New Results from RENO

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VERI LUX TAS MEA

KNRC

Korea Neutrino Research Center

RENO Collaboration

Reactor Experiment for Neutrino Oscillation

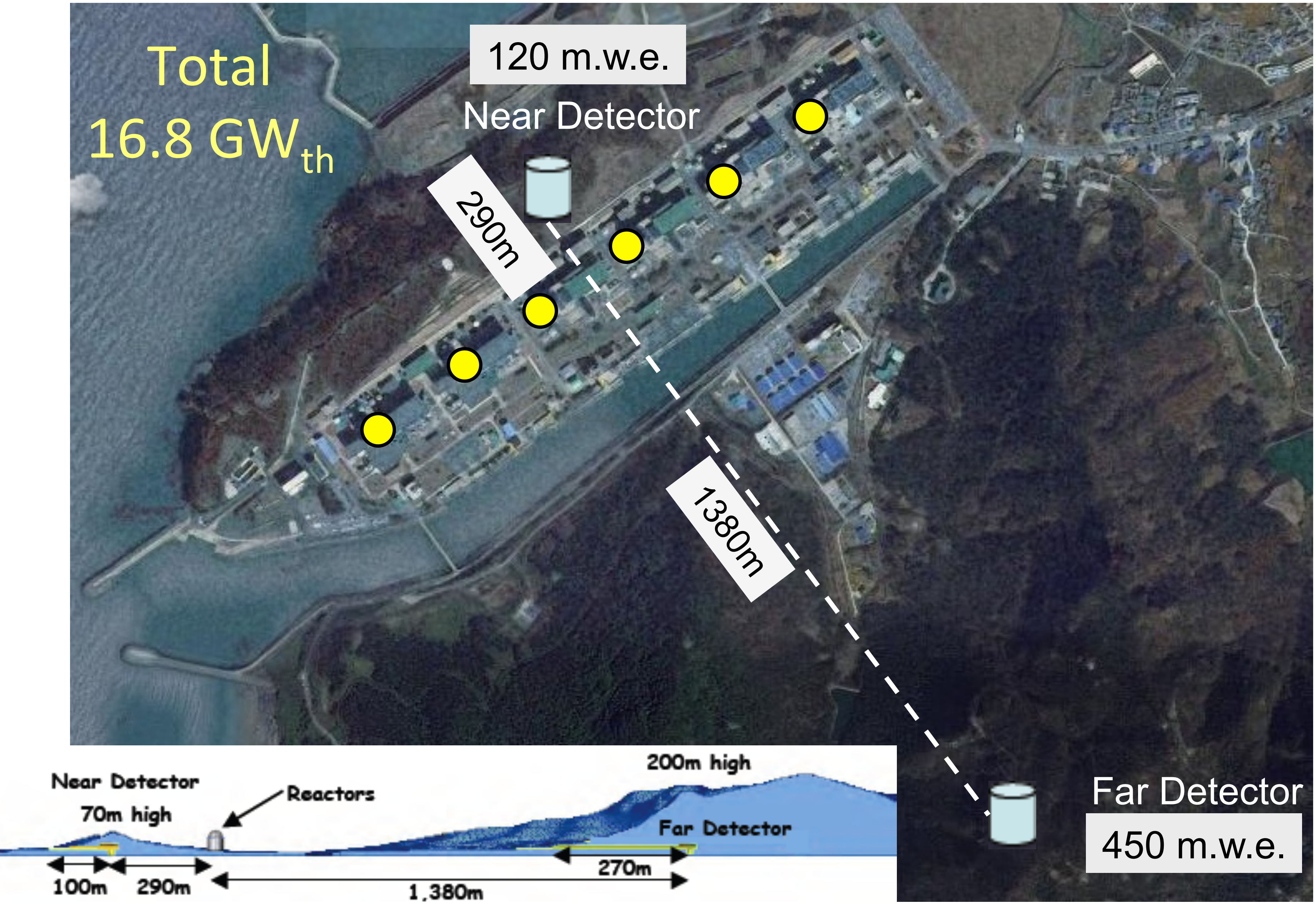
(10 institutions and 40 physicists)

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

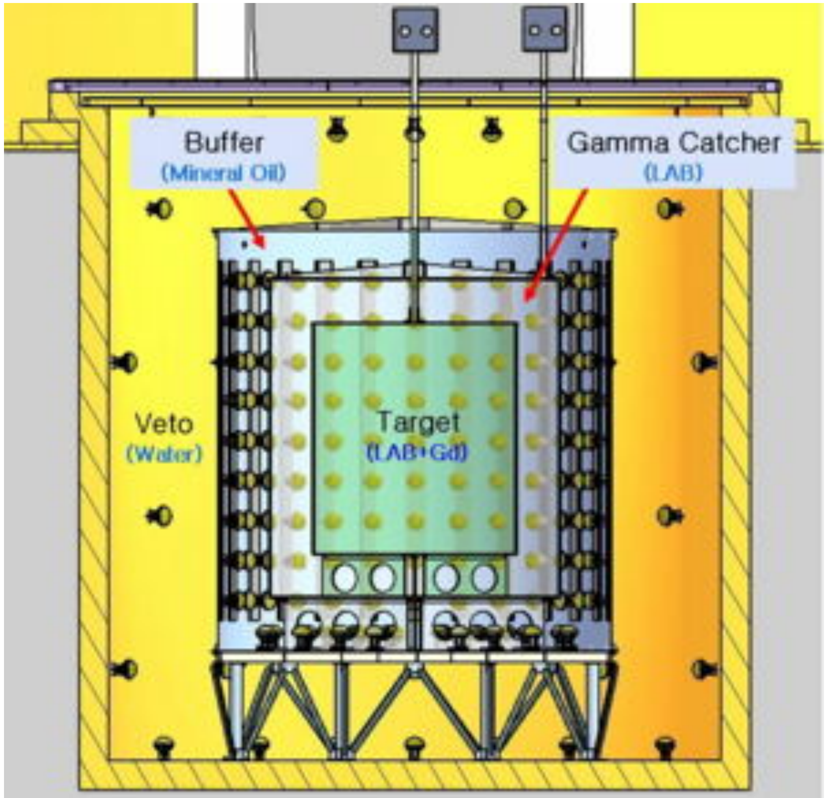
- Chonnam National University
- Chung-Ang University
- Dongshin University
- GIST
- Gyeongsang National University
- Kyungpook National University
- Sejong University
- Seoul National University
- Seoyeong University
- Sungkyunkwan University

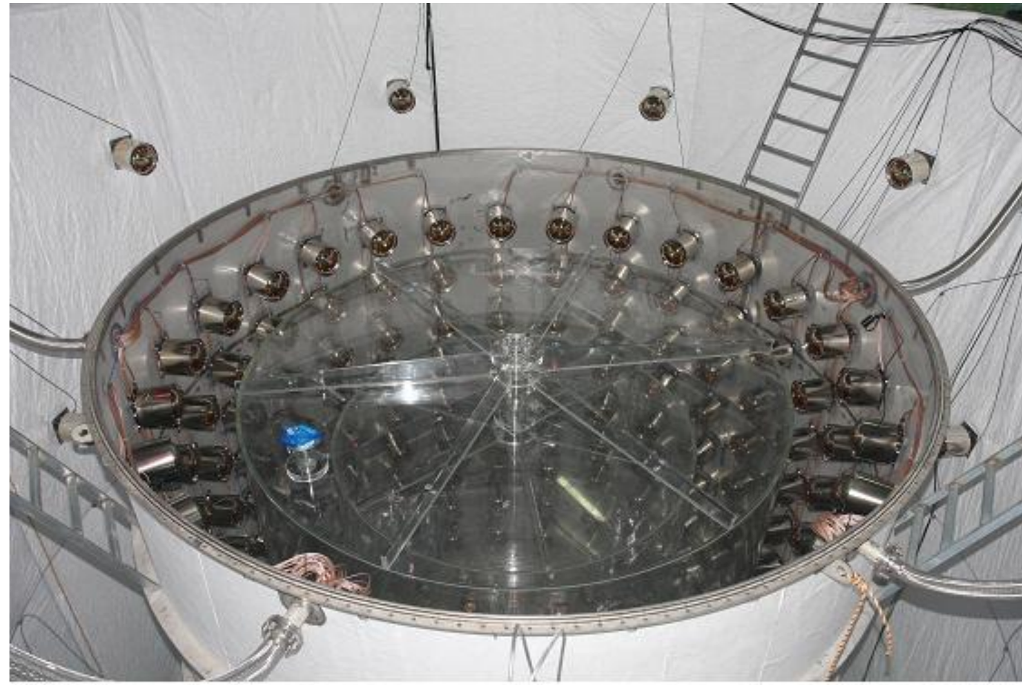
YongGwang (靈光) :

RENO Experimental Set-up



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

RENO Status

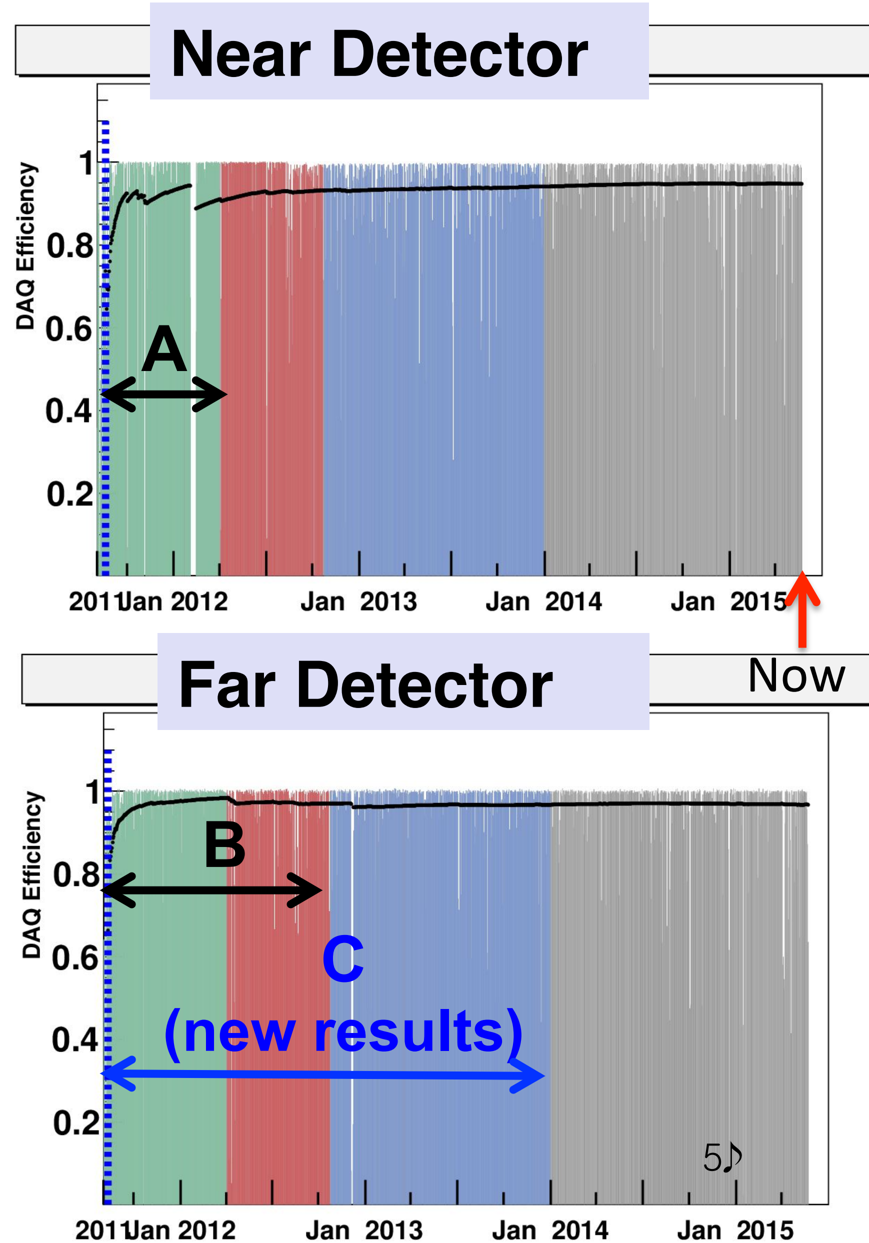
- Data taking began on Aug. 1, 2011 with both near and far detectors.
  (DAQ efficiency : ~95%)

- **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** (~800 days) : New **result**
  Shape+rate analysis (θ_{13} **and** Δm_{ee}^2)
  [11 Aug, 2011~31 Dec, 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]



New RENO Results at WIN 2015

- ~800 days of data
- New measured-value of θ_{13} from rate-only analysis
- Observation of energy dependent disappearance of reactor neutrinos to measure Δm_{ee}^2 (work in progress)
- Observation of an excess at 5 MeV in reactor neutrino spectrum

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

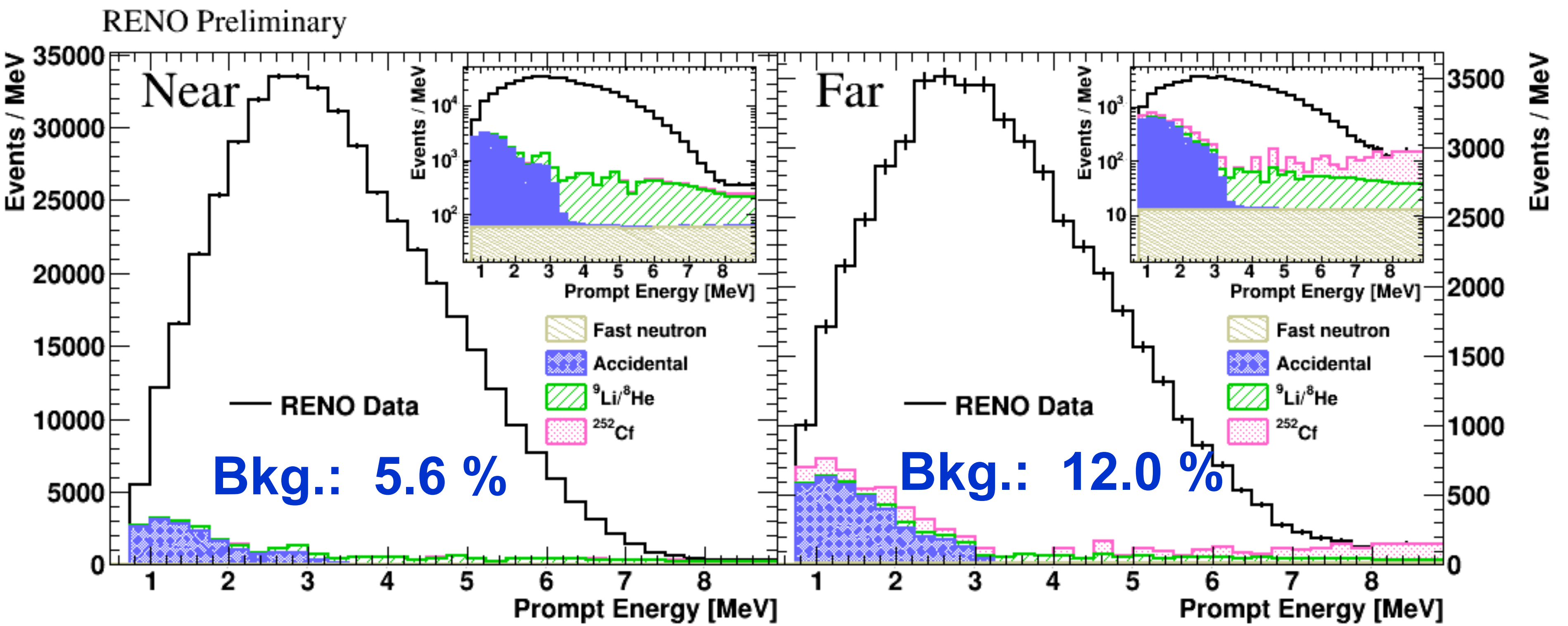
- More accurate energy calibration

  - 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

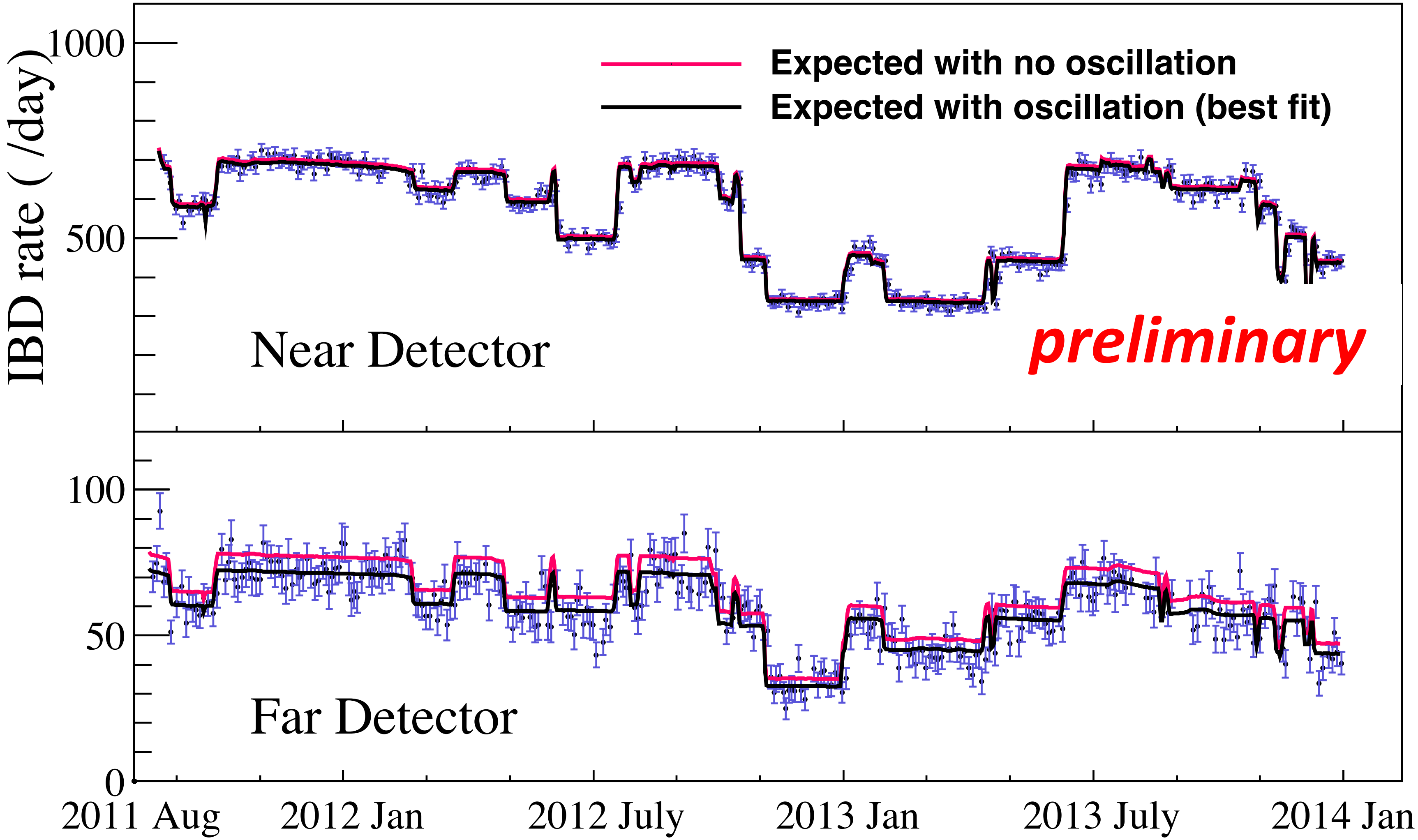
Measured Spectra of IBD Prompt Signal



Near Live time = 761.11 days
# of IBD candidate = 470,787
# of background = 26,375 (5.6 %)

Far Live time = 794.72 days
# of IBD candidate = 52,250
# of background = 6,292 (12.0 %)

Observed Daily Averaged IBD Rate



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

New θ_{13} Measurement by Rate-only Analysis

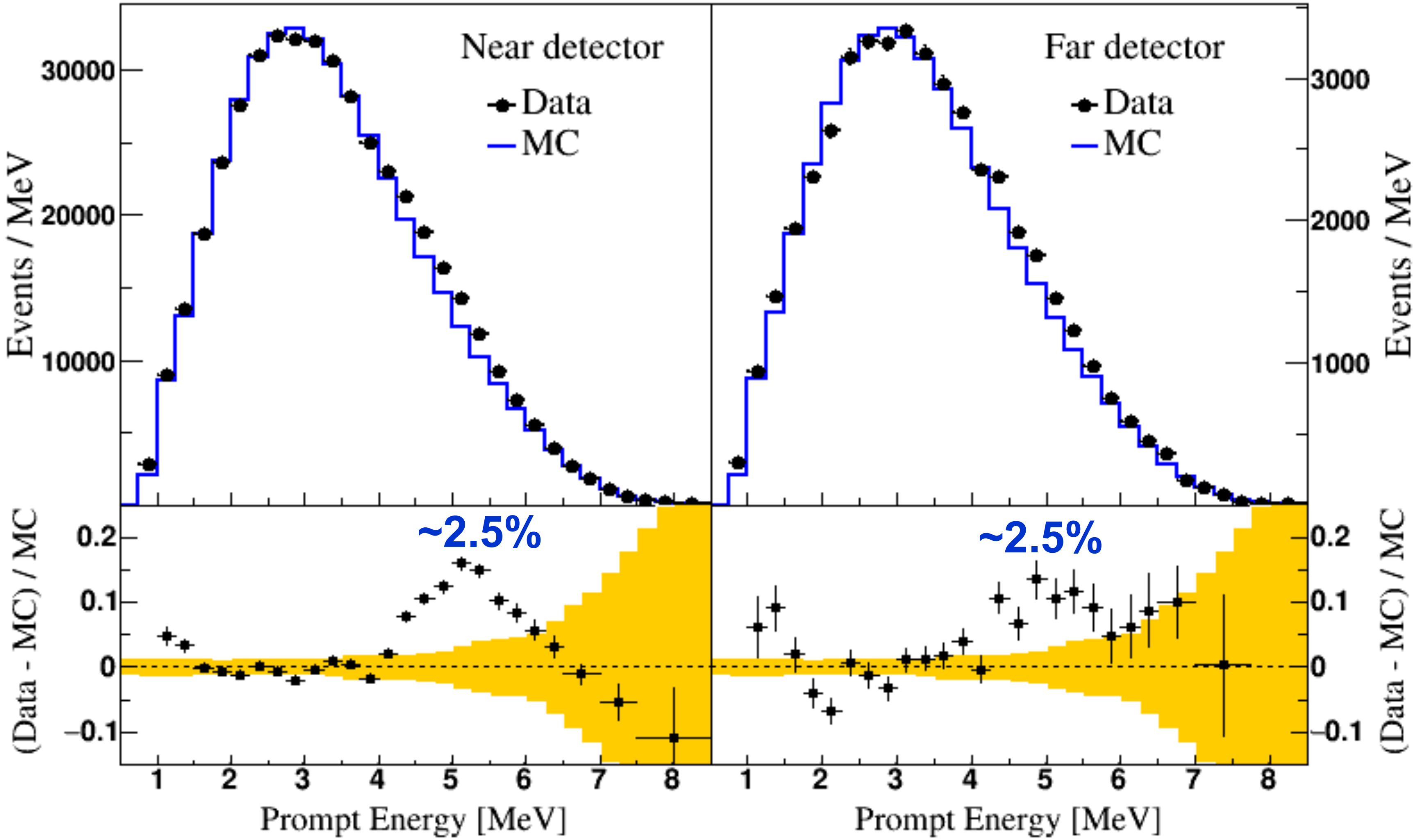
(Preliminary)

$$\sin^2 2\theta_{13} = 0.087 \pm 0.008(\text{stat.}) \pm 0.008(\text{syst.})$$

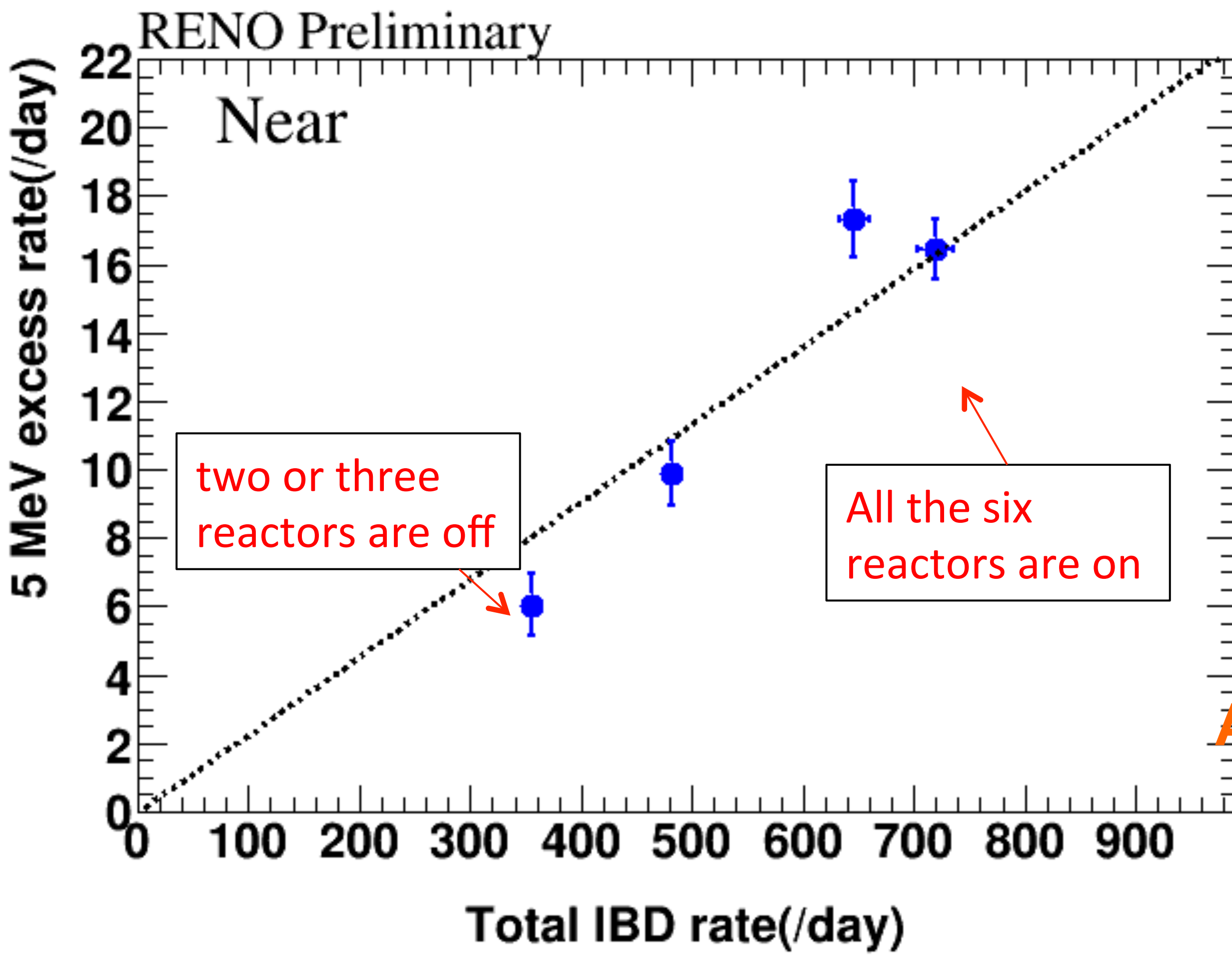
Uncertainties sources	Uncertainties (%)	Errors of $\sin^2 2\theta_{13}$ (fraction)
Statistics (near) (far)	0.21 % 0.54 %	0.0080
Total Systematic (near) (far)	0.94 % 1.06 %	**0.0081**
Reactor	0.9 %	0.0032 (39.5 %)
Detection efficiency	0.2 %	0.0037 (45.7 %)
Backgrounds (near) (far)	0.14 % 0.51 %	0.0070 (86.4 %)

Observation of an excess at 5 MeV

work in progress



Correlation of 5 MeV Excess with Reactor Power



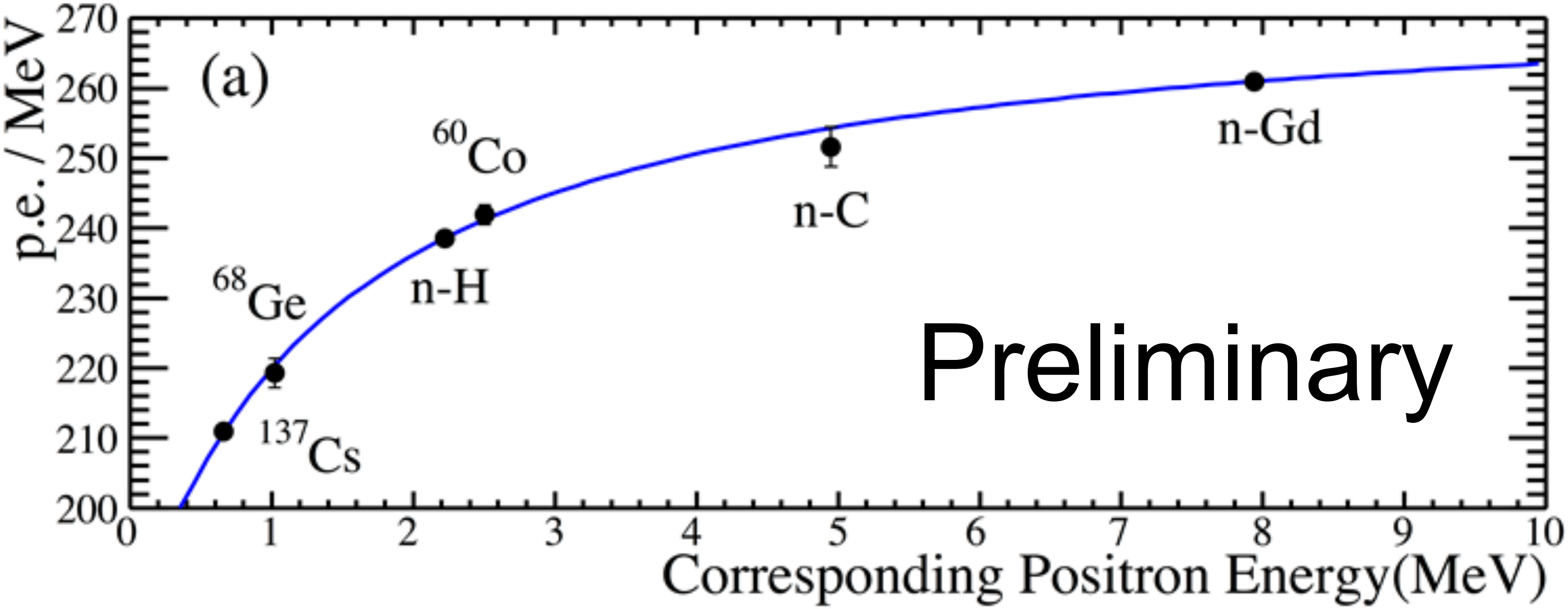
5 MeV excess has a clear correlation with reactor thermal power !

A new reactor neutrino component !!

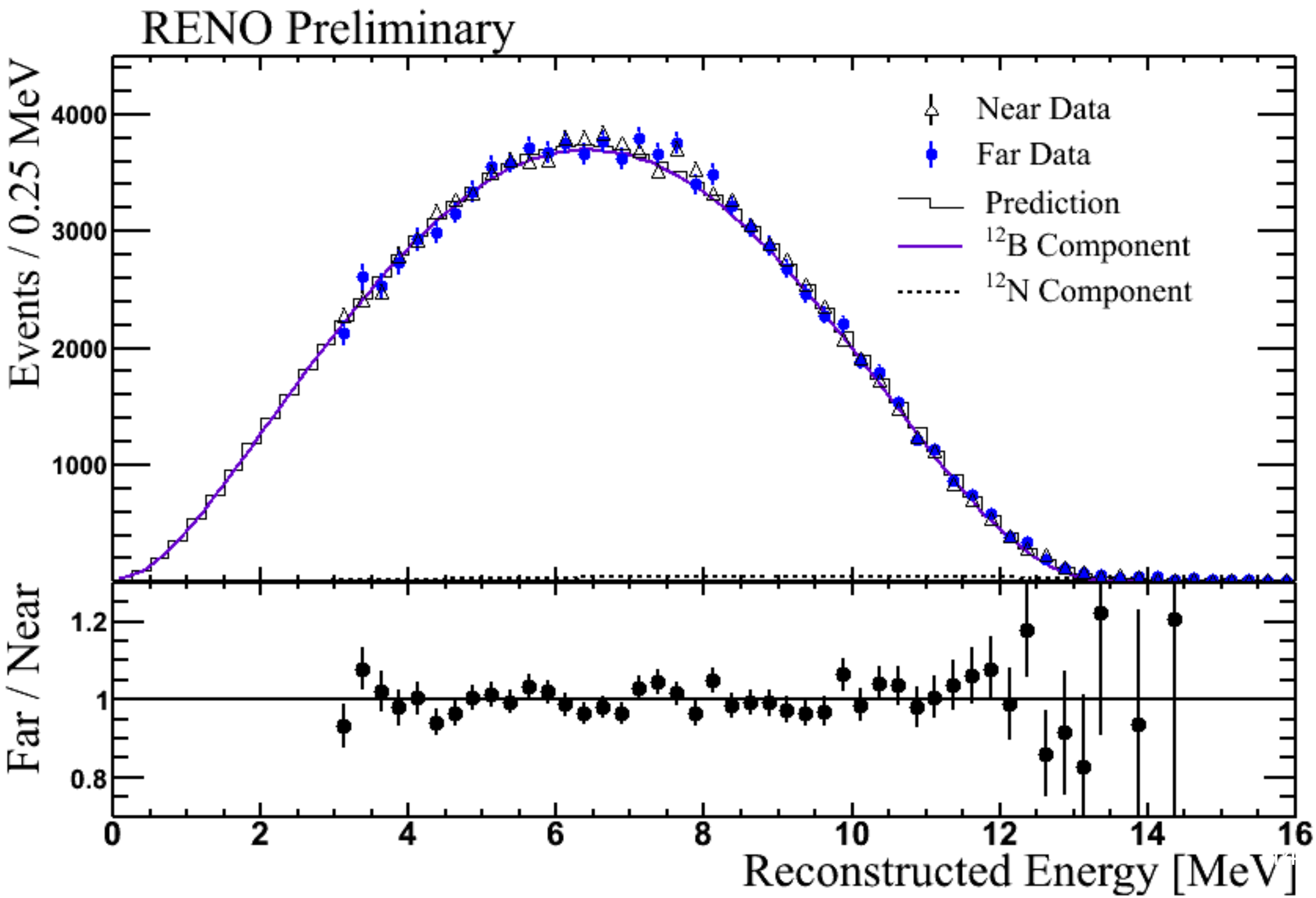
** Recent ab initio calculation [D. Dwyer and T.J. Langford, PRL 114, 012502 (2015)] :

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

Energy Calibration from γ-ray Sources

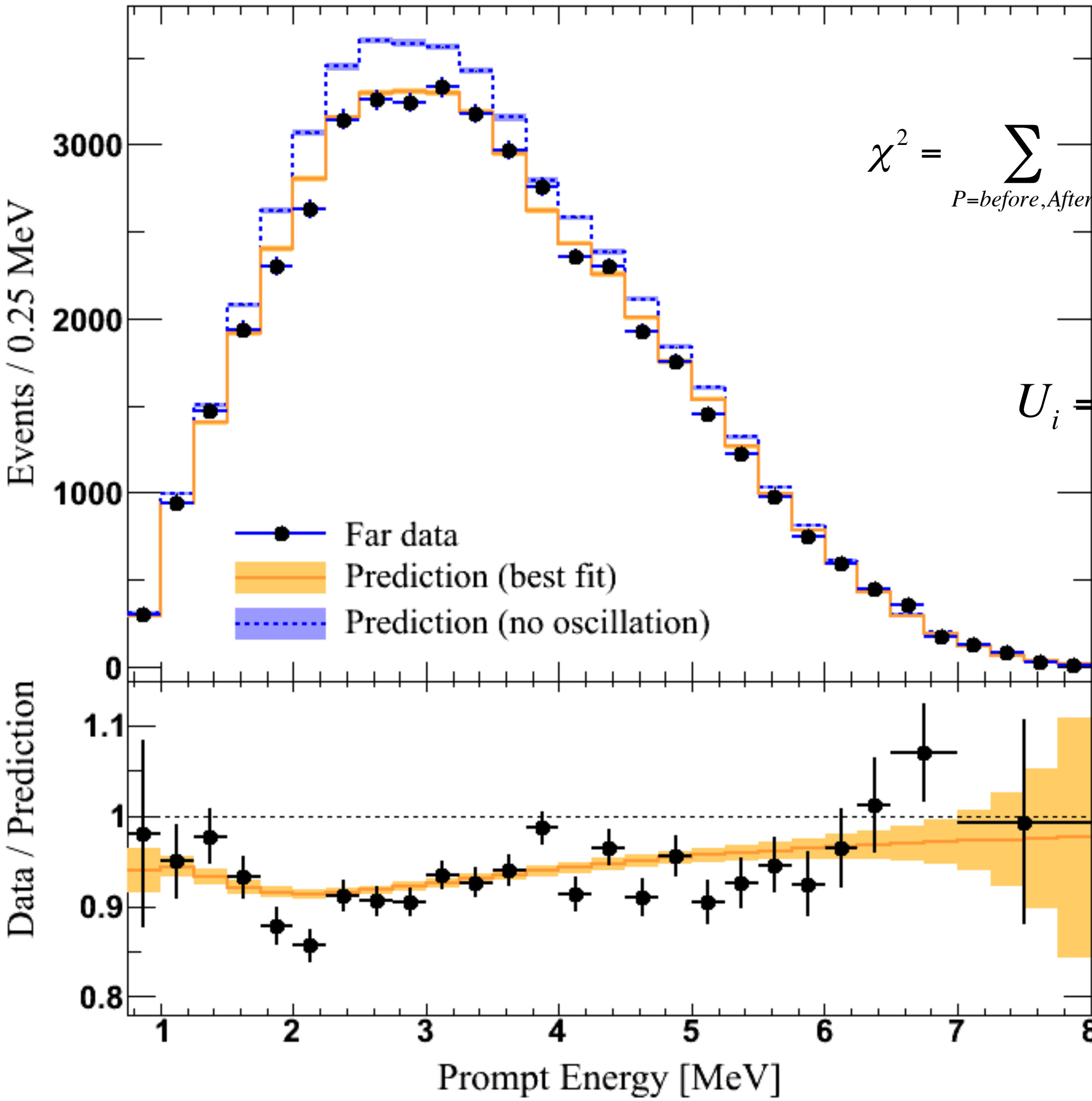


B12 Energy Spectrum (Near & Far)



Far/Near Shape Analysis for Δm_{ee}^2

(work in progress)

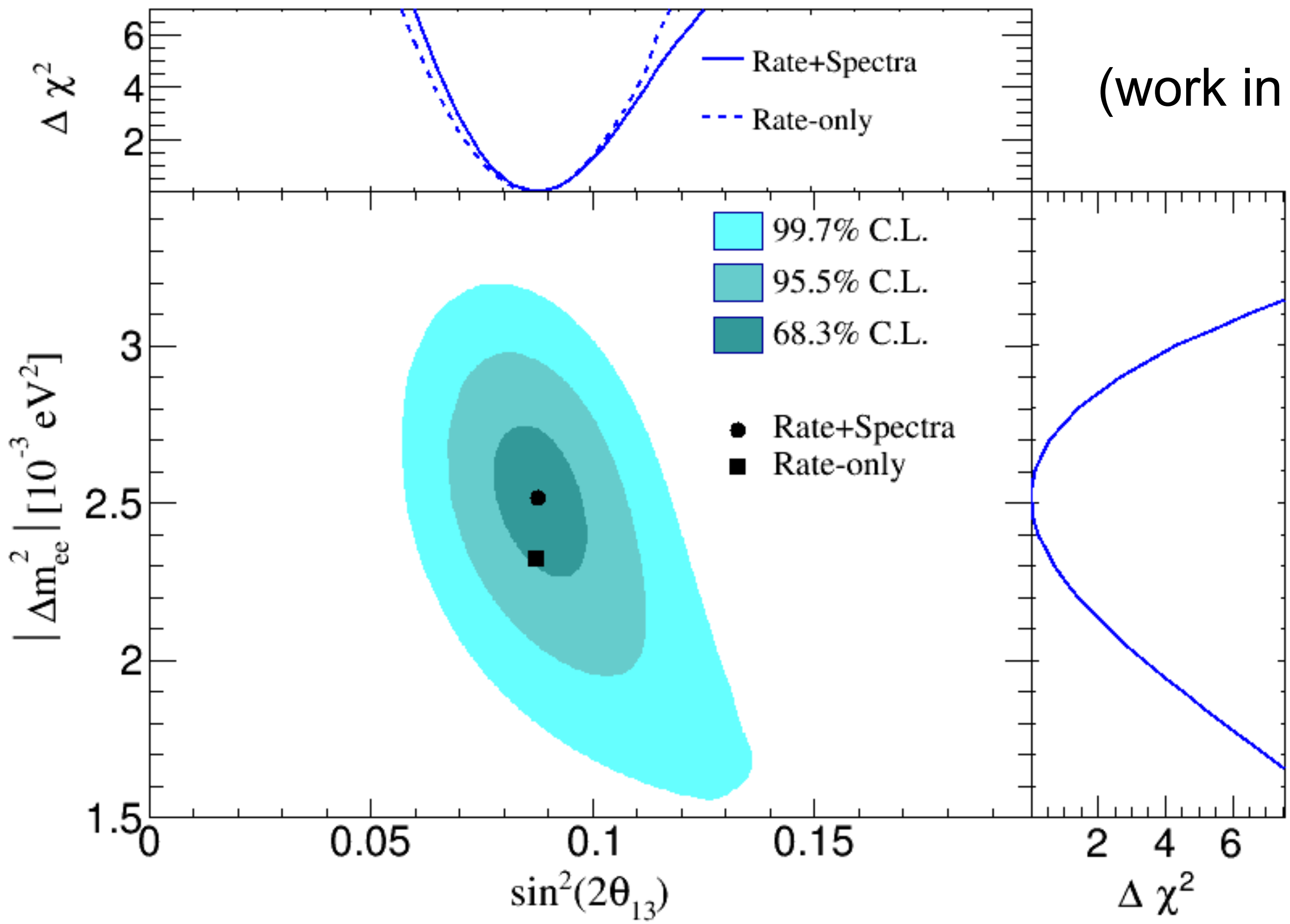


Minimize X^2 Function

$$\chi^2 = \sum_{P=before,After} \left\{ \sum_{i=1\sim N_b} \frac{\left(\frac{N_{obs}^{F,P,i}}{N_{obs}^{N,P,i}} - \frac{N_{Exp}^{F,P,i}}{N_{Exp}^{N,P,i}} \right)^2}{\left(U_i\right)^2} \right\} + Pull\_Terms$$

$$U_i = \frac{N_{obs}^{F,i}}{N_{obs}^{N,i}} \cdot \sqrt{\frac{N_{obs}^{F,i} + N_{bkg}^{F,i}}{(N_{obs}^{F,i})^2} + \frac{N_{obs}^{N,i} + N_{bkg}^{N,i}}{(N_{obs}^{N,i})^2}}$$

Results from Spectral Fit



(work in progress)

$$\Delta m_{ee}^{2} = [2.52 \pm 0.19(\text{stat}) \pm 0.17(\text{syst})] \times 10^{-3}\ \text{eV}^2$$

$$\sin^2 2\theta_{13} = 0.088 \pm 0.008(\text{stat}) \pm 0.007(\text{syst})$$

Systematic Errors of θ_{13} & Δm_{ee}^2

(work in progress)

$$\sin^2 2\theta_{13} = 0.088 \pm 0.008(\text{stat}) \pm 0.007(\text{syst})$$

$$\Delta m_{ee}^2 = [2.52 \pm 0.19(\text{stat}) \pm 0.17(\text{syst})] \text{x}10^{-3}\ \text{eV}^2$$

Uncertainties sources	Uncertainties (%)	Errors of $\sin^2 2\theta_{13}$ (fraction)	Error of $\lvert\Delta m_{ee}^2\rvert$ [$\times 10^{-3}$eV^2]
Statistics (near) (far)	0.21 % 0.54 %	0.008	0.19
Total Systematic (near) (far)	0.94 % 1.06 %	0.007	0.17
Reactor	0.9 %	0.0025 (34.2 %)	-
Detection efficiency	0.2 %	0.0025 (34.2 %)	-
Energy Scale Difference	0.15 %	0.0015 (15.6 %)	0.07
Backgrounds (near) (far)	0.14 % 0.51 %	0.0060 (82.2 %)	0.15

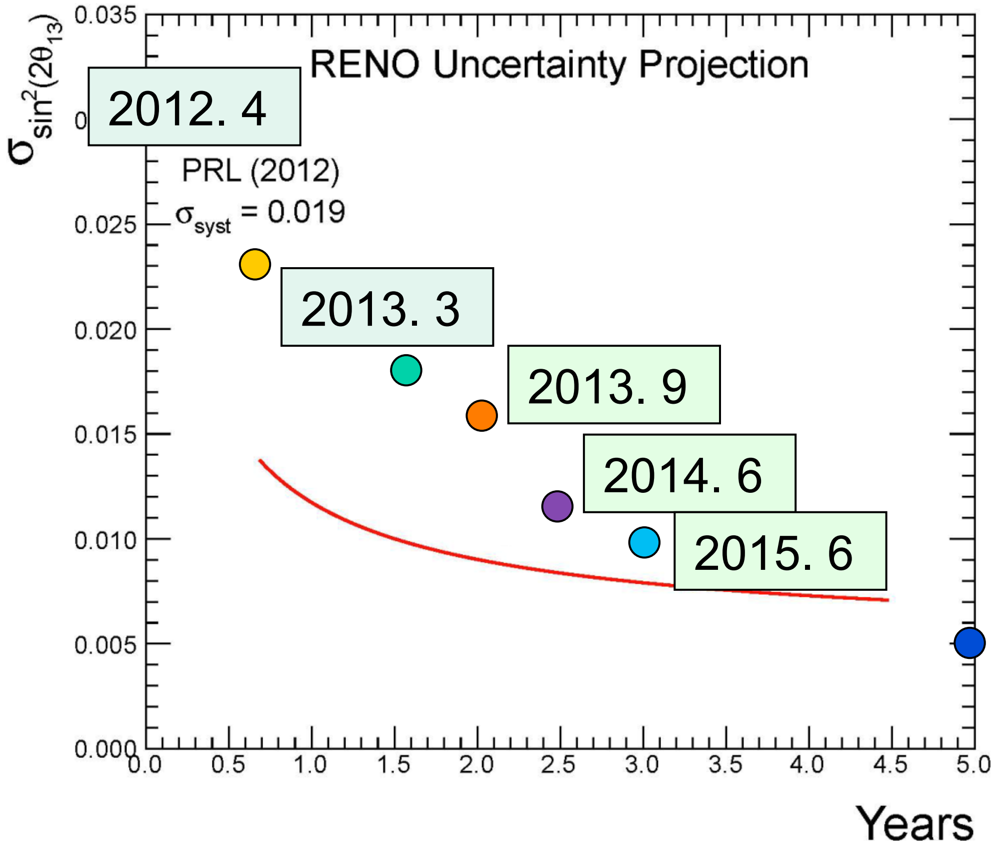
(* tentative)

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

NDM 2015 $\sin^2 2\theta_{13} = 0.088 \pm 0.011$ (~800 days)

$\Rightarrow$ $\pm$ 0.005 (5 % precision) (5 years of data)

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



(5 % precision)

(sensitivity goal of θ_{13})

Summary

- Observed an excess at 5 MeV in reactor neutrino spectrum
- New measurement of θ_{13} by rate-only analysis

$$\sin^2 2\theta_{13} = 0.087 \pm 0.008(\text{stat}) \pm 0.008(\text{syst})$$

(preliminary)

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

$$\sin^2 2\theta_{13} = 0.088 \pm 0.008(\text{stat}) \pm 0.007(\text{syst})$$

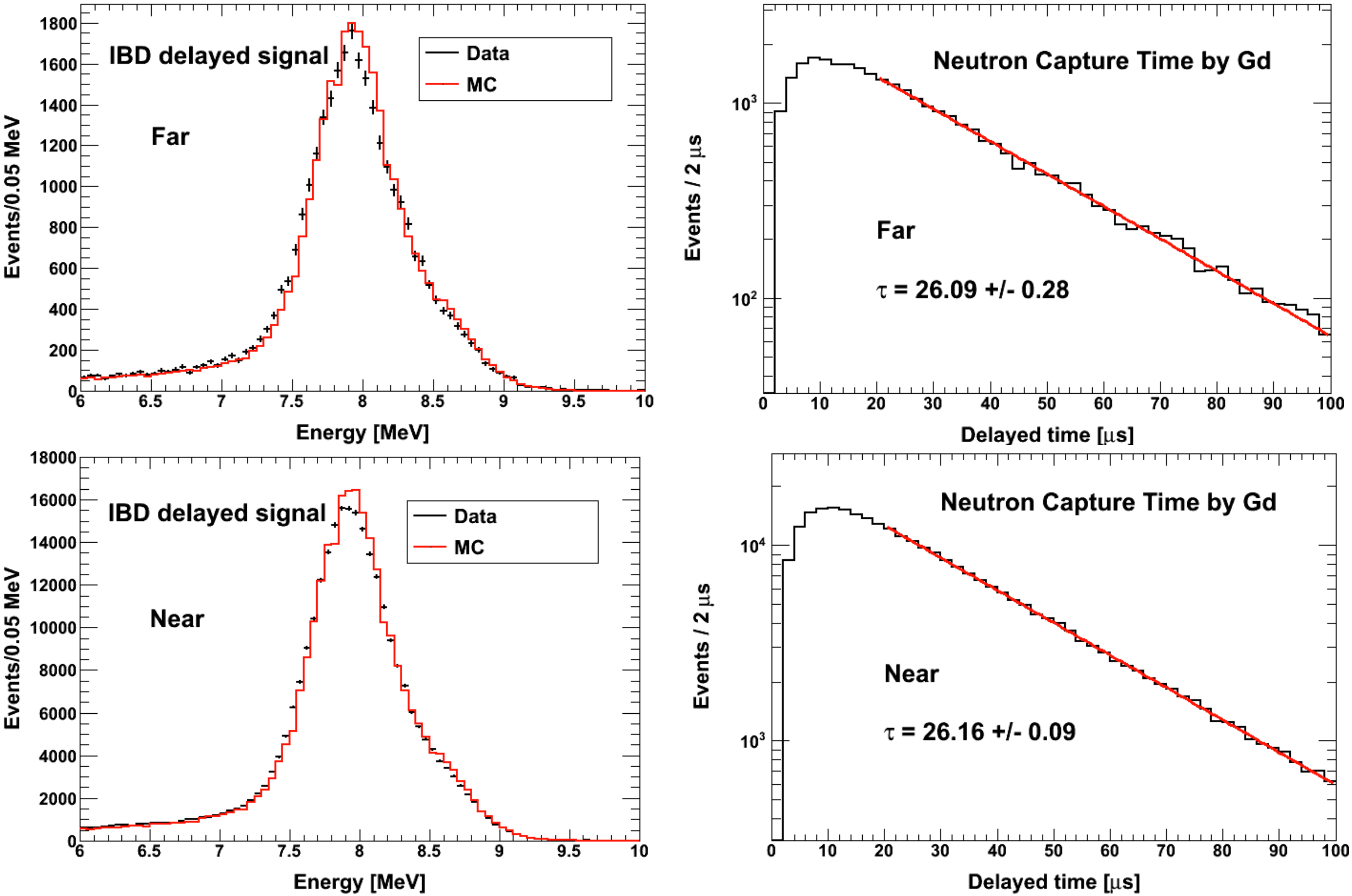
$$\Delta m_{ee}^2 = [2.52 \pm 0.19(\text{stat}) \pm 0.17(\text{syst})] \times 10^{-3}\ \text{eV}^2$$

(work in progress)

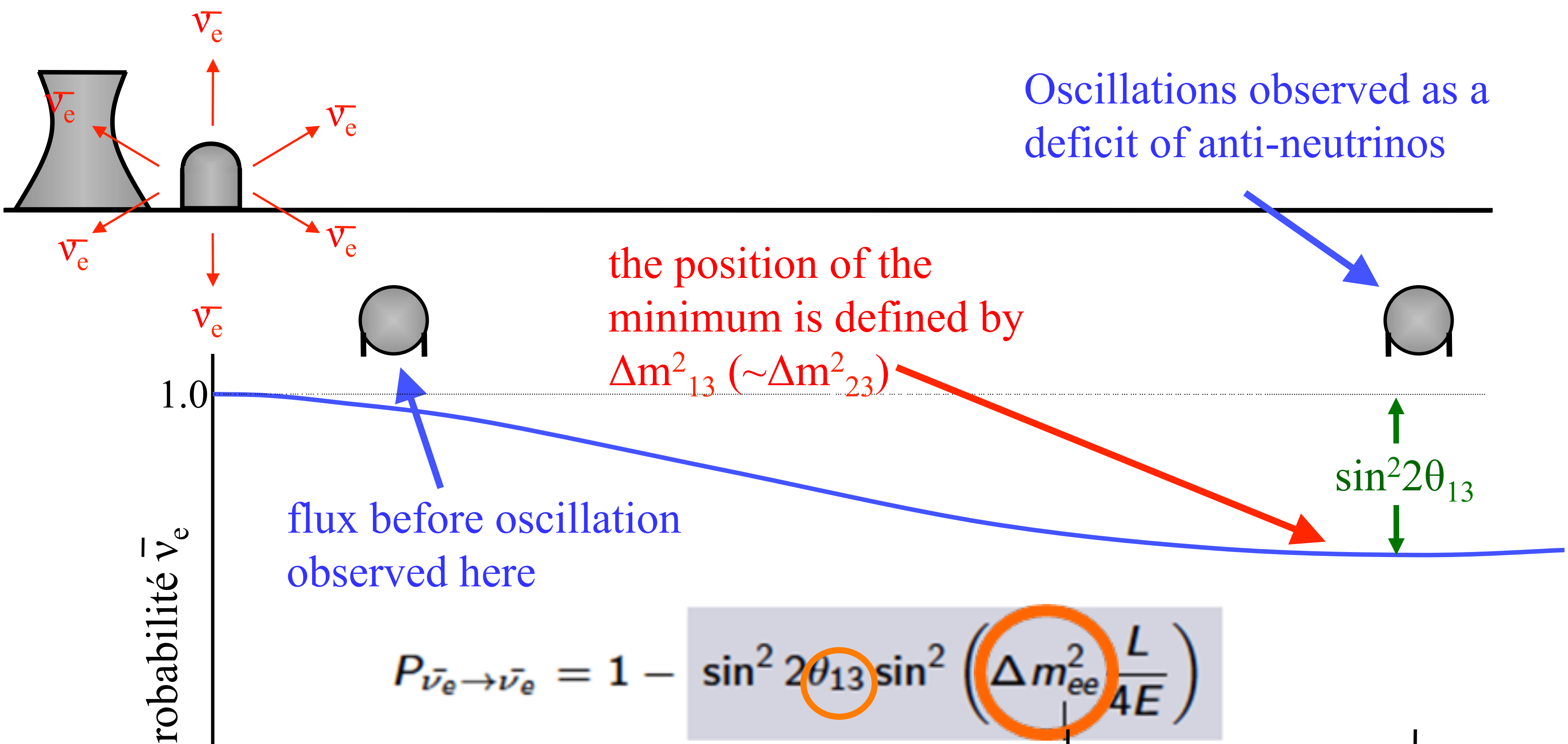
- $\sin(2\theta_{13})$ to 5% accuracy
  Δm_{ee}^2 to 0.1×10^{-3} eV^2 accuracy within 3 years

Thanks for your attention!

Neutron Capture by Gd



Reactor Neutrino Oscillations



$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \sin^2 2\theta_{13} \sin^2\left(\Delta m^2_{ee} \frac{L}{4E}\right)$$

+: Normal Hierarchy

−: Inverted Hierarchy

1200 to 1800 meters

$$|\Delta m^2_{ee}| \simeq |\Delta m^2_{32}| \pm 5.21 \times 10^{-5} \mathrm{eV}^2$$

cos↑2 θ↓12 |Δm2↓21↑|

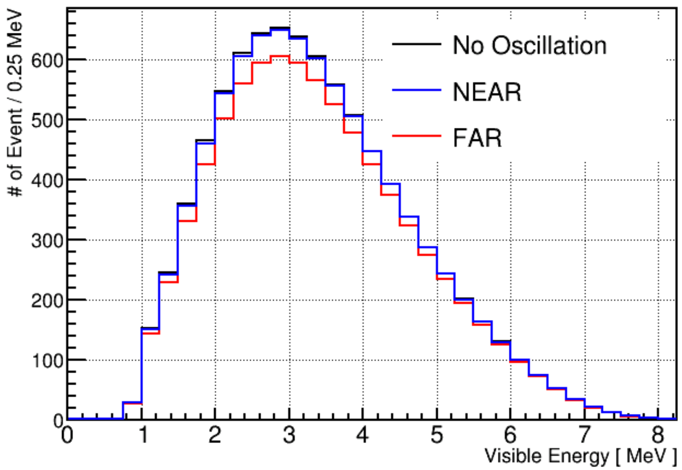
$$\sin^2\left(\Delta m^2_{ee} \frac{L}{4E}\right) = \cos^2\theta_{12} \sin^2\left(\Delta m^2_{31} \frac{L}{4E}\right) + \sin^2\theta_{12} \sin^2\left(\Delta m^2_{32} \frac{L}{4E}\right)$$

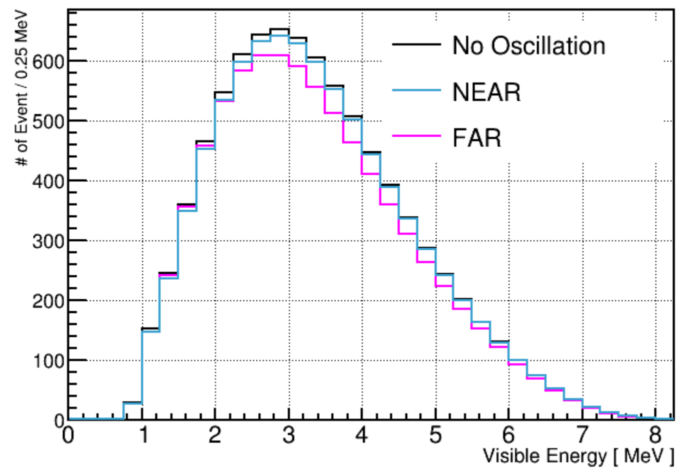
Expected Energy Dependent Oscillation

$$\left|\Delta m^2_{ee}\right| = 2.5\times10^{-3}\,eV^2$$

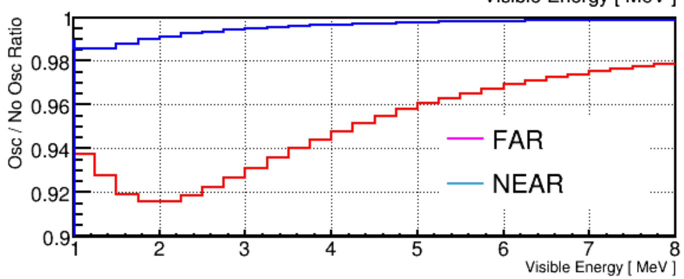
$$\left|\Delta m^2_{ee}\right| = 4.3\times10^{-3}\,eV^2$$

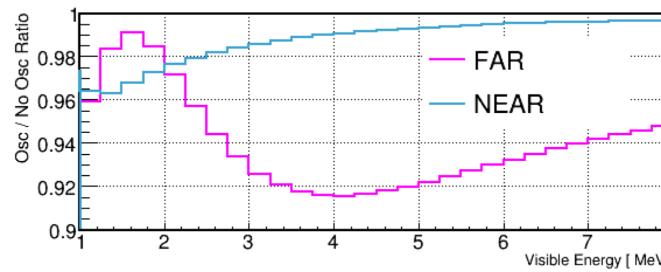
Expected oscillated spectra



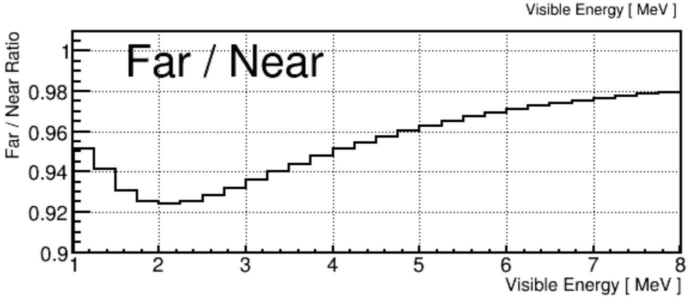


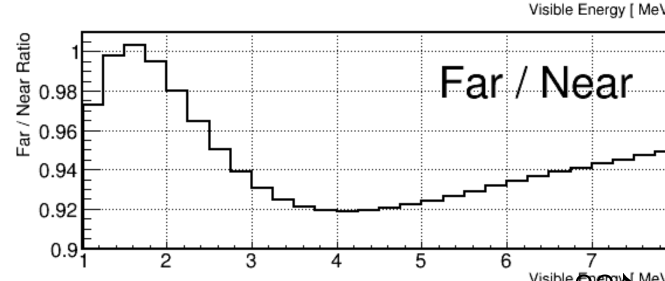
Ratio of osc, / no osc.





Ratio of Far / Near





Why n-H IBD Analysis?

<u>Motivation:</u>

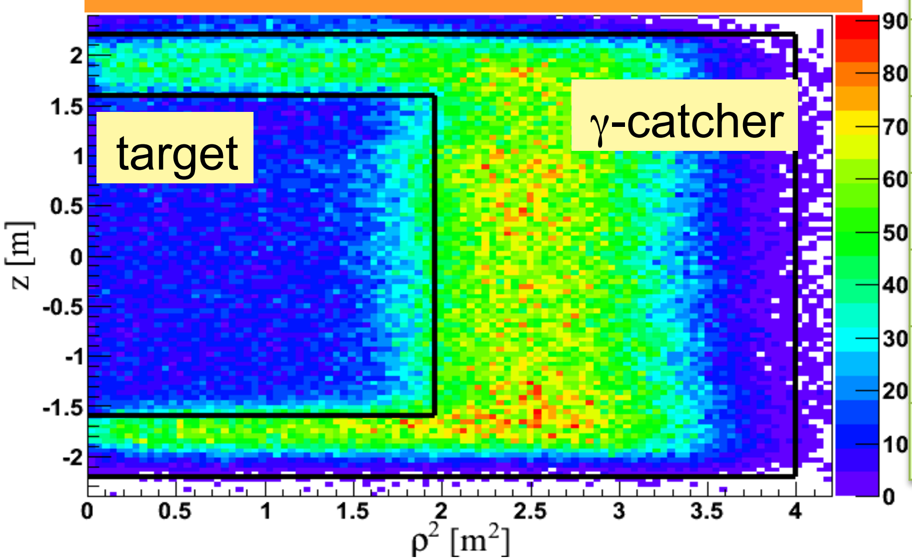
1. Independent measurement of θ_{13} value.
2. Consistency and systematic check on reactor neutrinos.

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

-- low radioactivity PMT

-- successful purification of LS and detector materials

n-H IBD Event Vertex Distribution



	Near	Far
Live time(day)	379.663	384.473
IBD Candidate	249,799	54,277
IBD(/day)	619.916	67.823
Accidental (/day)	25.16±0.42	68.90±0.35
Fast Neutron(/day)	5.62±0.30	1.30±0.08
LiHe(/day)	9.87±1.48	3.19±0.37

Results from n-H IBD sample

Very preliminary
Rate-only result

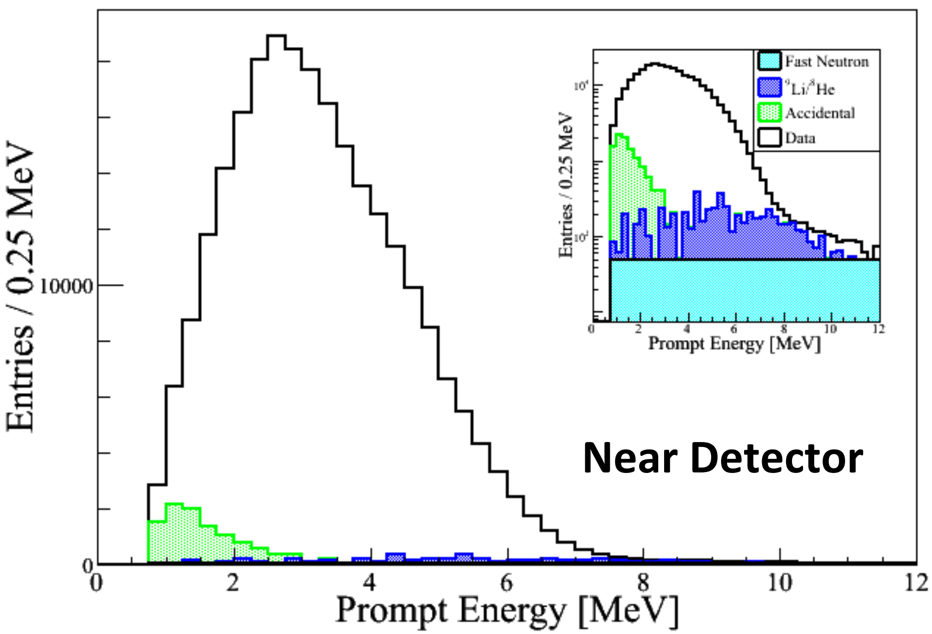
(B data set, ~400 days)

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

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

← *Removed a soft neutron background and reduced the uncertainty of the accidental background*

preliminary



preliminary