RENO Reactor Neutrino Experiment

"New Results from RENO”

RENO = Reactor Experiment for Neutrino Oscillation

(On behalf of RENO Collaboration)

K.K. Joo
Chonnam National University

February 11, 2016

Lake Louise Winter Institute 2016
@ Chateau Lake Louise, Canada

Outline

RENO

- Data taking status
- Improvements in data analysis
- Latest results of θ_{13} from RENO
- Spectral analysis for Δm_{ee}^2
- Results from n-H IBD sample
- Summary

RENO Collaboration

10 institutions and 40 physicists in Korea

- Chonnam National University
- Chung-Ang University
- Dongshin University
- GIST
- Gyeongsang National University
- Kyungpook National University
- Sejong University
- Seoul National University
- Seoyeong University
- Sungkyunkwan University

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

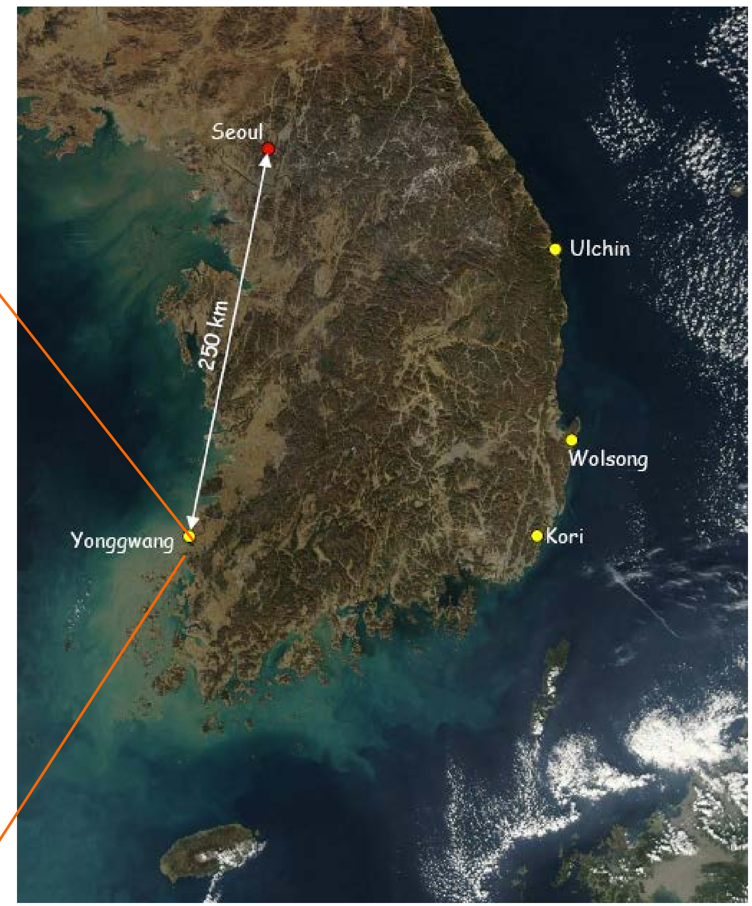
YongGwang (靈光) :

Reactor **E**xperiment for **N**eutrino **O**scillation

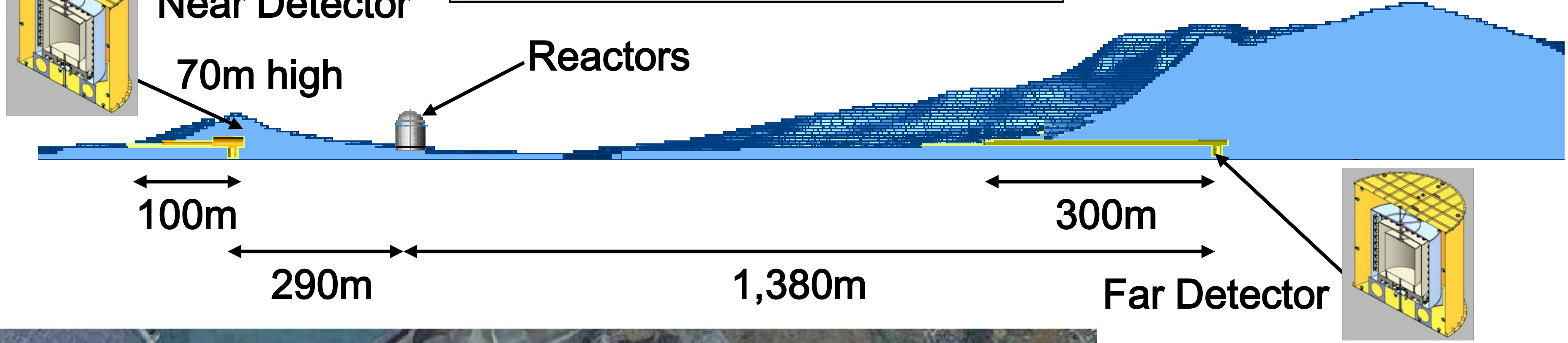
YongGwang Nuclear Power Plant

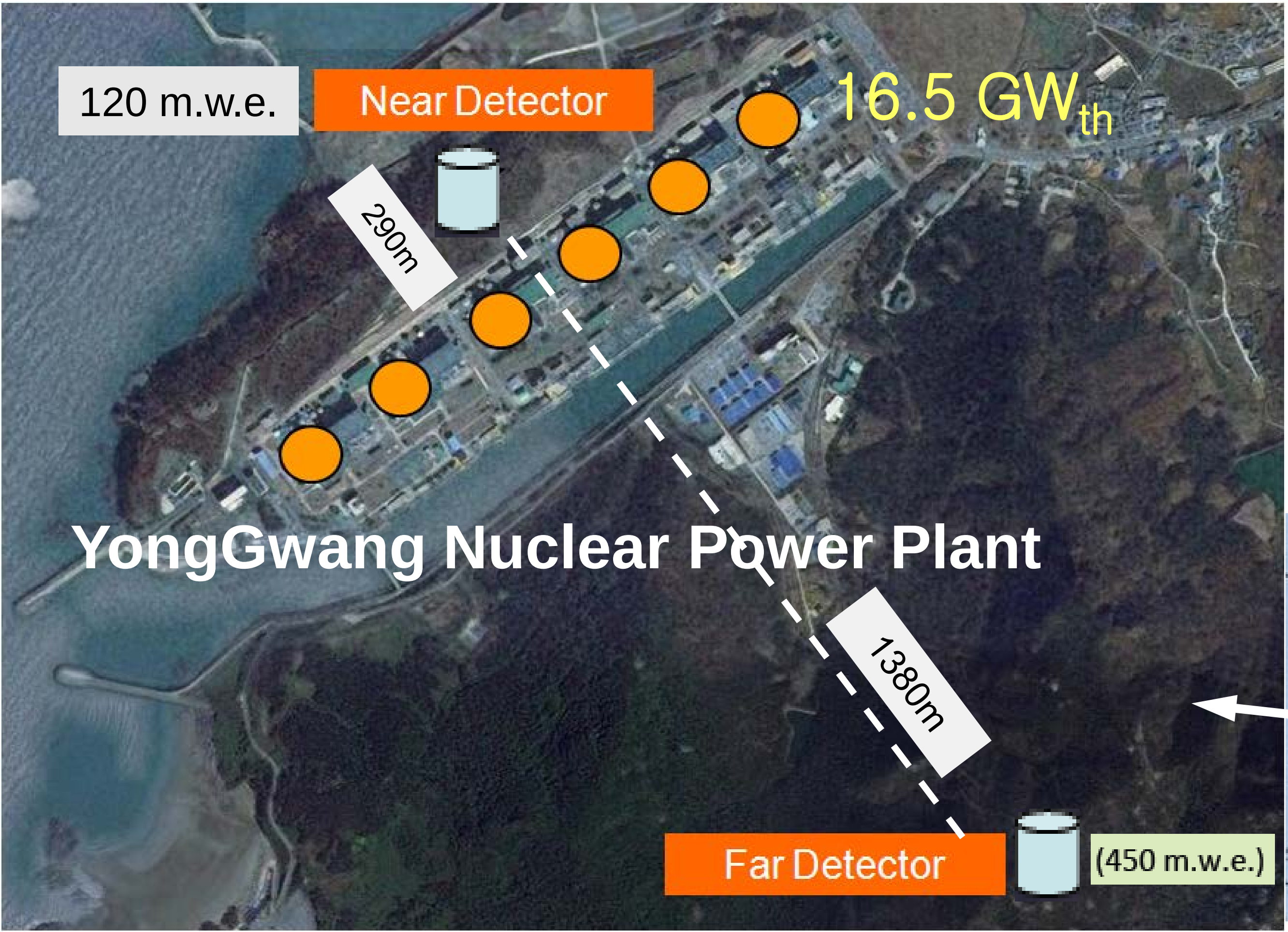
- Located in the west coast of southern part of Korea
- ~300 km from Incheon international airport
- 6 reactors are lined up in roughly equal distances and span ~1.3 km
- Total average thermal output ~16.7GW_{th} (2nd largest in the world)

YongGwang(靈光):
= glorious[splendid] light (~spirited)
New name: Hanbit



Google Satellite View of Experimental Site

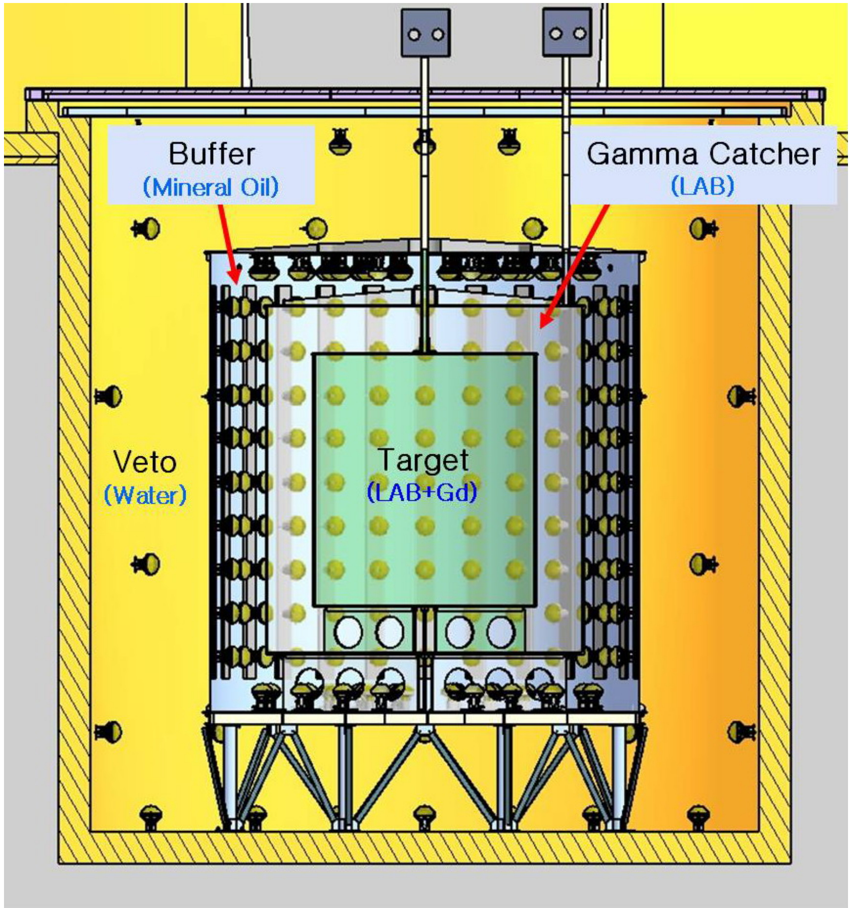


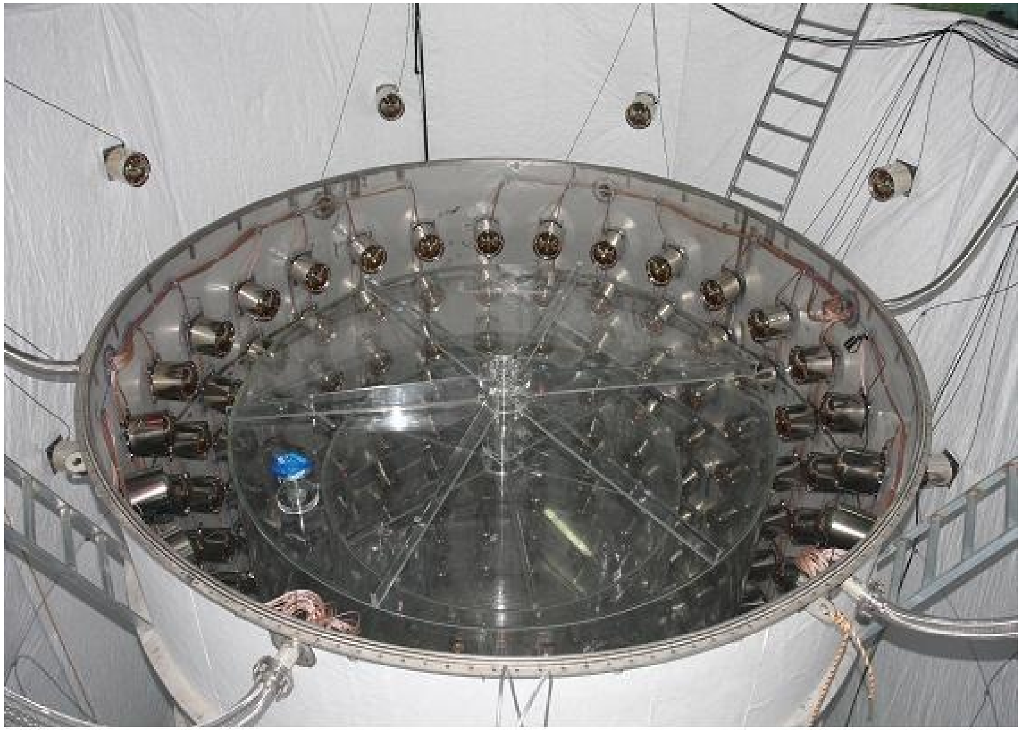


RENO

KNRC
Korea Neutrino Research Center

RENO Detector



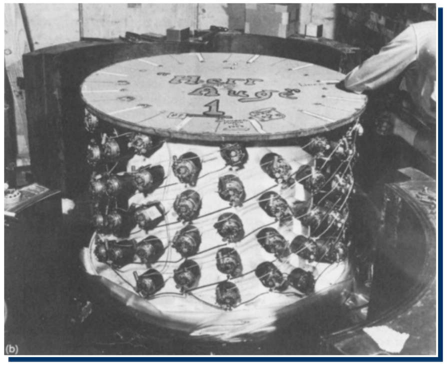


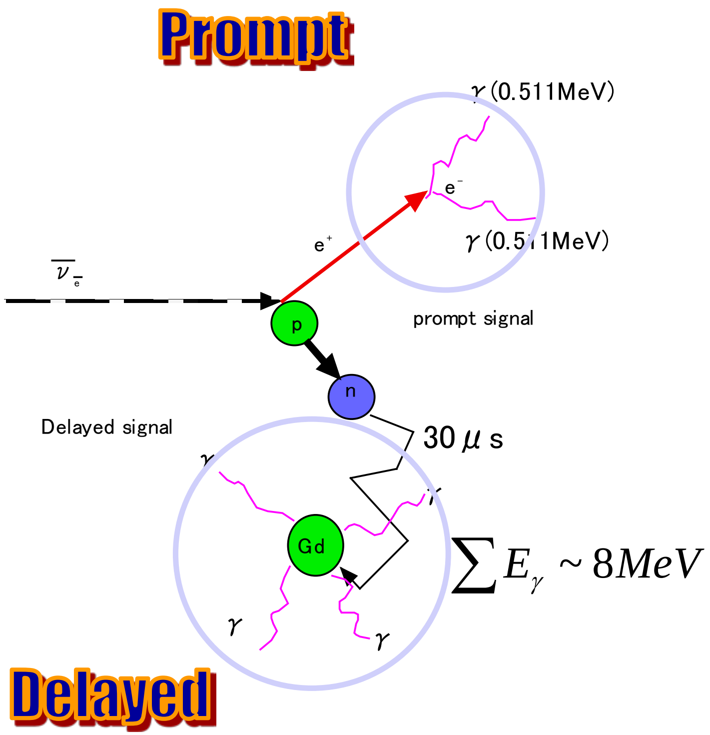
- Target : **16.5 ton** Gd-LS (R=1.4m, H=3.2m)
- Gamma Catcher : 30 ton LS (R=2.0m, H=4.4m)
- Buffer : 65 ton mineral oil (MO) (R=2.7m, H=5.8m)
- Veto : 350 ton water (R=4.2m, H=8.8m)

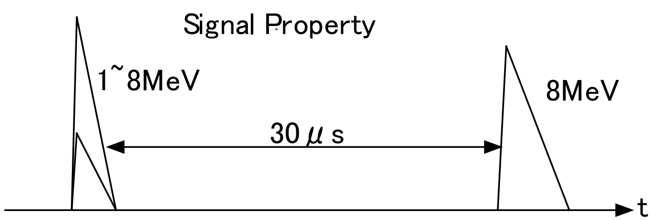
total ~460 tons

- **Inner PMTs: 354 10” PMTs**
  - solid angle coverage = ~14%
- **Outer PMTs: ~ 67 10” PMTs**

Detection of Reactor Antineutrinos







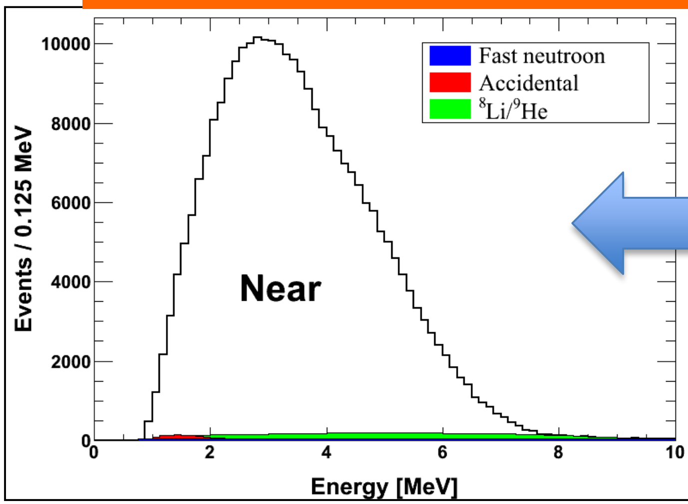
- Use inverse beta decay ($\overline{\nu}_e + p \rightarrow e^+ + n$) reaction process
- Prompt part:
  subsequent annihilation of the positron to two 0.511MeV γ
- Delayed part:
  neutron is captured
  ~200μs w/o Gd
  ~ 30μs w Gd
  Gd has largest n absorption cross section & emits high energy γ
- Signal from neutron capture
  ~2.2MeV w/o Gd
  ~ 8MeV w Gd
- Measure prompt signal & delayed signal
- "Delayed coincidence" reduces backgrounds drastically

Signal: IBD Pair

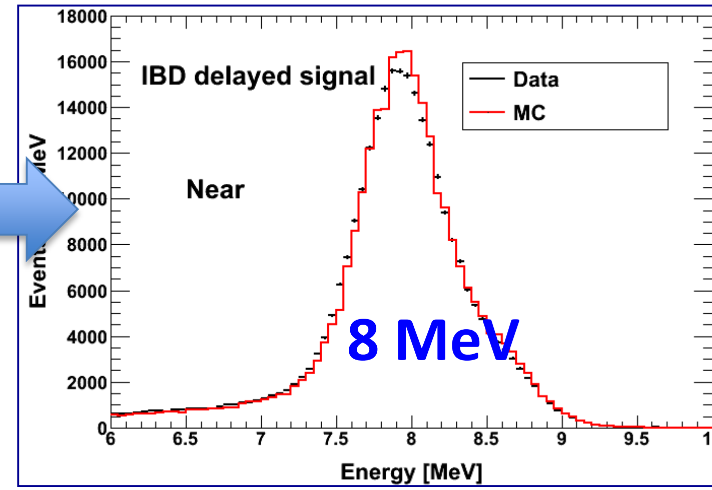
Prompt signal (S1)

n-Gd IBD

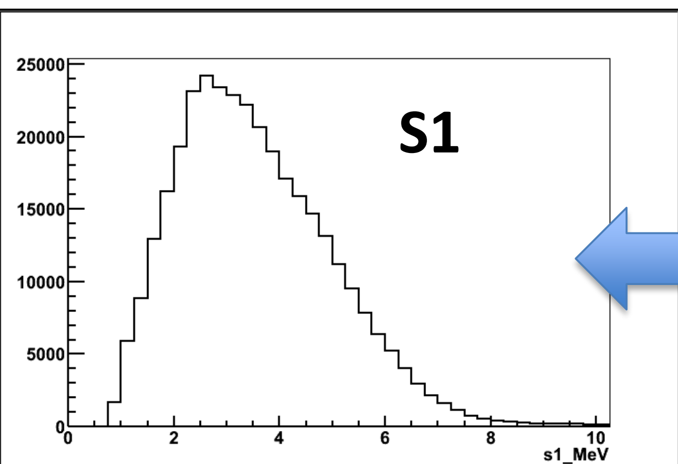
Delayed signal (S2)



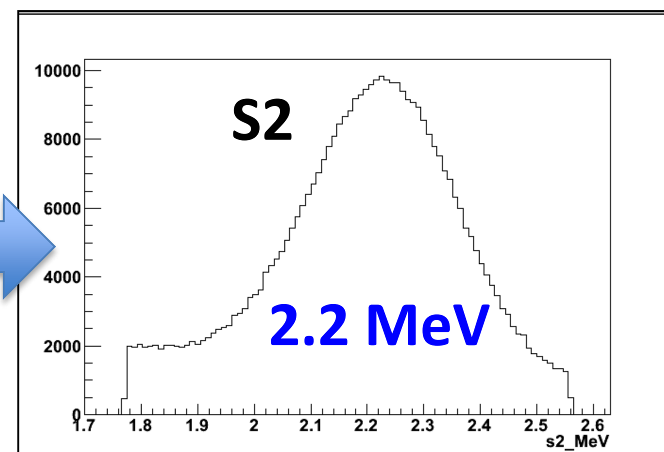
~30 μs



n-H IBD



~200 μs



Suppresses background a lot !

RENO Data Taking Status

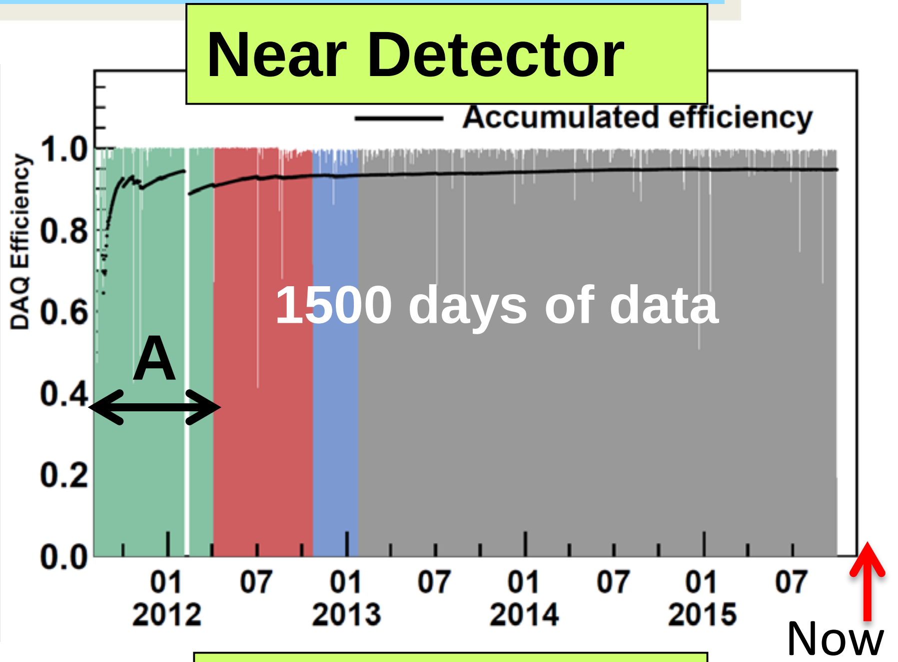
- Data taking began on Aug. 1, 2011 with both near and far detectors.
(DAQ efficiency : ~95%)

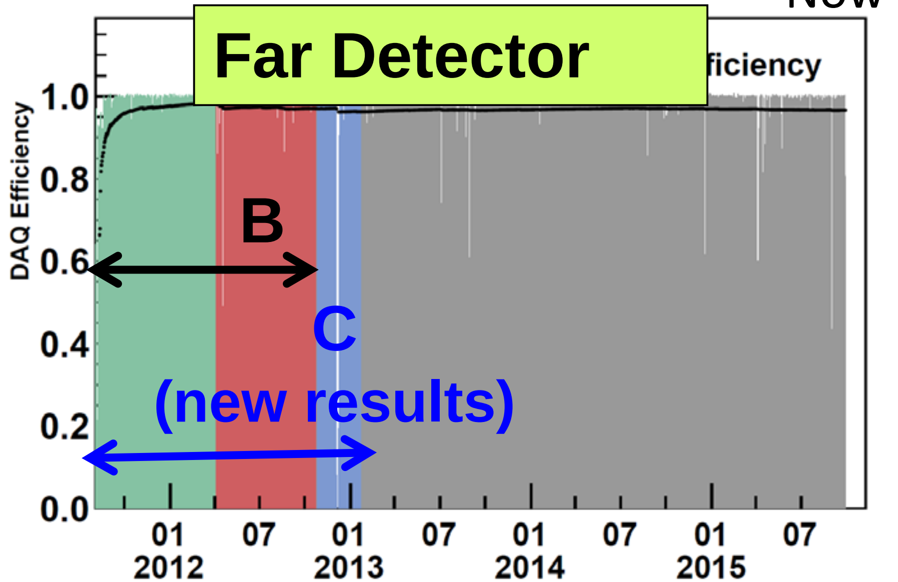
- **A** (220 days) : **First θ_{13} result**
[11 Aug, 2011~26 Mar, 2012]
PRL 108, 191802 (2012)

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

- **C** (~500 days) : New **θ_{13} result**
Shape+rate analysis (submitted in PRL)
[11 Aug, 2011~31 Jan, 2013]

- Total observed reactor neutrino events as of today : **~ 1.5M** (Near), **~ 0.15M** (Far)
→ Absolute reactor neutrino flux measurement in progress
[reactor anomaly & sterile neutrinos]





Recent Results from RENO

- New measured value of θ_{13} from rate-only analysis using ~500 days of data

- Observation of an excess at ~5 MeV in reactor neutrino spectrum

- Observation of energy dependent disappearance of reactor neutrinos to measure Δm_{ee}^2 and θ_{13}

"Observation of Energy and Baseline Dependent Reactor Antineutrino Disappearance in the RENO Experiment"

(submitted in PRL, arXiv:1511.05849 [hep-ex], Nov 2015)

- Details can be found there & PRD in preparation

- Rate-only analysis with neutron capture on Hydrogen using ~400 days of data

Improvements after Neutrino 2014

- Relax Q_{max}/Q_{tot} cut : 0.03 → 0.07

  - allow more accidentals to increase acceptance of signal and minimize any bias to the spectral shape

- More precisely observed spectra of Li/He background

  - reduced the Li/He background uncertainty based on an increased control sample

- More accurate energy calibration

  - best efforts on understanding of non-linear energy response and energy scale uncertainty

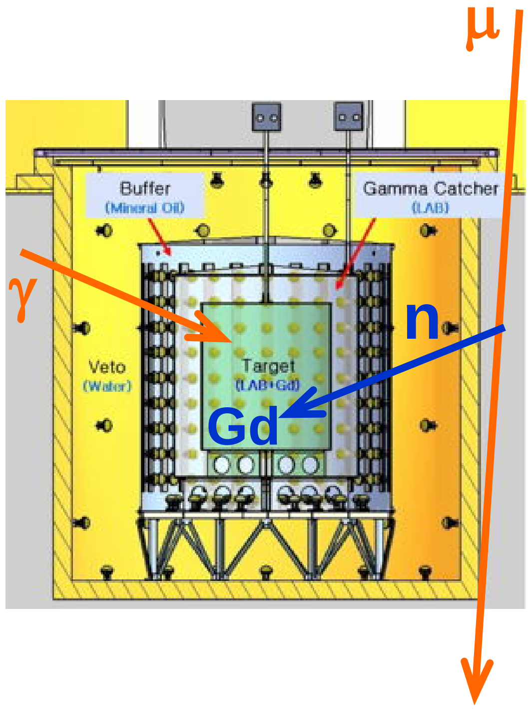
- Elaborate study of systematic uncertainties on a spectral fitter

  - estimated systematic errors based on a detailed study of spectral fitter in the measurement of Δm_{ee}^2

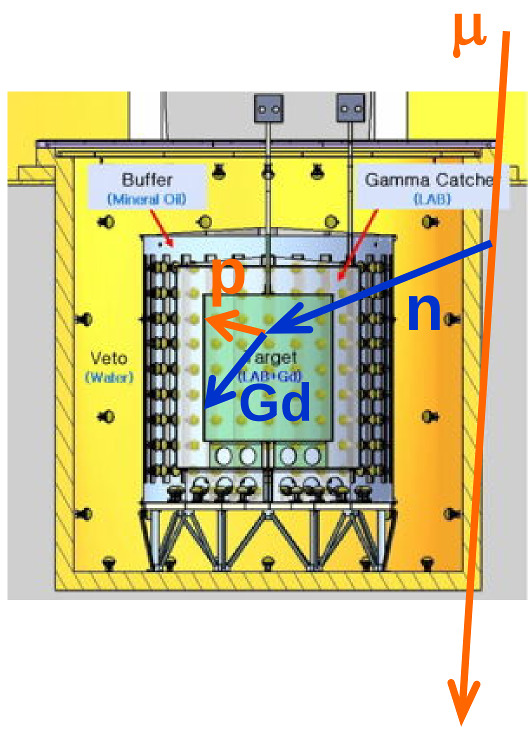
Backgrounds

- 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

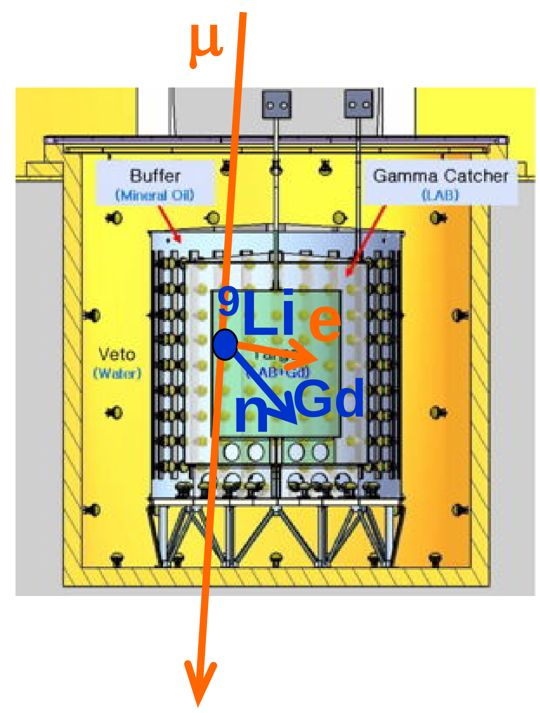
Accidentals



Fast neutrons



^{9}Li/^{8}He β-n followers



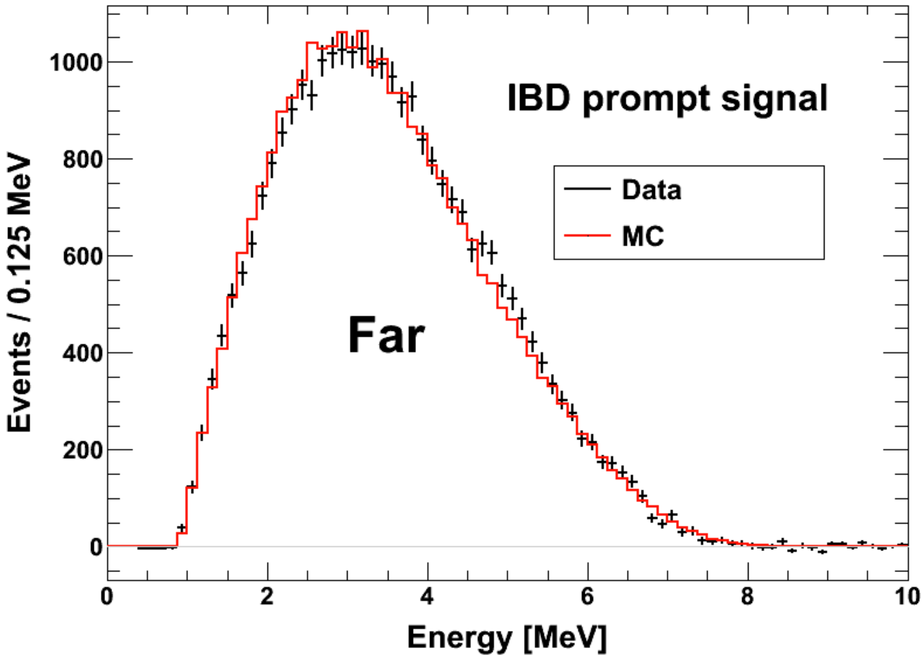
Signature of Reactor Neutrino Event (IBD)

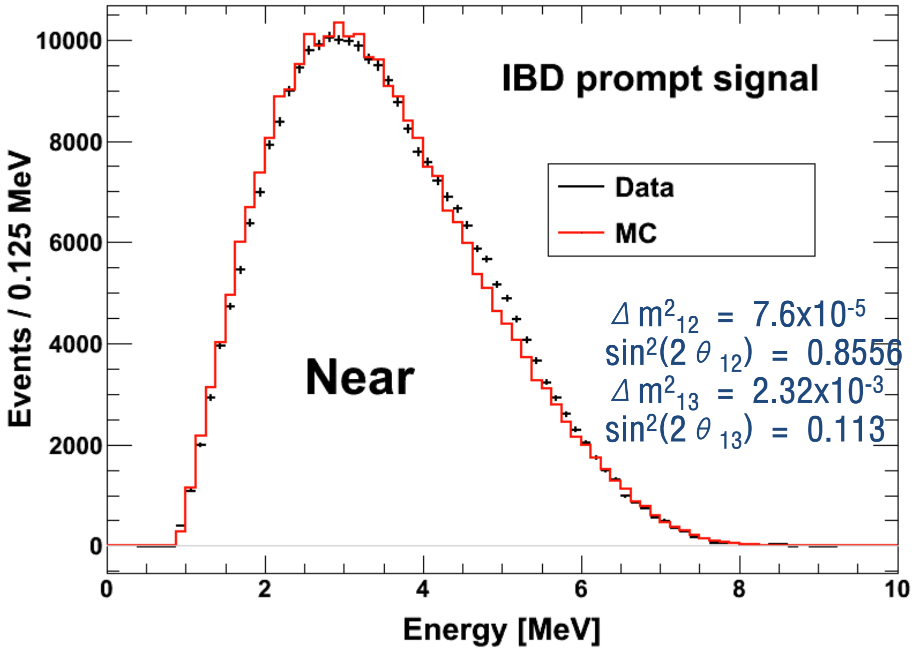
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

- 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

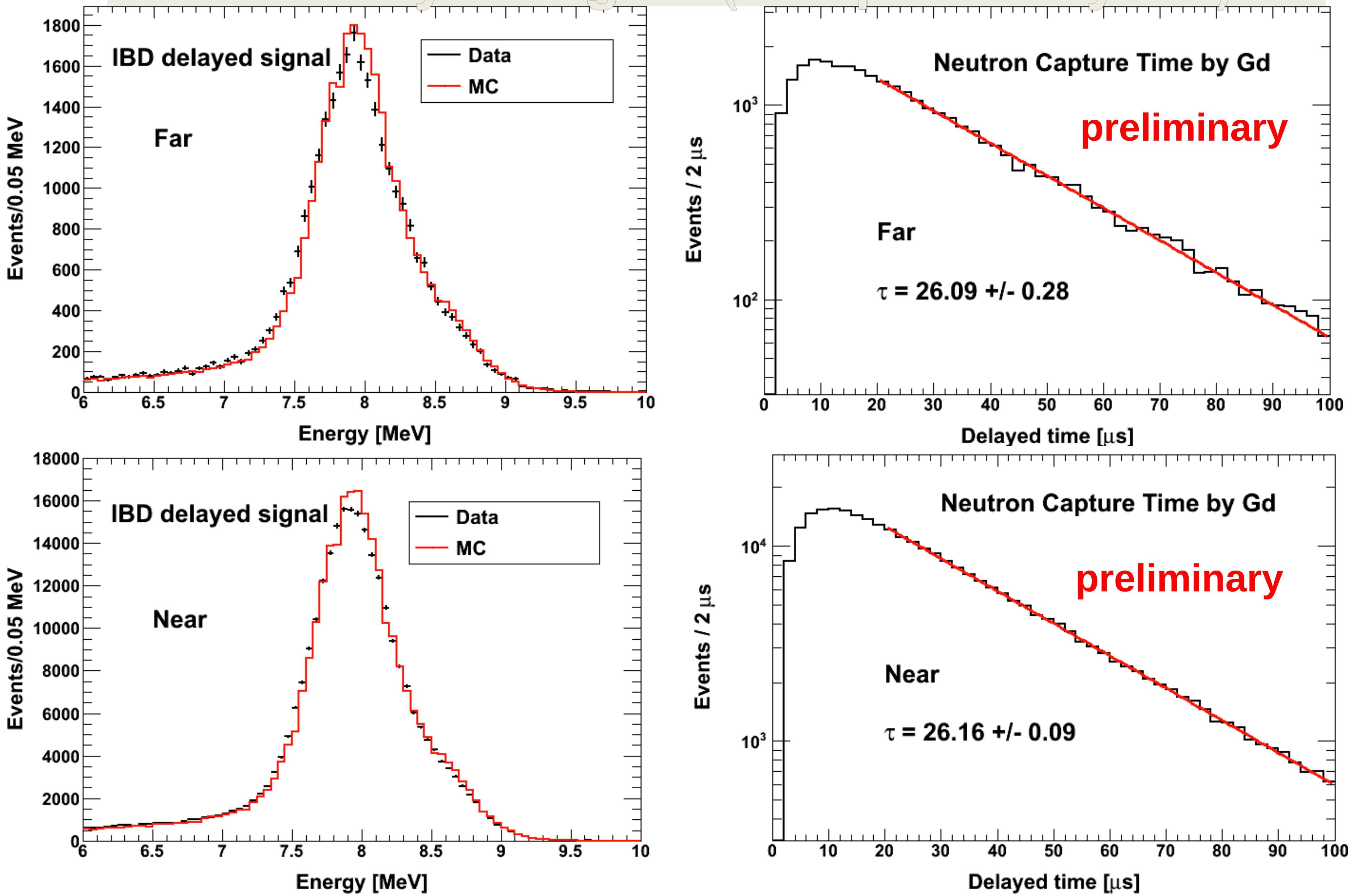
~26 μs (0.1% Gd) in LS

Observed spectra for Prompt Signal

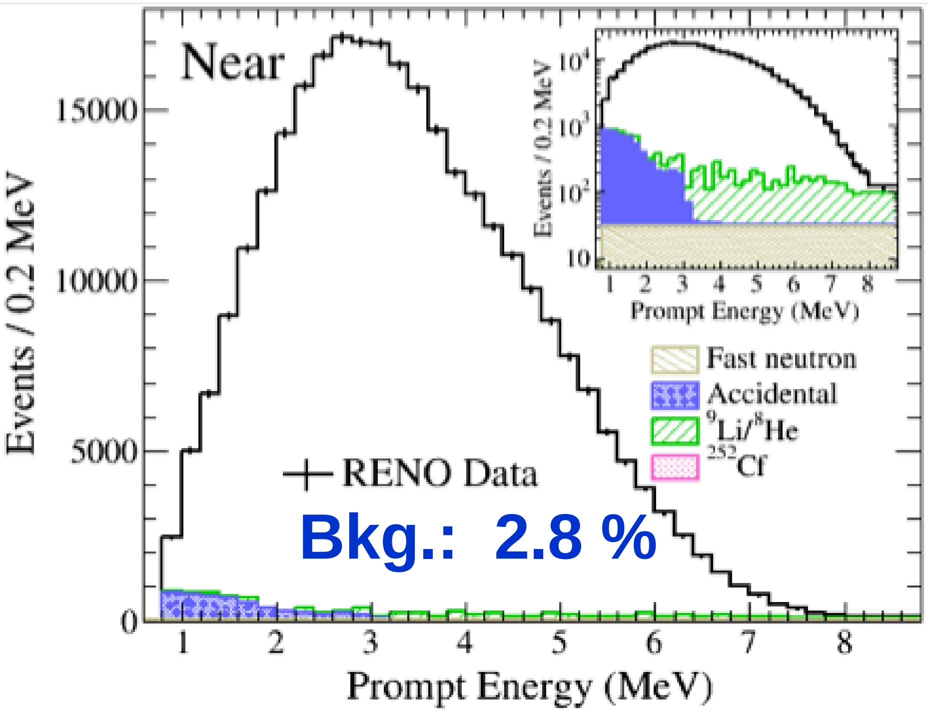


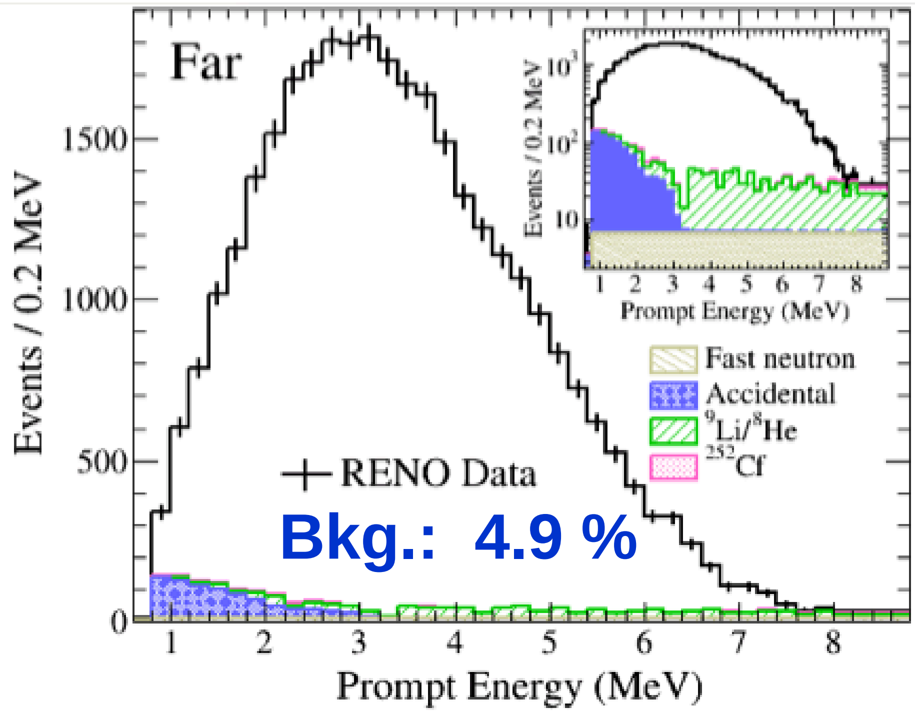


Observed Spectra for Delayed Signal (n captured by Gd)



Measured Spectra of IBD Prompt Signal





Near Live time = 458.49 days
# of IBD candidate = 290,775
# of background = 8,041 (2.8 %)

Far Live time = 489.93 days
# of IBD candidate = 31,541
# of background = 1540 (4.9 %)

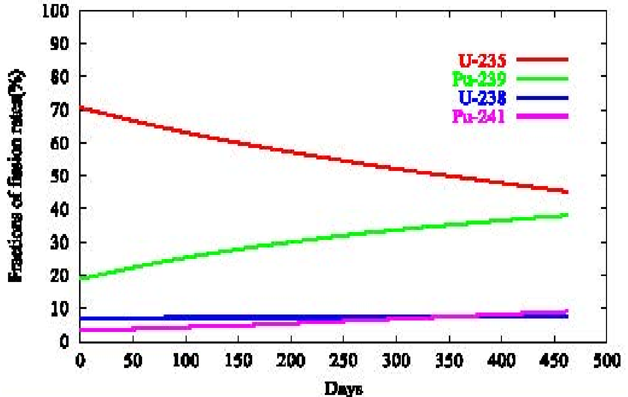
Expected Reactor Antineutrino Fluxes

- Reactor neutrino flux

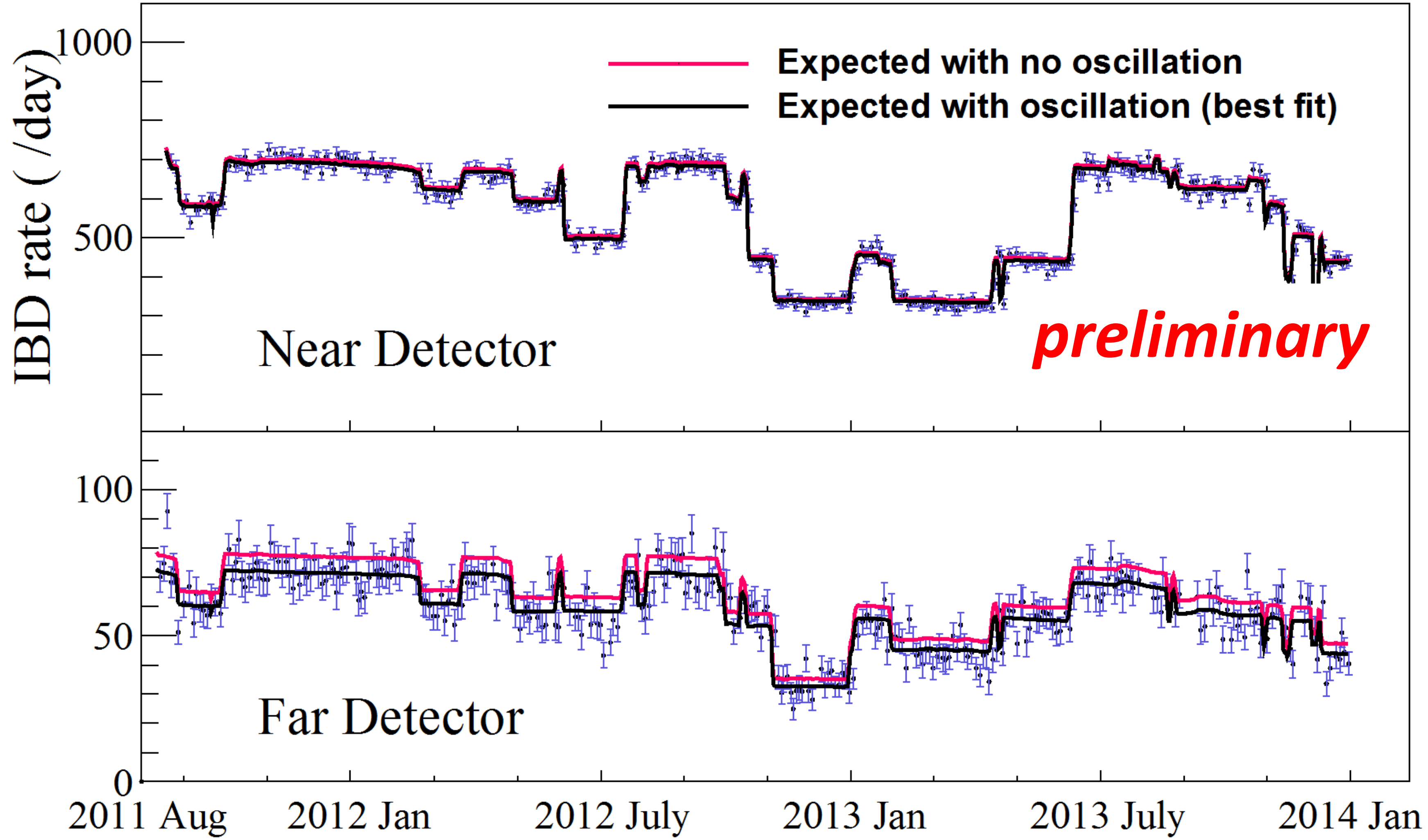
$$\Phi(E_\nu) = \frac{P_{th}}{\sum_i^{isotopes} f_i \cdot E_i} \sum_i^{isotopes} f_i \cdot \phi_i(E_\nu)$$

- 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

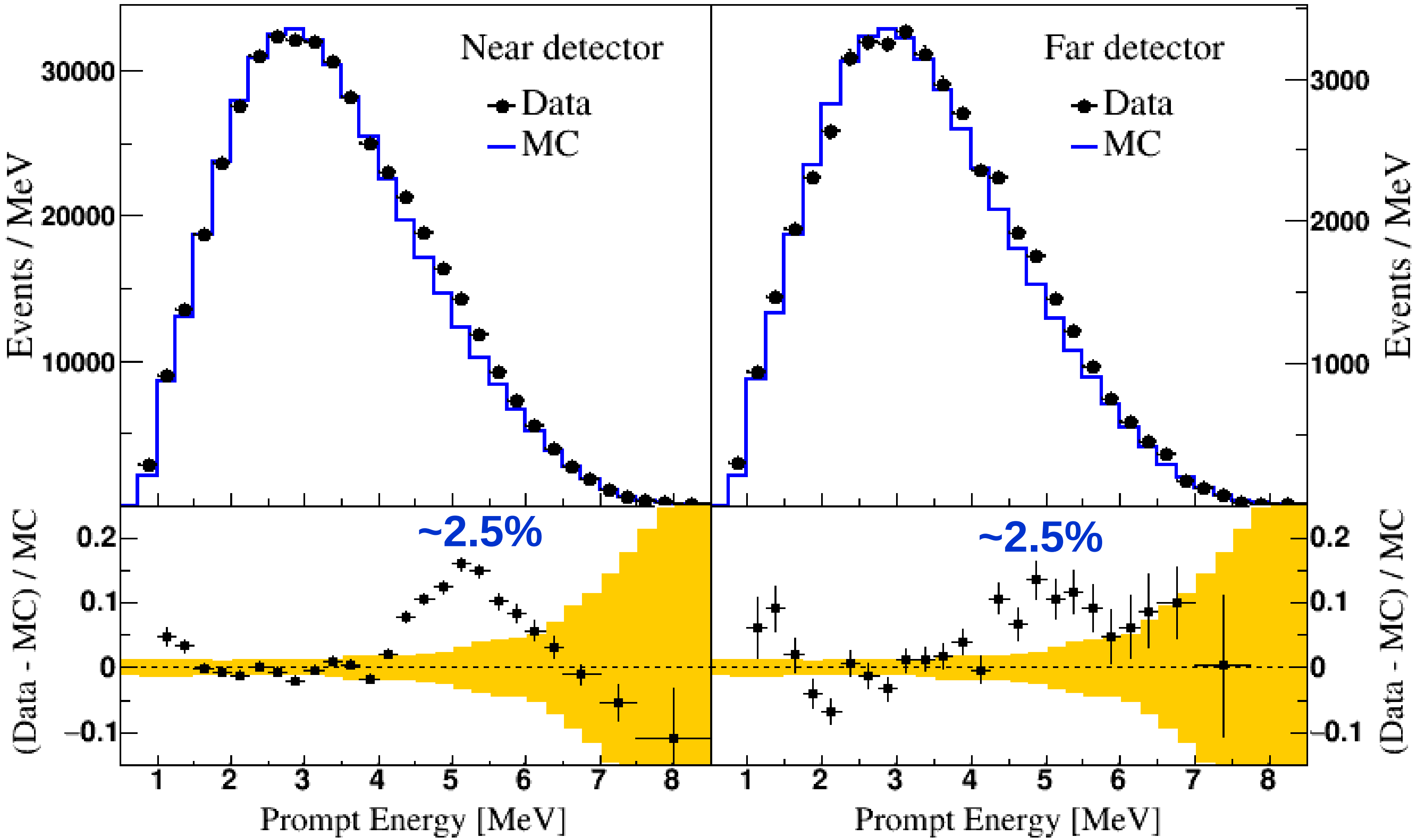


Observed Daily Averaged IBD Rate

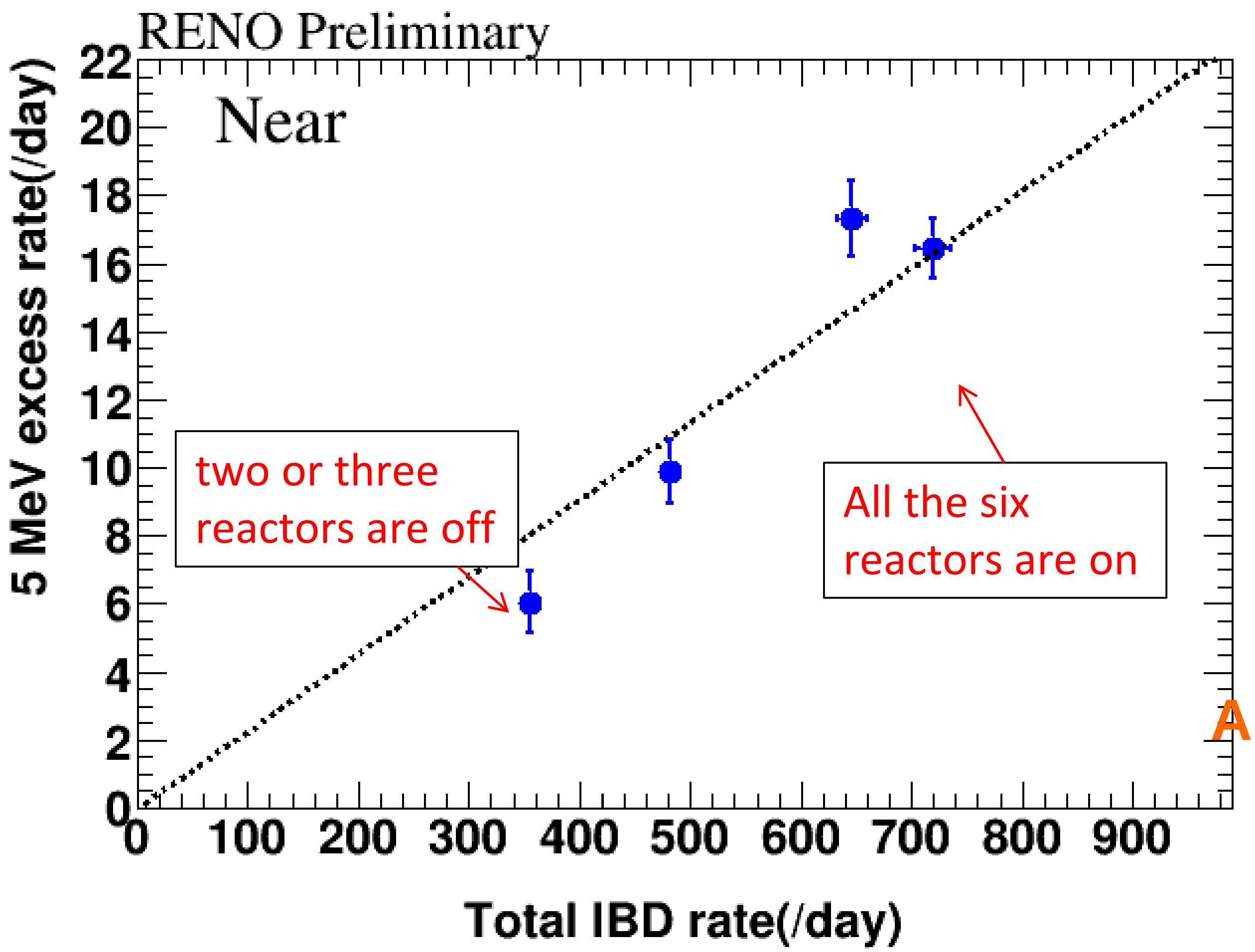


- Good agreement with observed rate and prediction
- Accurate measurement of thermal power by reactor neutrinos

Observation of an excess at 5 MeV



Correlation of 5 MeV Excess with Reactor Power



5 MeV excess has a clear correlation with reactor thermal power !

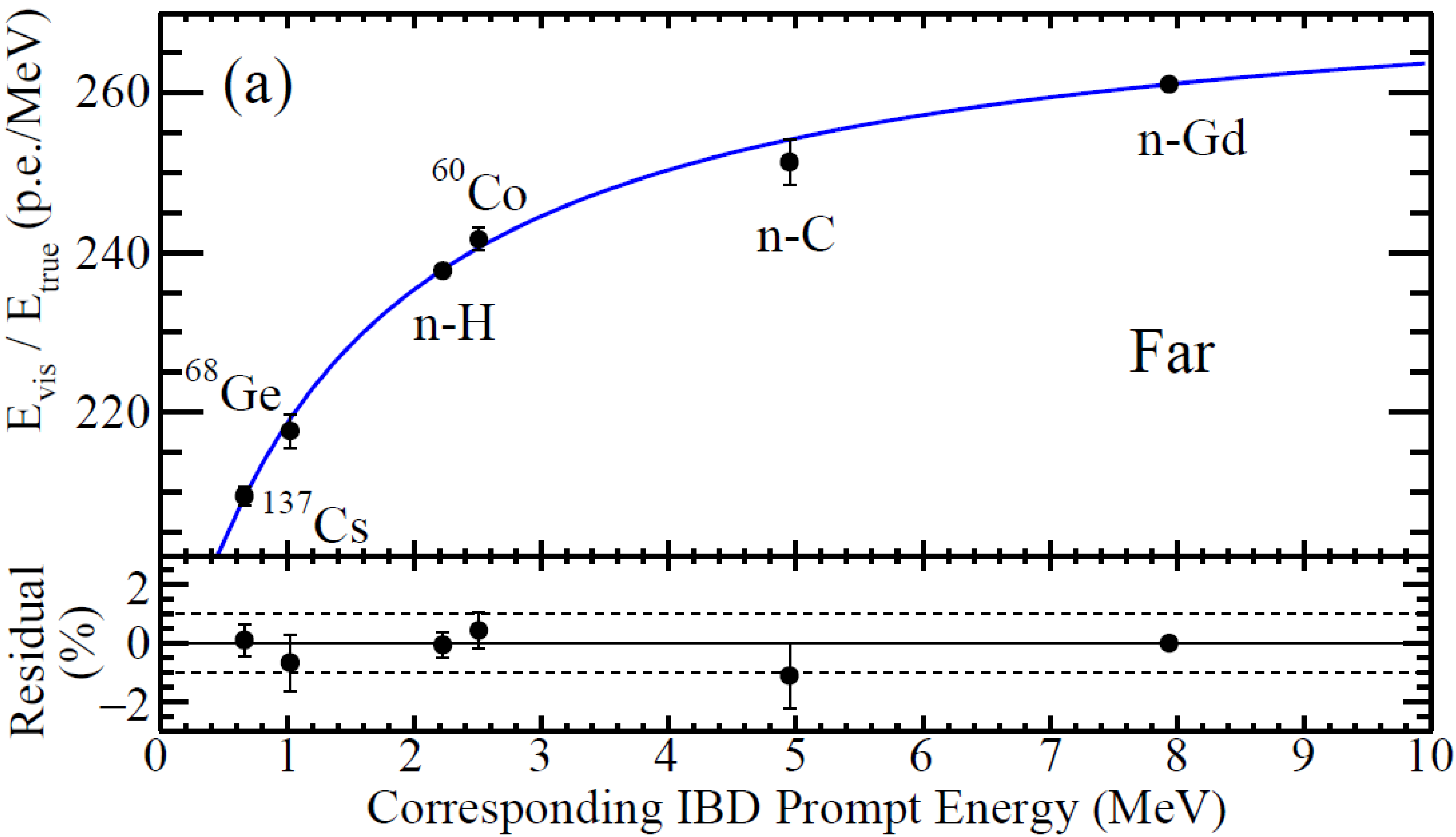
A new reactor neutrino component !!

** Recent ab initio calculation [D. Dwyer and T.J. Langford, PRL 114, 012502 (2015)] :

- The excess may be explained by addition of eight isotopes, such as ^{96}Y and ^{92}Rb

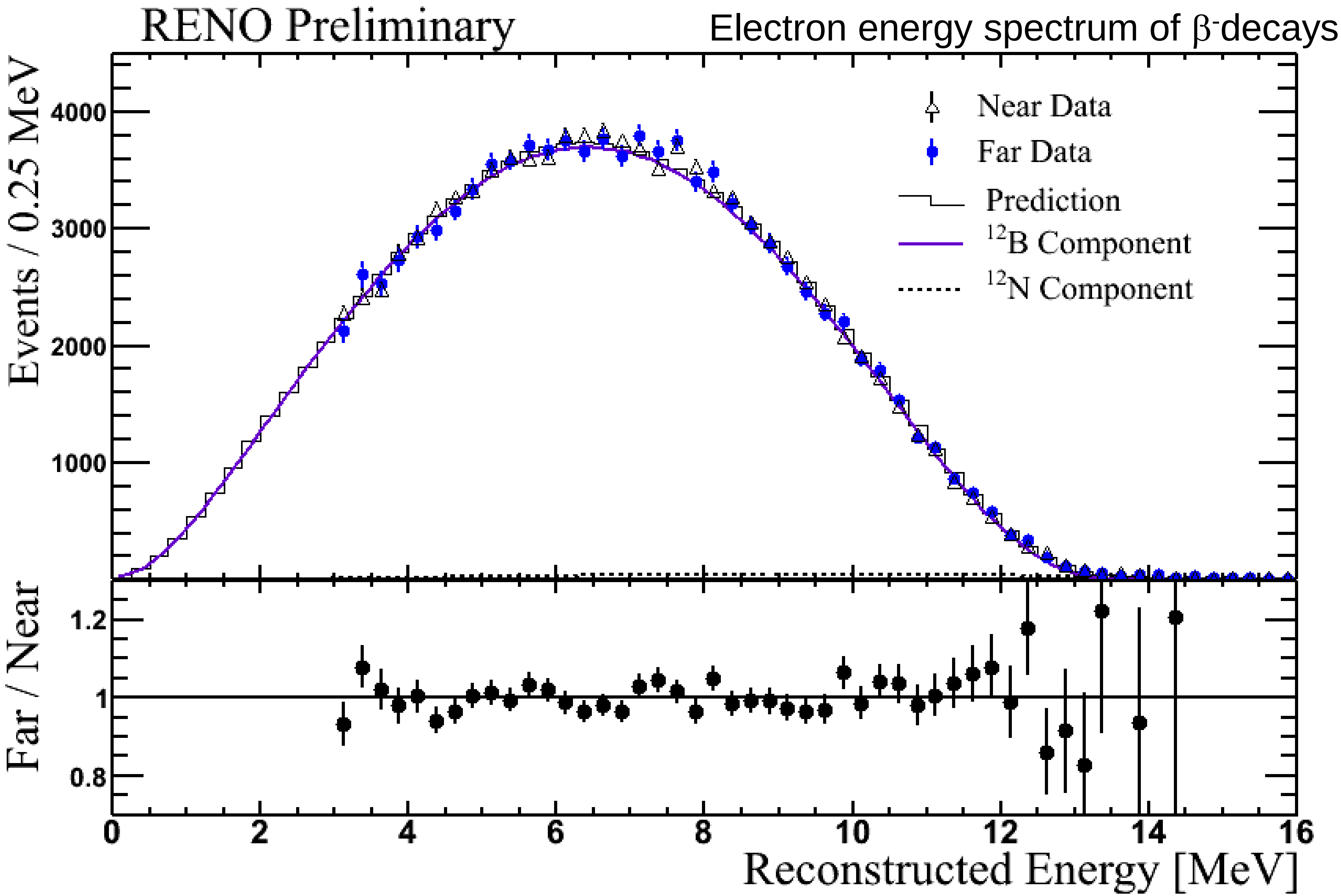
Energy Calibration from γ-ray Sources

- Non-linear resonse of the scintillation energy is calibrated using γ-ray source



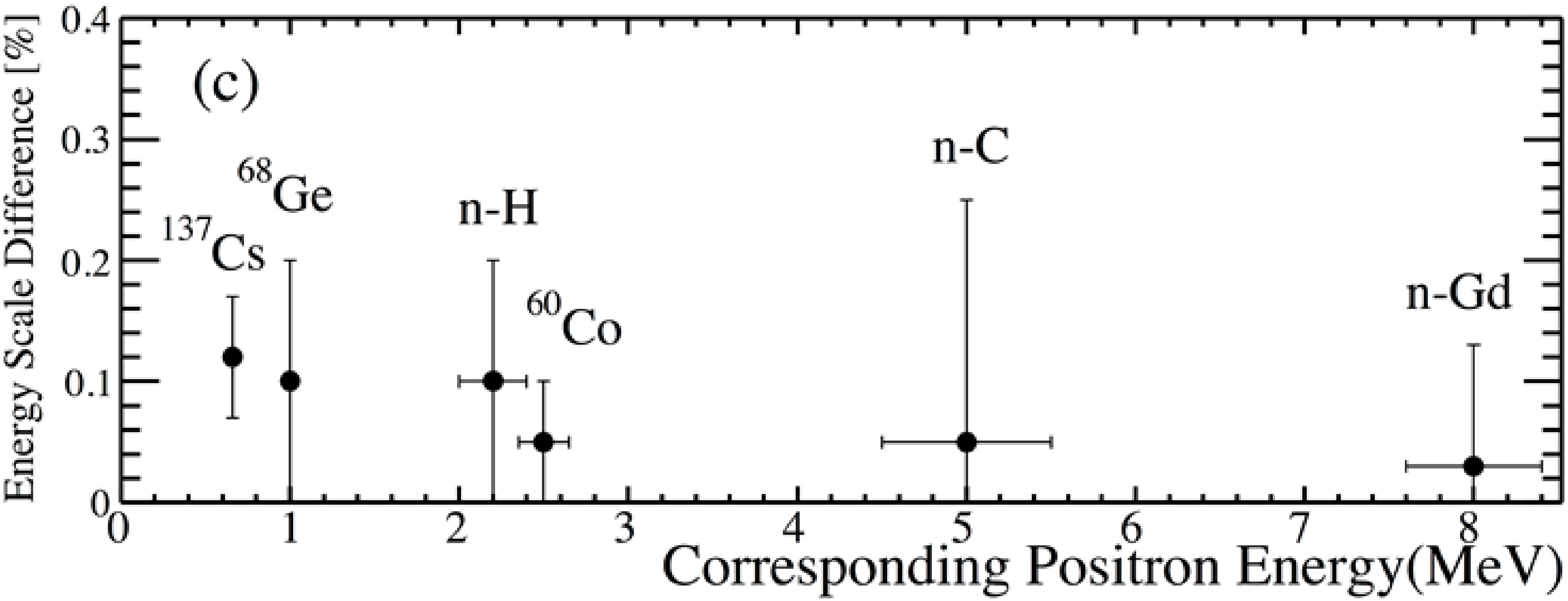
- Deviation of all calibration data points with respect to the best-fit is within ~1%

B12 Energy Spectrum (Near & Far)



Energy spectrum is well described between data and MC spectrum

Energy Scale Difference between Near & Far



Energy scale difference < 0.15% for E_p = 1~8 MeV

Systematic Uncertainties and Errors

Uncertainties	Rate Only $\sin^2 2\theta_{13}$	Rate + Shape $\sin^2 2\theta_{13}$	Rate + Shape $\lvert\Delta m_{ee}\rvert^2$ ($\times 10^3$ eV^2)
Statistics	0.0091	+ 0.0087 – 0.0085	+ 0.207 – 0.226
Reactor	0.0028	+ 0.0026 – 0.0028	+ 0.018 – 0.018
Detection Efficiency	0.0029	+ 0.0028 – 0.0029	+ 0.020 – 0.022
Energy Scale	-	+ 0.0026 – 0.0015	+ 0.081 – 0.094
Backgrounds	0.0054	+ 0.0030 – 0.0028	+ 0.084 – 0.106
Total Systematic	0.0068	+ 0.0055 – 0.0052	+ 0.115 – 0.133

1st Measurement (May, 2012, PRL)

$\sin^2 2\theta_{13}$=0.113 +- 0.013 (stat.) +- 0.019 (sys.)

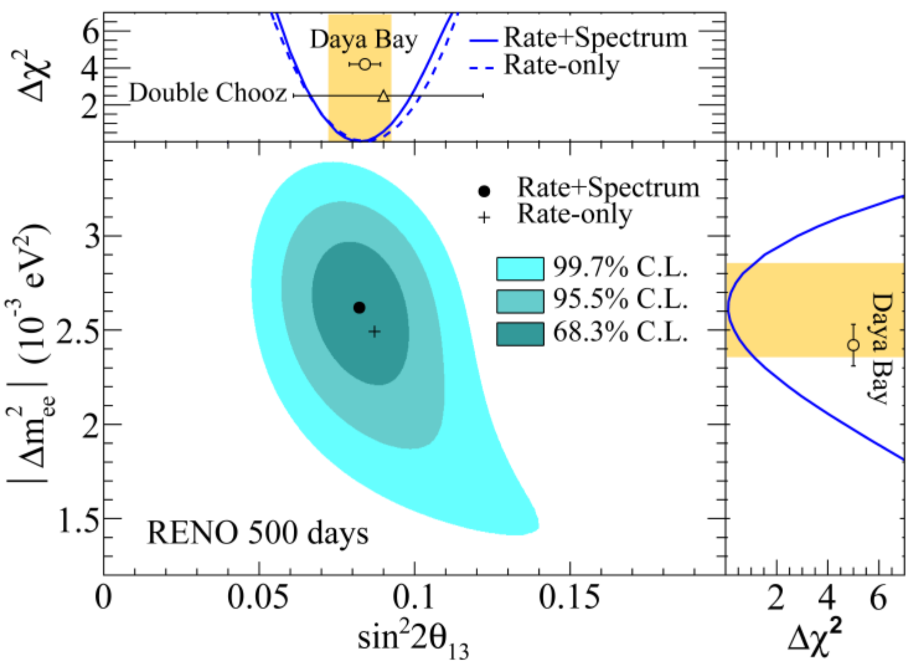
Analysis Results

Rate Only $\sin^2 2\theta_{13} = 0.087 \pm 0.009(\text{stat.}) \pm 0.007(\text{syst.})$ $\pm\ 0.011(\text{total})$

Rate + Shape

$$\left|\Delta m^2_{ee}\right| = 2.62^{+0.21}_{-0.23}(\text{stat.})^{+0.12}_{-0.13}(\text{syst.})\ (\times 10^{-3} eV^2)$$ $\pm\ 0.26\ (\text{total})$ 10 % precision

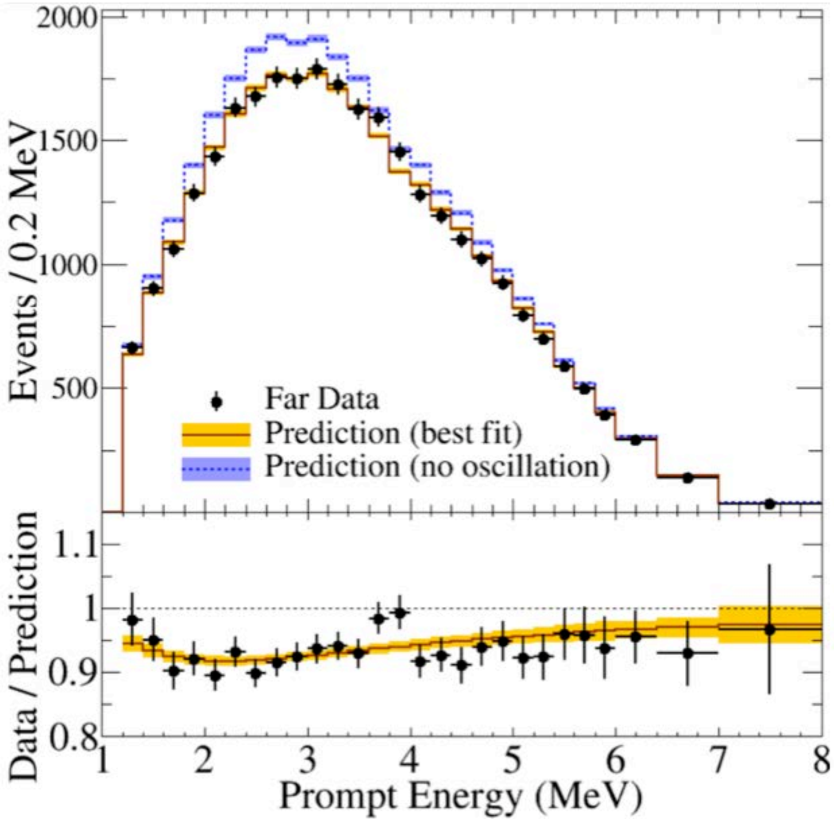
$$\sin^2 2\theta_{13} = 0.082 \pm 0.009(\text{stat.}) \pm 0.006(\text{syst.})$$ $\pm\ 0.010(\text{total})$ 13 % precision

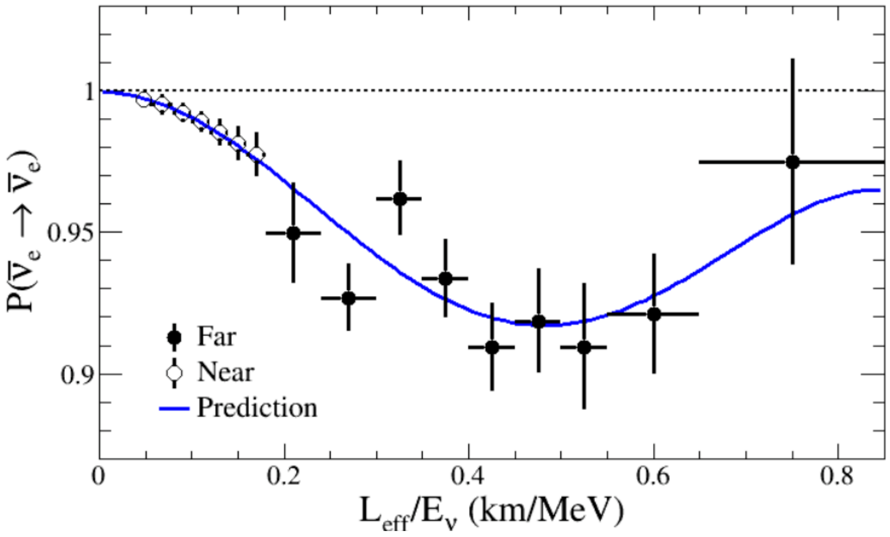


(submitted in PRL)

Far to Prediction from Near Data

Observed L/E Dependent Oscillation





$$P(\overline{\nu}_e \to \overline{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\Delta m^2_{ee} \frac{L}{4E_\nu}\right)$$

Clear energy-dependent disappearance of reactor antineutrinos

Projected Sensitivity of θ_{13} & Δm_{ee}^2

(submitted in PRL)

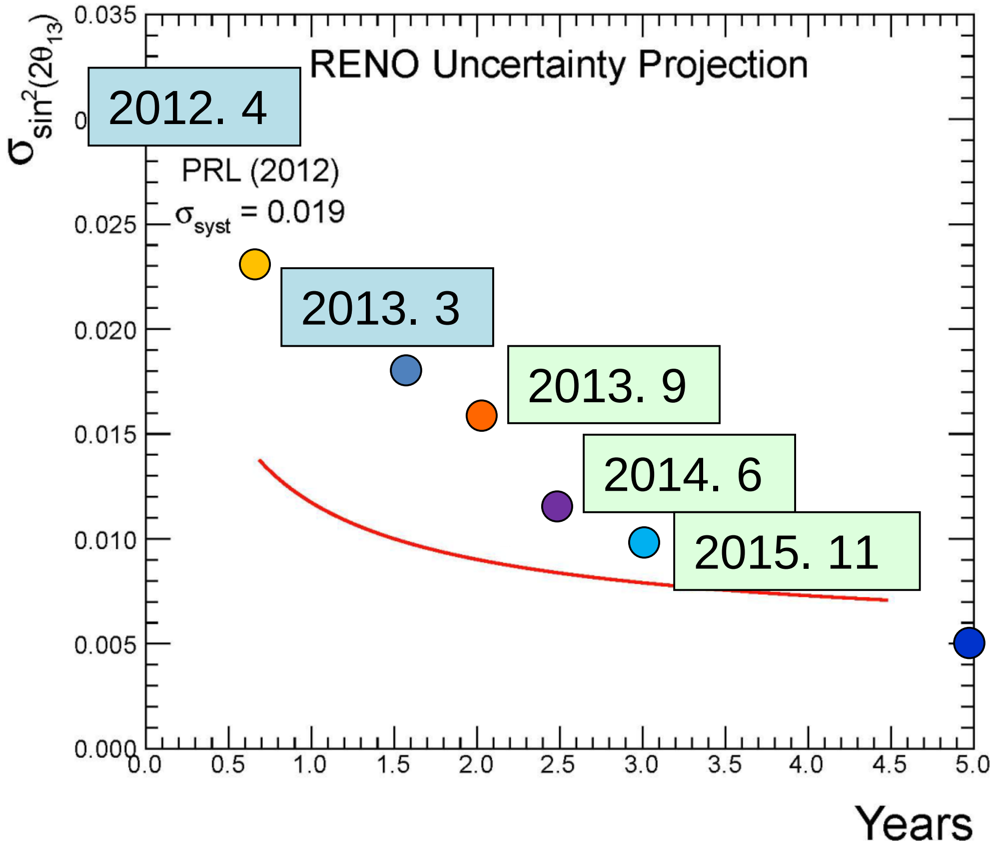
$$\sin^2 2\theta_{13} = 0.082 \pm 0.011$$

(~500 days)

$\rightarrow$ ± 0.005 (5 % precision) (5 years of data)

* Expected precision of Δm_{ee}^2 : ~ 0.1×10^{-3} eV^2

(~ 4% precision)



(5 % precision)

(sensitivity goal of θ_{13})

Why n-H IBD Analysis?

Motivation:

1. Independent measurement of θ_{13} value.
2. Consistency and systematic check on reactor neutrinos.

* RENO's low accidental background makes it possible to perform n-H analysis.

-- low radioactivity PMT
-- successful purification of LS and detector materials.

Results from n-H IBD sample

Very preliminary
Rate-only result

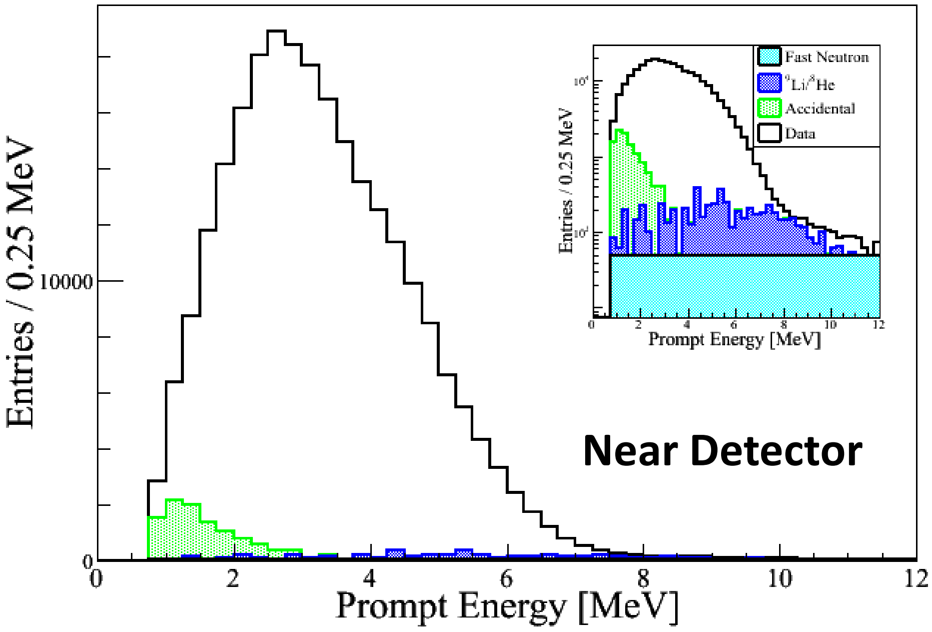
(B data set, ~400 days)

$$\sin^2 2\theta_{13} = 0.103 \pm 0.014(\text{stat.}) \pm 0.014(\text{syst.})$$

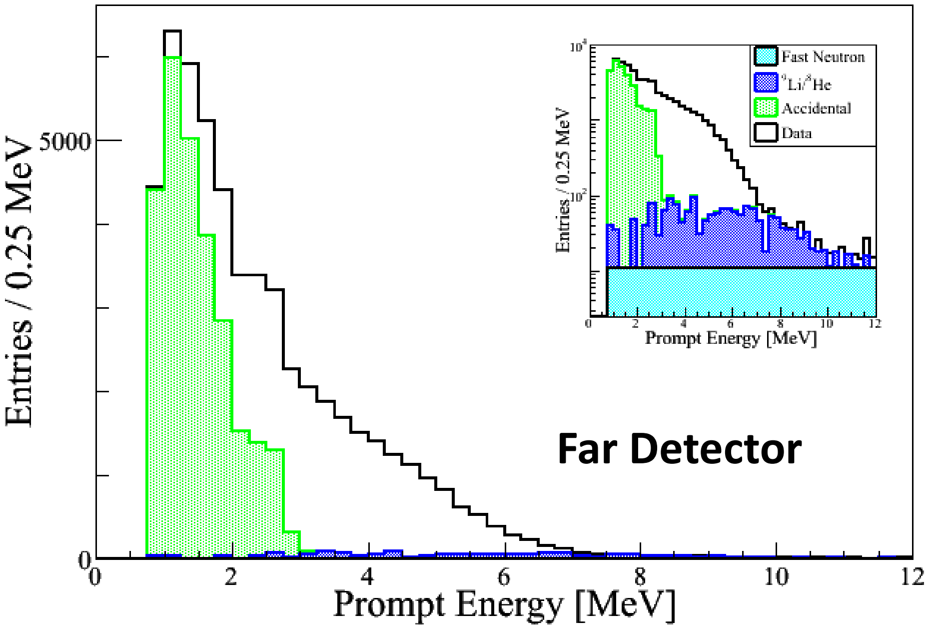
(Neutrino 2014) $\sin^2 2\theta_{13} = 0.095 \pm 0.015(\text{stat.}) \pm 0.025(\text{syst.})$

← Significant reduction in the uncertainty of the accidental background and new results coming soon.

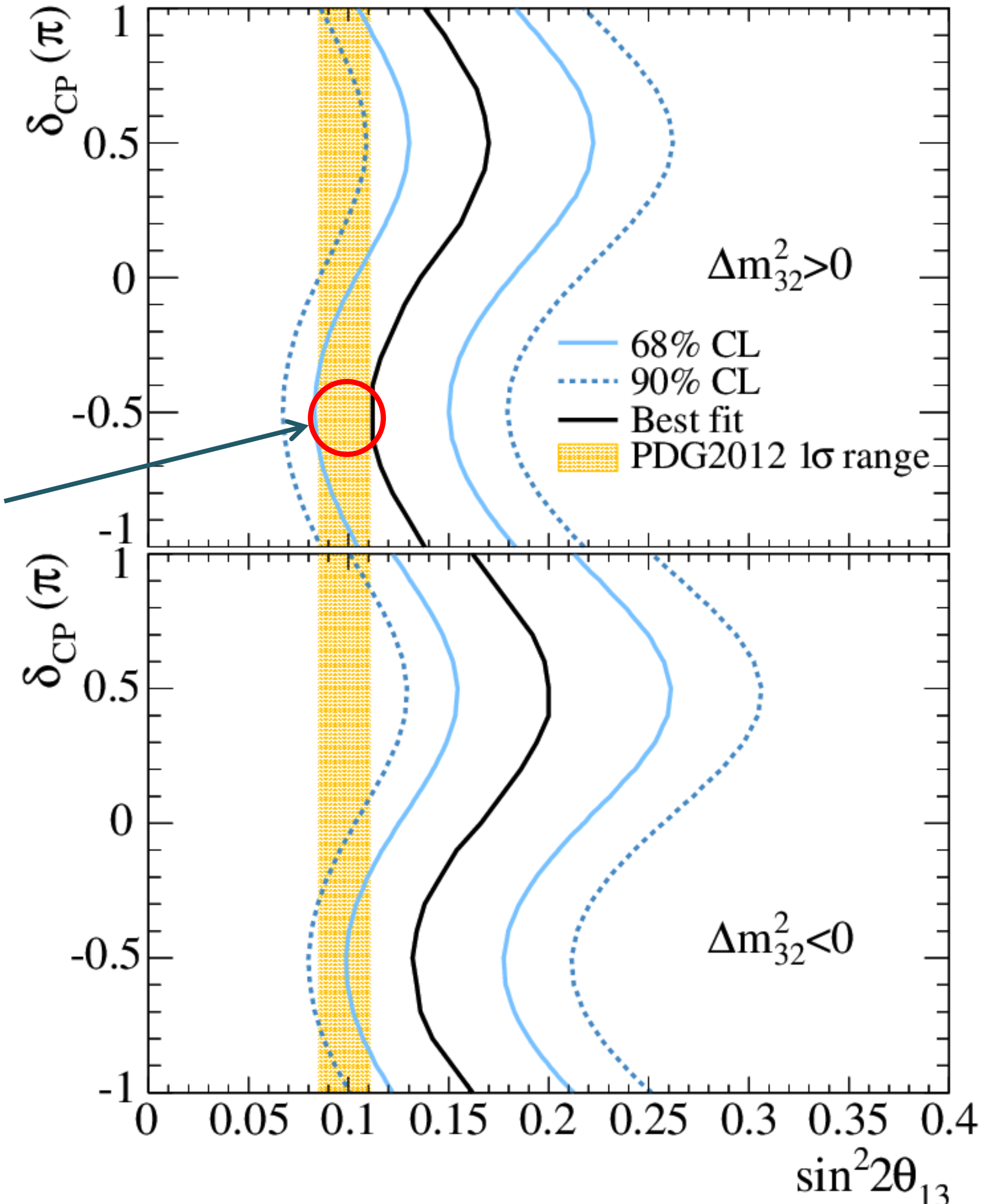
preliminary



preliminary



θ_{13} from Reactor and Accelerator Experiments



First hint of δ_{CP} combining Reactor and Accelerator data

Best overlap is for Normal hierarchy & δ_{CP} = - π/2

Is Nature very kind to us?
Are we very lucky?
Is CP violated maximally?

Strong motivation for anti-neutrino run and precise measurement of θ_{13}

(T2K: PRL 112, 061802, 2014)

Summary

- New measurement of θ_{13} by rate-only analysis

$$\sin^2 2\theta_{13} = 0.087 \pm 0.009(\text{stat}) \pm 0.007(\text{syst})$$

- Observed an excess at 5 MeV in reactor neutrino spectrum

- Observation of energy dependent disappearance of reactor neutrinos and our first measurement of Δm_{ee}^2

$$\left|\Delta m_{ee}^2\right| = 2.62^{+0.21}_{-0.23}(\text{stat.})^{+0.12}_{-0.13}(\text{syst.})\ (\times 10^{-3}\,eV^2) \quad \pm 0.26(\text{total})$$

10 % precision

$$\sin^2 2\theta_{13} = 0.082 \pm 0.009(\text{stat.}) \pm 0.006(\text{syst.}) \quad \pm 0.010(\text{total})$$

13 % precision

- Measurement of θ_{13} from on n-H IBD analysis

$$\sin^2 2\theta_{13} = 0.103 \pm 0.014(\text{stat}) \pm 0.014(\text{syst})$$

(preliminary)

- RENO: $\sin(2\theta_{13})$ to 5% accuracy
  Δm_{ee}^2 to 0.1×10^{-3} eV^2 (4%) accuracy within 3 years