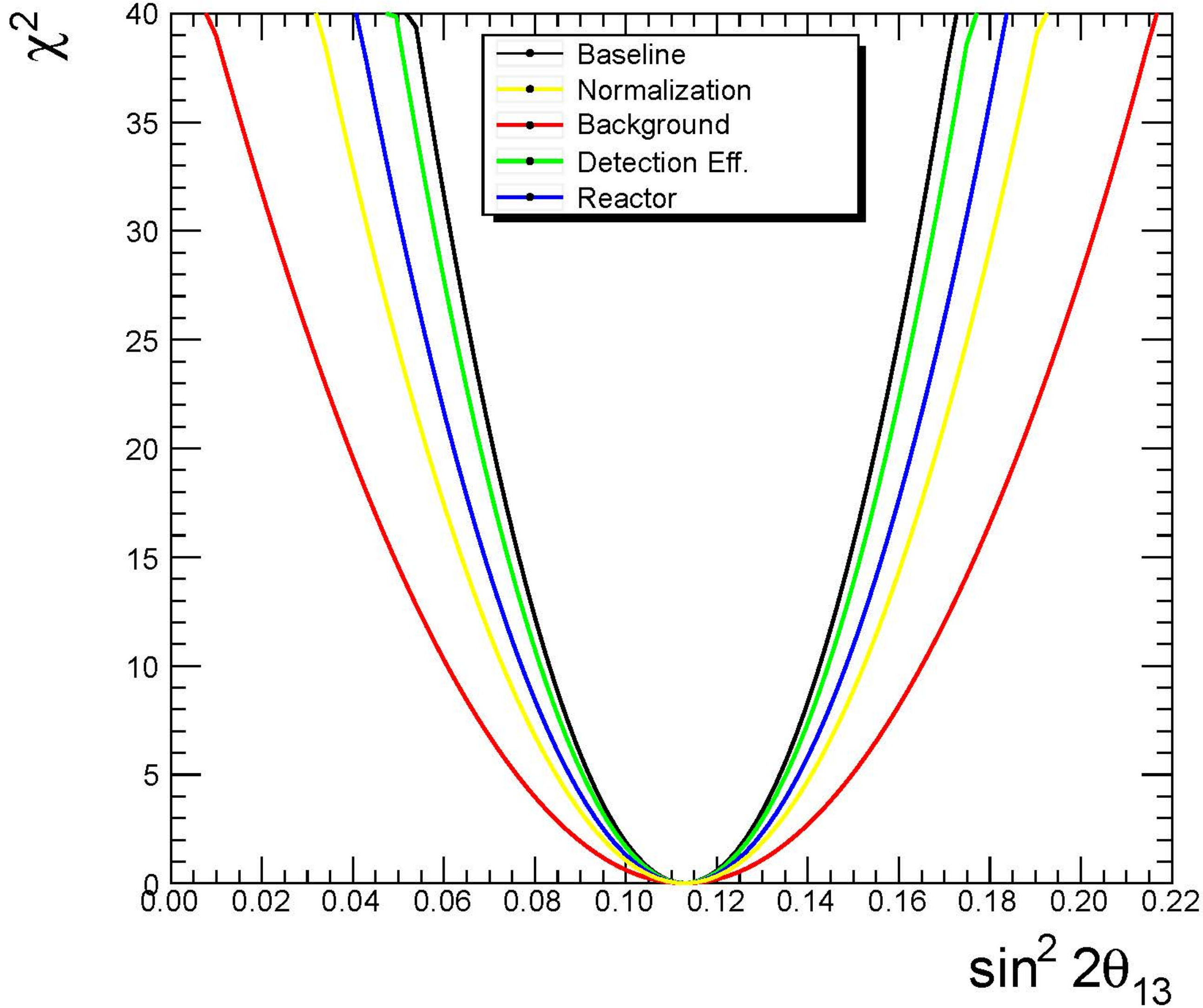
Definitive Measurement of θ_{13}

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





χ^2 Distributions for Uncertainties



Future Efforts for Precision Measurement of θ_{13}

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

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

- Contributions of the systematic errors :
  - Background uncertainties : 0.0165
    (far : 5.5%×17.7% = 0.97%, near : 2.7%×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.

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

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

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

- 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.