OBSERVATION OF REACTOR NEUTRINO DISAPPEARANCE AT RENO

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On behalf of RENO collaboration

2012. 5. 8

NuTurn, Gran Sasso, INFN

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- Θ_{13} measurement with reactor neutrinos
- RENO Sites
- Final Construction of RENO
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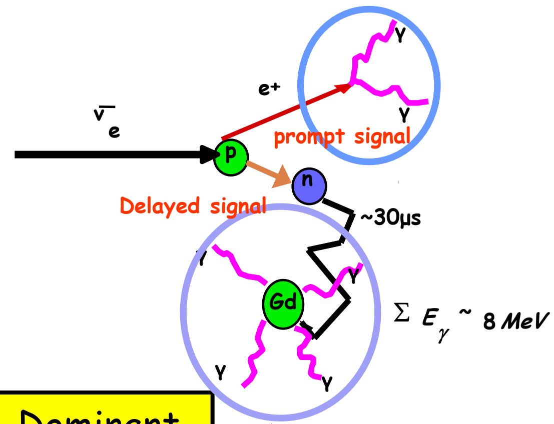
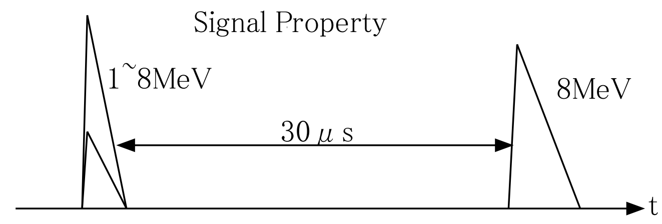
- Summary & Perspectives

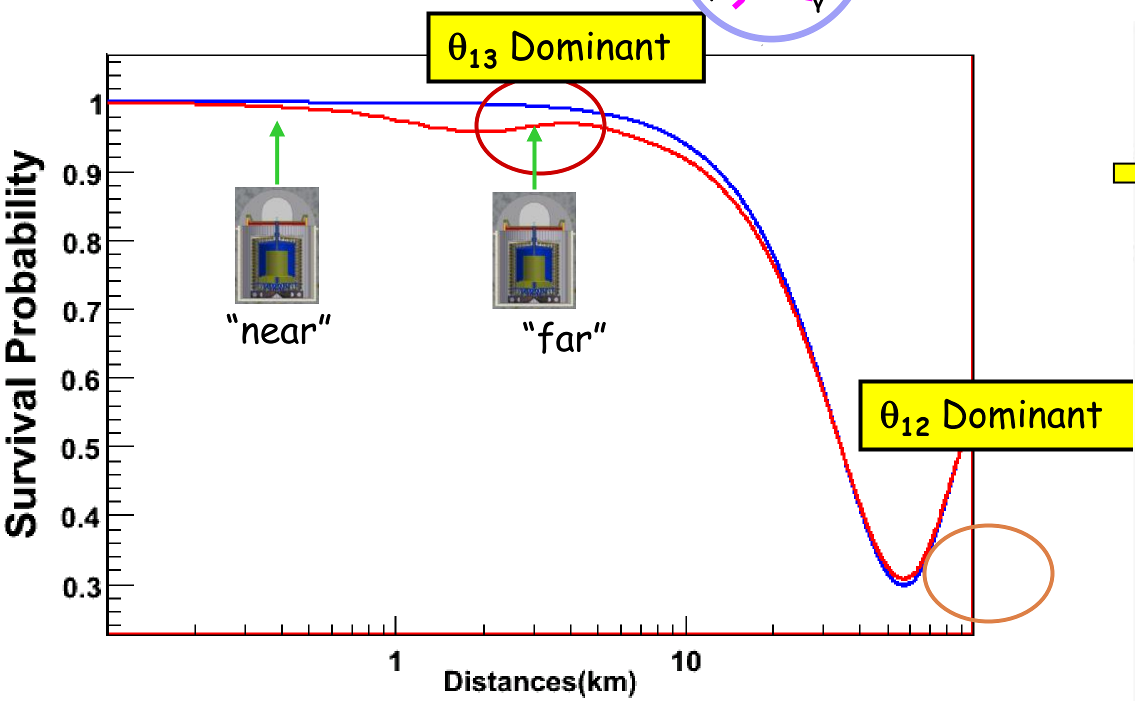
Reactor Neutrino Experiment at a Glance

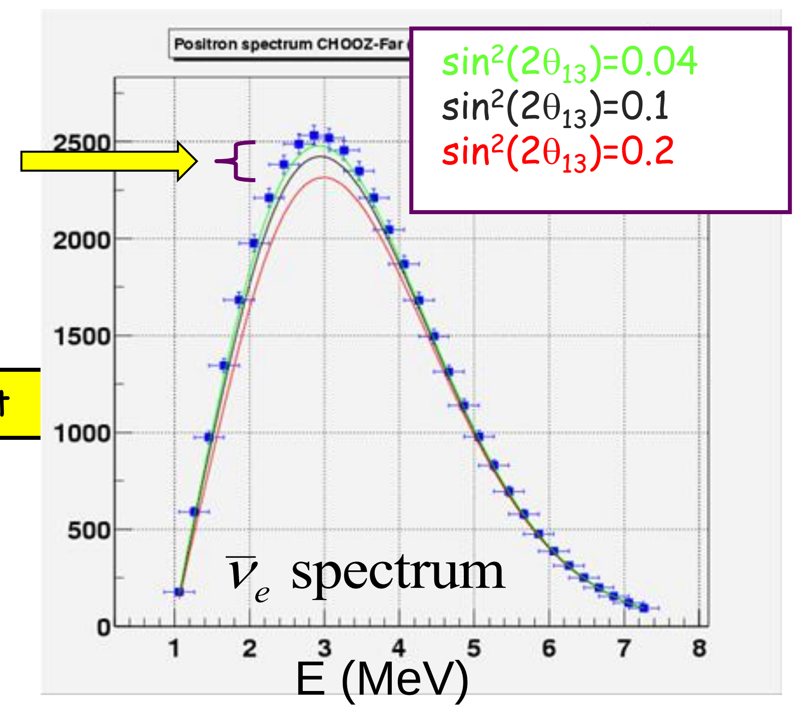
Inverse Beta Decay

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









$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2(2\theta_{13})\sin^2\Delta_{31} - \cos^4\theta_{13}\sin^2(2\theta_{12})\sin^2\Delta_{21}$$

RENO Collaboration

Project of Only Korean Institutes

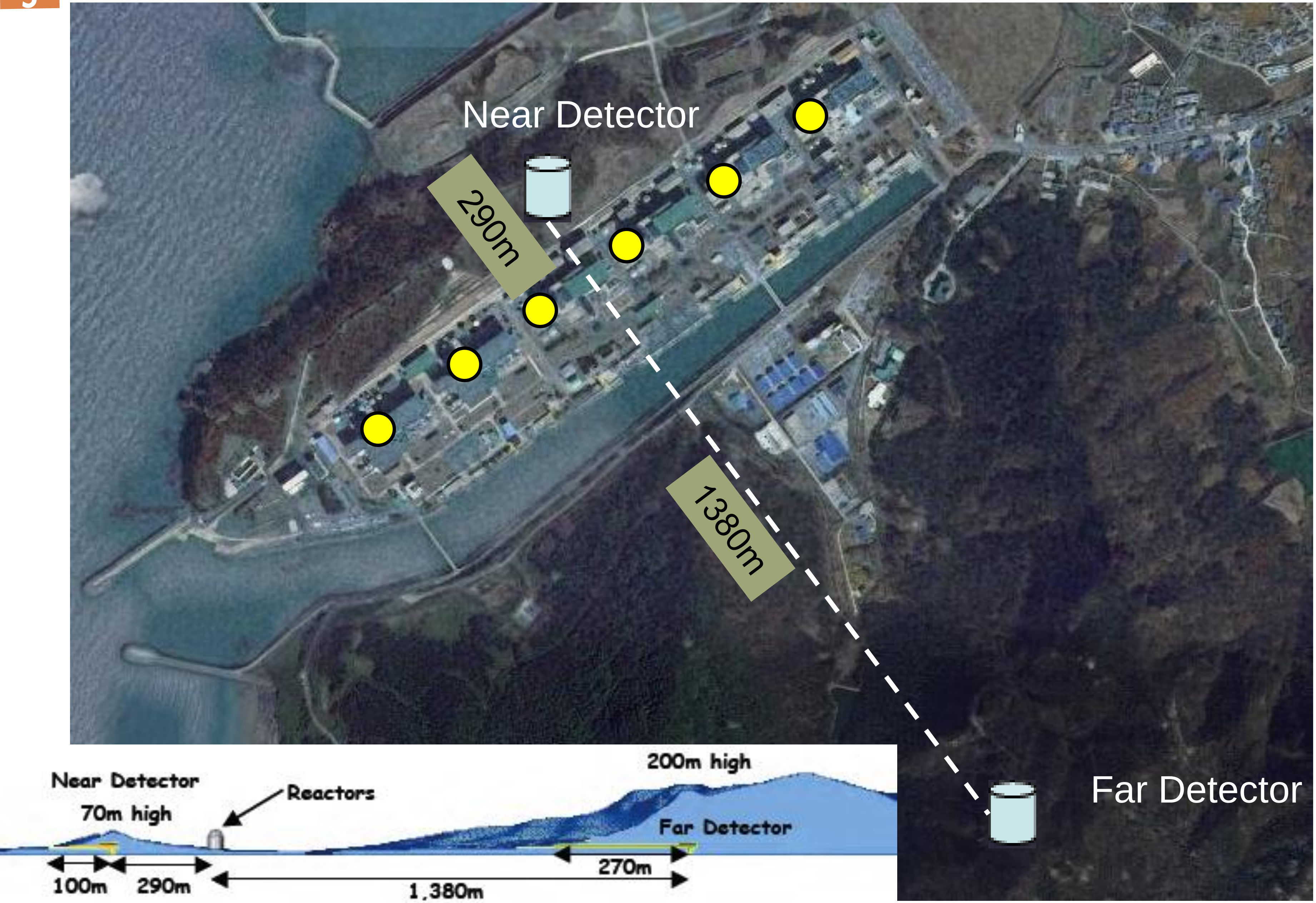
(12 institutions and 40 physicists)

- 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 Sites

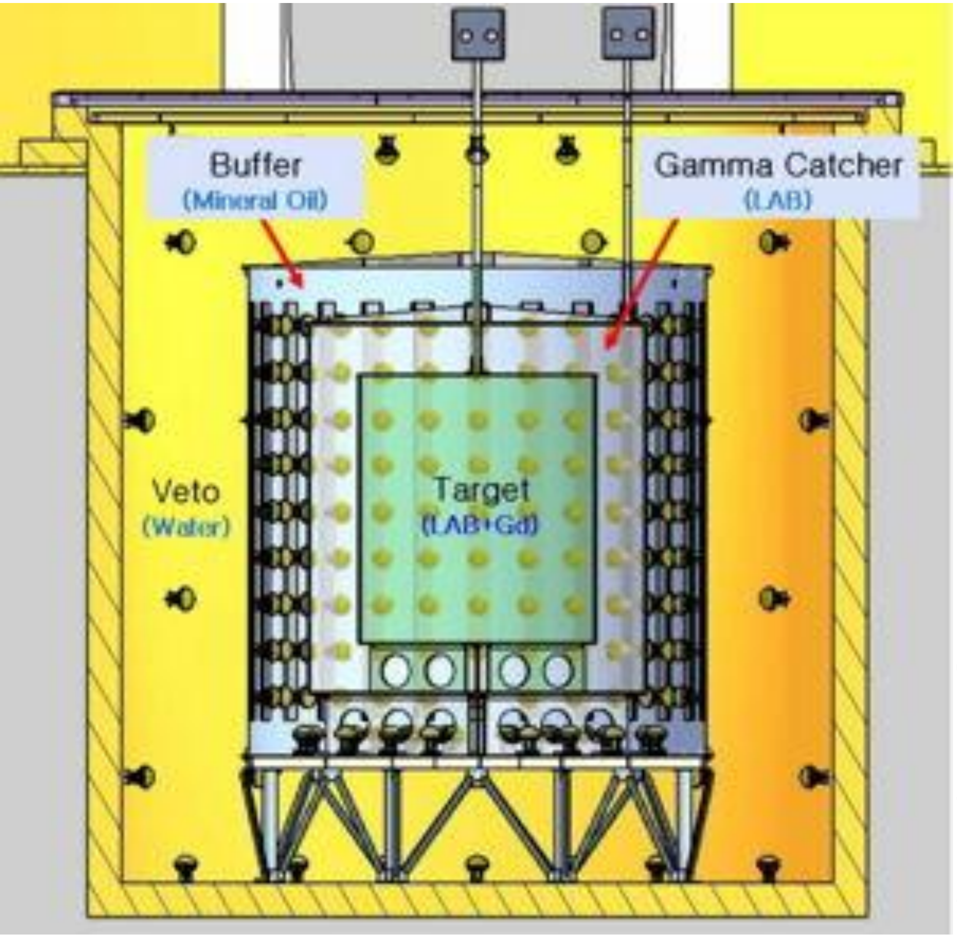

Near Detector
290m
1380m
Far Detector
200m high
Near Detector
70m high
Reactors
Far Detector
100m
290m
1,380m
270m

Contributions of Reactors to Neutrino Flux

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 10” ID PMTs : 14% surface coverage
- 67 10” OD PMTs
- Both PMTs : HAMAMATSU, R7081
- Mu-metal shielding for each PMT. (-5cm)
- No special reflector for ID
- Tyvek reflector at OD

LAYER	D (cm)	H (cm)	vessel	Filled with	Mass (tons)
Target	280	320	Acrylic	Gd(0.1%) +LS	16.5
Gamma catcher	400	440	Acrylic	LS	30.0
Buffer	540	580	SUS	Mineral oil	64.4
Veto	840	880	Concrete	water	352.6

Summary of Milestones for RENO

- 2006. 03 : Start of the RENO project
- 2008. 06 ~ 2009. 03 : Civil construction including tunnel excavation
- 2008. 12 ~ 2009. 11 : Detector structure & buffer tanks complete.
- 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. 05 ~ 07 : Liquid scintillator production & filling
- 2011. 08 : Start data-taking.

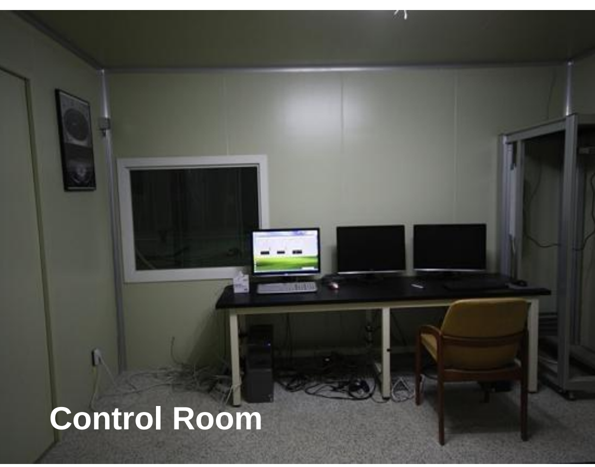
- 2011. 11 : Double Chooz — $\sin^2(2\theta_{13}) = 0.086 \pm 0.041(\text{stat.}) \pm 0.030(\text{syst.})$
- 2012. 3. 8 : Daya Bay — $\sin^2(2\theta_{13}) = 0.092 \pm 0.016(\text{stat.}) \pm 0.005(\text{syst.})$
- 2012. 4. 3 : RENO results.

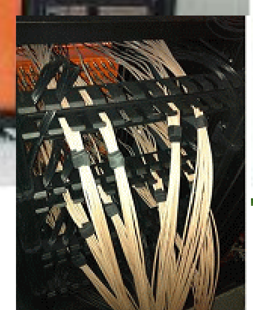
Detector Construction & Closing (Jan. 2011)

Near : Jan. 21, 2011

Far : Jan. 24, 2011

Completed RENO Detector (Feb. 2011)



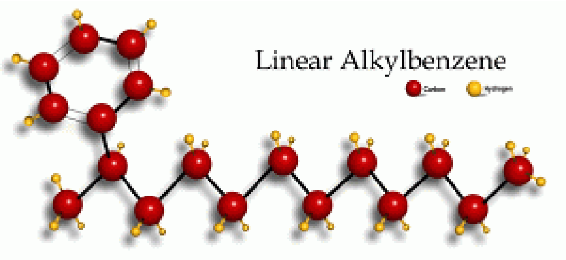


Gd Loaded Liquid Scintillator

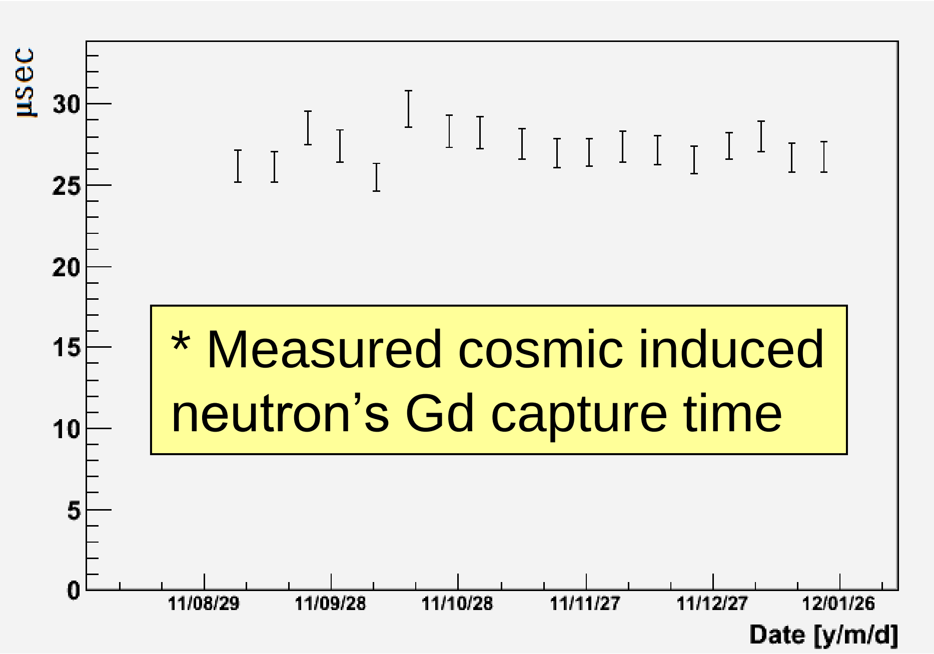
❑ Recipe of Liquid Scintillator

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

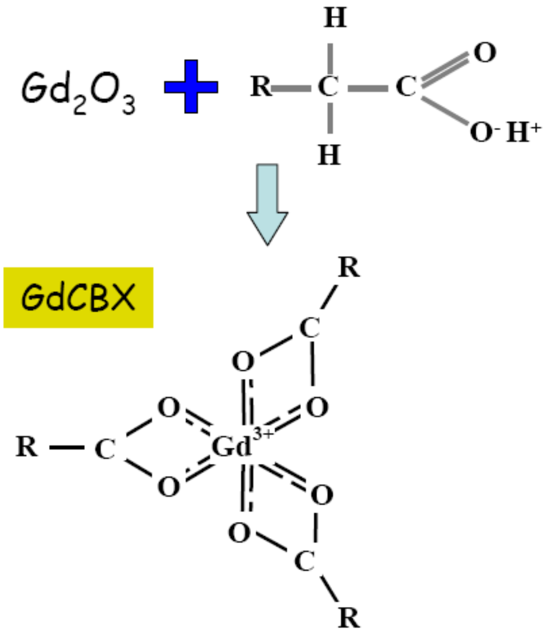
Aromatic Solvent & Flour	WLS	Gd−compound
LAB	PPO + Bis−MSB	0.1% Gd+(TMHA)^3 (trimethylhexanoic acid)



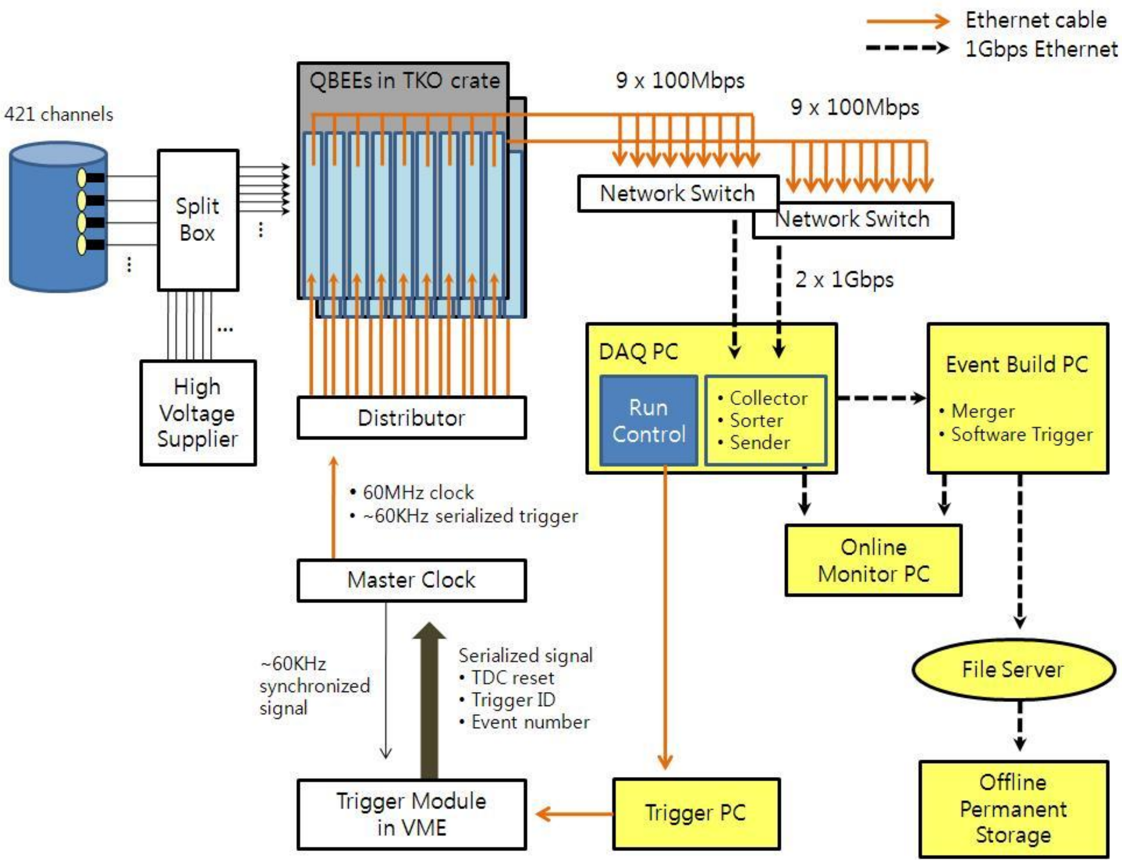
* Stable light yield over the time period : ~250 pe/MeV



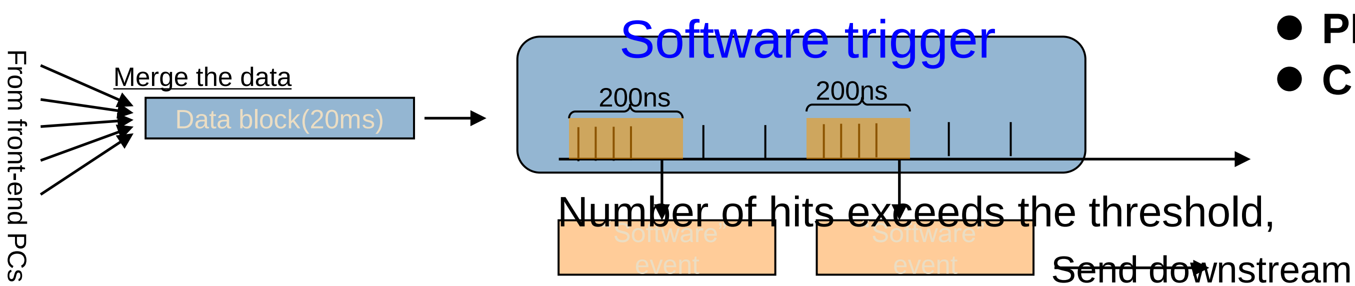
Carboxylic acids



Electronics & Trigger



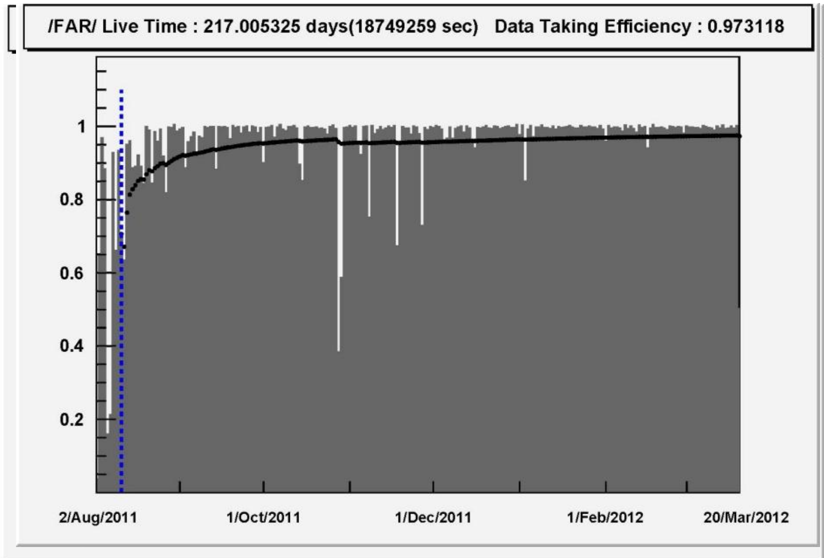
- QBEE : each channel digitized if over threshold.
- All the hits are sorted in time and grouped into an event if number of hits exceeds preset trigger condition. (ID:90, OD:10)
- Pedestal hits are collected realtime
- Intrinsic charge Injector into each channel for electronics calibration.
- Types of Trigger :
  - ID
  - OD
  - LASER
  - PEDESTAL
  - Charge Injector

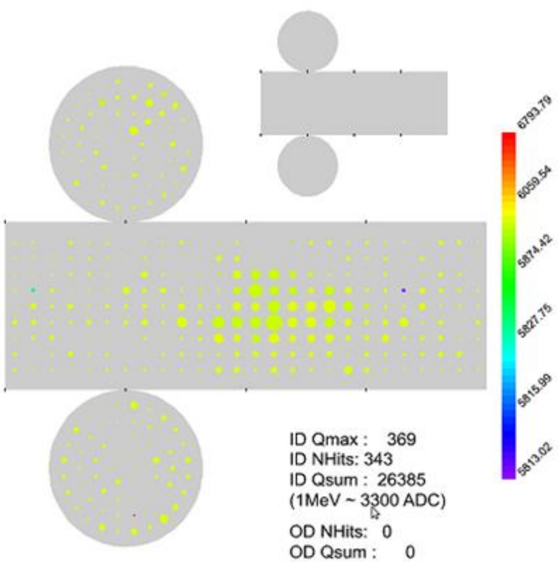


Data-Taking & Data Set

- 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 : 229 days Aug. 11, 2011 ~ Mar. 26, 2012

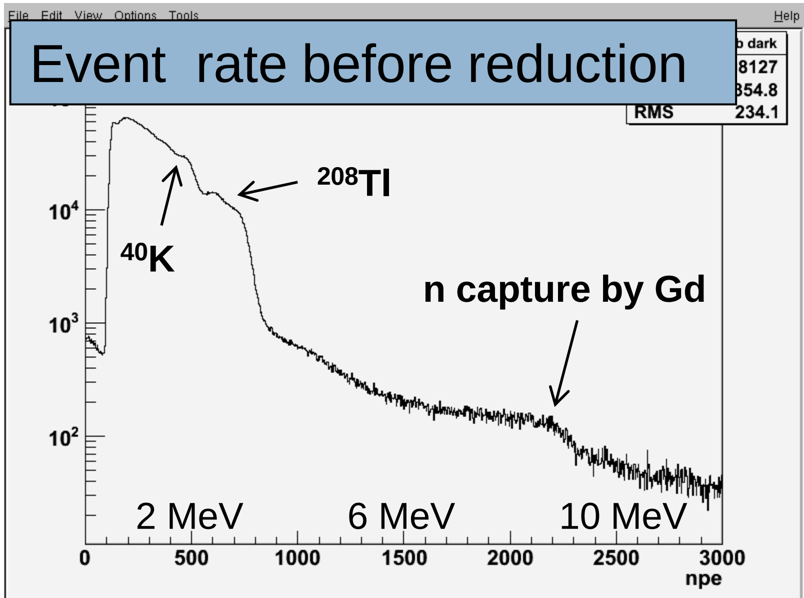
- Data-taking efficiency





A candidate for a neutron capture by Gd

Event rate before reduction



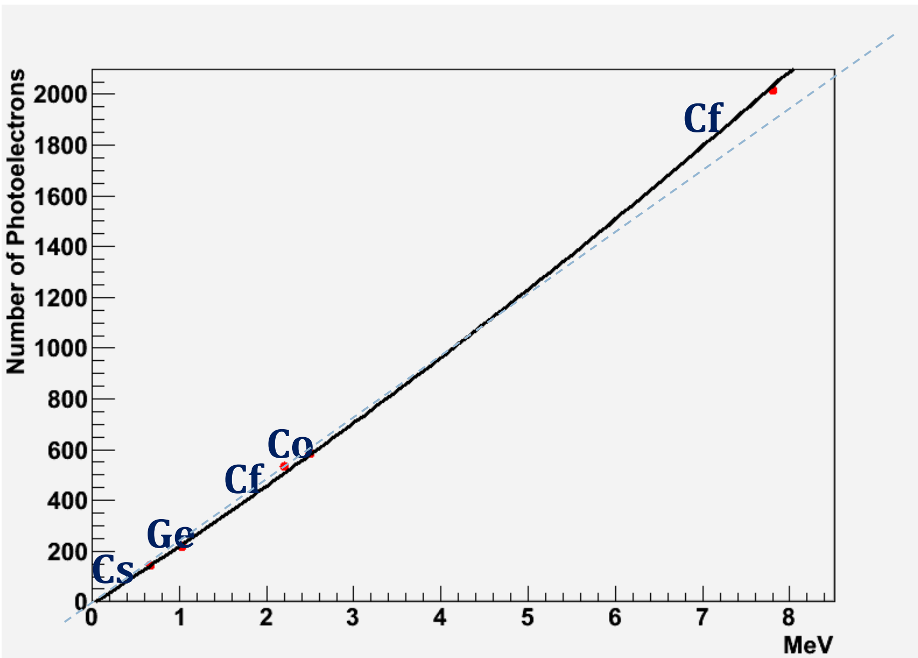
Trigger Rates

	NEAR	FAR
Depth (mwe)	120	450
Distance from Reactor baseline(m)	294	1383
Flux weighted distance (m)	408.56	1443.99
Muon Rate (Simulation)(/m^2 sec)#	5.5	0.85
Average Muon energy (GeV)#	34.3	65.2
Inner Detector (Hz) (N_{PMT} >90)*	~280	~110
Outer Detector (Hz) (N_{PMT} >10)*	~533	~66

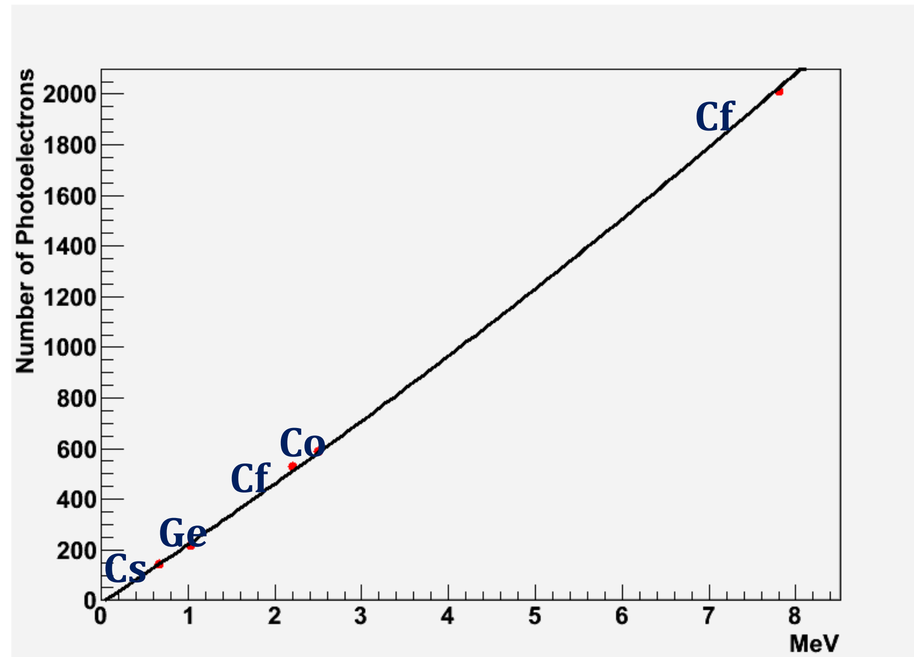
- * N_{PMT} is counted within 50nsec.
- # Simulated for Near (70m), Far(200m) depths.

Energy Calibration w/ source

Near Detector



Far Detector

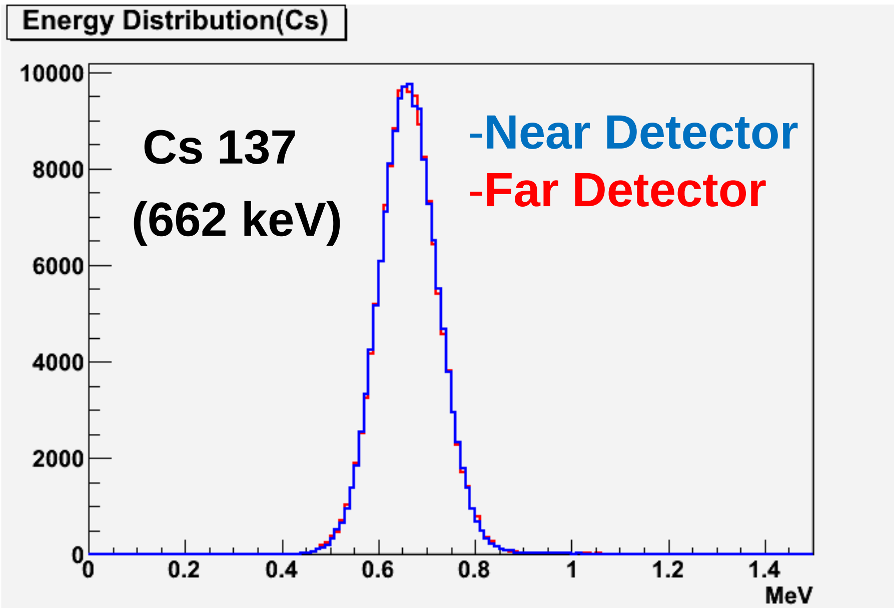


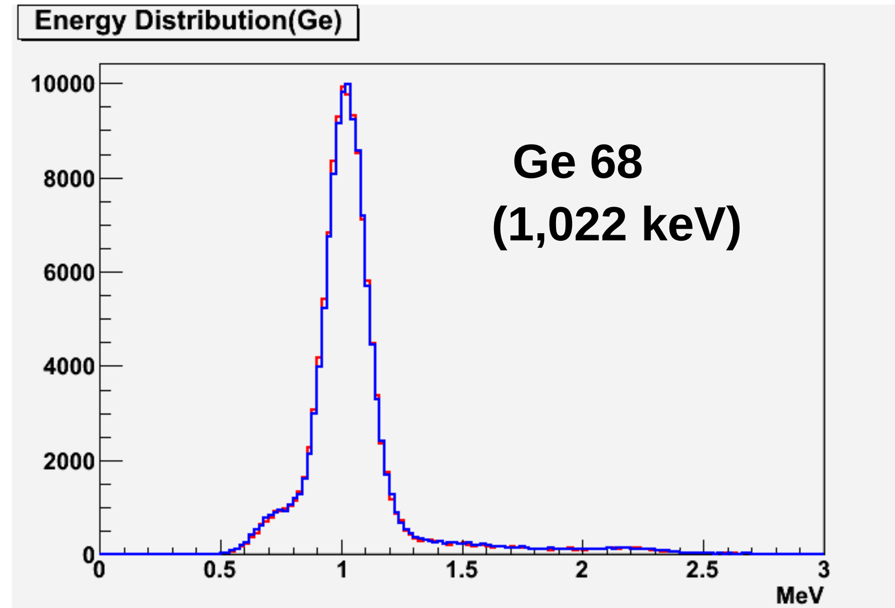
$$\delta E = \frac{5.9\%}{\sqrt{E(MeV)}} + 1.1\%$$

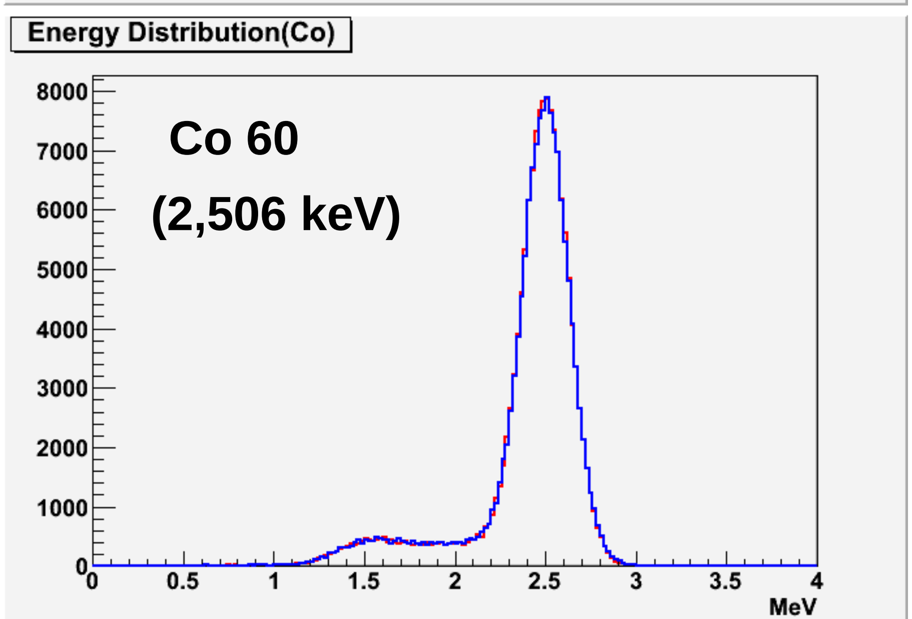
Plots to be updated !
E(neutron capture) → 8.047MeV
4.438 MeV (Po-Be source) will be added.

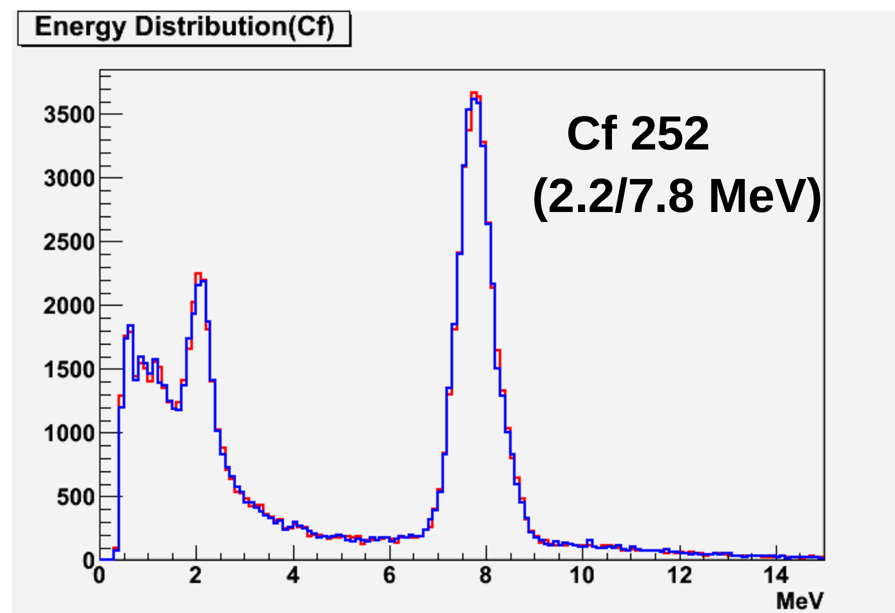
- ~ 250 pe/MeV (sources at center)
- Identical energy response (< 0.1%) of ND & FD
- Slight non-linearity observed

Spectra w/ sources after calibration



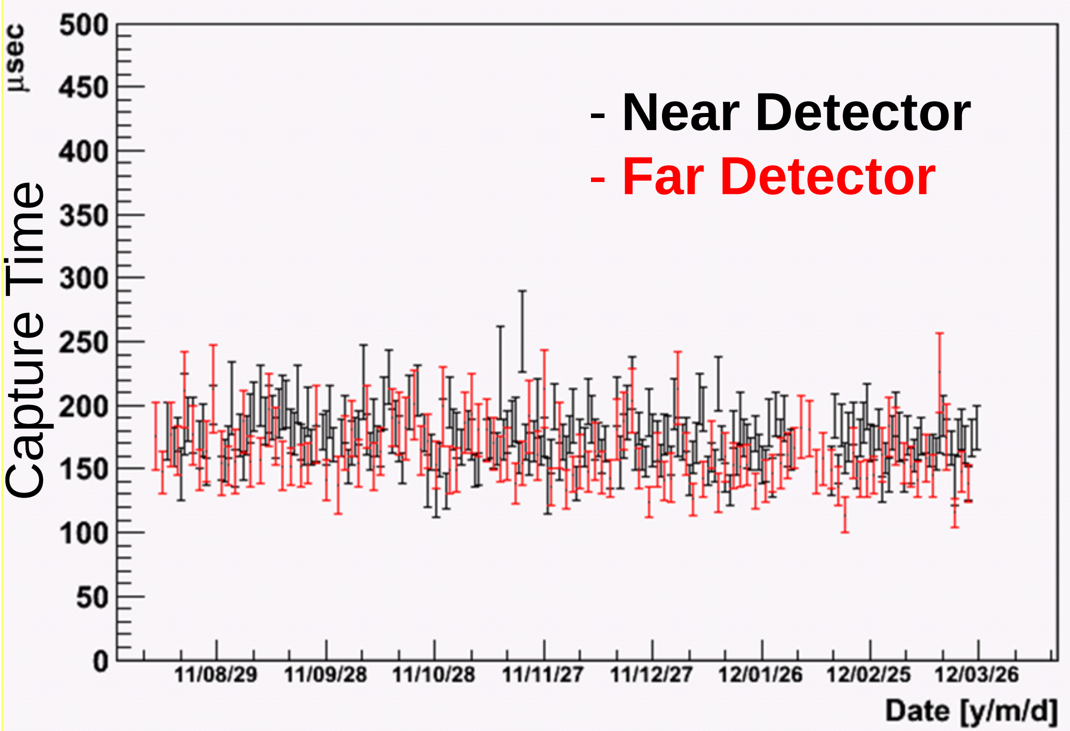




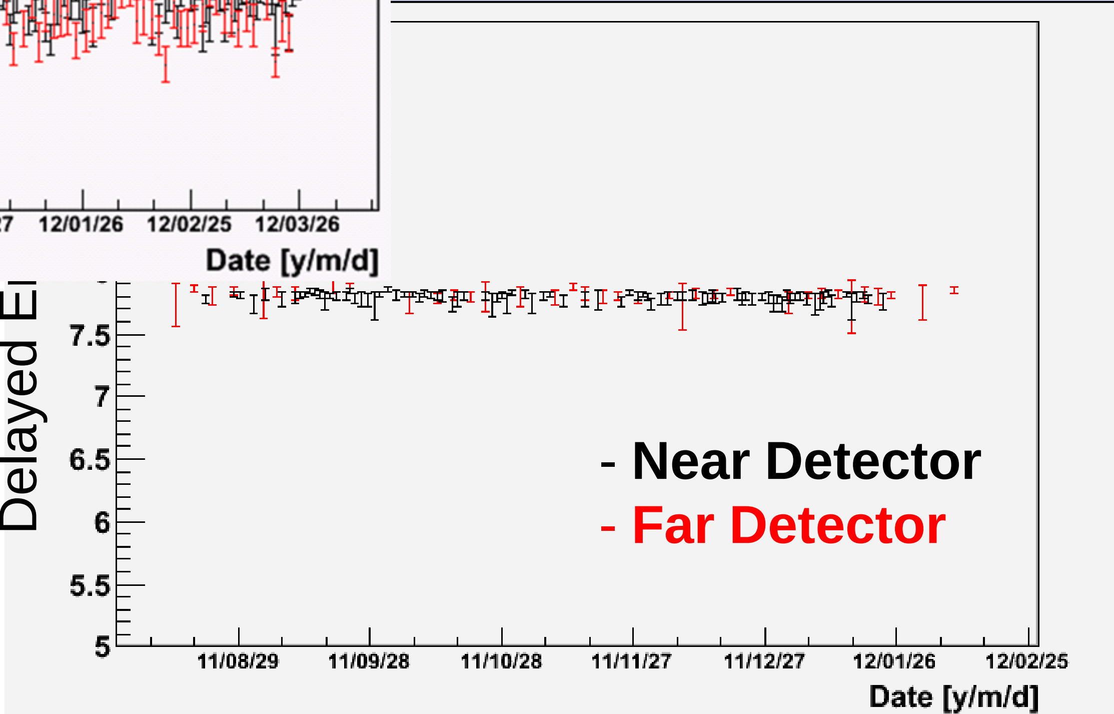


Long-term Stabilities

- Cosmic muon induced neutron's capture by H



delayed signals (capture on Gd)

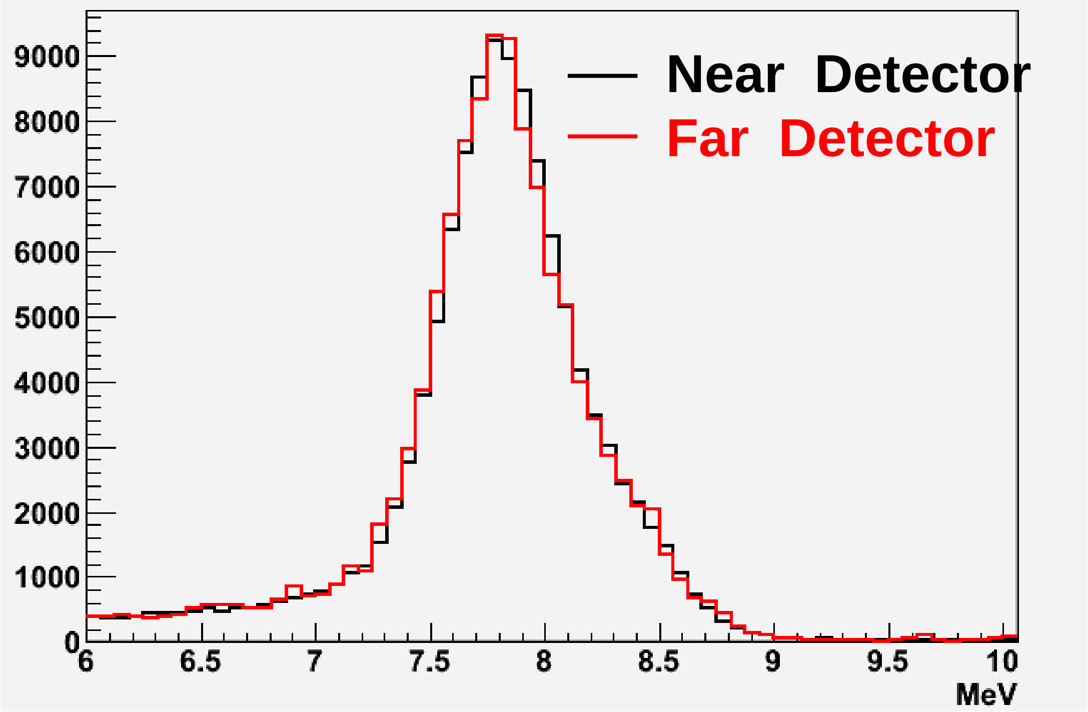


Cuts for ν Events

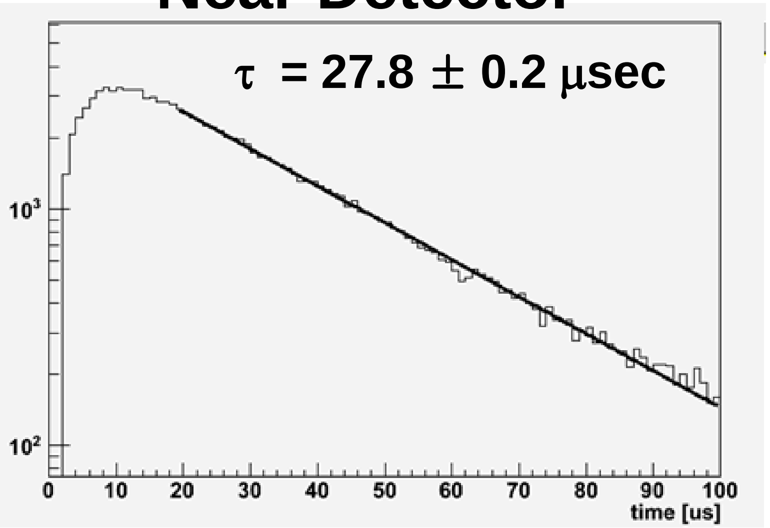
1. Reject flashers and external gamma rays : $Q_{max}/Q_{tot} < 0.03$
2. Muon veto cuts : reject events after the following muons
   - 1 ms DEAD time for
     - ✓ E(ID) > 70 MeV
     - ✓ 20MeV < E(ID) < 70 MeV & N_{PMT} (OD) > 50
   - 10 ms DEAD time for E(ID) > 1.5 GeV
3. Coincidence :
   - E_{prompt} : 0.7 ~ 12.0 MeV, $E_{delayed}$: 6.0 ~ 12.0 MeV
   - coincidence : $2\ \mu s < \Delta t_{e+n} < 100\ \mu s$
4. Multiplicity cut : reject pairs if there is an any trigger in the preceding 100 μs window.

Spectra & capture time of neutrons

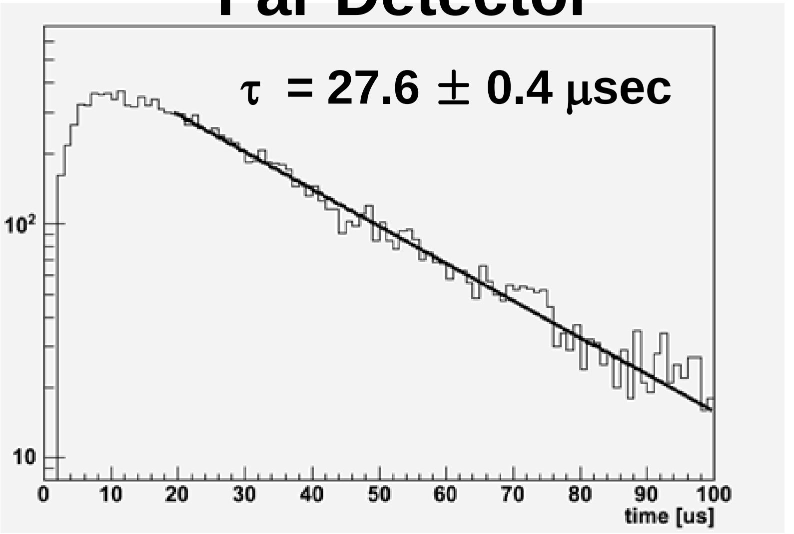
Observed spectra of IBD delayed signals



Near Detector



Far Detector



Backgrounds I - Accidentals

❑ Calculation of accidental coincidence

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

- ΔT = 100 μs time window
- Near detector :

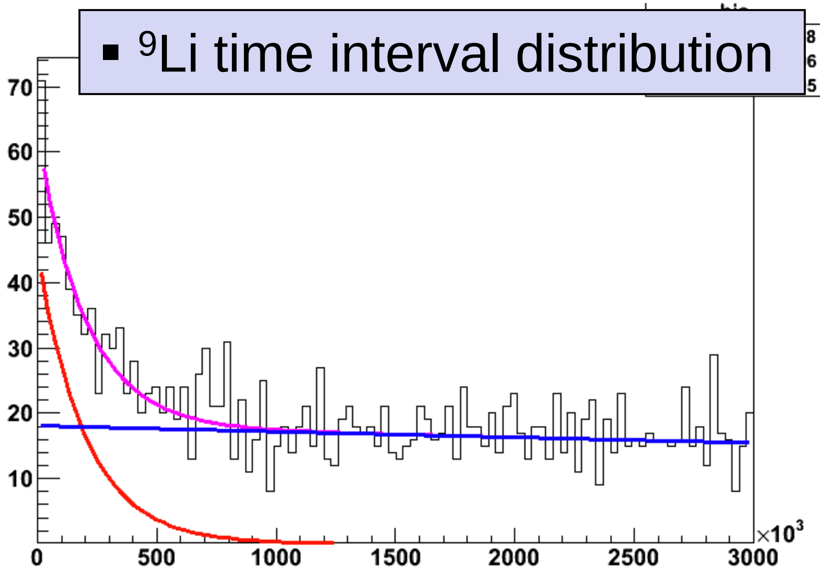
  R_{prompt} = 8.8 Hz, N_{delay} = 4884/day $\rightarrow$ $BG^{near}_{accidental} = 4.30 \pm 0.06 / day$
- Far detector :

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

Backgrounds II – $^{9}Li/^{8}Be$

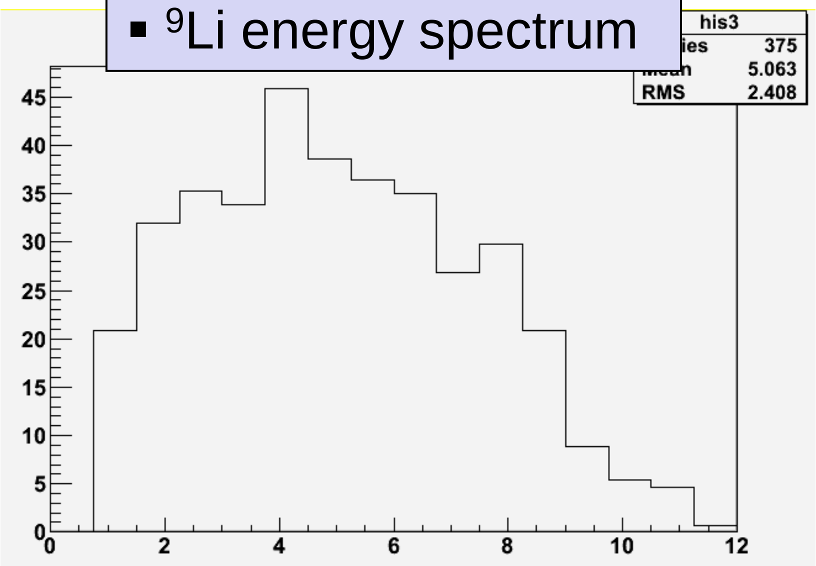
Find prompt-delay pairs after muons, and obtain their time interval distribution with respect to the preceding muon.

- ^{9}Li time interval distribution



Time interval (μs)

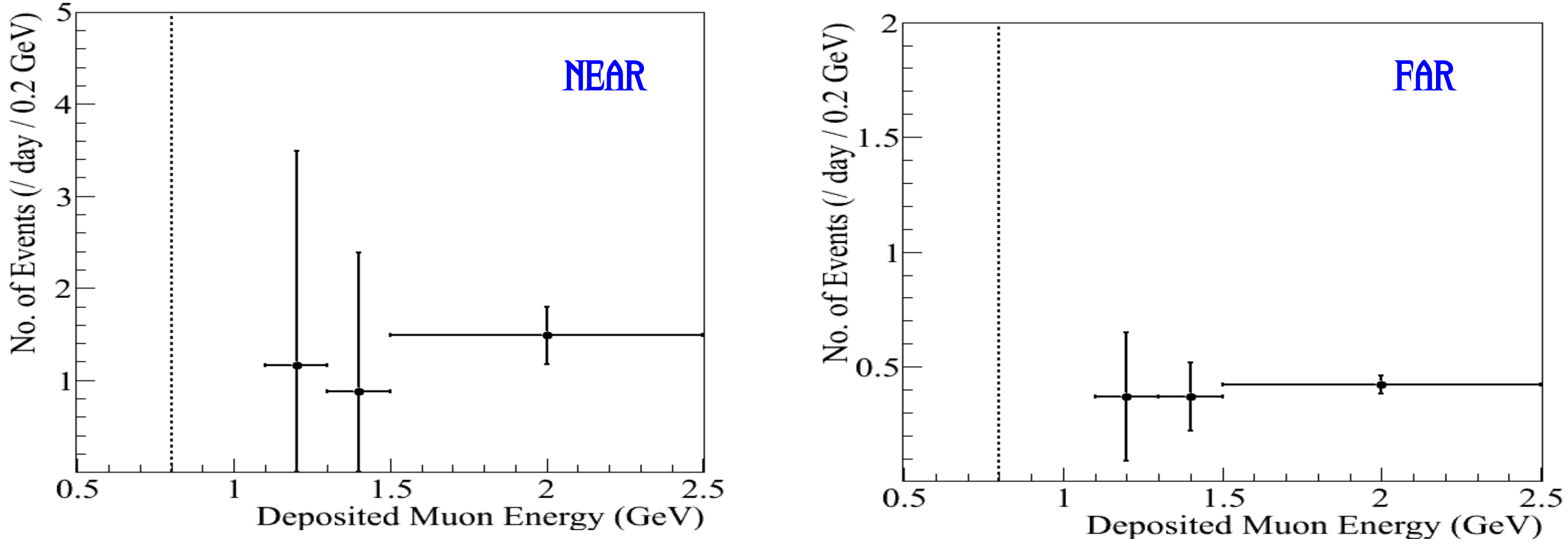
- ^{9}Li energy spectrum



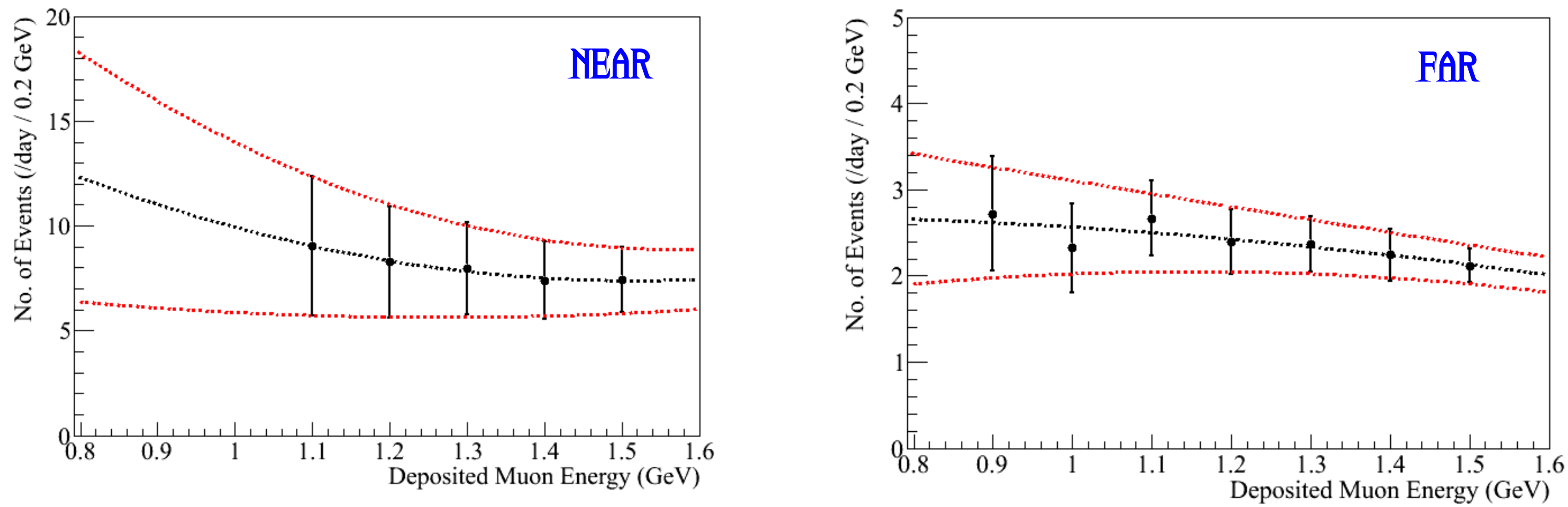
Energy (MeV)

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

We have tried to extend to lower energy muons, but limited by high rates.

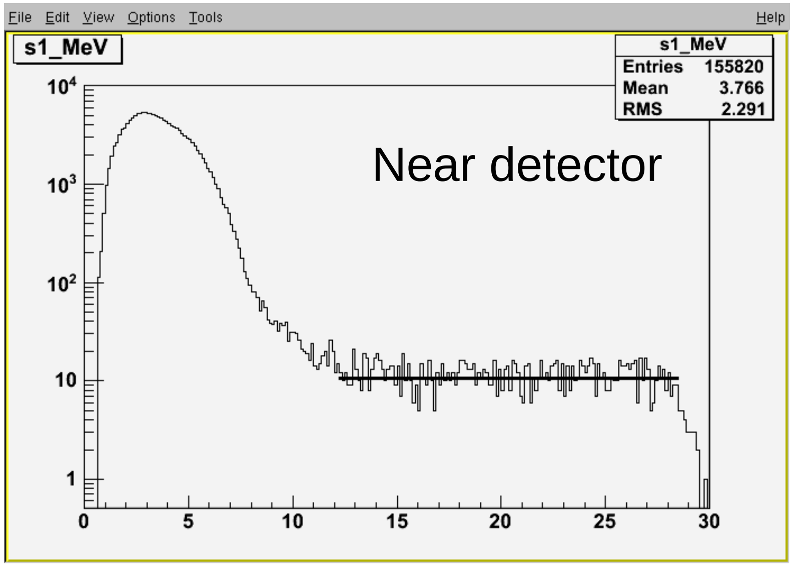


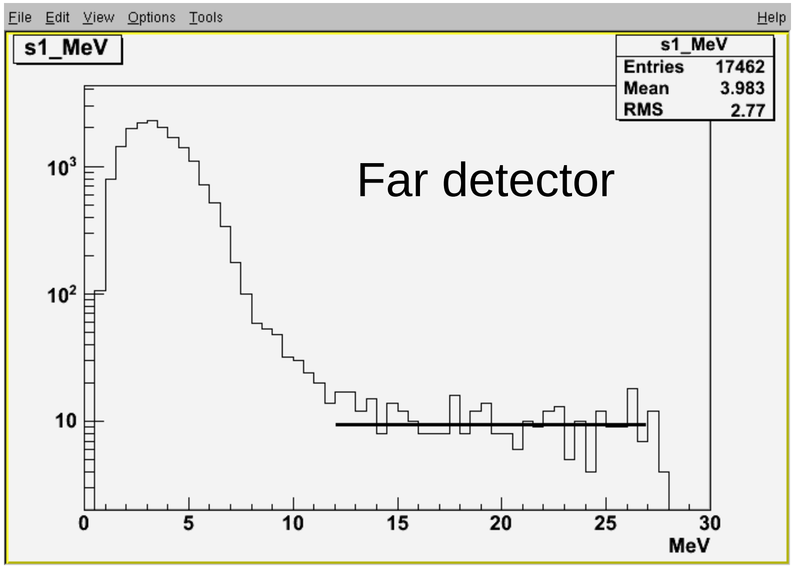
We have extrapolated higher energy data to lower threshold data.



Backgrounds III – fast neutrons

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



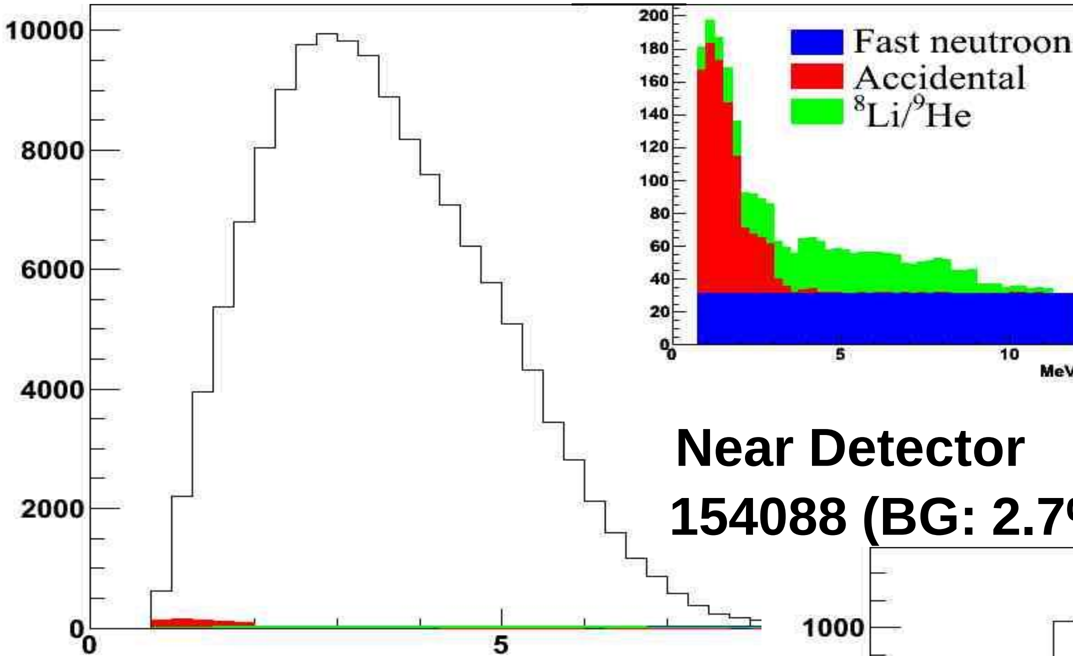


- Near detector : $BG_{neutron}^{near} = 5.00 \pm 0.13 \quad / day$
- Far detector : $BG_{neutron}^{far} = 0.97 \pm 0.06 \quad / day$

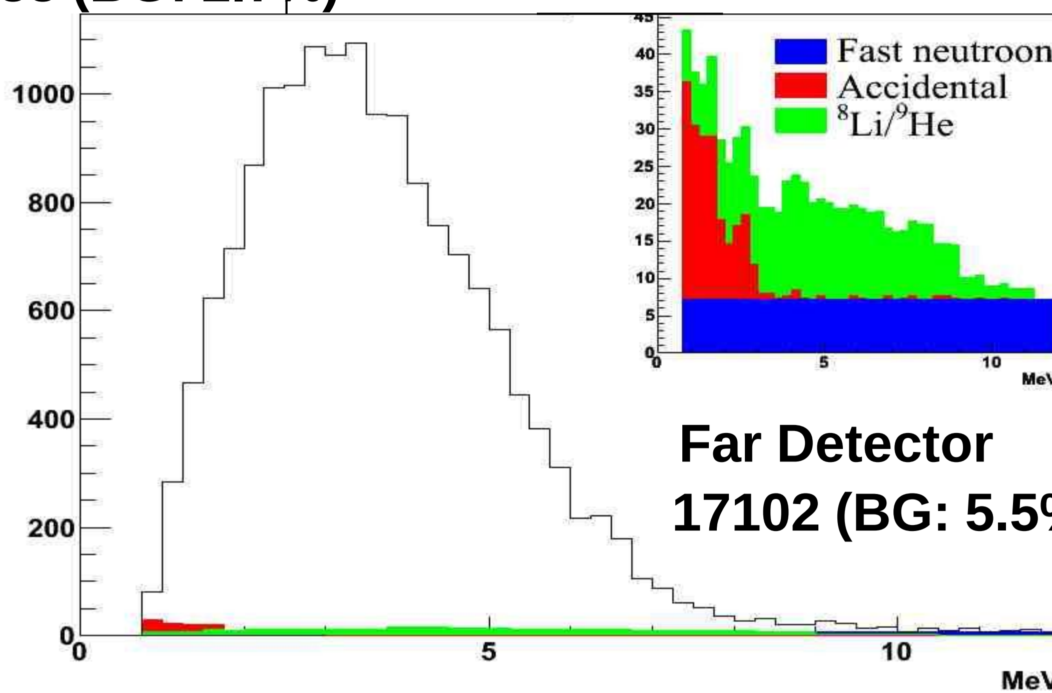
Summary of Final Counts

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

Visible energy spectra of neutrinos



Near Detector
154088 (BG: 2.7%)



Far Detector
17102 (BG: 5.5%)

Estimation of ν event rates

1. Neutrino flux

$$\Phi_i^r(E_\nu) = \frac{P_i^r}{\sum_{iso=1}^{4} f_i^{iso} \cdot E_f^{iso}} \sum_{iso=1}^{4} f_i^{iso} \cdot \varphi^{iso}(E_\nu)$$

Flux of r reactor on ith day

P_i^r : thermal power of reactor r in ith day from power plant

f_i^{iso} : fission fraction of each isotope in ith day (Burn=up)

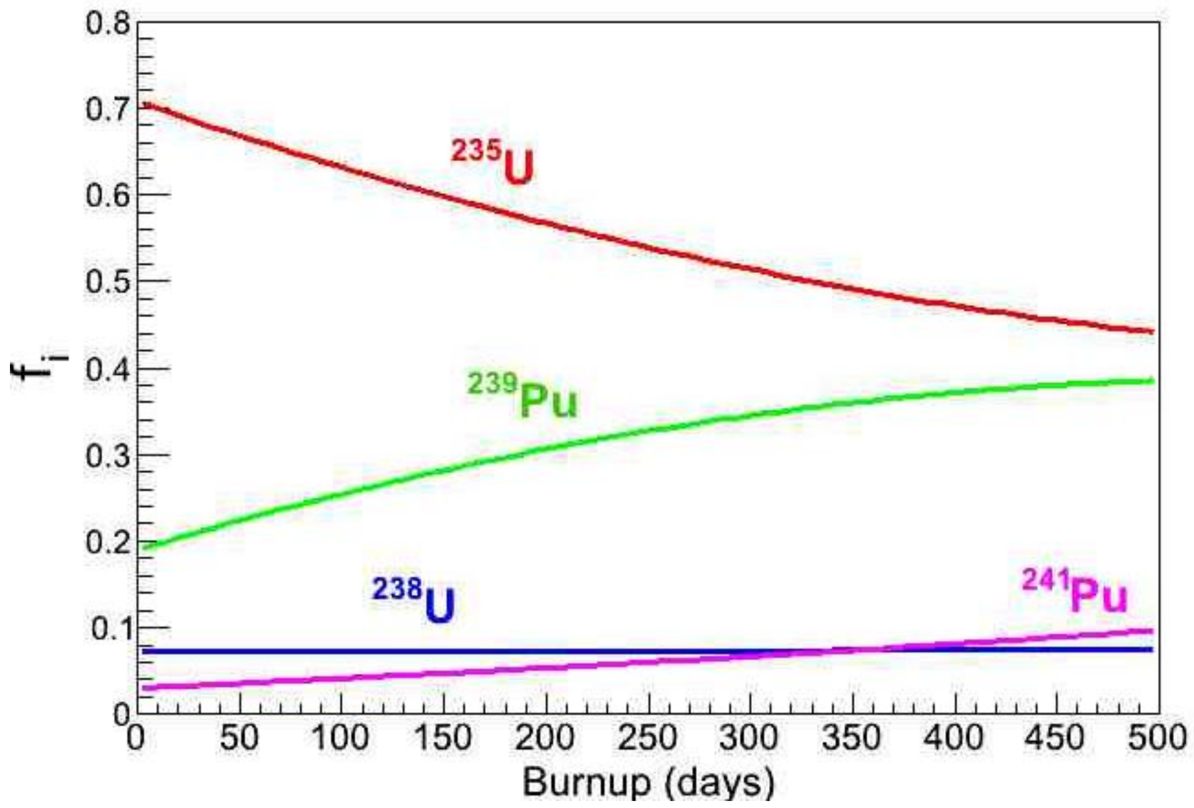
E_f^{iso} : fission energy of each isotope

V.Kopeikin et al., Phys. Atom.Nucl. 67, 1982 (2004)

$\varphi^{iso}(E_\nu)$: flux of each isotope for E_ν

^{235}U, ^{239}Pu, ^{241}Pu in P. Huber, Phys. Rev. C84, 024617 (2011)

^{238}U in T. Mueller et al., Phys. Rev. C83, 054615 (2011)



Supplied by power plant
Daily thermal power
Last Fuel Exchange period
Fission fractions

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

Estimation of ν event rates

2. Event rates

$$N_{\exp}^{d,r} = \sum_{d=n,f} \frac{n_d}{4\pi R_{dr}} \sum_{i=1}^{days} \int_{E_\nu=1.804}^{E_\nu=10} \sigma_{total}(E_\nu)\Phi_i^r(E_\nu)\Delta T_i P_{OSC}(E_\nu, r_{jk})dE_\nu$$

R_{dr} : distance between each detector and reactor

n_d : # of protons in each detector

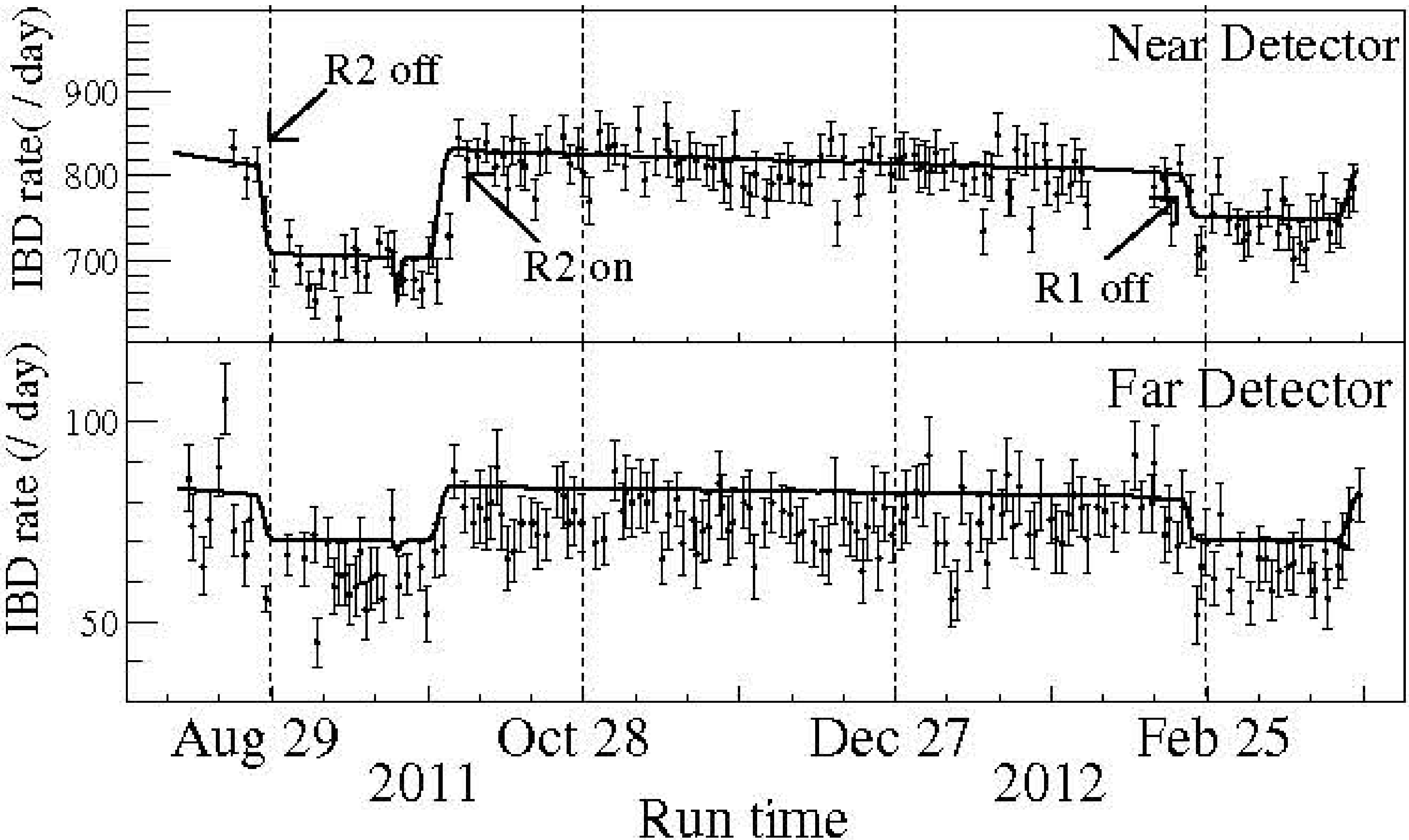
$\sigma_{total}(E_\nu)$: total cross section of IBD

P. Vogel, PRD60, 053003 (1999)

ΔT_i : DAQ time

P_{OSC} : Oscillation probability

Observed Daily Averaged ν Rate



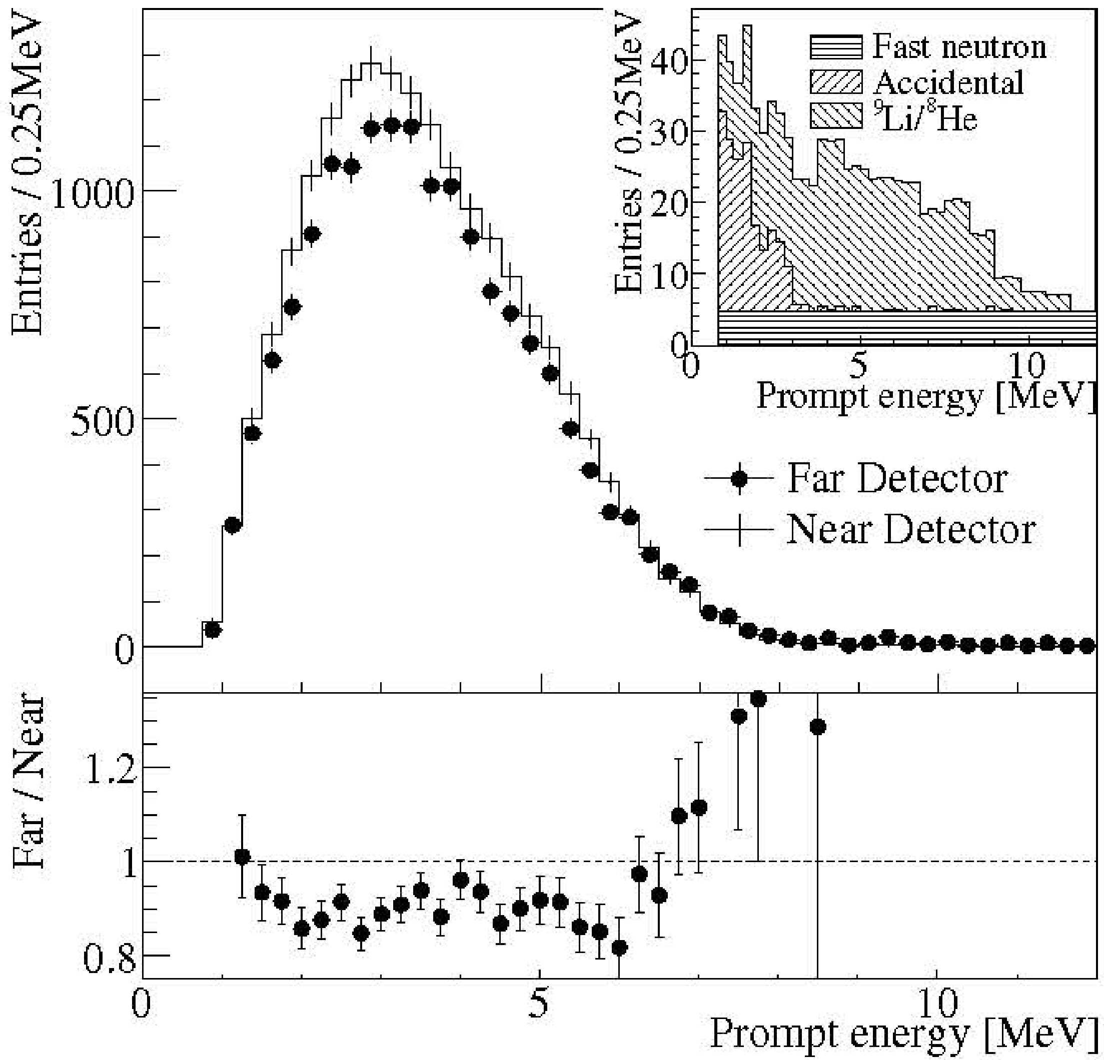
Efficiency & Systematic Uncertainties

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	(6

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



- Consistent with neutrino oscillation in the spectral distortion.
- E>6 MeV distortion is not understood yet.

χ^2 Pull Analysis for Rate Only data

$$\chi^2 = \sum_{d=N,F} \frac{\left[N_{obs}^{d} + b_d - (1 + a + \xi_d) \sum_{r=1}^{6} (1 + f_r) N_{\exp}^{d,r} \right]^2}{N_{obs}^{d}} + \sum_{d=N,F} \left(\frac{\xi_d^2}{\sigma_d^{\xi 2}} + \frac{b_d^2}{\sigma_d^{b2}} \right) + \sum_{r=1}^{6} \left(\frac{f_r}{\sigma_r} \right)^2$$

$N_{\exp}^{d,r}$: expected # of events in d detector from r reactor

parameters to fit :

a : *absolute normalization parameter*

ξ_d : *efficiency of* detector d

f_r : *reactor core fluctuation*

b_d : *backgrounds of* detector d

$\sigma_{N,F}^{\xi} = 0.002$

$\sigma_r = 0.009$

$\sigma_N^b = 5.93 / day$

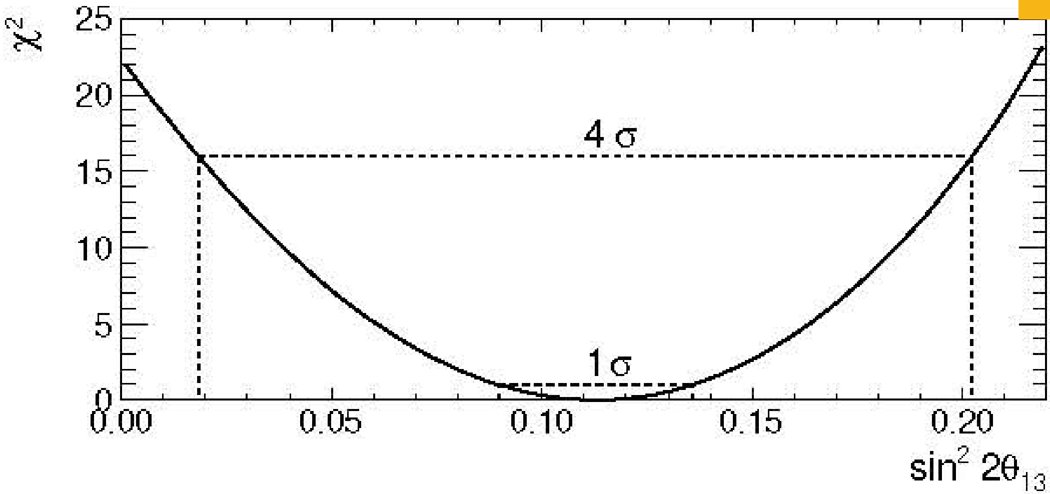
$\sigma_F^b = 0.76 / day$

Definitive Measurement of θ_{13}

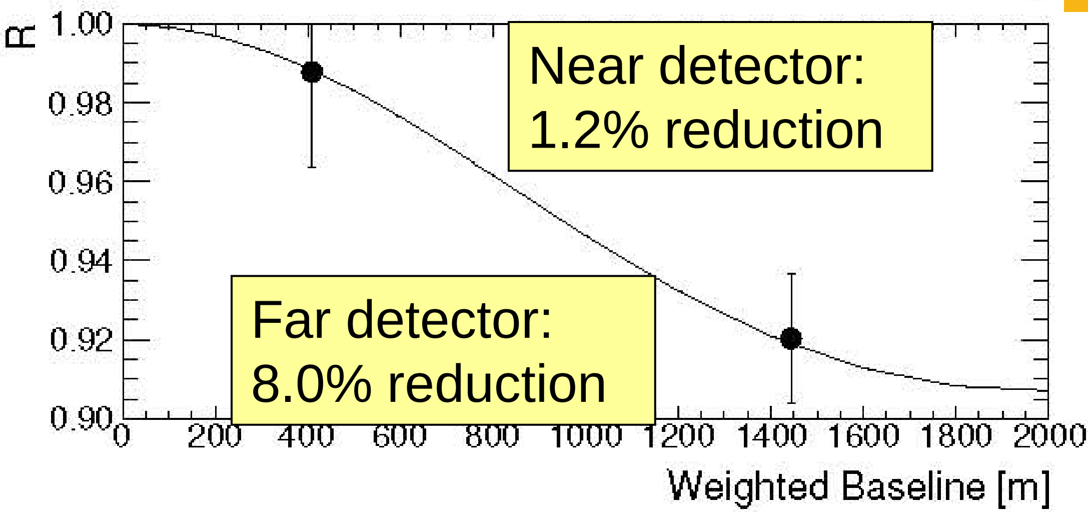
$$\sin^2 2\theta_{13} = 0.113 \pm 0.023$$

- 4.9σ significant signal

$$0.013(stat.) \pm 0.019(syst.)$$



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



~ 6%(Preliminary) deficit is observed for absolute normalization parameter a.
→ consistent with reactor neutrino anomaly & Double Chooz.

Accepted by PRL, will be on-line May 11th.

Observation of Reactor Electron Antineutrino Disappearance in the RENO Experiment

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Future Efforts for θ_{13} at RENO

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

- Reduce the amound of backgrounds !
- Do 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.

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

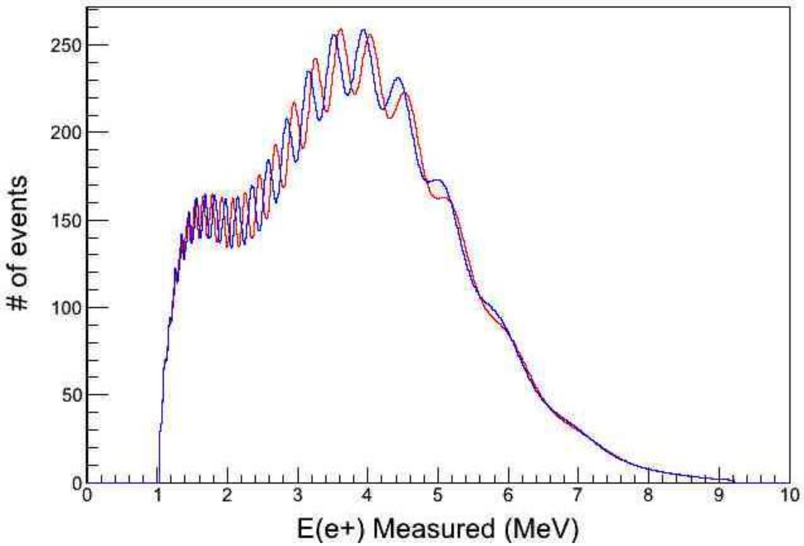
- RENO measured the last, smallest mixing angle θ_{13} unambiguously that was the most elusive puzzle of neutrino oscillations

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

Perspectives

A large value of θ_{13} :

- Need to update the designs for the future neutrino experiments.
- Three reactor measurement will strongly promote the next round of neutrino experiments to find the CP phase.
- May open a bright window of understanding why there is much more matter than antimatter in the Universe today.



Mass Hierarcht with reactor neutrinos @ 50 km

$$\sin^2 2\theta_{13} = 0.1$$

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

Grazie !