New Results from RENO

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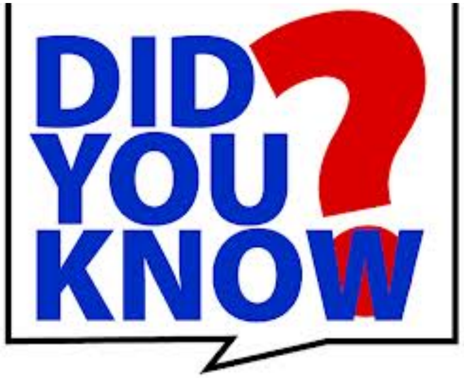
On behalf of the RENO Collaboration
KNRC & Seoul National University

(June 3, 2014)

RENO

NEUTRINO2014
XXVI International Conference on Neutrino Physics and Astrophysics
June 2-7, 2014, Boston, U.S.A.

KNRC
Korea Neutrino Research Center



RENO Trivia

- ✓ RENO is the first experiment to take data using both near and far detectors since Aug. 2011.
- ✓ RENO's 1st θ_{13} measurement (4.9σ) was published in PRL in 11 May, 2012 (2 weeks later than Daya Bay).
- ✓ RENO reaches 3 years of data taking in two months.

<u>Total reactor ν observed in RENO as of today:</u>

Near detector = ~ 1 M

Far detector = ~ 0.1 M

→ Precise Measurement Possible !!


We are very glad
to announce our new results
in Neutrino 2014 !!

RENO New Results

- Rate-only Analysis Results
- Observation of New Reactor ν Component at 5 MeV
- Shape Analysis Results (progress report this time)
- Neutron Capture on Hydrogen Analysis

Reactor Experiment for Neutrino Oscillation

More details: 7 Posters from RENO

- Precise measurement of **reactor neutrino flux** and spectrum at RENO (**B.H. Lee**)
- **Event selection and background** estimation for the reactor neutrinos at RENO (**W.Q. Choi**)
- Measurement of reactor neutrinos with **neutron captures on hydrogen** at RENO (**J.S. Park**)
- Monitoring **stability of Gd loaded liquid scintillator** at RENO (**S.H. So**)
- **Energy calibration** and slow control monitoring at RENO (**J.H. Choi**)
- Monitoring **PMT performance** at RENO (**D.H. Lee**)
- **RENO-50**: Neutrino Mass hierarchy and Neutrino Observatory (**S.H. Seo**)

RENO Collaboration

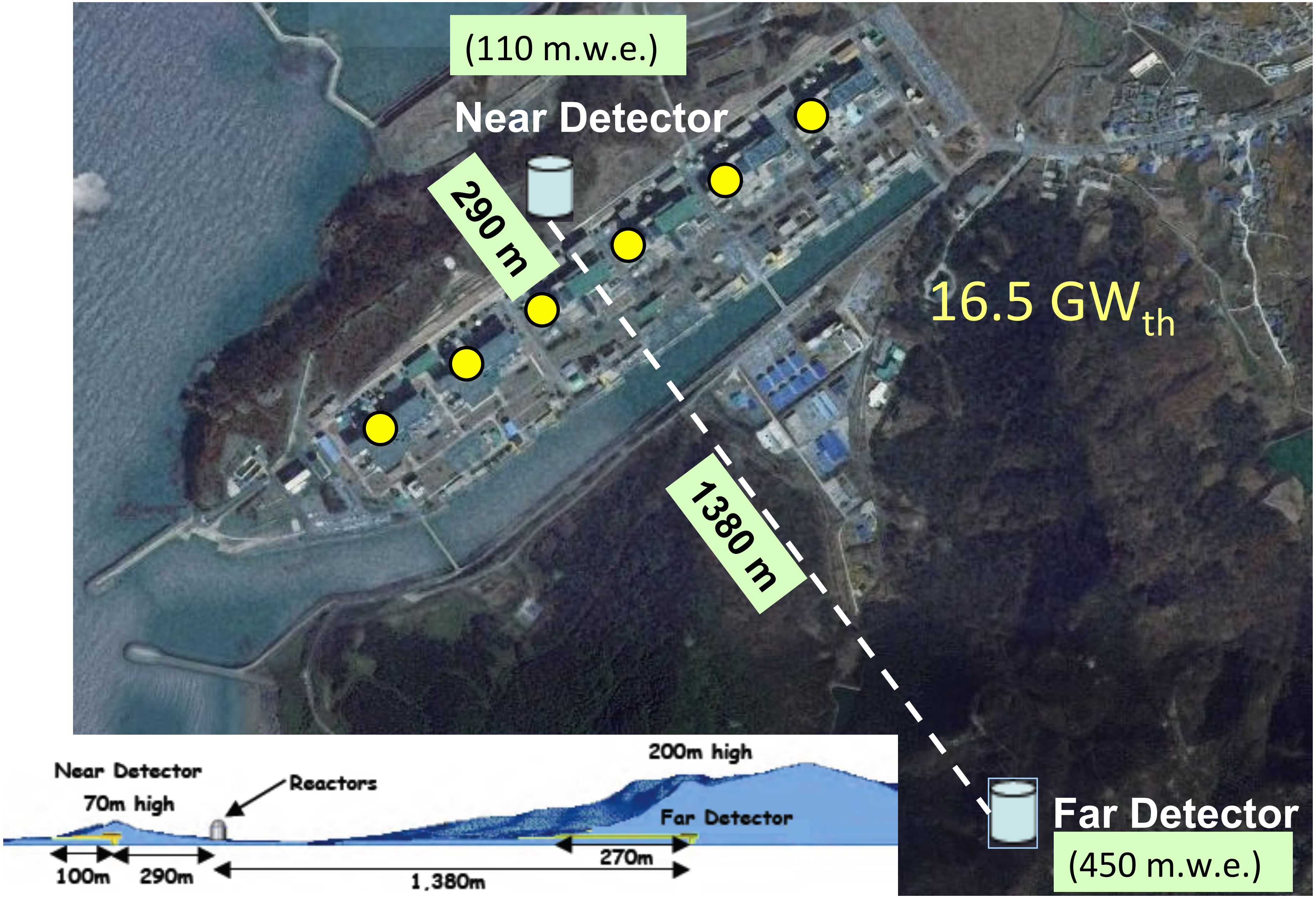
11 institutions and 40 physicists

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

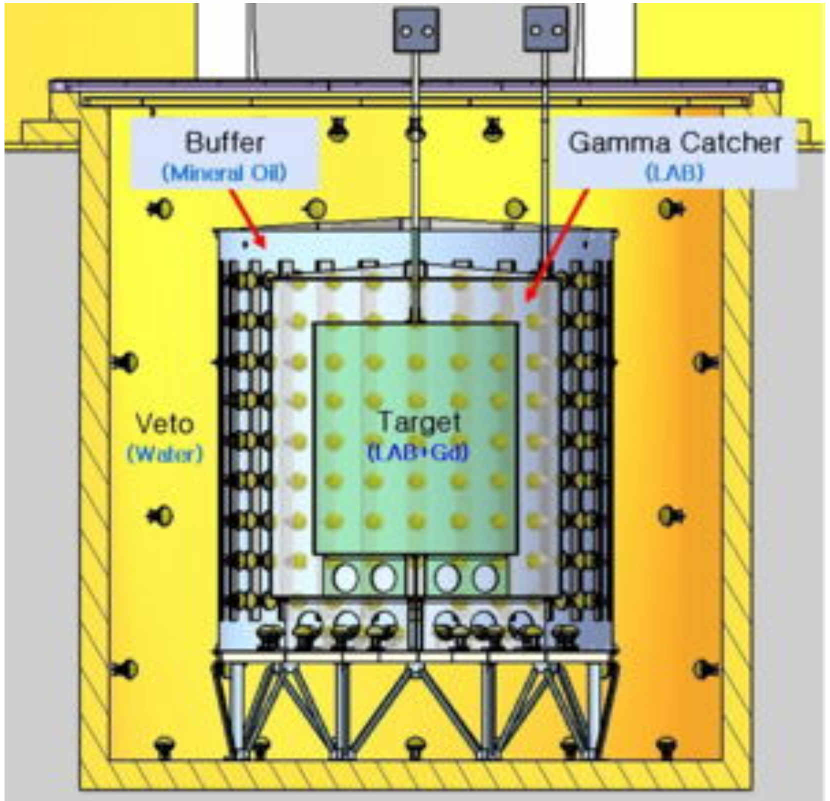
- **Total cost : $10M**
- Start of project : **2006**
- The first experiment running with both near & far detectors from **Aug. 2011**

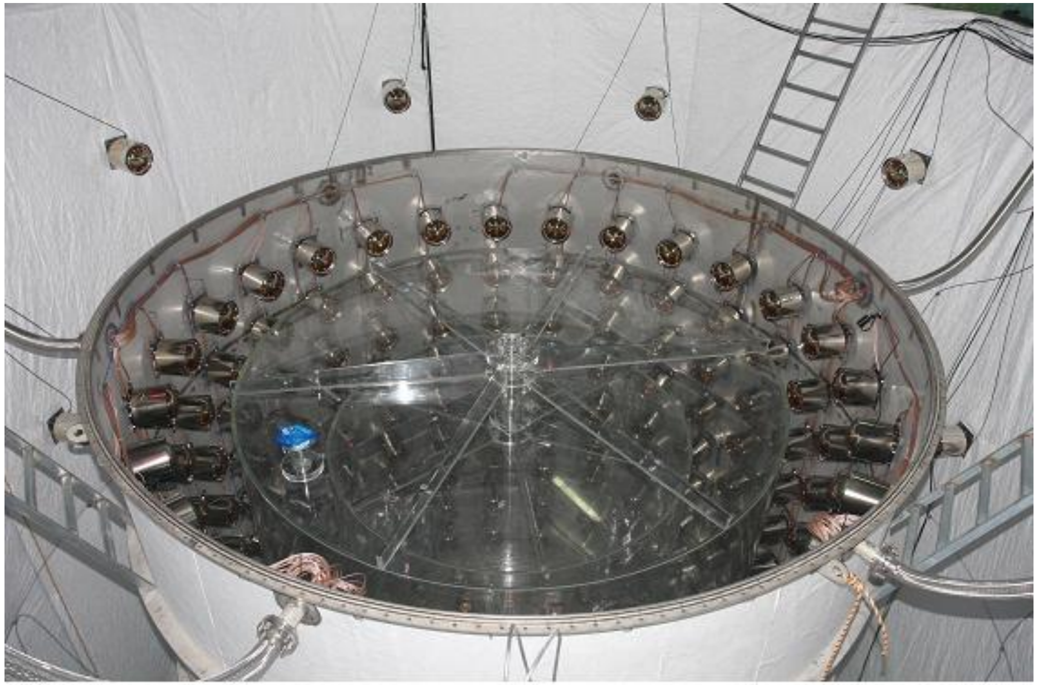
YongGwang (靈光) :

RENO Experimental Setup



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 Data Taking Status

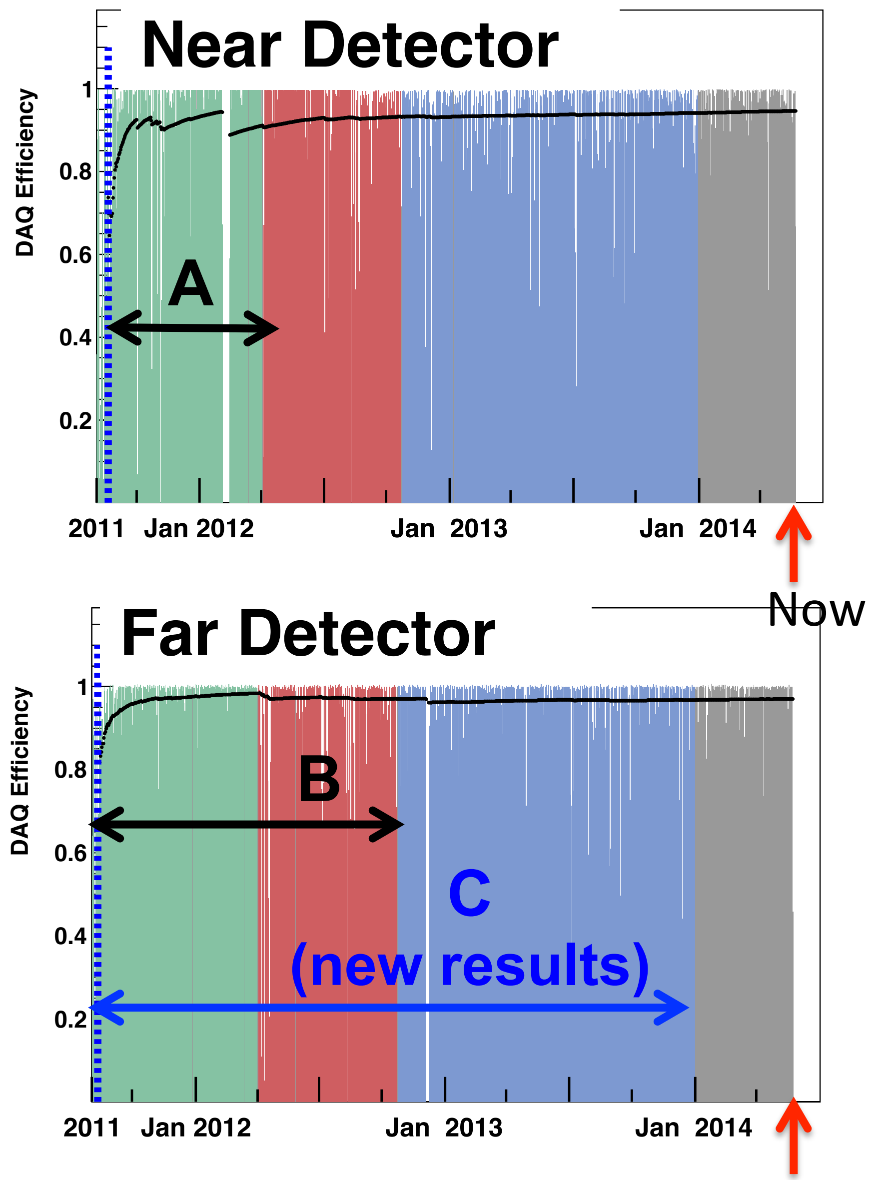
- Data taking began on Aug. 1, 2011 with both near and far detectors. (DAQ efficiency : ~95%)

- **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 (~800 days)**: **Shape+rate analysis** (this work)
  [11 Aug, 2011~31 Dec, 2013]

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



Signal & Background Summary

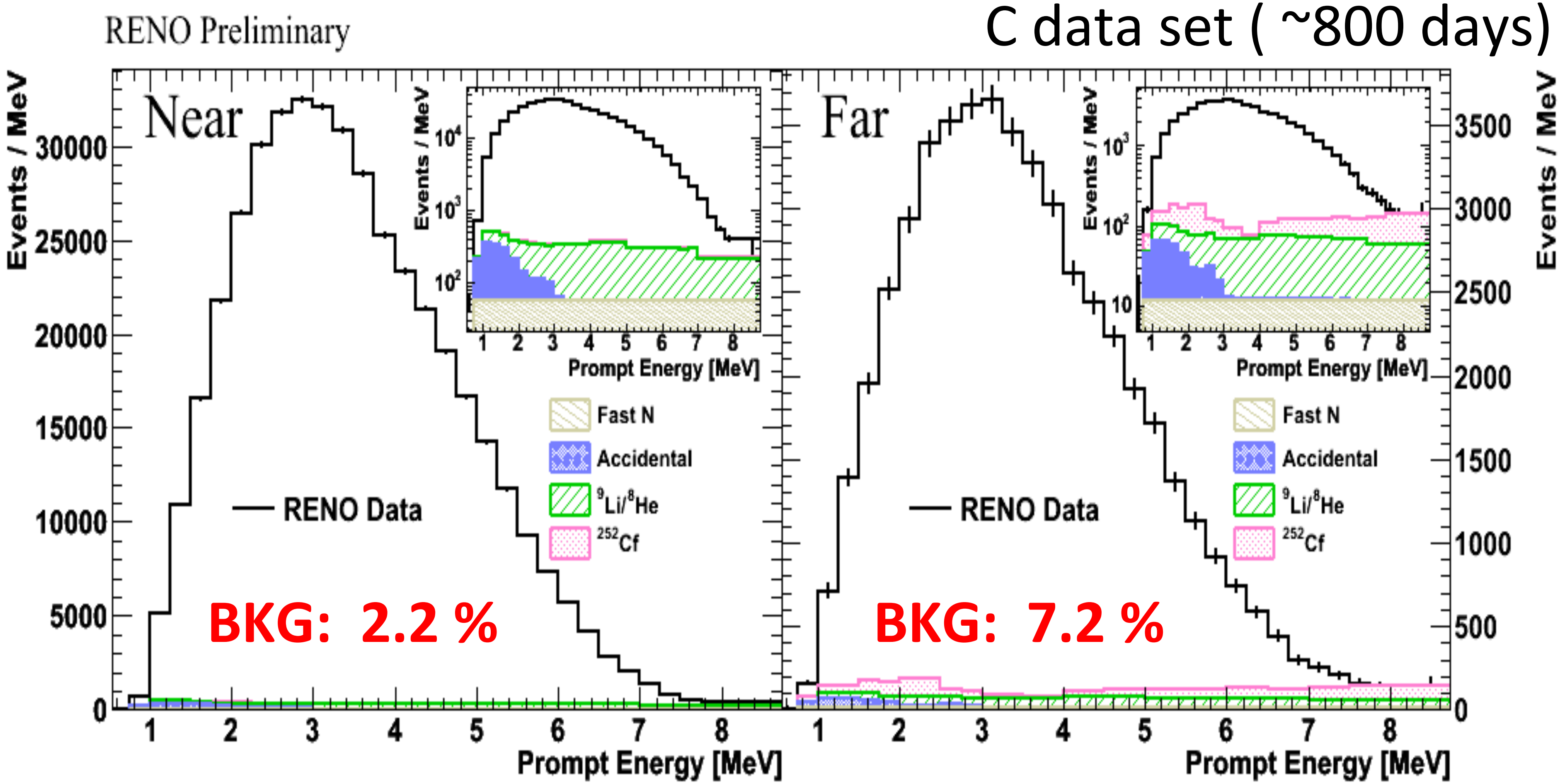
Preliminary result

C data set (~800 days)

	Near	Far
Live time (days)	761.11	794.72
IBD Candidate events	433,196	50,750
IBD after background Subtraction (/day)	569.16 ± 0.87	63.86 ± 0.28
Total Background (/day)	12.48 ± 0.68	4.62 ± 0.34
Accidental (/day)	1.82 ± 0.11	0.36 ± 0.01
Fast Neutron(/day)	2.09 ± 0.06	0.44 ± 0.02
$^{9}Li/^{8}He$(/day)	8.28 ± 0.66	1.85 ± 0.20
^{252}Cf contamination(/day)	0.28 ± 0.05	1.98 ± 0.27

For more details, see poster by W.Q. Choi.

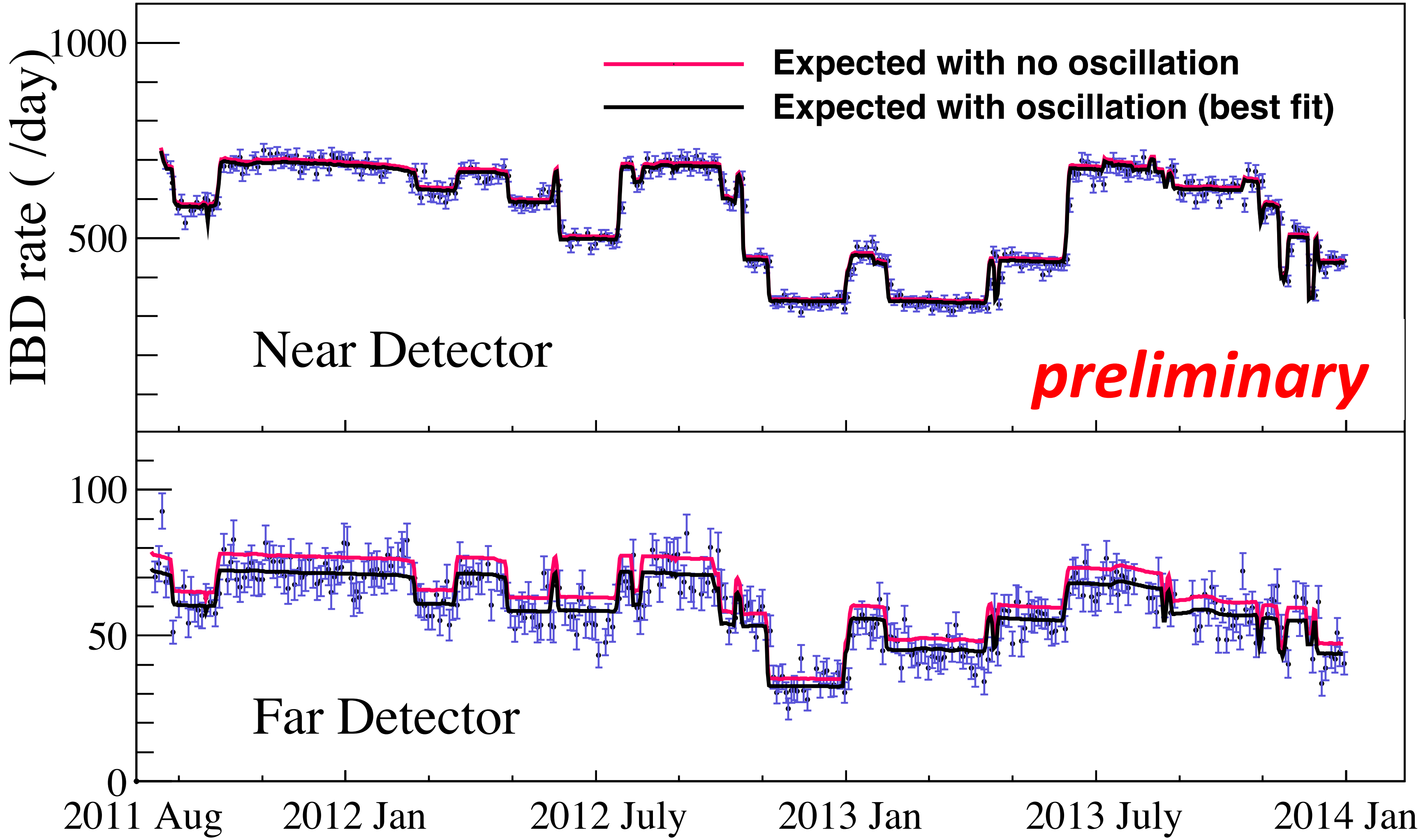
Signal & Background Spectrum



Near Live time = 761.11 days
# of IBD candidate = 433,196
# of background = 9499 (2.2 %)

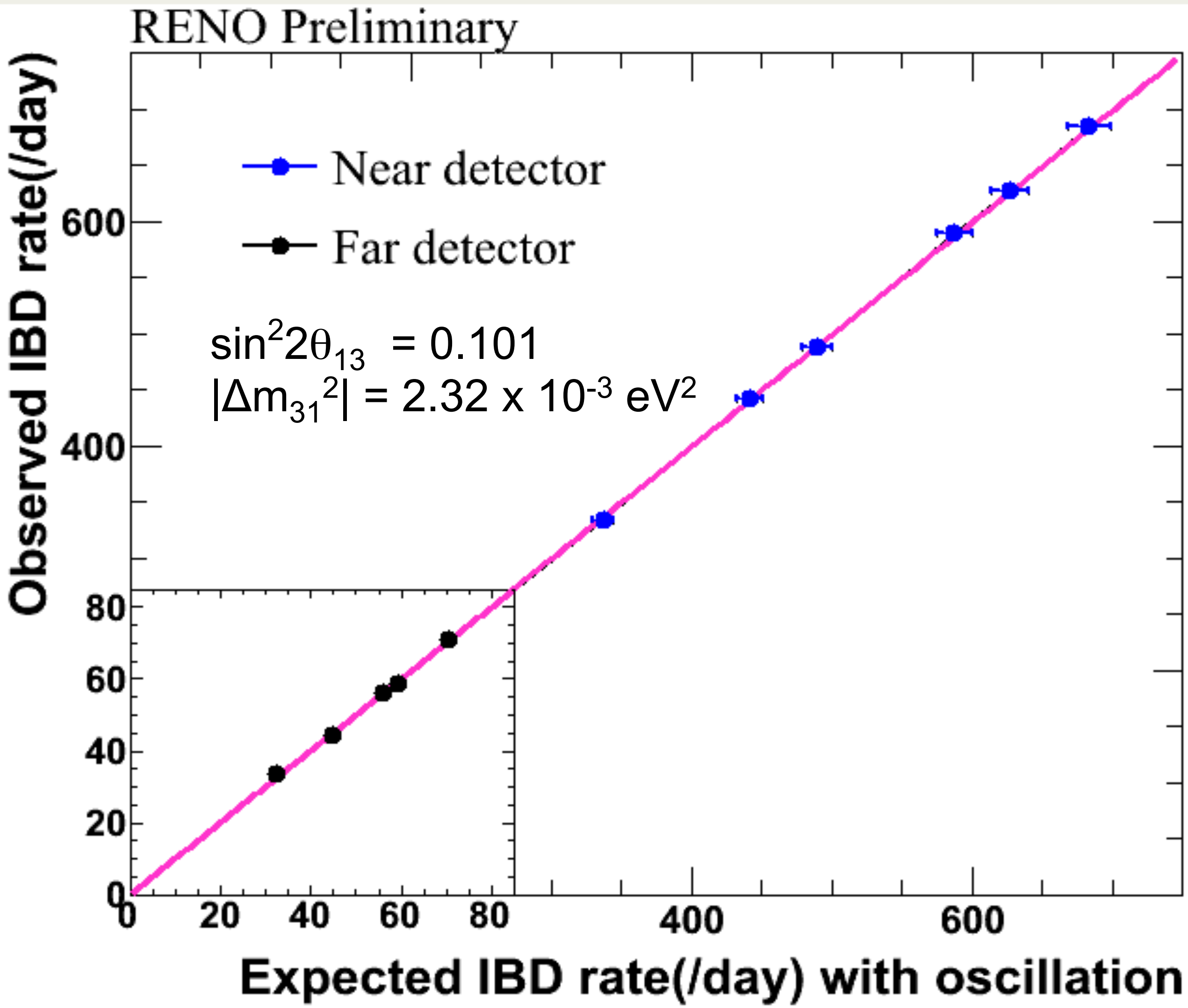
Far Live time = 794.72 days
# of IBD candidate = 50,750
# of background = 3672 (7.2 %)

Observed Daily IBD Rate



- Observed points have very good agreement with prediction.
- It's the accurate flux (or thermal power) measurement.

Observed vs. Expected IBD Rates



Observed & expected IBD rates match well within oscillation hypothesis.
Background subtraction is correctly done.

Rate-only θ_{13} Measurements in RENO

Preliminary result

C data set (~800 days)

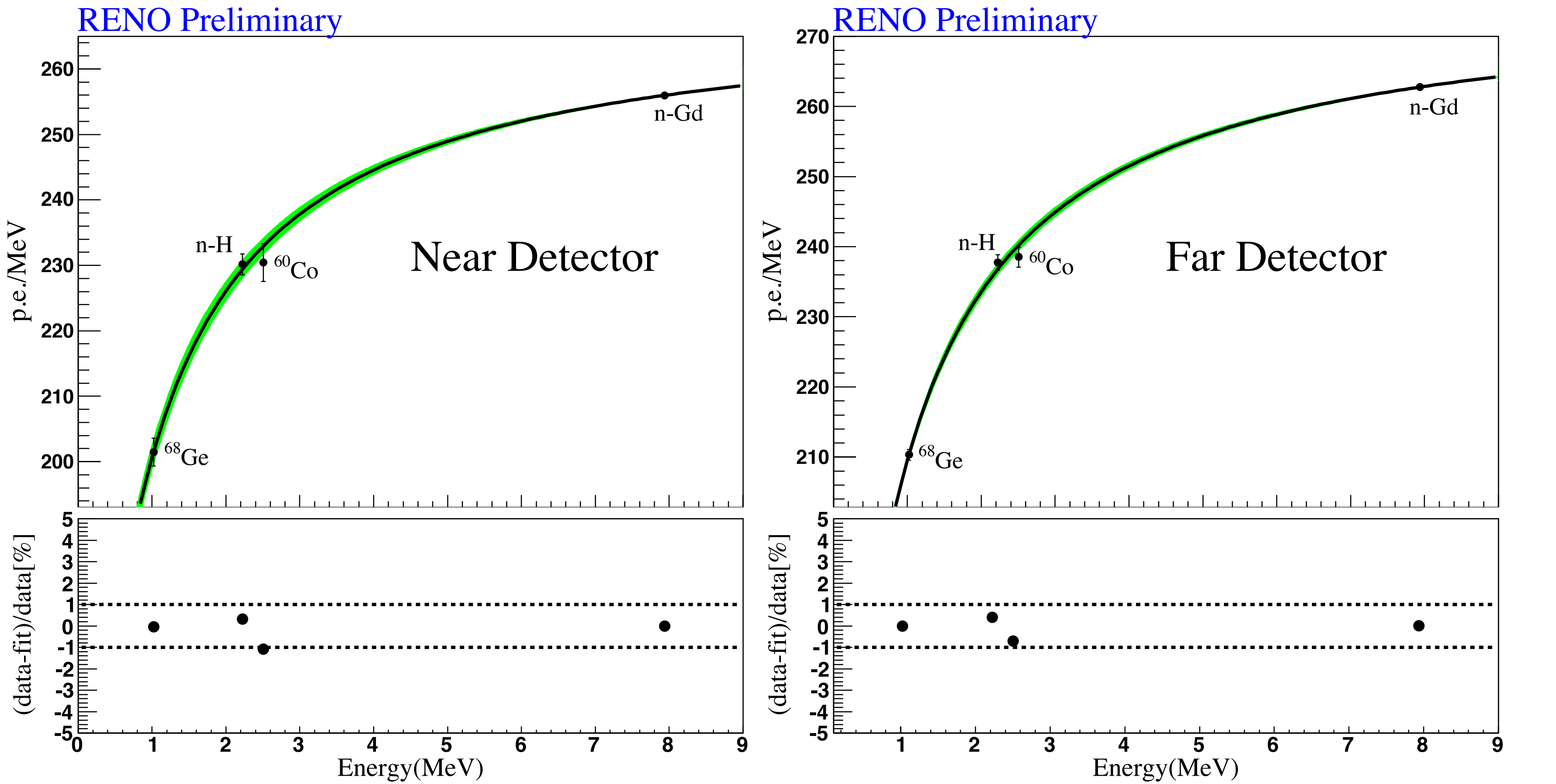
$\sin^2(2\,\theta_{13}) = 0.101 \pm 0.008\ (\text{stat.}) \pm 0.010\ (\text{sys.})$

- Data before ^{252}Cf contamination: previous **0.012 (sys.)** → **0.007 (sys.)**
- Data after ^{252}Cf contamination: → **0.018 (sys.)**

$\sin^2(2\theta_{13}) = 0.113$ +/- 0.023	4.9 σ	(2012, Neutrino)
→ 0.100 +/- 0.016	6.3 σ	(2013, TauP/WIN)
→ 0.101 +/- 0.013	7.8 σ	(2014, Neutrino)


Let’s talk about
the shape analysis.

Energy Scale Calibration

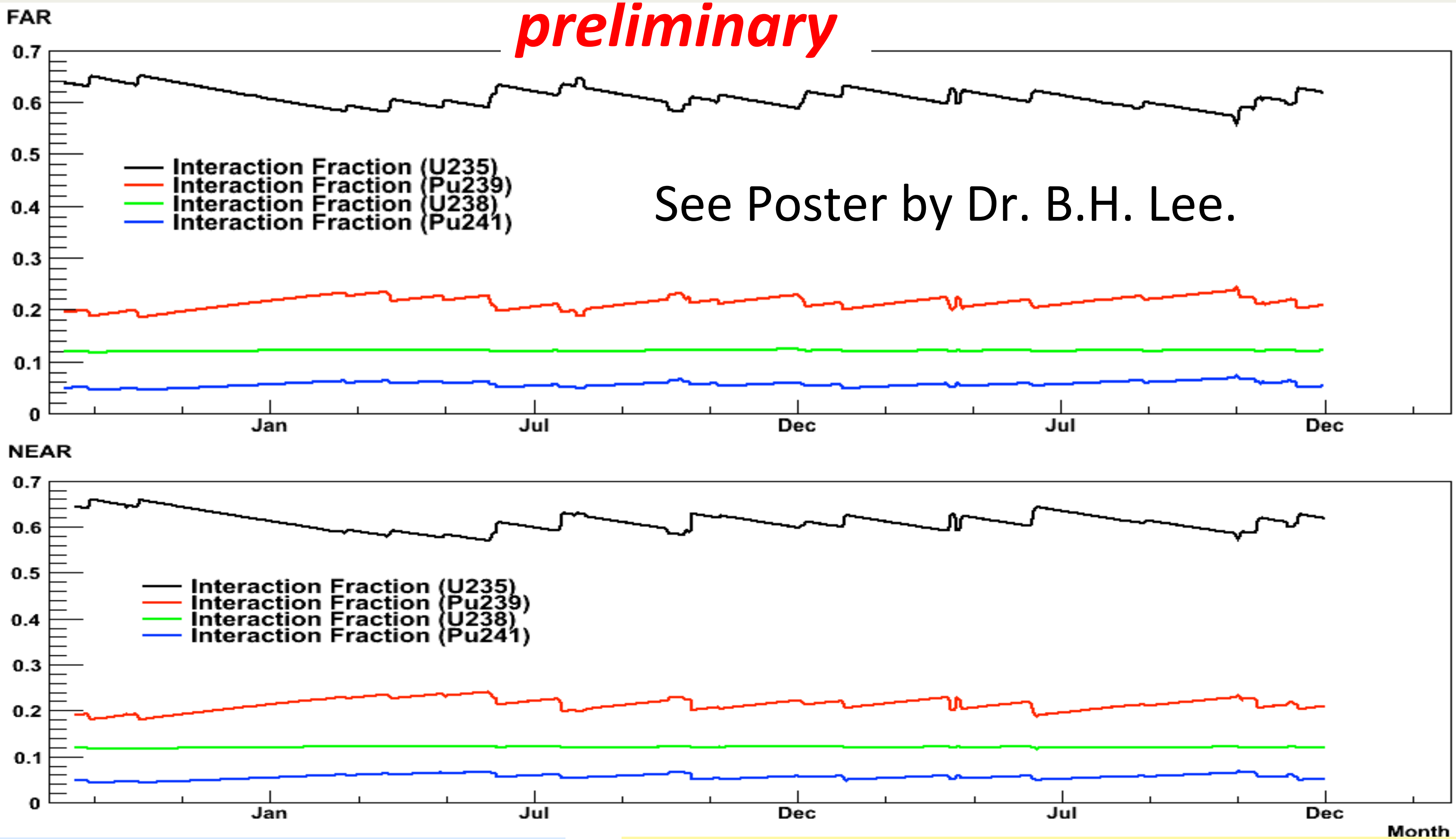


p.e. → MeV conversion function

Fitting accuracy is within 1% level.

See poster
by Dr. J.H. Choi.

Expected Neutrino Spectrum

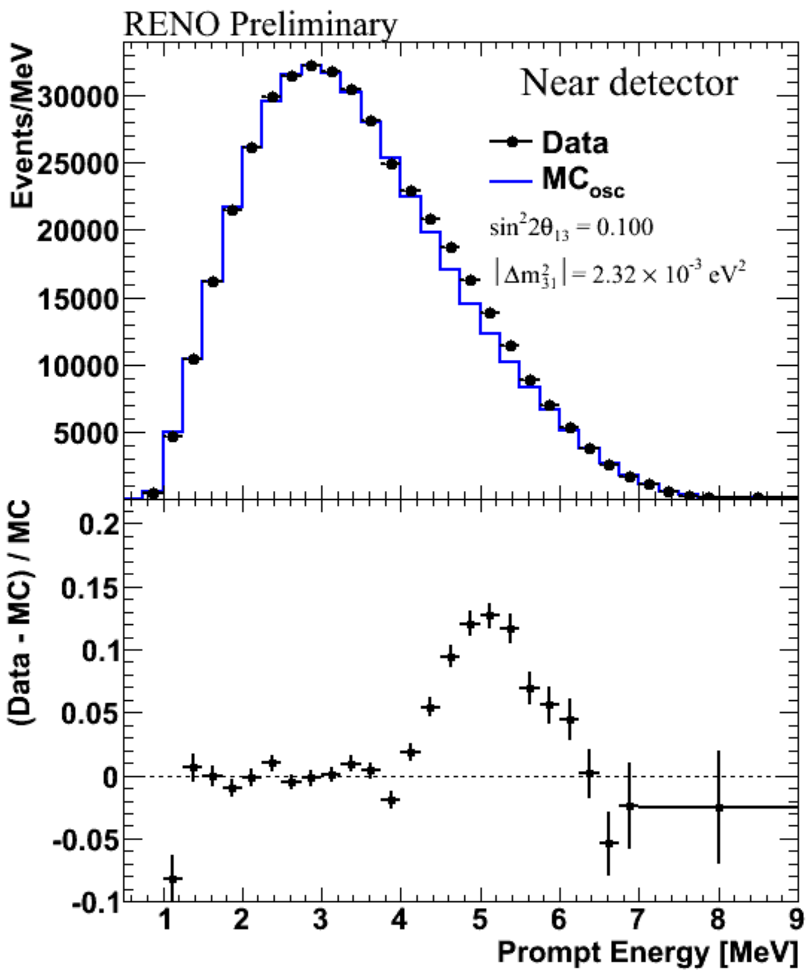


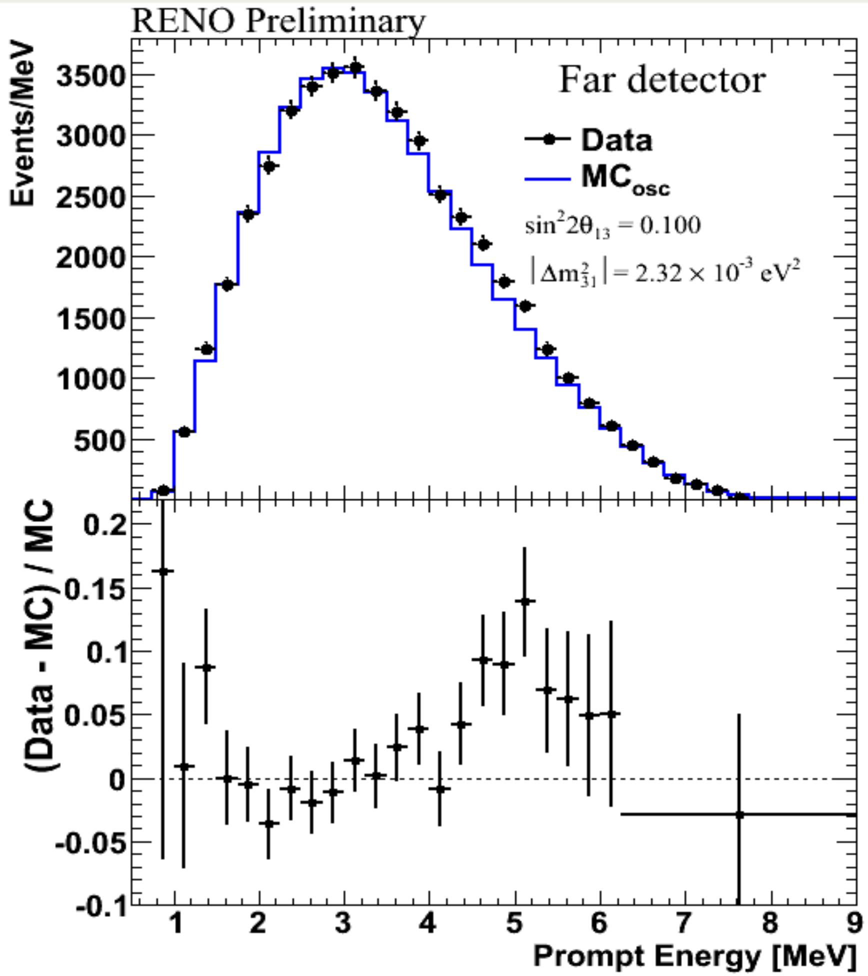
Spectral shape depends on isotope fraction.

→

We considered daily fission fraction in the expected ν spectrum & flux.

Observation of new reactor ν component at 5 MeV

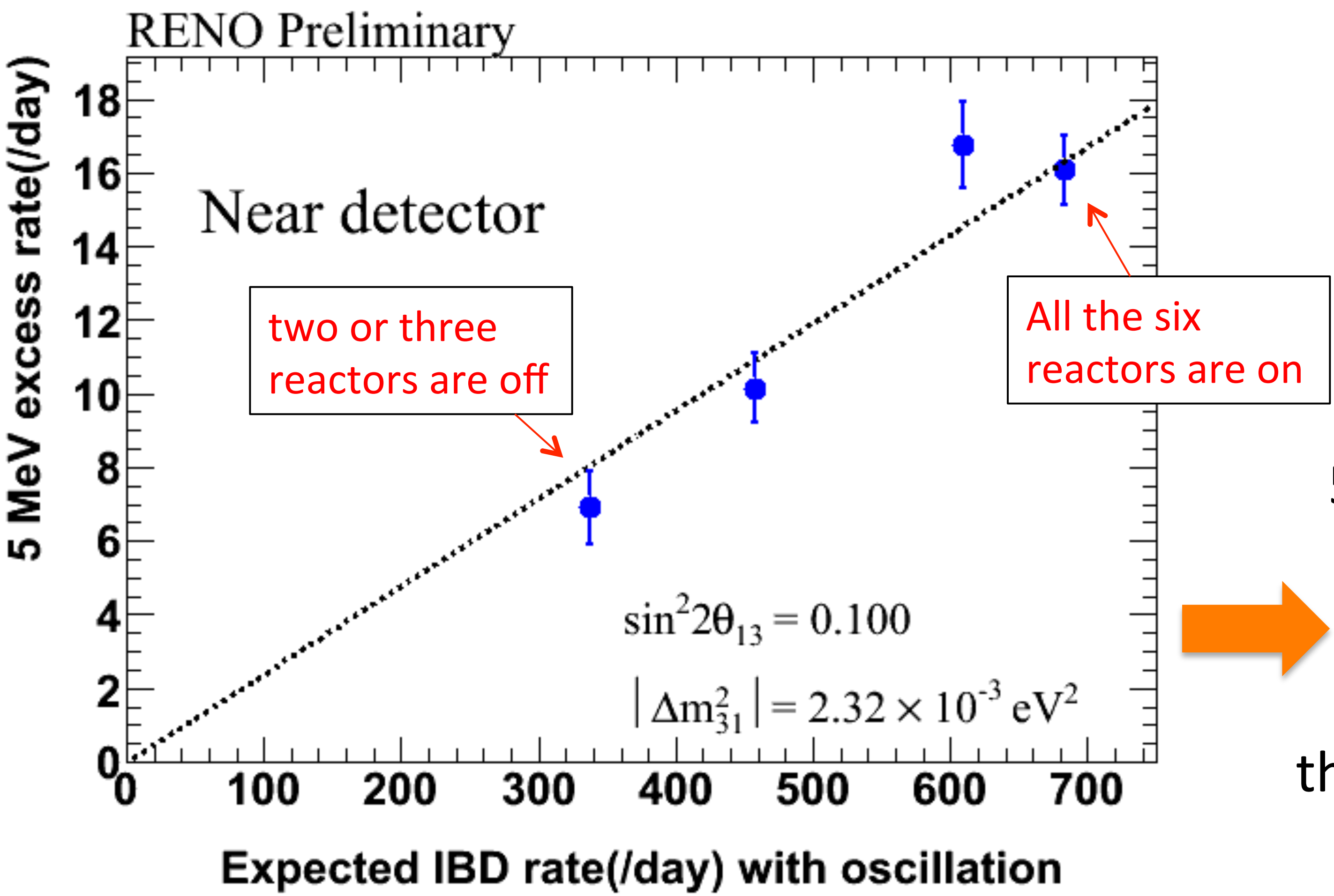




Fraction of 5 MeV excess (%) to expected flux

- Near : 2.303 +/- 0.401 (experimental) +/- 0.492 (expected shape error)
- Far : 1.775 +/- 0.708 (experimental) +/- 0.486 (expected shape error)

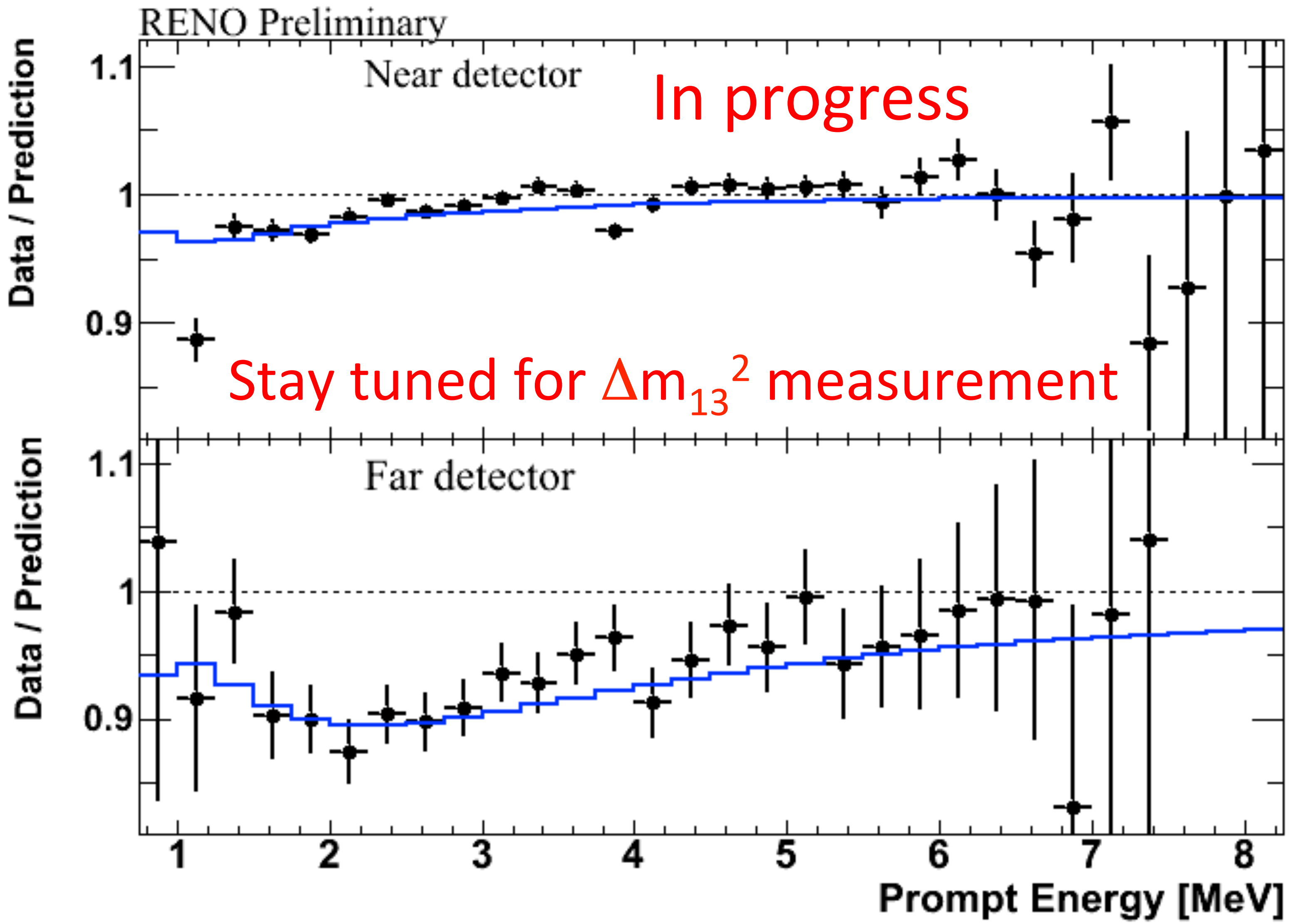
Observation of new reactor ν component at 5 MeV



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

We take into account the excess at 5 MeV to the expected spectral shape.

Status of Shape Analysis

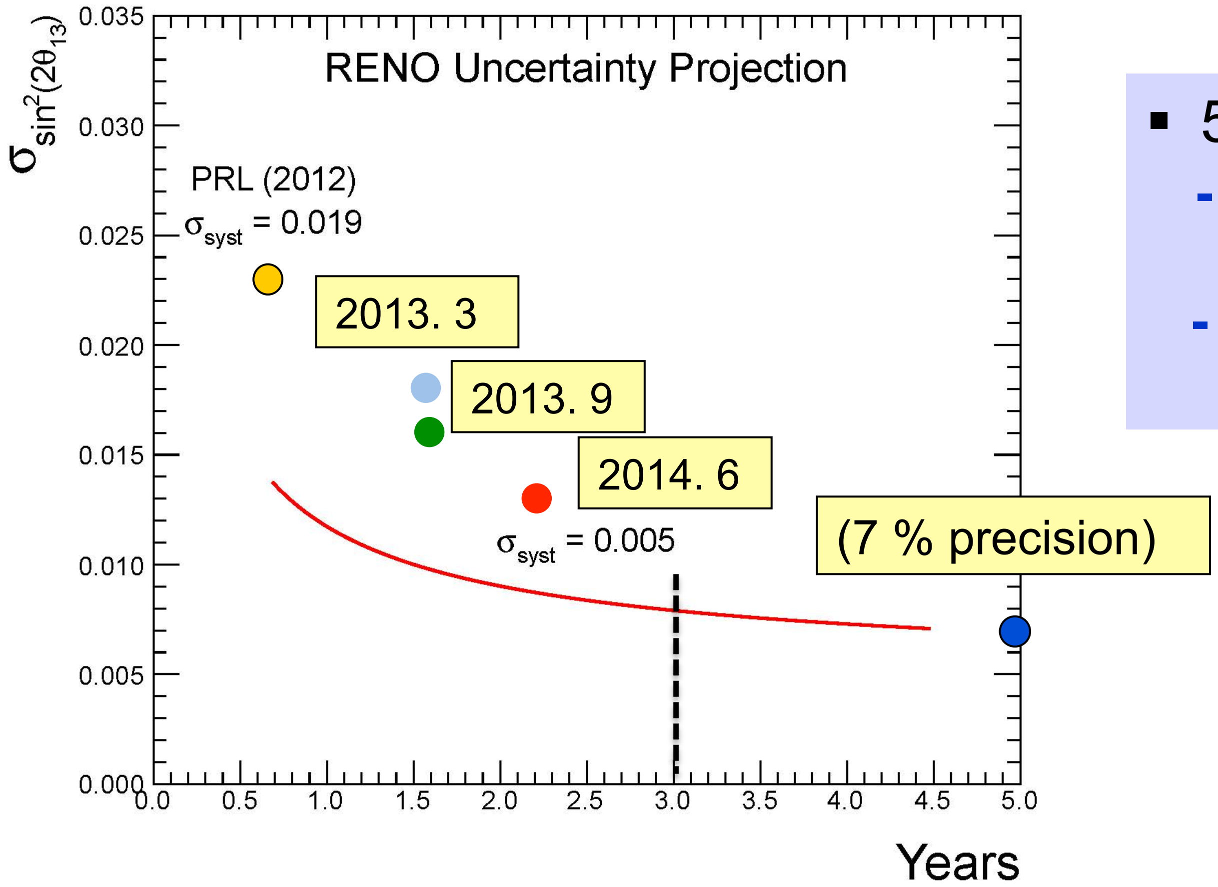


Data and expected shape (blue line) agree well.

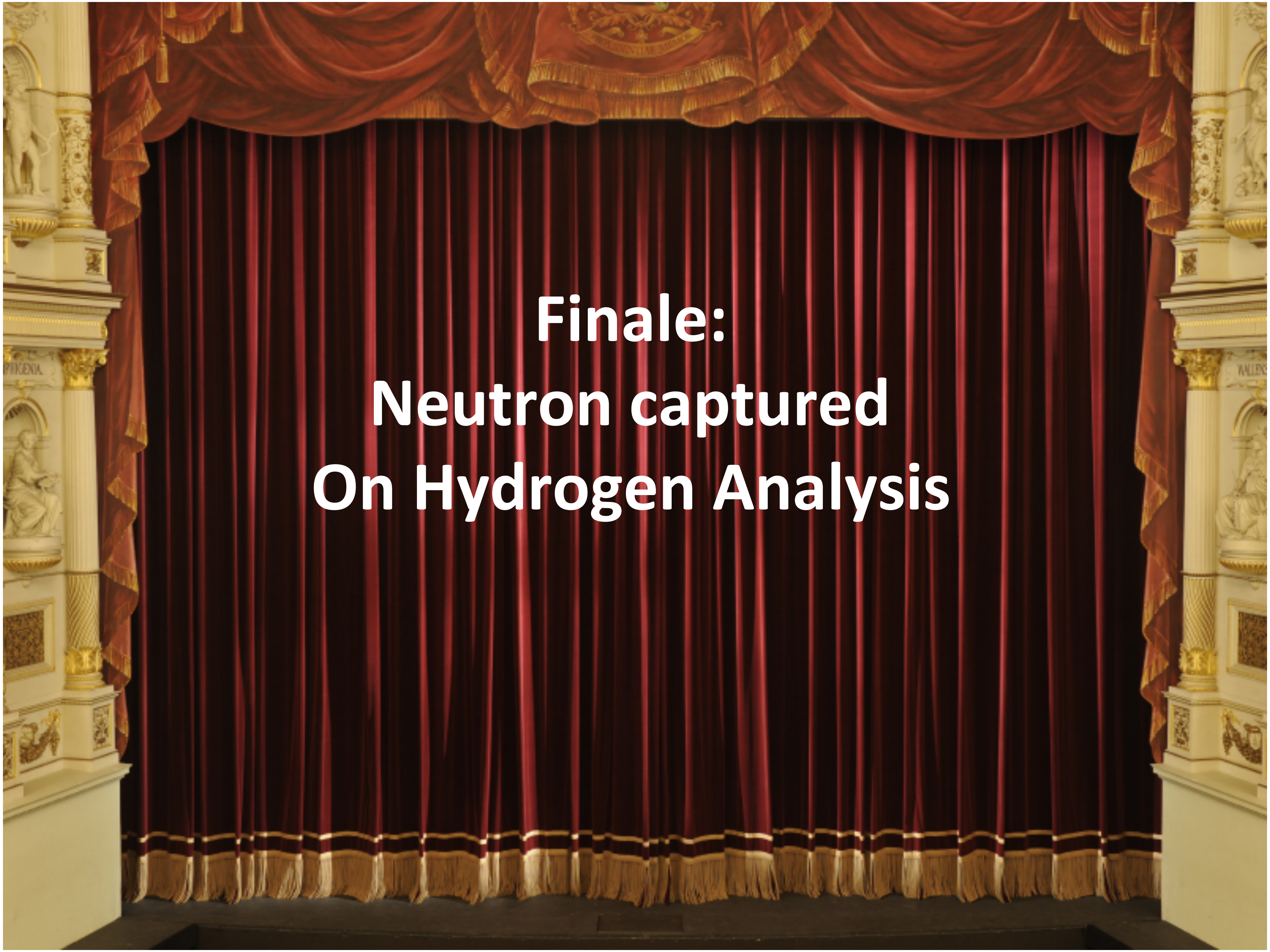
RENO Prospects for θ_{13} Measurement

$$\sin^2 2\theta_{13} = 0.101 \pm 0.008(stat.) \pm 0.010(syst.)$$

(~800 days) 0.101 ± 0.013 (7.8 σ) → ±0.007 (14 σ) (in 3 years)



- 5 years of data : 7 %
  - **stat. error :**
    ±0.008 → ±0.005
  - **sys. error :**
    ±0.010 → ±0.005


Finale:
Neutron captured
On Hydrogen Analysis

Why n-H IBD Analysis ?

Motivation:

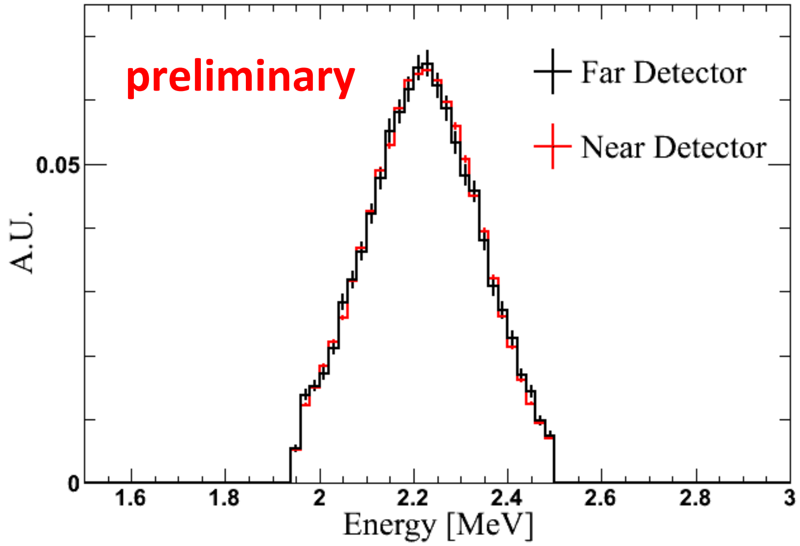
1. Independent measurement of θ_{13} value.

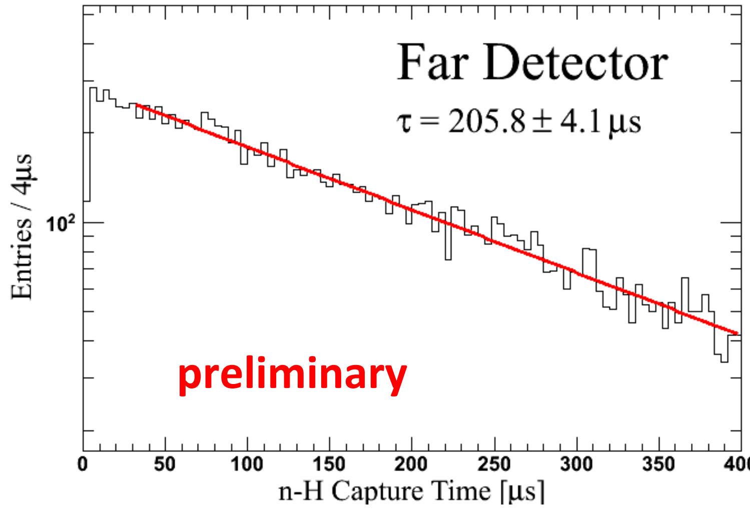
2. Consistency and systematic check on reactor neutrinos.

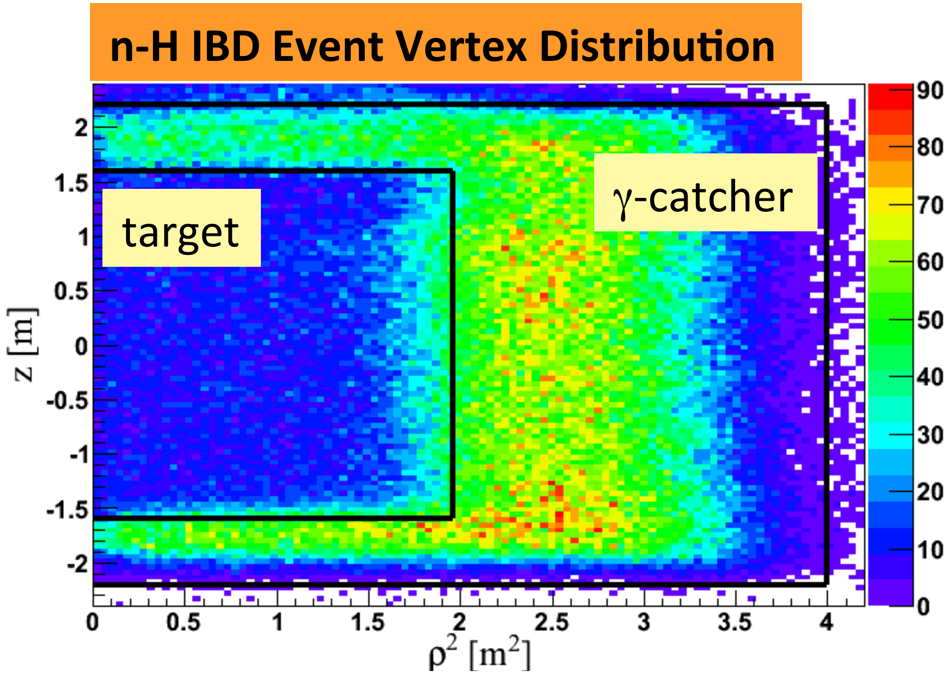
RENO's low accidental background makes it possible to perform n-H analysis.

-- low radio-activity PMT
-- successful purification of LS and detector materials.

n-H IBD Analysis (I)







Neutron-H Capture cut criteria	
Prompt Energy	0.7 ~ 12 MeV
Delayed Energy	1.95~2.50 MeV
deltaT	2 ~ 400 us
deltaR	< 50 cm
Qmax/Qtot	< 0.08
Muon Veto time	1 ms
Shower Muon Veto time	700 ms
Additional Trigger veto time cuts	

n-H IBD Analysis (II)

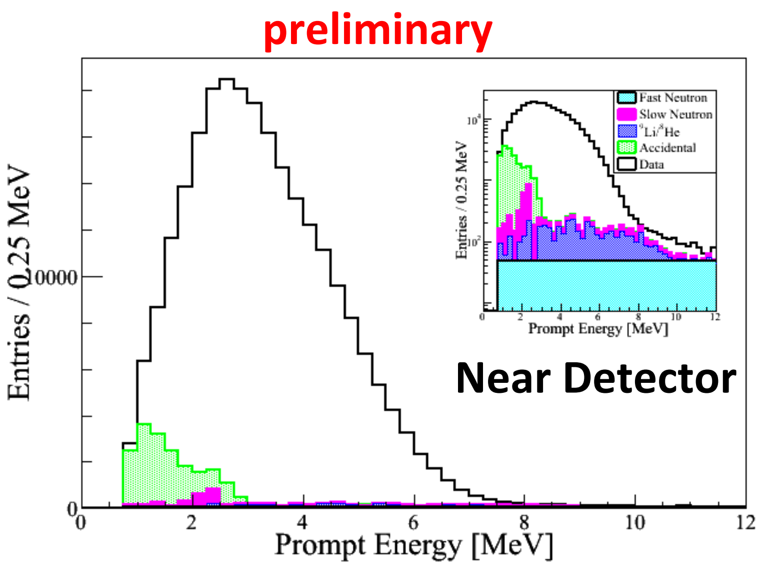
	Near	Far
Live time(day)	379.663	384.473
IBD Candidate	245,281	55,545
IBD(/day)		
Accidental (/day)	40.87+-1.74	72.69+-0.83
Fast Neutron(/day)	5.63+-0.09	1.28+-0.10
Soft Neutron(/day)	6.42+-0.35	1.04+-0.47
LiHe(/day)	7.24+-0.92	3.17+-0.35

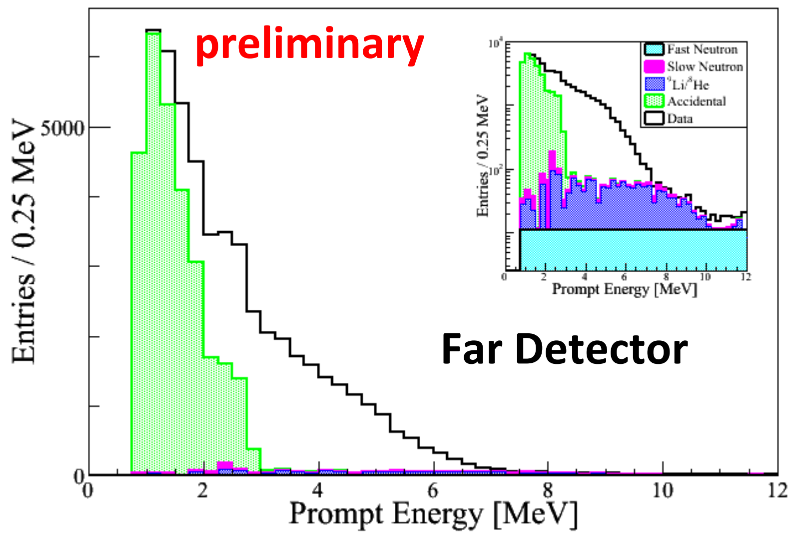
B data set result

$\sin^2(2\theta_{13}) = 0.095 \pm 0.015$ (stat.) ± 0.025 (sys.)

Very preliminary
Rate-only result

See poster by Dr. J.S. Park.





Summary

- We observed new reactor neutrino component at 5 MeV. (3.6 σ)

- Rate analysis result: preliminary

  $\sin^2(2\theta_{13}) = 0.101 \pm 0.008 \text{ (stat.)} \pm 0.010 \text{ (sys.)}$

- Shape analysis is in progress… : stay tuned !

- Very preliminary result on n-H IBD analysis: **Very preliminary Rate analysis**

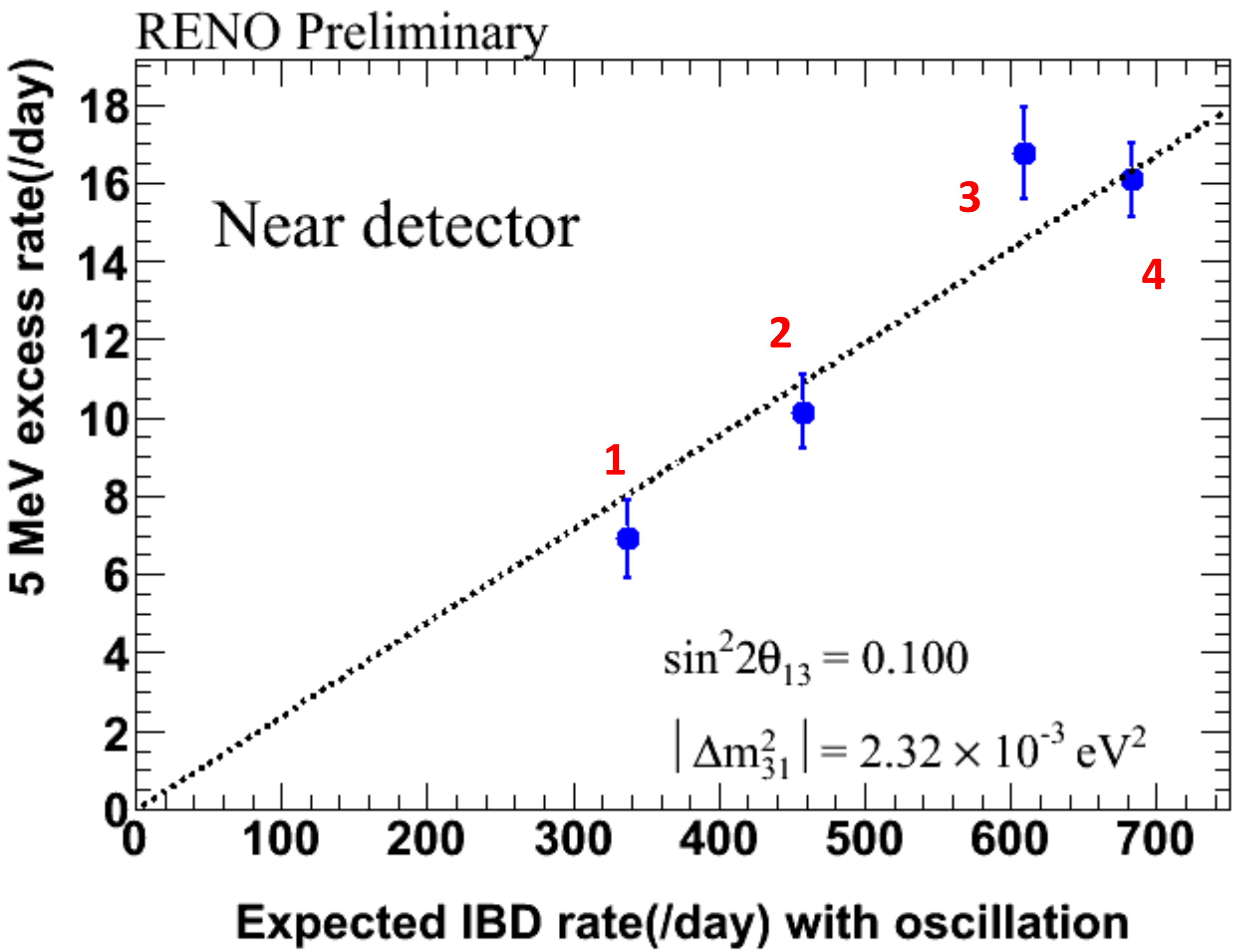
  $\sin^2(2\theta_{13}) = 0.095 \pm 0.015 \text{ (stat.)} \pm 0.025 \text{ (sys.)}$

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

Thank you very much
for your attention !!

Back Up Slides

5 MeV excess vs. expected IBD rate



1	Reactor 3,5,6 are off Reactor 2,3 are off
2	Reactor 3 is off Reactor 4 is ff Reactor 5,6 are off
3	Reactor 1 is off Reactor 2 is off Reactor 5 is off Reactor 6 is off
4	No reactor is off

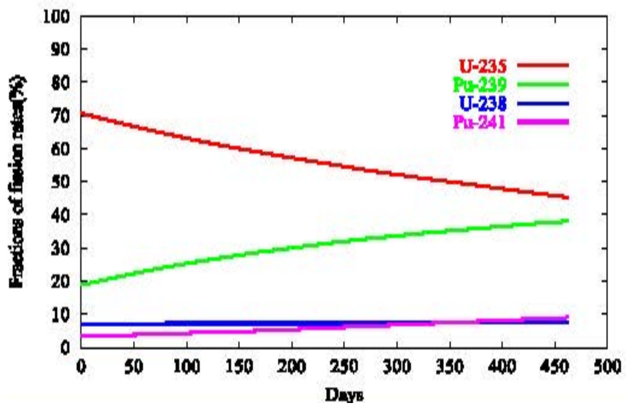
Expected Neutrino Flux

- Reactor neutrino flux

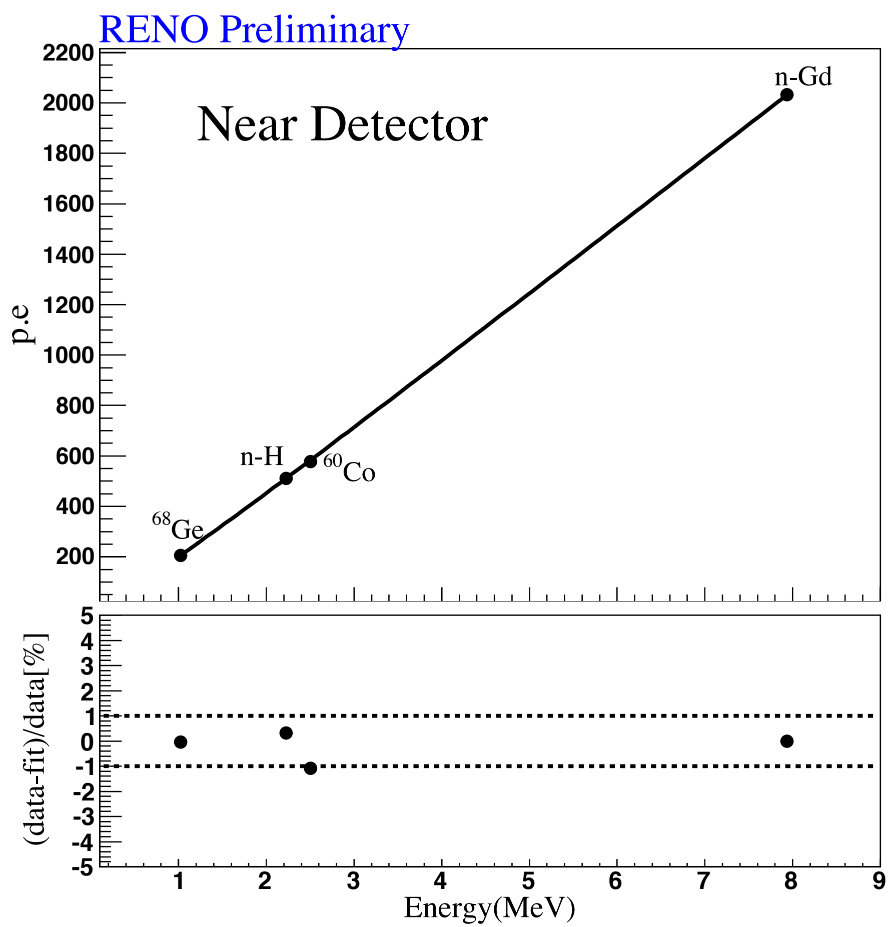
$$\Phi(E_\nu) = \frac{P_{th}}{\sum_i^{isotopes} f_i \cdot E_i} \sum_i^{isotopes} f_i \cdot \phi_i(E_\nu)$$

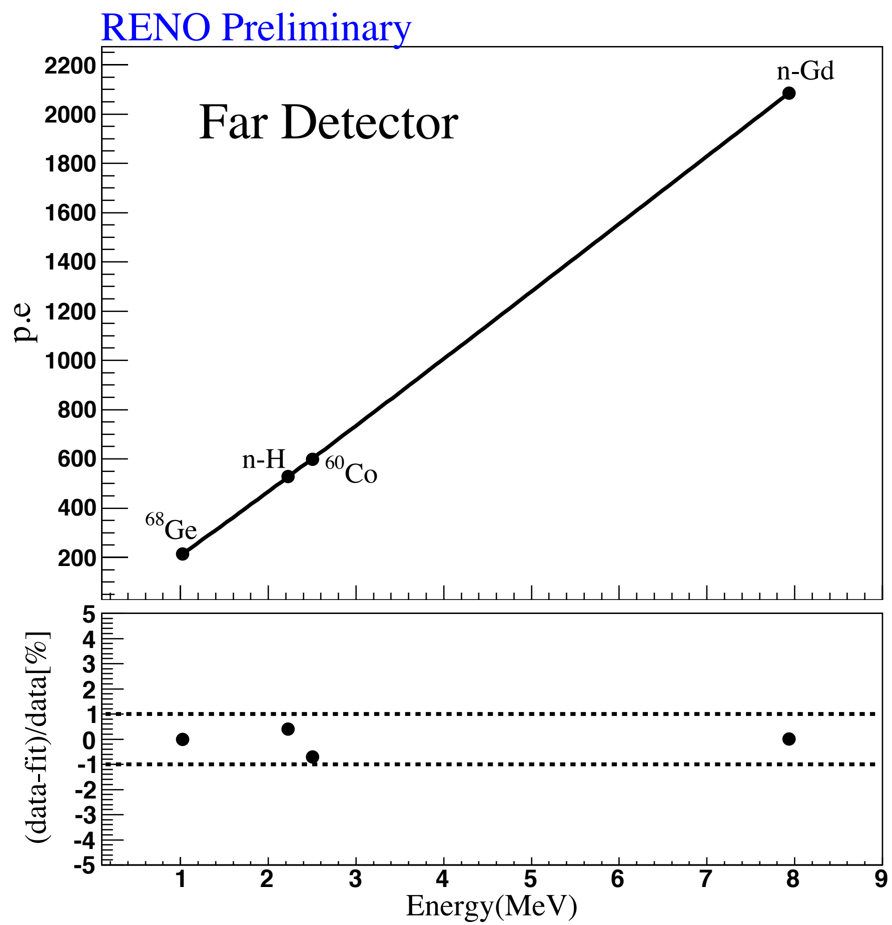
- P_{th} : Reactor thermal power provided by the YG nuclear power plant
- f_i : Fission fraction of each isotope determined by reactor core simulation of Westinghouse ANC
- $\phi_i(E_\nu)$: Neutrino spectrum of each fission isotope
  [* P. Huber, Phys. Rev. C84, 024617 (2011)
  T. Mueller *et al.*, Phys.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



Energy Scale Calibration





p.e. → MeV conversion function

Fitting accuracy is within 1% level.

Shape Analysis χ^2 Formula

$$\chi^2 = \min_{\{\alpha,\beta,\delta,\varepsilon,\gamma,\xi\}} \left\{ \sum_{d=N,F} \left[\sum_{i=1}^{N_b} \left(\frac{O_i^d - N_i^d}{U_i^d} \right)^2 + \left(\beta^d\right)^2 + \left(\frac{\delta^d}{\sigma_{eff}^d} \right)^2 + \left(\frac{\varepsilon^d}{\sigma_{cal}^d} \right)^2 \right] + \sum_{i=1}^{N_b} \sum_{j=1}^{N_{iso}} \left(\frac{\gamma_{ij}}{\left(\sigma_{shape}\right)_{ij}} \right)^2 + \sum_{r=1}^{N_c} \left(\frac{\xi_r}{\sigma_{cfl}} \right)^2 \right\}$$

where,

$$N_i^d = (1 + \alpha + \delta^d) \sum_{r=1}^{N_c} (1 + \xi_r) T_{ir}^d + \varepsilon^d \left(\frac{\partial T_i^d}{\partial \varepsilon^d} \right)_{\varepsilon=0} + \sigma_{bi}^d \beta^d$$

$$T_{ir}^d = \sum_{j=1}^{N_{iso}} (1 + \gamma_{ij}) T_{ijr}^d \qquad U_i^d = O_i^d + B_i^d$$