



# New results of reactor $\bar{\nu}_e$ oscillation using 3800 days of RENO data

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for the RENO Collaboration

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# RENO

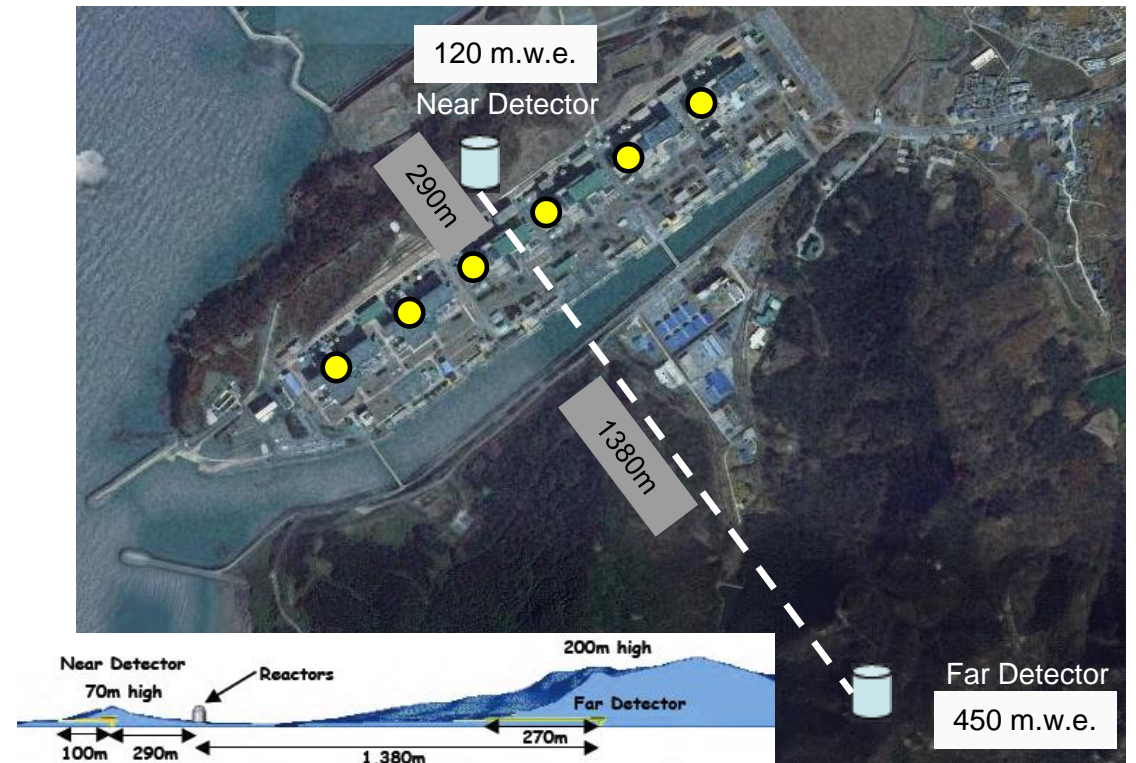


- Reactor Experiment for Neutrino Oscillation
- reactor  $\bar{\nu}_e$  oscillation at Hanbit Nuclear Plant
- 9 institutions and 40 physicists

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

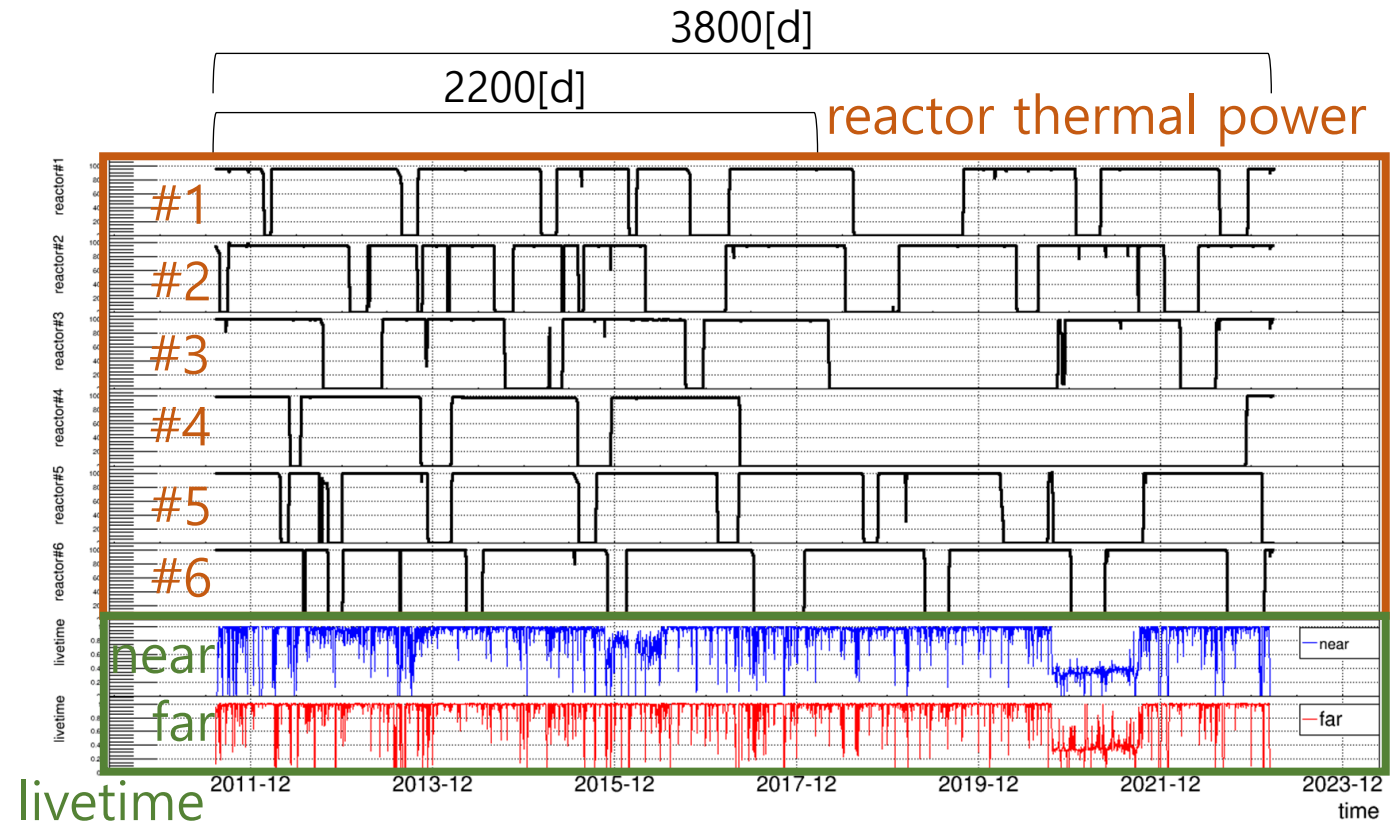


YongGwang (靈光) :



# 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)



period	live time	result
Aug. 2011 ~ Feb. 2018	2200 [days]	2018 PRL
Aug. 2011 ~ Mar. 2023	3800 [days]	new result

# Major Results from RENO & Future

- Precise measurement of  $|\Delta m_{ee}^2|$  and  $\theta_{13}$  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

will be finished with 3800[d] analyses.

- Measurement of  $\theta_{13}$  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) - 2900[d]

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

- sterile neutrino search

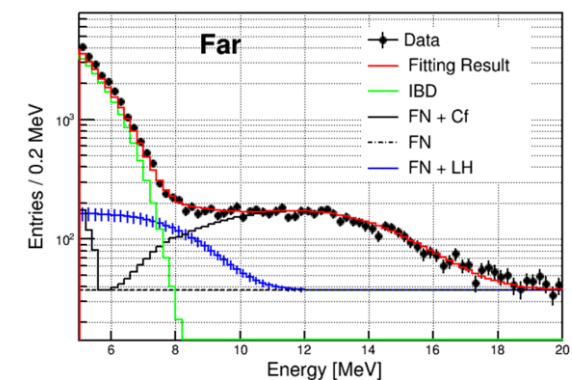
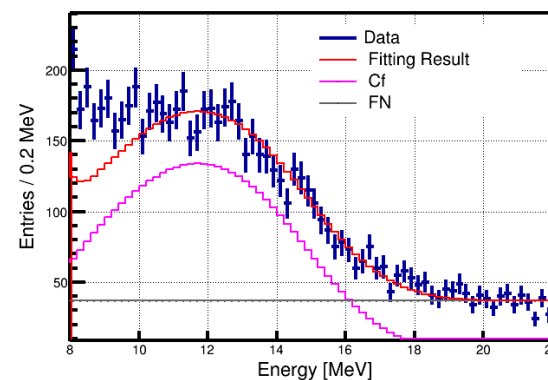
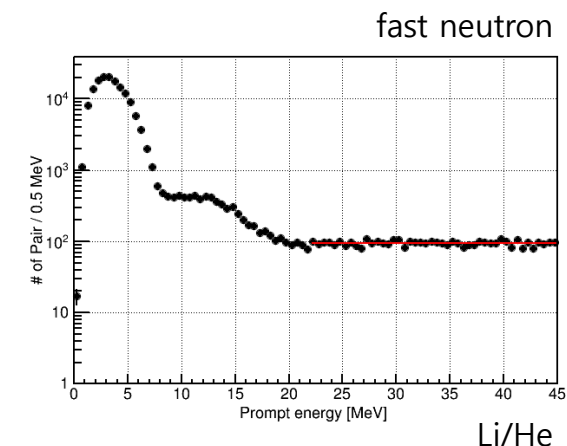
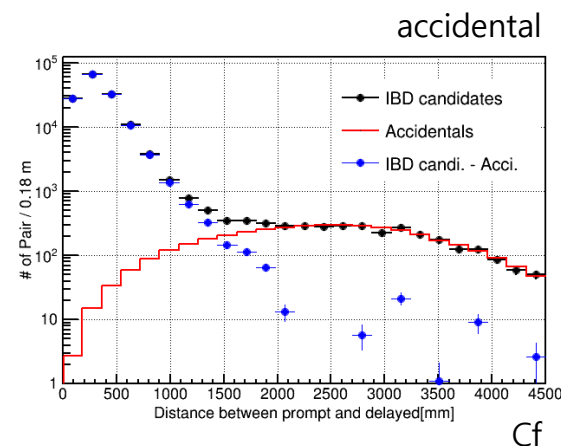
- Phys. Rev. Lett. 125, 191801 (2020) - 2200[d]
- Phys. Rev. D 105, L111101 (2022) - 2500[d] x NEOS 180[d]

# IBD Candidate Sample & Background Estimation

- 1,211,995(144,667)  $\bar{\nu}_e$  candidate events observed for near(far).
- The total background rates :
  - near :  $9.08 \pm 0.18$  [events/day] (2.5%)
  - far :  $2.06 \pm 0.13$  [events/day] (5.3%)

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

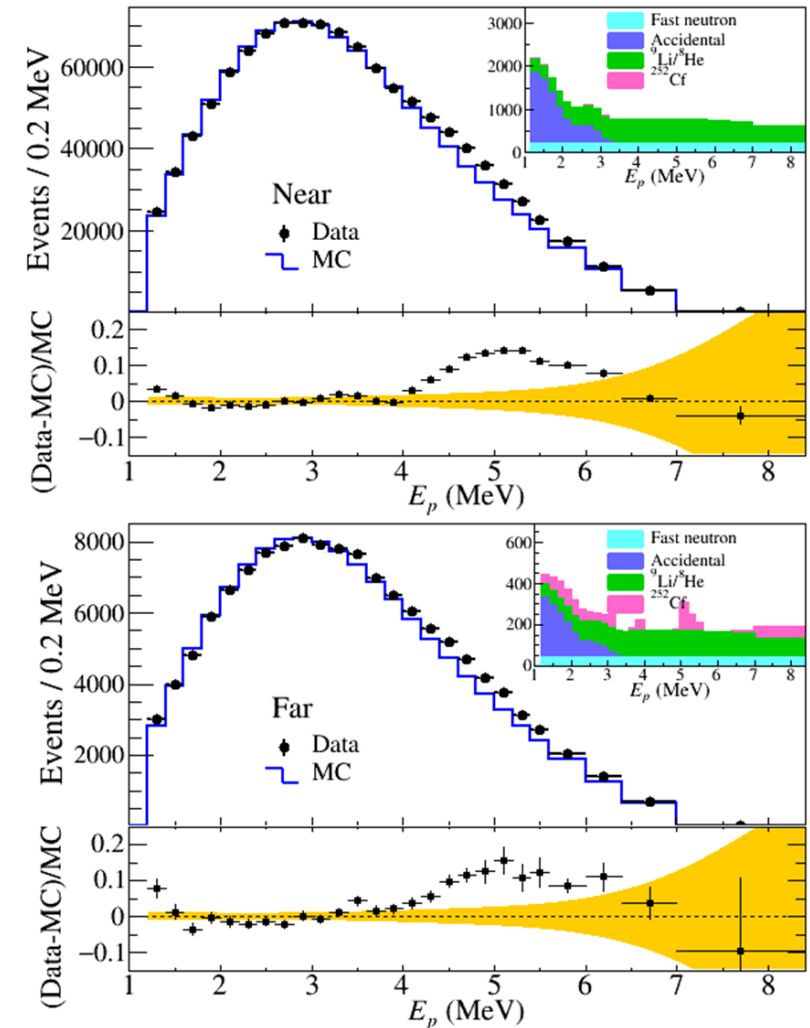
measured IBD and estimated background rates with  $1.2 < E_p < 8.0$  [MeV], given per day





# 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]

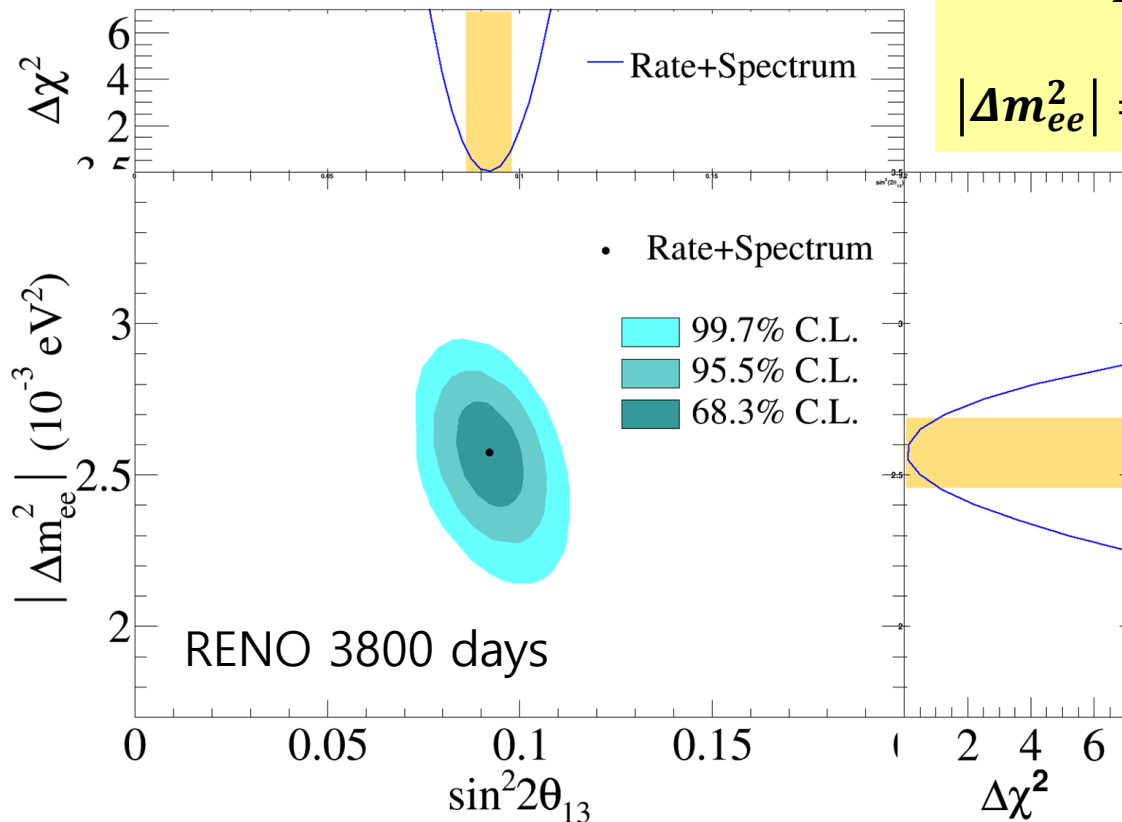


# Results of $|\Delta m_{ee}^2|$ and $\theta_{13}$

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

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

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



source of the systematic uncertainty

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

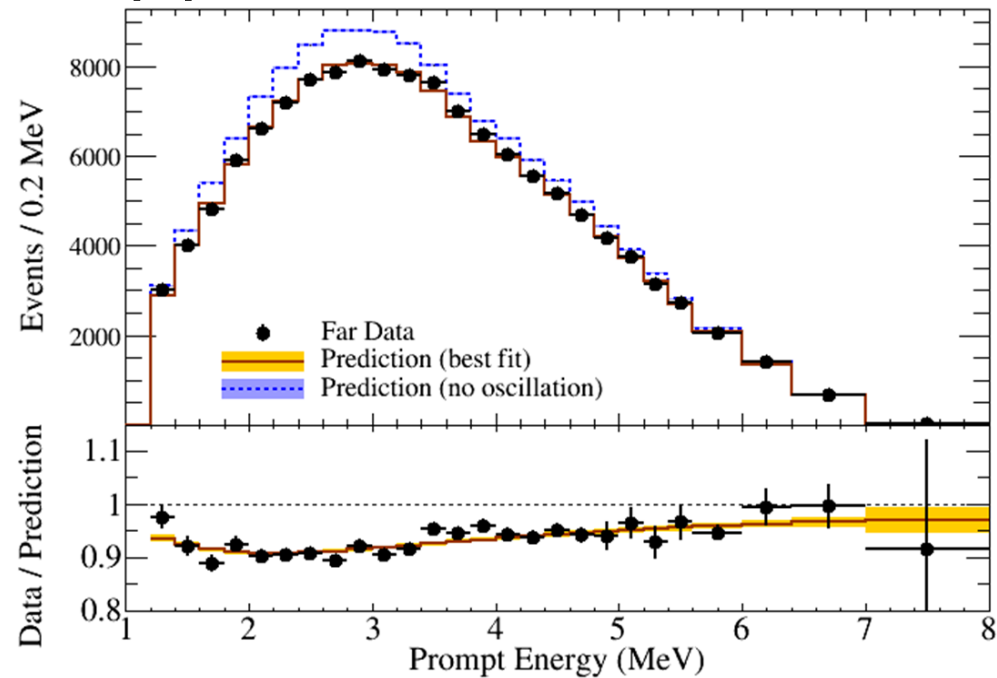
(reference) 2018 PRL

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

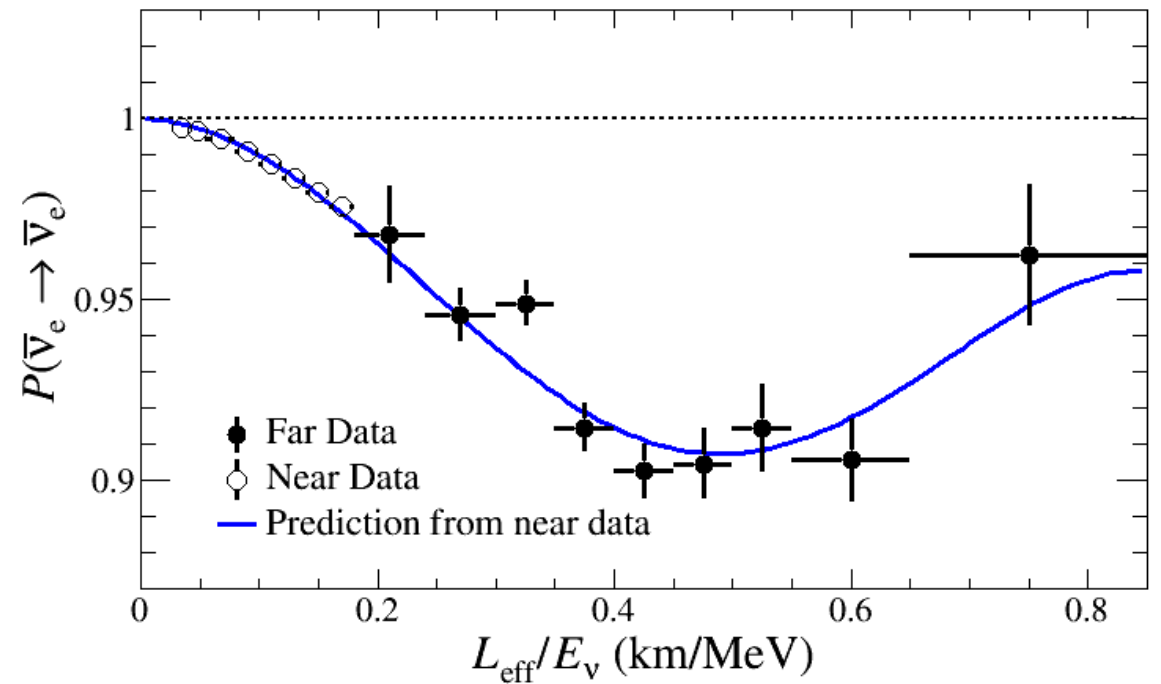
$$|\Delta m_{ee}^2| = 2.68 \pm 0.12(\text{stat.}) \pm 0.07(\text{syst.}) [\times 10^{-3} eV^2]$$

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

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



observed L/E dependent oscillation



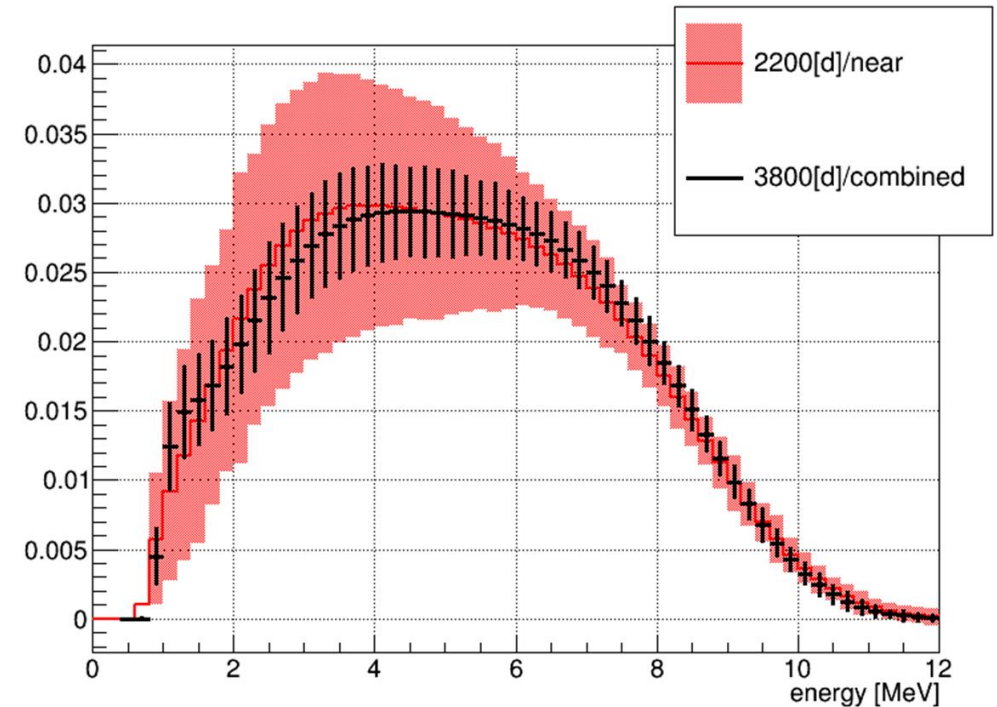
$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2 \left( \Delta m_{ee}^2 \frac{L}{4E_\nu} \right)$$



# Improvement

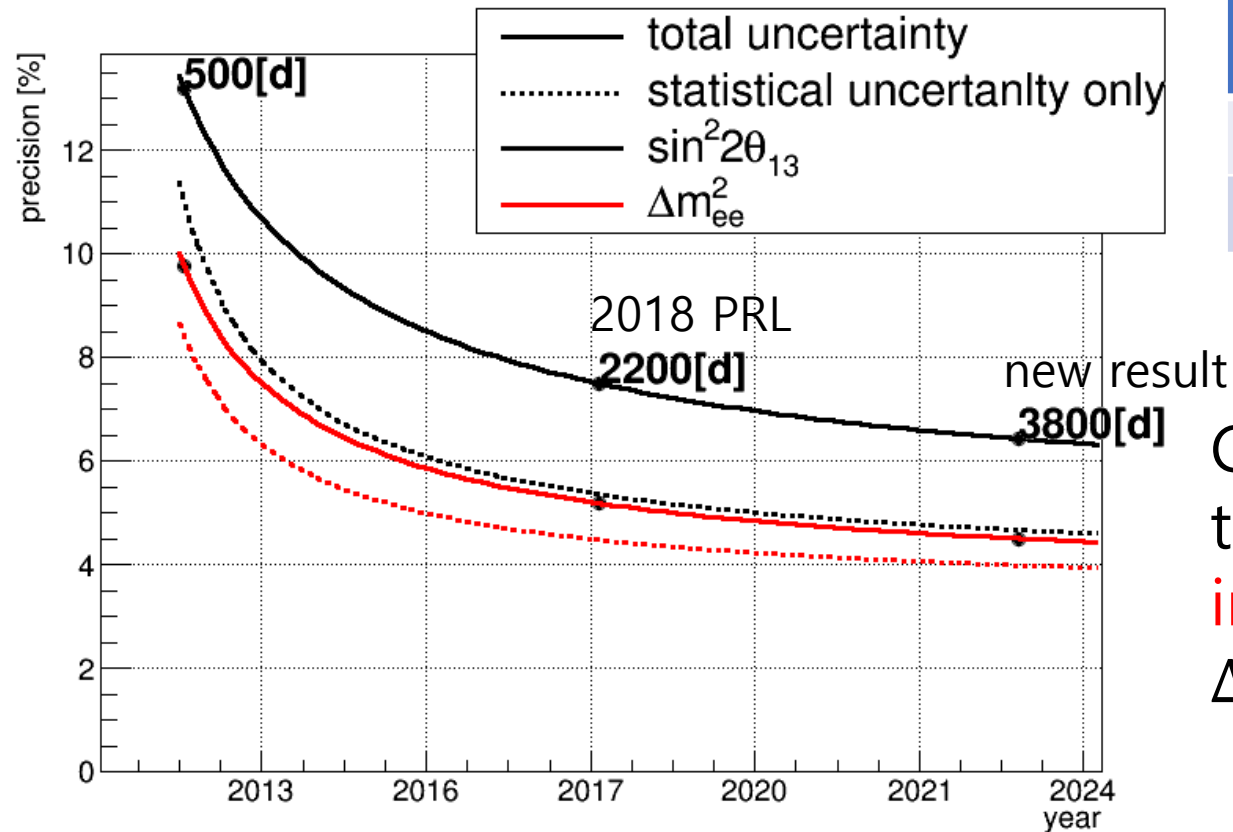
- Li/He Background Spectrum
  - extension of dataset
  - combined far & near spectrum
- reactor-related uncertainties
  - decomposition of detector-correlated & detector-uncorrelated components
  - only detector-uncorrelated component can be considered for far-to-near ratio analysis.

comparison of the Li/He spectrums



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

Precision of oscillation measurement in the RENO's analyses



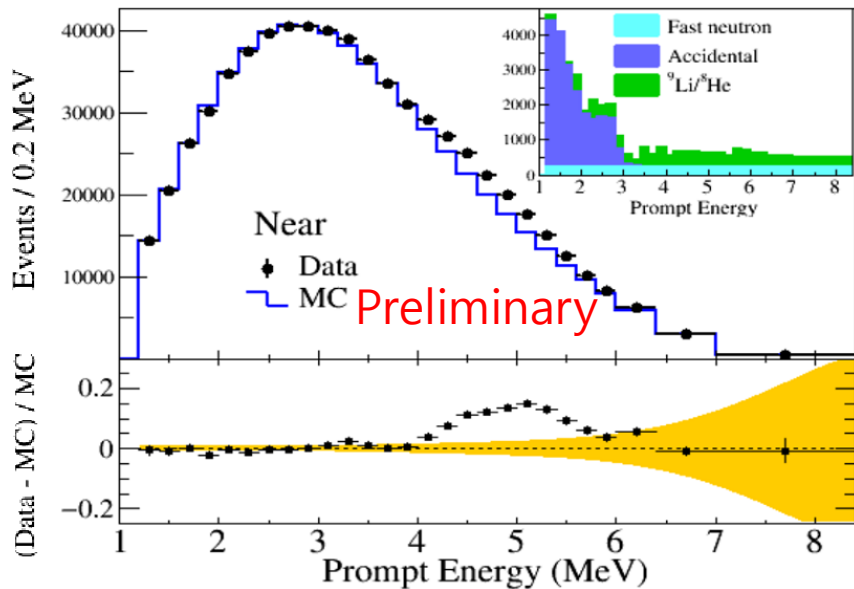
	live time	precision	
		$\sin^2 2\theta_{13}$	$\Delta m_{ee}^2$
2018 PRL	2200 [d]	7.5%	5.2%
new result	3800 [d]	6.4%	4.5%

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

# $\theta_{13}$ Measurement with n-H capture

Based on 2800[d] n-H sample,

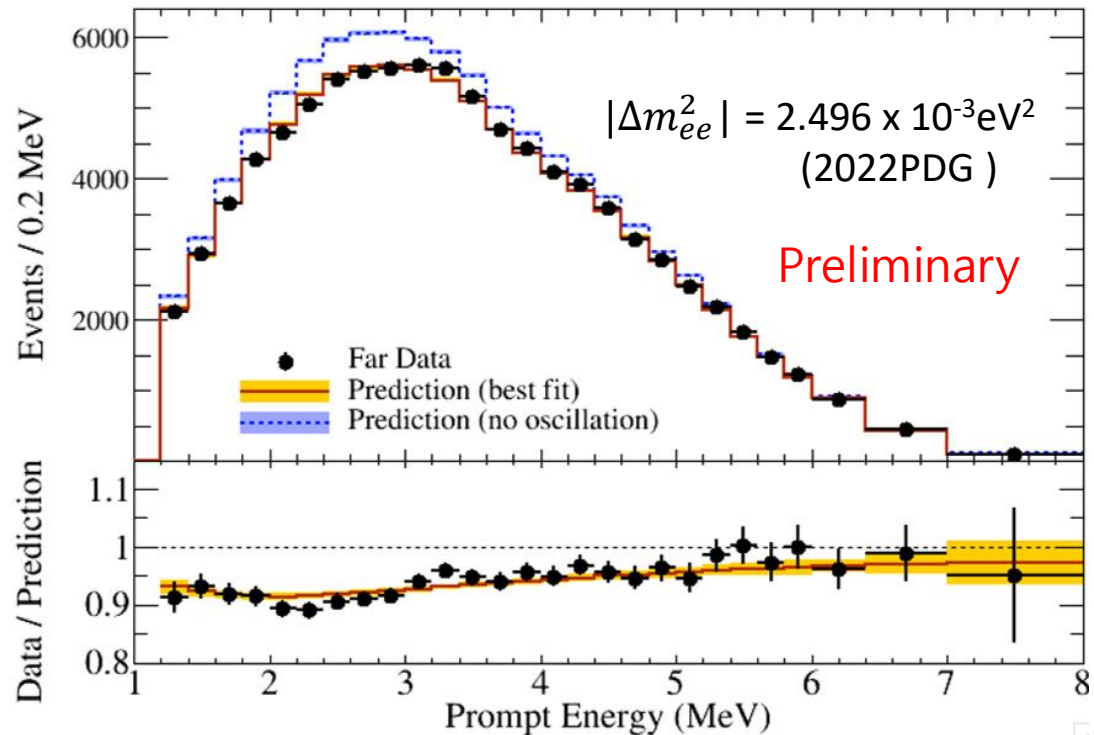
$$\sin^2(2\theta_{13}) = 0.082 \pm 0.007(\text{stat.}) \pm 0.011(\text{syst.}) \quad (15.9\% \text{ precision})$$



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

(reference) 2019 JHEP with 1500[d]

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



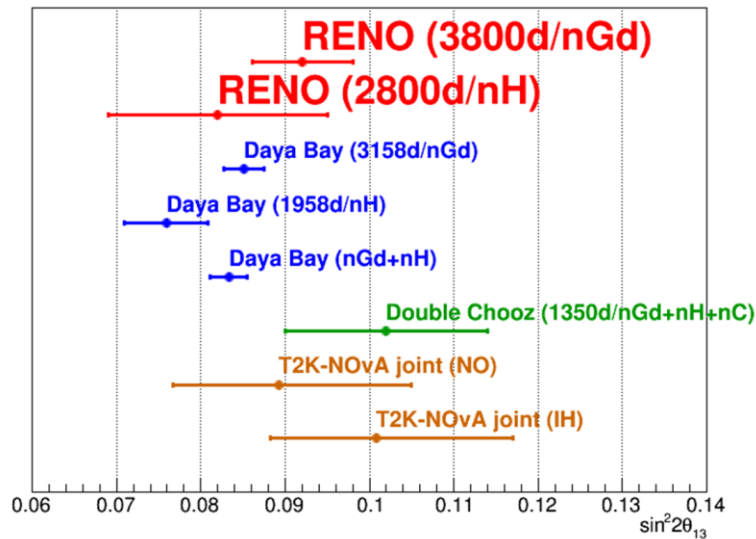
*This shows the possibility of  $\Delta m_{ee}^2$  measurement in nH analysis.*

# Global Comparison

The new result shows good agreement with the global results.

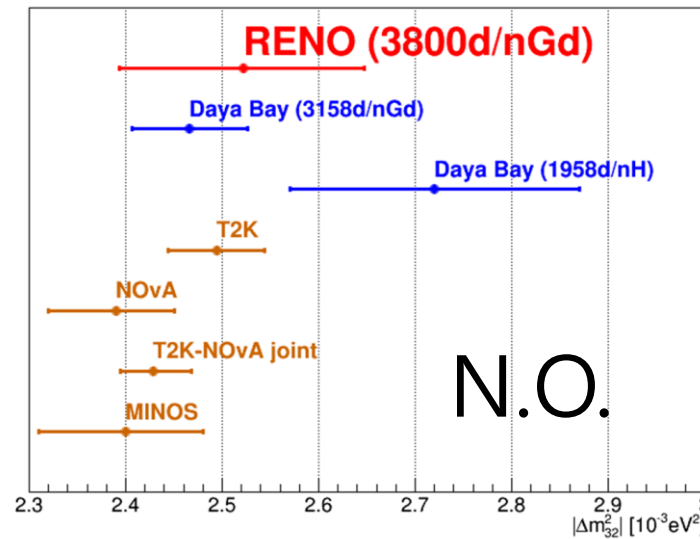
$$\sin^2 2\theta_{13}$$

Global Comparison for  $\sin^2 2\theta_{13}$

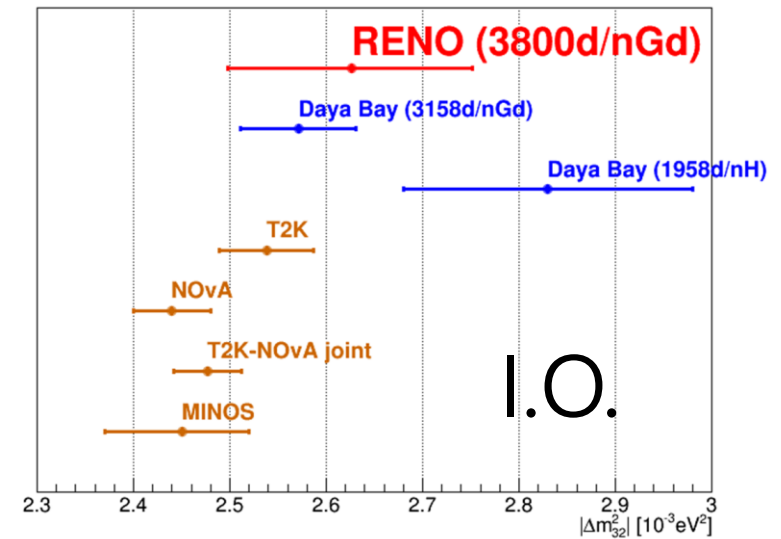


$$|\Delta m_{32}^2|$$

Global Comparison for  $|\Delta m_{32}^2|$  (Normal Ordering)



Global Comparison for  $|\Delta m_{32}^2|$  (Inverted Ordering)



# Summary

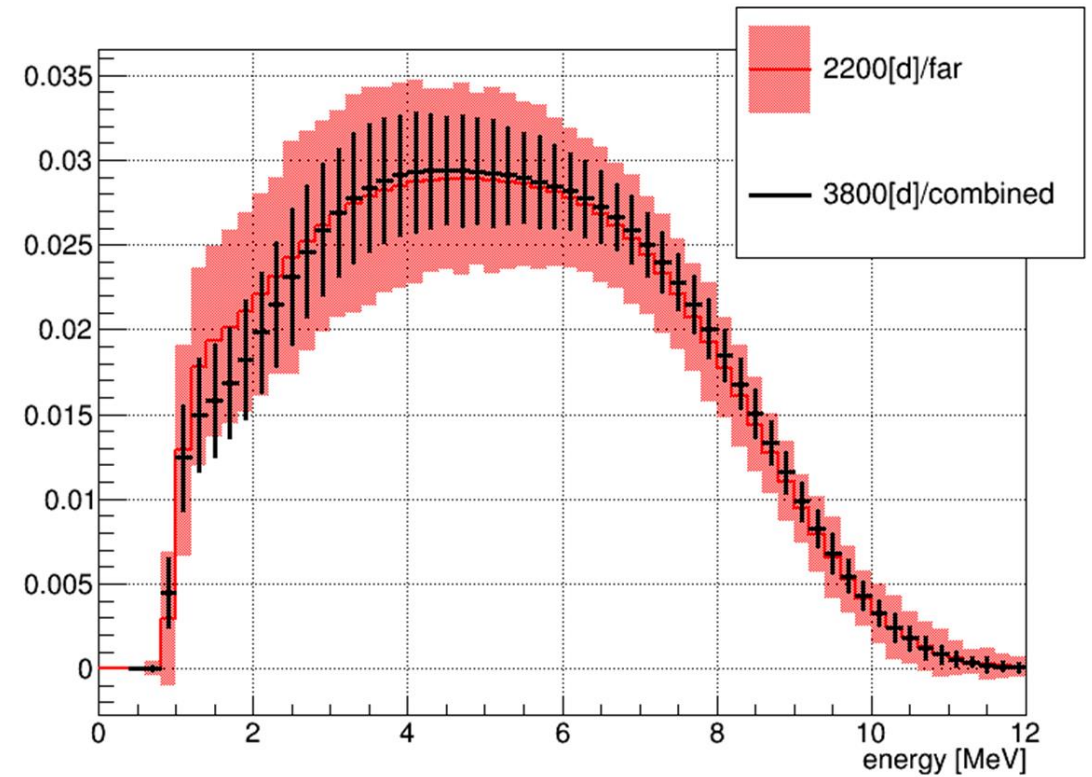
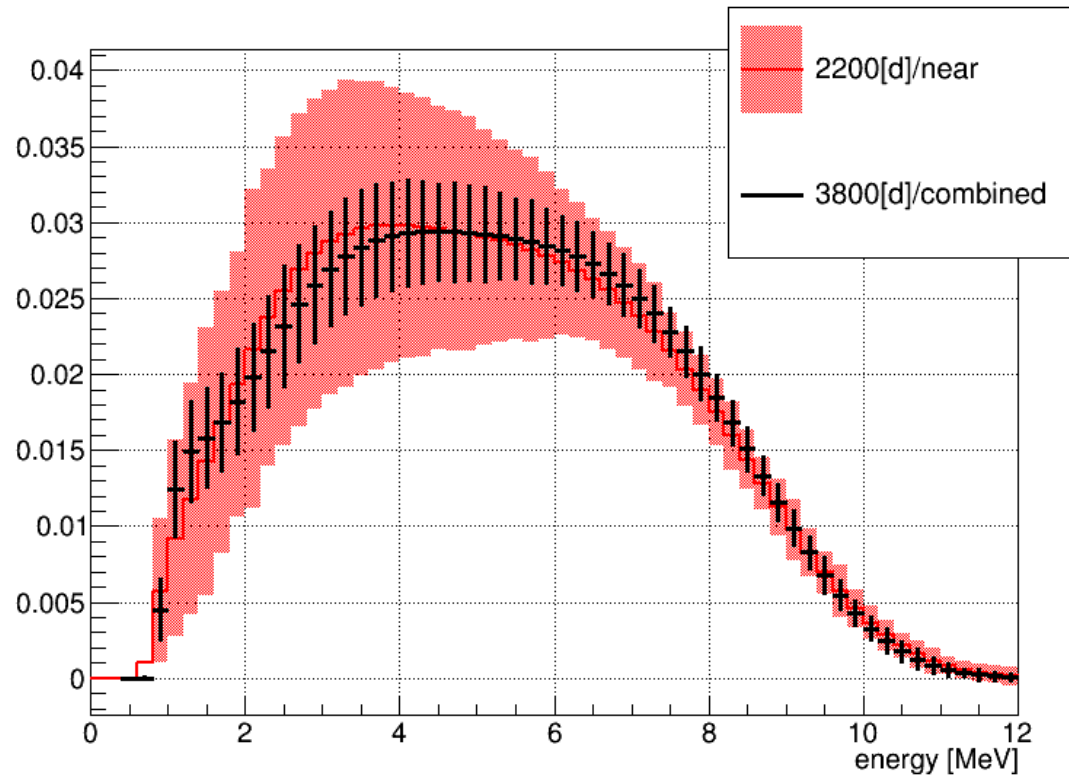
- The RENO experiment has precisely measured the amplitude and frequency of reactor  $\bar{\nu}_e$  oscillation at Hanbit Nuclear Power Plant since Aug. 2011.
- As of Mar. 2023, the RENO DAQ was shut down, and 3800[d] live time of dataset was obtained.
- From 3800[d] n-Gd sample,
  - 1,211,995(144,667) IBD candidates are observed during 3307.25(3737.85) [d] in the near(far) detector.
  - the far-to-near ratio analysis gives
    - $\sin^2 2\theta_{13} = 0.0920^{+0.0044}_{-0.0042} (stat.)^{+0.0041}_{-0.0041} (syst.)$  (7.5% -> 6.4% precision improved)
    - $\Delta m_{ee}^2 = 2.57^{+0.10}_{-0.11} (stat.)^{+0.05}_{-0.05} (syst.) [\times 10^{-3} eV^2]$  (5.2% -> 4.5% precision improved)
- 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.

↳ to be published

# Backup



# Improved Li/He Background Spectrum



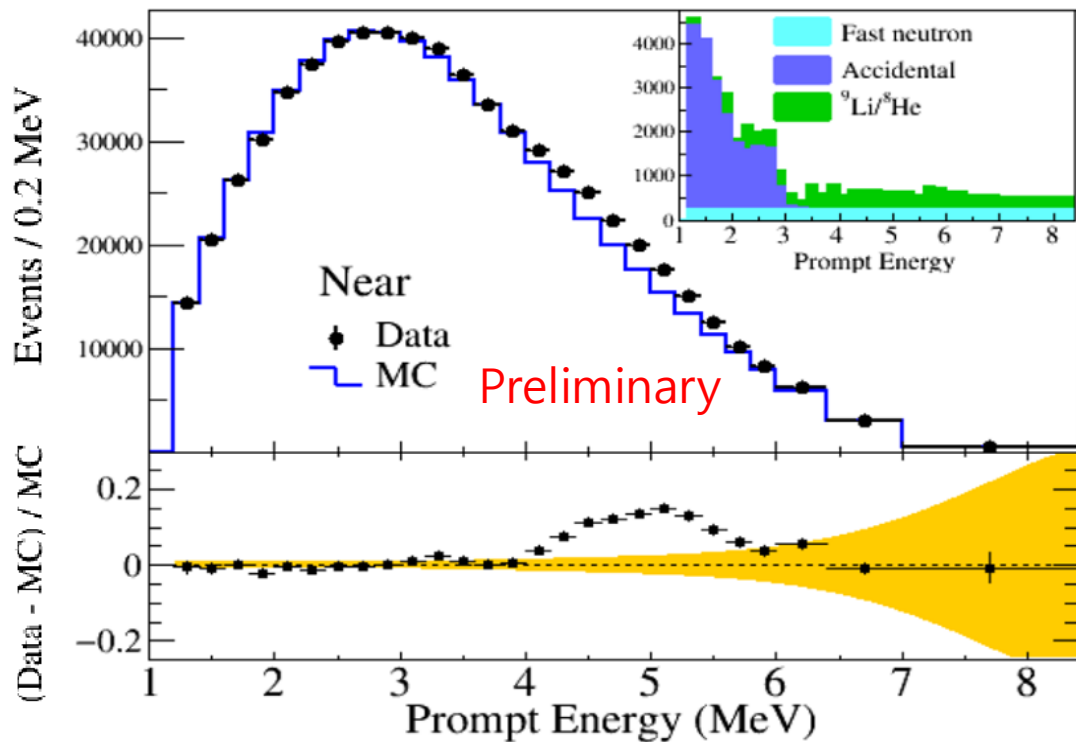
# Global Comparison Reference

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)

# Final Sample of IBD Candidates (n-H)

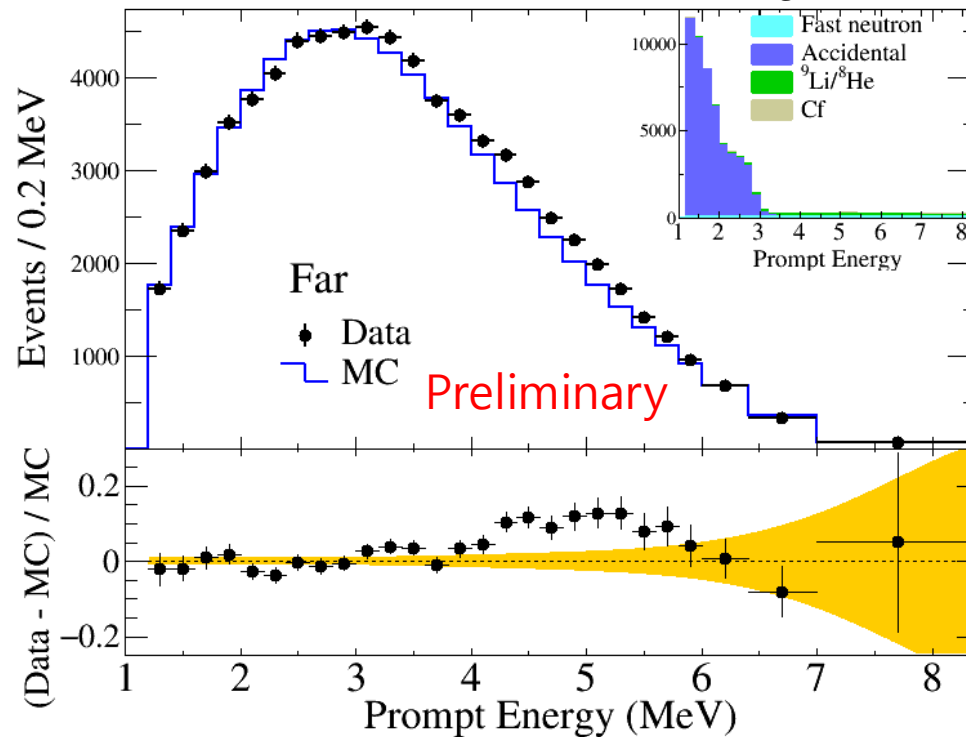
Total : 715443

Background : ~ 5.7 %

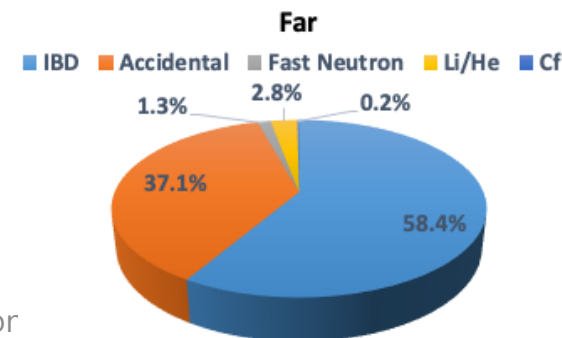
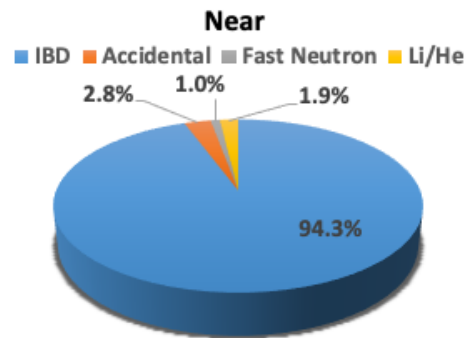


Total : 162113

Background : ~41.6 %



	Near	Far
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After background subtraction	$298.60 \pm 0.62$	$35.67 \pm 0.28$
Total background rate	$18.06 \pm 0.50$	$25.43 \pm 0.24$



New R

or