Recent Results from RENO

XXIV Workshop on Weak Interactions and Neutrinos

Sep. 16 to 21, 2013 Natal, Brazil

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Summary of RENO's History & Status

- RENO began design, tunnel excavation, and detector construction in March 2006, and was the first reactor neutrino experiment to search for θ_{13} with both near & far detectors running, from Aug. 2011.

- 1st result : 220 days (April, 2012), PRL 108

$$\sin^2 2\theta_{13} = 0.113 \pm 0.013(stat) \pm 0.019(syst) \quad (4.9\sigma)$$

- 2nd result : 403 days (March, 2013), NuTel 2013

$$\sin^2 2\theta_{13} = 0.100 \pm 0.010(stat) \pm 0.015(syst) \quad (5.6\sigma)$$

[~ twice more data + improvements in energy calibration & background estimation and reduction]

- Updated result : 403 days, systematic error 0.015 → 0.012 **(6.4σ)**

[Better understanding of Li/He background estimation]

RENO Collaboration

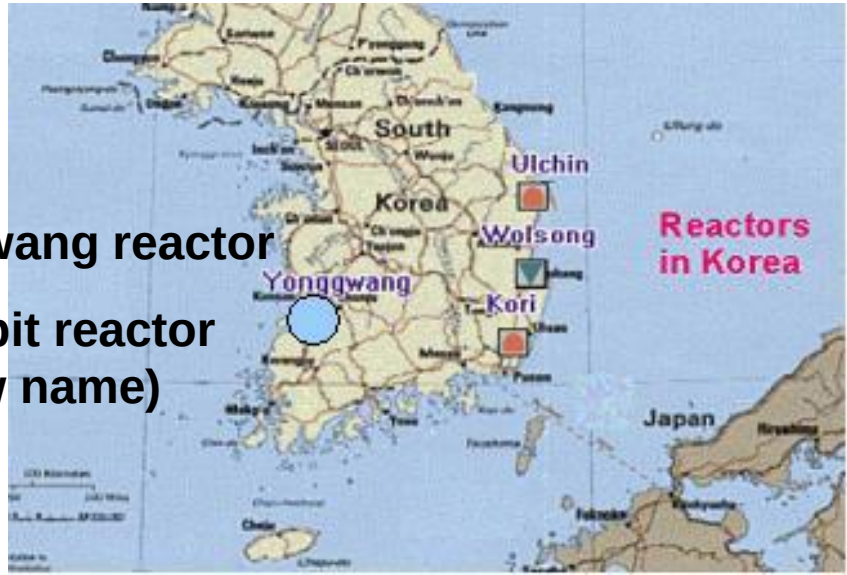
(12 institutions and 40 physicists)

- 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

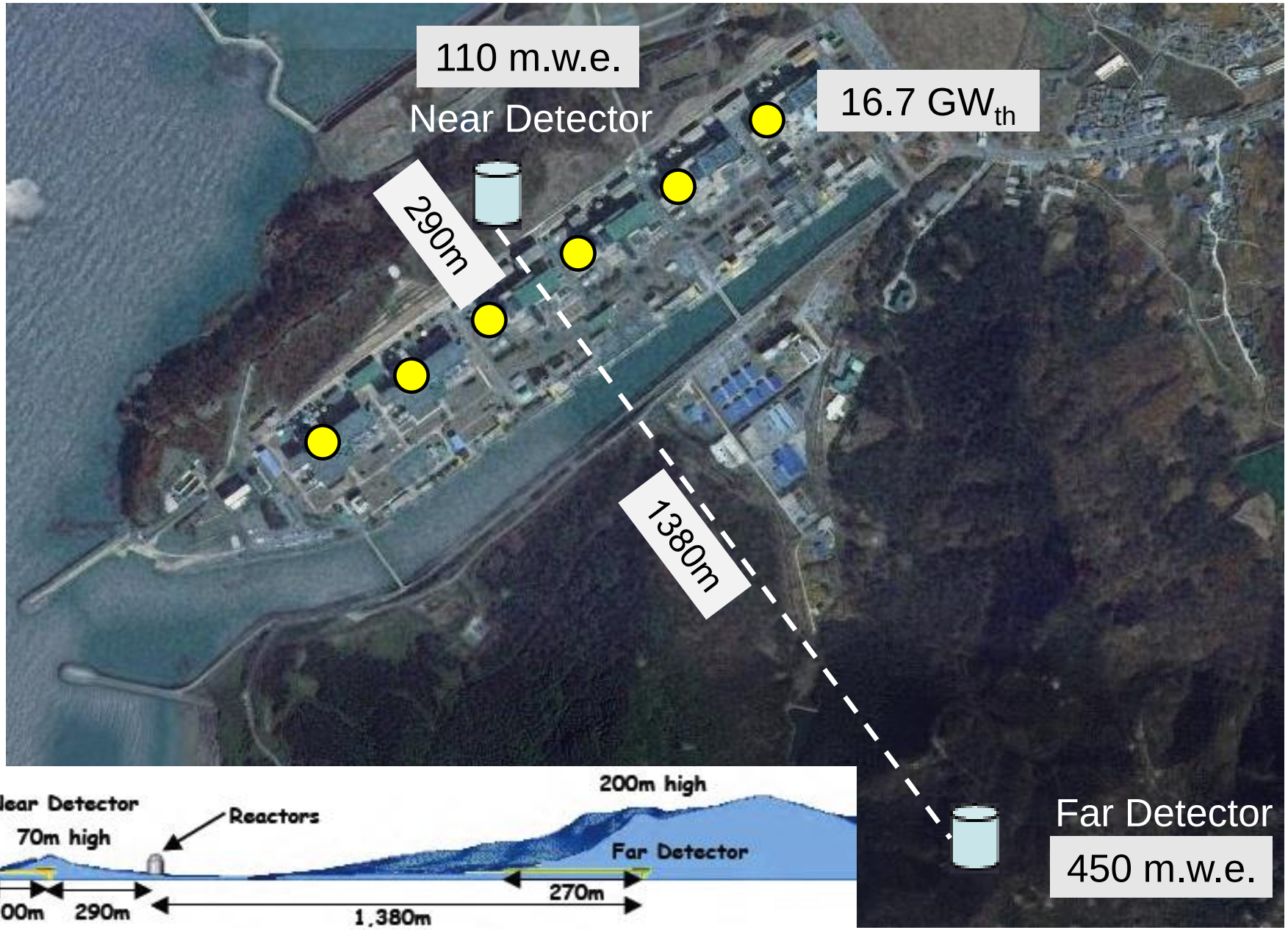
- Total cost : $10M
- Start of project : 2006
- The first experiment running with both near & far detectors from Aug. 2011

Yonggwang reactor

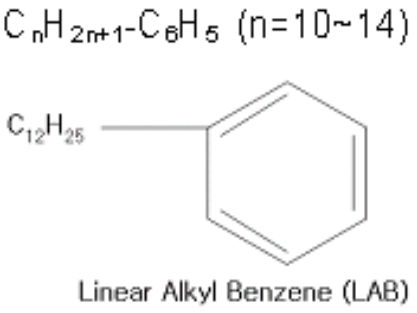
→ Hanbit reactor (new name)



RENO Experimental Setup



Detection of Reactor Antineutrinos



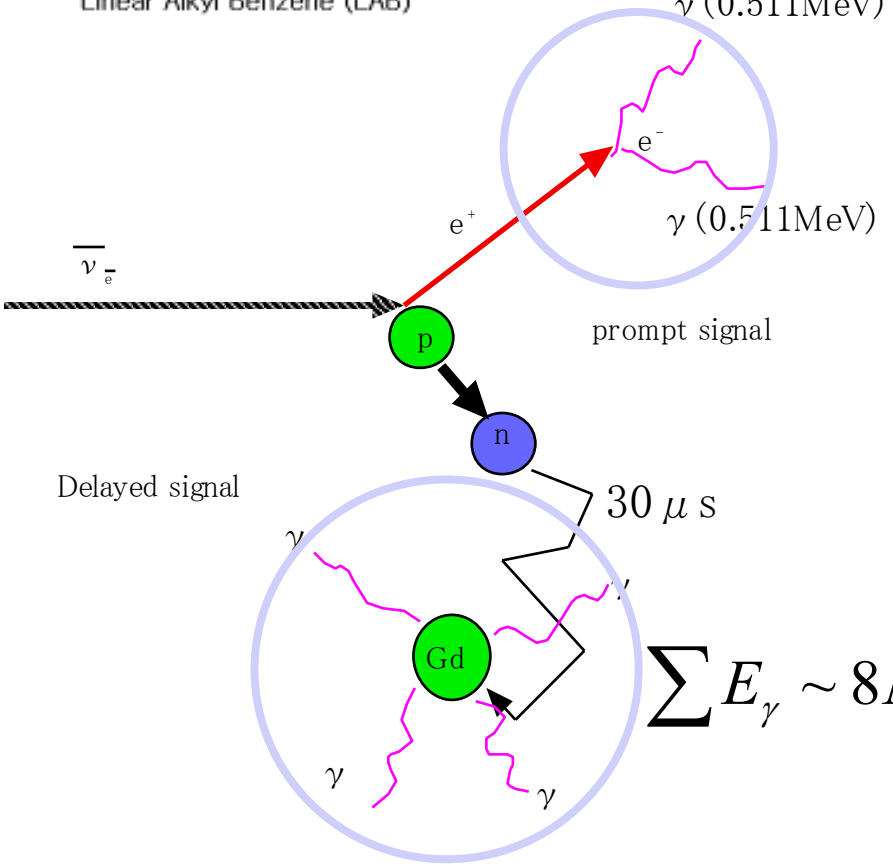
(prompt signal)

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

(delayed signal)

~180 μs: + p → D + γ (2.2 MeV)

~28 μs (0.1% Gd): + Gd → Gd + γ's (8 MeV)

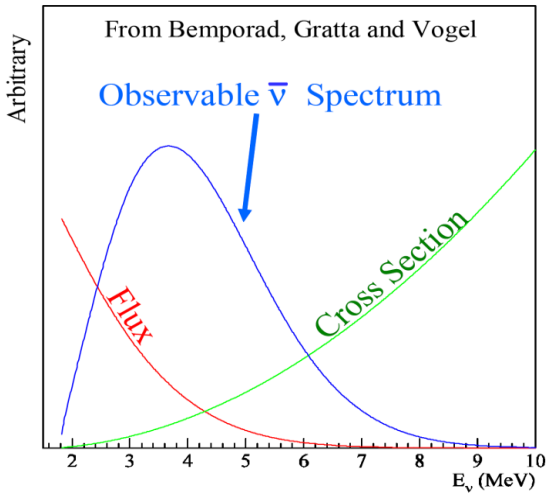


$$\sum E_\gamma \sim 8MeV$$

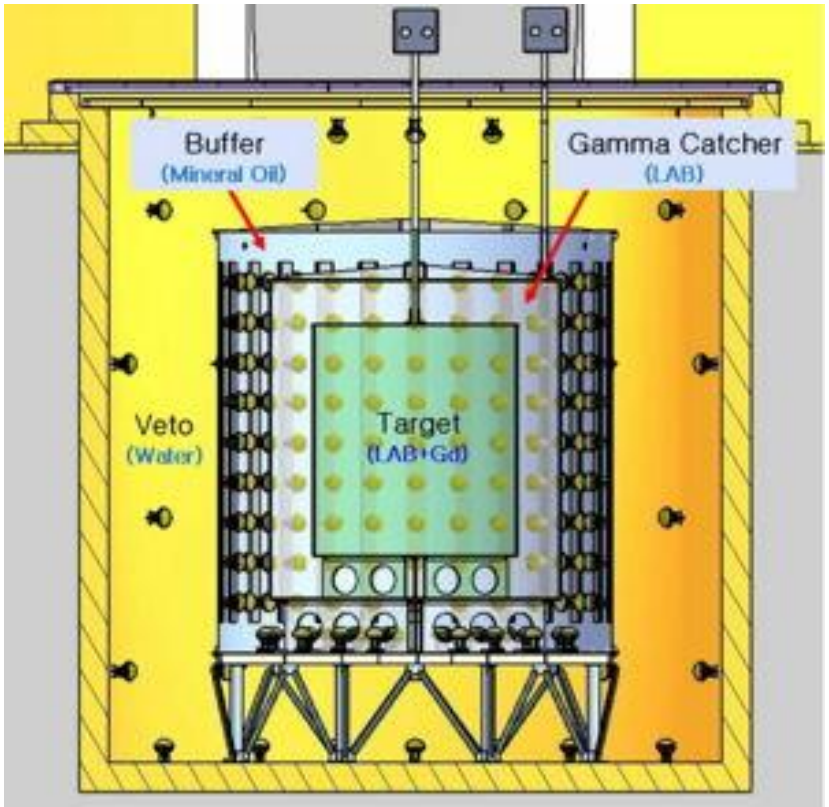
- **Neutrino energy measurement**

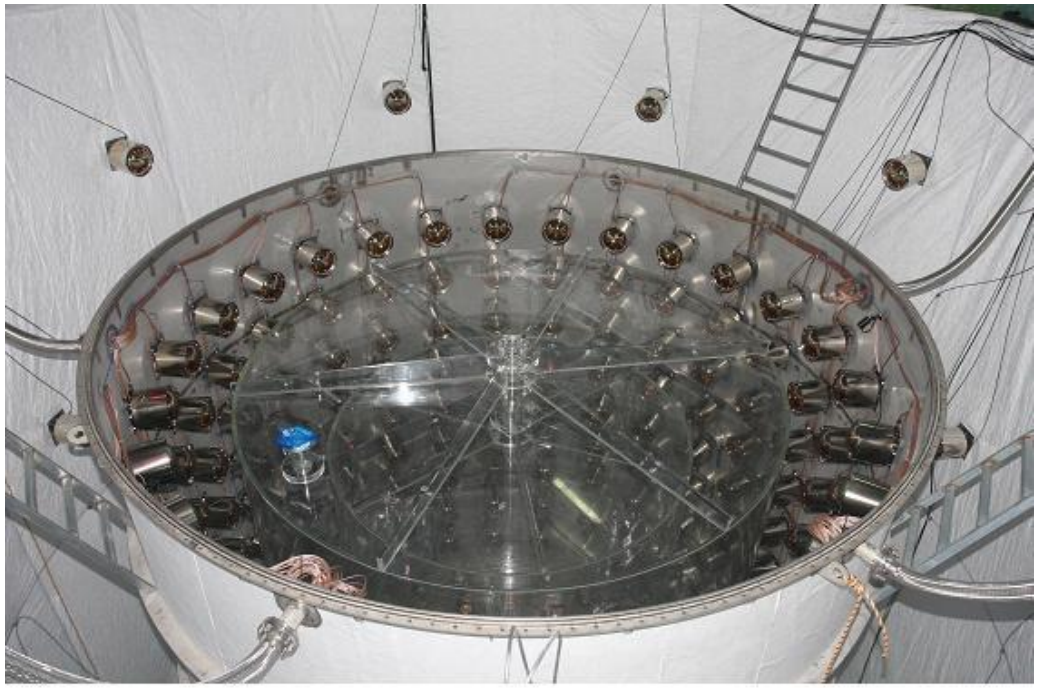
$$E_{\bar{\nu}} \cong T_{e^+} + T_n + (M_n - M_p) + m_{e^+}$$

10-40 keV *1.8 MeV*



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

Data-Taking & Analysis Status

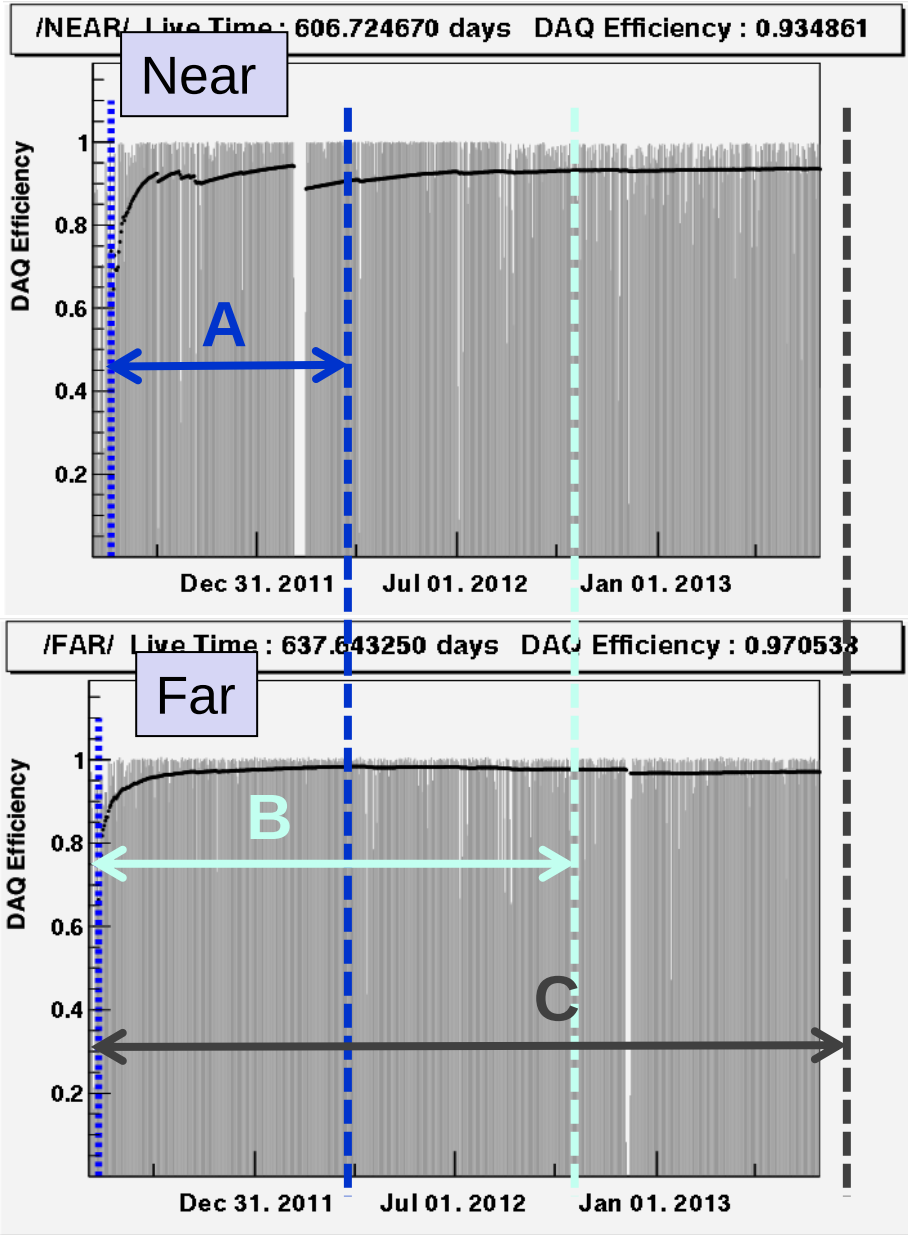
- Data taking began on Aug. 1, 2011 with both near and far detectors. (DAQ efficiency : ~95%)

- **A** (220 days) : **First θ_{13} result**
  [11 Aug, 2011~26 Mar, 2012]
  PRL 108, 191802 (2012)

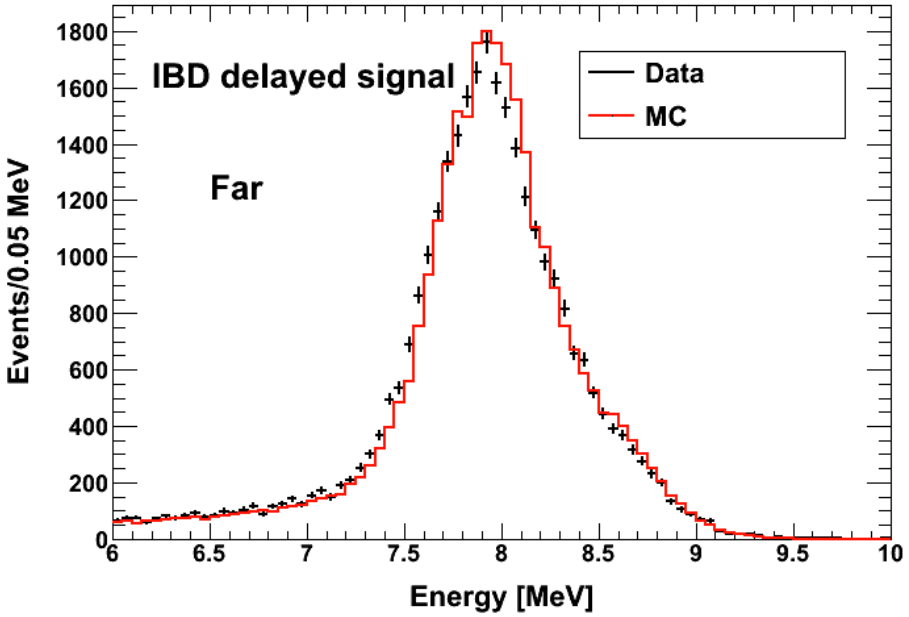
- **B** (403 days) : **Improved θ_{13} result**
  [11 Aug, 2011~13 Oct, 2012]
  NuTel 2013

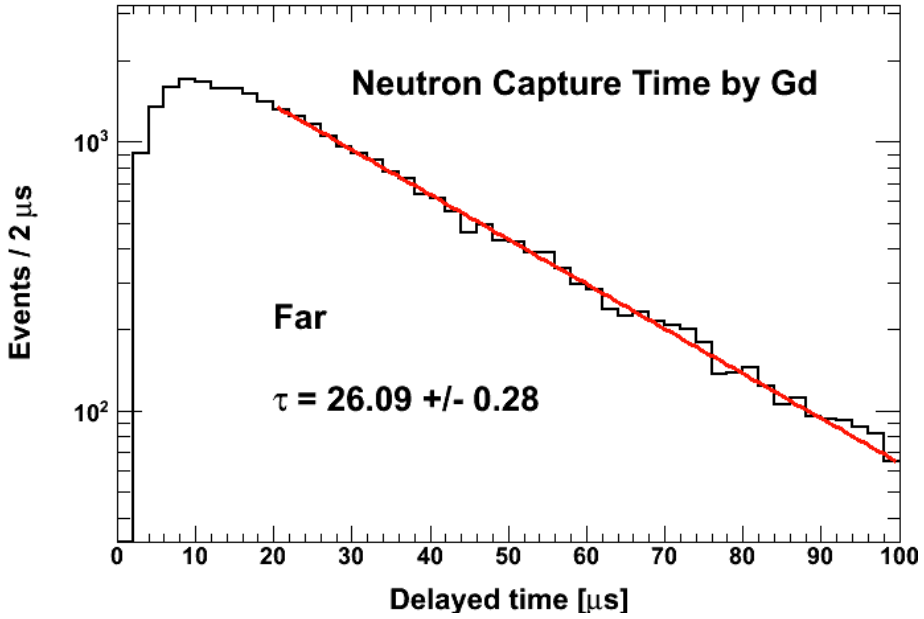
- **C** (~700 days) : **Shape+rate analysis** (in progress)
  [11 Aug, 2011~31 Aug, 2013]

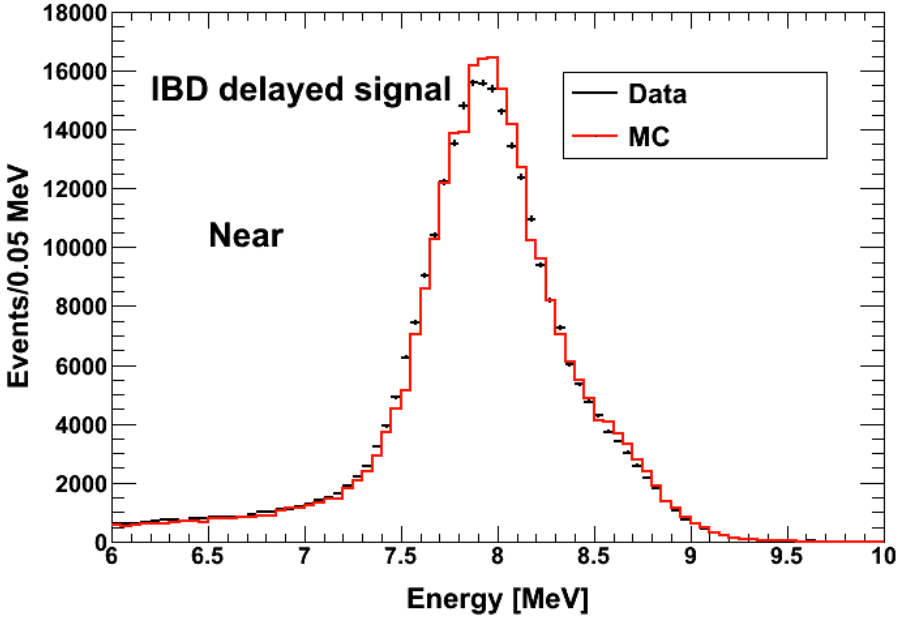
- Absolute reactor neutrino flux measurement in progress
  [reactor anomaly & sterile neutrinos]

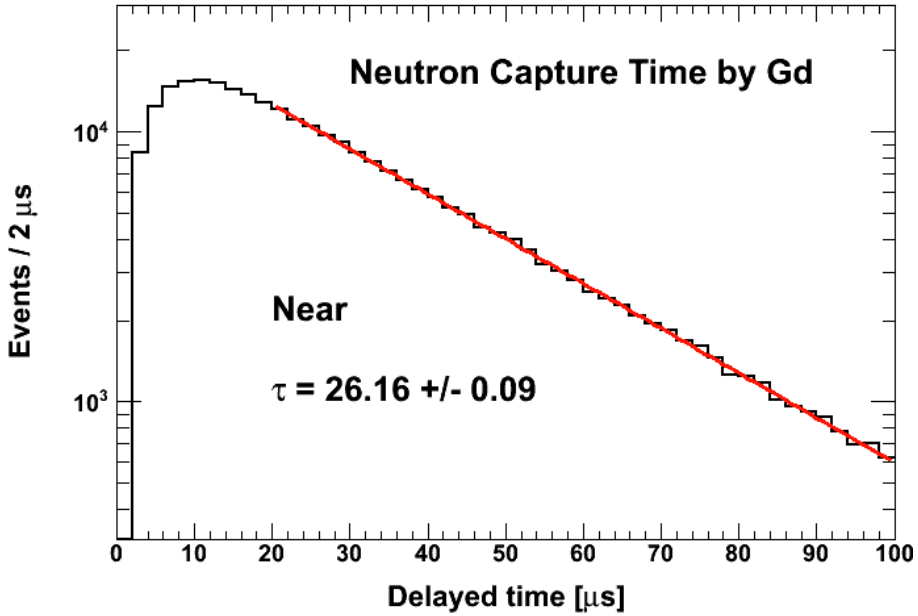


Neutron Capture by Gd



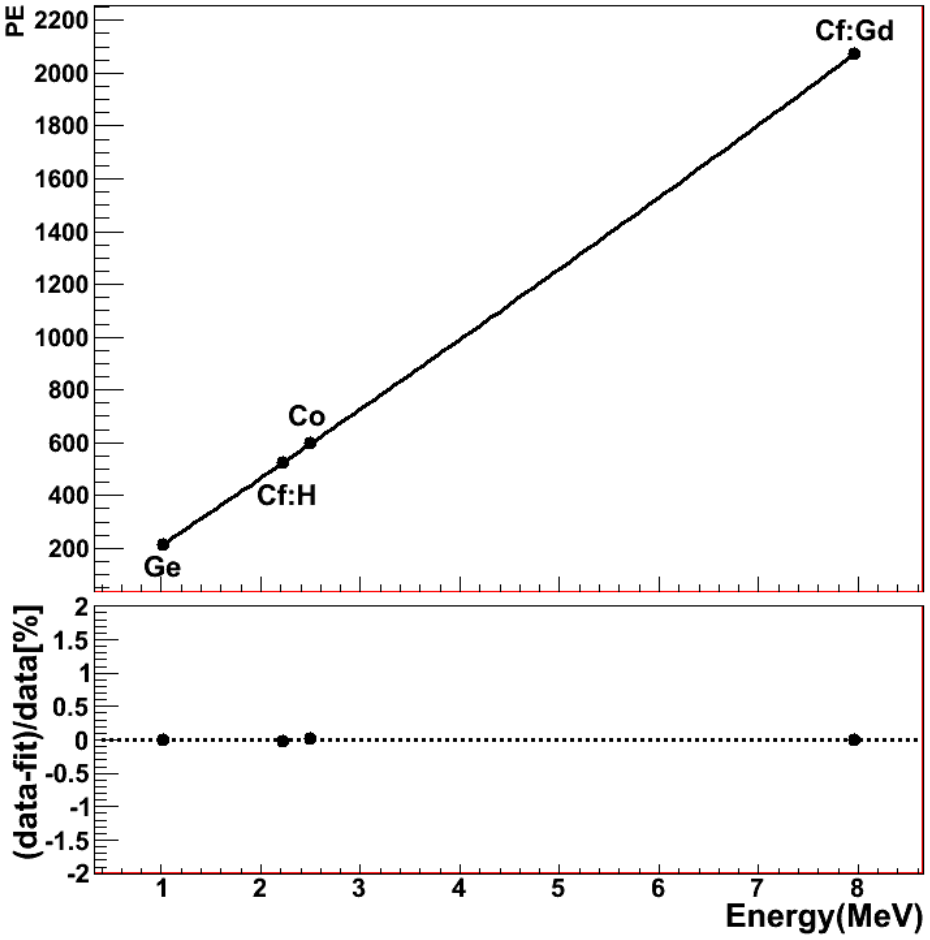




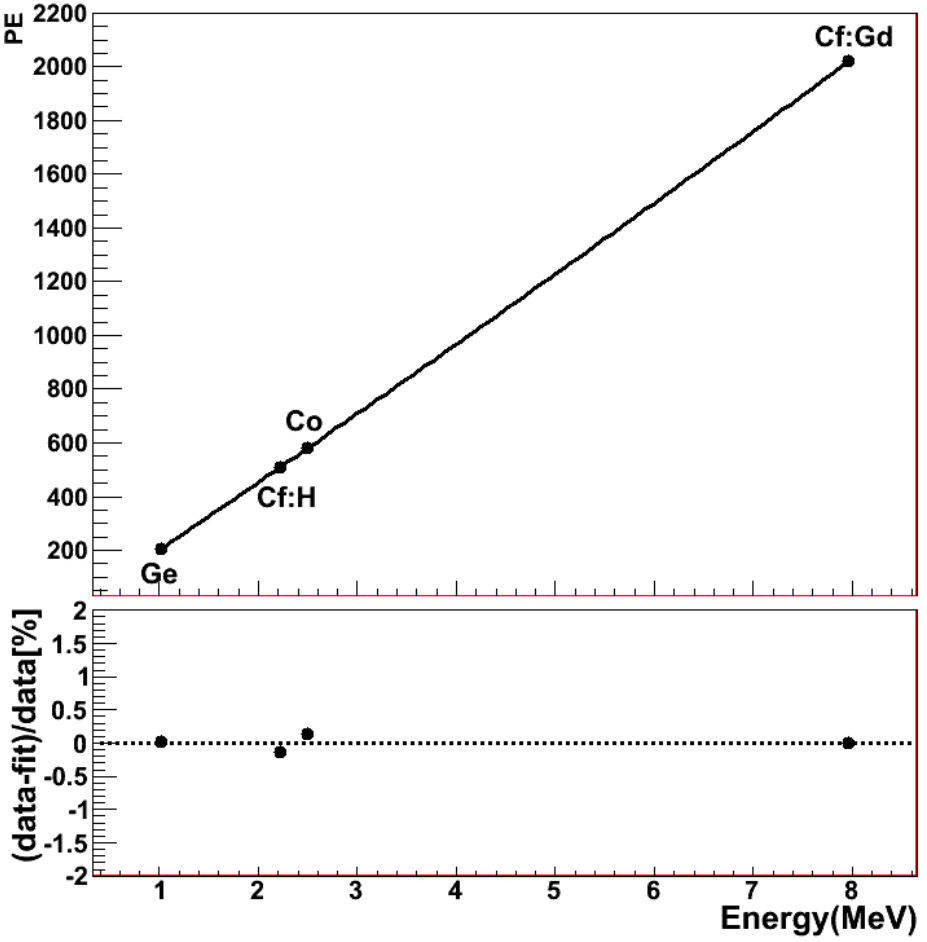


Energy Calibration

Far Detector

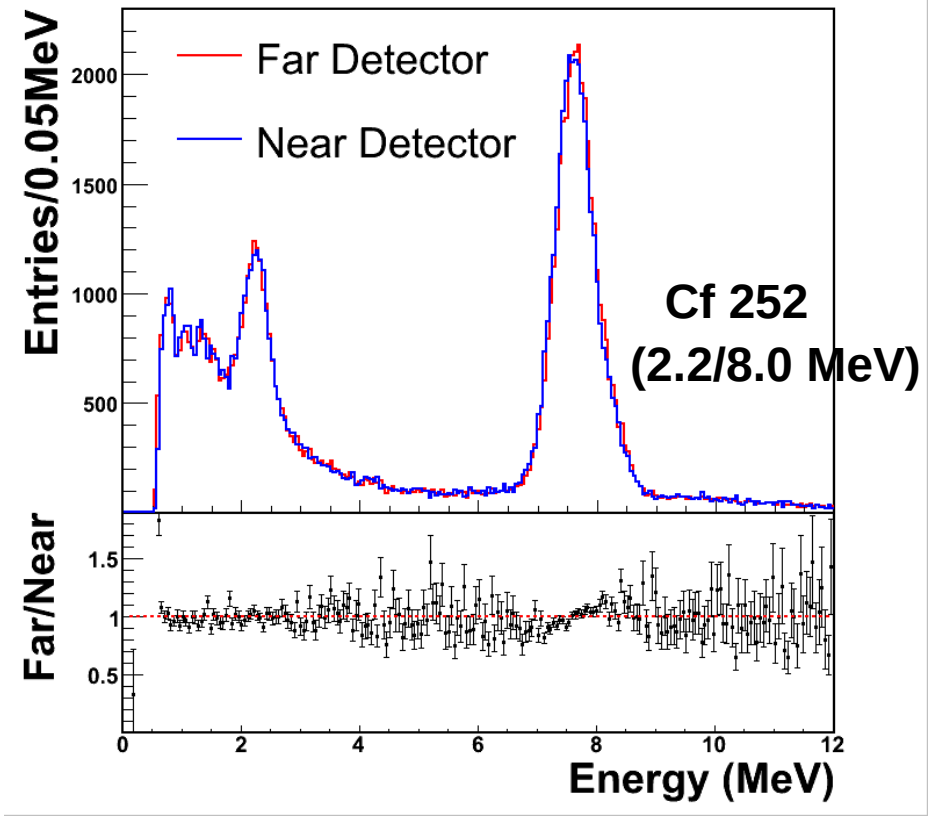


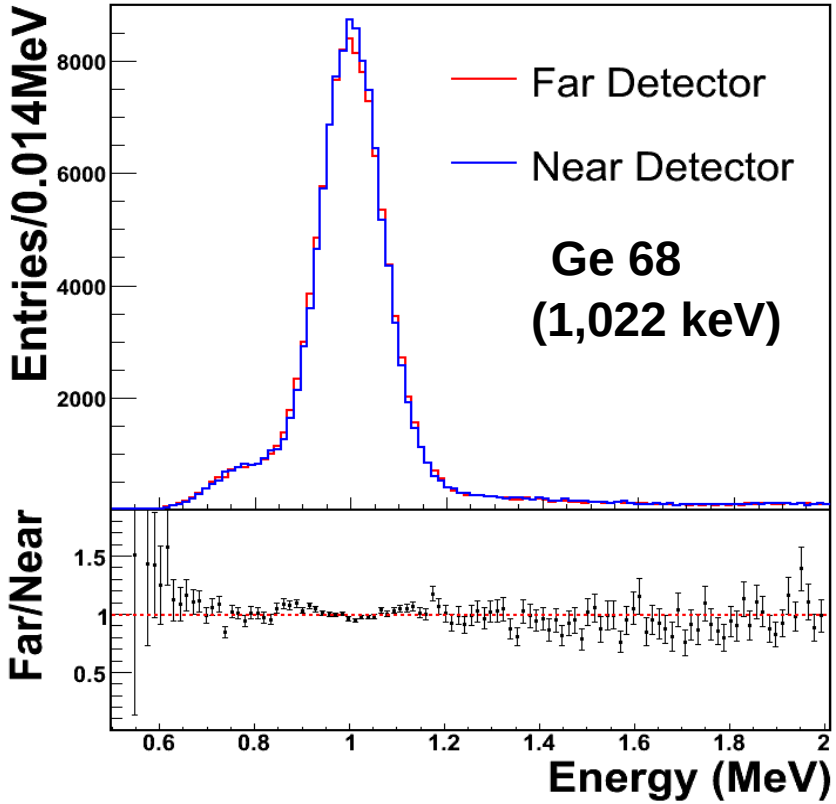
Near Detector



Fitting accuracy: 0.1 %

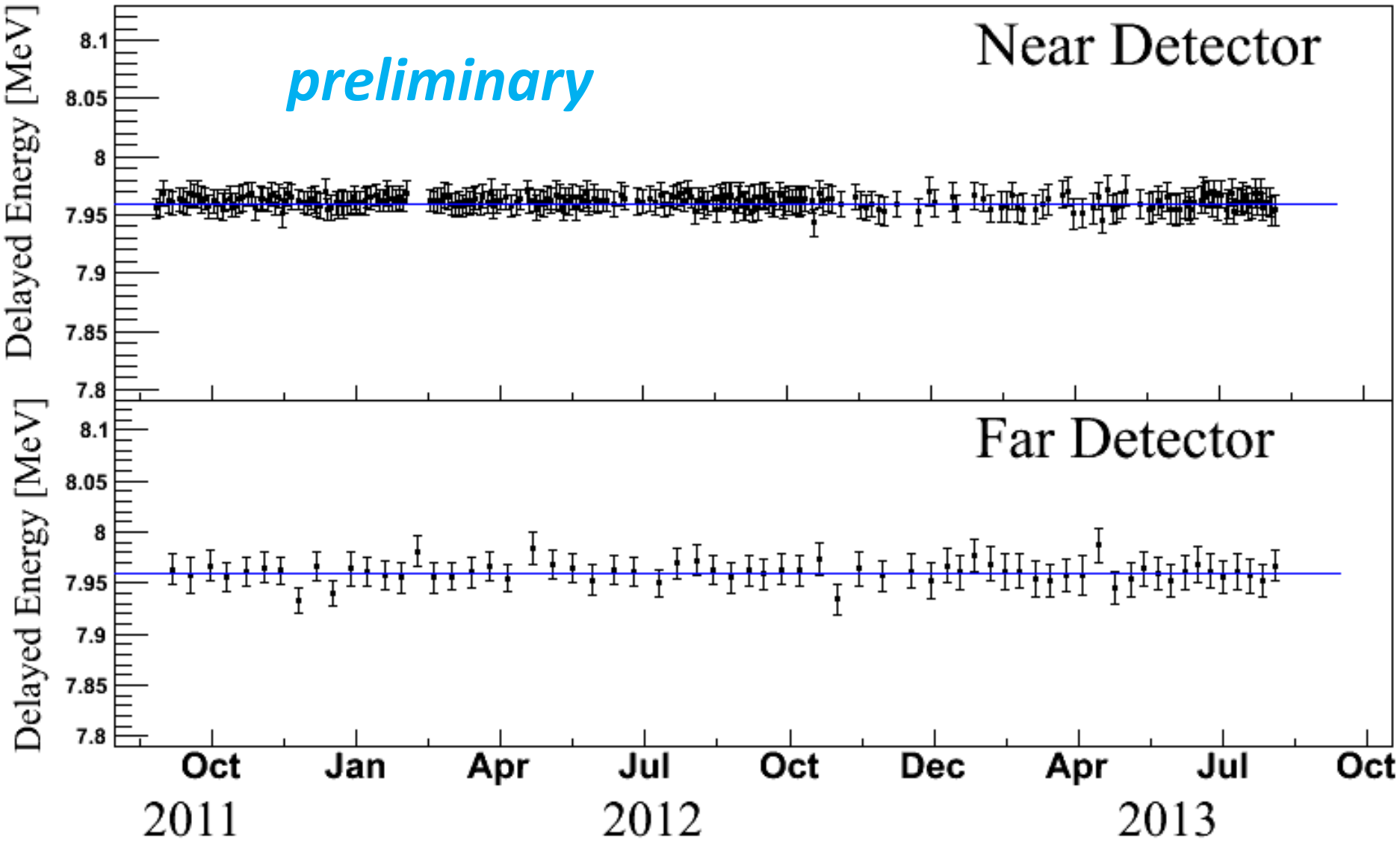
Energy Calibration





Detector Stability of Energy Scale

- IBD candidate's delayed signals (neutron capture by Gd)



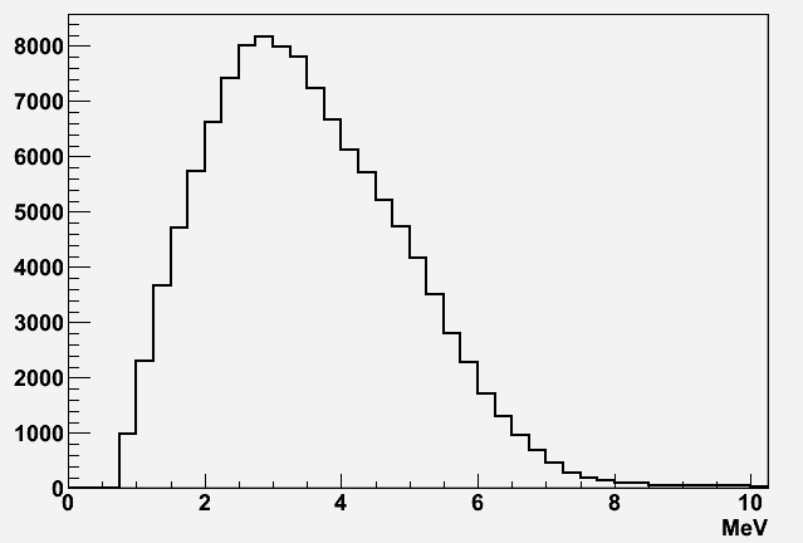
IBD Event Signature

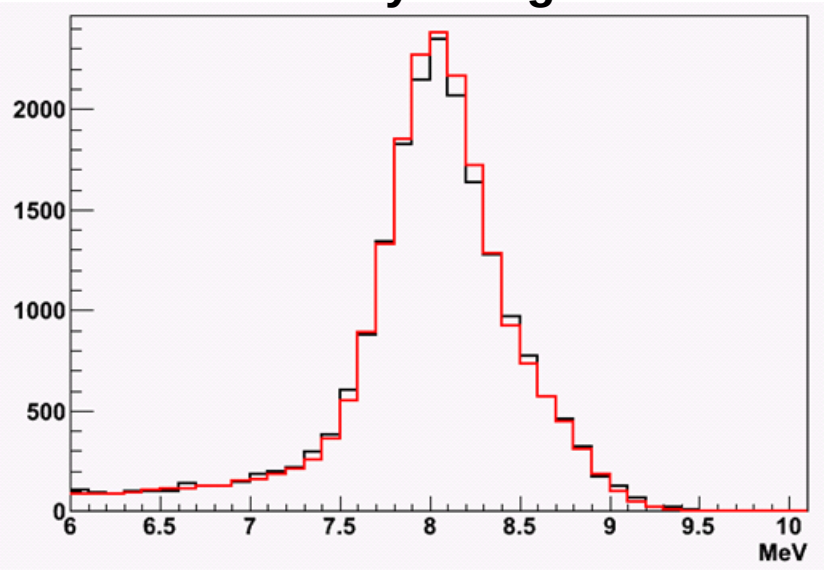
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

- 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

~26 μs (0.1% Gd) in LS

Prompt Signal → **Delayed Signal**

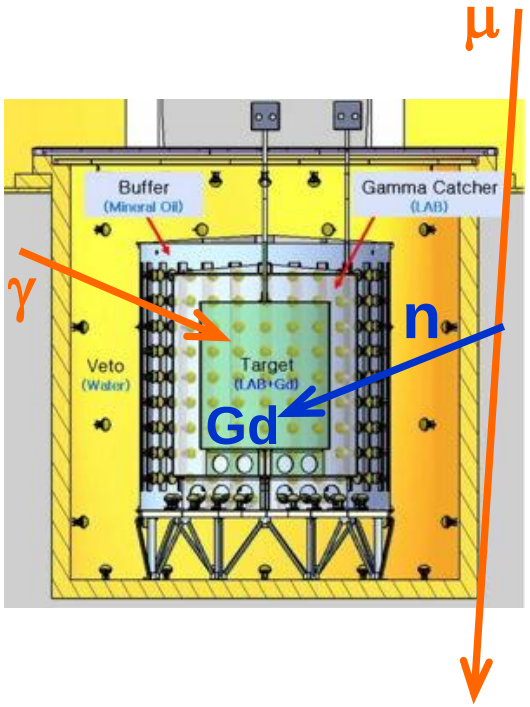




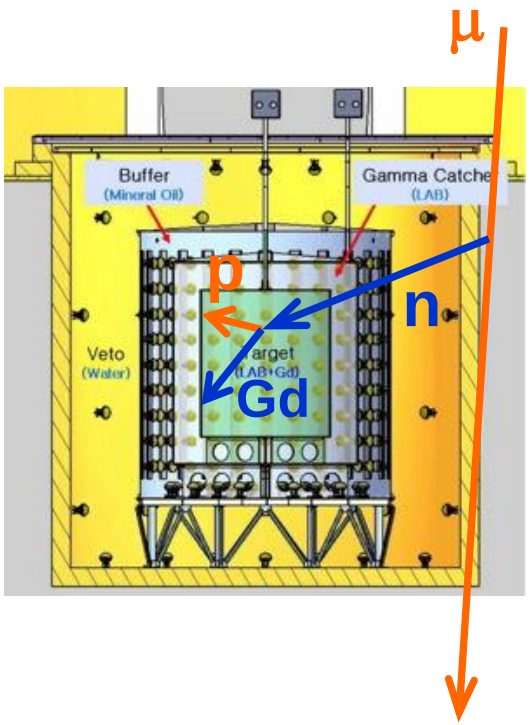
Backgrounds

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

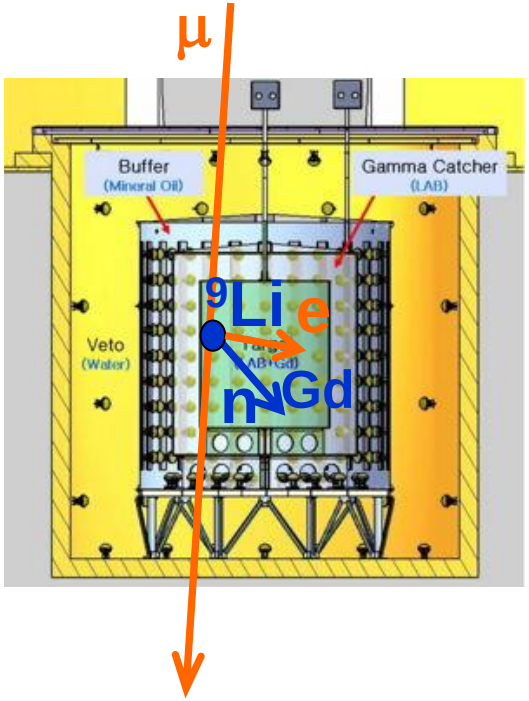
Accidentals



Fast neutrons



^{9}Li/^{8}He β-n followers



Improved Background Estimation

- Better estimation of Li/He background :

$3.61 \pm 0.59(\mathrm{sys}) \pm 0.11(\mathrm{stat})/\,day \rightarrow 3.55 \pm 0.44(sys) \pm 0.11(stat)/\,day$ (far)

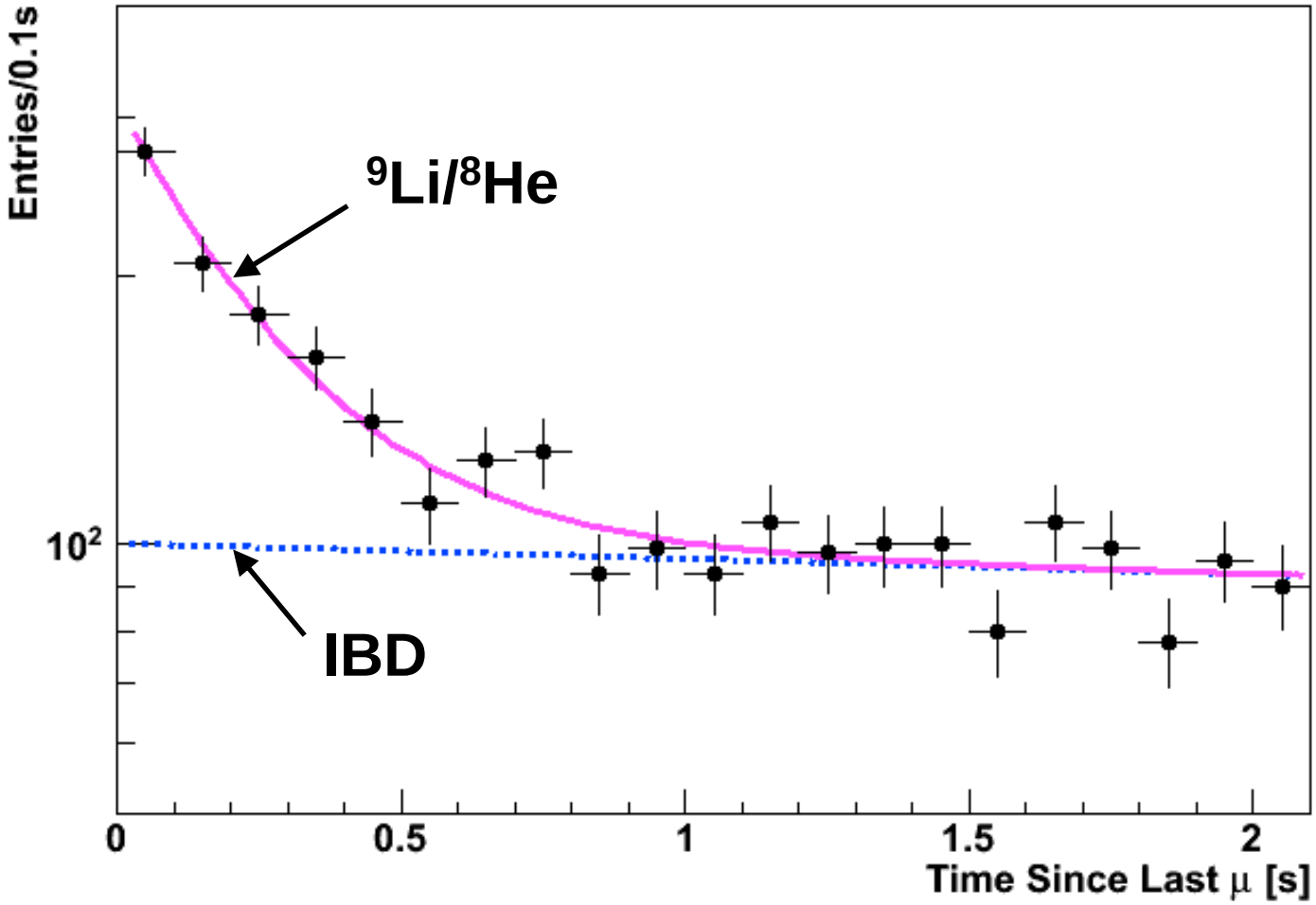
$13.73 \pm 2.12(\mathrm{sys}) \pm 0.22(\mathrm{stat})/\,day \rightarrow 13.97 \pm 1.52(sys) \pm 0.22(stat)/\,day$ (near)

$$\sin^2 2\theta_{13} = 0.100 \pm 0.010\,(stat) \pm 0.015\,(syst)$$

$$\sin^2 2\theta_{13} = 0.100 \pm 0.010\,(stat) \pm 0.012\,(syst)$$

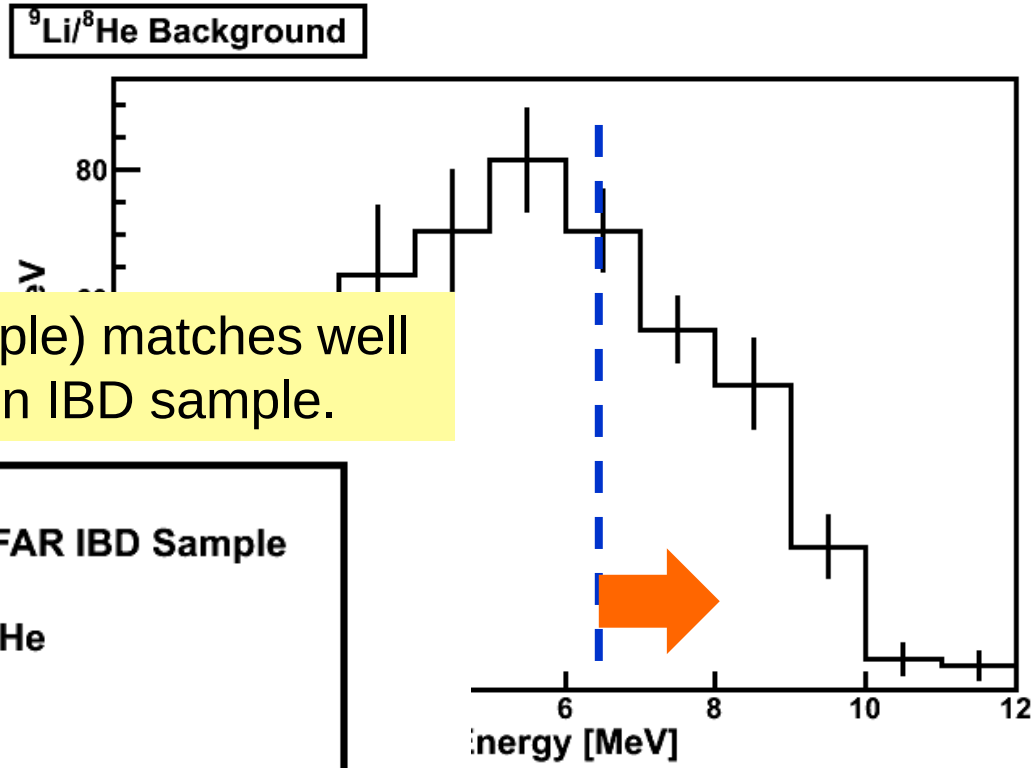
^{9}Li/^{8}He Background

- ^{9}Li/^{8}He are unstable isotopes emitting (β,n) followers and produced when a muon interacts with carbon in the LS.

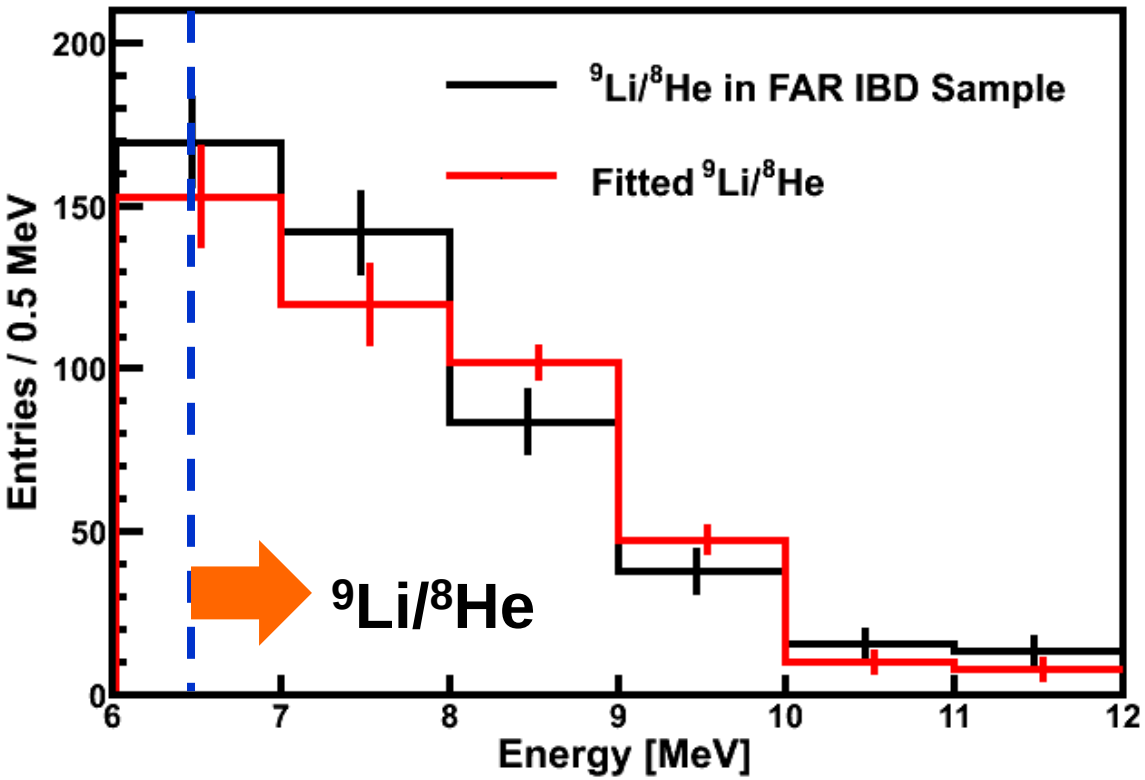


^{9}Li/^{8}He Background Estimation

- Scaling method;
  $N_{LH} = \alpha * n_{LH}$



Fitted shape (from BG only sample) matches well with the Li/He shape contained in IBD sample.



Error improvement:
1) 8 MeV → 6.5 MeV
($\delta\alpha$ improved)
2) Increased statistics of Li/He BG spectrum
(δn_{LH} improved)

Summary of Final Data Sample

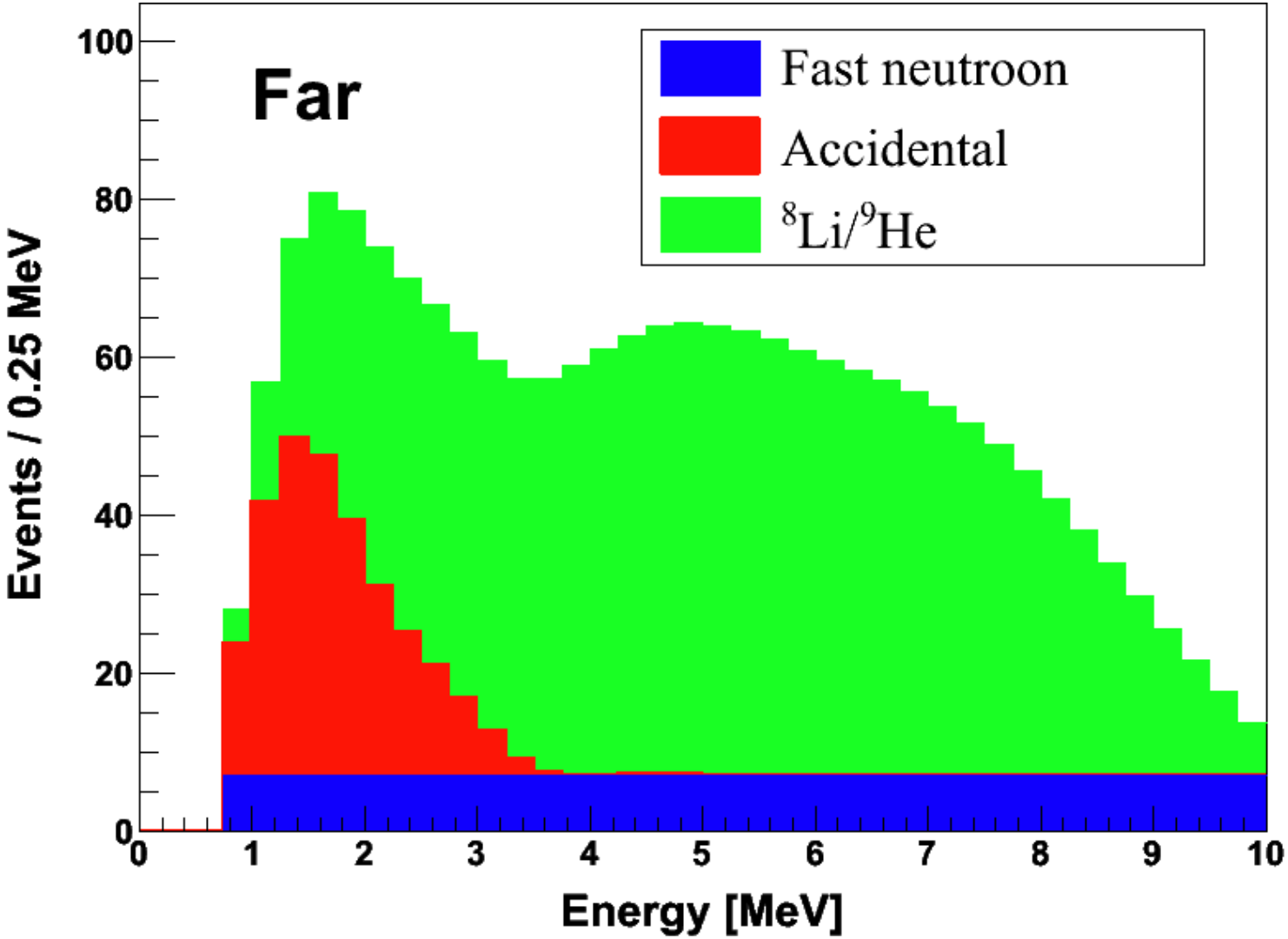
(Prompt energy < 10 MeV)

Detector	Near	Far
Selected events	279787	30211
Total background rate (per day)	21.17± 1.81	4.80± 0.46
IBD rate after background subtraction (per day)	737.00± 2.31	70.22± 0.64
DAQ Live time (days)	369.03	402.69
Detection efficiency (ϵ)	62.0± 0.014	71.4± 0.014
Accidental rate (per day)	3.61± 0.05	0.60± 0.03
^{9}Li/^{8}He rate (per day)	13.97± 1.54	3.55± 0.45
Fast neutron rate (per day)	3.59± 0.95	0.65± 0.10

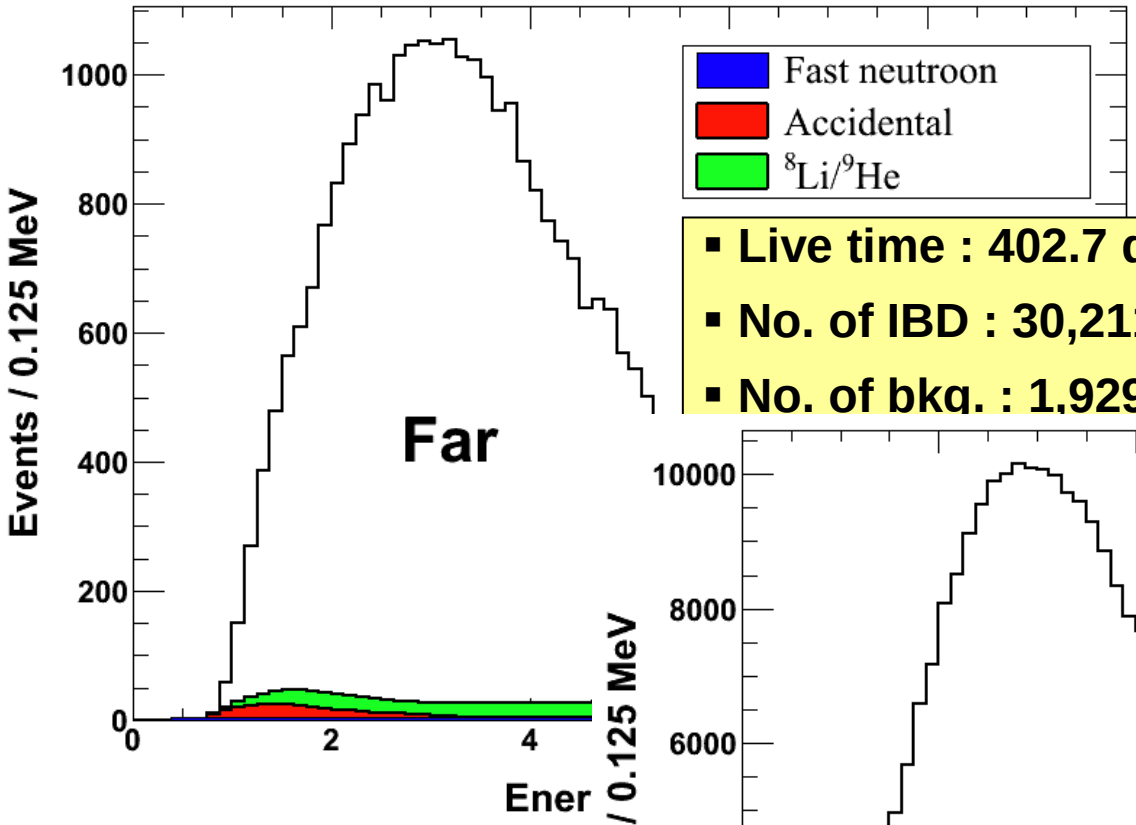
Background Spectra

- Background shapes and rates are well understood

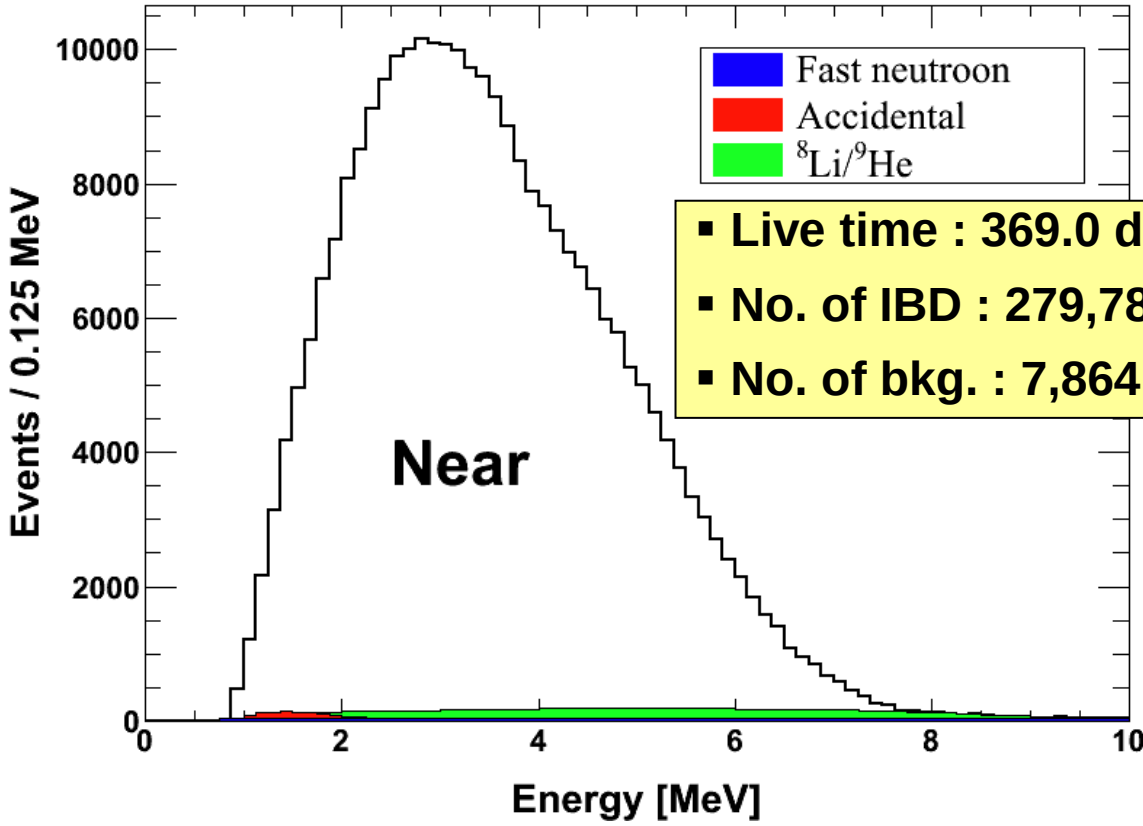
- Total backgrounds : 6.4% at Far
  2.8% at Near



Measured Spectra of IBD Prompt Signal

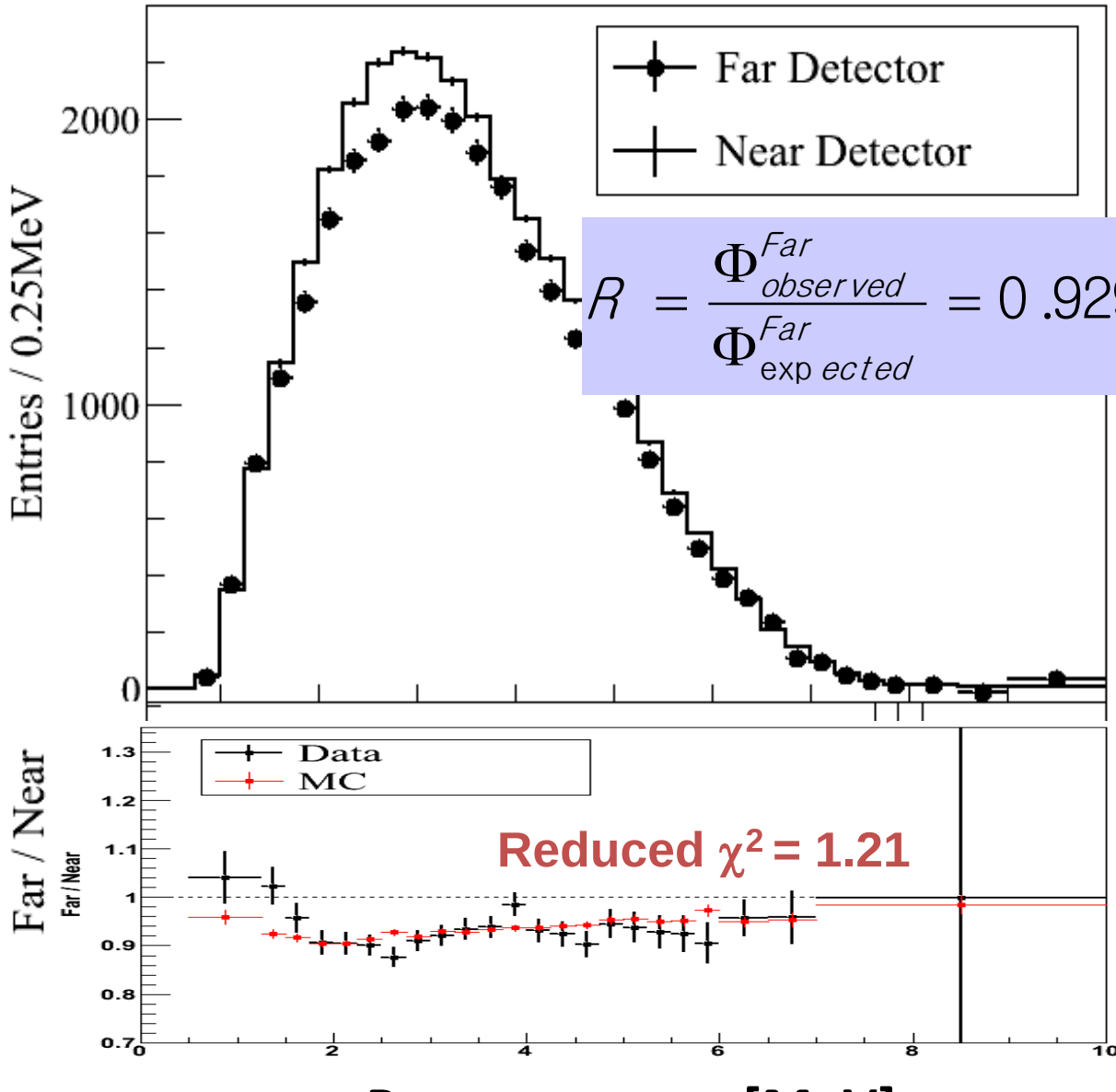


- Live time : 402.7 days
- No. of IBD : 30,211
- No. of bkg. : 1,929 (6.4%)



- Live time : 369.0 days
- No. of IBD : 279,787
- No. of bkg. : 7,864 (2.8%)

Reactor Antineutrino Disappearance



preliminary

$$R = \frac{\Phi^{Far}_{observed}}{\Phi^{Far}_{expected}} = 0.929 \pm 0.006\,(stat) \pm 0.007\,(s$$

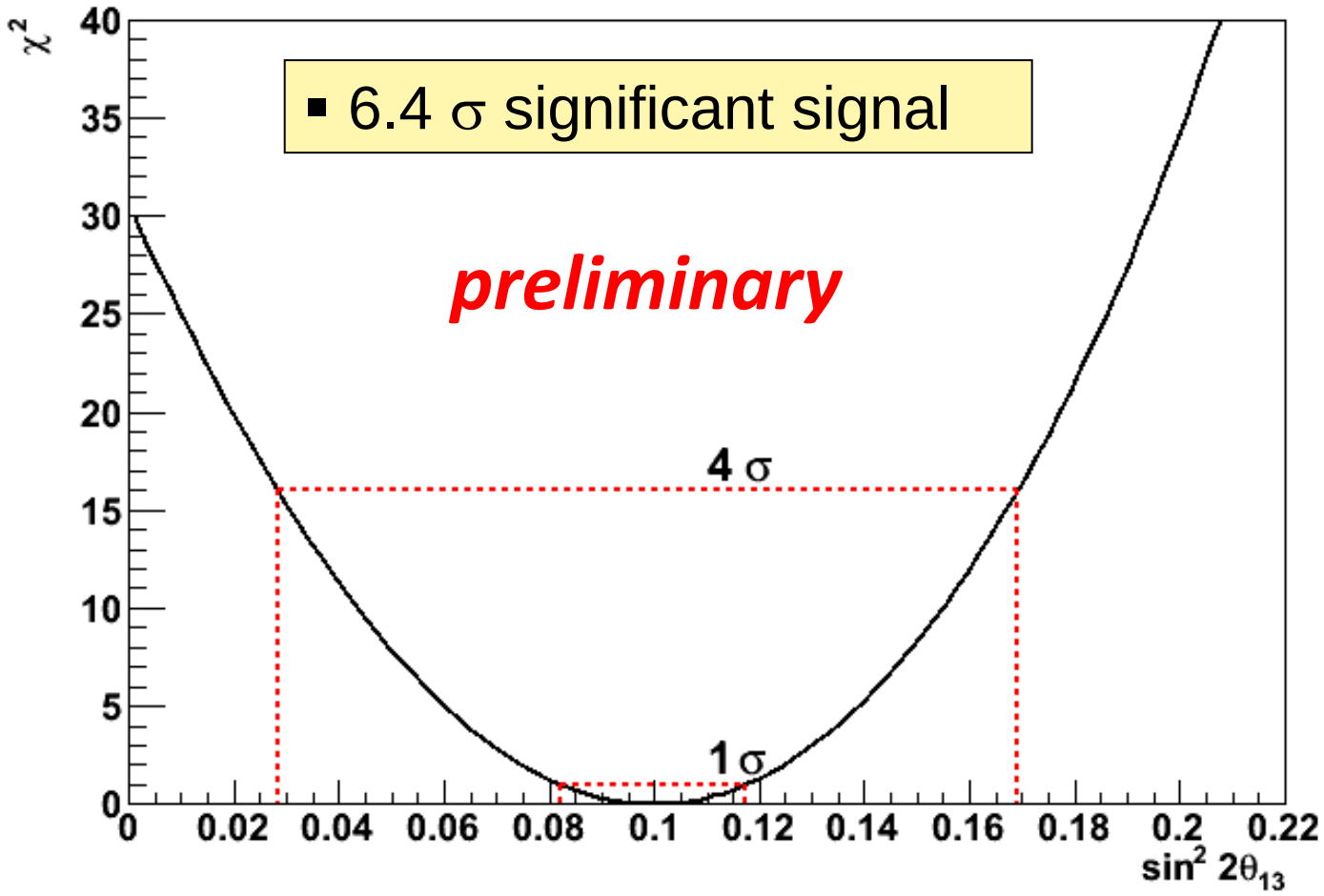
- A clear deficit in rate

  (~ 7 % reduction)

- Consistent with neutrino oscillation in the spectral distortion

Definitive Measurement of θ_{13}

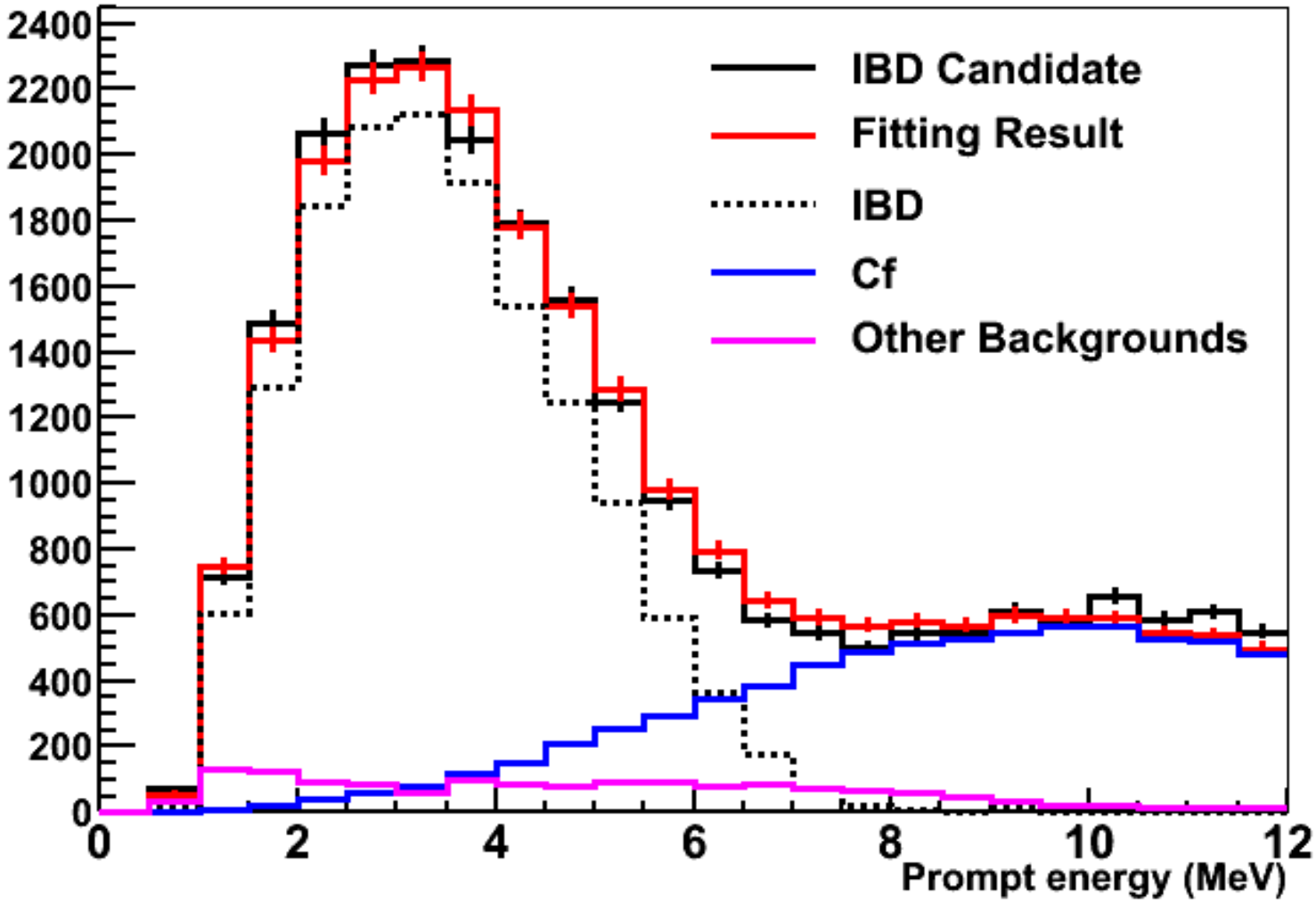
$$\sin^2 2q_{13} = 0.100 \pm 0.010(stat.) \pm 0.012(syst.)$$



IBD Analysis of ^{252}Cf contaminated data

13th Oct. 2012 ~ 25th July. 2013

IBD (/day) : 54.5094 +- 0.489393
Cf (/day): 26.2655 +- 0.361229



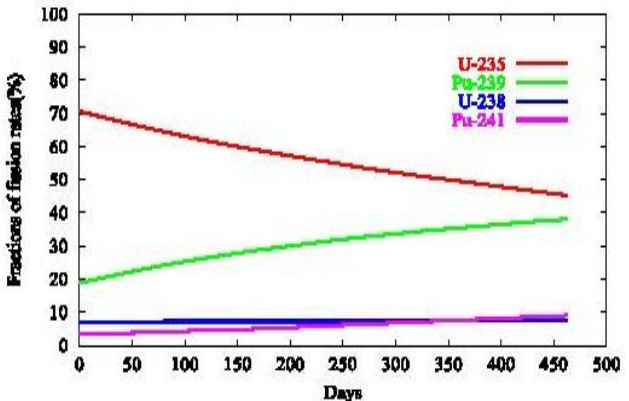
Expected Reactor Antineutrino Fluxes

- Reactor neutrino flux

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

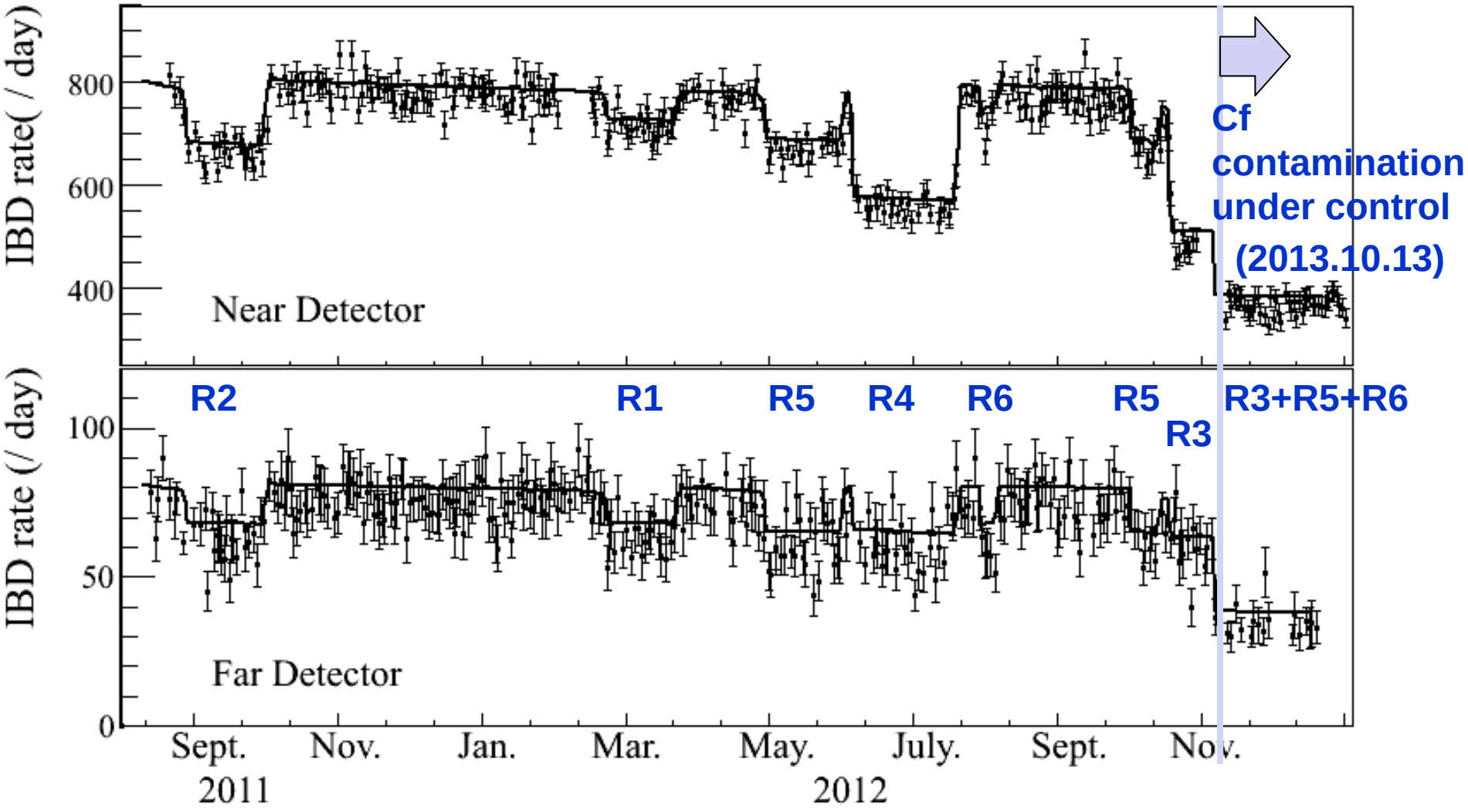
- P_{th} : Reactor thermal power provided by the YG nuclear power plant
- f_i : Fission fraction of each isotope determined by reactor core simulation of Westinghouse ANC
- $\phi_i(E_\nu)$: Neutrino spectrum of each fission isotope
  [* P. Huber, Phys. Rev. C84, 024617 (2011)
  T. Mueller *et al*., Phys. 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

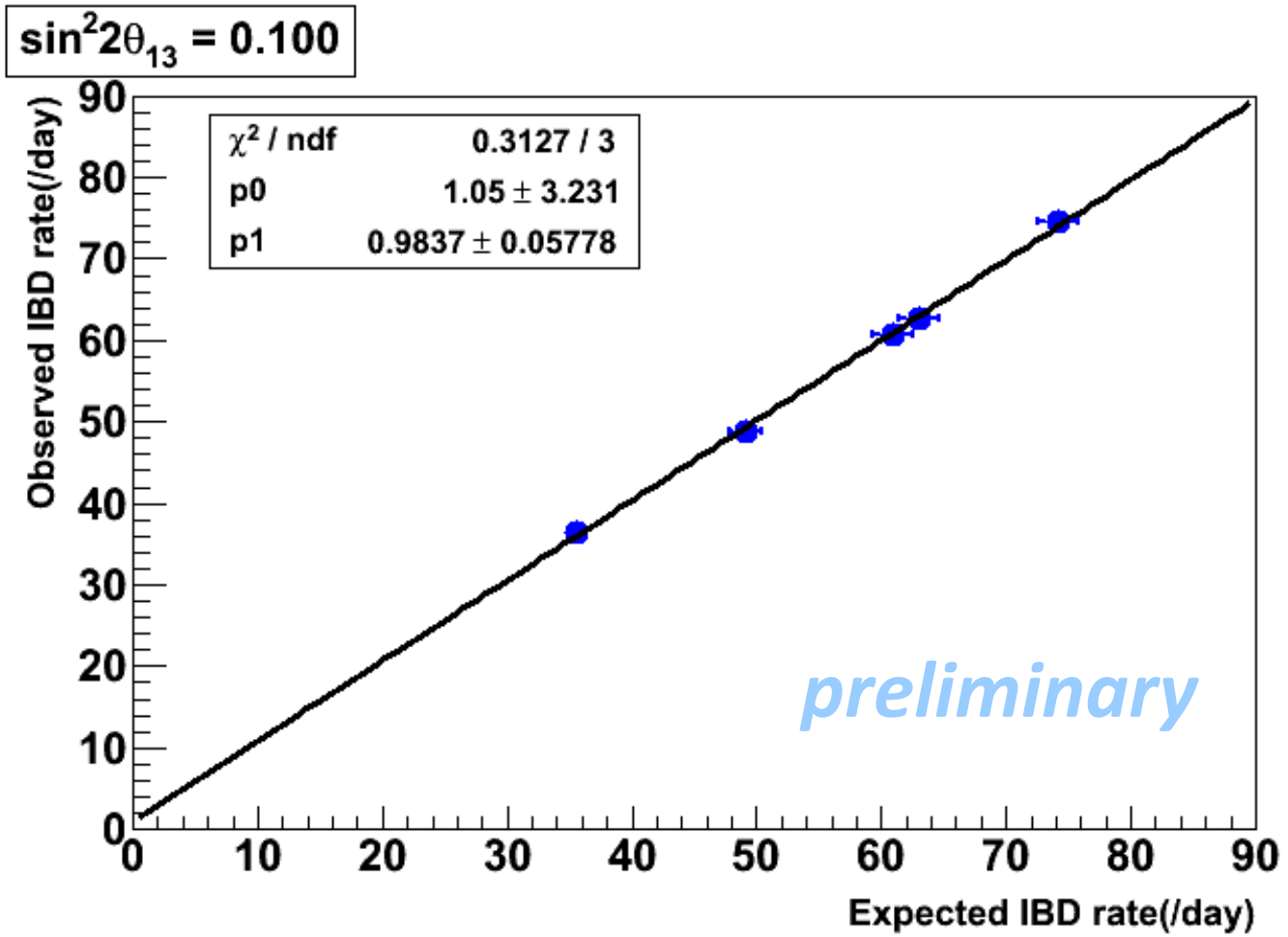


Observed Daily Averaged IBD Rate

- A new way to measure the reactor thermal power remotely!!!



Observed vs. Expected IBD Rates



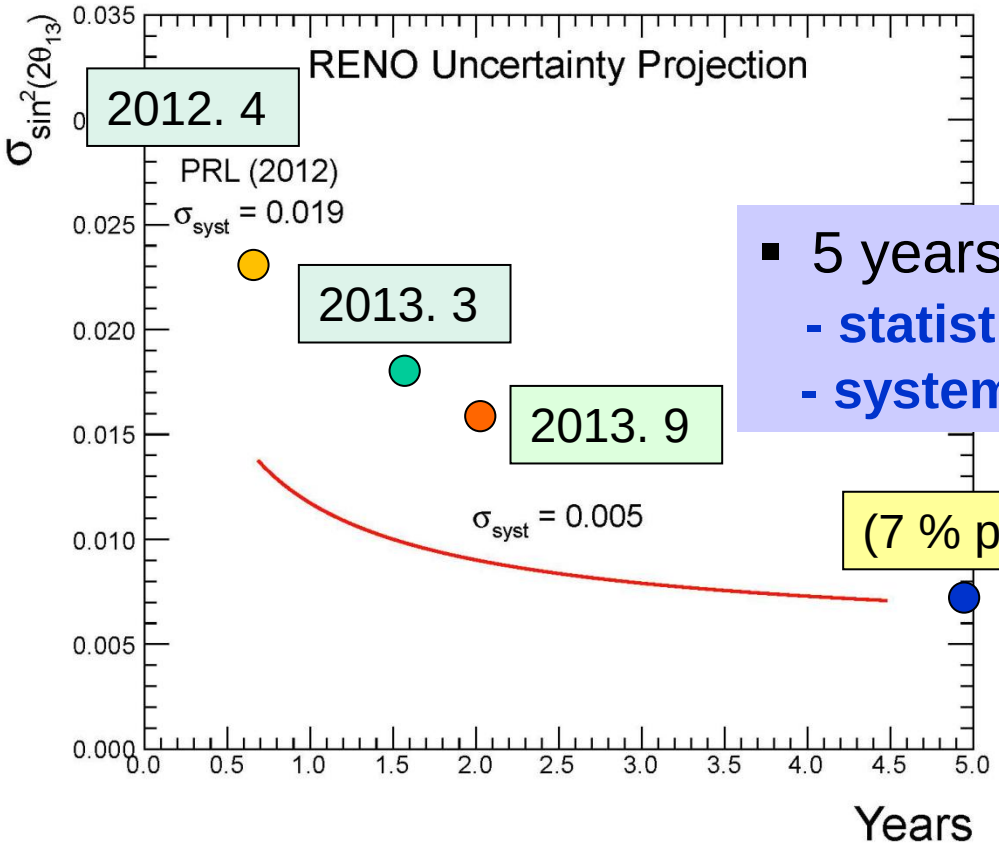
- ✓ A good agreement between observed and expected IBD rates with oscillation hypothesis
- ✓ Correct background subtraction

RENO's Projected Sensitivity of θ_{13}

$$\sin^2 2\theta_{13} = 0.100 \pm 0.010\,(stat.) \pm 0.012\,(syst.)$$

(402 days) 0.100 ± 0.016 (6.4 σ) (16 % precision)

± 0.007 (~ 13 σ) (7 % precision) (5 years)



- 5 years of data : ±0.007 (7% precision)
  - **statistical error : ±0.010 → ±0.005**
  - **systematic error : ±0.012 → ±0.005**

Expected Results from RENO

- **$\sin^2(2\theta_{13})$** to 7% accuracy within 3 years :
  → determination of CP phase with accelerator results

- **Δm^2_{31}** directly from reactor neutrinos :
  ← spectral disappearance of reactor antineutrinos

- Precise measurement of reactor antineutrino flux & spectra :
  → study reactor anomaly or sterile neutrinos

- Observation of reactor neutrinos based on neutron capture by Hydrogen

Summary

- RENO has observed a clear disappearance of reactor neutrinos.

- RENO has obtained a new result on the smallest mixing angle θ_{13}.

$$\sin^2 2\theta_{13} = 0.100 \pm 0.010\,(stat) \pm 0.012\,(syst)$$ (402 days)

- RENO has collected ~700 live days of reactor neutrino data, and improved analysis methods on energy calibration and background estimation.

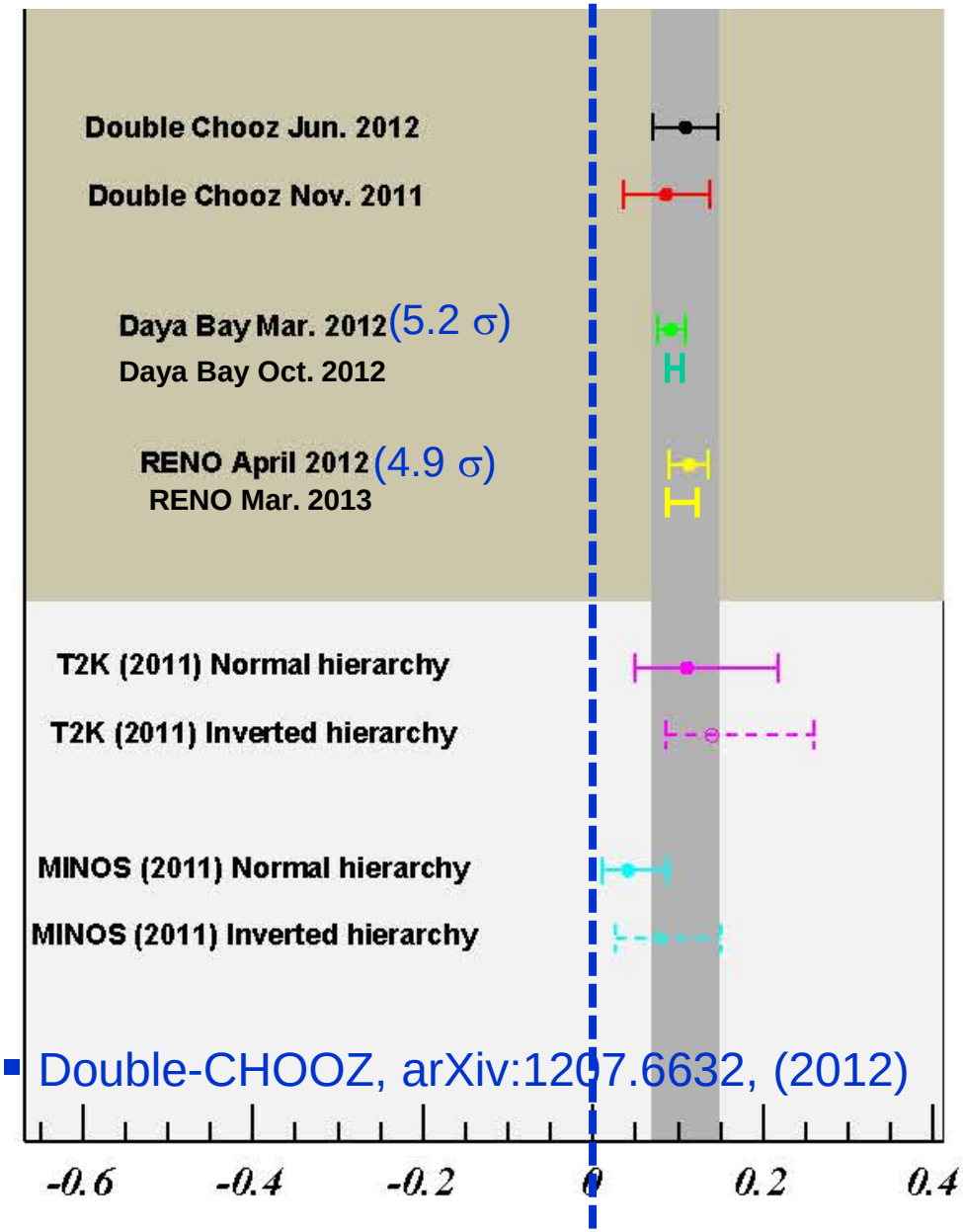
- RENO is expected to obtain new results from 700 live days of reactor neutrino data. Several analyses are under progress.

Backup

A Brief History of θ_{13} from Reactor Experiments

- Nov. 2011 (Double Chooz)
  $\sin^2(2\theta_{13}) = 0.086 \pm 0.051$
- March 2012 (Daya Bay)
  $\sin^2(2\theta_{13}) = 0.092 \pm 0.017$
- April 2012 (RENO)
  $\sin^2(2\theta_{13}) = 0.113 \pm 0.023$
- June 2012 (Double Chooz)
  $\sin^2(2\theta_{13}) = 0.109 \pm 0.039$
- Oct. 2012 (Daya Bay)
  $\sin^2(2\theta_{13}) = 0.089 \pm 0.011$
- Sep. 2013 (RENO)
  $\sin^2(2\theta_{13}) = 0.100 \pm 0.016$
- August 2013 (Daya Bay)
  $\sin^2(2\theta_{13}) = 0.090 \pm 0.009$

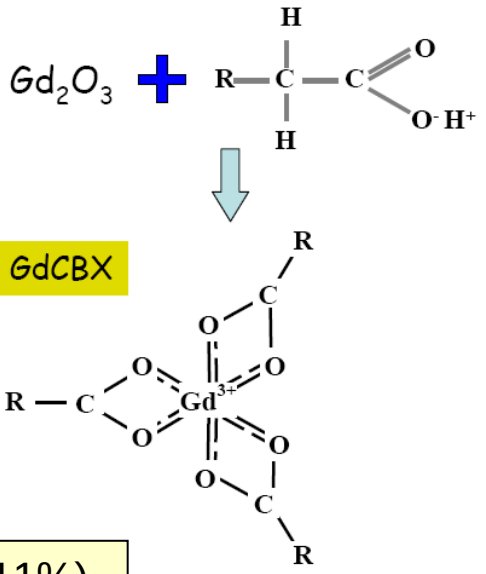
$\Delta m^2_{31} = (2.54 \pm 0.20) \times 10^{-3}$ eV^2



- Double-CHOOZ, arXiv:1207.6632, (2012)

Gd Loaded Liquid Scintillator

Carboxylic acids

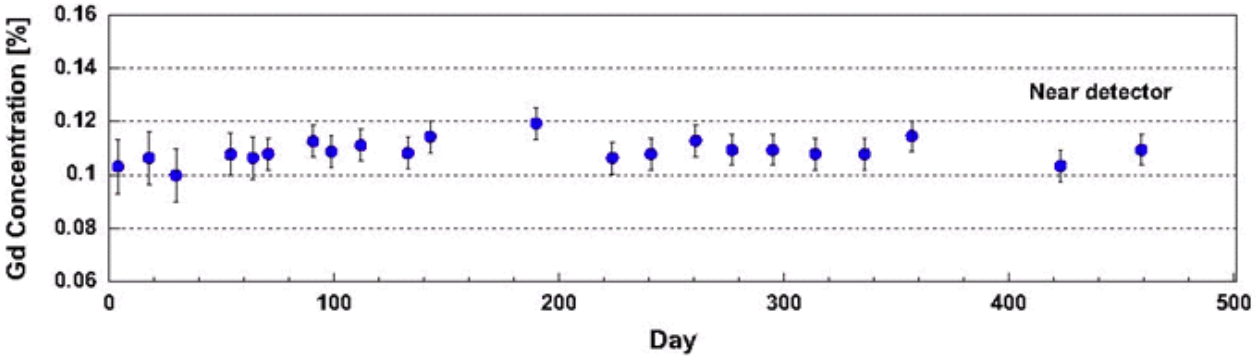


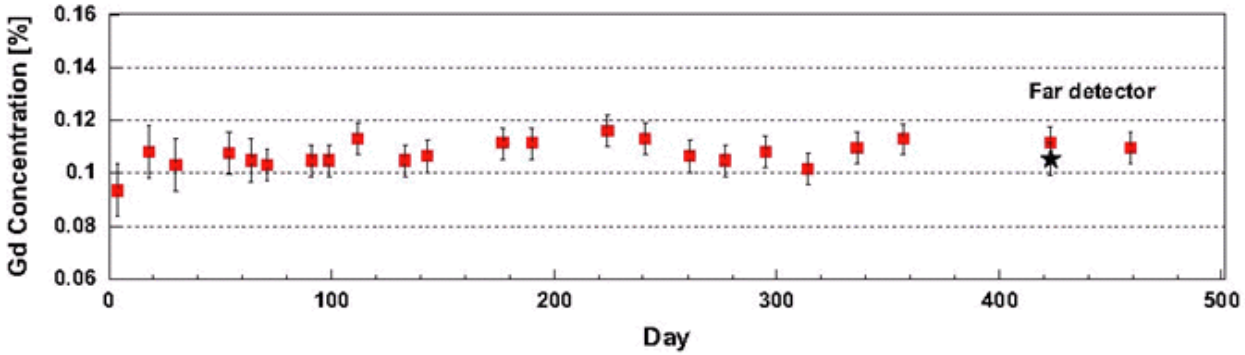
❑ Recipe of Liquid Scintillator

Solvent & Flour	WLS	Gd-compound
LAB	PPO + Bis-MSB	0.1% Gd + $(TMHA)^3$

❑ Steady properties of Gd-LS

• Stable light yield (~250 pe/MeV) , transparency & Gd concentration (0.11%)





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IBD Prompt Signal (Data vs. MC)