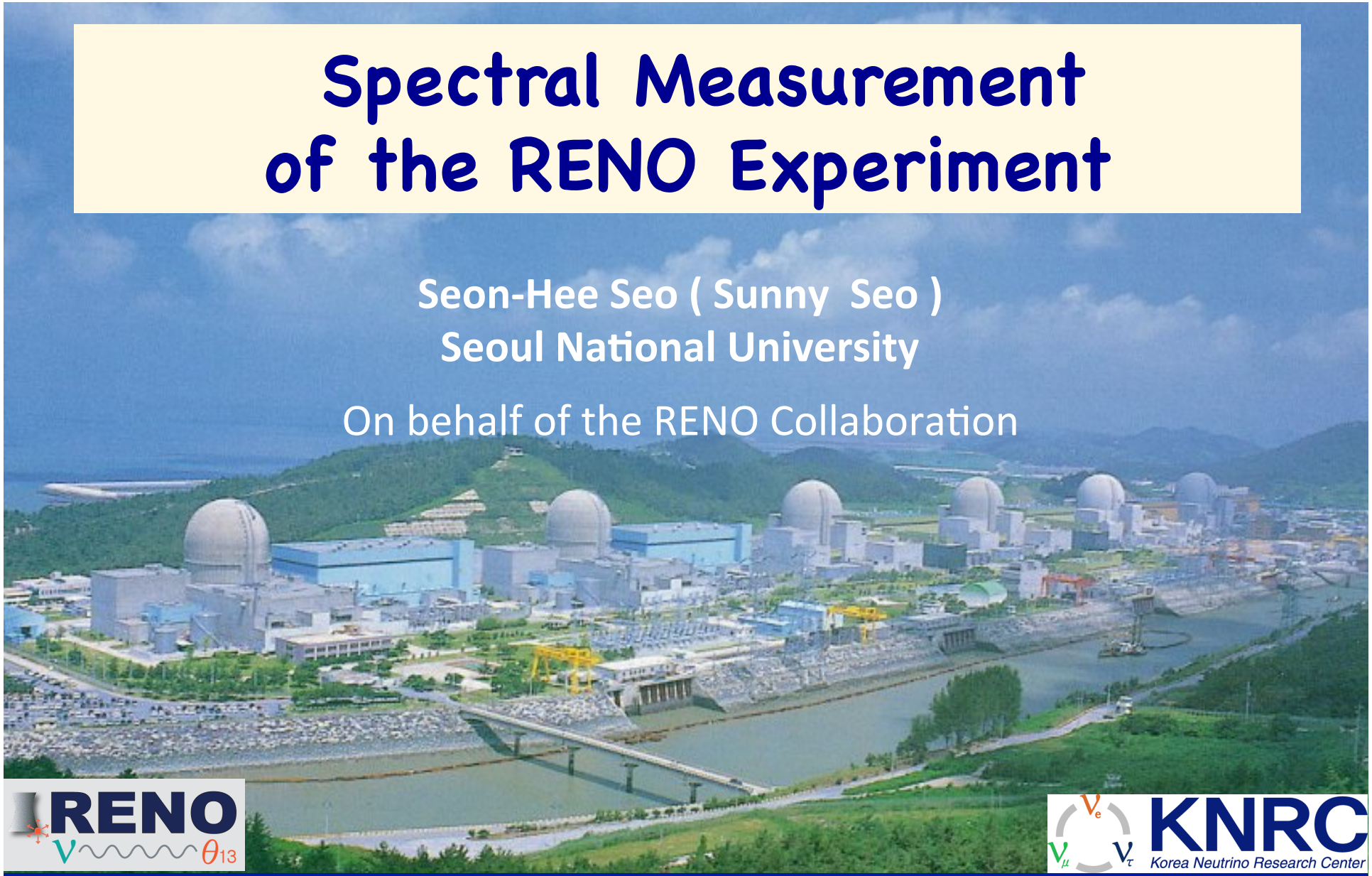
Spectral Measurement of the RENO Experiment

Seon-Hee Seo (Sunny Seo)
Seoul National University

On behalf of the RENO Collaboration



Jan. 21-23, 2015 **Nantes, France**

Status of Reactor Neutrino Flux Modeling Workshop

Quick Overview

- Results with ~800 days of data sample
- New measured value of θ_{13} from rate-only analysis (Neutrino 2014)
- Shape analysis in progress: finalizing the result now !
- Observation of a new reactor neutrino component at 5 MeV
- Results of reactor neutrinos with neutron capture on H (Significant improvement since Neutrino 2014)

RENO Collaboration

11 institutions and 40 physicists in Korea

- 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 since **Aug. 2011**

YongGwang (靈光) :

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

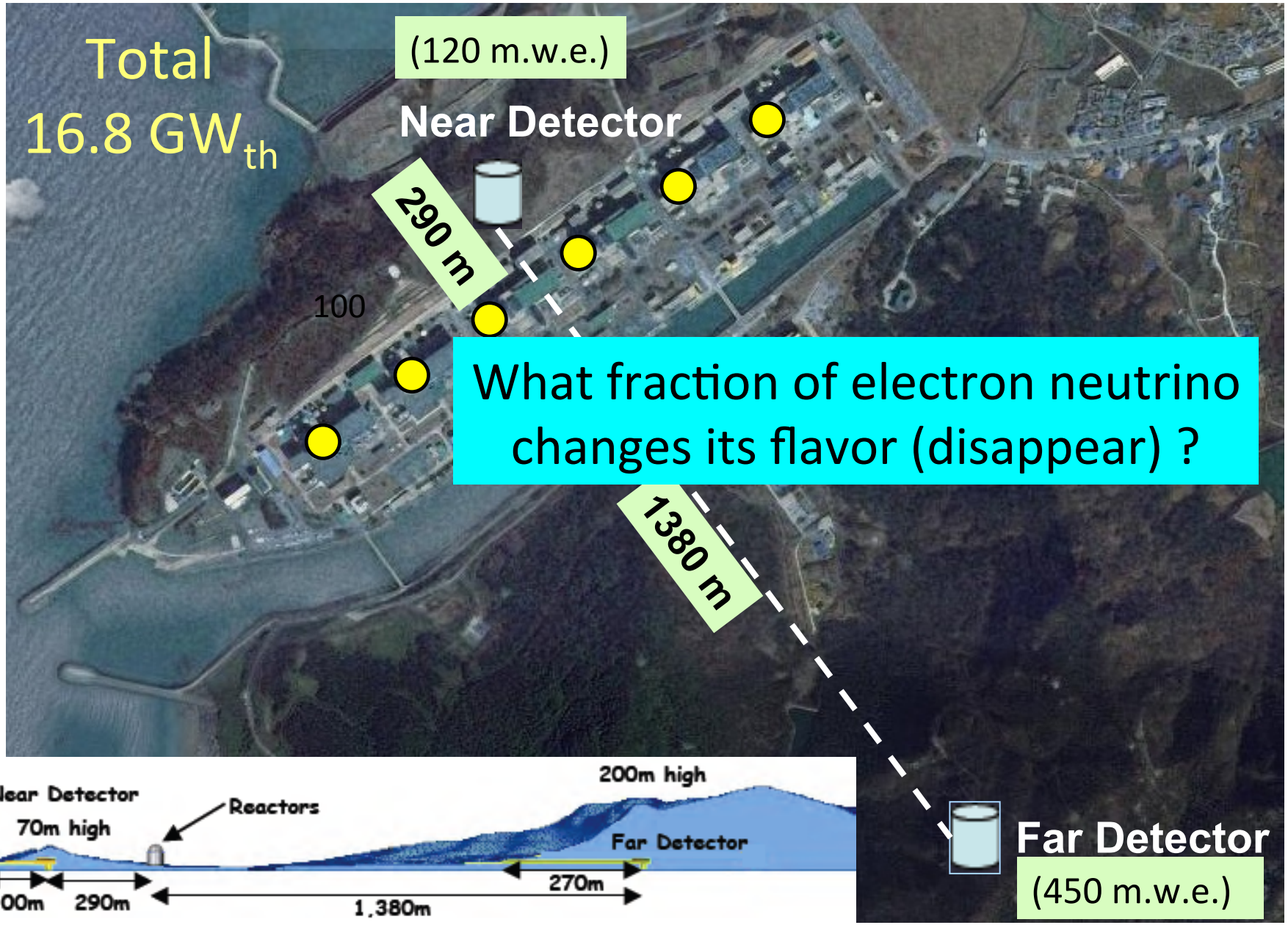
RENO Location: YongGwang S. Korea

YongGwang (靈光) :

means "Glorious light"

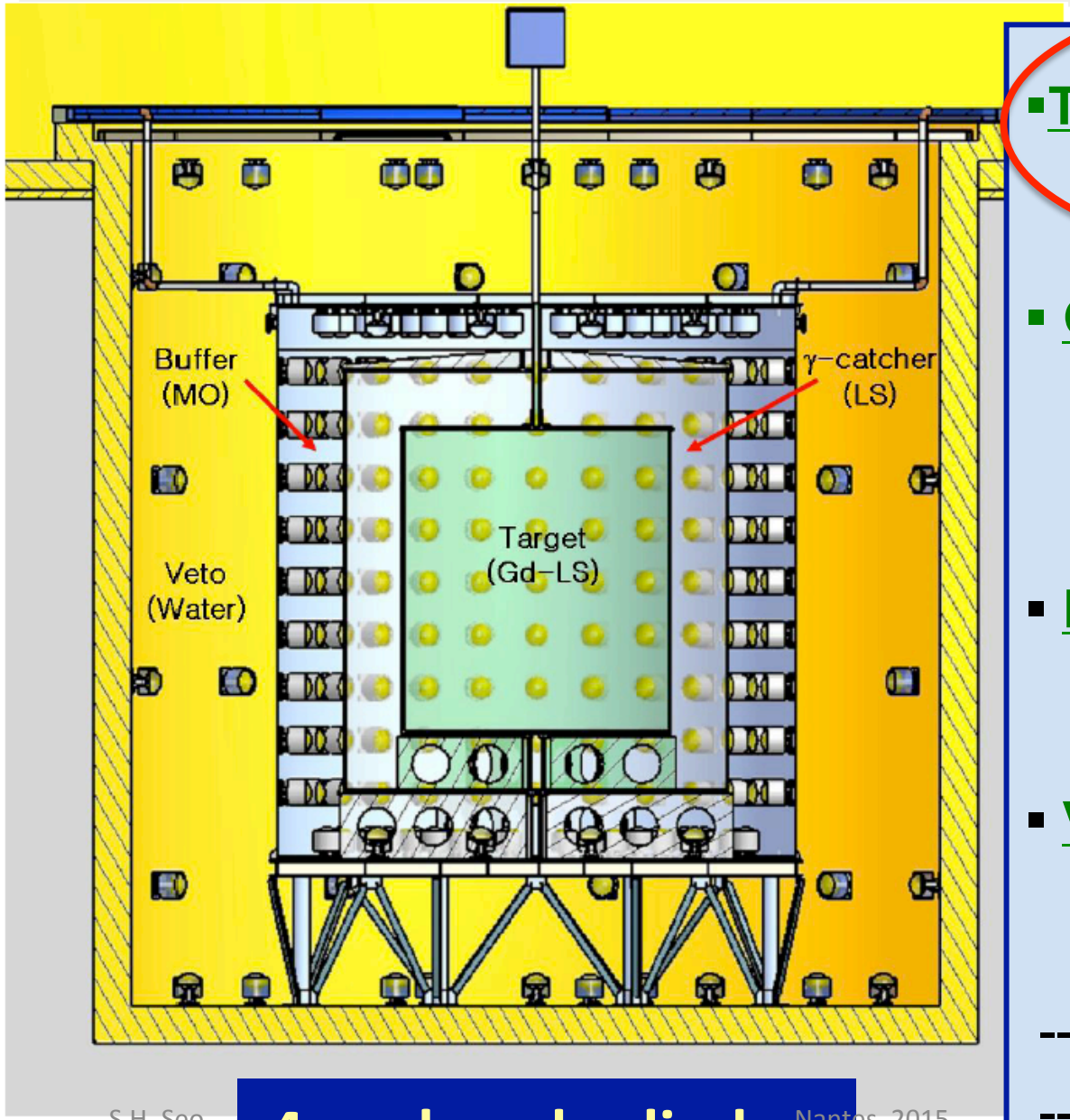
~ 4 hours driving distance from Seoul

RENO Experimental Setup



What fraction of electron neutrino changes its flavor (disappear) ?

The 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
  (R=2.7m, H=5.8m)
- **Veto :** 350 ton water
  (R=4.2m, H=8.8m)

-- 354 ID 10 " PMTs

-- 67 OD 10" PMTs

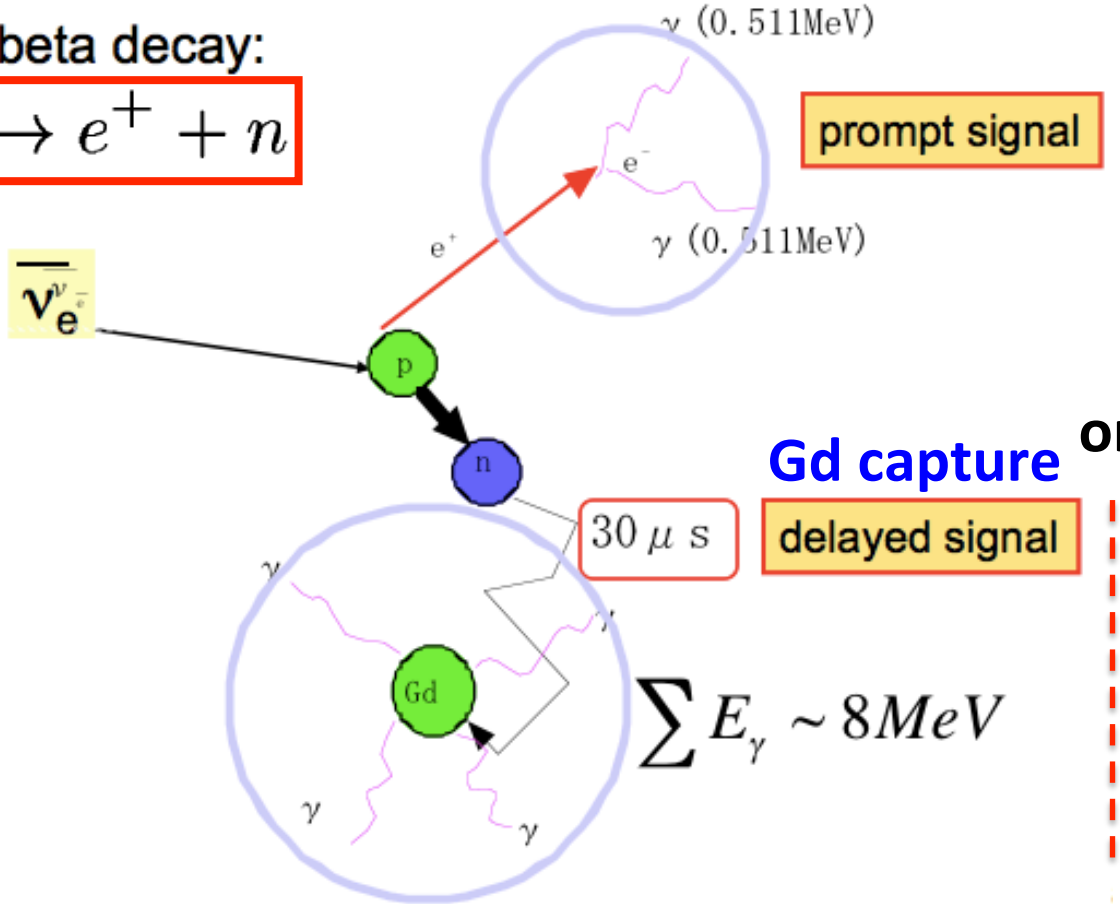
4 enclosed cylinders

The RENO Detector

Detection Principle of Reactor Neutrinos

Inverse beta decay:

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



Gd capture or **H capture**

Delayed signal

~200 μs

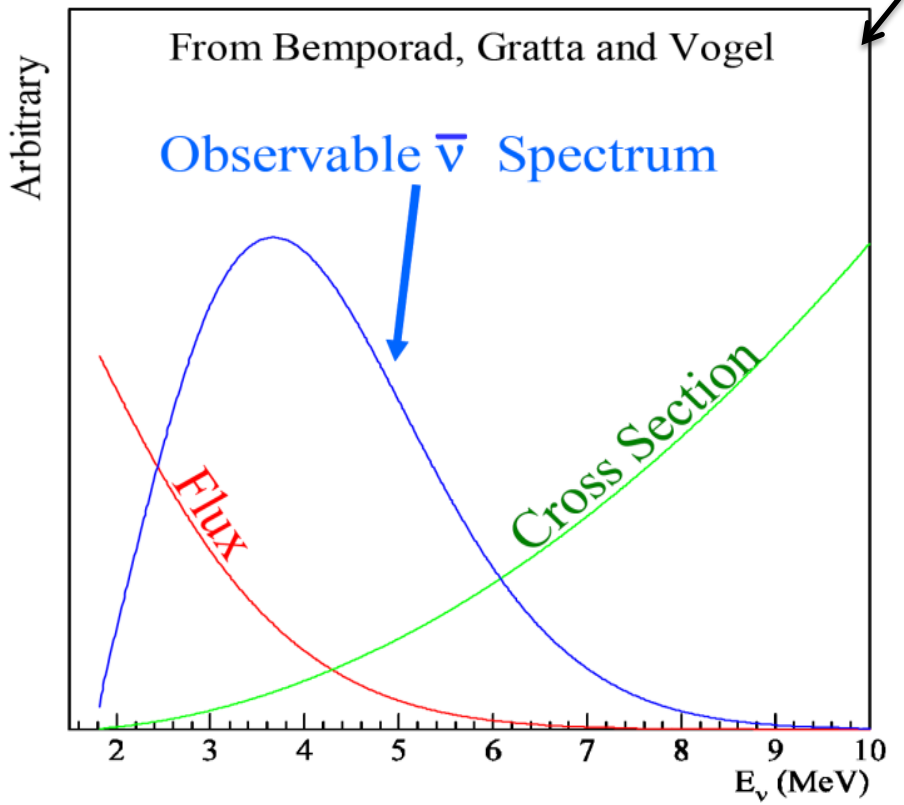
~ 2.2 MeV

- 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** or **H**

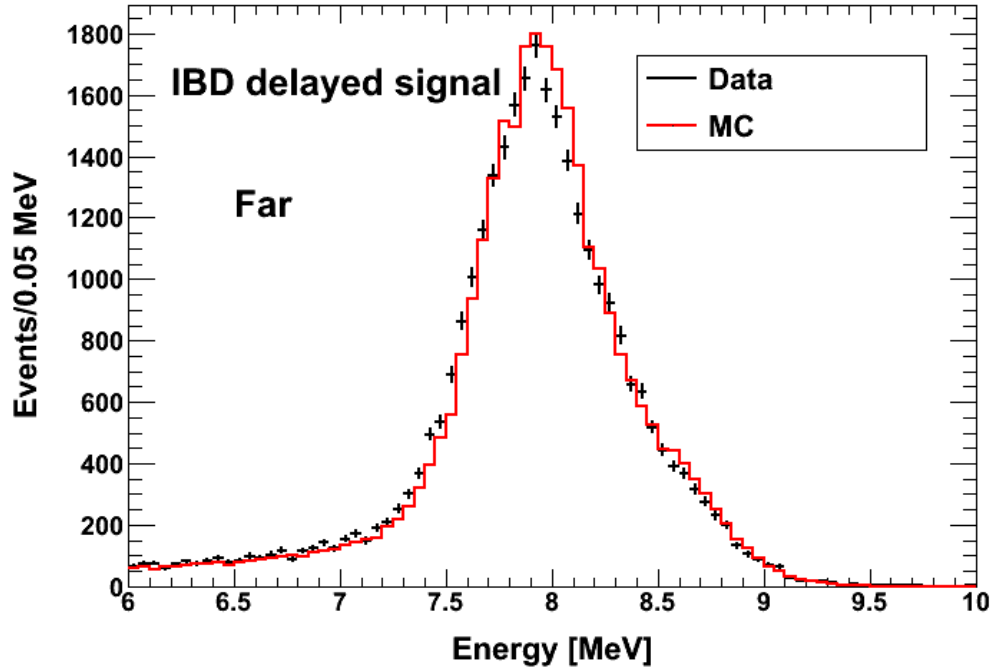
~30 μs or ~200 μs

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

Prompt signal



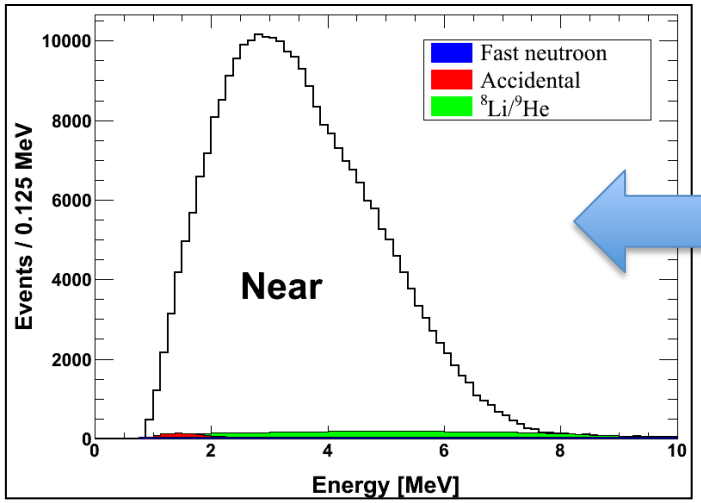
delayed signal



$$E_{\bar{\nu}} \cong T_{e^+} + \underbrace{T_n}_{10\text{-}40\ keV} + \underbrace{(M_n - M_p) + m_{e^+}}_{1.8\ MeV}$$

Signal: IBD Pair

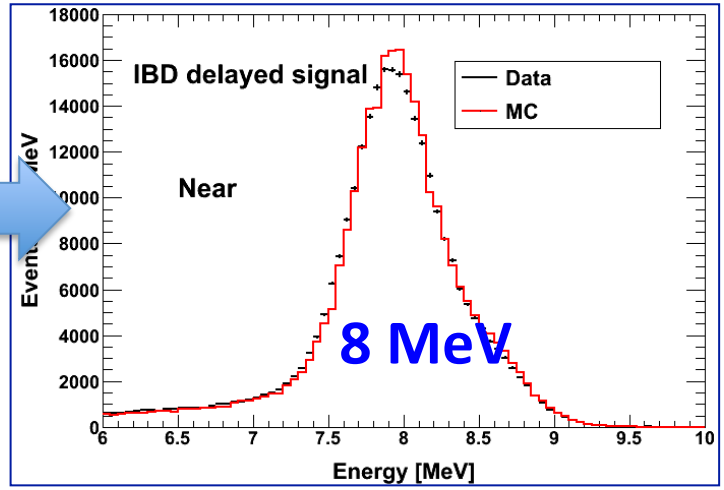
Prompt signal (S1)

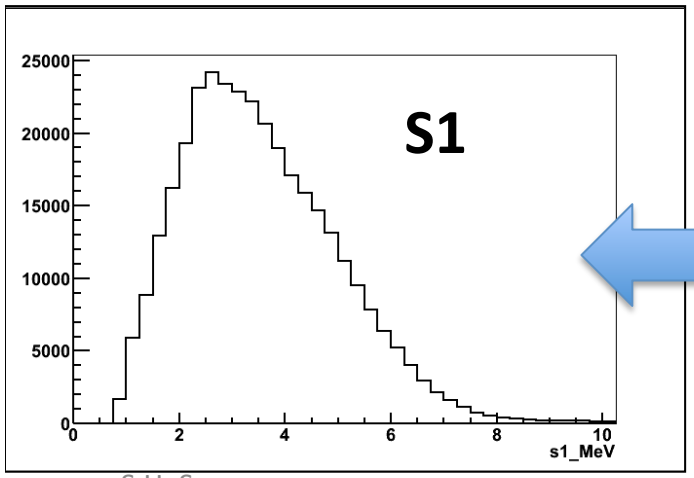


n-Gd IBD

~30 μs

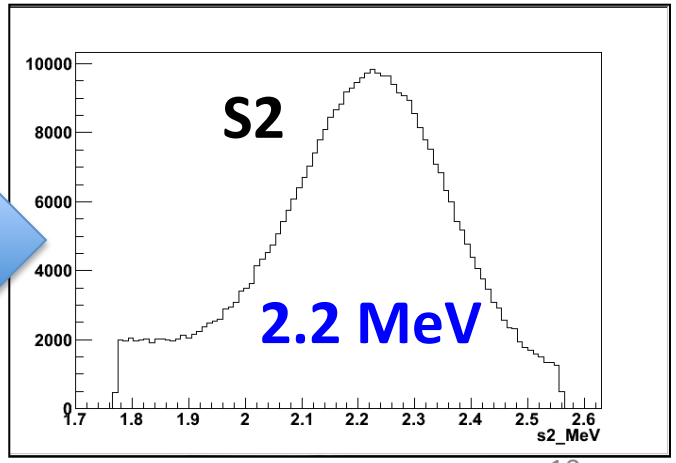
Delayed signal (S2)





n-H IBD

~200 μs



Suppresses background a lot !

RENO Status

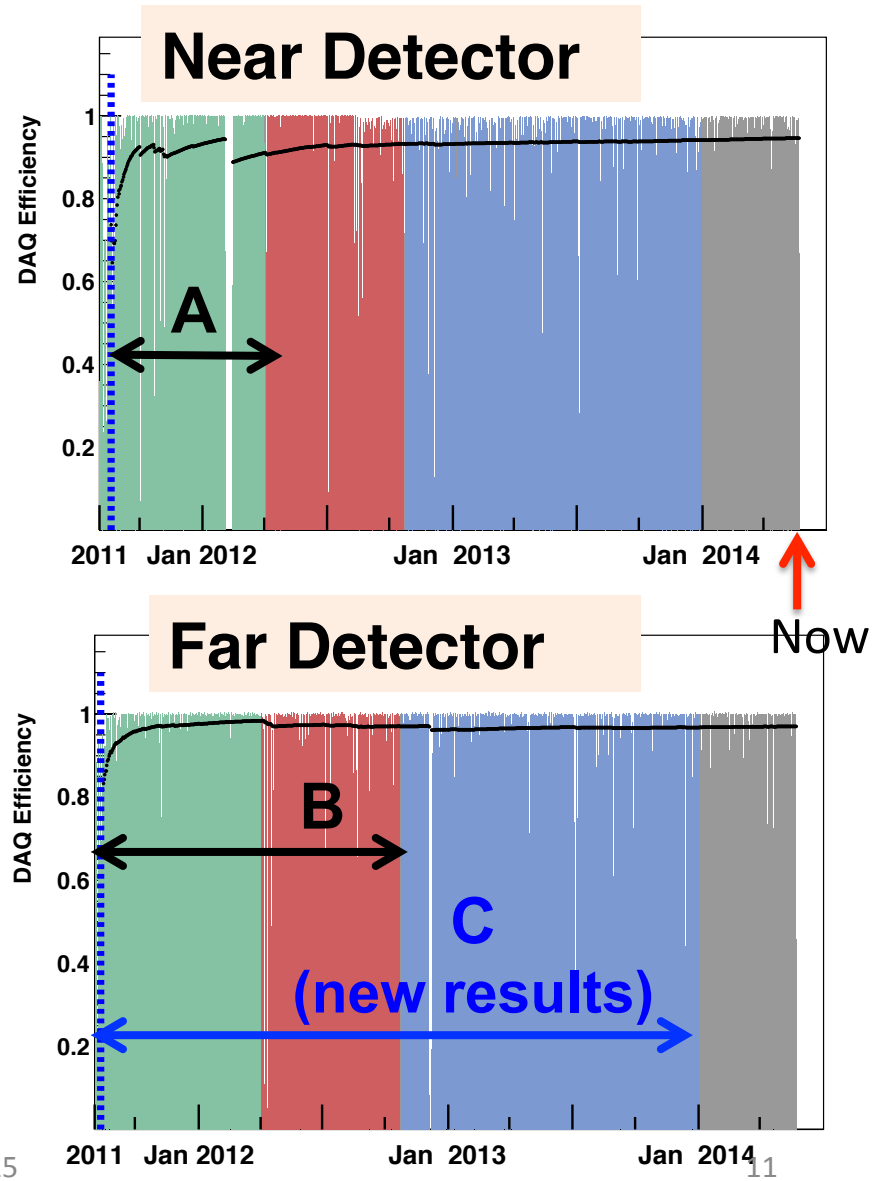
- Data taking began on Aug. 1, 2011 with both near and far detectors.
  (DAQ efficiency : ~95%)

- **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 **θ_{13} result Shape +rate analysis** (in progress)
  [11 Aug, 2011~31 Dec, 2013]

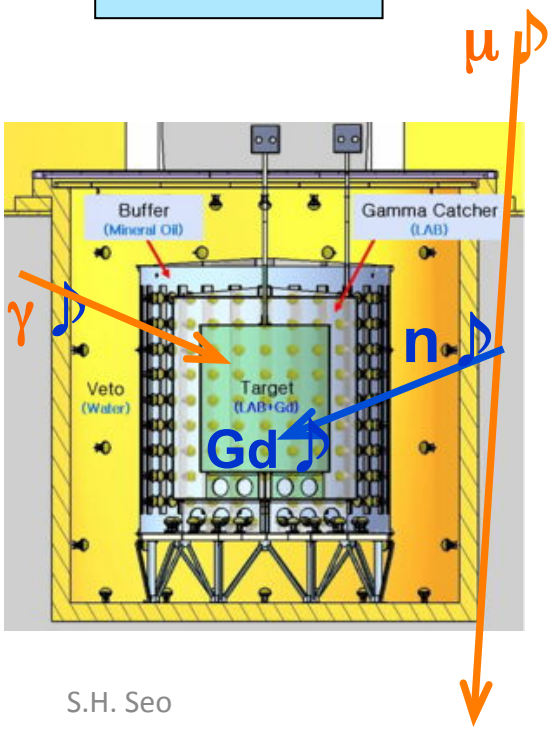
- Total observed reactor neutrino events as of today : **~ 1.5M** (Near), **~ 0.15M** (Far)
  → Absolute reactor neutrino flux measurement in progress
  [reactor anomaly & sterile neutrinos]



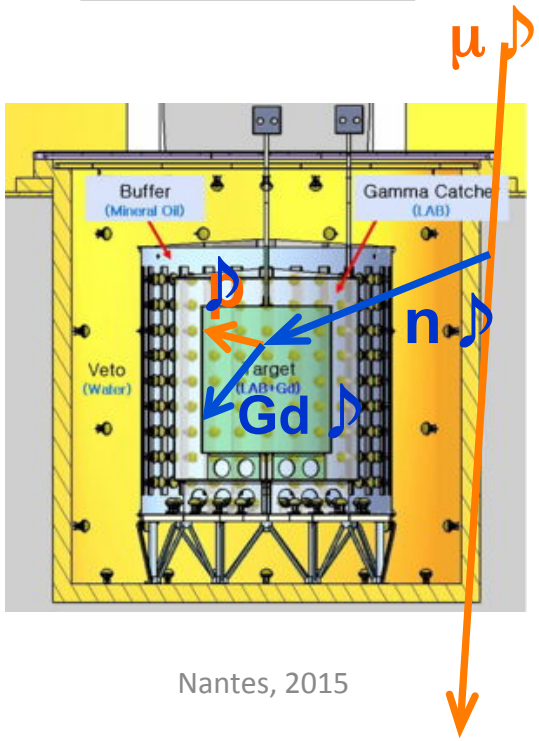
Backgrounds

- 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

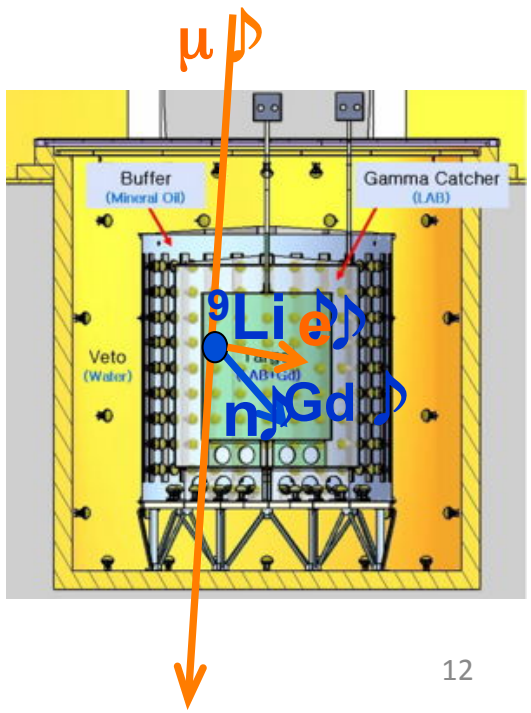
Accidentals



Fast neutrons



^{9}Li/^{8}He β-n followers



Backgrounds

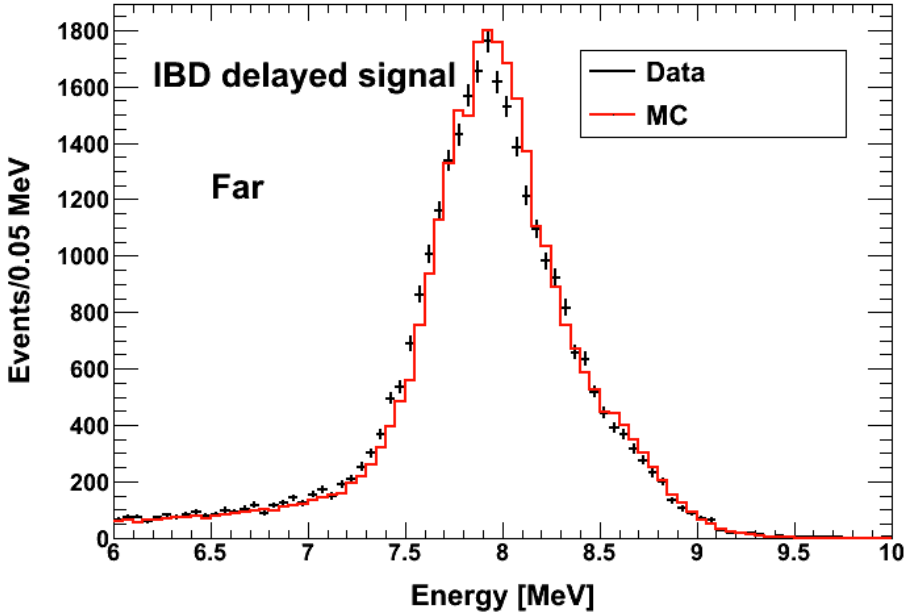
- After Neutrino 2014, Q_{max}/Q_{tot} cut : 0.03 → 0.04

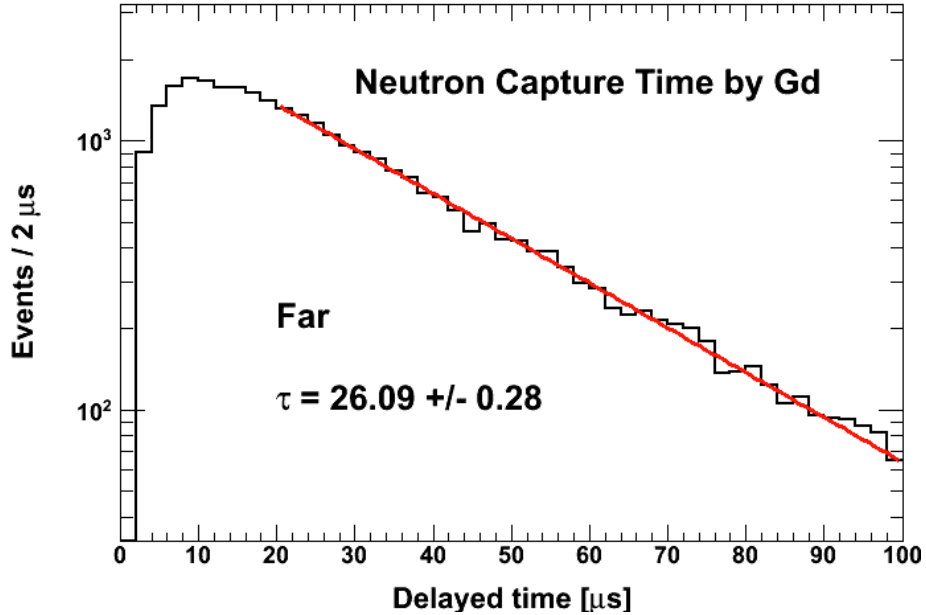
  - allow more accidentals to increase acceptance of signal and minimize any bias to the spectral shape ♪

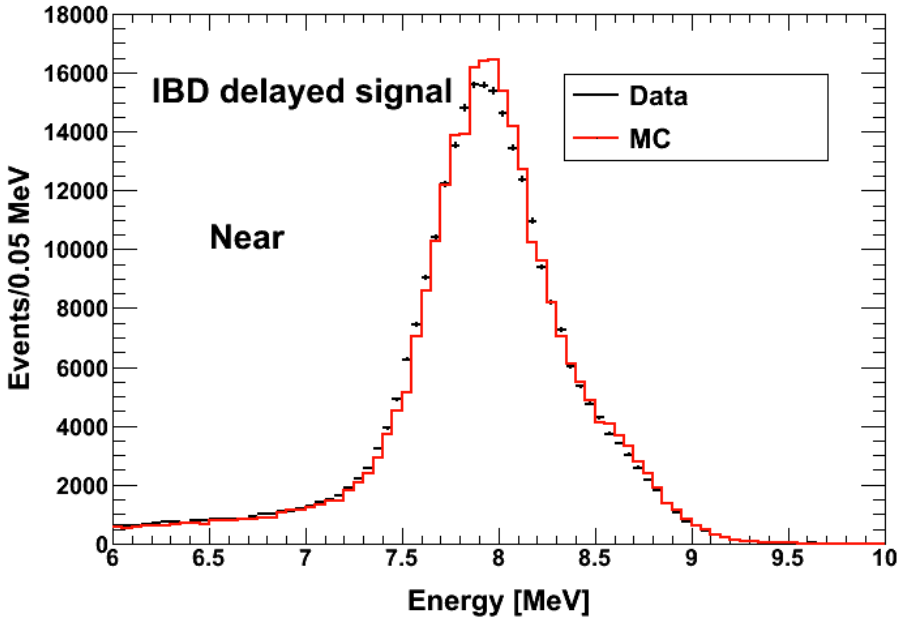
Backgrounds (/day)	Near	Far
Accidentals	1.82±0.11 → **4.45±0.01**	0.36±0.01 → **0.89±0.01**
Fast Neutron	2.67±0.08 → **2.21±0.03**	0.56±0.02 → **0.49±0.01**
Li/He	9.18±0.67 → **11.64±1.04**	2.07±0.21 → **2.12±0.22**
Cf contamination	0.45±0.07 → **0.31±0.05**	3.17±0.28 → **2.01±0.26**
Total	14.18±0.69 → **18.61±1.04**	6.17±0.35 → **5.49±0.34**

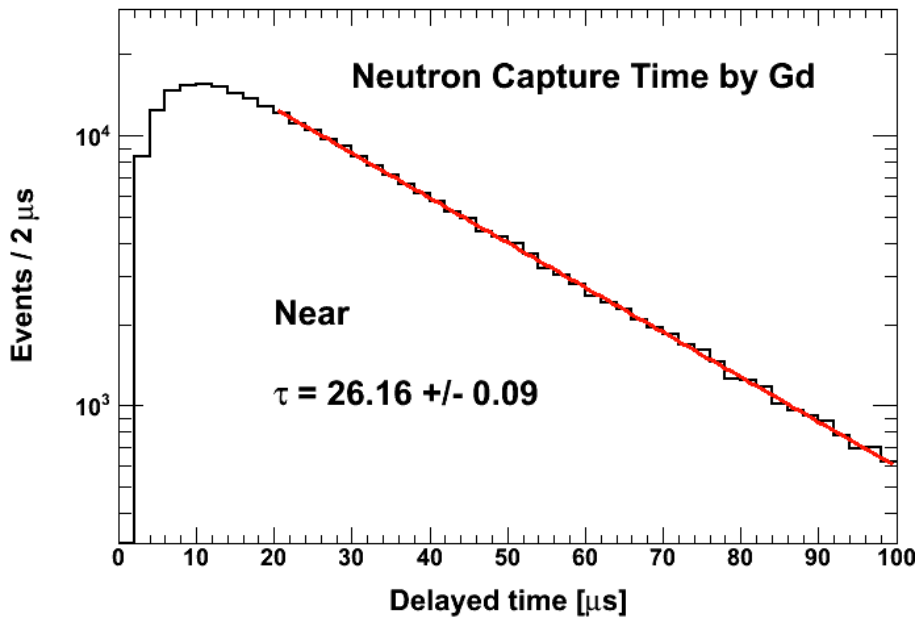
Fraction to total IBD: 3.1 % (Near) 8.1% (Far)

Neutron Capture by Gd

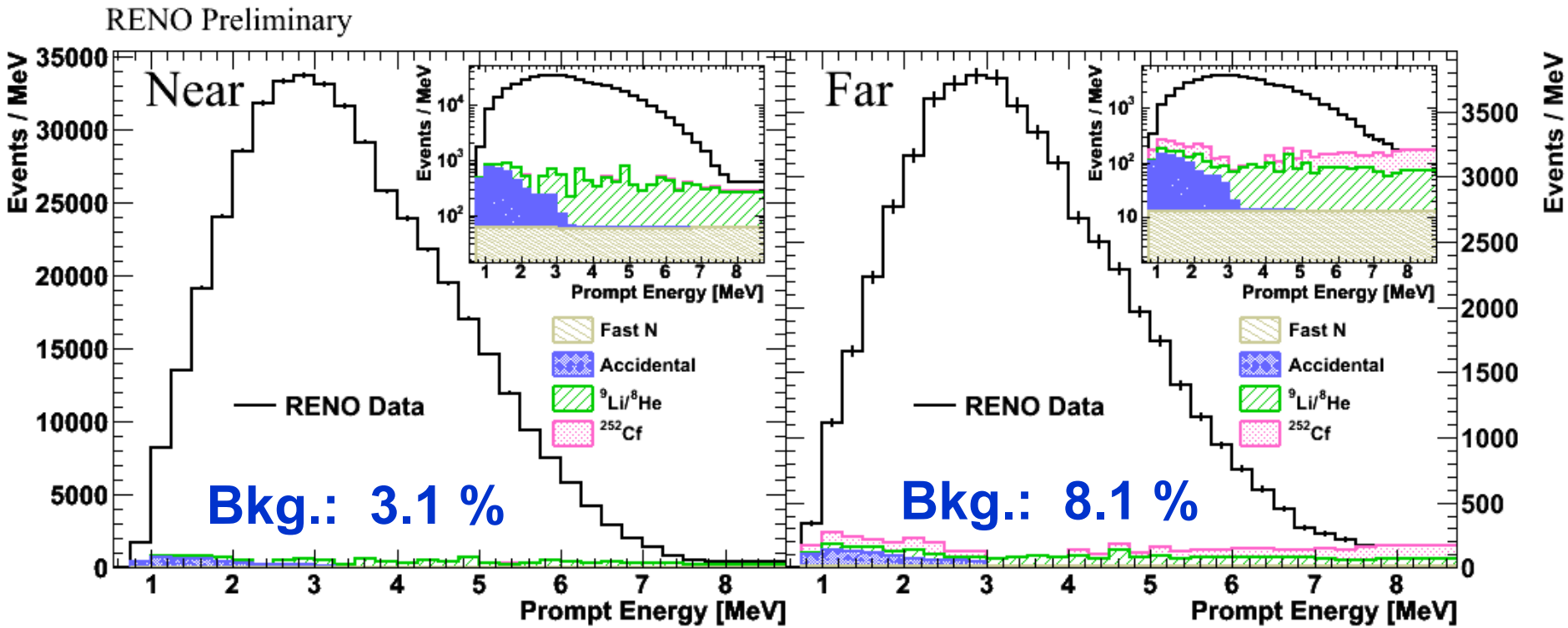








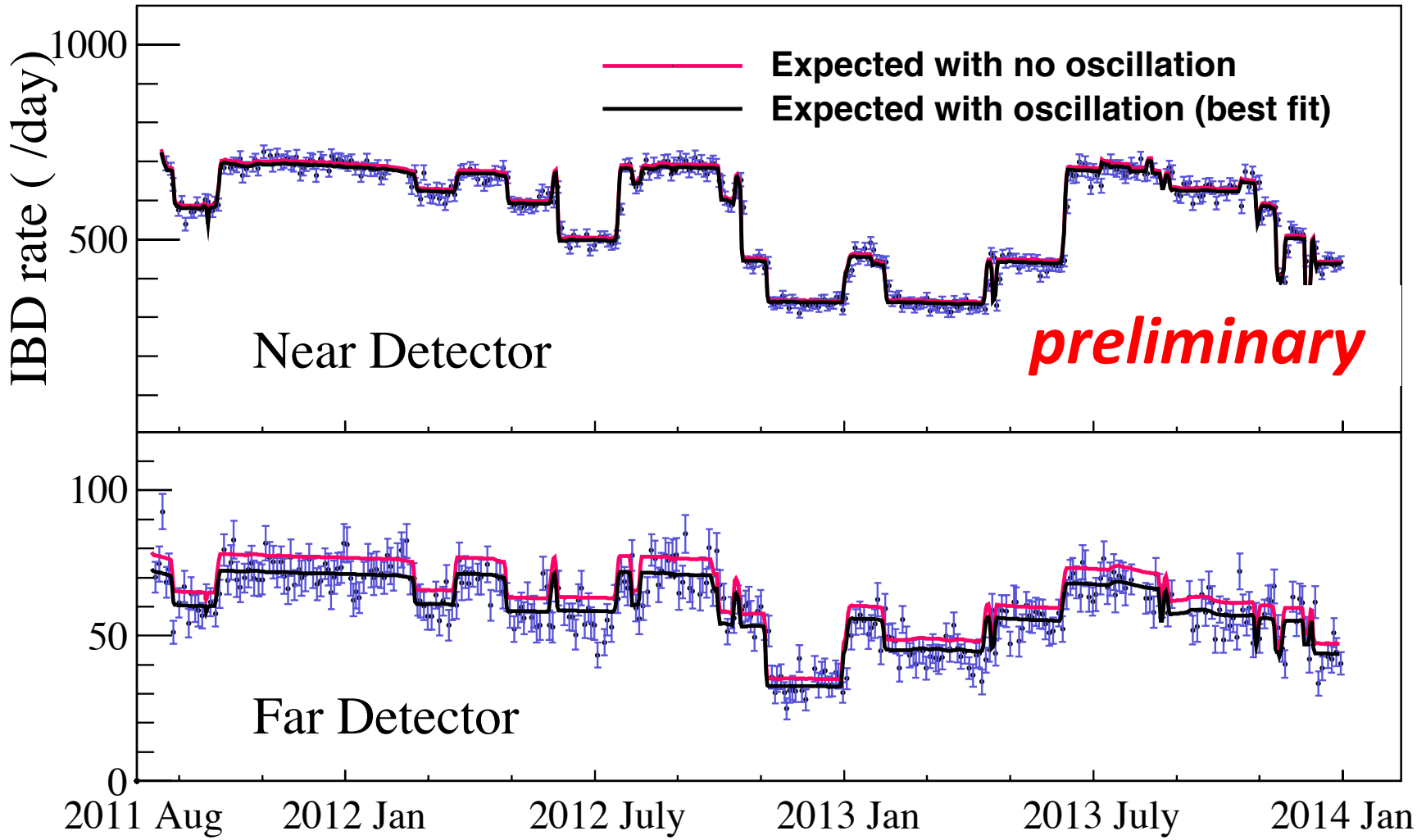
Measured Spectra of IBD Prompt Signal



Near Live time = 761.11 days
# of IBD candidate = 457,176
# of background = 14,165 (3.1 %)

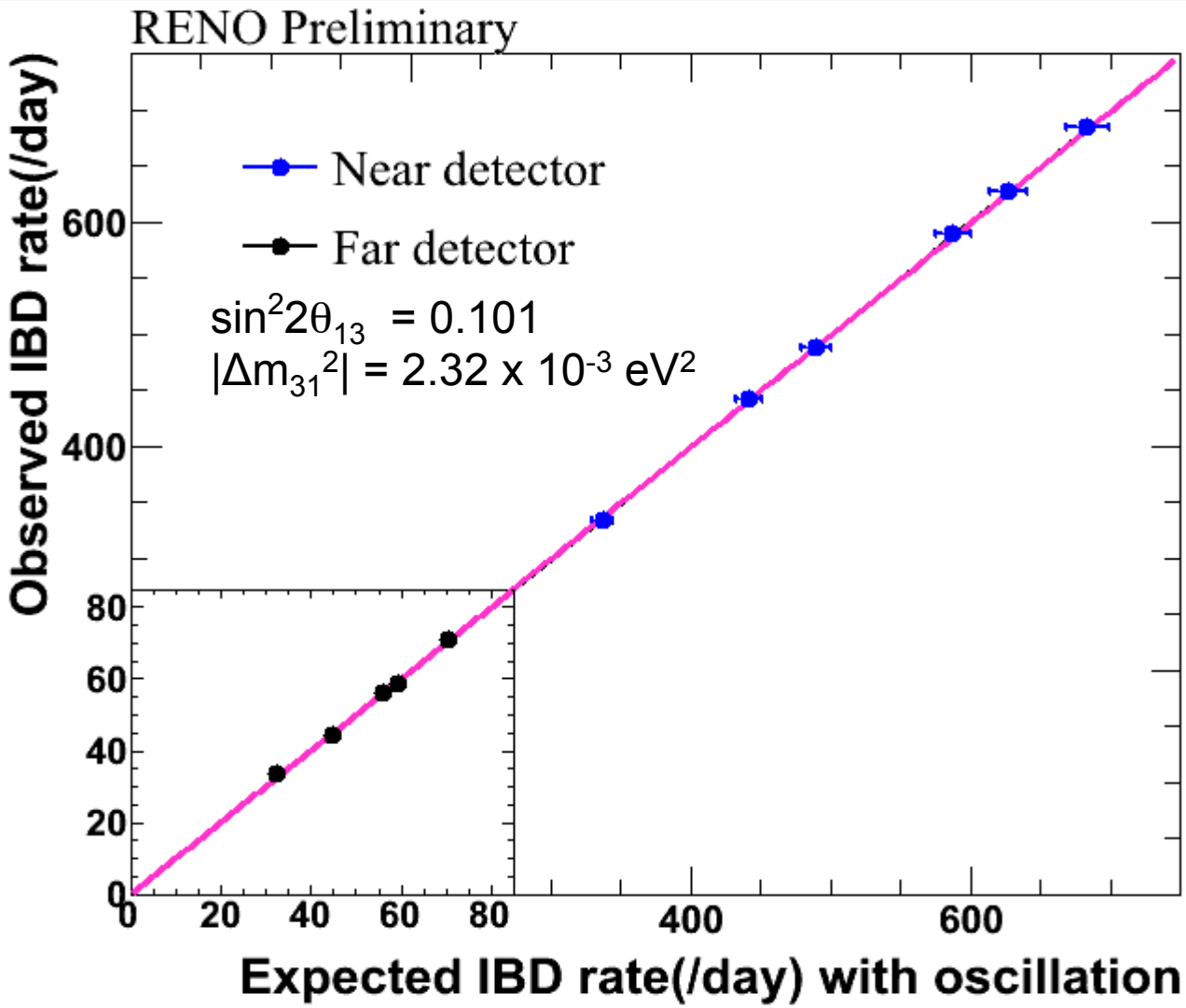
Far Live time = 794.72 days
# of IBD candidate = 53,632
# of background = 4366 (8.1 %)

Observed Daily Averaged IBD Rate



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

Observed vs. Expected IBD Rates

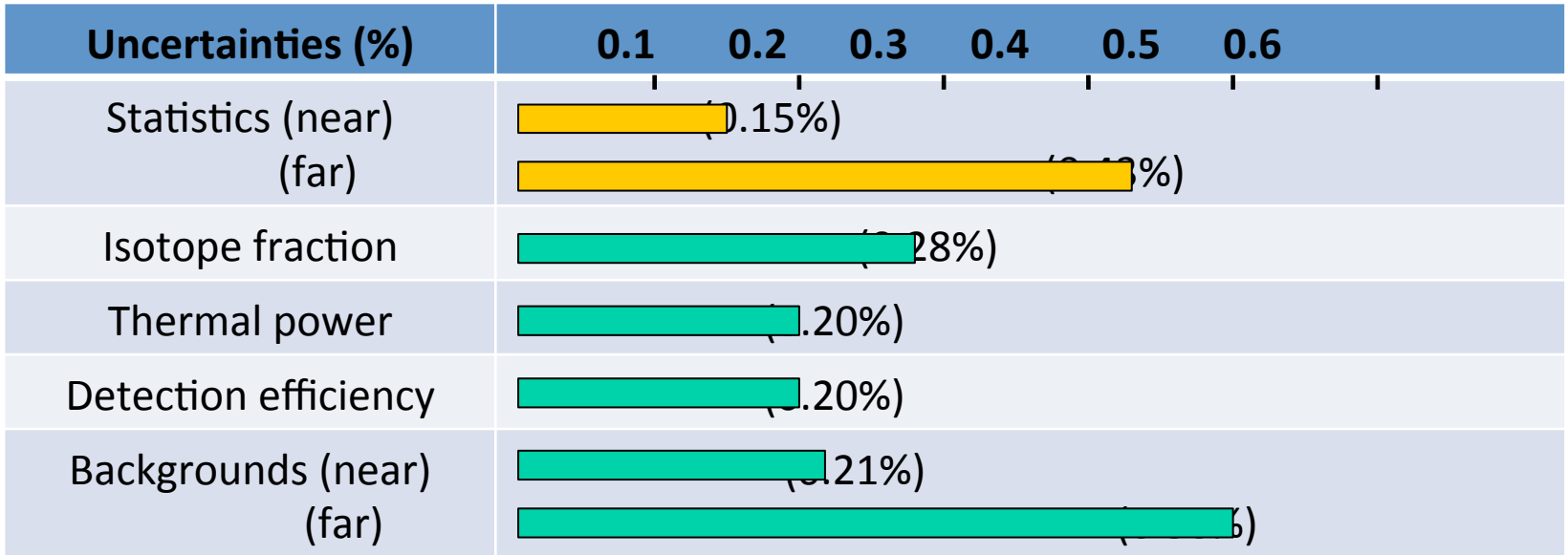


- Good agreement between observed rate & prediction
- Indication of correct background subtraction

New θ_{13} Measurement by Rate-only Analysis

(Preliminary)

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

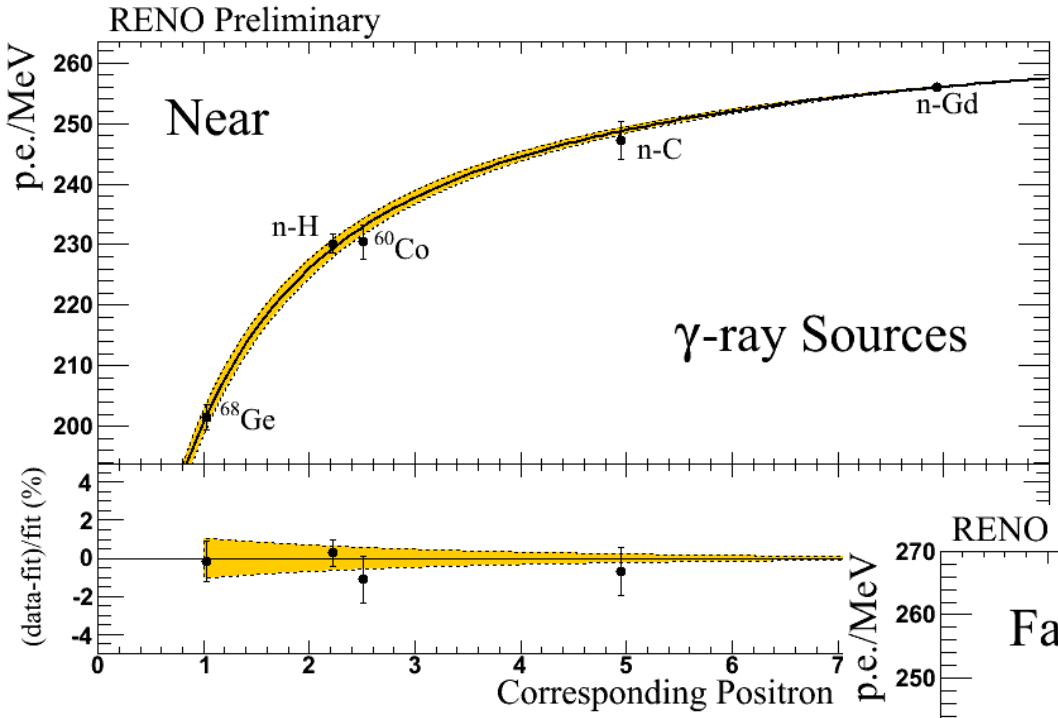


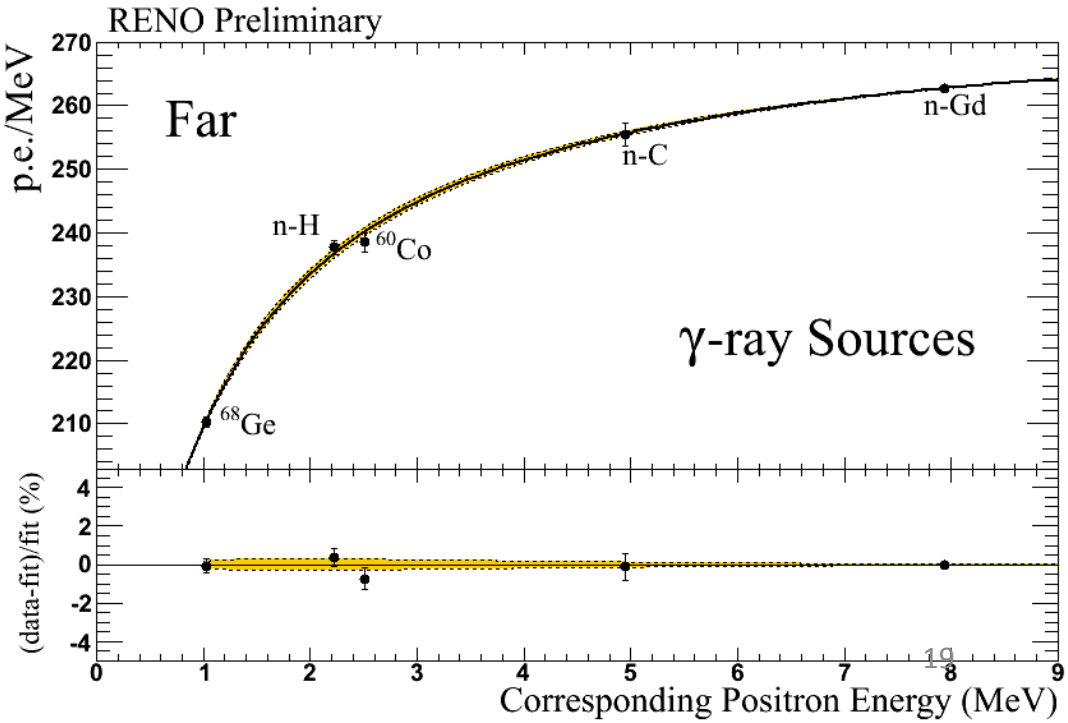
$\sin^2 2\theta_{13} = 0.113 \pm 0.023$ 4.9 σ (Neutrino 2012)

→ 0.100 ± 0.016 6.3 σ (TAUP/WIN 2013)

→ 0.101 ± 0.013 7.8 σ (Neutrino 2014)

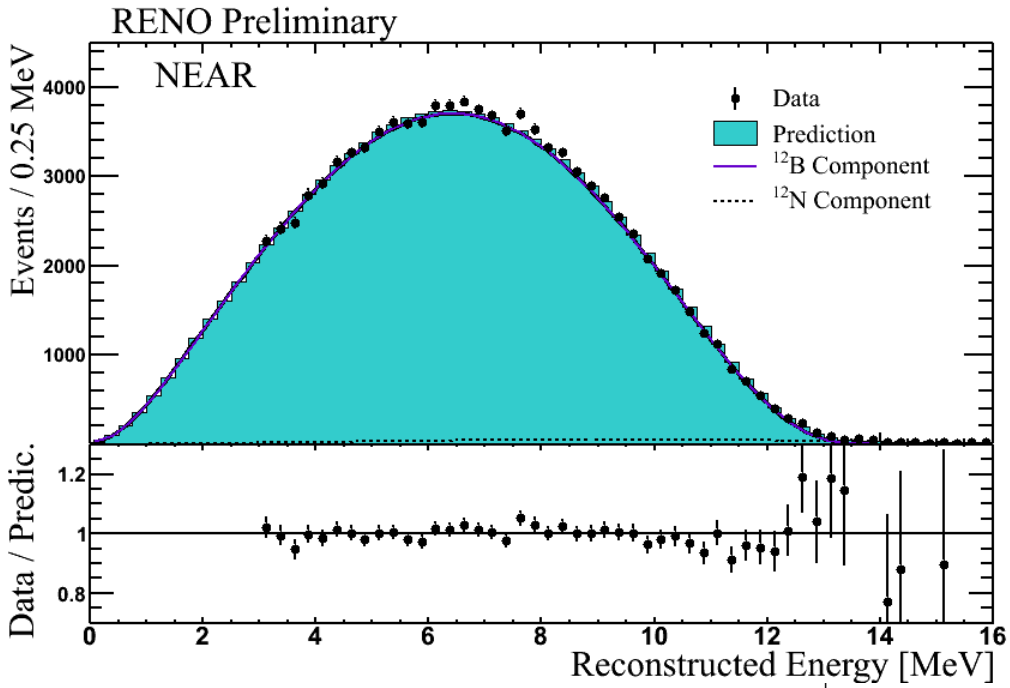
Energy Calibration from γ-ray Sources

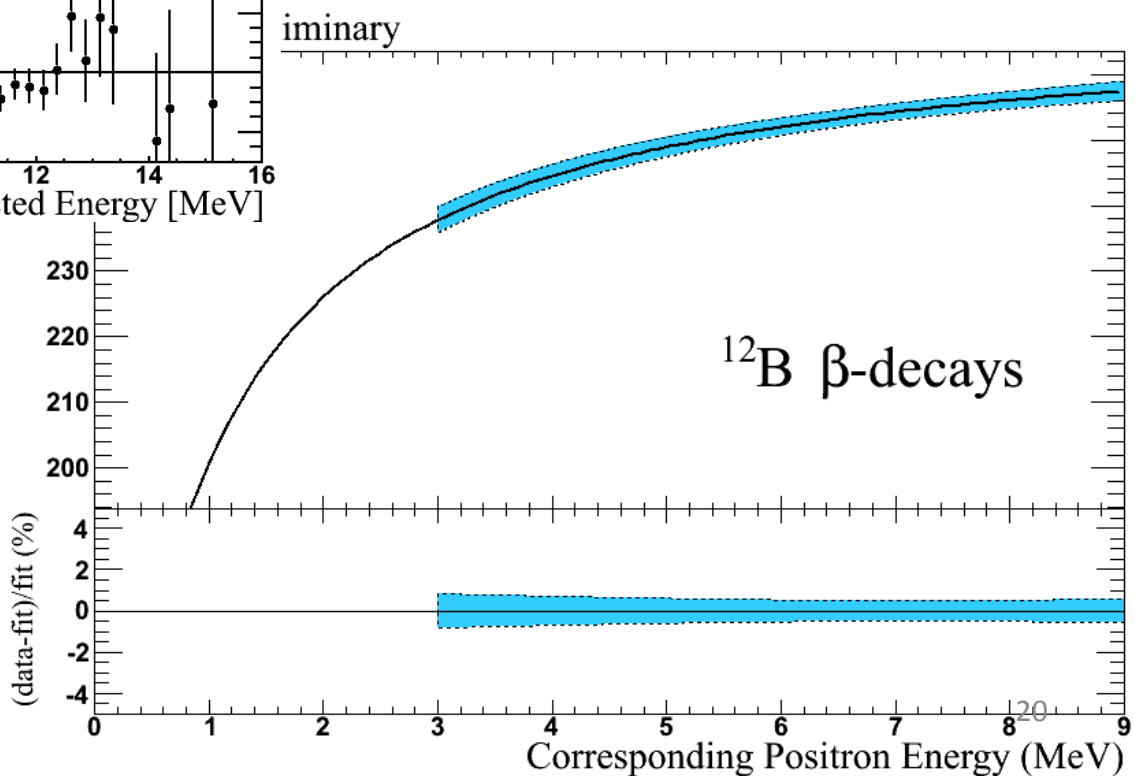




Energy Calibration from ^{12}B β-decays

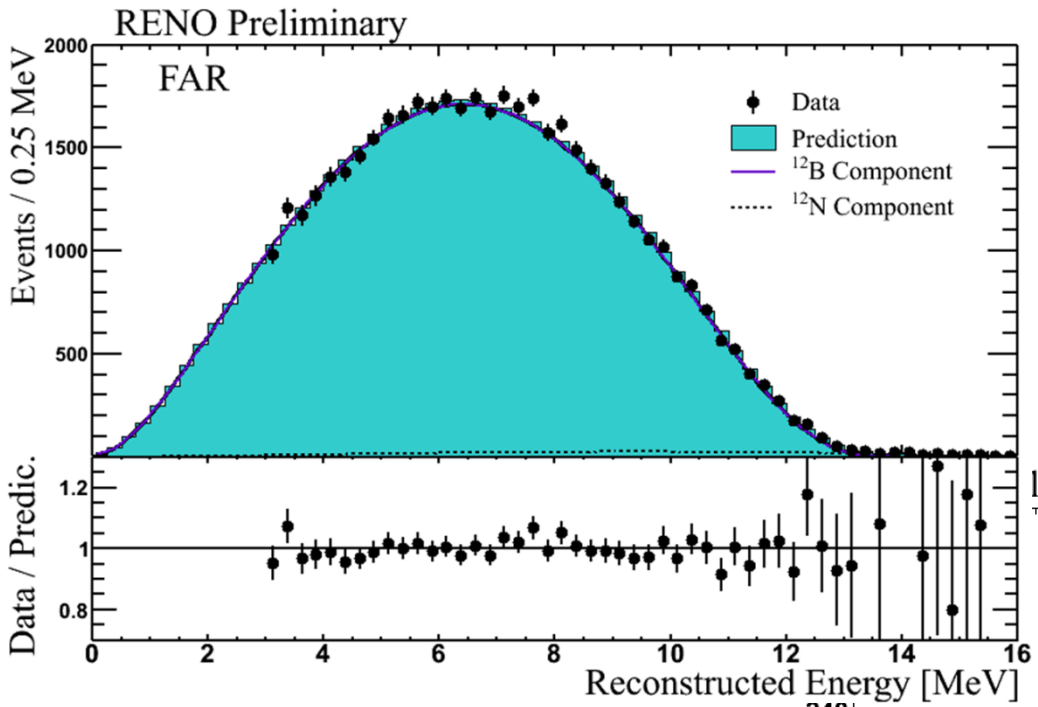
Near detector

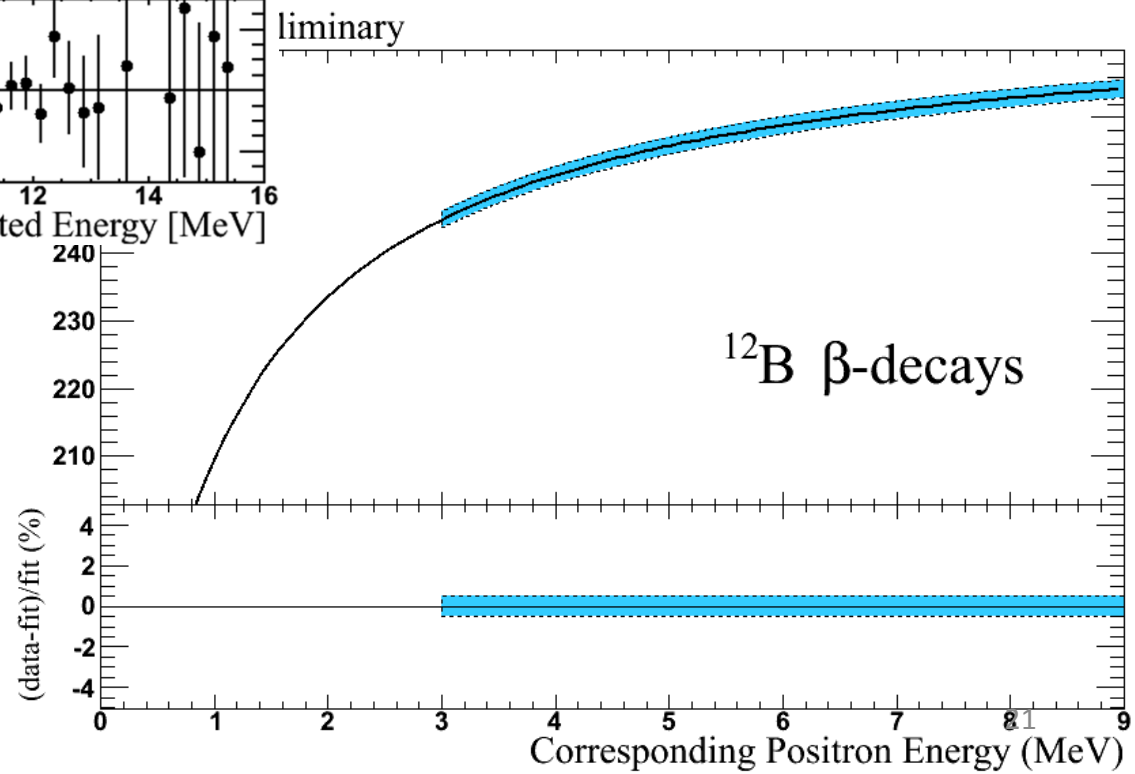




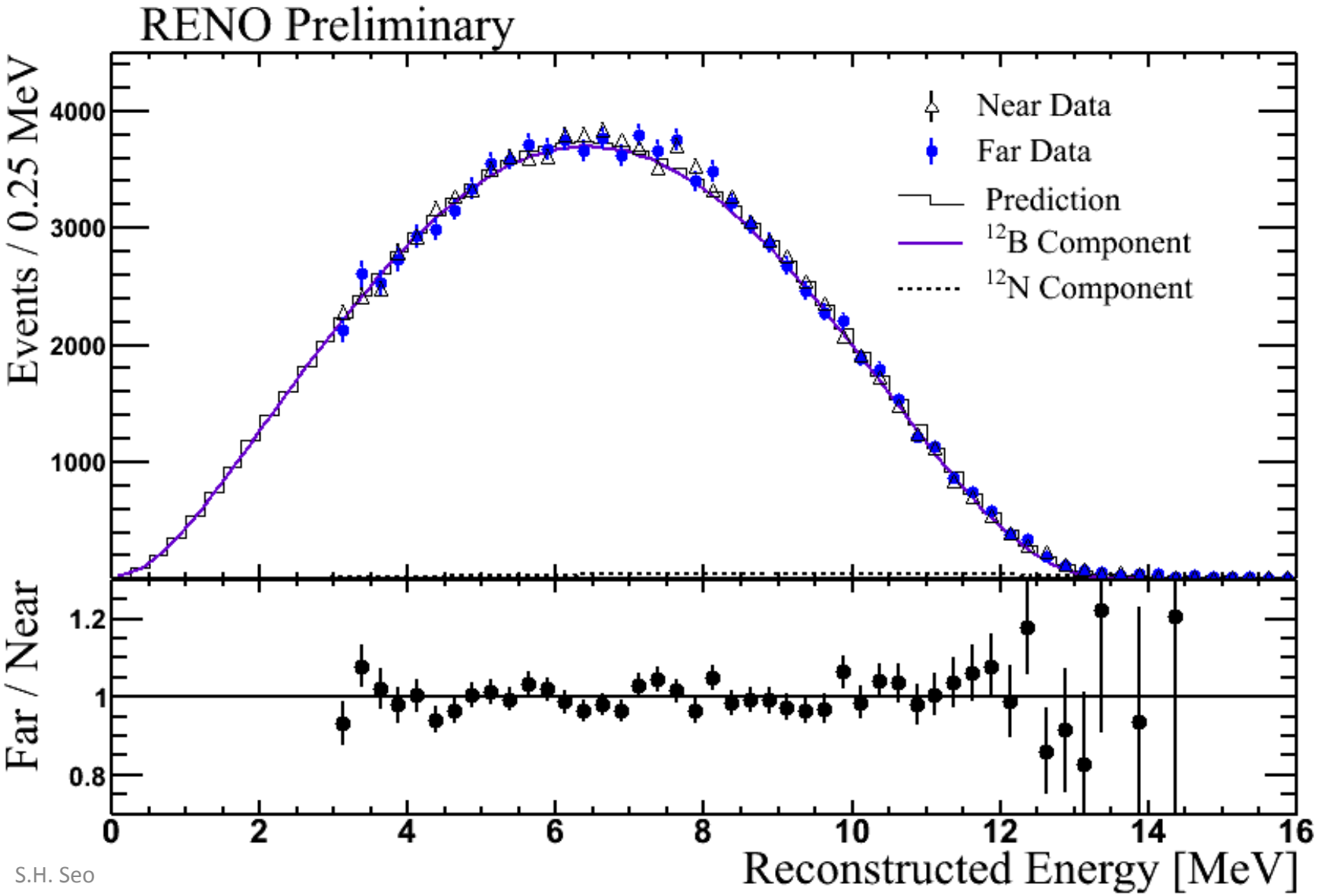
Energy Calibration from ^{12}B β-decays

Far detector

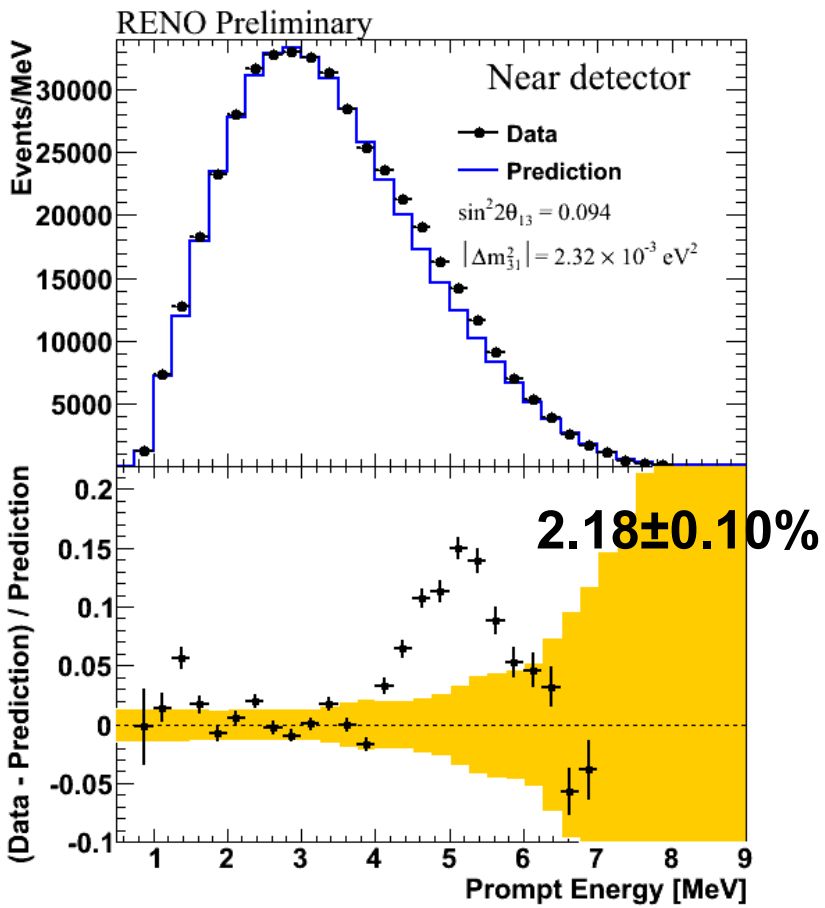


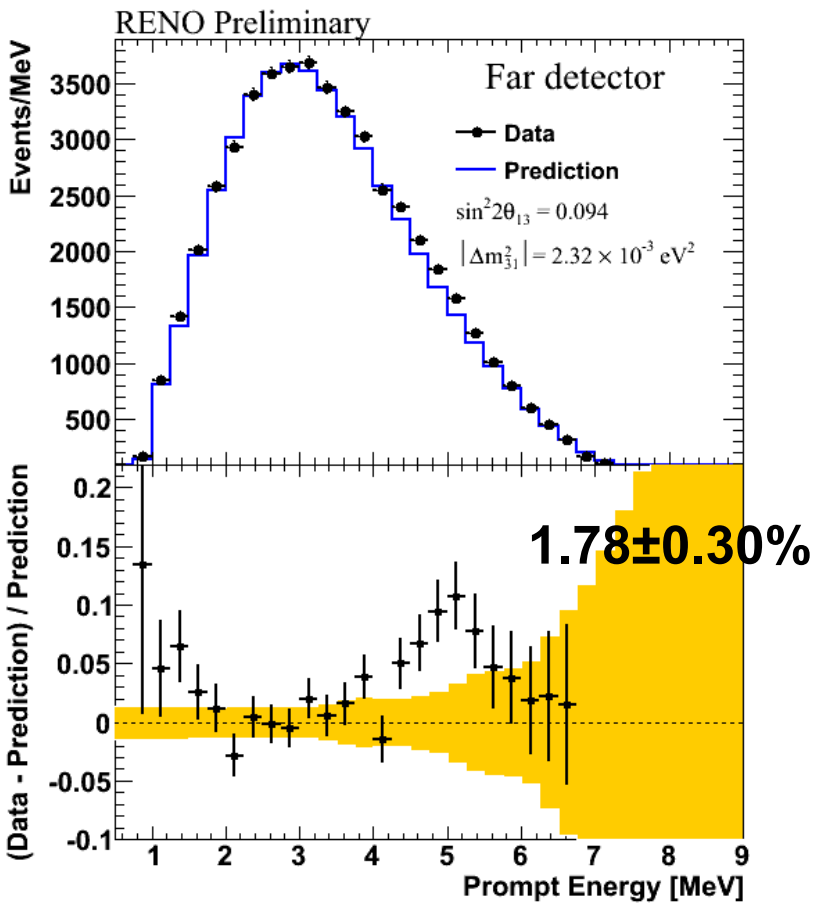


^{12}B Energy Spectrum (Near & Far)



Observation of a New Reactor Neutrino Component at 5 MeV

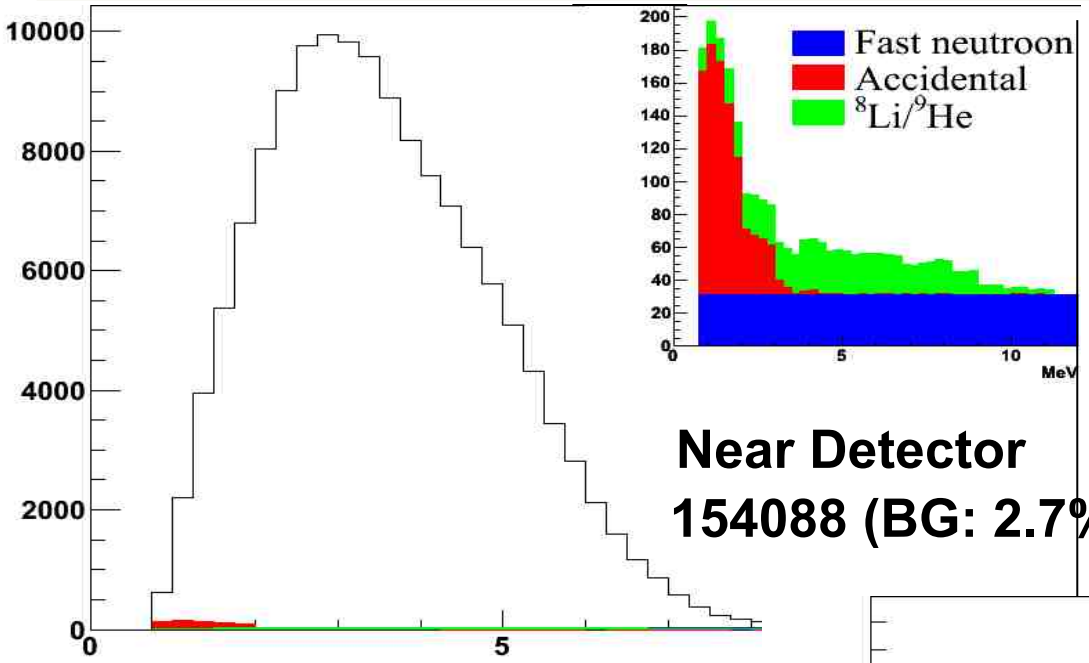




<u>Fraction of 5 MeV excess (%) to expected flux</u> **[2011 Huber+Mueller]**

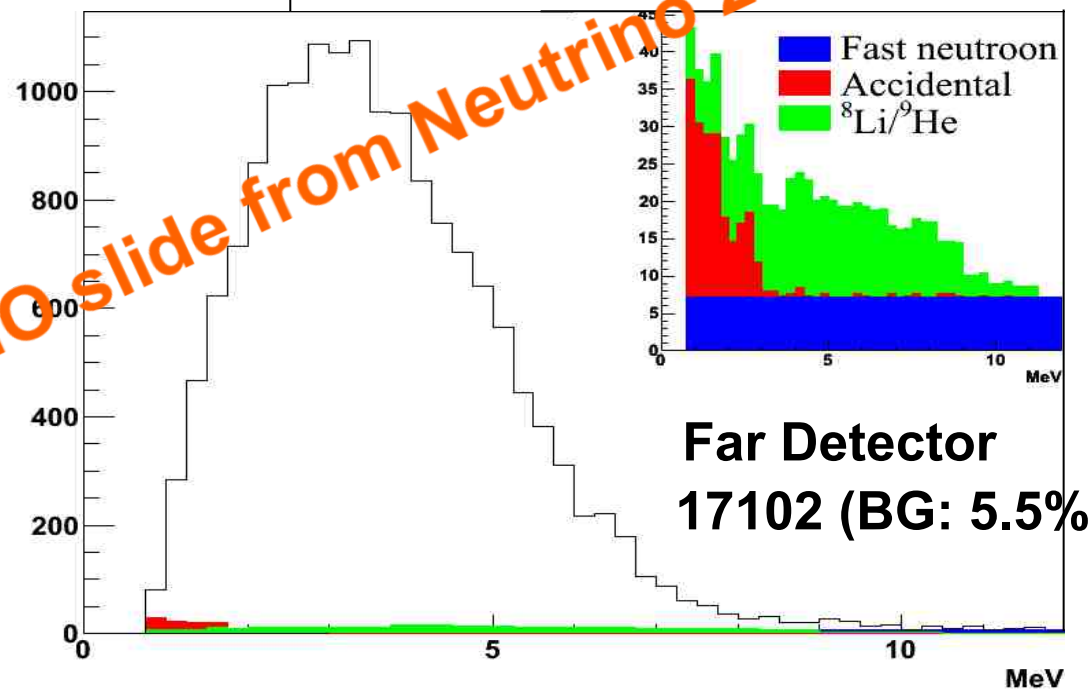
- Near : 2.18 ± 0.40 (experimental) ± 0.49 (expected shape error)
- Far : 1.78 ± 0.71 (experimental) ± 0.49 (expected shape error)

Observed Spectra of IBD Prompt Signal



Near Detector
154088 (BG: 2.7%)

- The expected IBD prompt spectra from the RENO MC do not reproduce the shape in the energy region of 4~6 MeV.....

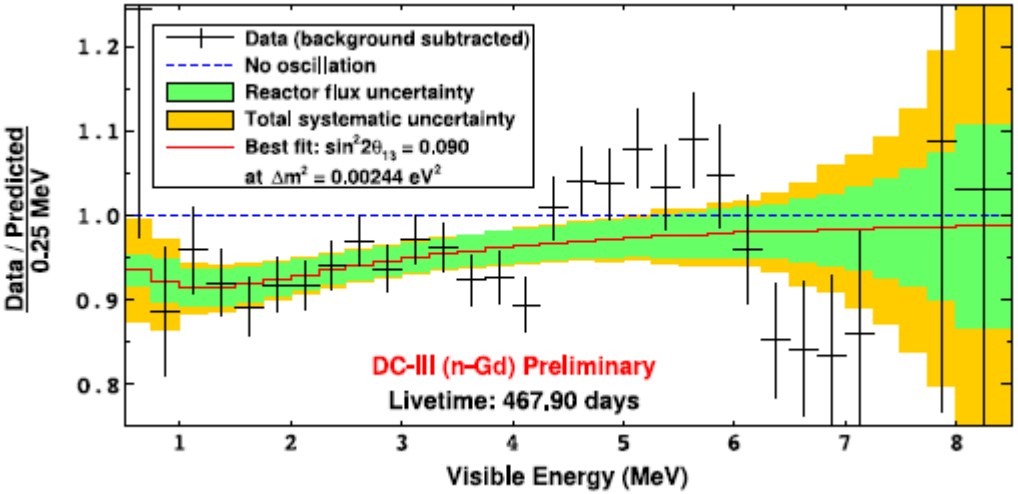


Far Detector
17102 (BG: 5.5%)

- Need more detailed energy calibration between 3 and 8 MeV using new radioactive sources.
- Any new components of background sources?
- Is the prediction of reactor neutrino spectra correct??

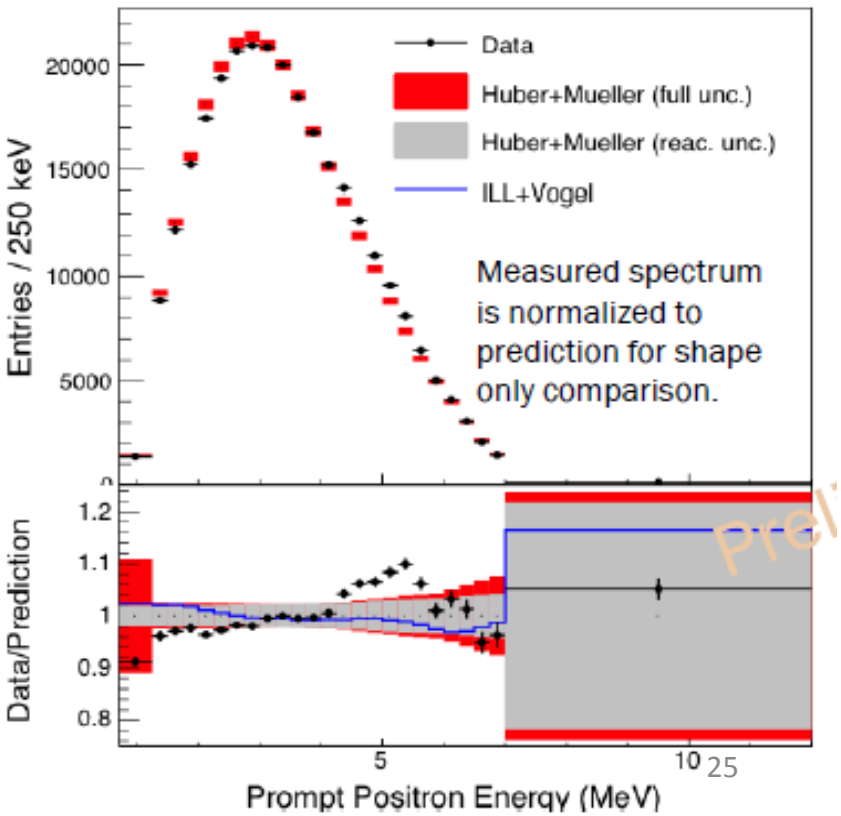
RENO slide from Neutrino 2012, Kyoto

The 5 MeV Excess Seen at Double-Chooz and Daya Bay

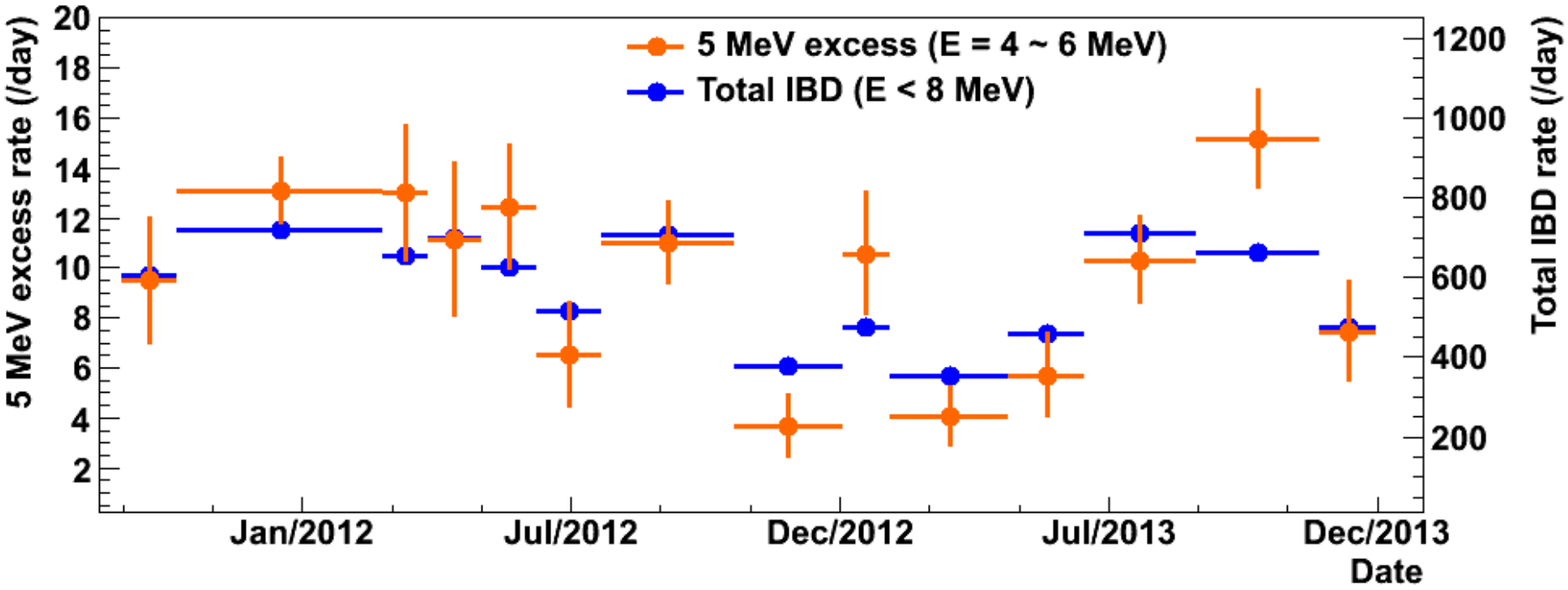


Double-Chooz, Neutrino 2014

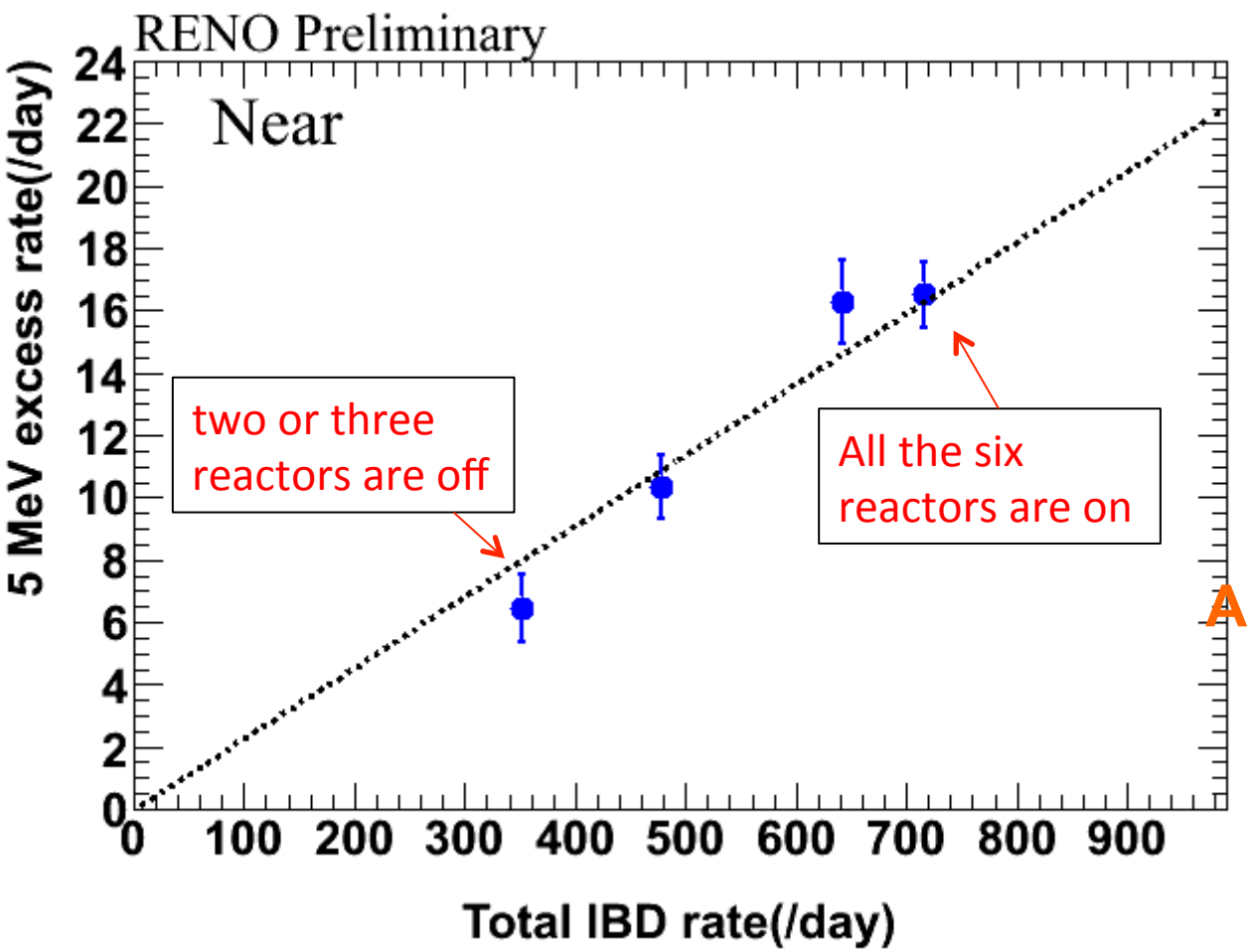
Daya Bay, ICHEP 2014



Correlation of 5 MeV Excess with Reactor Power



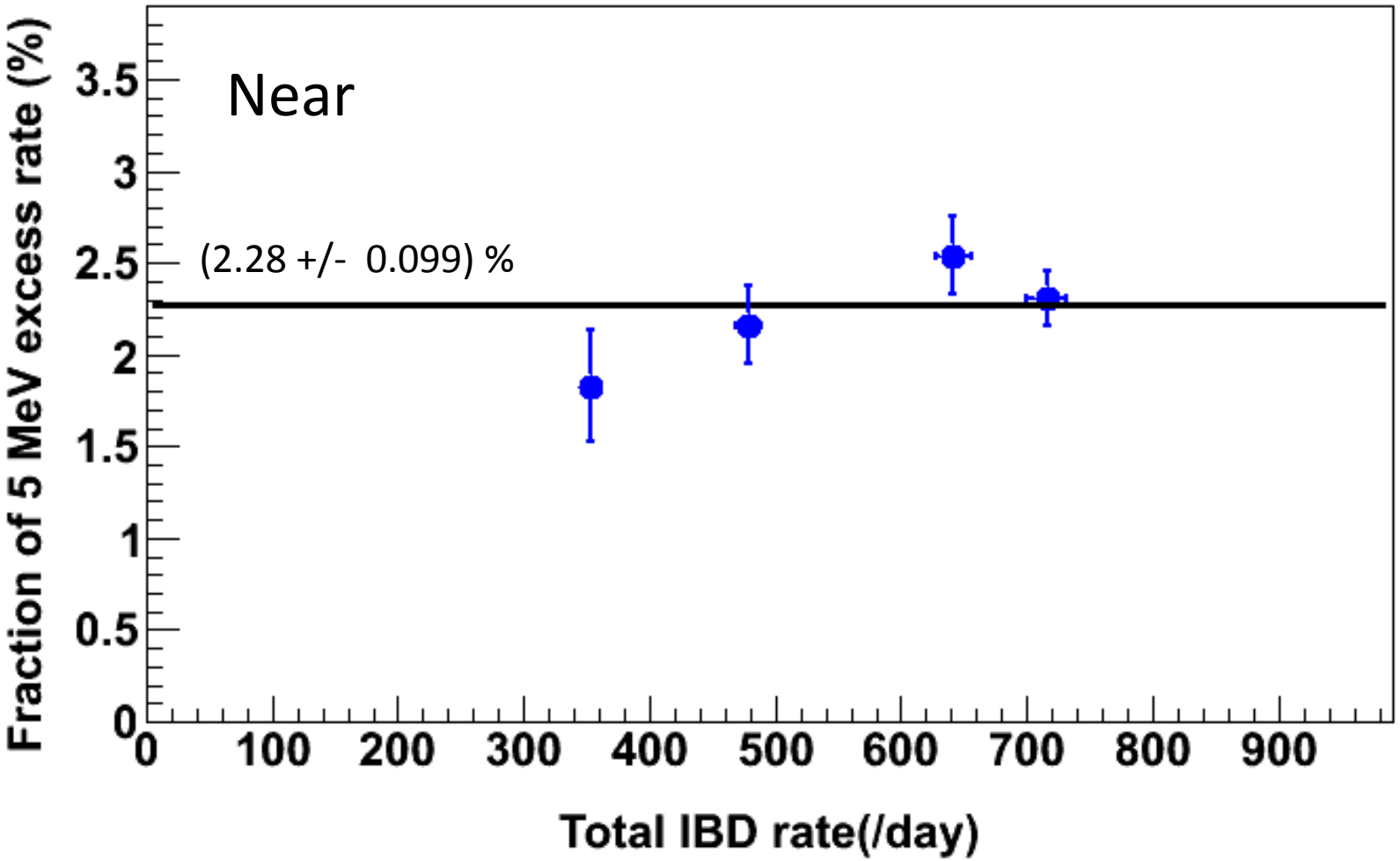
Correlation of 5 MeV Excess with Reactor Power



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

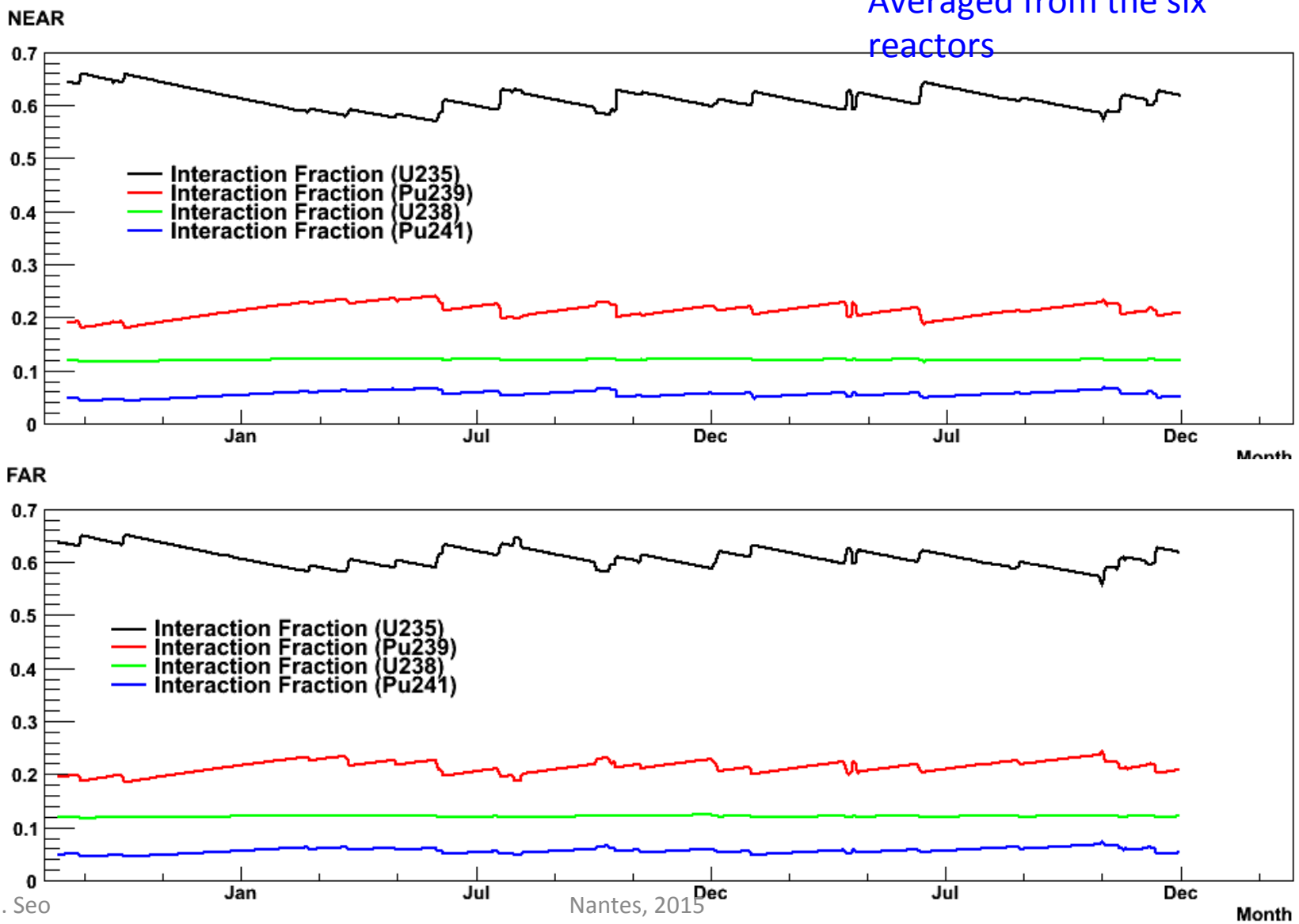
A new reactor neutrino component !!

Constant Fraction of 5 MeV Excess vs. IBD Rate

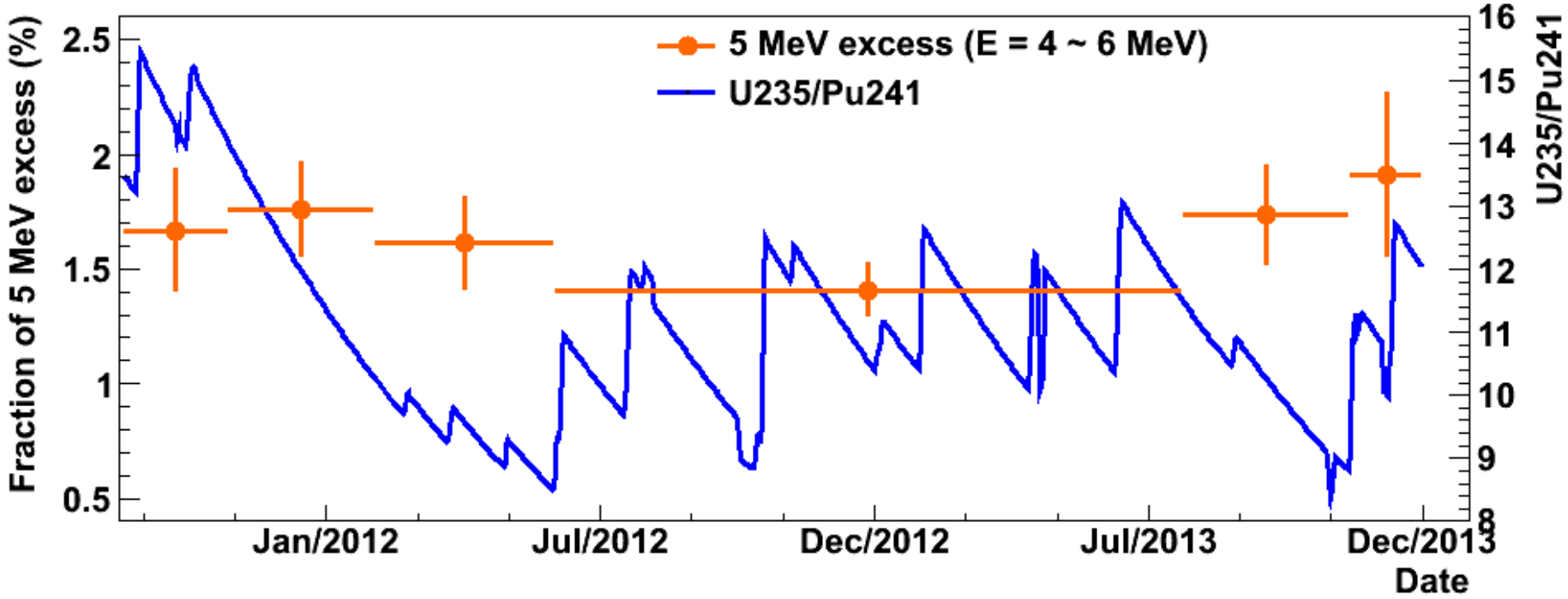


Interacting Reactor Isotope Fraction

Averaged from the six reactors



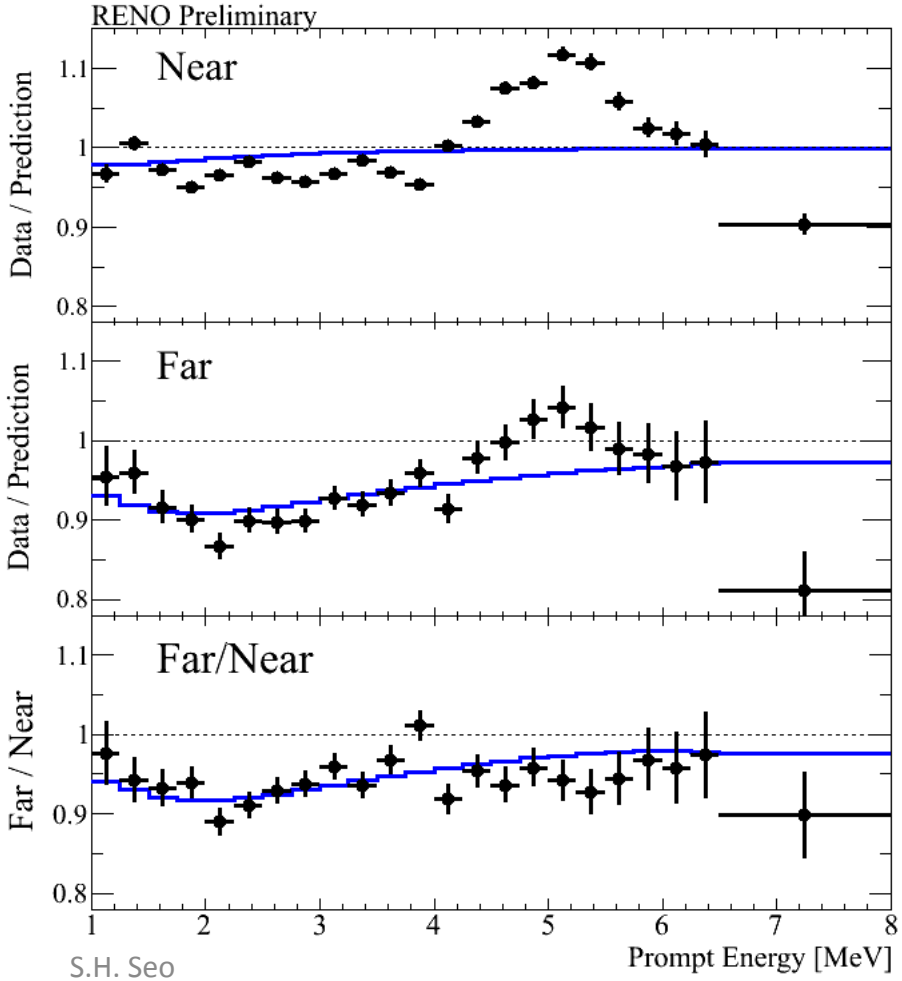
Fraction of 5 MeV Excess vs. Isotope Fraction (U235/Pt241)



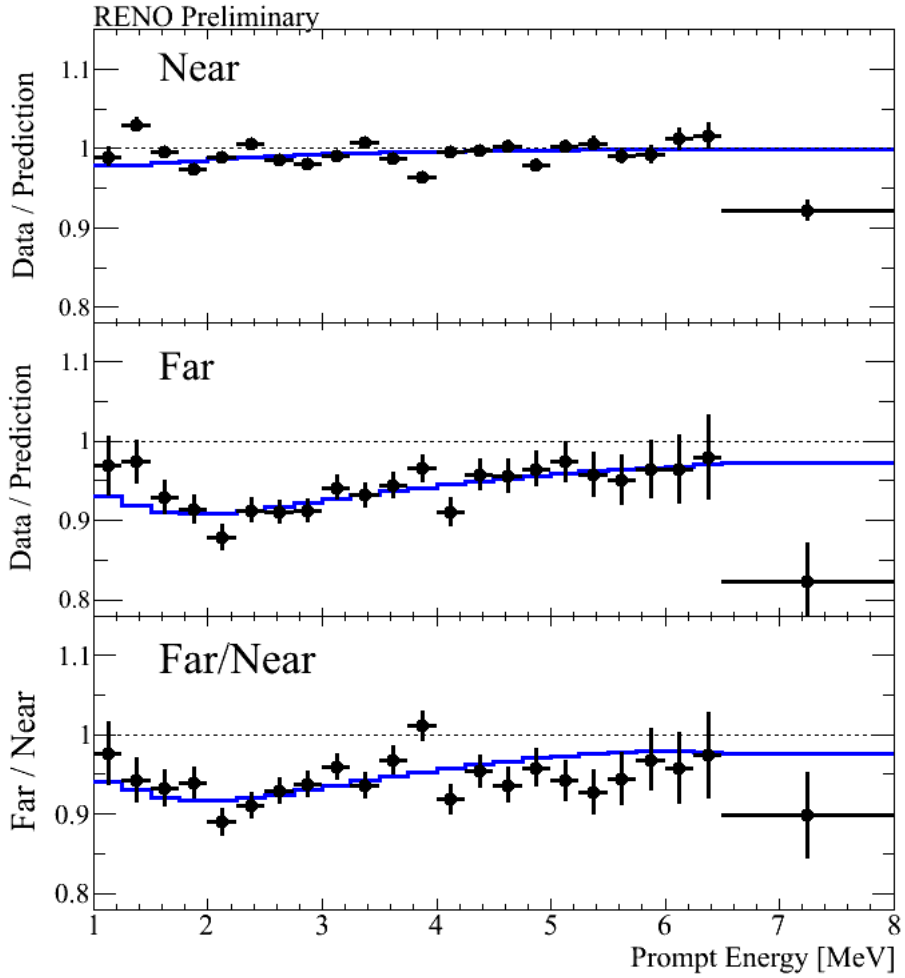
Shape Analysis for Δm_{ee}^2

Finalizing… Stay tuned…

Without 5 MeV excess

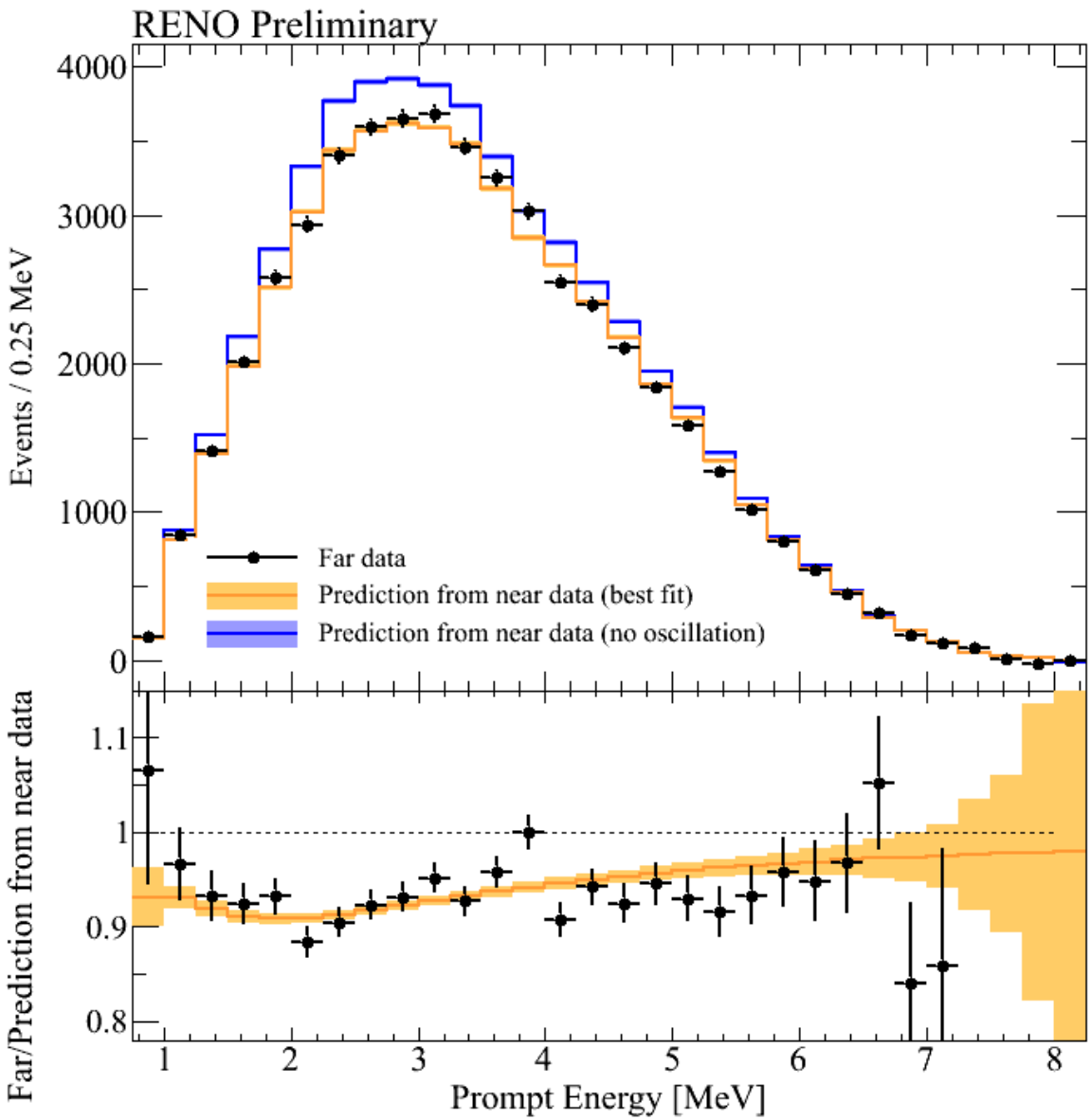


With 5 MeV excess

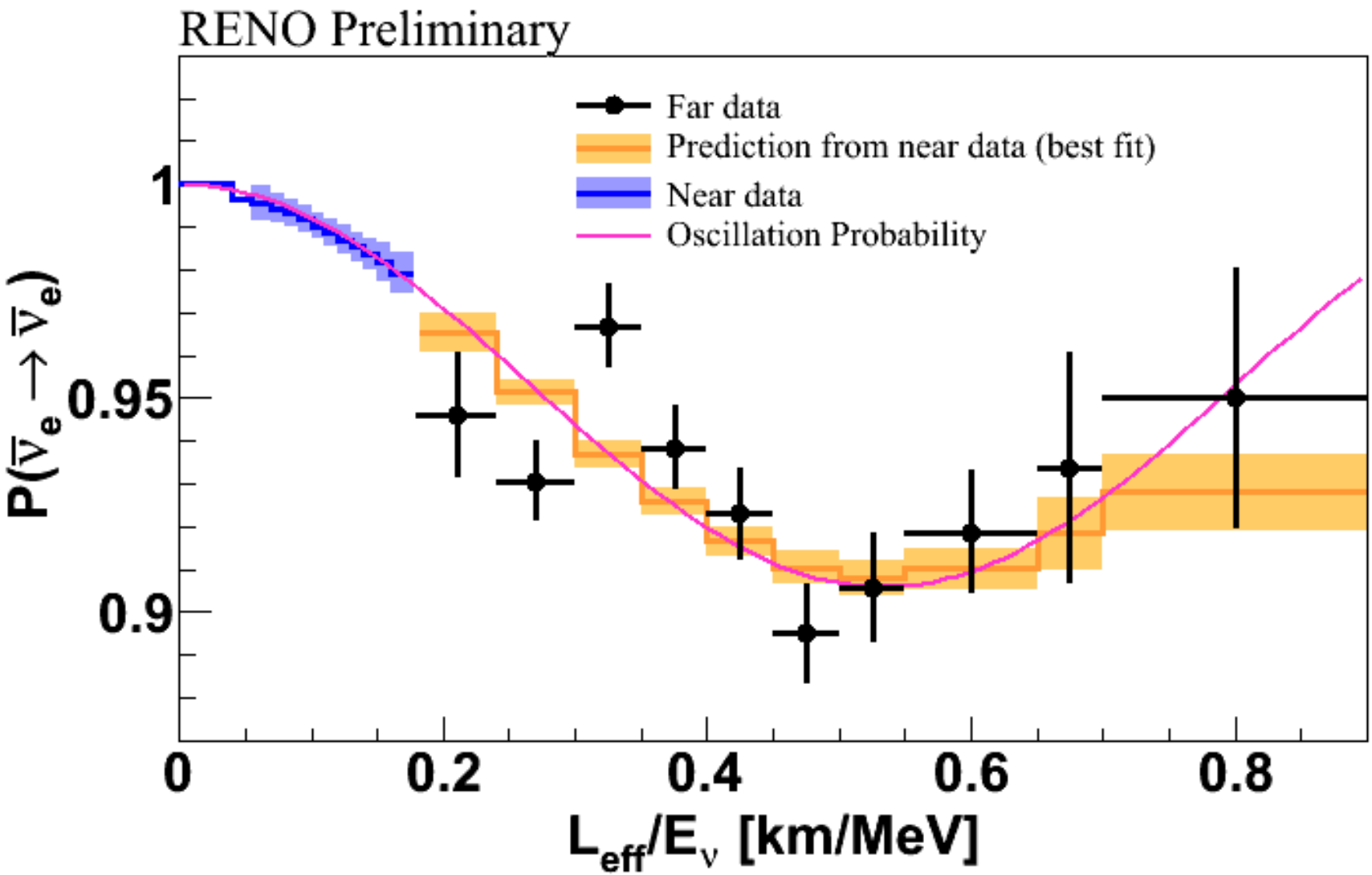


S.H. Seo

Far/Near Shape Analysis for Δm_{ee}^2

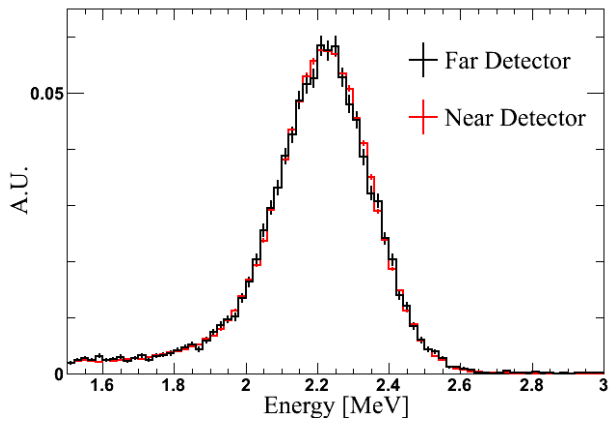


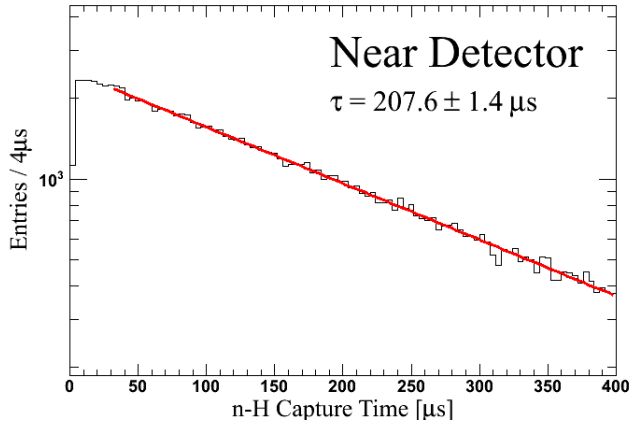
Reactor Neutrino Disappearance on L/E

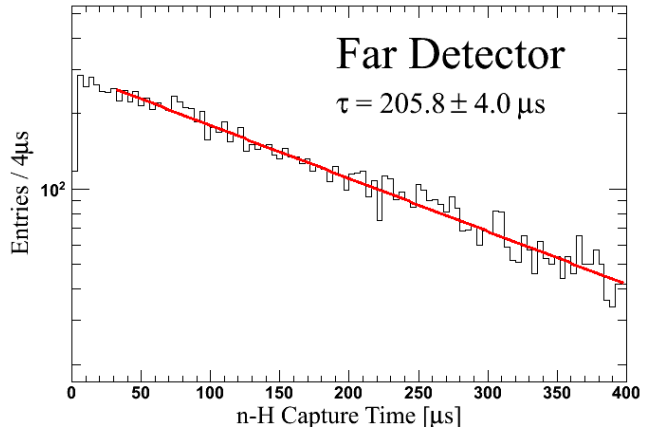


IBD Sample with n-H

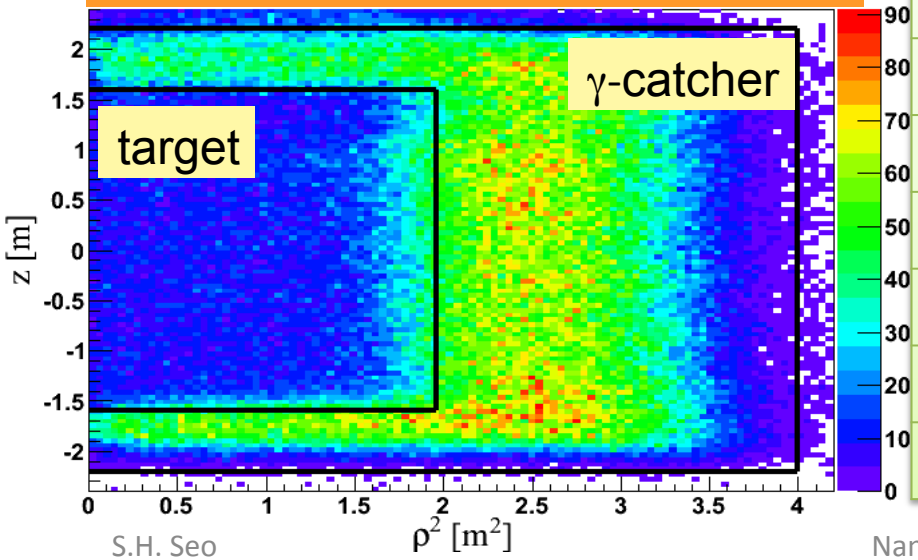
preliminary







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

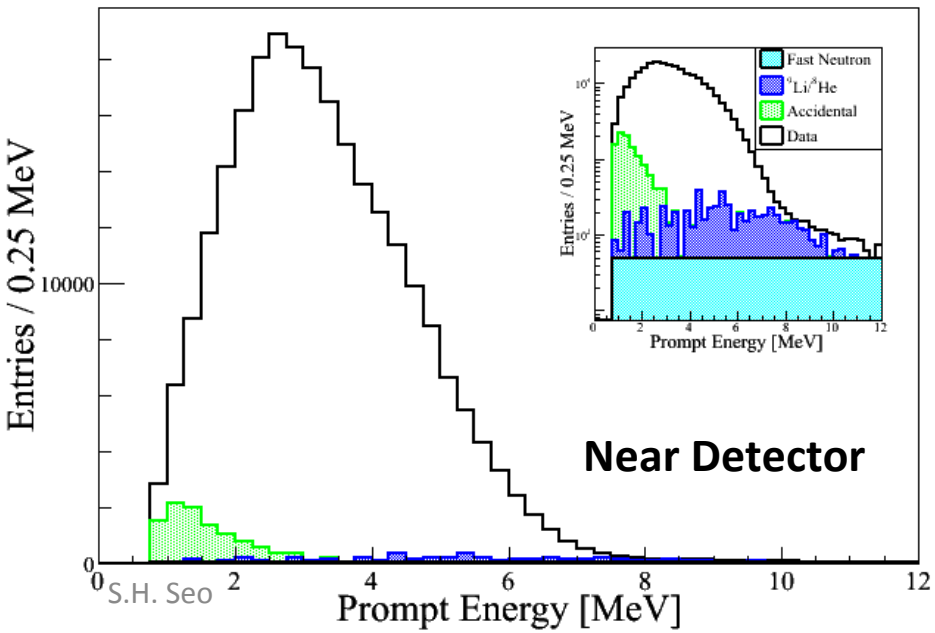
(B data set, ~400 days)

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

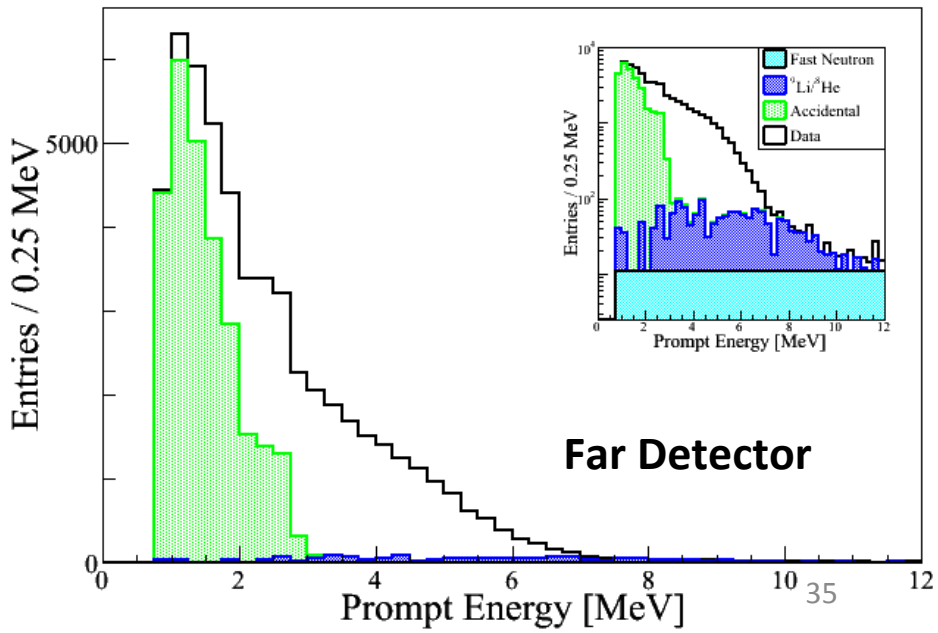
(Neutrino 2014) $\sin^2 2\theta_{13} = 0.095 \pm 0.015(\text{stat.}) \pm 0.025(\text{syst.})$

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

preliminary



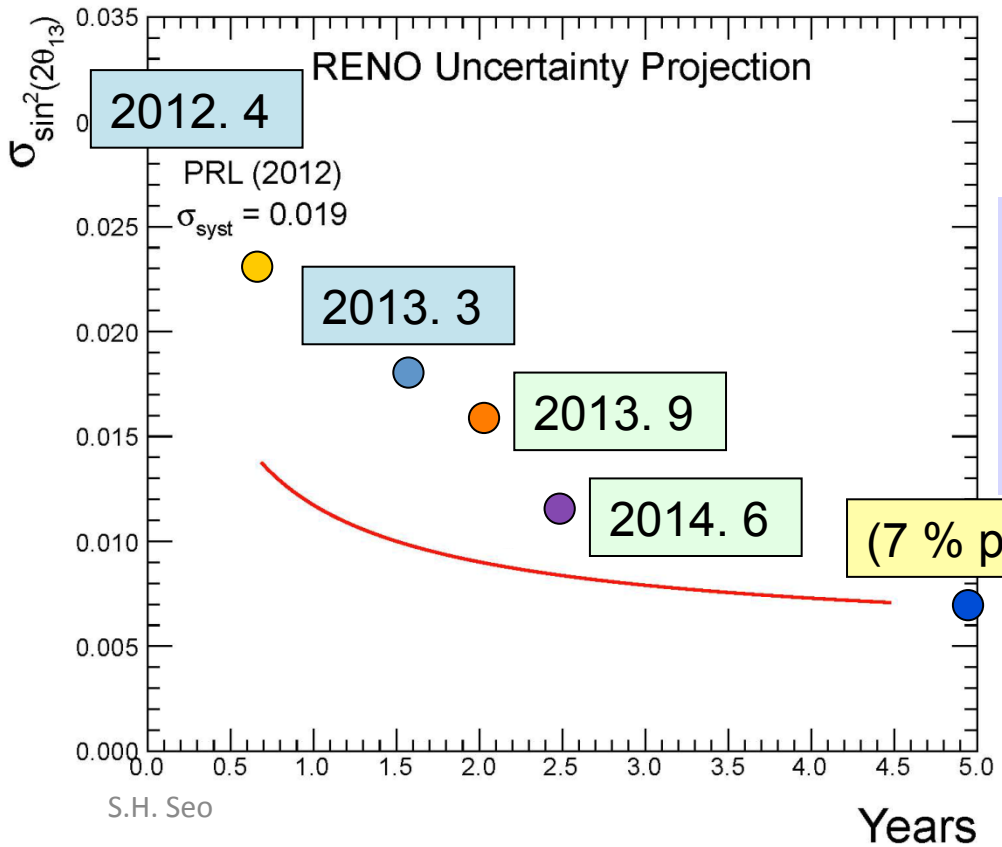
preliminary



RENO's Projected Sensitivity of θ_{13}

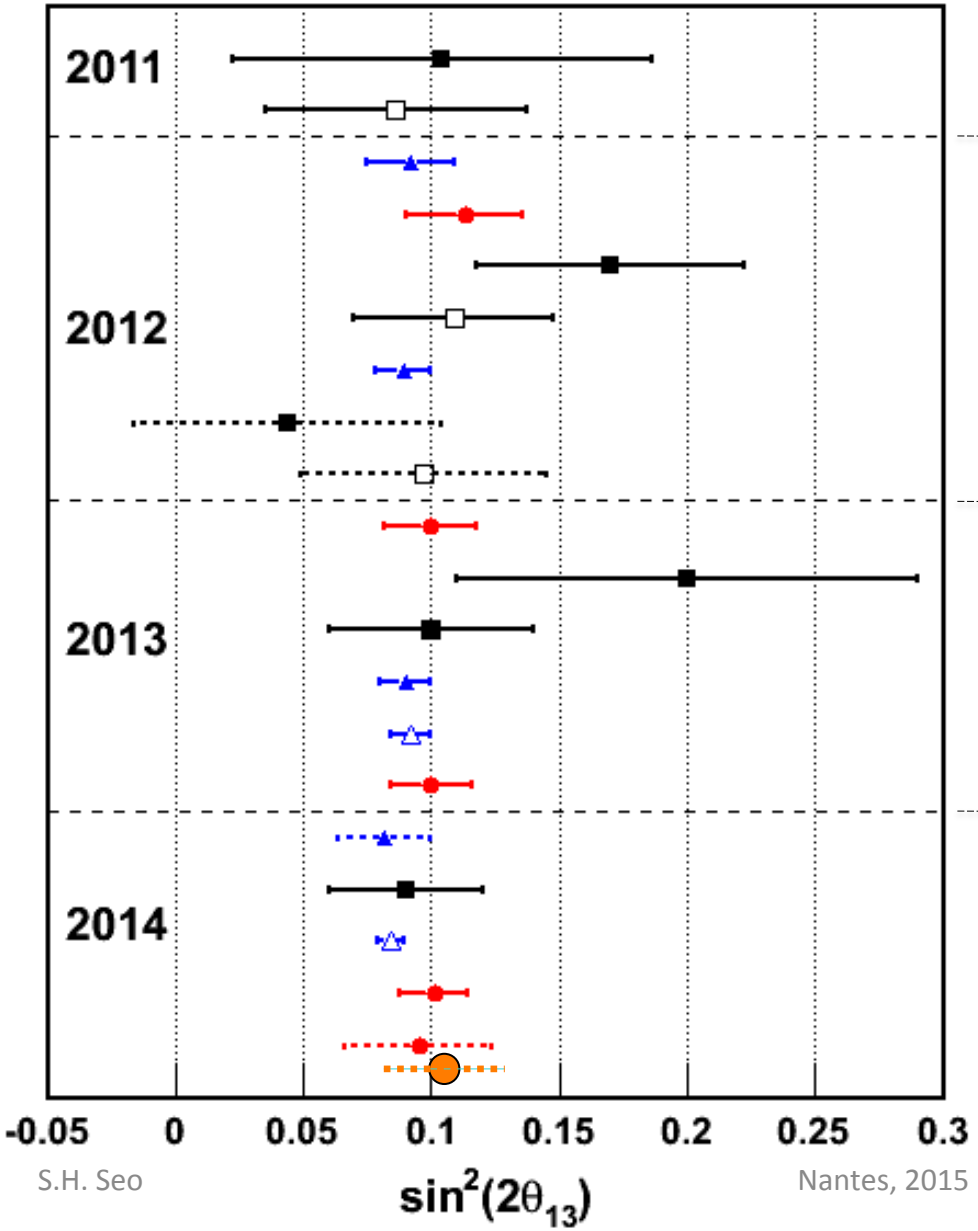
Neutrino 2014 $\sin^2 2\theta_{13} = 0.101 \pm 0.008(stat.) \pm 0.010(syst.)$

(~800 days) 0.101 ± 0.013 (7.8 σ) (13 % precision) → ± 0.007 (14 σ) (in 3 years) (7 % precision)



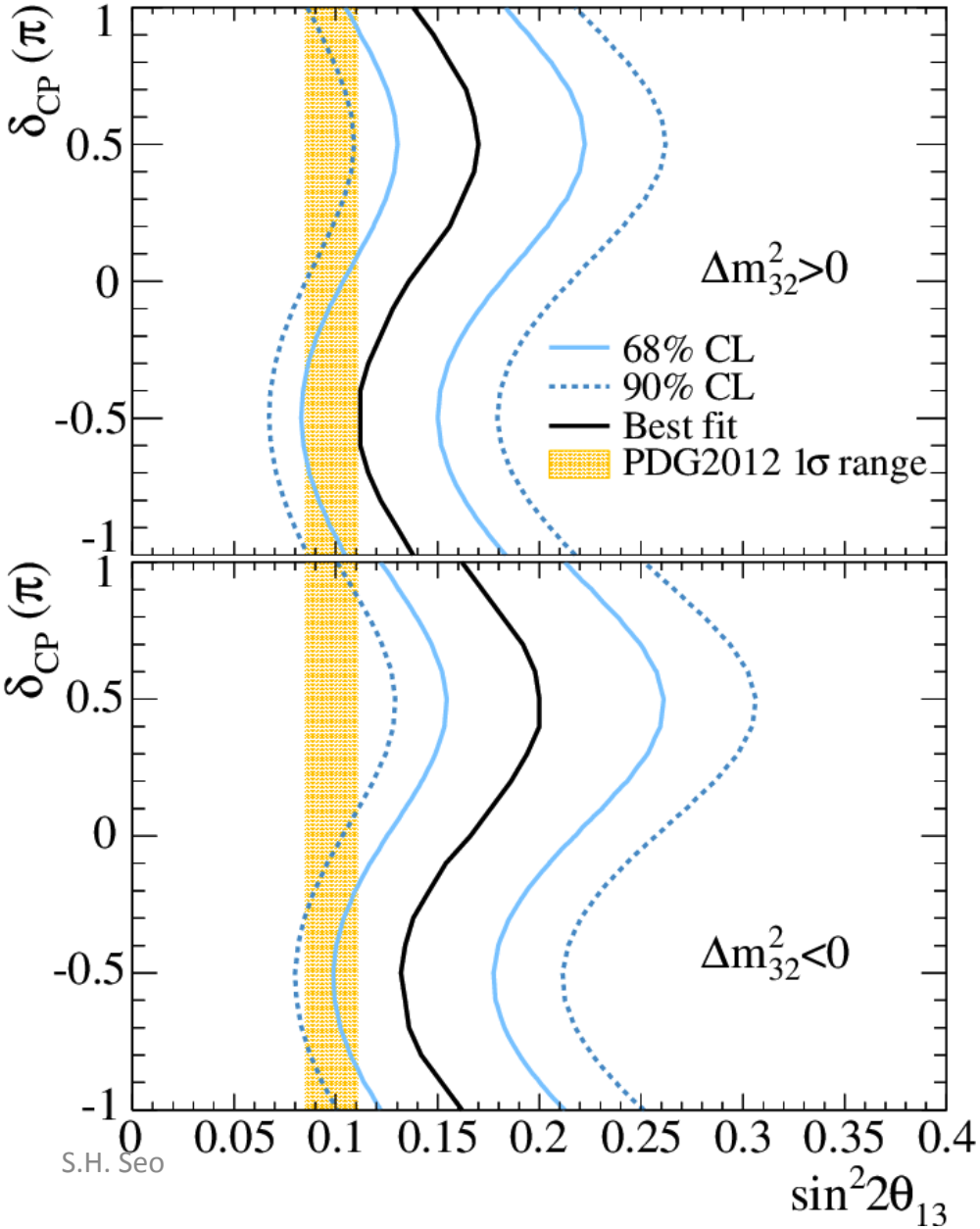
- 5 years of data : ±7%
  - **stat. error : ±0.008 → ±0.005**
  - **syst. error : ±0.010 → ±0.005**
  - **shape information** → ±5%

A Brief History of θ_{13} from Reactor Experiments



DC: 97 days	[1112.6353]
R+S	
DB: 49 days	[1203.1669]
RENO: 222 days	[1204.0626]
DC: 228 days	[1207.6632]
R+S	
DB: 139 days	[1210.6327]
DC: n-H	[1301.2948]
R+S	
RENO: 403 days	[NuTel2013]
DC: RRM analysis	[1305.2734]
R+S	
DB: 190 days	[1310.6732]
R+S	
RENO: 403 days	[TAUP2013]
DB: 190 days n-H	[Moriond2014]
DC: 469 days	[ν 2014]
DB: 563 days	[ν 2014]
RENO: 795 days	[ν 2014]
384 days n-H	[ν 2014]
RENO 384 days n-H	**[NOW 2014]**

θ_{13} from Reactor and Accelerator Experiments



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

Best overlap is for Normal hierarchy & $\delta_{CP} = -\pi/2$

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

Strong motivation for anti-neutrino runs and precise measurements of θ_{13}

Courtesy C. Walter (T2K Collaboration) Talk at Neutrino 2014

Summary

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

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

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

(preliminary)

- Shape analysis for Δm^2 is being finalized… (stay tuned)

- First result on n-H IBD analysis

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

(very preliminary)

- $\sin^2(2\theta_{13})$ to 7% accuracy within 3 years
  → will provide the first glimpse of δ_{CP}.
  If accelerator results are combined.

Towards World θ_{13} Value

We will organize a workshop in Korea around April.

1. Goal: to obtain world θ_{13} value

2. Contents:
   --- understand details of analysis from each experiment
   --- systematics
   --- need to think how to construct χ^2

$$\chi^2 = \chi^2_{DC} + \chi^2_{DB} + \chi^2_{RENO} \quad ?$$