The RENO Experiment

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for the RENO Collaboration

K-Neutrino Symposium 2024

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Neutrino in Standard Model

- Standard Model
  - zero-mass neutrinos
- Solar neutrino problem at 1960s
- Neutrino oscillation suggested

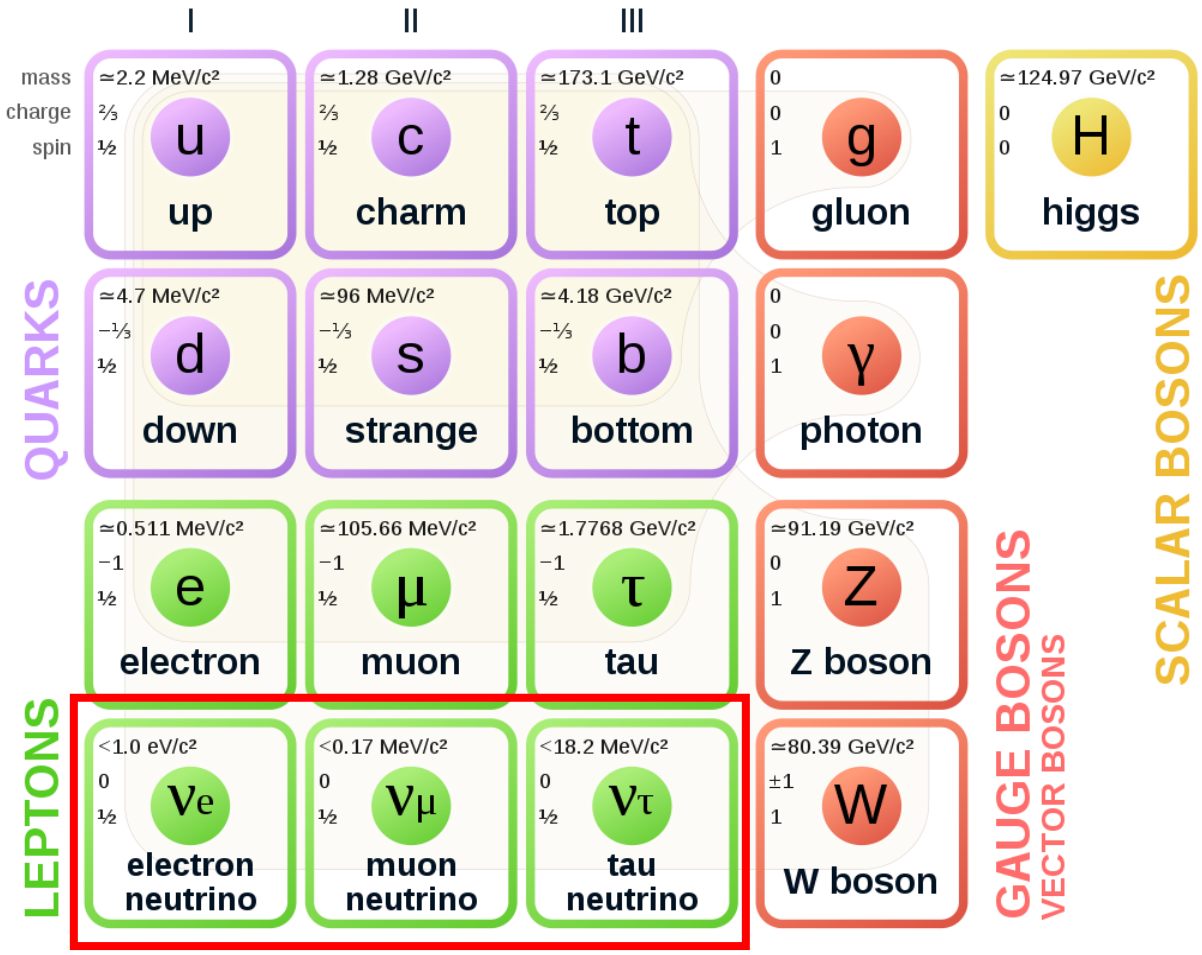


image from Google

Neutrino Oscillation

$$\begin{pmatrix} |\nu_e> \\ |\nu_\mu> \\ |\nu_\tau> \end{pmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{pmatrix} |\nu_1> \\ |\nu_2> \\ |\nu_3> \end{pmatrix}$$

PMNS matrix (θ_{12}, θ_{13}, θ_{23}, δ_{CP})

neutrino mass difference : Δm^2_{21}, Δm^2_{32}

Neutrino Mixing

The following values are obtained through data analyses based on the 3-neutrino mixing scheme described in the review "Neutrino Masses, Mixing, and Oscillations."

$\sin^2(\theta_{12}) = 0.307 \pm 0.013$
$\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}$ eV^2
$\sin^2(\theta_{23}) = 0.553^{+0.016}_{-0.024}$ (S = 1.1) (Inverted order)
$\sin^2(\theta_{23}) = 0.558^{+0.015}_{-0.021}$ (Normal order)
$\Delta m^2_{32} = (-2.529 \pm 0.029) \times 10^{-3}$ eV^2 (Inverted order)
$\Delta m^2_{32} = (2.455 \pm 0.028) \times 10^{-3}$ eV^2 (Normal order)
$\sin^2(\theta_{13}) = (2.19 \pm 0.07) \times 10^{-2}$ (S = 1.2)
δ, *CP* violating phase $= 1.19 \pm 0.22\ \pi$ rad (S = 1.2)
$\langle \Delta m^2_{21} - \Delta \overline{m}^2_{21} \rangle < 1.1 \times 10^{-4}$ eV^2, CL = 99.7%
$\langle \Delta m^2_{32} - \Delta \overline{m}^2_{32} \rangle = (-0.12 \pm 0.25) \times 10^{-3}$ eV^2

https://pdg.lbl.gov/2024/tables/contents_tables.html

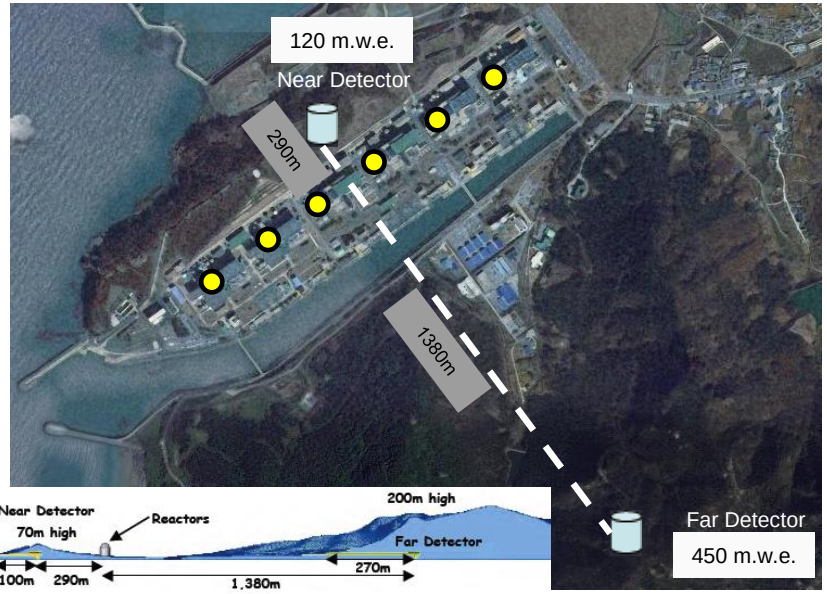
measured by the reactor experiments : RENO, Daya Bay, Double Chooz

RENO

- Reactor Experiment for Neutrino Oscillation
- reactor $\bar{\nu}_e$ oscillation at Hanbit Nuclear Plant
- 9 institution and 40 physicsists

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

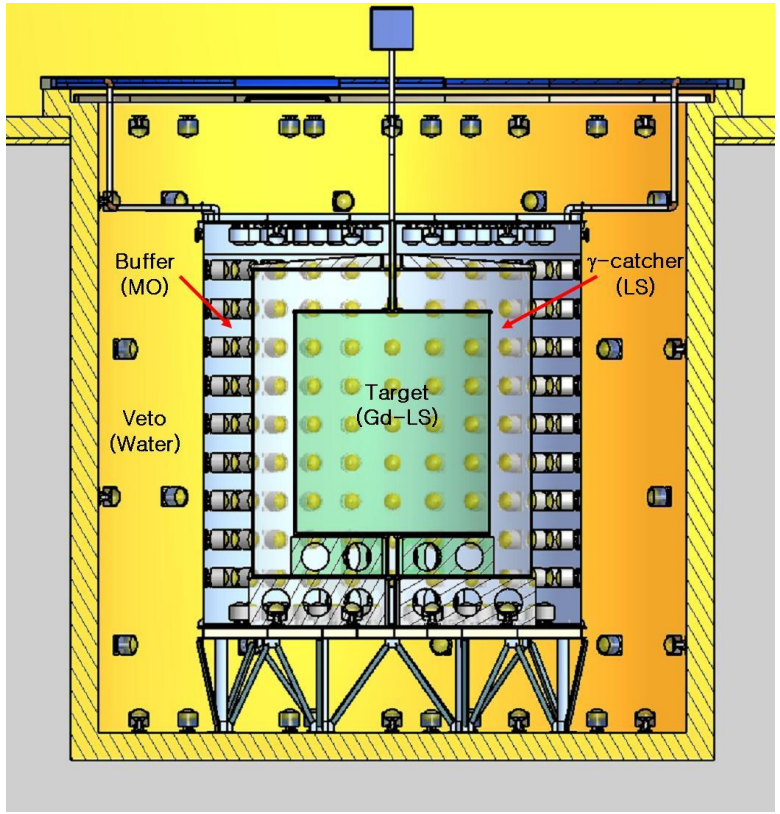
YongGwang (靈光) :



survival probability $P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - cos^4\theta_{13} sin^2 2\theta_{12} sin^2\left(\Delta m^2_{21} \frac{L}{4E_\nu}\right) - sin^2 2\theta_{13} sin^2\left(\Delta m^2_{ee} \frac{L}{4E_\nu}\right)$

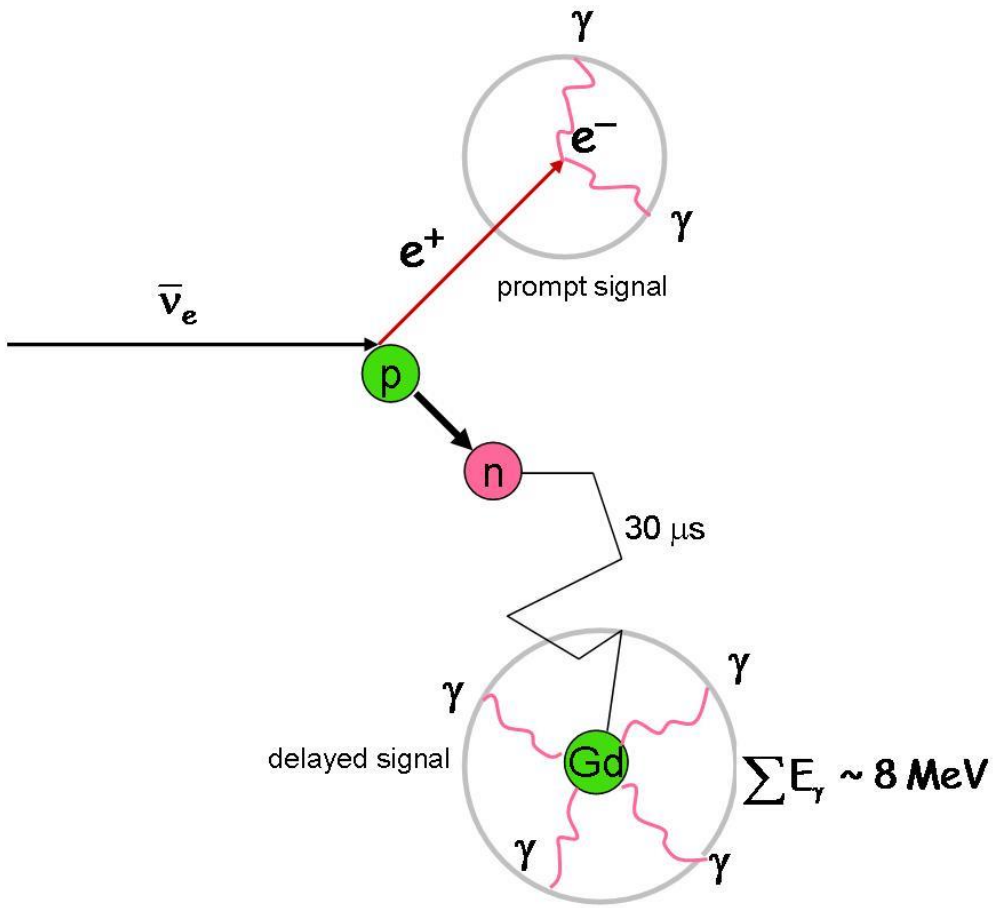
Detector & $\bar{\nu}_e$ Detection

The RENO Detectors



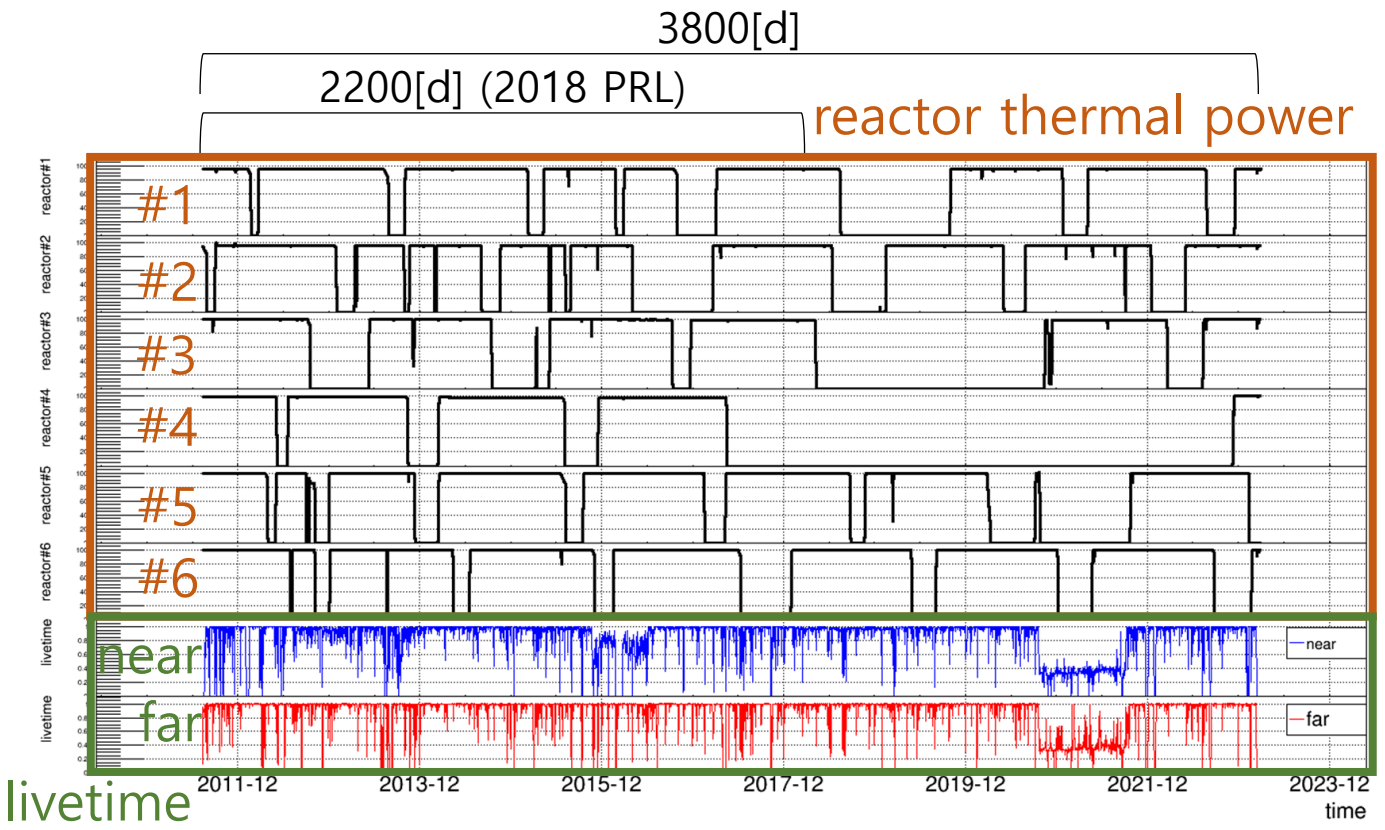
- Identical for the far & near detectors
- Multi-layered structure for their own purposes

$\bar{\nu}_e$ detection via inverse-beta-decay



RENO Status & Data Taking

- RENO DAQ running
  - Aug. 2011 ~ Mar. 2023.
- ~3800[days] livetime
- planning to re-operate DAQ of the near detector
  =>RENE experiment (sterile neutrino search)



Major Results from RENO & Future

- Precise measurement of $|\Delta m^2_{ee}|$ and θ_{13} with n-Gd capture
  - Phys. Rev. Lett. 108, 191802 (2012) - 229[d]
  - Phys. Rev. Lett. 116, 211801 (2016) - 500[d]
  - Phys. Rev. D 98, 012002(2018) - 500[d]
  - Phys. Rev. Lett. 121, 201801 (2018) - 2200[d]
  - 3800[d] days of data -> new result
- Measurement of θ_{13} with n-H capture
  - JHEP 04 029 (2020) - 1500[d]
  - 2800[d] days of data
- reactor neutrino yield & spectrum
  - Phys. Rev. Lett. 122, 232501 (2019) - 1800[d]
  - Phys. Rev. D 104, L111301 (2021) - 2500[d]
  - 2500[d] days of data / fuel composition
- sterile neutrino search
  - Phys. Rev. Lett. 125, 191801 (2020) - 2200[d]
  - Phys. Rev. D 105, L111101 (2022) - 2500[d] x NEOS 180[d]

will be finished with 3800[d] analyses.

will be continued beyond 3800[d] analyses according to re-operation of the near detector.

IBD Candidate Sample & Background Estimation

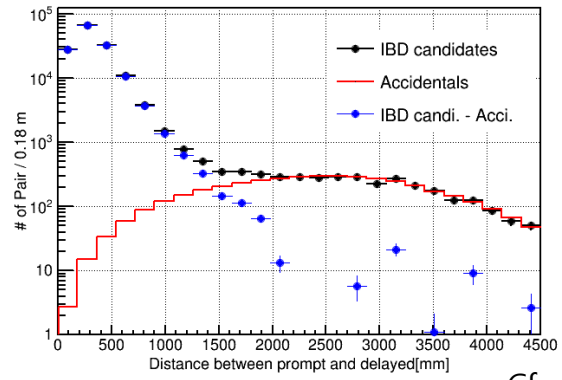
- 1,211,995(144,667) $\bar{\nu}_e$ candidate events observed for near(far).

- The total background rates :
  - near : 9.08±0.18 [events/day] (2.5%)
  - far : 2.06±0.13 [events/day] (5.3%)

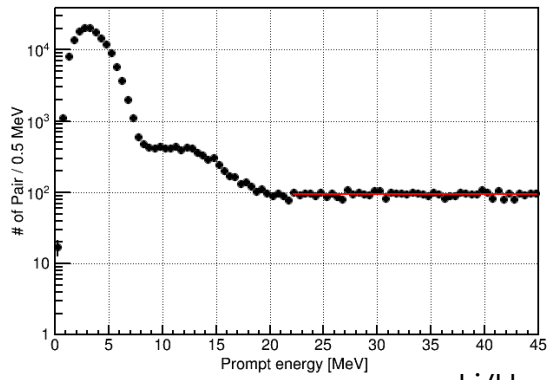
Detector	Near	Far
IBD rate	366.47 ± 0.33	38.70 ± 0.10
after background subtraction	357.39 ± 0.38	36.64 ± 0.16
total background rate	9.08 ± 0.18	2.06 ± 0.13
live time [days]	3307.25	3737.85

measured IBD and estimated background rates with 1.2 < E_p < 8.0 [MeV], given per day

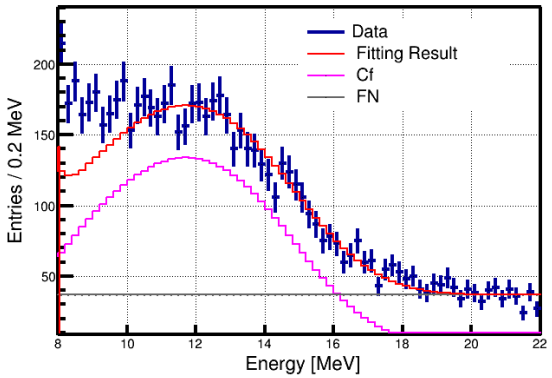
accidental



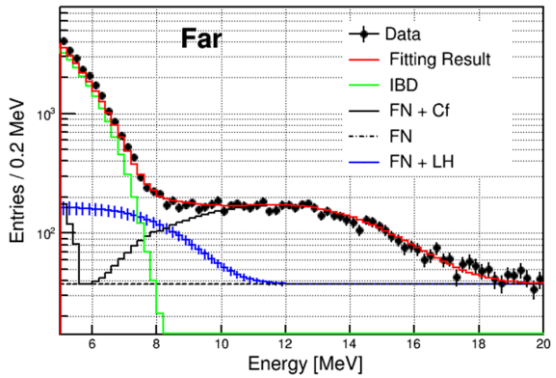
fast neutron



Cf

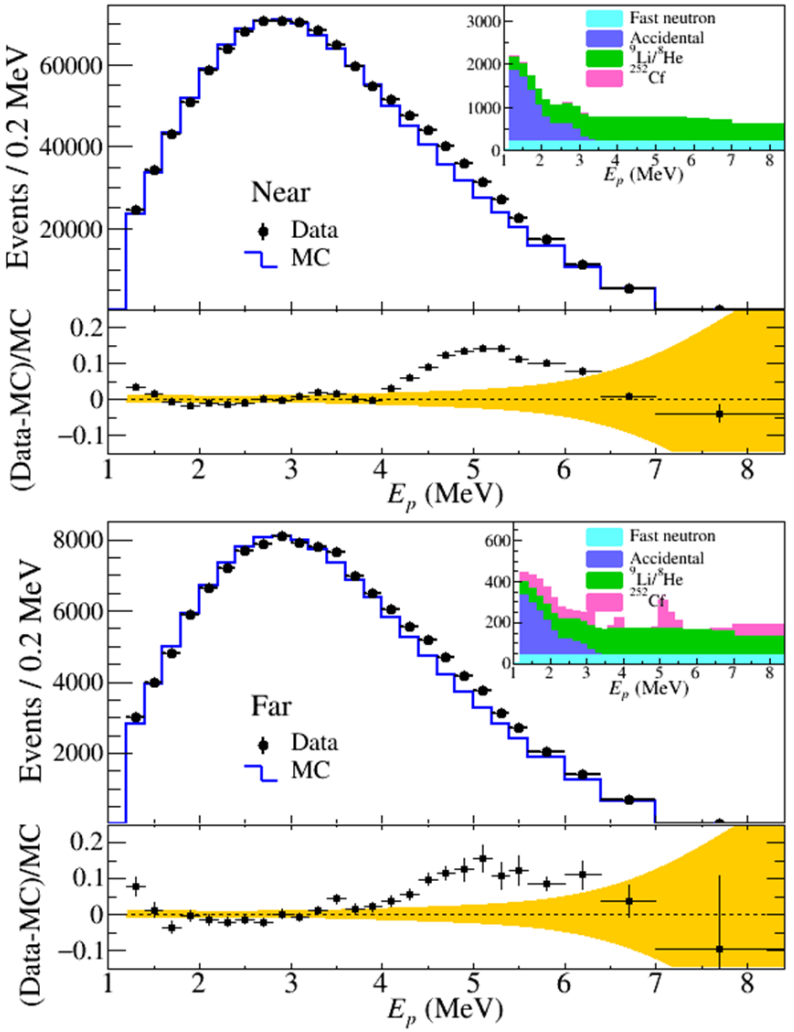


Li/He



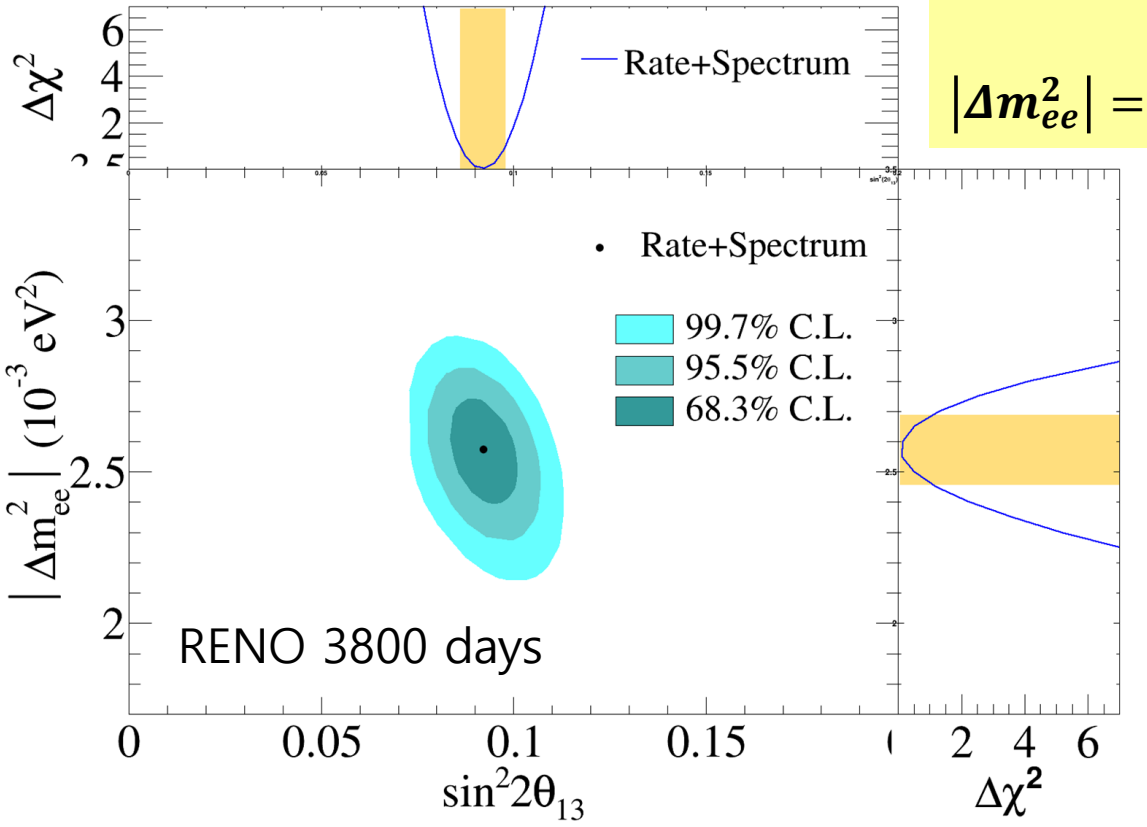
IBD Prompt Spectrum

- A shape comparison between the observed IBD prompt spectrum and the prediction from a reactor $\bar{\nu}_e$ model
  - data : observed IBD prompt spectrum after background subtraction
  - MC : prediction with best-fit oscillation
- The fractional difference between data and prediction in the lower panel
- A clear discrepancy between the observed and the predicted spectral shapes in the region of 5 [MeV]



Results of $|\Delta m^2_{ee}|$ and θ_{13}

Based on the measured far-to-near ratio of prompt spectra from the 3800[d] sample,



$$\boldsymbol{sin^2 2\theta_{13} = 0.0920\ ^{+0.0044}_{-0.0042}(stat.)\ ^{+0.0041}_{-0.0041}(syst.)}$$ (6.4% precision)

$$\boldsymbol{|\Delta m^2_{ee}| = 2.57\ ^{+0.10}_{-0.11}(stat.)\ ^{+0.05}_{-0.05}(syst.)[\times 10^{-3} eV^2]}$$ (4.5% precision)

source of the systematic uncertainty

	Δm^2_{ee} $[10^{-3}eV^2]$	$sin^2 2\theta_{13}$ []
reactor	-	± 0.0013
detection efficiency	-	± 0.0032
energy scale	± 0.05	± 0.0016
backgrounds	± 0.02	± 0.0020

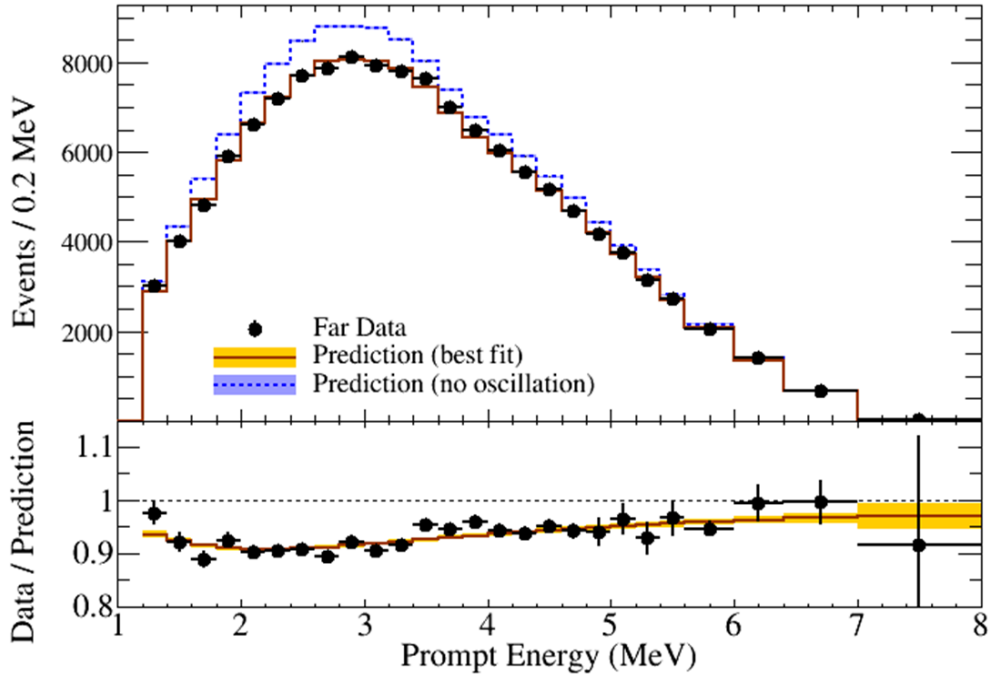
(reference) 2018 PRL

$sin^2 2\theta_{13} = 0.0896 \pm 0.0048(stat.) \pm 0.0047(syst.)$

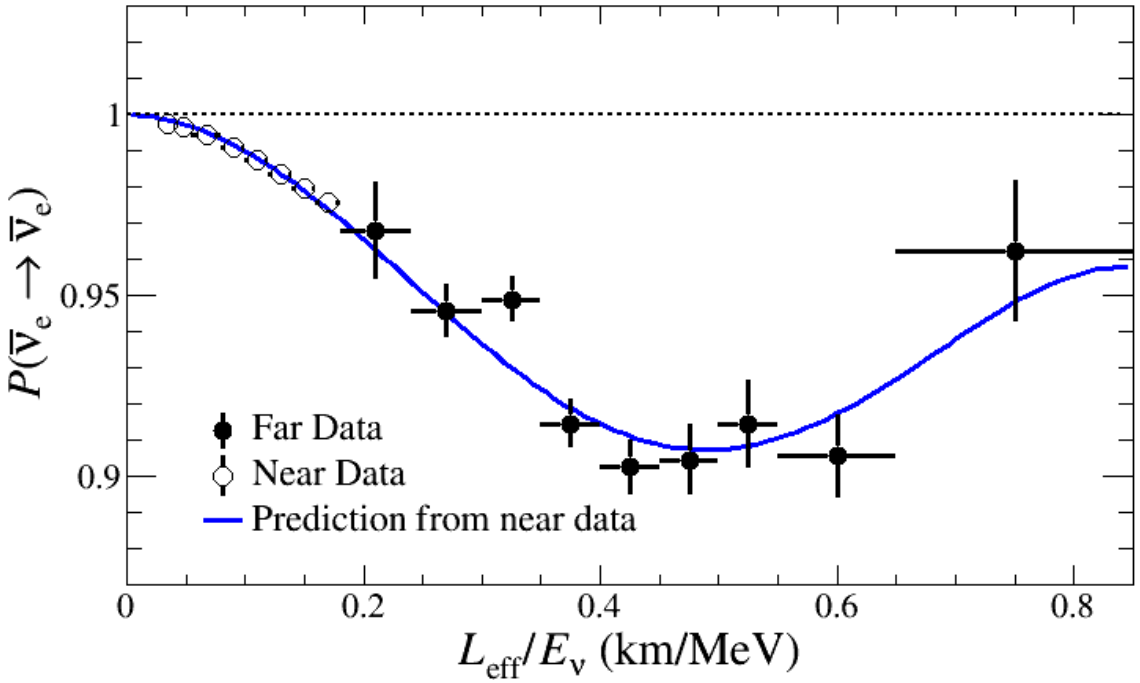
$|\Delta m^2_{ee}| = 2.68 \pm 0.12(stat.) \pm 0.07(syst.)[\times 10^{-3} eV^2]$

Energy & L/E Dependent $\bar{\nu}_e$ Oscillation

Energy-dependent disappearance of reactor $\bar{\nu}_e$



observed L/E dependent oscillation



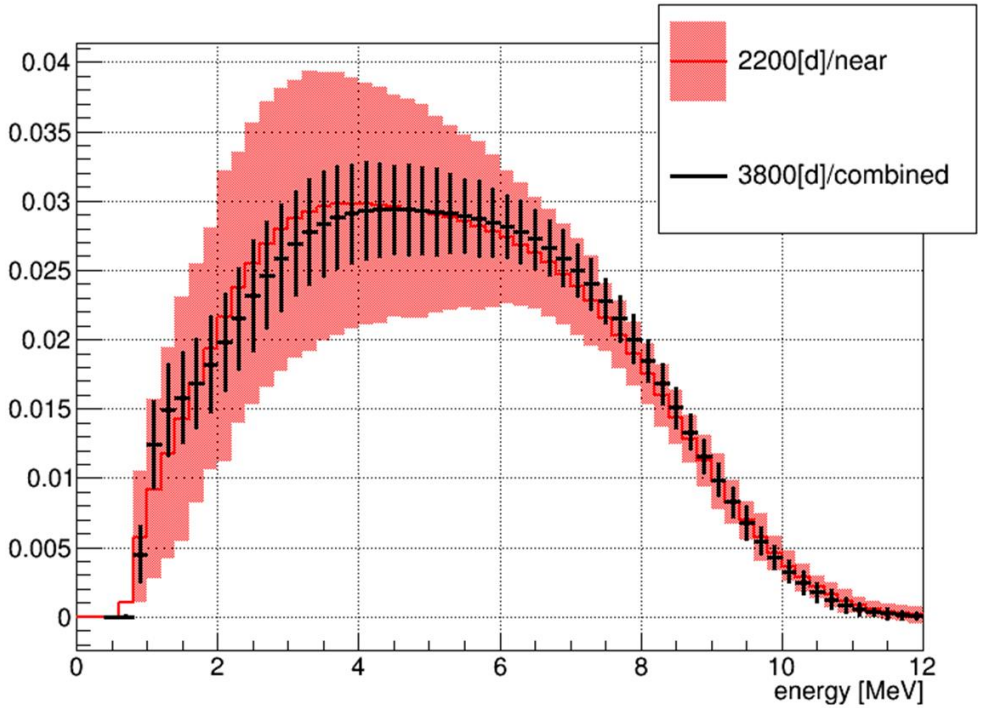
$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - sin^2 2\theta_{13} sin^2\left(\Delta m^2_{ee} \frac{L}{4E_\nu}\right)$$

Improvement

- Li/He Background Spectrum
  - extension of dataset
  - combined far & near spectrum

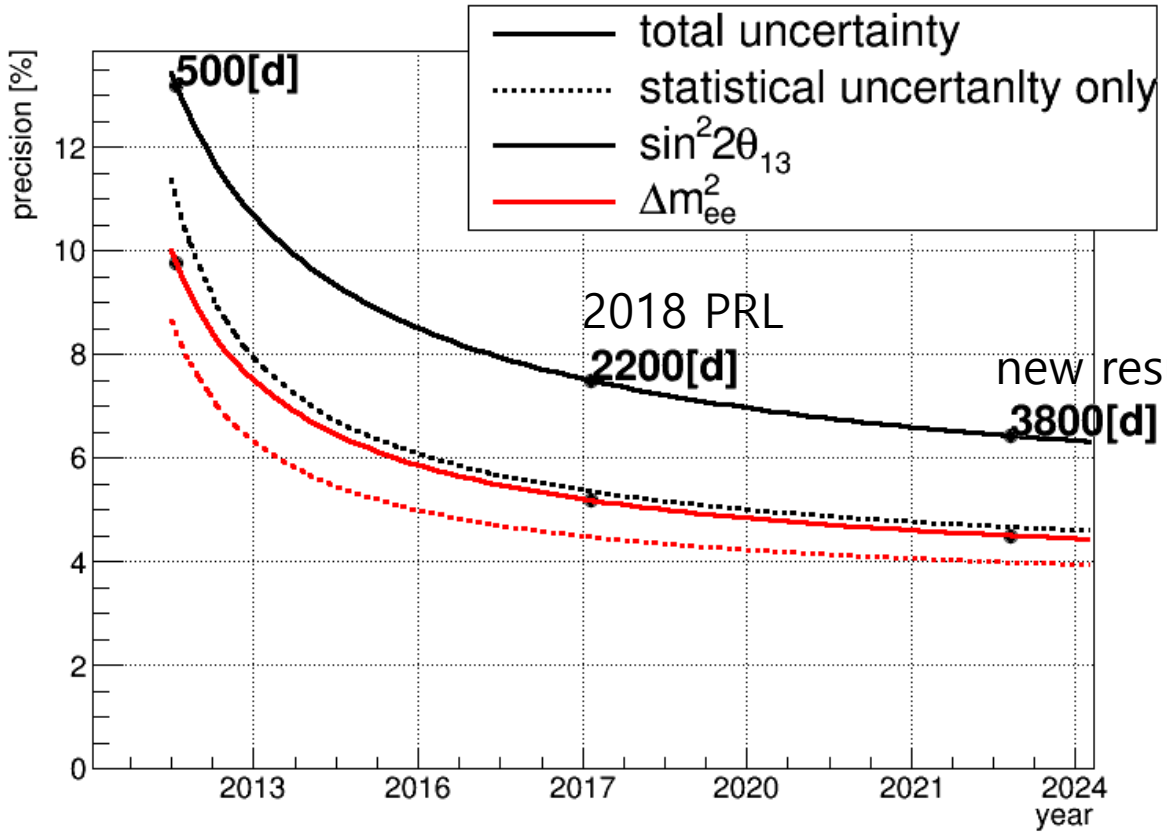
- reactor-related uncertainties
  - decomposition of detector-correlated & detector-uncorrelated components
  - only detector-uncorrelated component can be considered for far-to-near ratio analysis.

comparison of the Li/He spectrums



New Result(3800[d]) vs 2018 PRL(2200[d])

Precision of oscillation measurement in the RENO's analyses



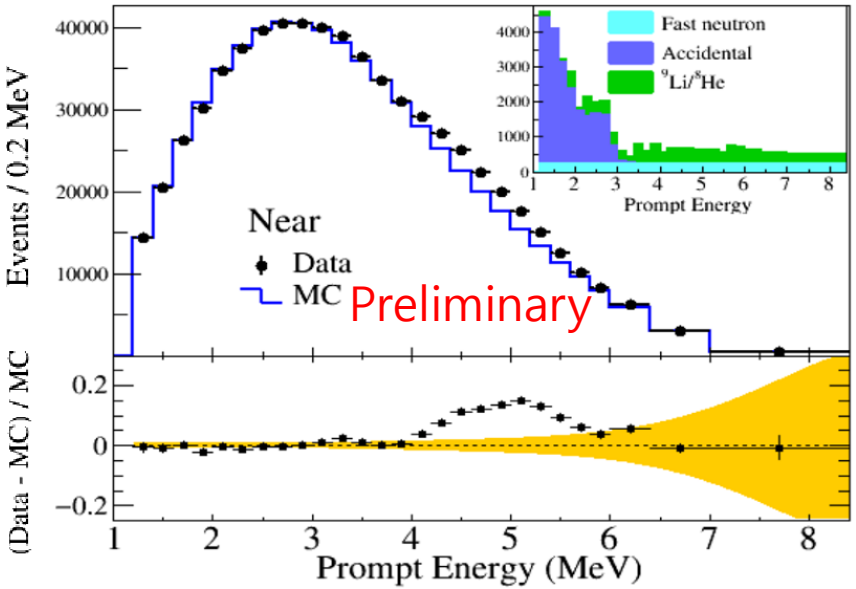
	live time	precision	
		$sin^2 2\theta_{13}$	Δm^2_{ee}
2018 PRL	2200 [d]	7.5%	5.2%
new result	3800 [d]	6.4%	4.5%

Comparing with the 2018 PRL result, the new result gives 14% and 13% improved precision for $sin^2 2\theta_{13}$ and Δm^2_{ee} each.

θ_{13} Measurement with n-H capture

Based on 2800[d] n-H sample,

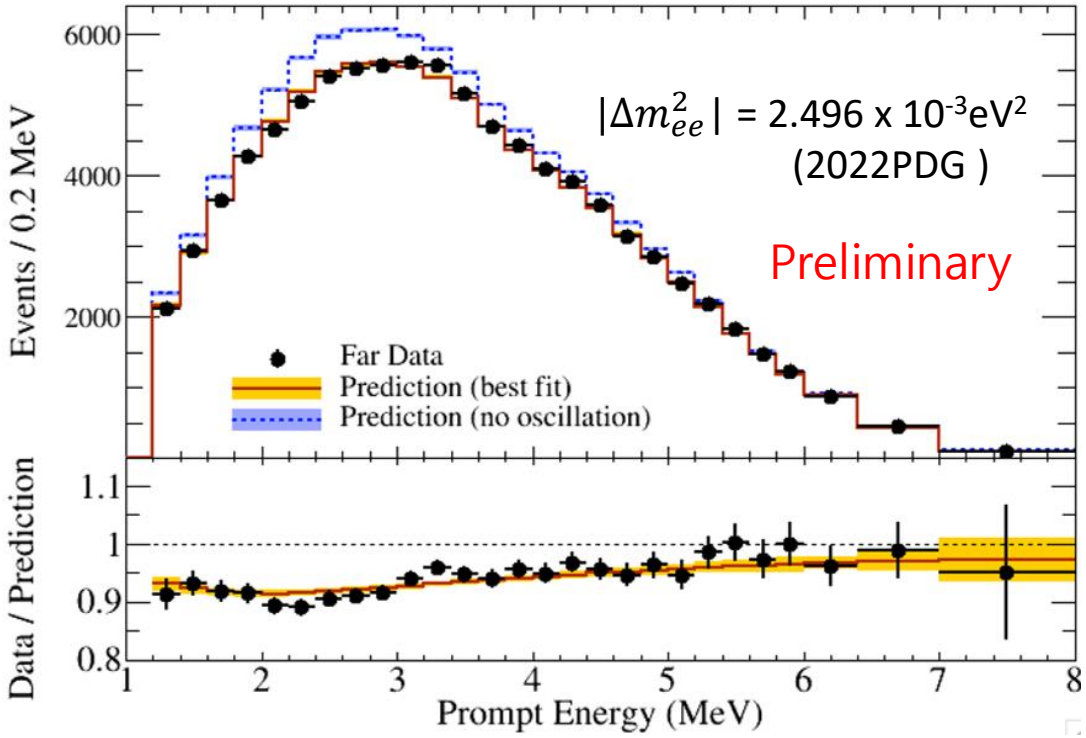
$$\boldsymbol{sin^2(2\theta_{13}) = 0.082 \pm 0.007(stat.) \pm 0.011(syst.)}$$ (15.9% precision)



	Near	Far
DAQ live time (days)	2259.298	2653.297
IBD candidates & backgrounds rate	316.67 ± 0.37	61.10 ± 0.15
After background subtraction	298.60 ± 0.62	35.67 ± 0.28
Total background rate	18.06 ± 0.50	25.43 ± 0.24

(reference) 2019 JHEP with 1500[d]

$sin^2 2\theta_{13} = 0.086 \pm 0.008(stat.) \pm 0.014(syst.)$

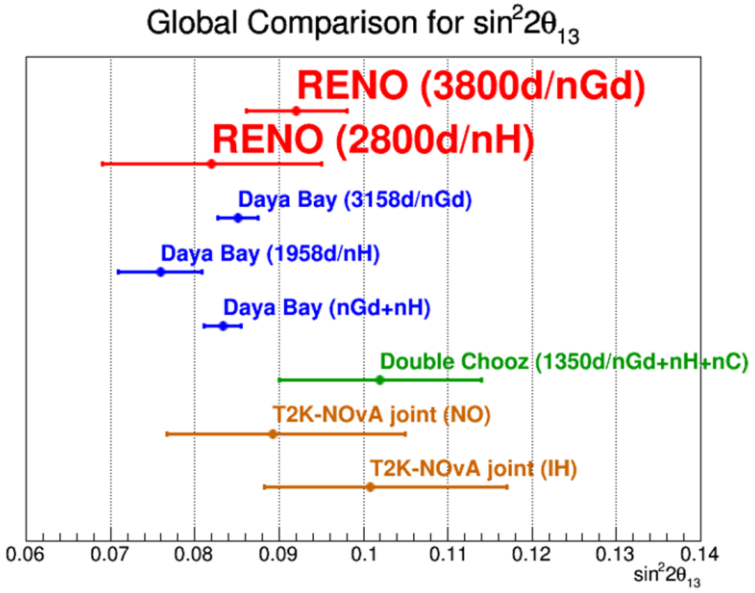


This shows the possibility of Δm^2_{ee} measurement in nH analysis.

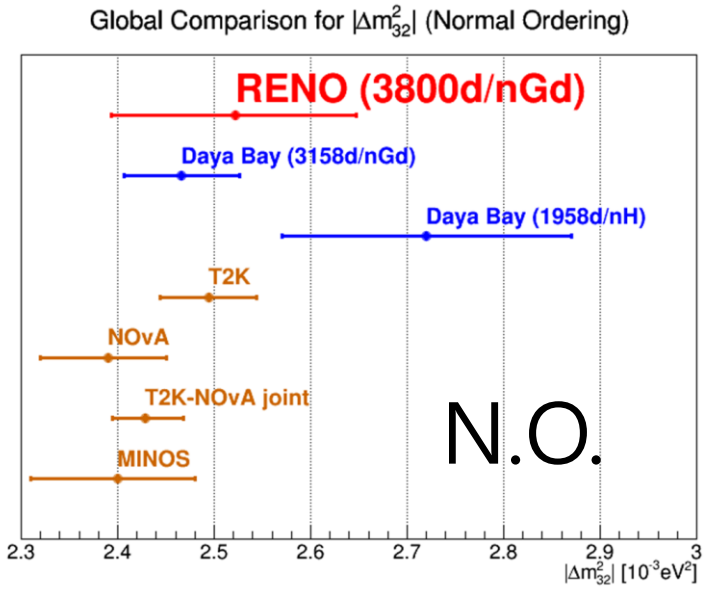
Global Comparison

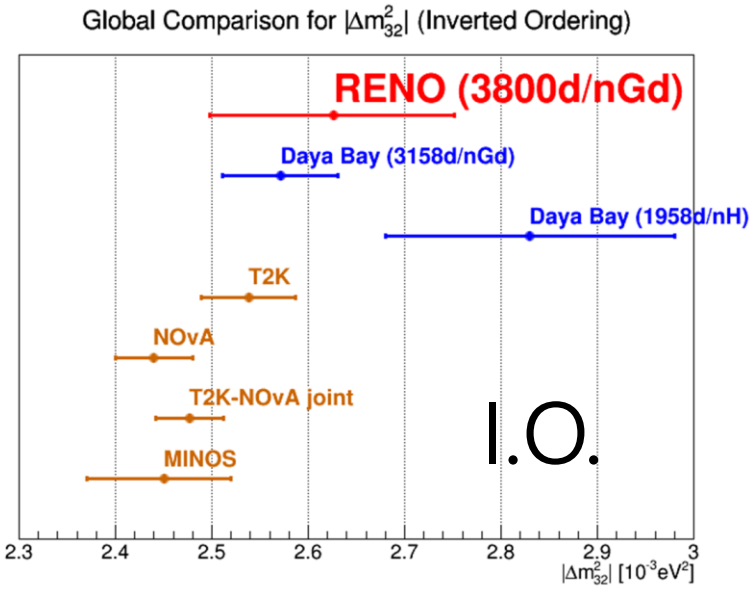
The new result shows good agreement with the global results.

$sin^2 2\theta_{13}$



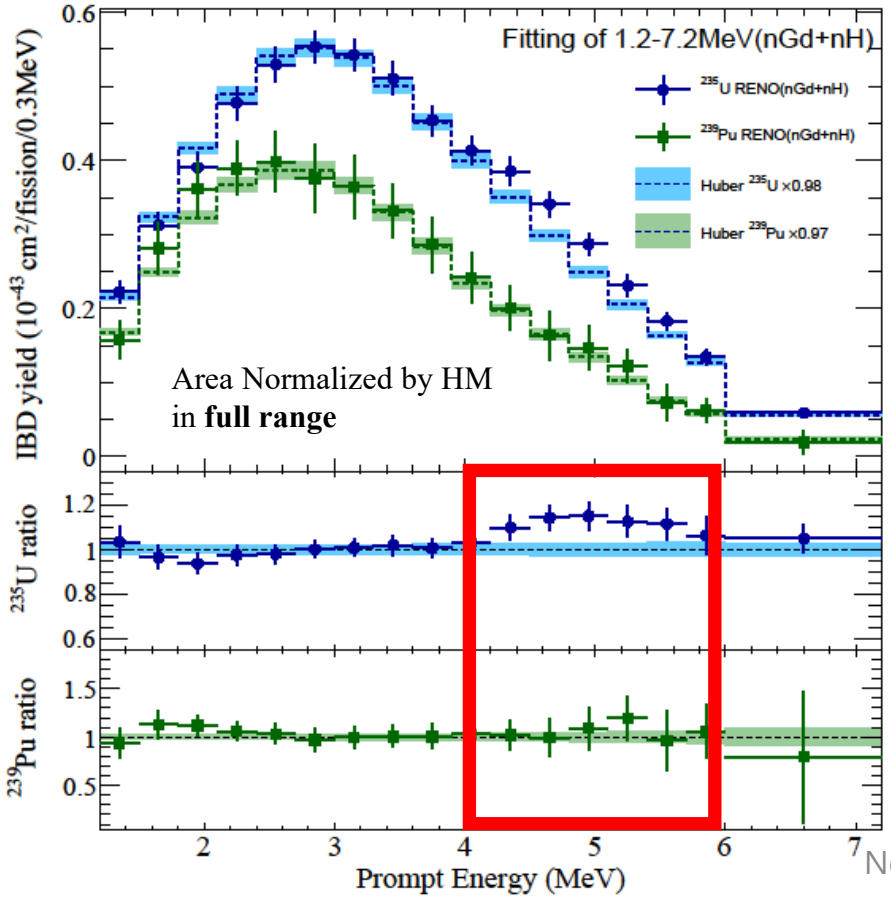
$|\Delta m^2_{32}|$

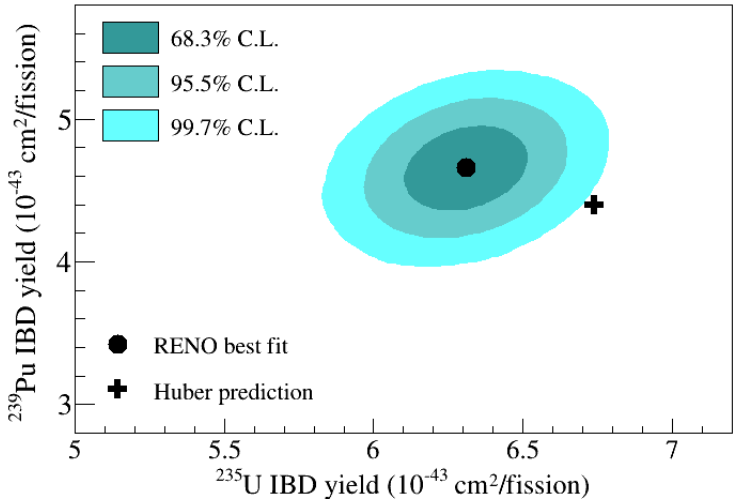




Reactor Neutrino Spectrum

Based on 2500[d] n-Gd + 2300[d] n-H, analysis for spectral decomposition was performed.



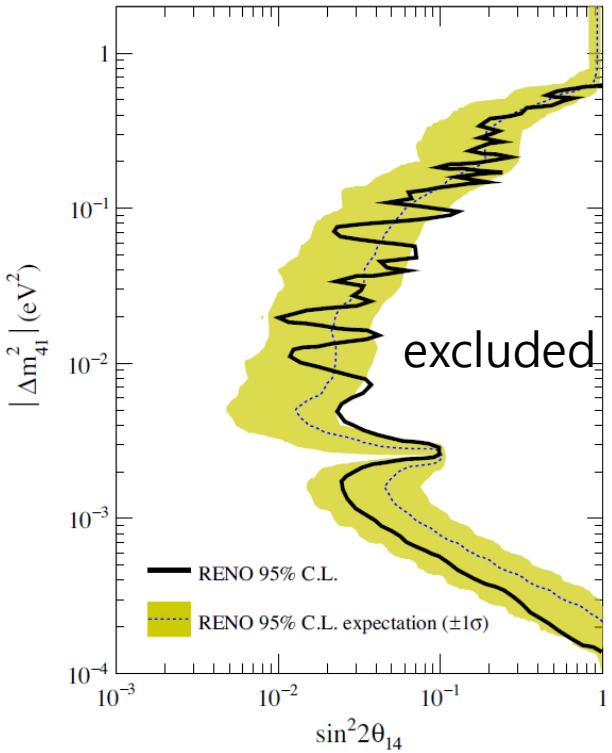


	^{235}U	^{239}Pu
Total IBD yield ($10^{-43} cm^2/fission$)	6.31±0.13	4.66±0.19
5 MeV Excess ($10^{-43} cm^2/fission$)	0.14±0.04 (2.18±0.63%)	0.08±0.06 (1.86±1.41%)

An analysis with the 3800[d] data set on-going

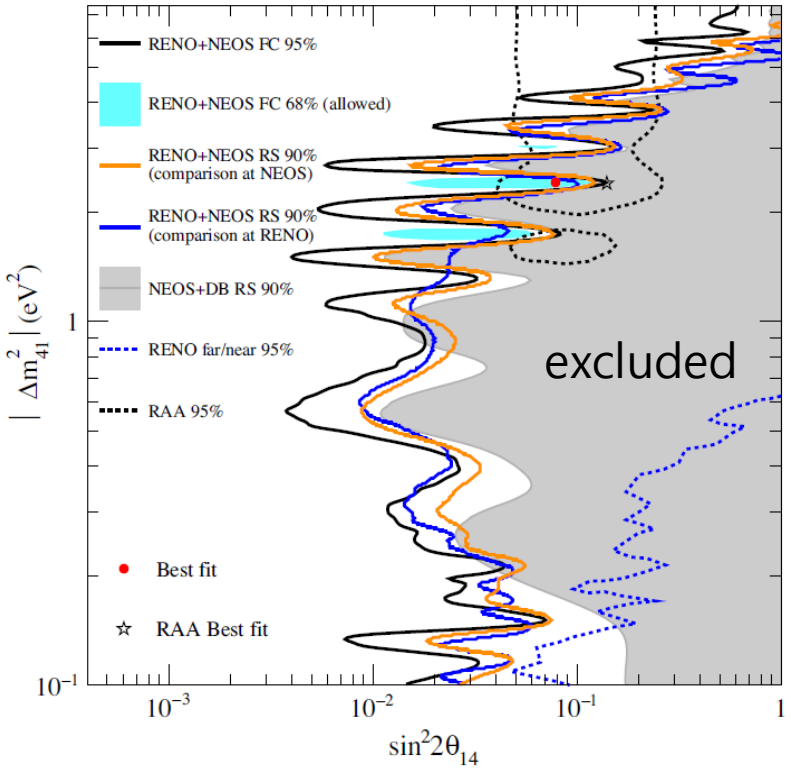
Sterile Neutrino Search

- RENO 2200[d]
- stringent limits in $10^{-3} < \Delta m^2_{41} < 0.1$ eV^2



Phys. Rev. Lett. 125, 191801 (2020)

- RENO 2500[d] x NEOS joint
- exclusion at $0.1 < \Delta m^2_{41} < 7$ eV^2



Phys. Rev. D 105, L111101 (2022)

Summary

- The RENO experiment has precisely measured the amplitude and frequency of reactor $\bar{\nu}_e$ oscillation at Hanbit Nuclear Power Plant since Aug. 2011.

- As of Mar. 2023, the RENO DAQ was shut down, and 3800[d] live time of dataset was obtained.

- From 3800[d] n-Gd sample,
  - 1,211,995(144,667) IBD candidates are observed during 3307.25(3737.85) [d] in the near(far) detector.
  - the far-to-near ratio analysis gives
    - $\boldsymbol{sin^2 2\theta_{13} = 0.0920\ ^{+0.0044}_{-0.0042}(stat.)\ ^{+0.0041}_{-0.0041}(syst.)}$ (7.5% -> 6.4% precision improved)
    - $\boldsymbol{\Delta m^2_{ee} = 2.57\ ^{+0.10}_{-0.11}(stat.)\ ^{+0.05}_{-0.05}(syst.)[\times 10^{-3} eV^2]}$ (5.2% -> 4.5% precision improved)

↳ to be published

- In the future,
  - other analyses (n-H, $\bar{\nu}_e$ spectrum, sterile neutrino, etc.) with the 3800[d] full data set
  - further improvements expected with a re-operating near detector.

Backup

Global Comparison Reference

experiment	reference
RENO (3800d/nGd)	new result
RENO (2800d/nH)	new result
Daya Bay (3158d/nGd)	PRL 130, 161802 (2023)
Daya Bay (1958d/nH)	arXiv:2406.01007
Double Chooz (1350d/nGd+nH+nC)	Neutrino 2020
T2K	EPJC 83, 782 (2023)
NOvA	arXiv:2311.07835
T2K-NOvA joint	Neutrino 2024
MINOS	PRL 125, 131802 (2020)