Current Results & Future Perspectives from Reactor Neutrino Experiments

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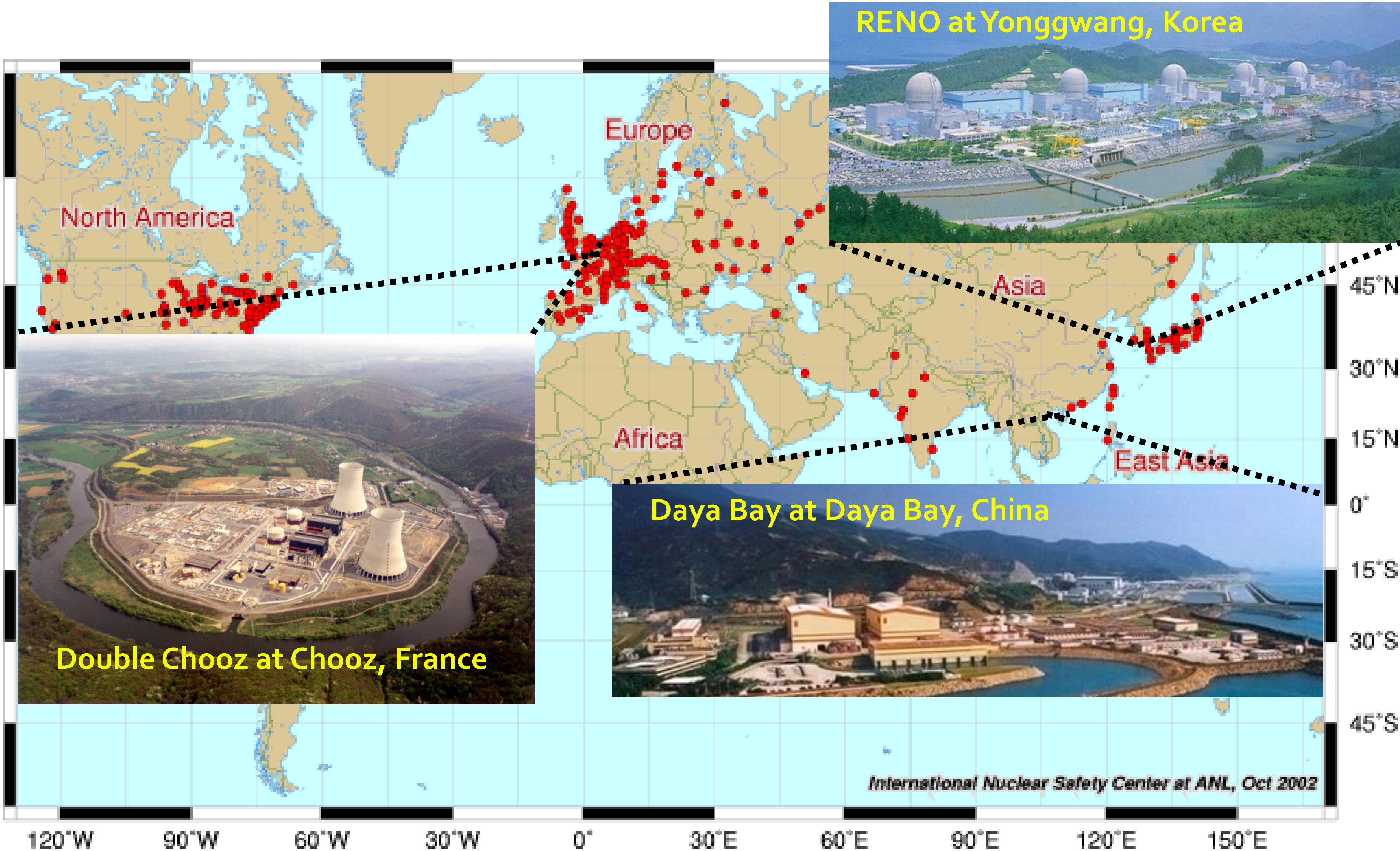
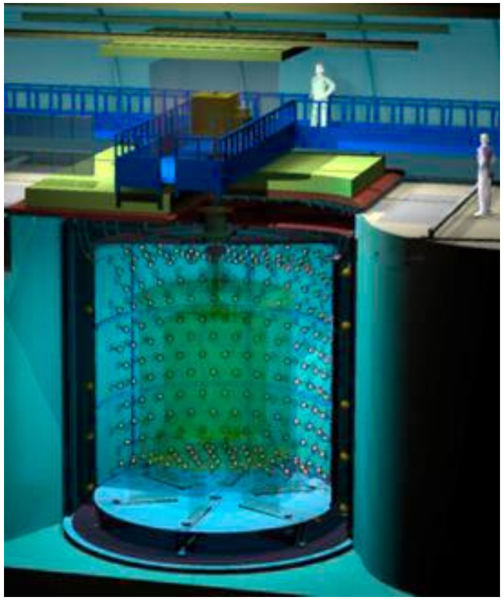
"Tsukuba Global Science Week (TGSW2014), Tsukuba, Sep. 28-30, 2014"

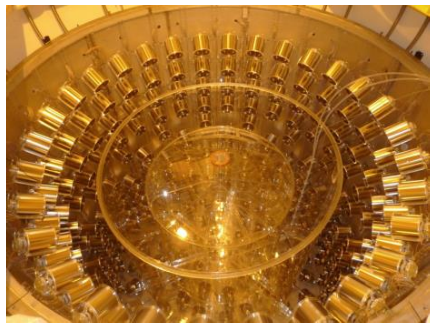
KNRC
Korea Neutrino Research Center

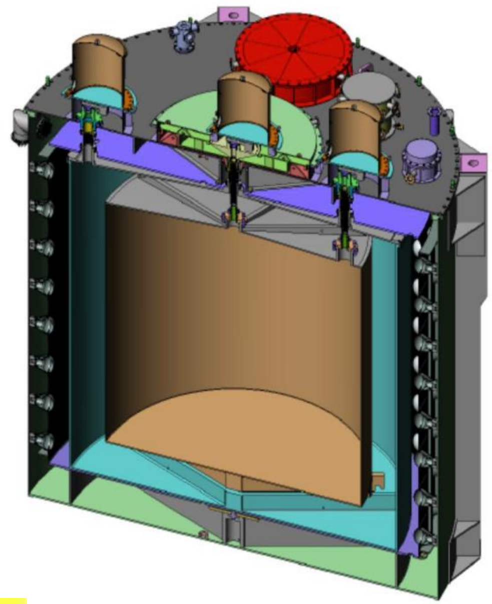
Reactor θ_{13} Experiments

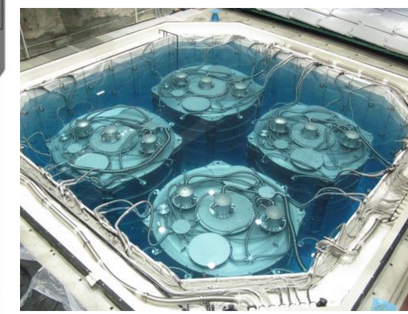


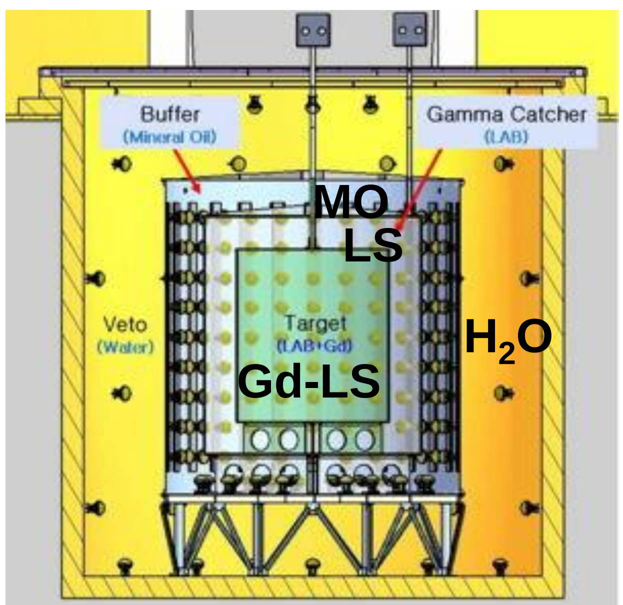
θ_{13} Reactor Neutrino Detectors











RENO Collaboration

Reactor Experiment for Neutrino Oscillation

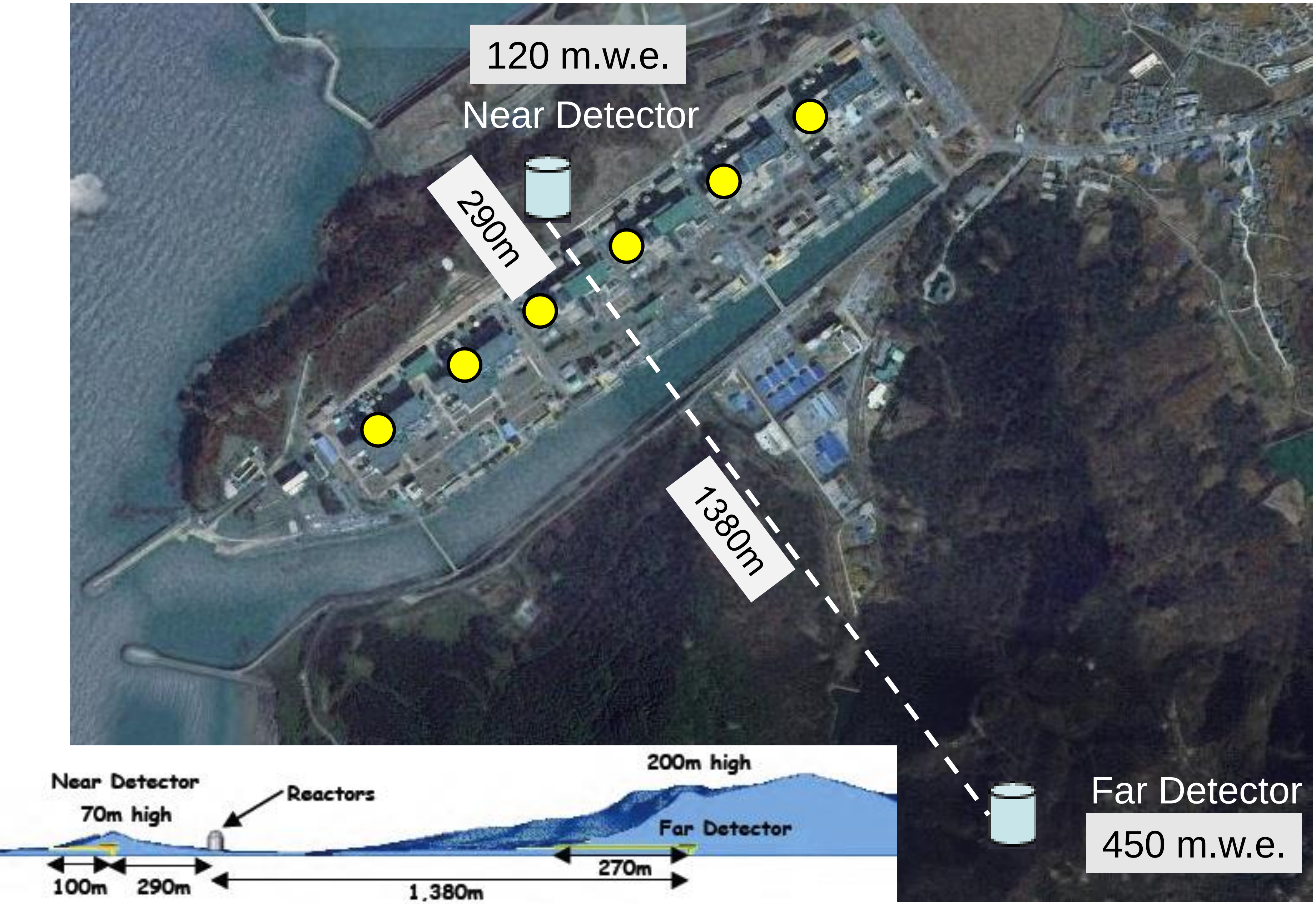
(11 institutions and 40 physicists)

- 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 Set-up



RENO Status

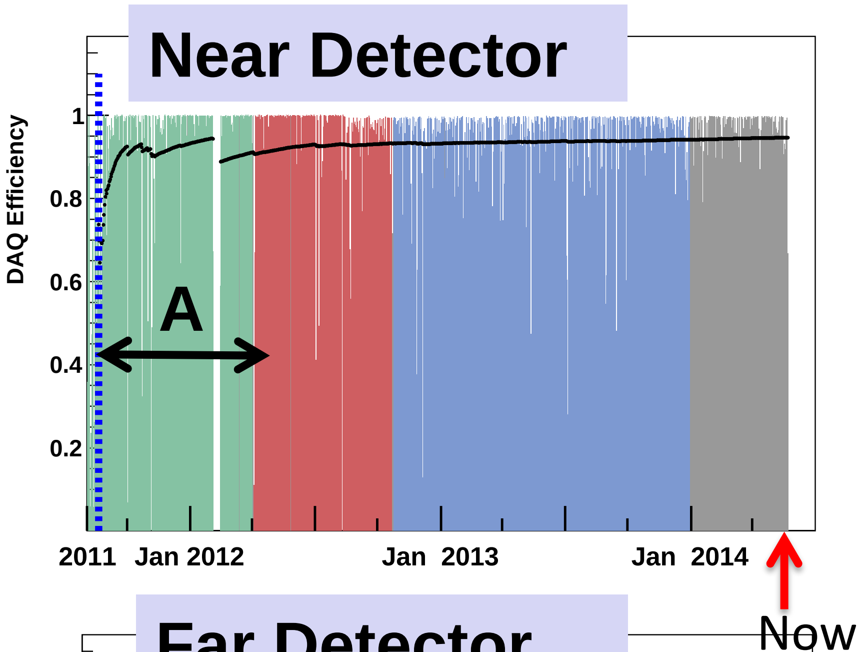
- Data taking began on Aug. 1, 2011 with both near and far detectors. (DAQ efficiency : ~95%)

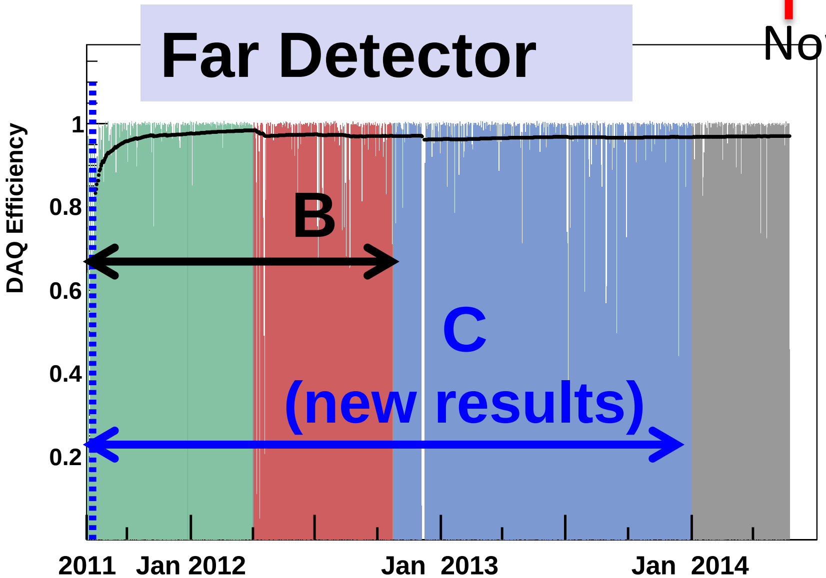
- **A** (220 days) : **First θ_{13} result**
  [11 Aug, 2011~26 Mar, 2012]
  PRL 108, 191802 (2012)

- **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]

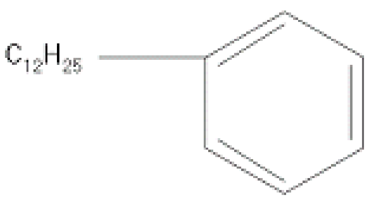
- Total observed reactor neutrino events as of today : **~ 1.5M** (Near), **~ 0.15M** (Far)
  → Absolute reactor neutrino flux measurement in progress
  [reactor anomaly & sterile neutrinos]





Detection of Reactor Antineutrinos

C_nH_{2n+1}-C_6H_5 (n=10~14)



Linear Alkyl Benzene (LAB)

(prompt signal)

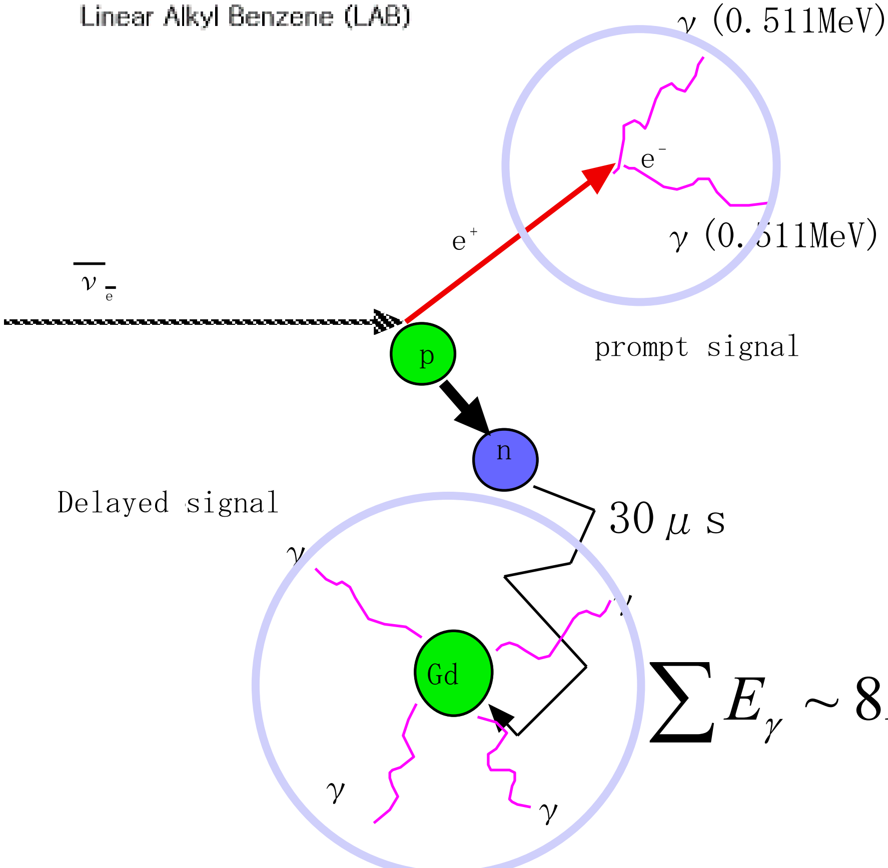
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

~180 μs (delayed signal)

+ p → D + γ (2.2 MeV)

~28 μs (0.1% Gd)

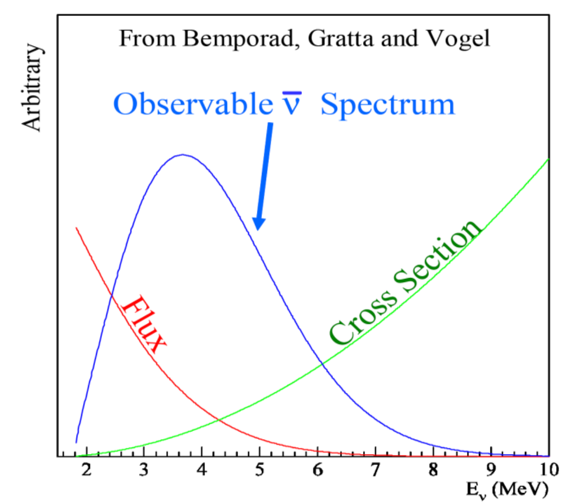
+ Gd → Gd + γ's (8 MeV)



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

- **Neutrino energy measurement**

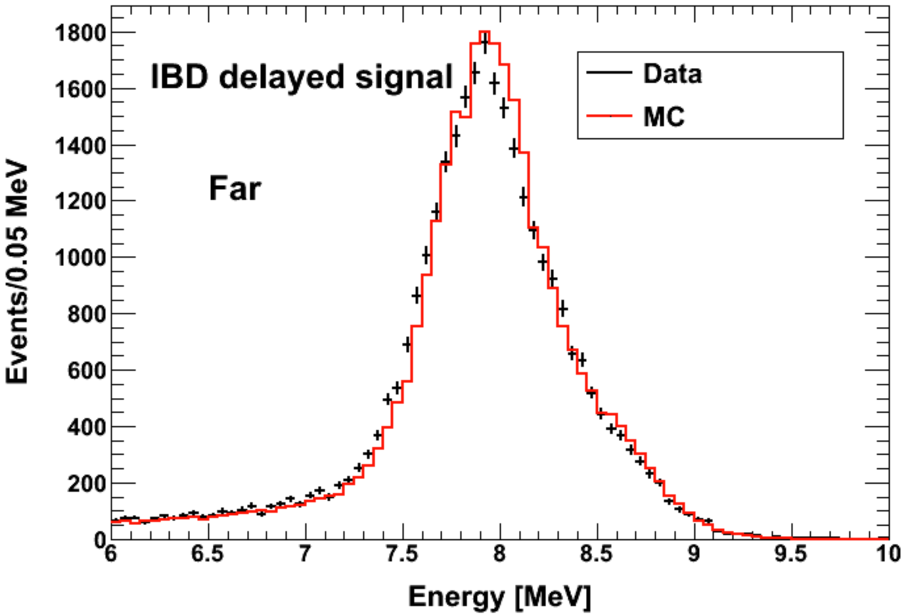
$$E_{\bar{\nu}} \cong T_{e^+} + \underbrace{T_n}_{10\text{-}40\ keV} + \underbrace{(M_n - M_p) + m_{e^+}}_{1.8\ MeV}$$

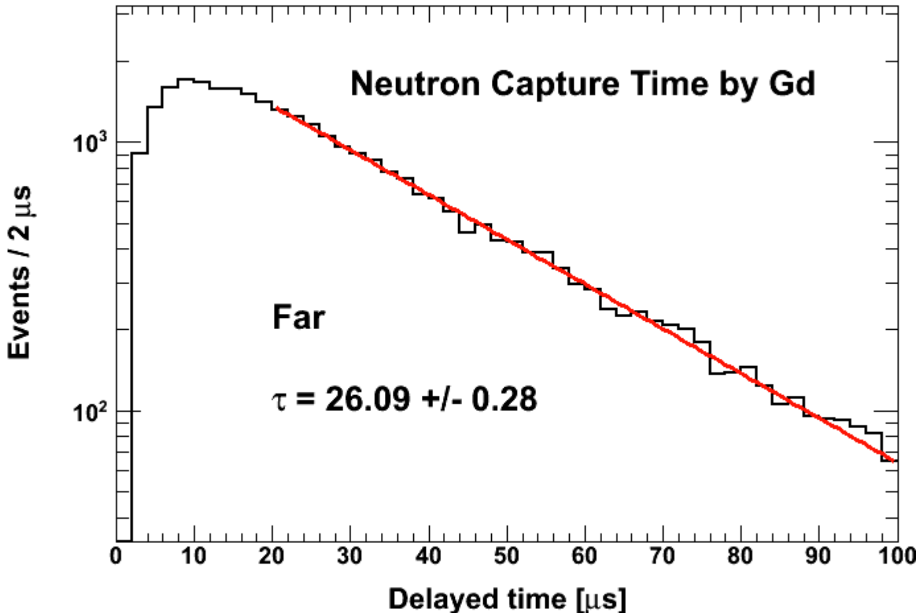


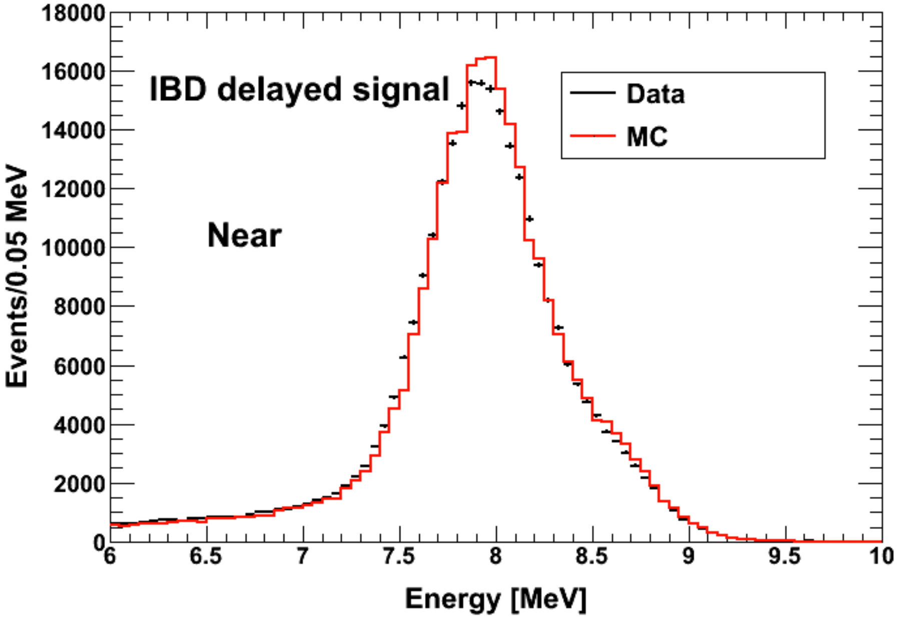
New RENO Results

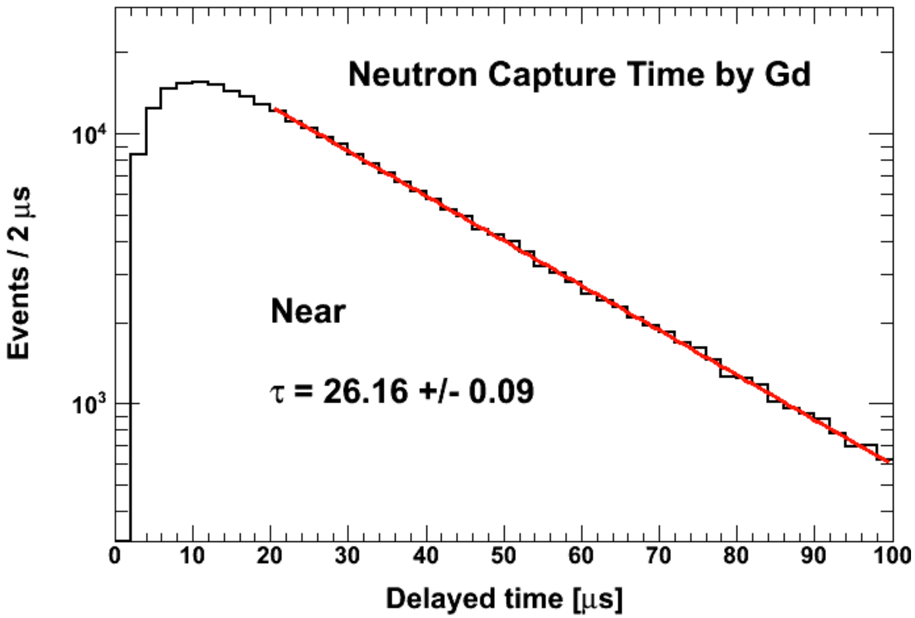
- ~800 days of data
- New measured value of θ_{13} from rate-only analysis (Neutrino 2014)
- Shape analysis in progress
- Observation of a new reactor neutrino component at 5 MeV
- Results of reactor neutrinos with neutron capture on H (Significant improvement from Neutrino 2014)

Neutron Capture by Gd

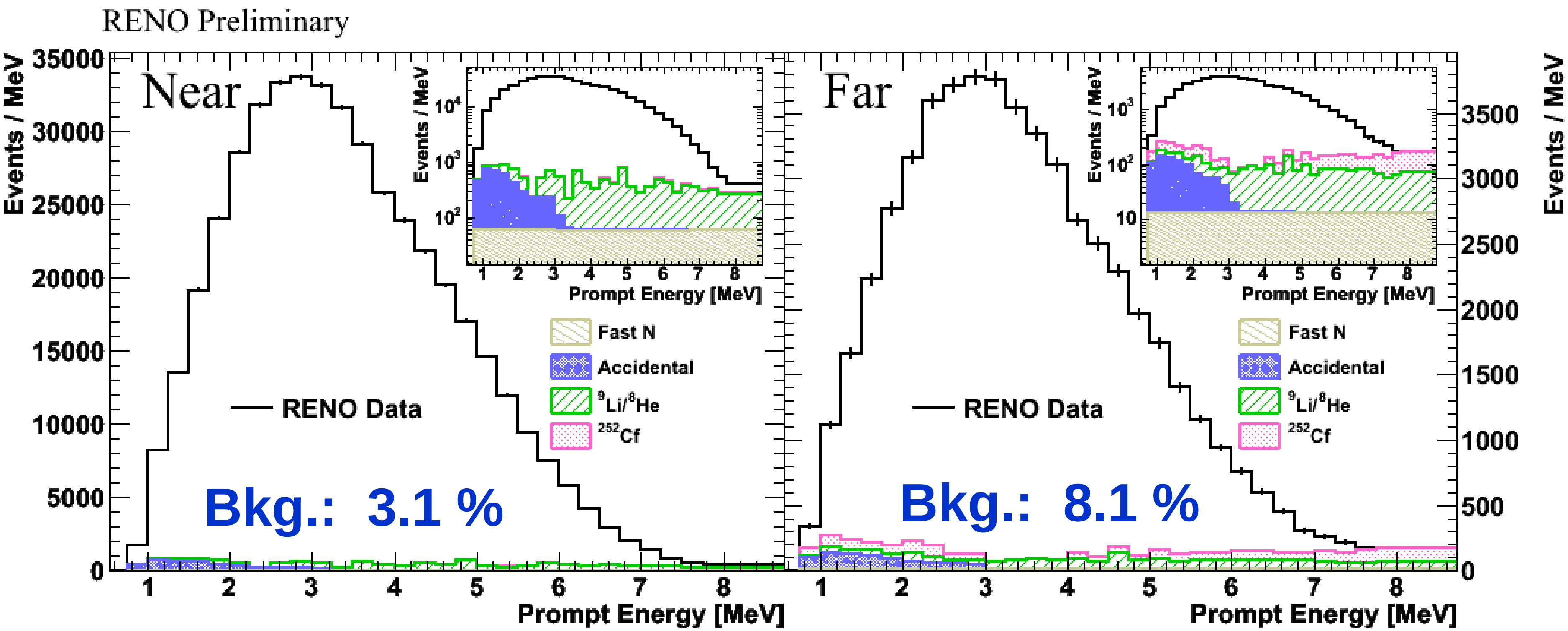








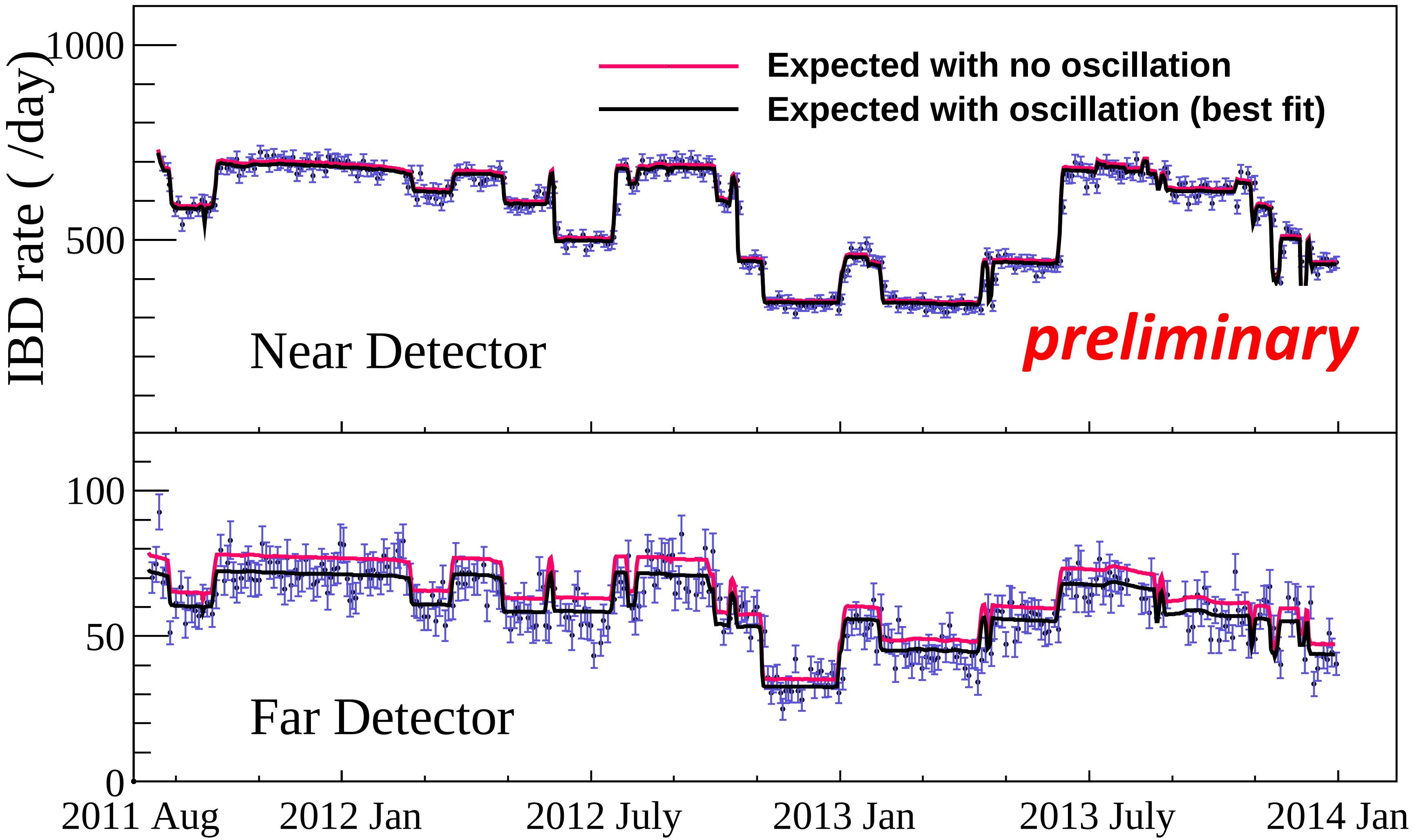
Measured Spectra of IBD Prompt Signal



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

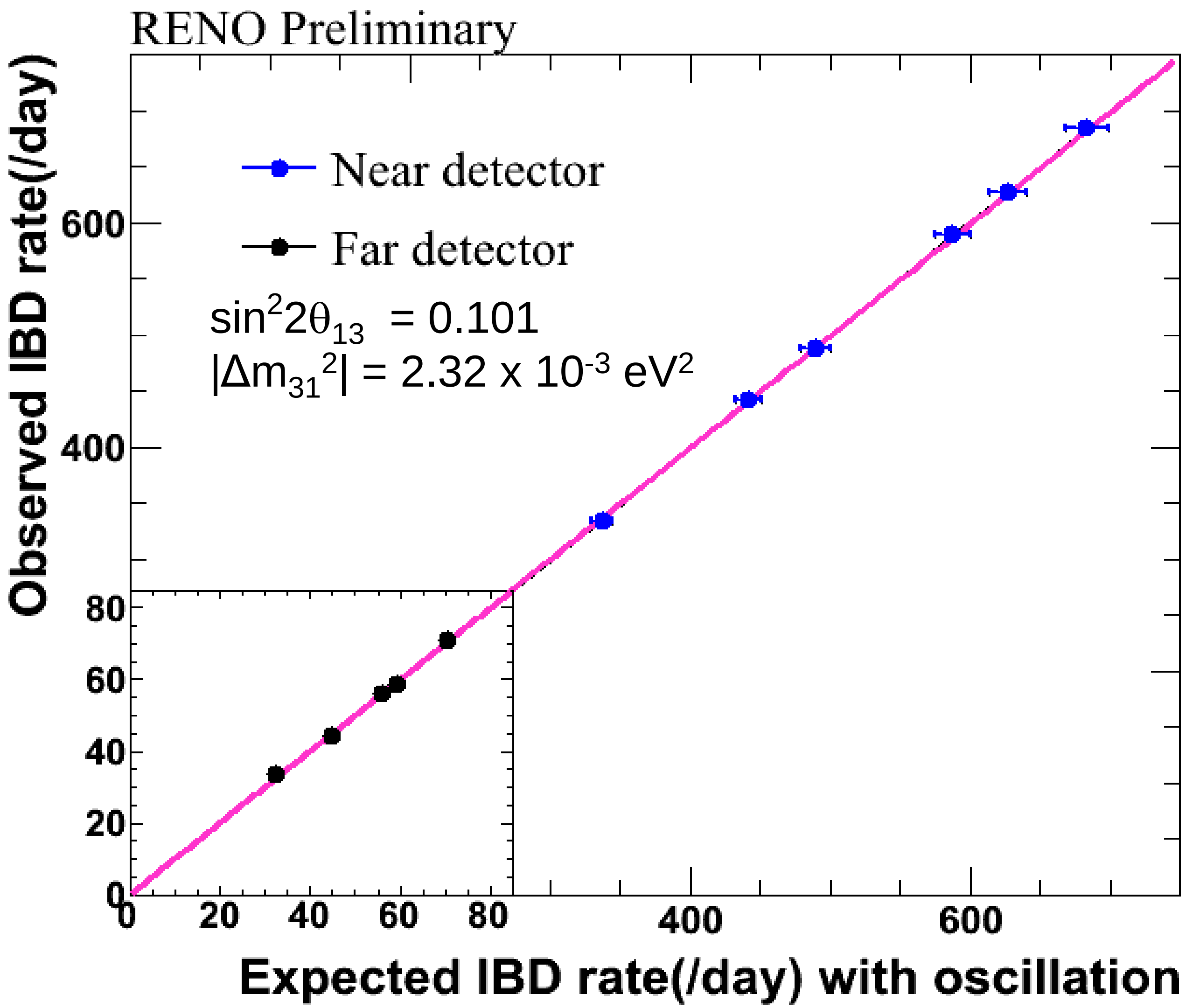
Far Live time = 794.72 days
# of IBD candidate = 53,632
# of background = 4366 (8.1 %)

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)

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

Uncertainties (%)	0.1 0.2 0.3 0.4 0.5 0.6
Statistics (near)	(0.15%)
(far)	(0.43%)
Isotope fraction	(0.28%)
Thermal power	(0.20%)
Detection efficiency	(0.20%)
Backgrounds (near)	(0.21%)
(far)	(0.50%)

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

$\rightarrow 0.100 \pm 0.016$ 6.3 σ (TAUP/WIN 2013)

$\rightarrow 0.101 \pm 0.013$ 7.8 σ (Neutrino 2014)

Why n-H IBD Analysis?

Motivation:

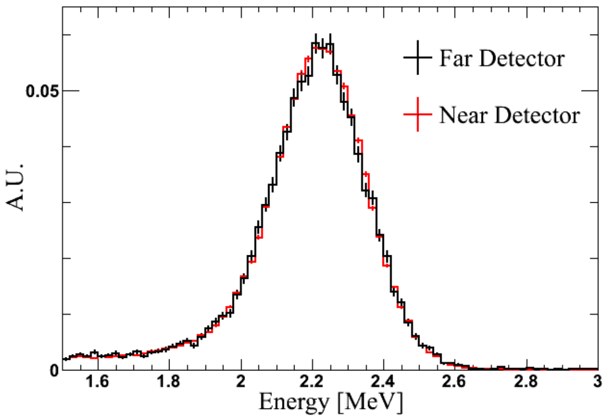
1. Independent measurement of θ_{13} value.
2. Consistency and systematic check on reactor neutrinos.

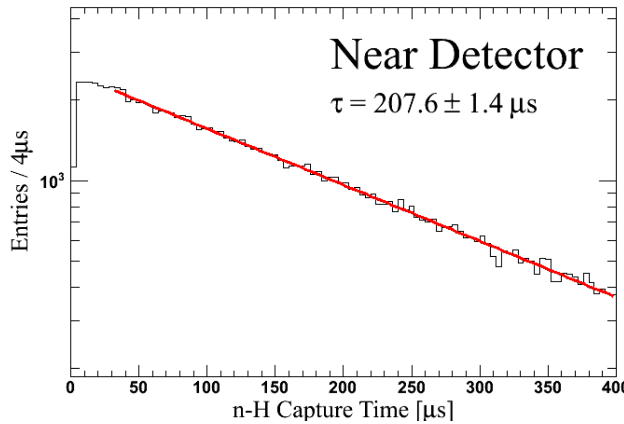
* RENO's low accidental background makes it possible to perform n-H analysis.

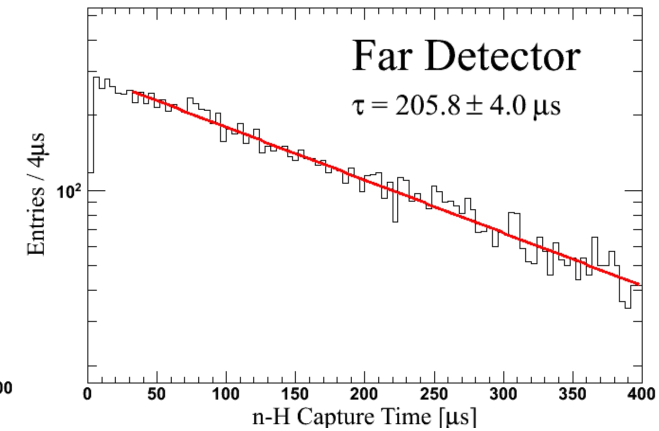
-- low radio-activity PMT
-- successful purification of LS and detector materials.

IBD Sample with n-H

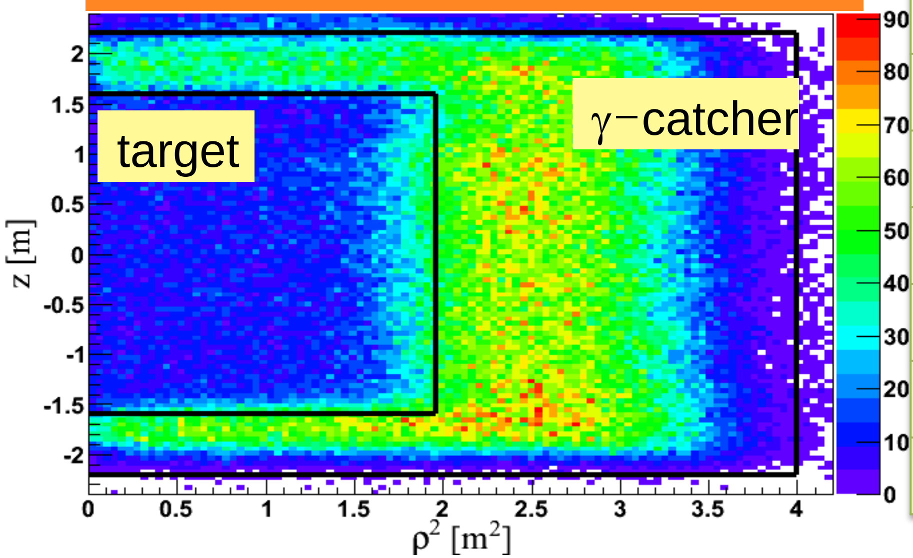
preliminary







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

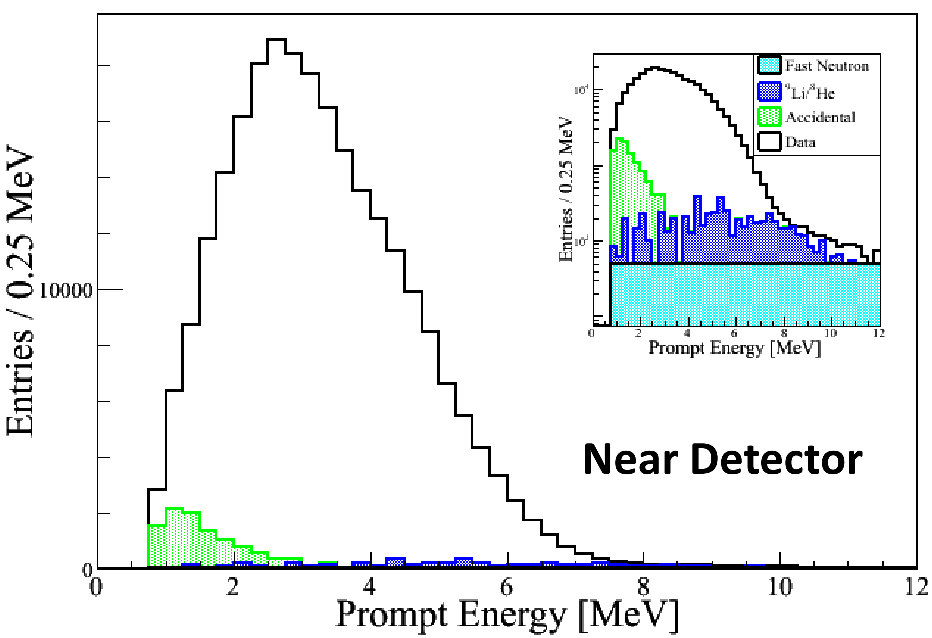
(B data set, ~400 days)

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

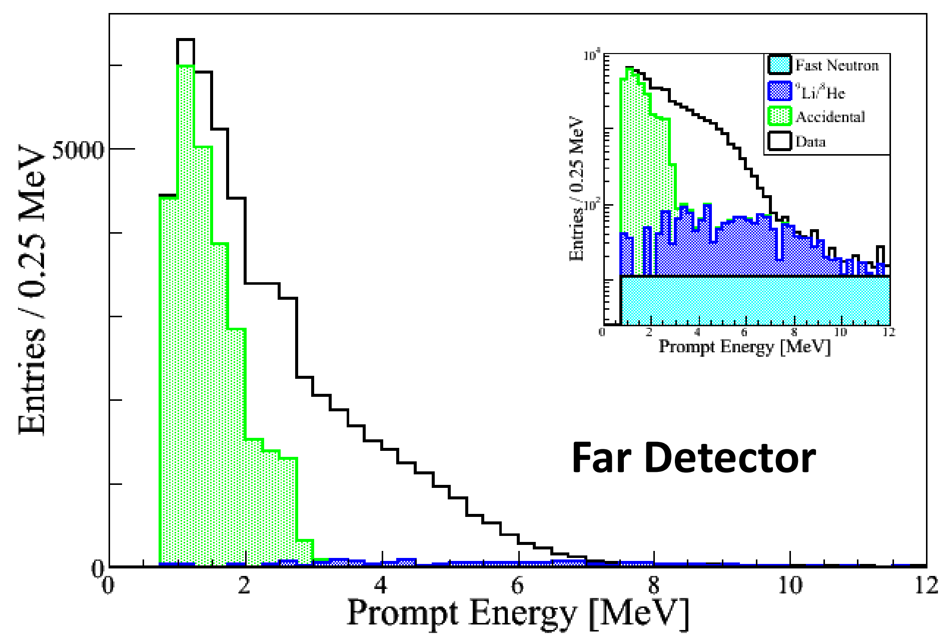
(Neutrino 2014) $\sin^2 2\theta_{13} = 0.095 \pm 0.015(\text{stat.}) \pm 0.025(\text{syst.})$

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

preliminary



preliminary



Reactor Neutrino Oscillations

$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \sin^2 2\theta_{13} \sin^2\left(\Delta m^2_{ee} \frac{L}{4E}\right) - \sin^2 2\theta_{12} \cos^4 2\theta_{13} \sin^2\left(\Delta m^2_{21} \frac{L}{4E}\right)$$

Short Baseline

Long Baseline

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

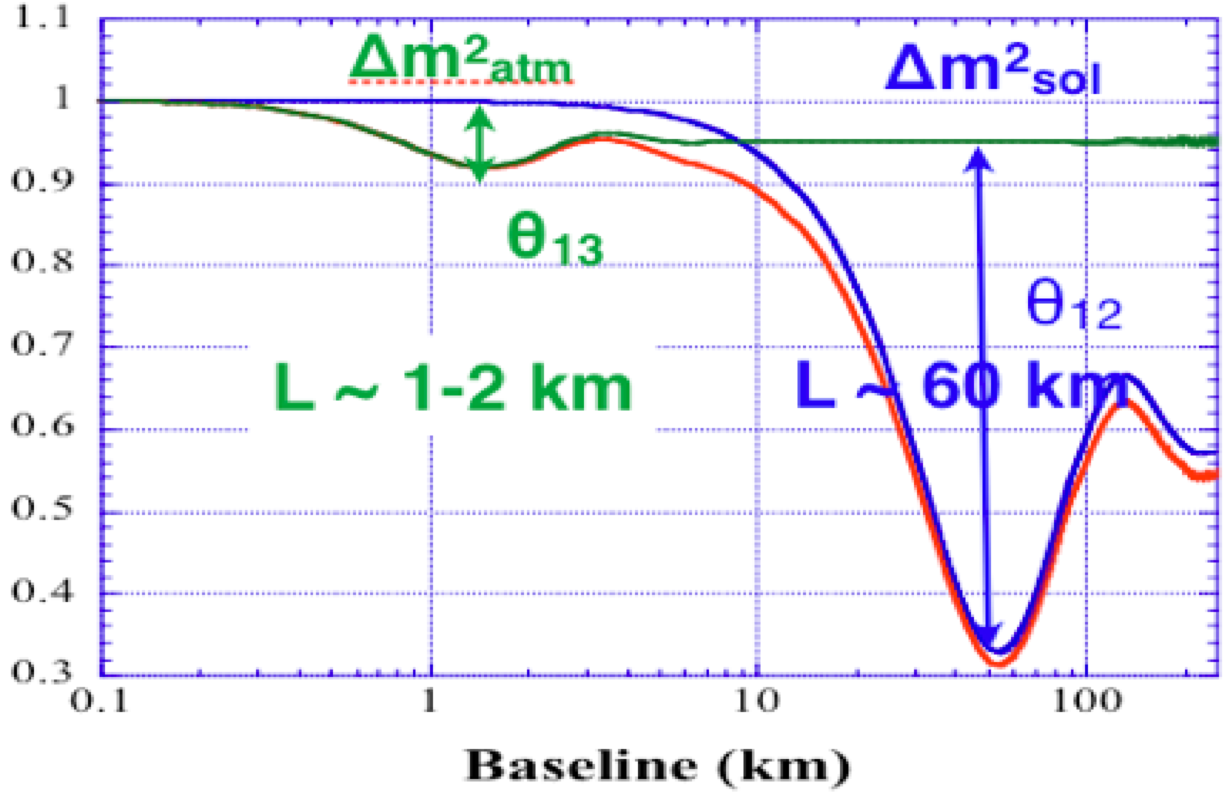
$$|\Delta m^2_{ee}| \simeq |\Delta m^2_{32}| \pm 5.21 \times 10^{-5}\,\mathrm{eV}^2$$

$\cos^2\theta_{12}|\Delta m^2{}_{21}|$

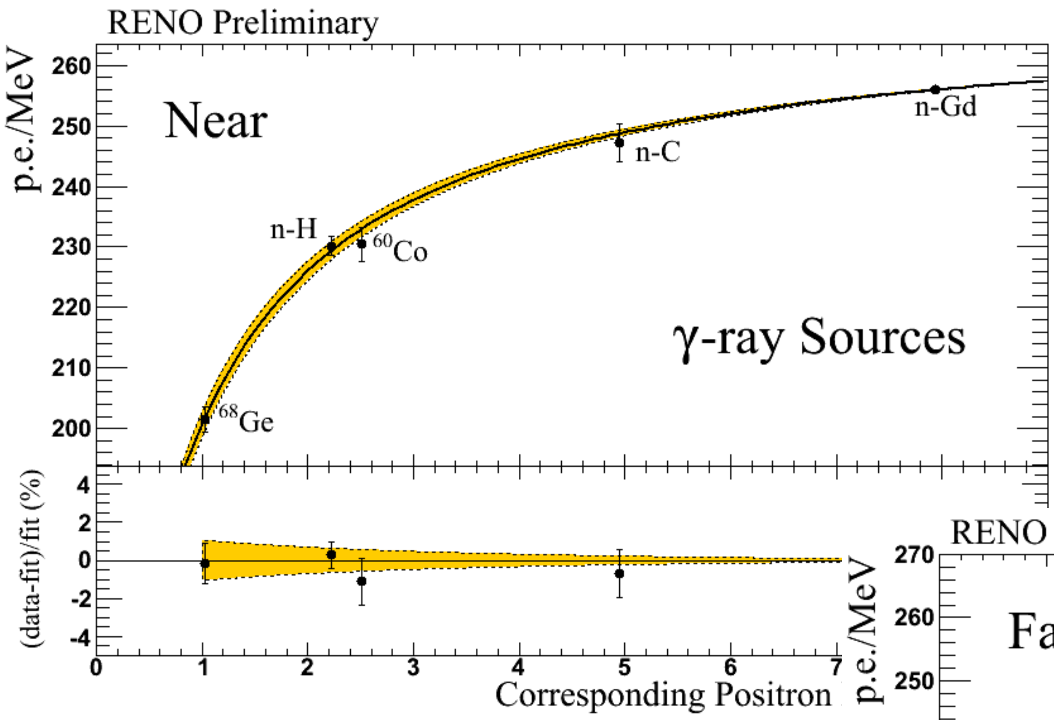
+: Normal Hierarchy

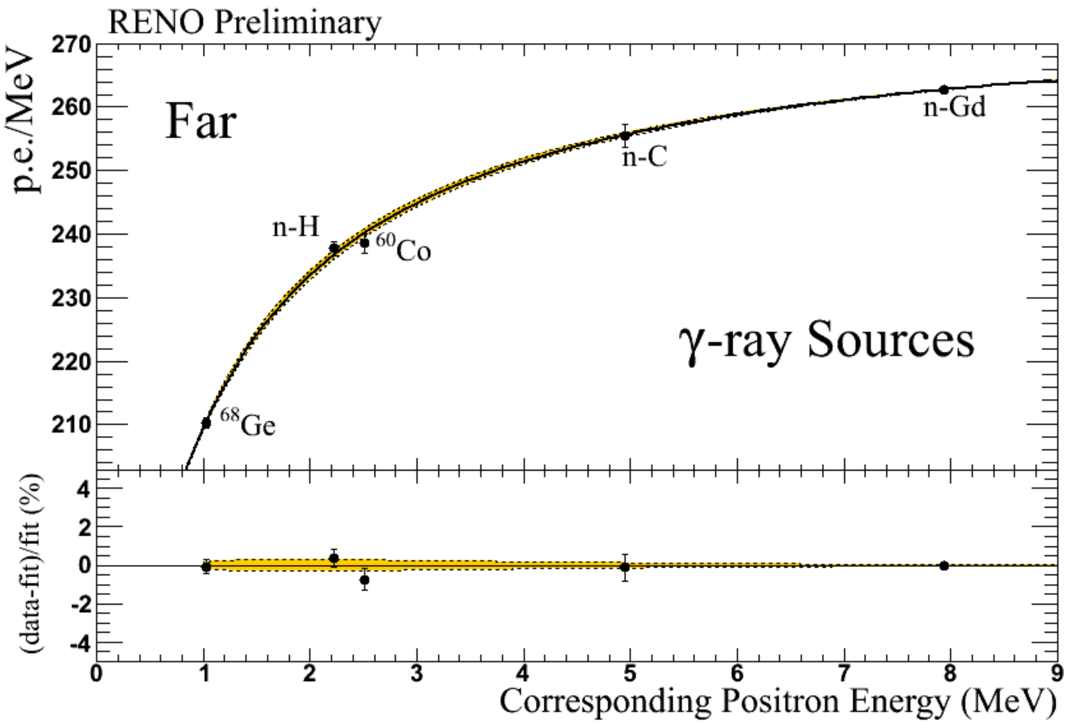
−: Inverted Hierarchy

[Nunokawa & Parke (2005)]



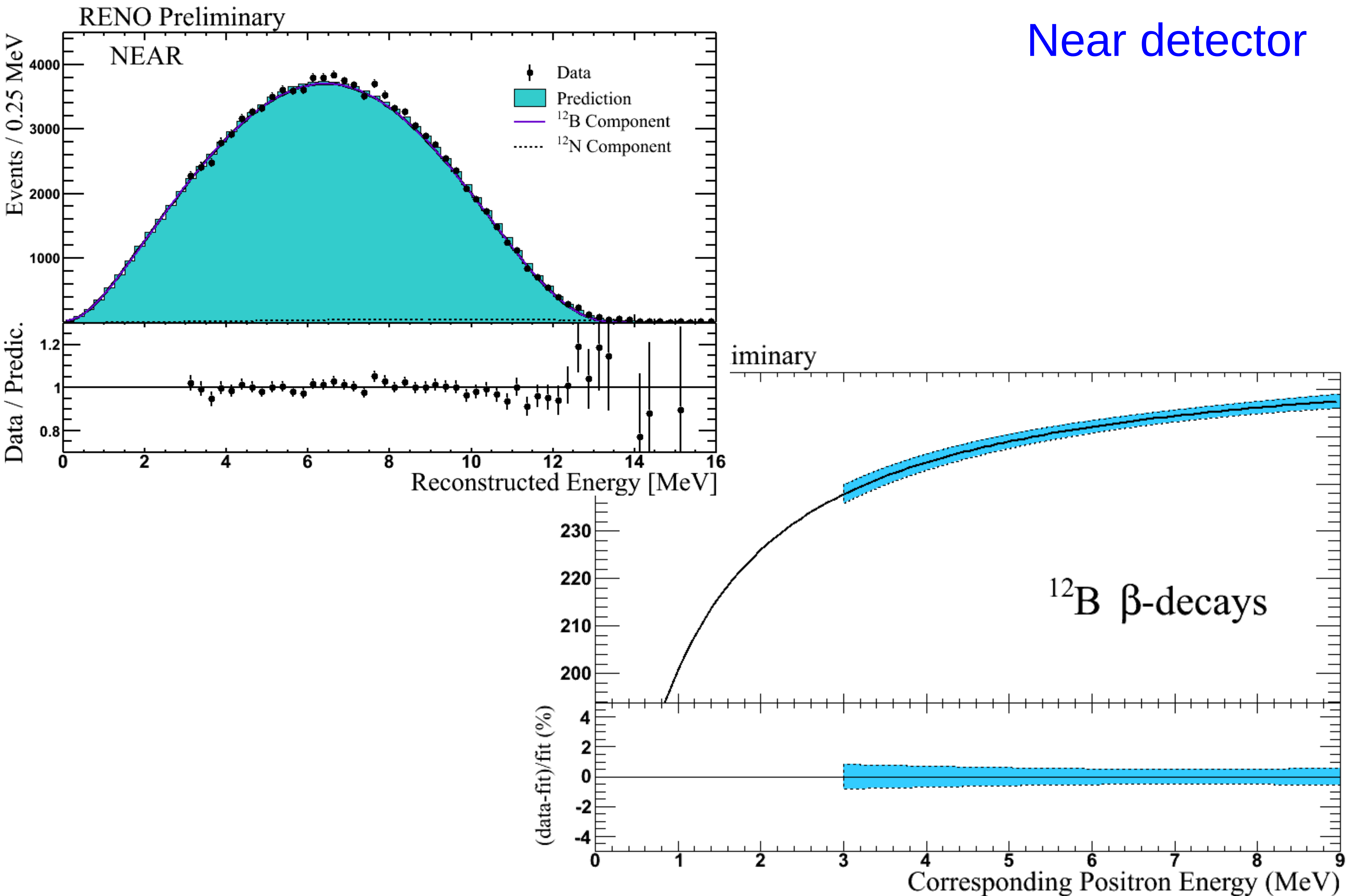
Energy Calibration from γ-ray Sources





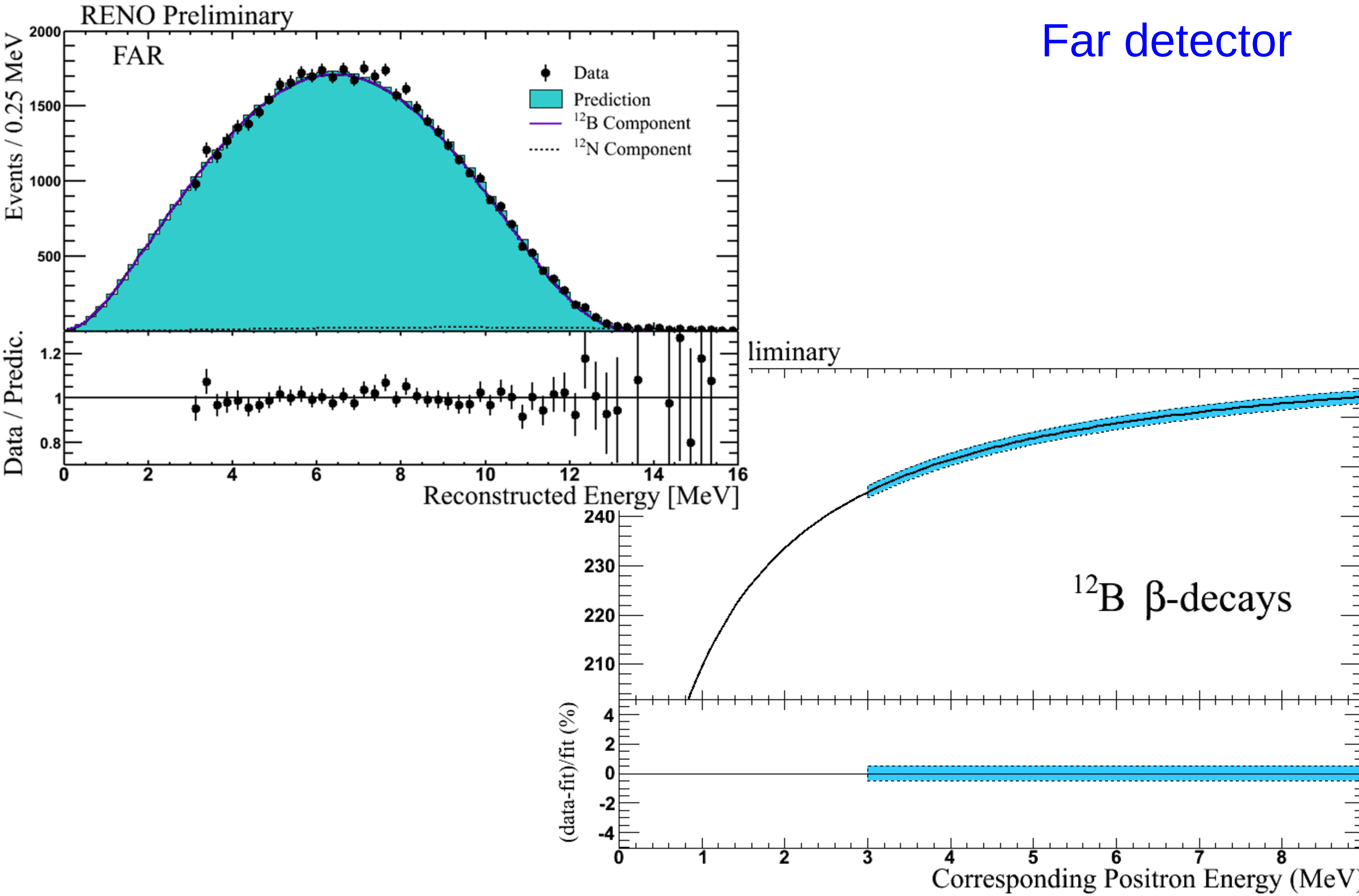
Energy Calibration from B12 β-decays

Near detector

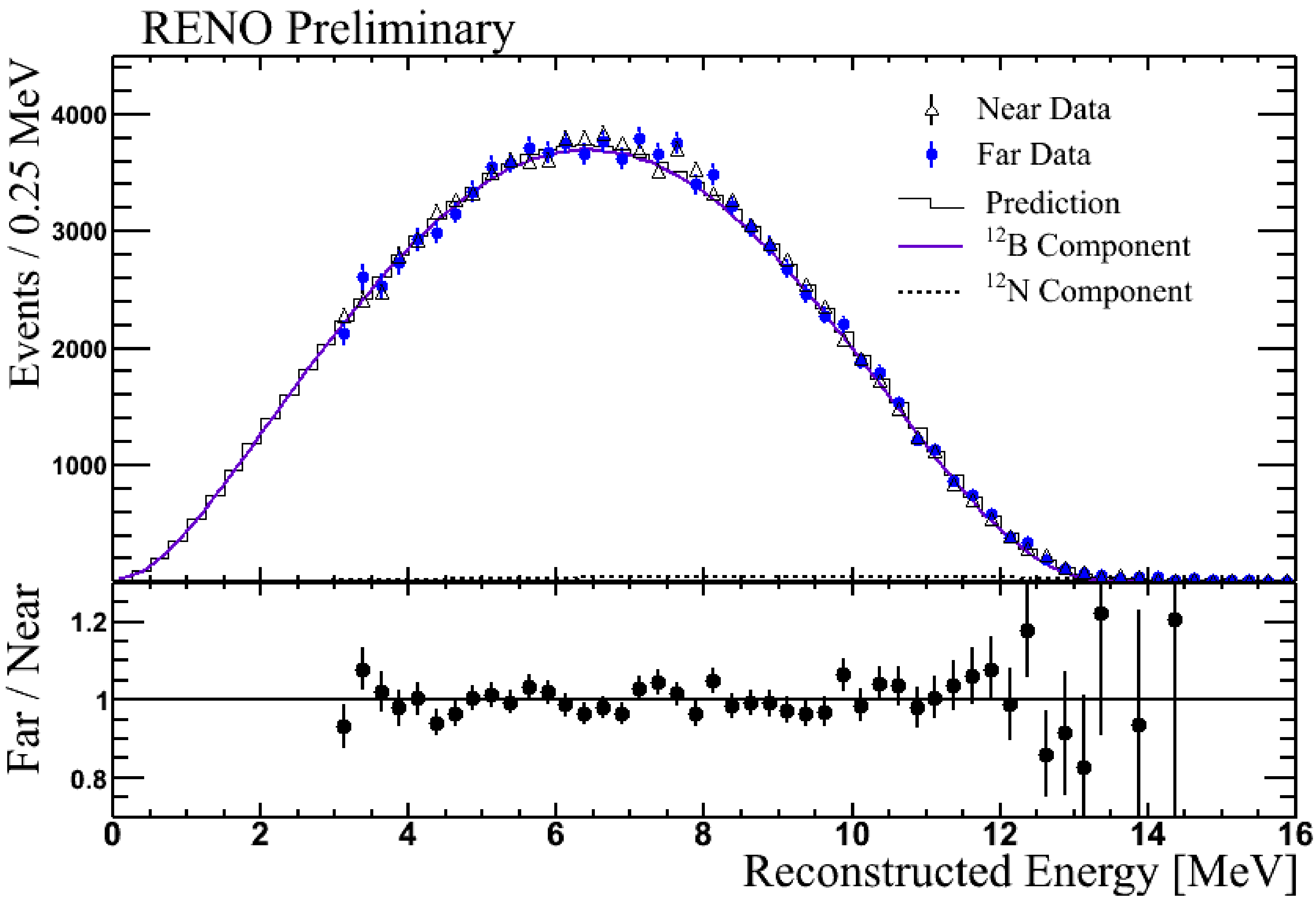


Energy Calibration from B12 β-decays

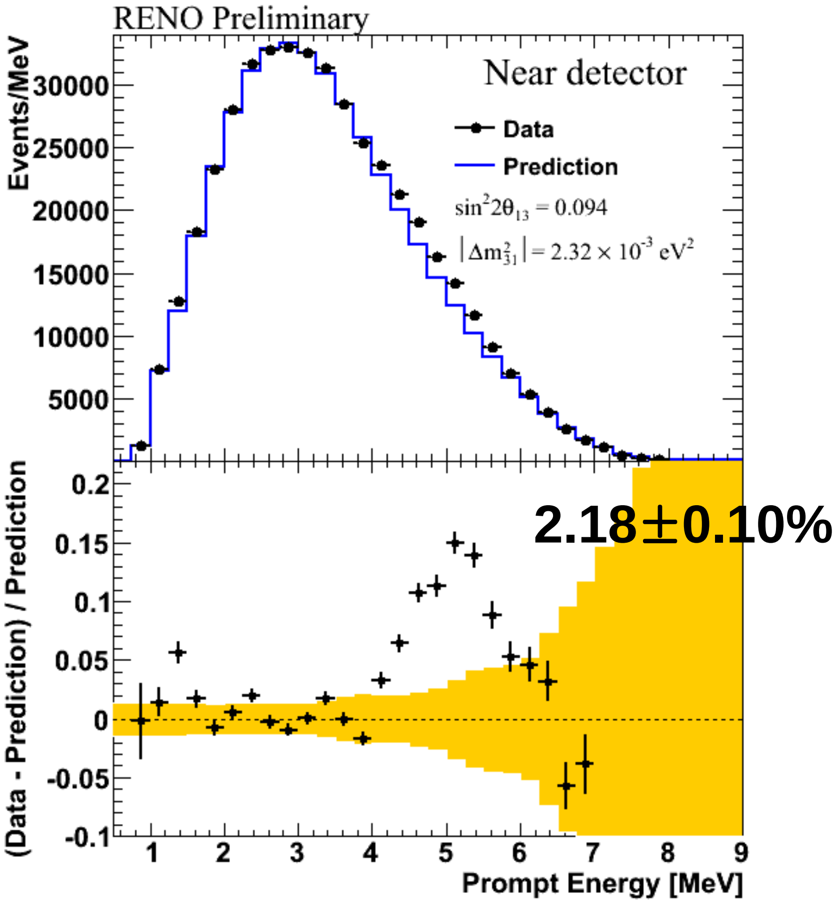
Far detector

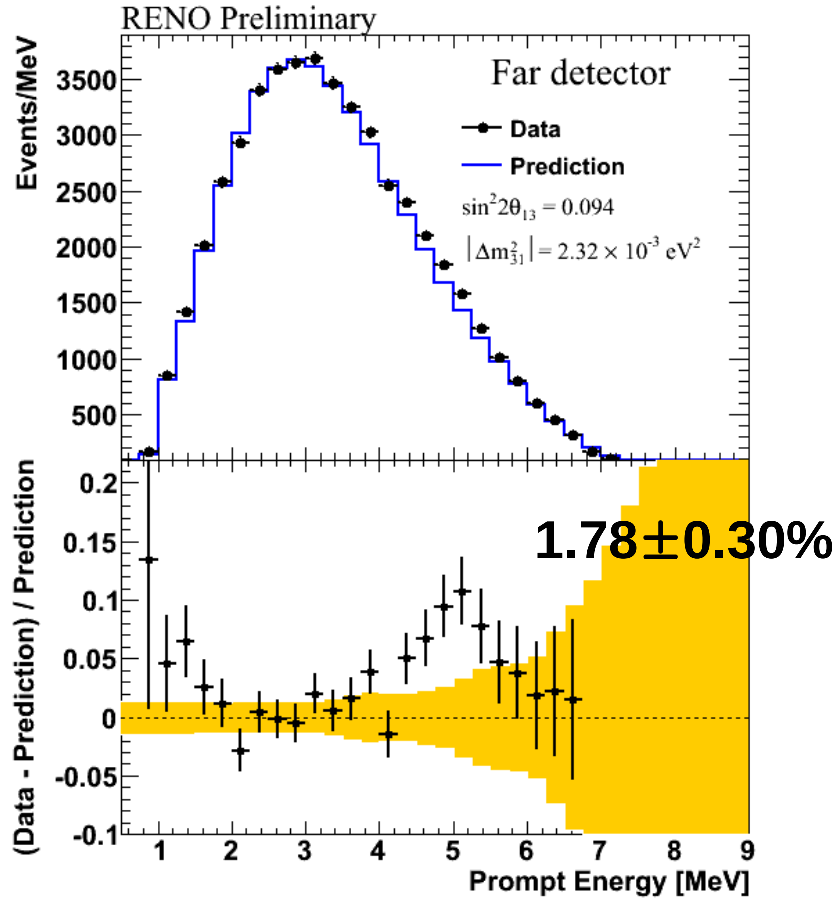


B12 Energy Spectrum (Near & Far)



Observation of a New Reactor Neutrino Component at 5 MeV

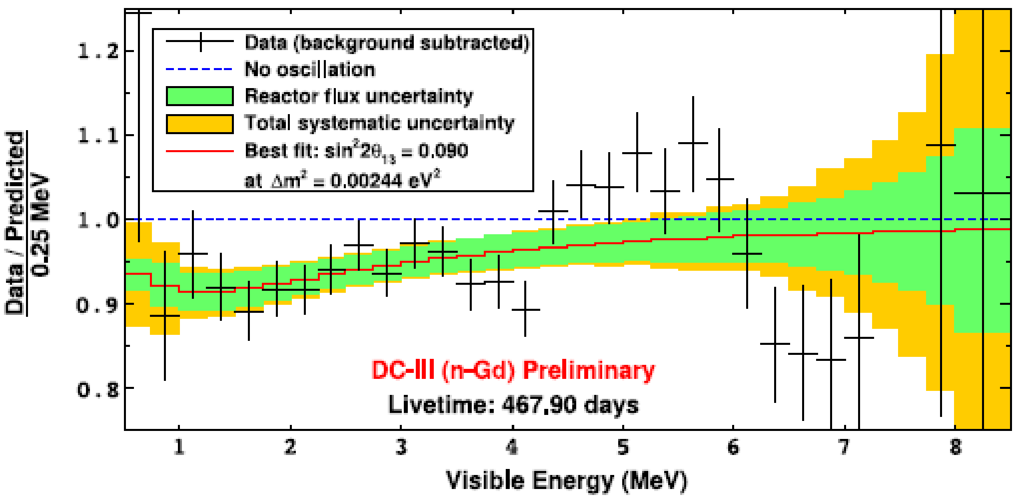




Fraction of 5 MeV excess (%) to expected flux [2011 Huber+Mueller]

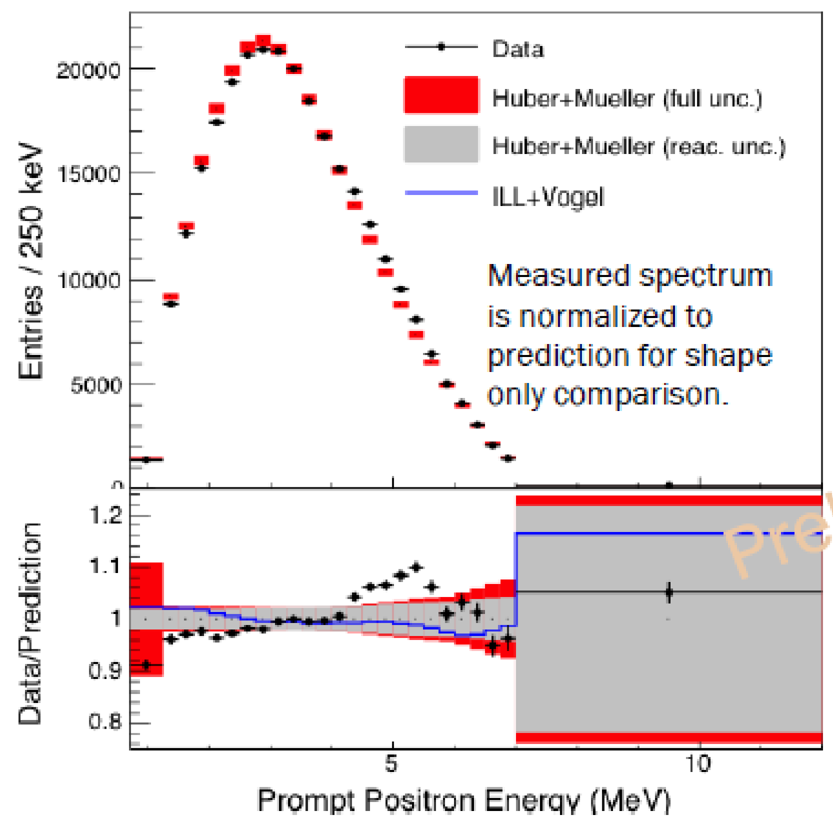
- Near : 2.18 ± 0.40 (experimental) ± 0.49 (expected shape error)
- Far : 1.78 ± 0.71 (experimental) ± 0.49 (expected shape error)

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

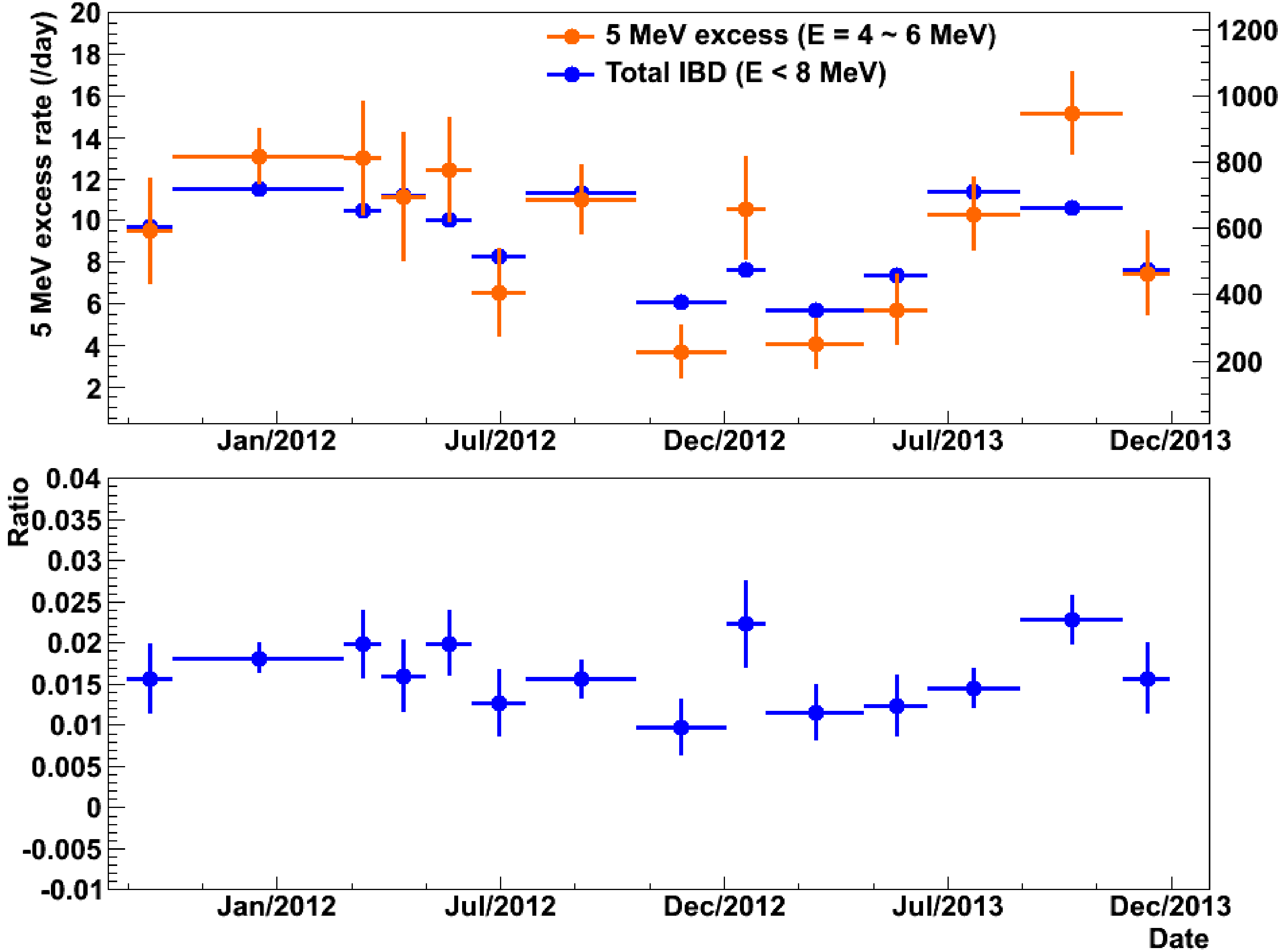


Double-Chooz, Neutrino 2014

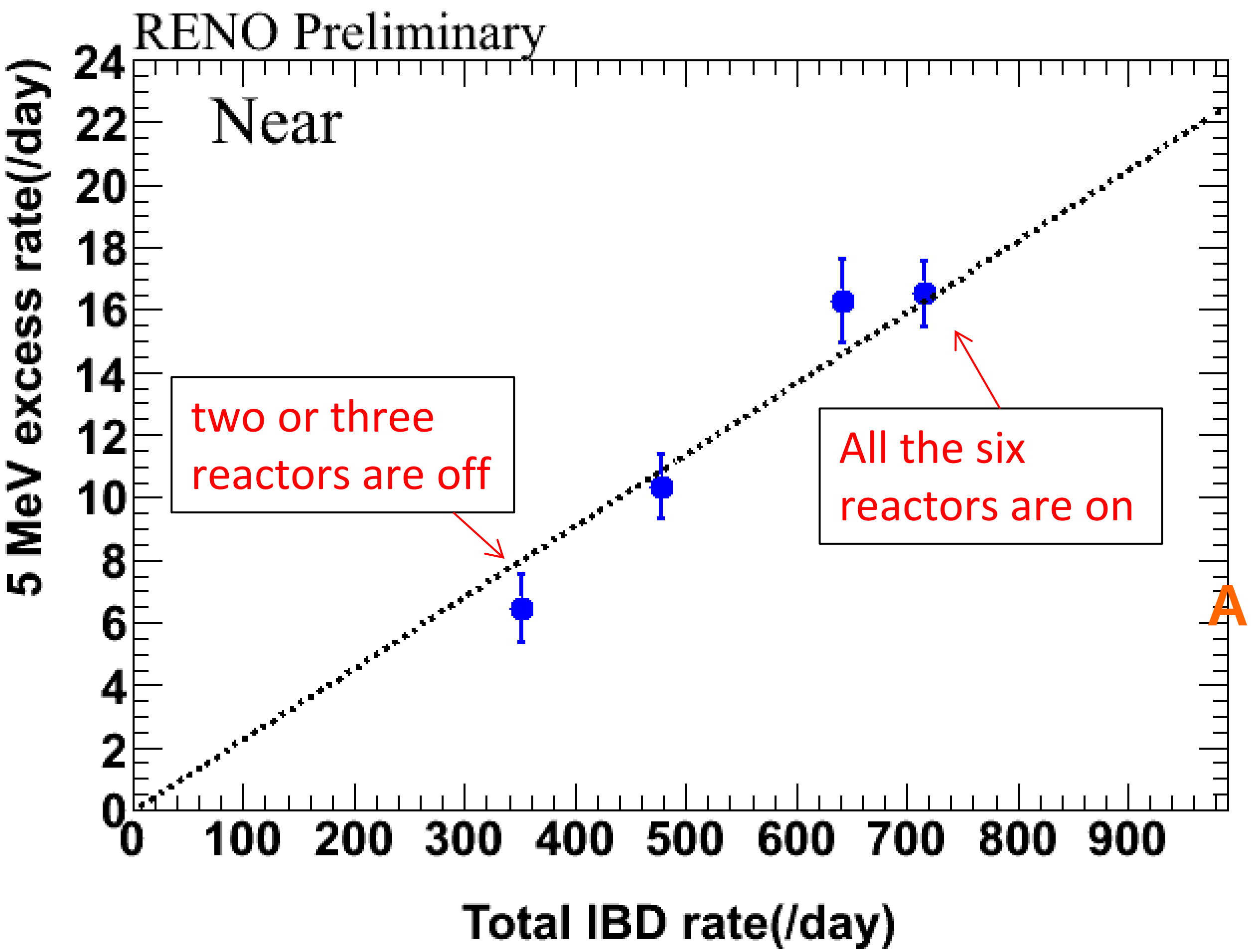
Daya Bay, ICHEP 2014



Correlation of 5 MeV Excess with Reactor Power



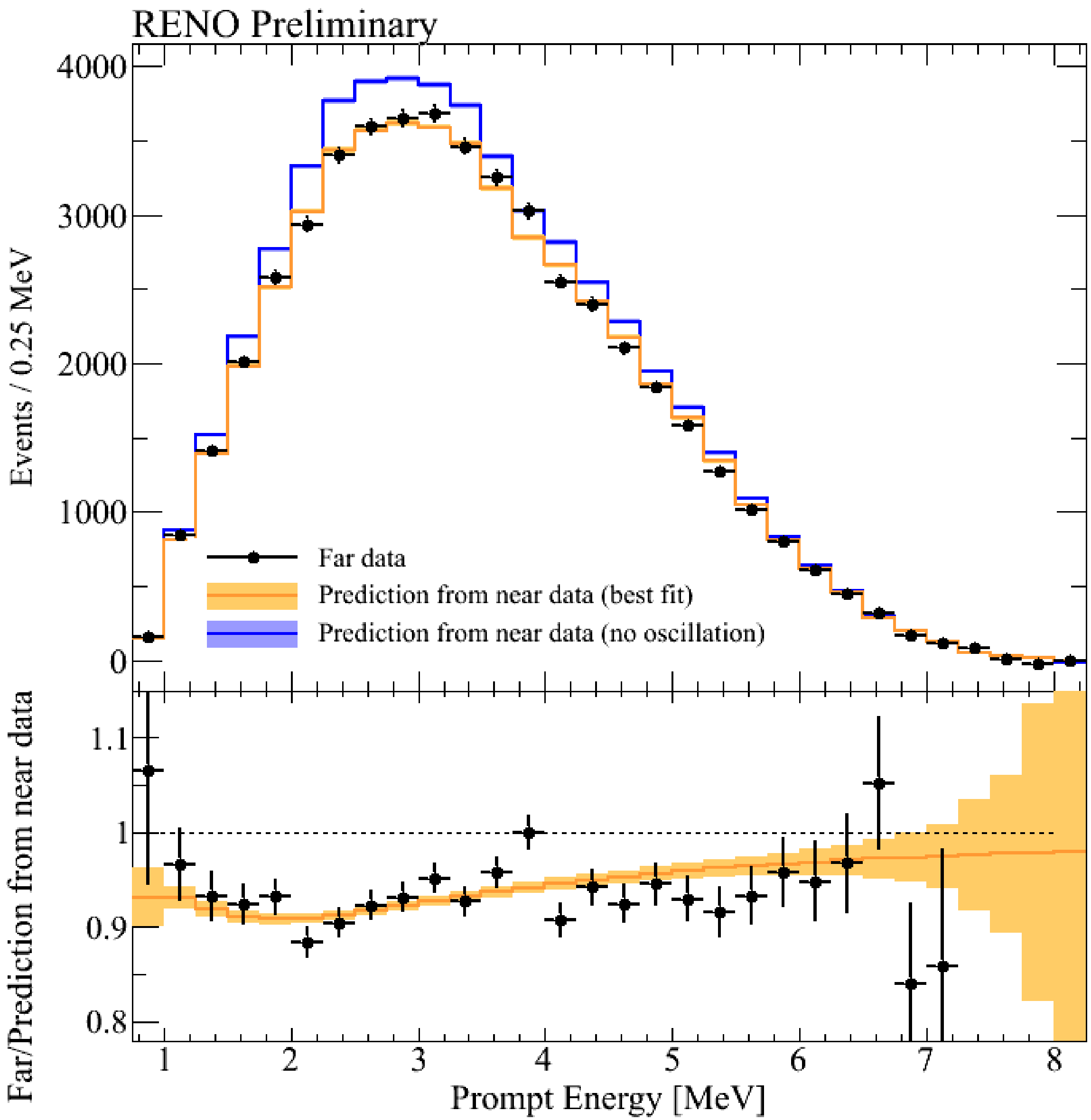
Correlation of 5 MeV Excess with Reactor Power



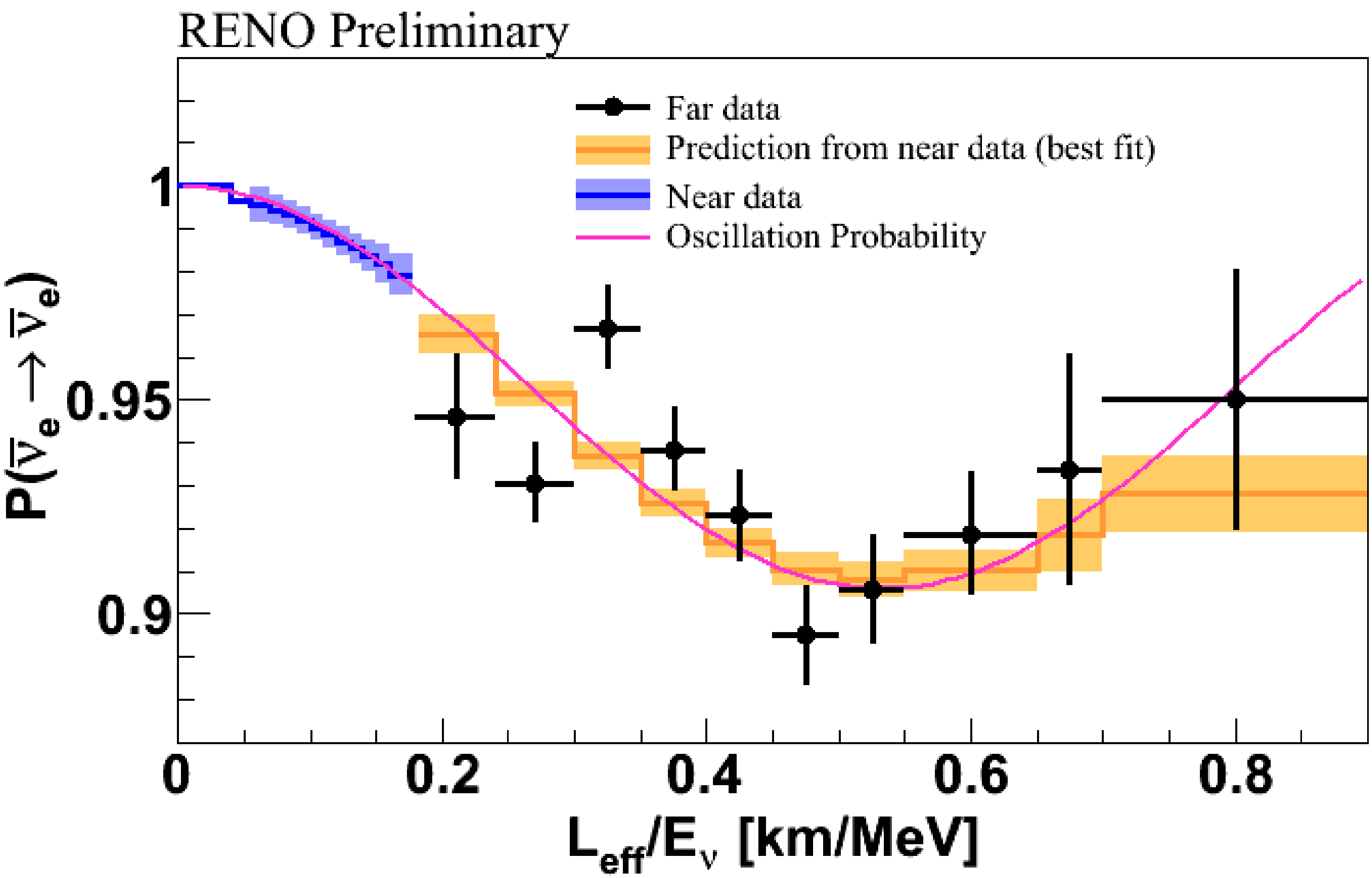
5 MeV excess has a clear correlation with reactor thermal power !

A new reactor neutrino component !!

Far/Near Shape Analysis for Δm_{ee}^2



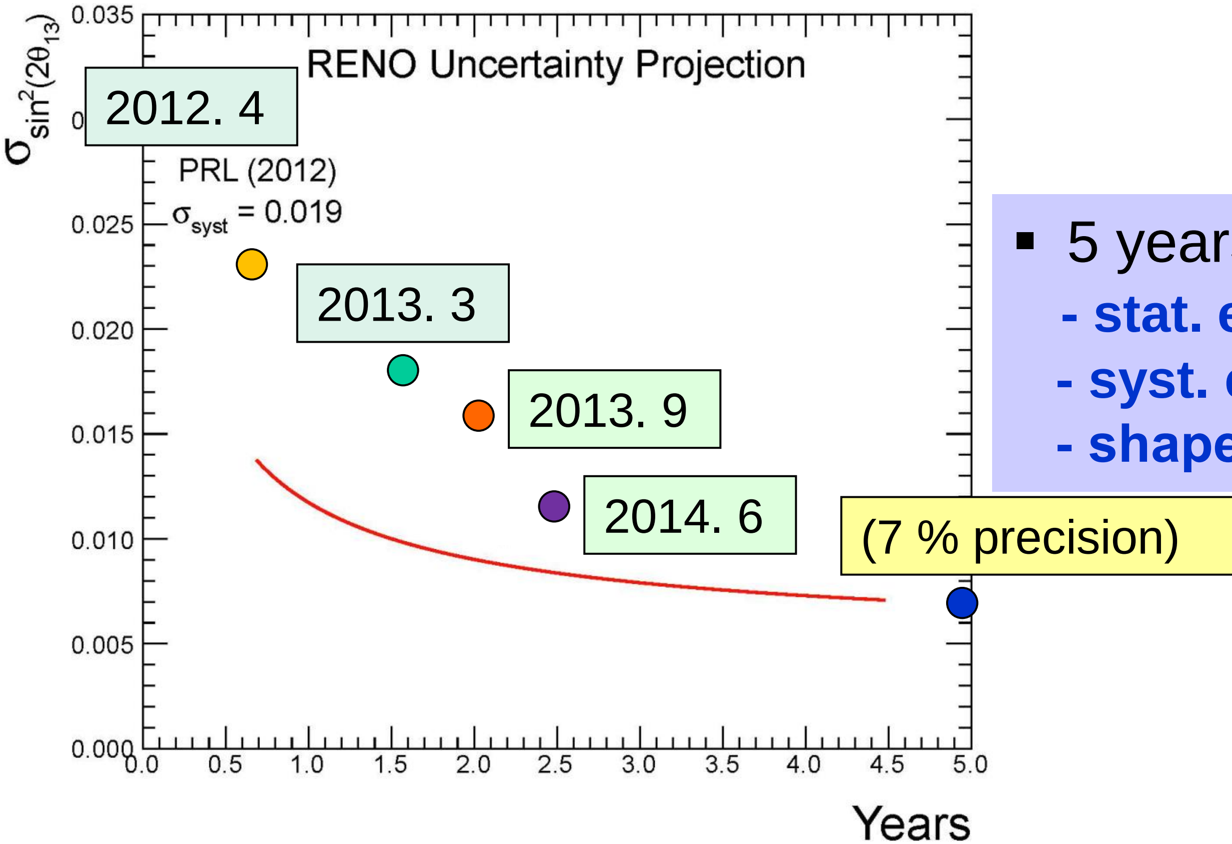
Reactor Neutrino Disappearance on L/E



RENO's Projected Sensitivity of θ_{13}

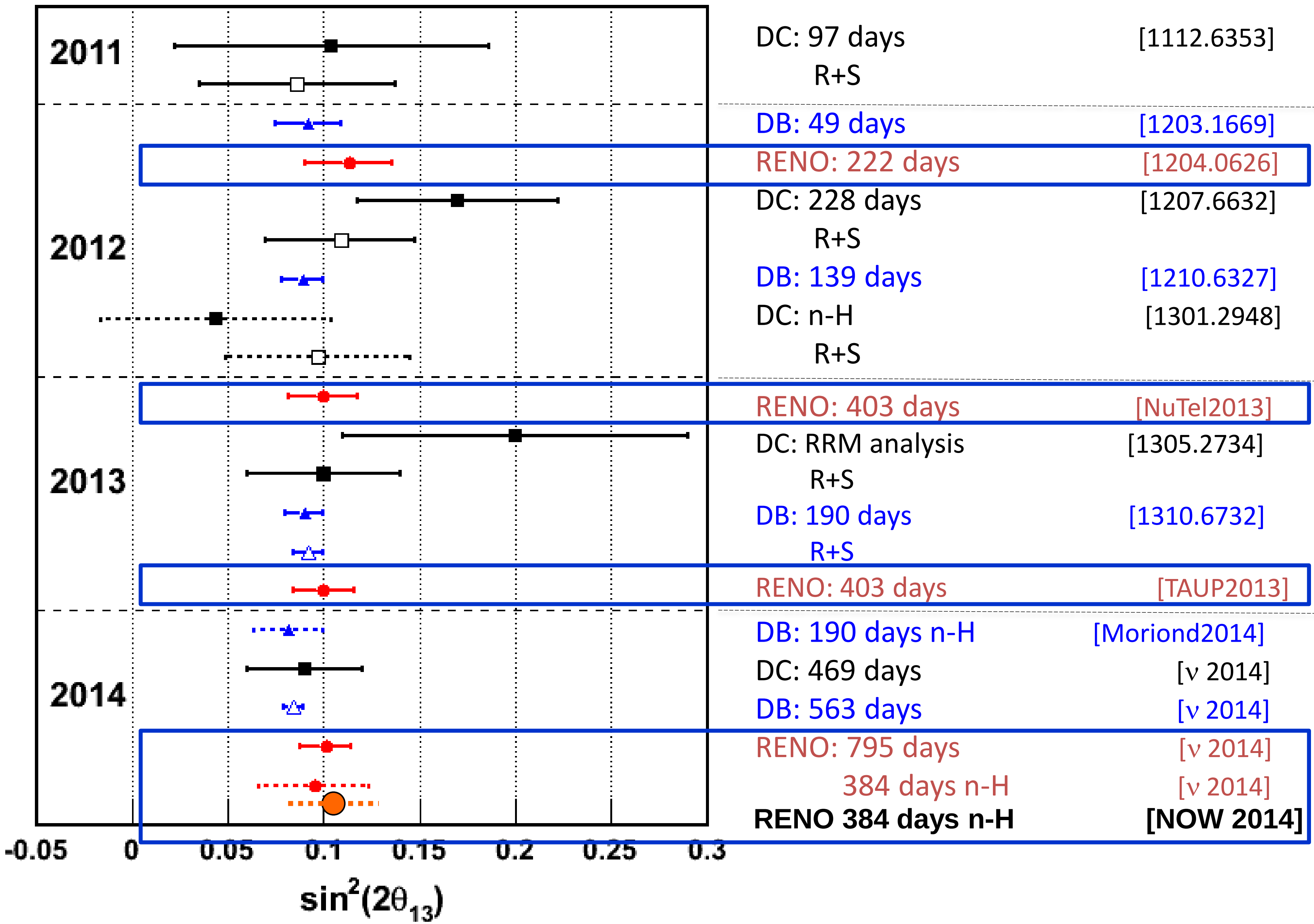
Neutrino 2014 $\sin^2 2\theta_{13} = 0.101 \pm 0.008(stat.) \pm 0.010(syst.)$

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

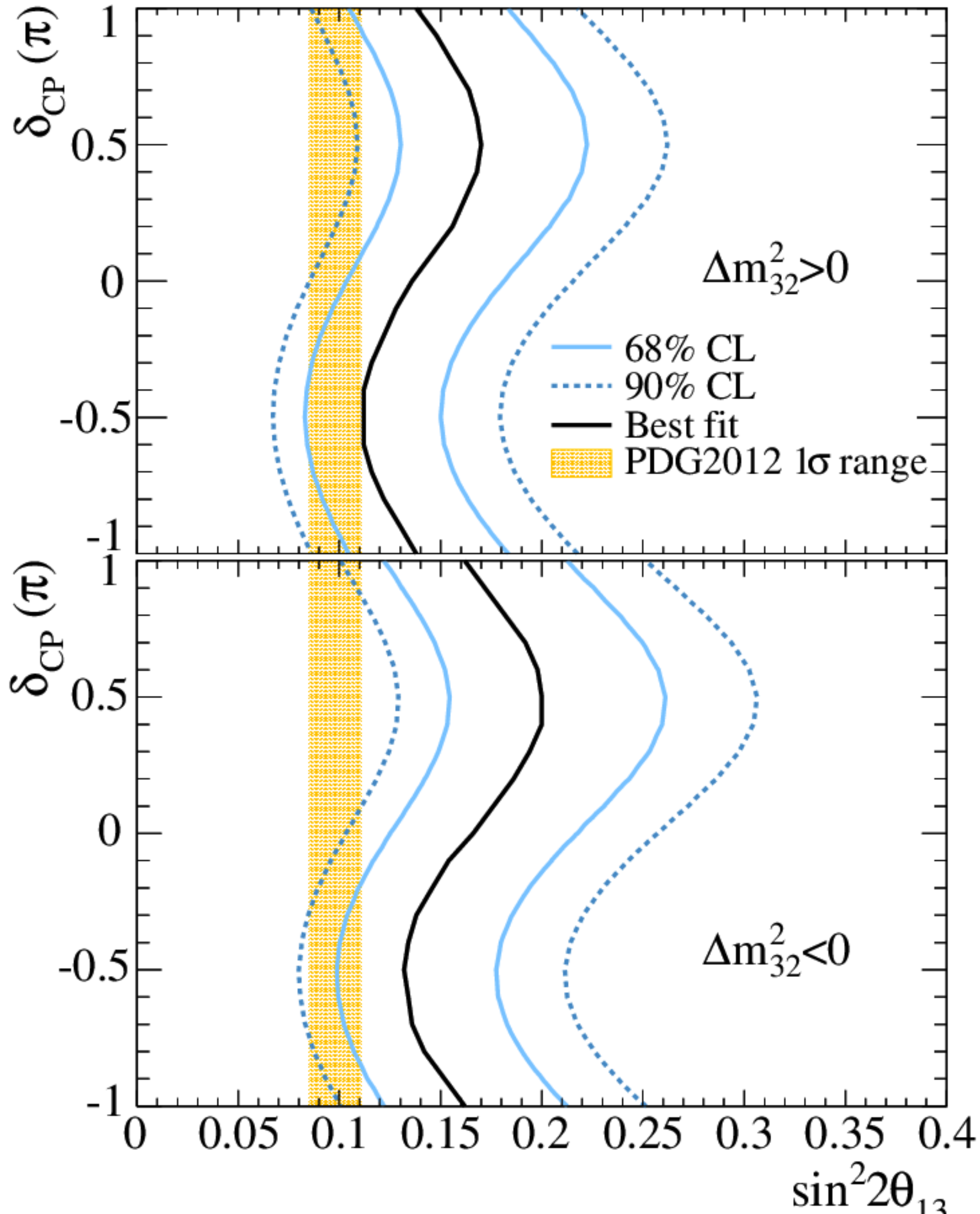


- 5 years of data : ±7%
  - stat. error : ±0.008 → ±0.005
  - syst. error : ±0.010 → ±0.005
  - shape information → ±5%

A Brief History of θ_{13} from Reactor Experiments



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}

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 in progress… (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
  $\rightarrow$ will provide the first glimpse of $\delta_{CP.}$
  If accelerator results are combined.

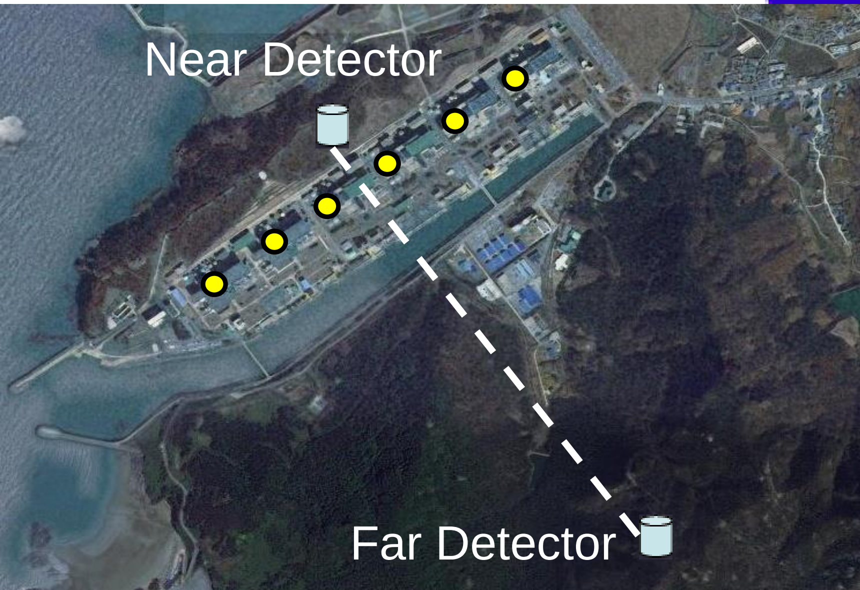
Overview of RENO-50

- **RENO-50** : An underground detector consisting of 18 kton ultra-low-radioactivity liquid scintillator & 15,000 20” PMTs, at 50 km away from the Hanbit(Yonggwang) nuclear power plant

- **Goals** : - Determination of neutrino mass hierarchy
  - High-precision measurement of θ_{12}, Δm^2_{21} and Δm^2_{31}
  - Study neutrinos from reactors, the Sun, the Earth, Supernova, and any possible stellar objects

- **Budget** : $ 100M for 6 year construction
  (Civil engineering: $ 15M, Detector: $ 85M)

- **Schedule** : 2014 ~ 2019 : Facility and detector construction
  2020 ~ : Operation and experiment



RENO

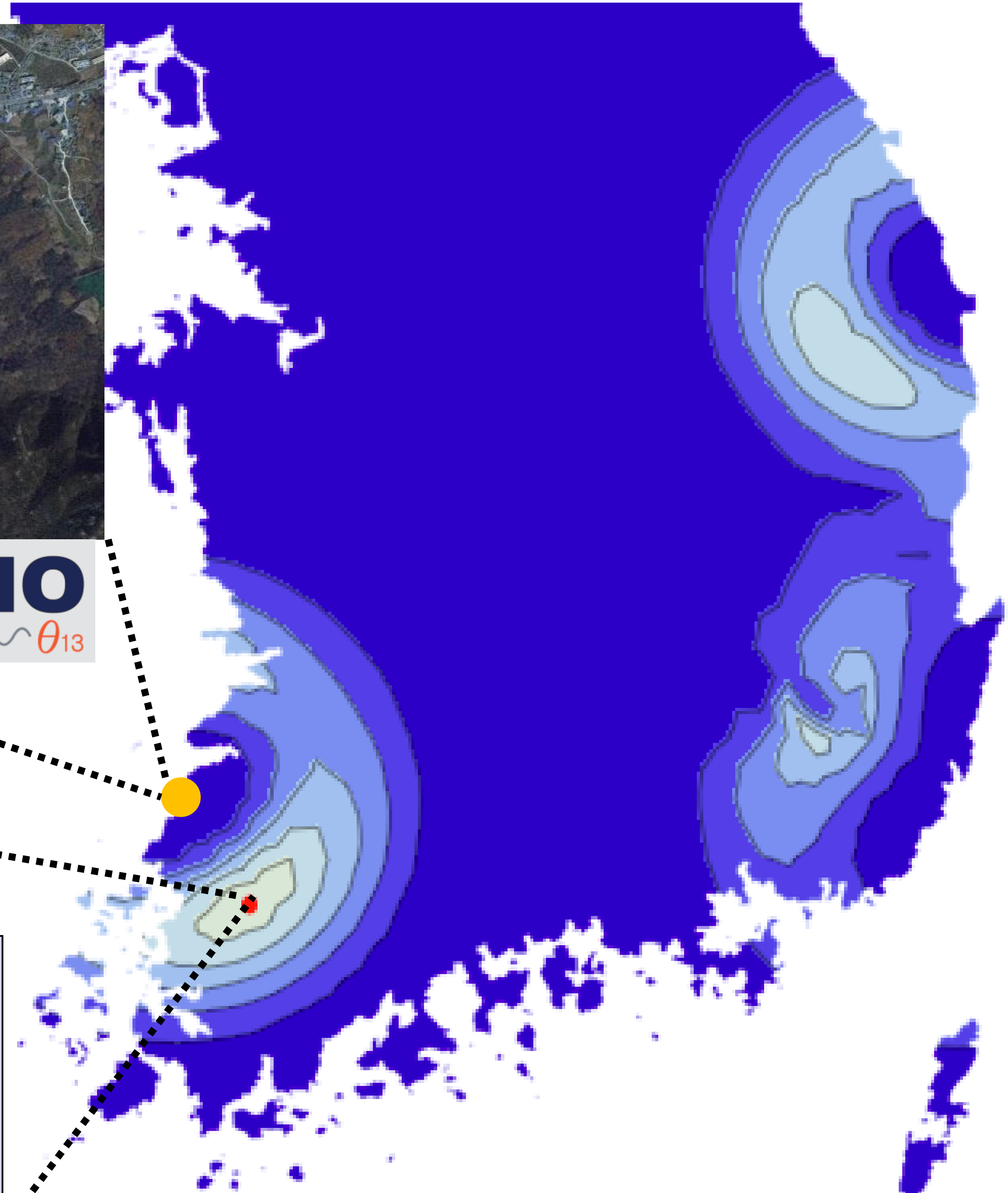
(NEAR Detector)

(FAR Detector)

RENO-50

10 kton LS Detector
~47 km from YG reactors

Mt. Guemseong (450 m)
~900 m.w.e. overburden



2012 Particle Data Book

LEPTONS

Neutrino Mixing

$\sin^2(2\theta_{12}) = 0.857 \pm 0.024$ **(±2.8%)**

$\Delta m^2_{21} = (7.50 \pm 0.20) \times 10^{-5}\ \mathrm{eV}^2$ **(±2.7%)**

$\sin^2(2\theta_{23}) > 0.95$ [i] **(±3.1%)**

$\Delta m^2_{32} = (2.32^{+0.12}_{-0.08}) \times 10^{-3}\ \mathrm{eV}^2$ [j] **(+5.2-3.4%)**

$\sin^2(2\theta_{13}) = 0.098 \pm 0.013$ **(±13.3%)**

$\sin^2\theta_{12} = 0.312 \pm 0.017$ **(±5.4%)**

$\Delta m_{21}{}^2 / |\Delta m_{31(32)}{}^2| \approx 0.03$

- Precise measurement of θ_{12}, Δm^2_{21} and Δm^2_{32}

$$\frac{\delta \sin^2\theta_{12}}{\sin^2\theta_{12}} < 1.0\% (1\sigma) \quad (\leftarrow 5.4\%)$$

$$\frac{\delta \Delta m^2_{21}}{\Delta m^2_{21}} < 1.0\% (1\sigma) \quad (\leftarrow 2.7\%)$$

$$\frac{\delta \Delta m^2_{32}}{\Delta m^2_{32}} < 1.0\% (1\sigma) \quad (\leftarrow 5.2\%)$$

Additional Physics with RENO-50

- Neutrino burst from a Supernova in our Galaxy
  - ~5,600 events (@8 kpc) (* NC tag from 15 MeV deexcitation γ)
  - A long-term neutrino telescope

- Geo-neutrinos : ~ 1,000 geo-neutrinos for 5 years
  - Study the heat generation mechanism inside the Earth

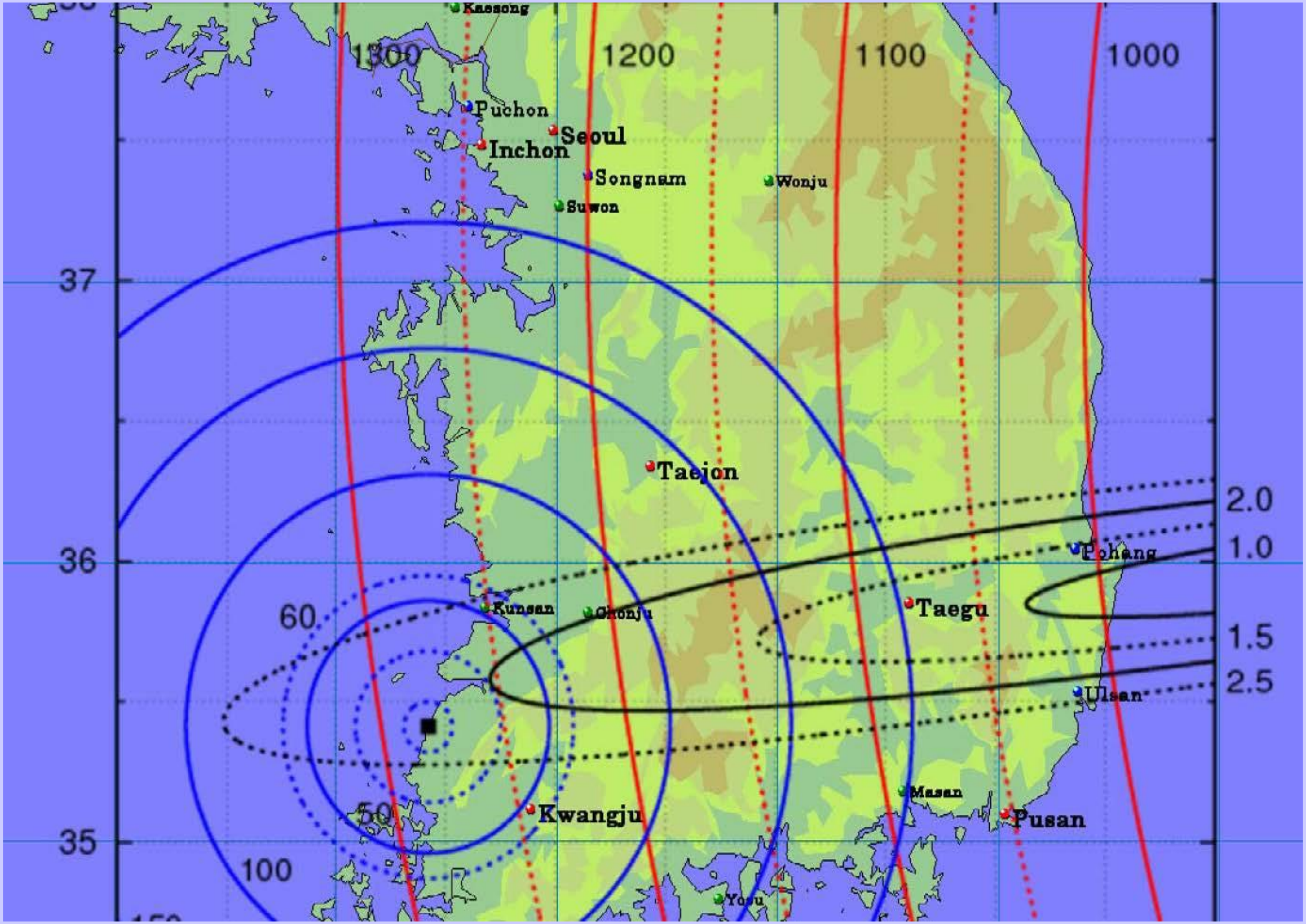
- Solar neutrinos : with ultra low radioacitivity
  - MSW effect on neutrino oscillation
  - Probe the center of the Sun and test the solar models

- Detection of J-PARC beam : ~200 events/year

- Neutrinoless double beta decay search : possible modification like KamLAND-Zen

J-PARC neutrino beam

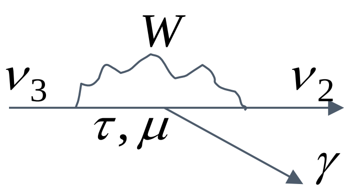
Dr. Okamura & Prof. Hagiwara



Motivation of Search for Cosmic Background Neutrino Decay

* See talks by Yuji Tacheuchi and Takuya Okudaira

- Only neutrino mass is unknown in elementary particle physics.
- Detection of neutrino decay ⇒ neutrino mass itself if combined with Δm^2 measured by neutrino oscillation experiments.



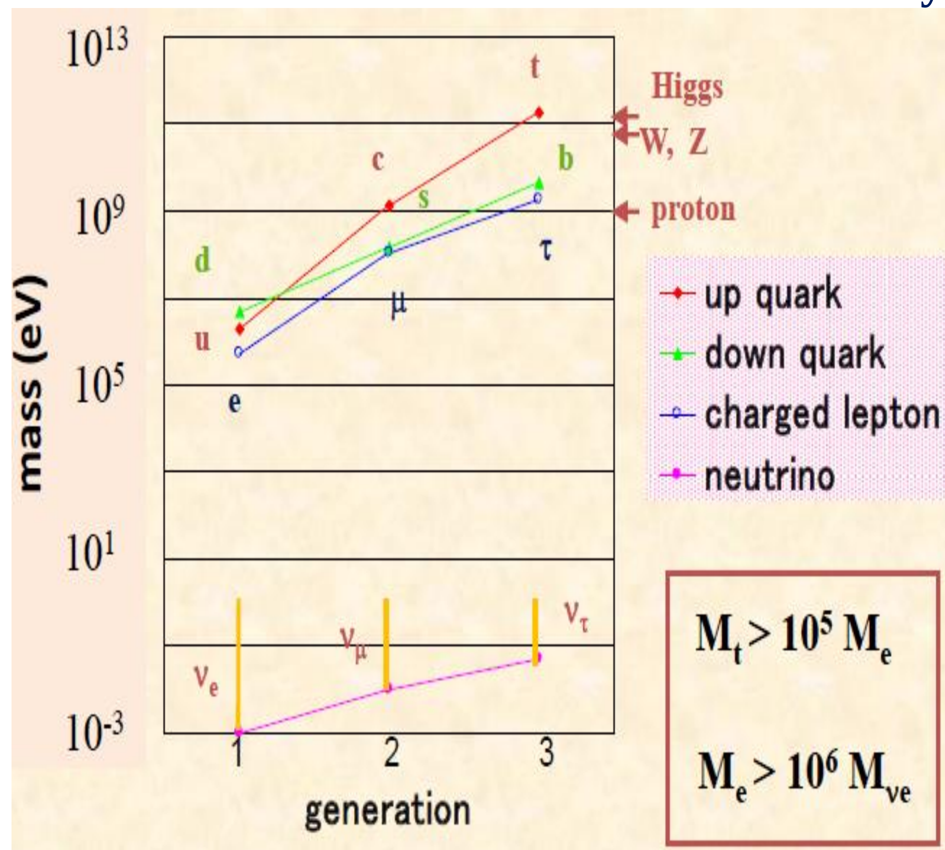
$$\nu_3 \rightarrow \nu_2 + \gamma$$

$$E_\gamma = \frac{m_3^2 - m_2^2}{2m_3} = \frac{\Delta m_{23}^2}{2m_3}$$

Using $\Delta m_{23}^2 = (2.43 \pm 0.09) \times 10^{-3}\,\mathrm{eV}^2$

$E_\gamma = 10 \sim 25\,\mathrm{meV}$ at ν_3 rest frame.

(Far-Infrared region $\lambda = 50 \sim 125\,\mu$)

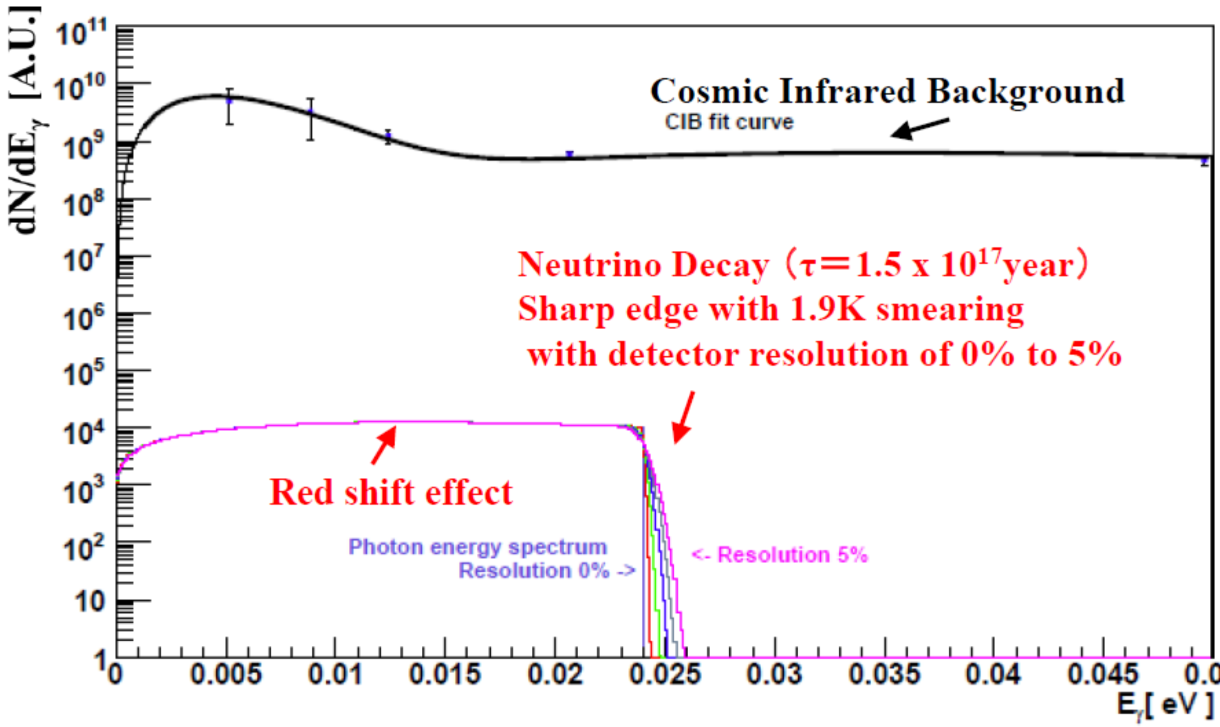


- As the neutrino lifetime is very long, we need use cosmic background neutrinos to observe the neutrino decay. Observation of neutrino decay ⇒ a discovery of the cosmic background neutrinos predicted by cosmology.

Neutrino Decay Detection Sensitivity

Cosmic Infrared Background : ~10^5 higher than neutrino decay signal expected from a lifetime of 1.5×10^{17}year (Left-Right symmetric model).

10-hour running with a telescope with 20cm diameter, a viewing angle of 0.1 degrees and 100% detection efficiency (Satellite Experiment)



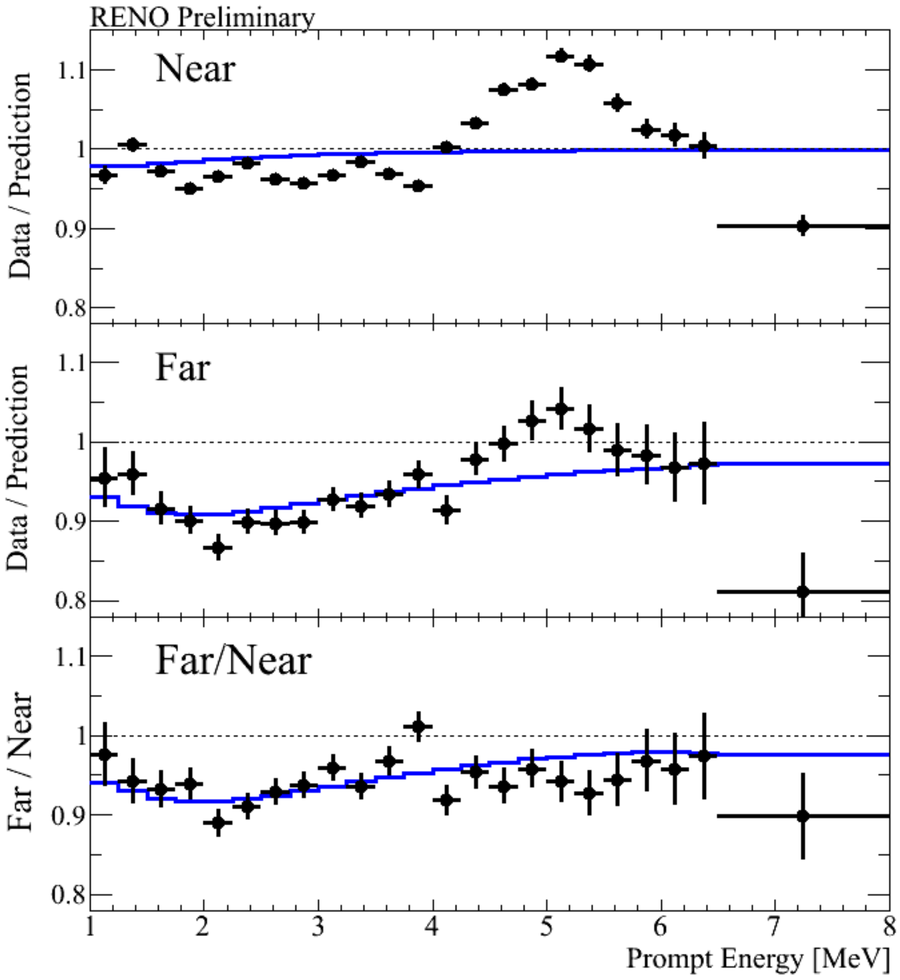
- Need the energy resolution better than 2%.
- Can observe the ν_3 decay with a mass of 50meV, and a lifetime of 1.5×10^{17} year (present lifetime limit: 3×10^{12}year)
- A rocket experiment in 2017 as a preparatory trial for the satellite experiment
  → Improve lifetime limit by two orders of magnitude (~10^{14}year).
- R&D of superconducting tunnel junction (STJ) detector

Thanks for your attention!

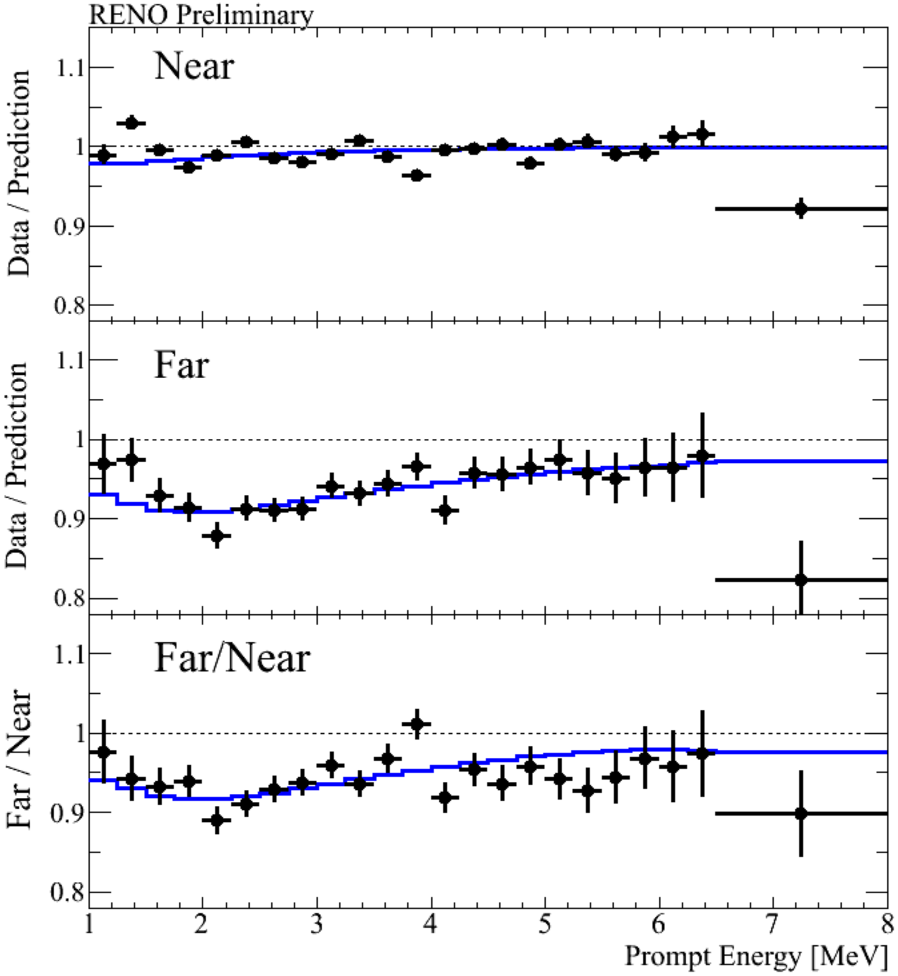
Shape Analysis for Δm_{ee}^2

In progress…. Stay tuned…

Without 5 MeV excess



With 5 MeV excess



Reactor Neutrino Oscillations at 50 km

Neutrino mass hierarchy (sign of Δm^2_{31})+precise values of θ_{12}, Δm^2_{21} & Δm^2_{31}