Neutrino oscillation measurements with reactor antineutrinos

Liang Zhan
Institute of High Energy Physics, CAS

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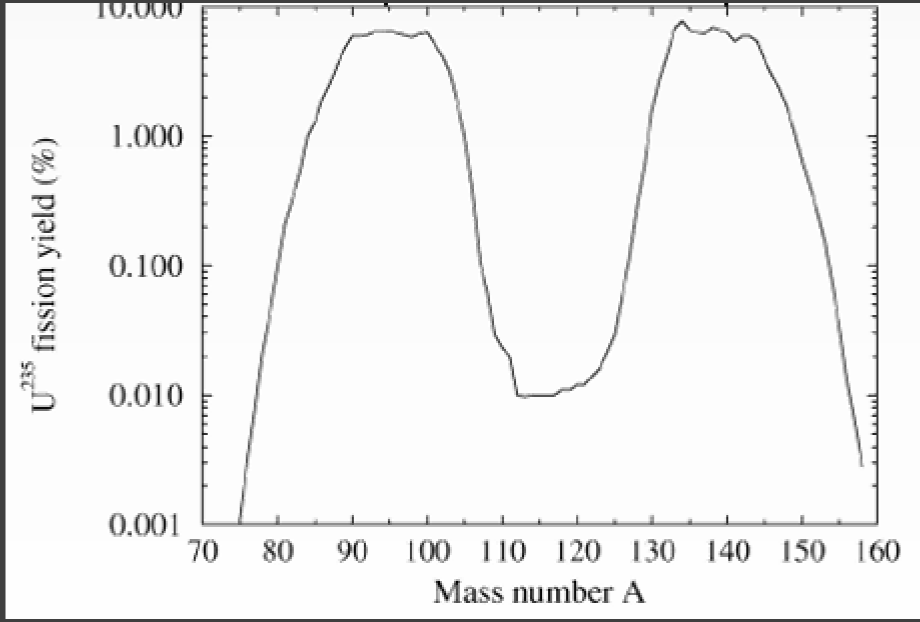
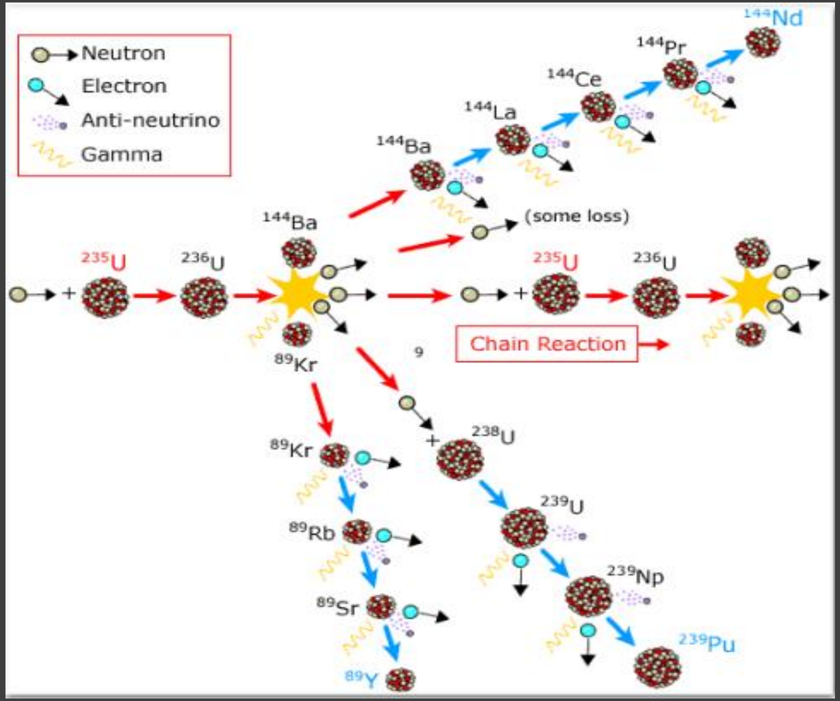
Reactor neutrino flux

- Pure electron antineutrinos $\bar{\nu}_e$
- $\sim 6\ \bar{\nu}_e$ per fission
- $2 \times 10^{20}\ \bar{\nu}_e$ /second/GW_{th}
- Produced by fission products from four major isotopes: ^{235}U, ^{238}U, ^{239}Pu, and ^{241}Pu in commercial nuclear power plants

$$^{235}_{92}U + n \rightarrow X_1 + X_2 + 2n$$

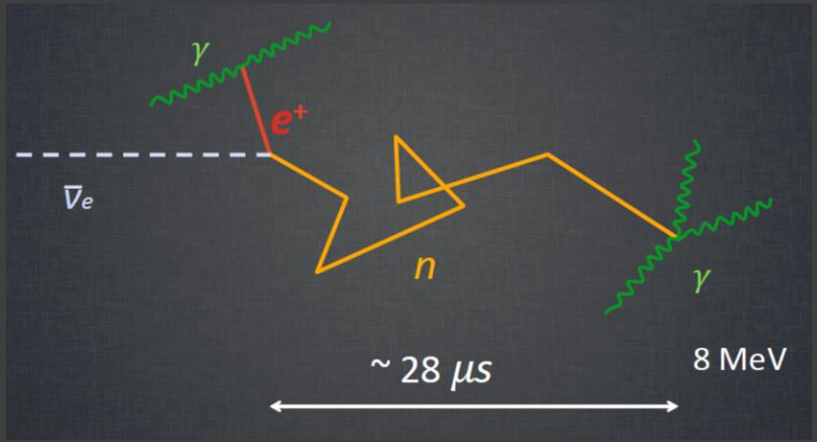




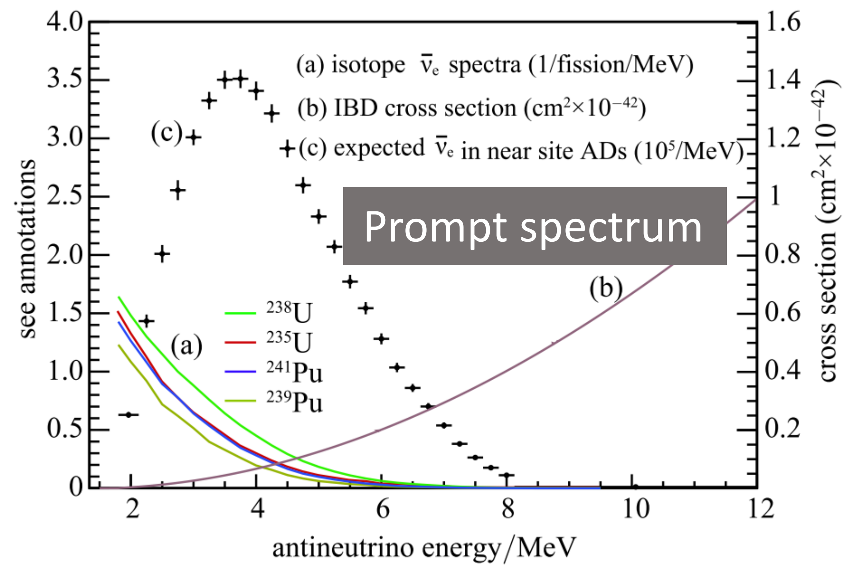
Neutrino detection

Detect neutrino via inverse beta decay (IBD) in liquid scintillator

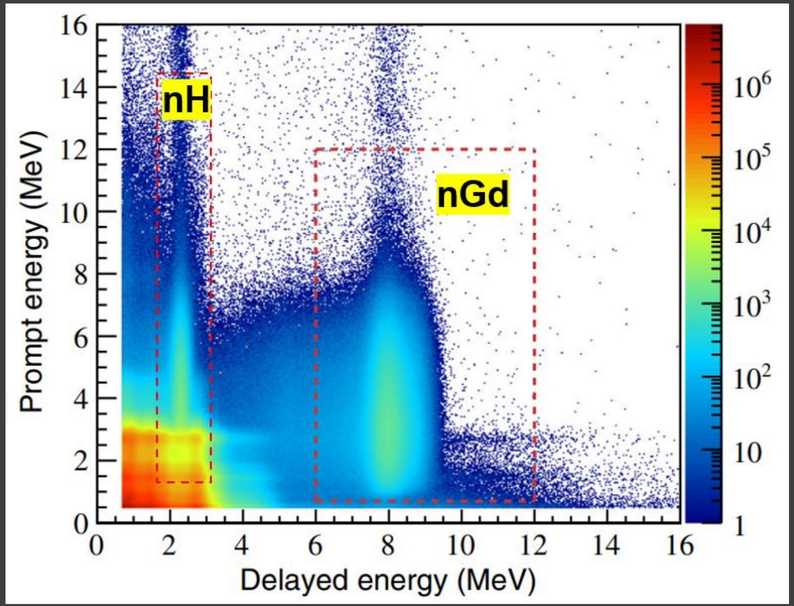
$$\bar{\nu}_e + p \rightarrow e^+ + n \text{ (prompt)}$$
$$\hookrightarrow +p \rightarrow D + \gamma \text{ (2.2 MeV delayed)}$$
$$\hookrightarrow + Gd \rightarrow Gd^*$$
$$\hookrightarrow Gd + \gamma\text{'s (8 MeV delayed)}$$



Prompt signal: a proxy of neutrino energy
Delayed signal: a tag of neutrino event by nH capture of nGd capture



Daya Bay, Chinese Physics C Vol. 41, No. 1 (2017) 013002



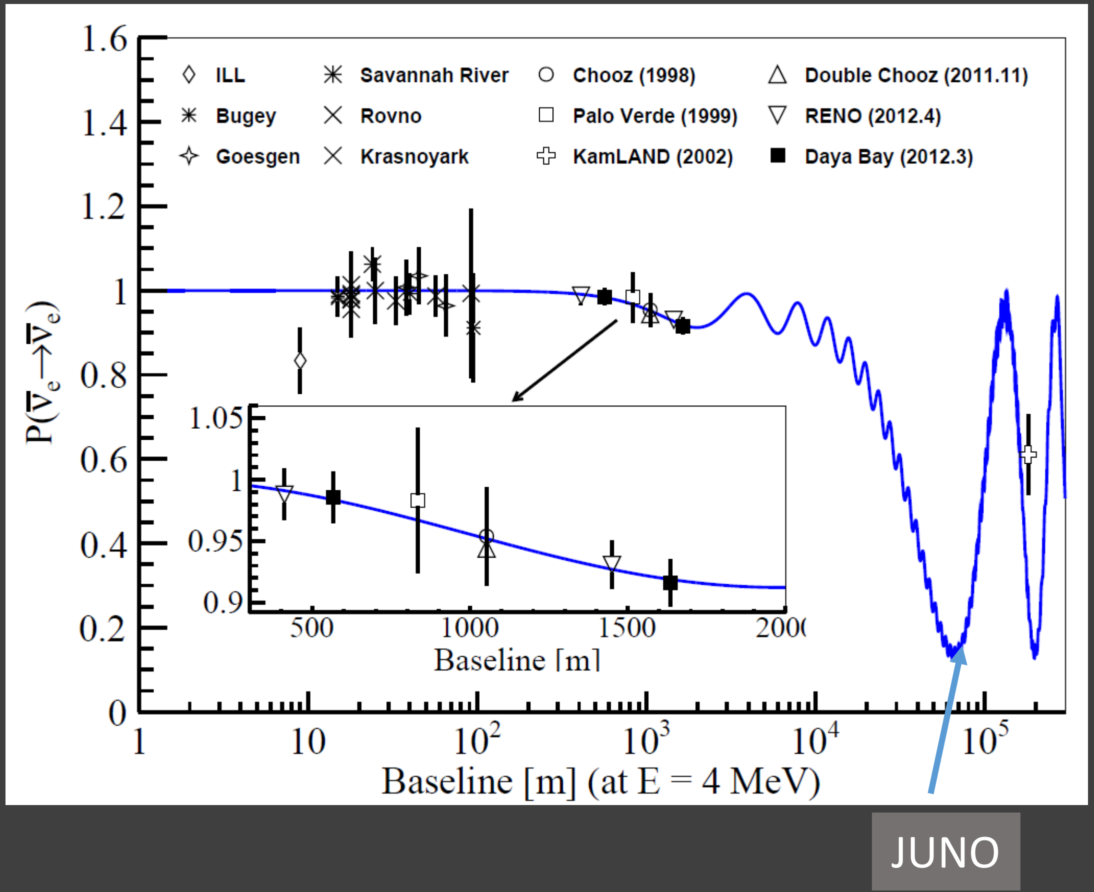
Daya Bay, PHYSICAL REVIEW D 95, 072006 (2017)

Reactor neutrino oscillation

A "golden" channel **at km baseline** for oscillation parameters and mass ordering

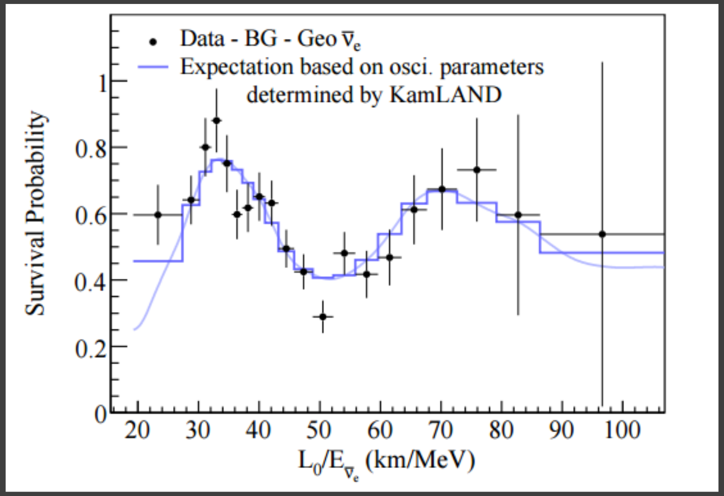
$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \sin^2 2\theta_{13} \sin^2\left(\Delta m^2_{ee} \frac{L}{4E}\right) - \sin^2 2\theta_{12} \cos^4\theta_{13} \sin^2\left(\Delta m^2_{21} \frac{L}{4E}\right)$$

- $\bar{\nu}_e \rightarrow \bar{\nu}_e$ disappearance
- No dependence on CP phase and θ_{23}
- 2-km oscillation: θ_{13} and Δm^2_{ee}
- 50-km oscillation: θ_{12} and Δm^2_{21}
- JUNO can observe both Δm^2_{ee} and Δm^2_{21} driven oscillations, and is sensitivity to neutrino mass ordering (talk by Vanessa Cerrone at NOW 2024)

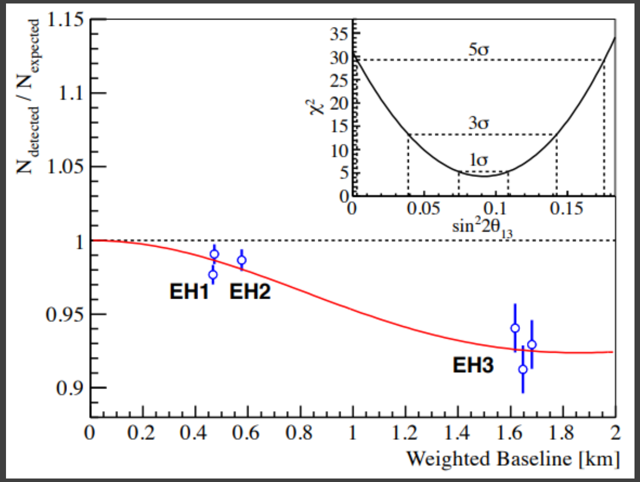


The history

- Discovery of neutrinos by Clyde L. Cowan and Frederick Reines in 1956
- First confirmation of solar neutrino oscillation by KamLAND in 2002
- Observation of non-zero θ_{13} at Daya Bay, RENO, Double Chooz in 2012

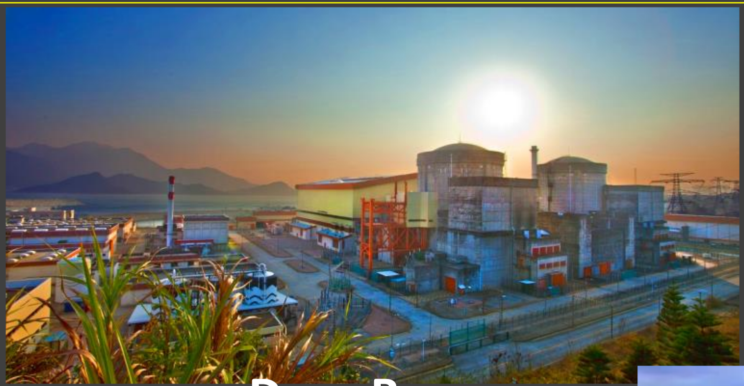


KamLAND



Daya Bay

θ_{13} measurements



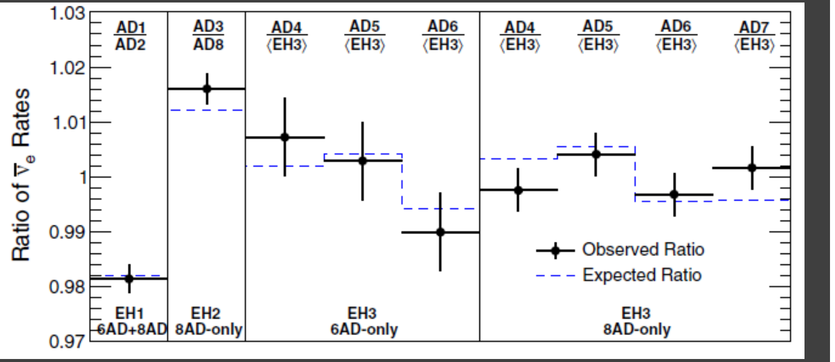
Daya Bay

RENO

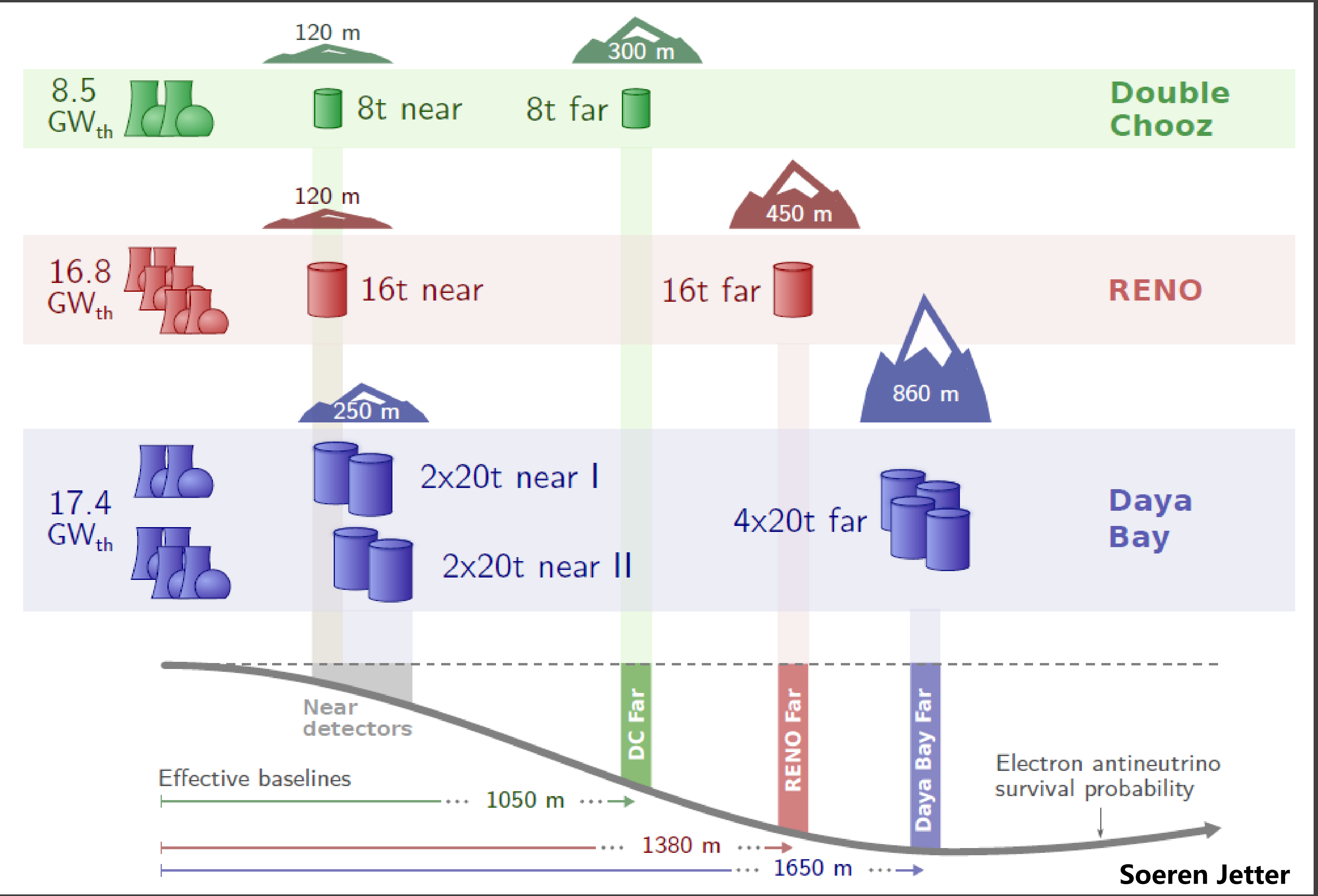
Double Chooz

Experiment layout

- Common feature: near/far relative measurement to reduce the flux uncertainty
- Identical detector: cancel detection efficiency uncertainty
- Unique feature in Daya Bay: side-by-side detectors ➔ Verification of identical detectors



Daya Bay

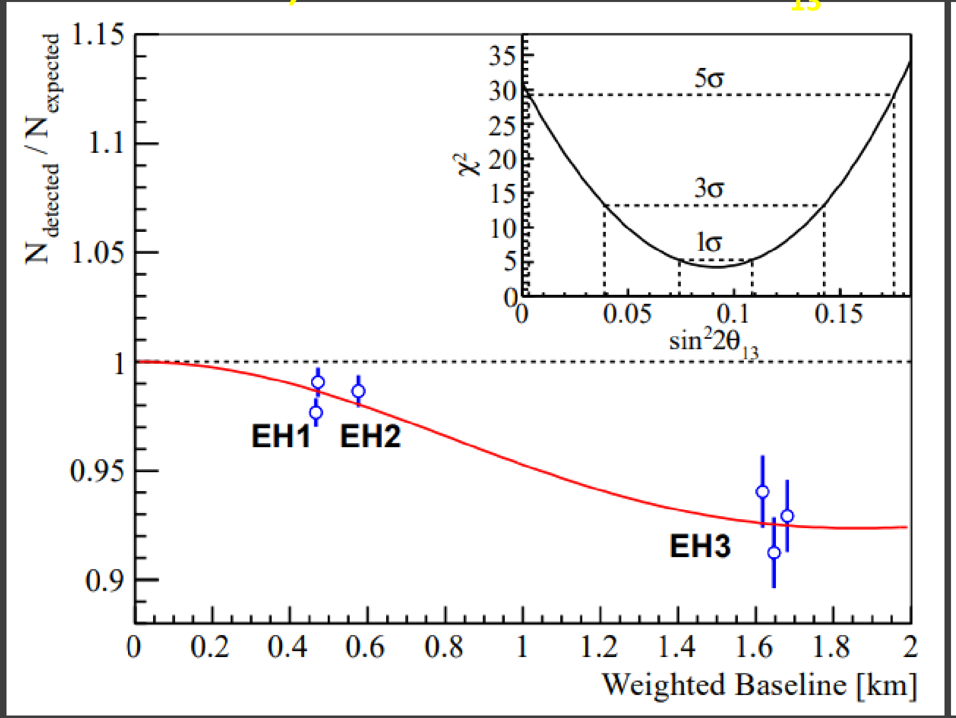


Discovery of non-zero θ_{13}

Nature is kind to us!

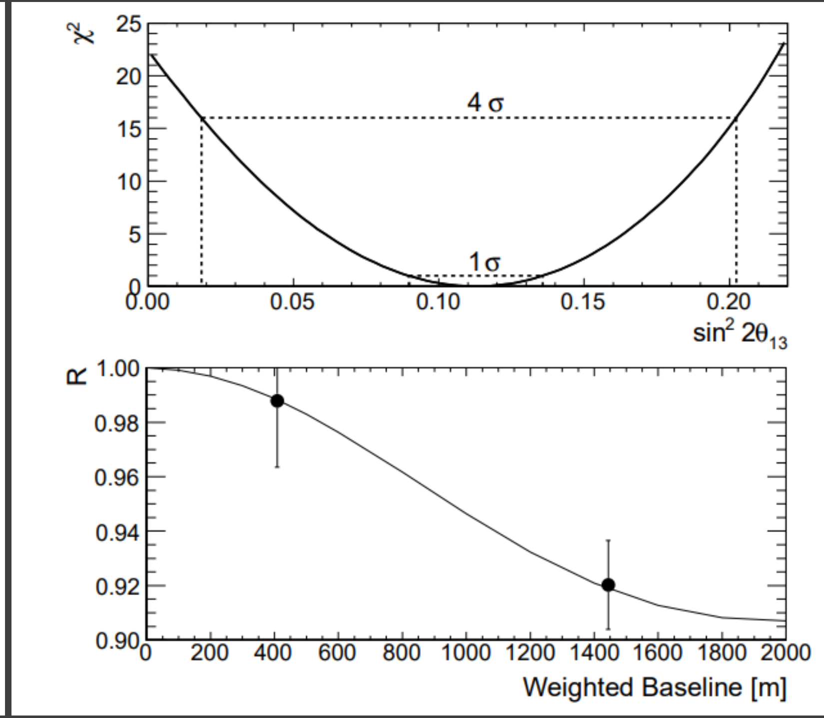
We will be able to measure the neutrino mass ordering and δ_{CP} in 2030s

$\sin^2 2\theta_{13} = 0.092 \pm 0.016(\text{stat}) \pm 0.005(\text{syst})$
March 2012, 5.2σ for non-zero $\sin^2 2\theta_{13}$



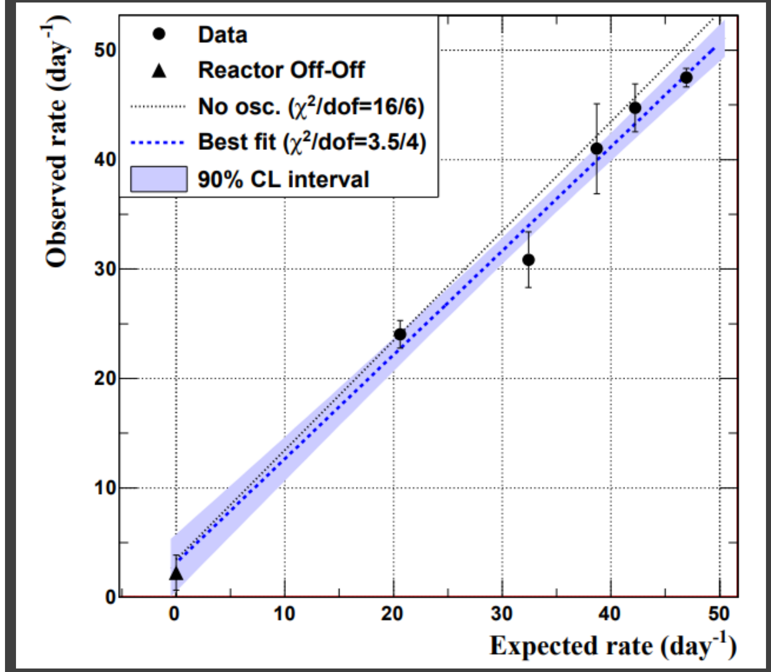
Daya Bay, March 2012
Phys.Rev.Lett. 108 (2012) 171803

$0.113 \pm 0.013(\text{stat.}) \pm 0.019(\text{syst.})$
April 2012, 4.9σ



RENO, April 2012
Phys.Rev.Lett. 108 (2012) 191802

$0.086 \pm 0.041(\text{stat.}) \pm 0.030(\text{syst.})$
Nov. 2011, 94.6% C.L.



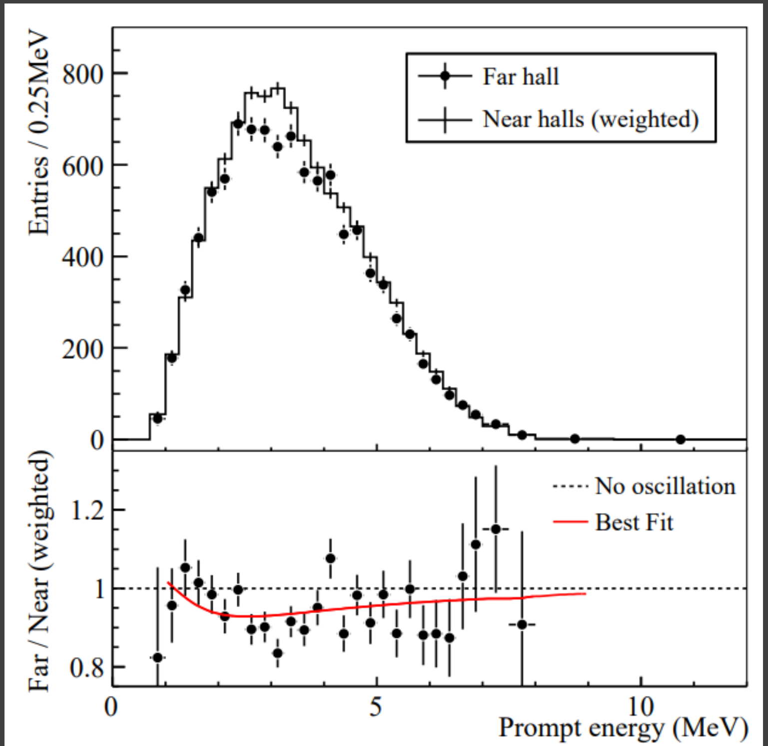
Double Chooz far detector
Phys.Rev.Lett. 108 (2012) 131801

Discovery of non-zero θ_{13}

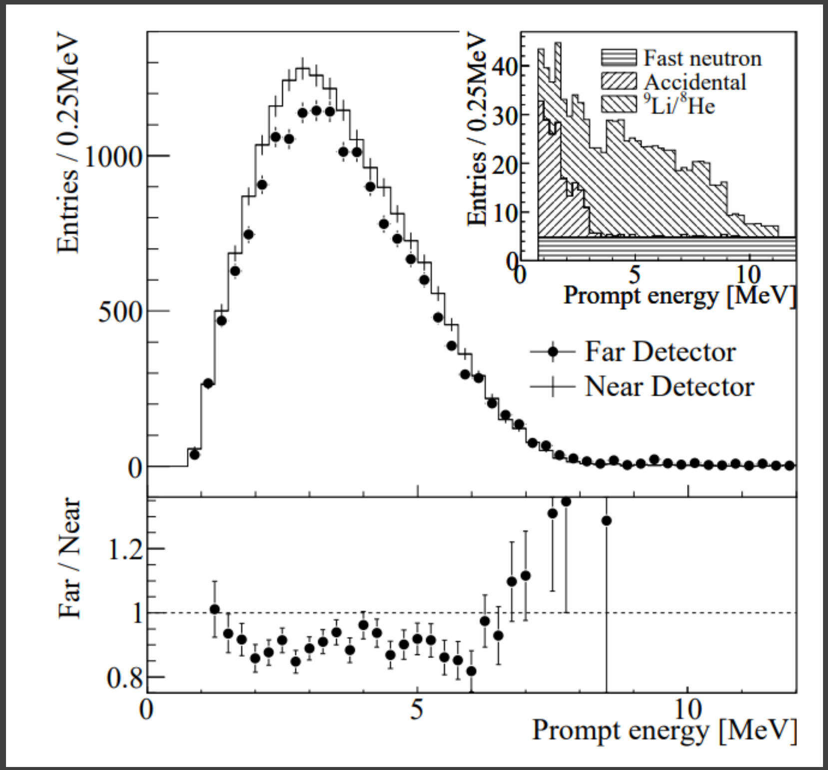
Nature is kind to us!

We will be able to know the neutrino mass ordering and δ_{CP} in 2030s

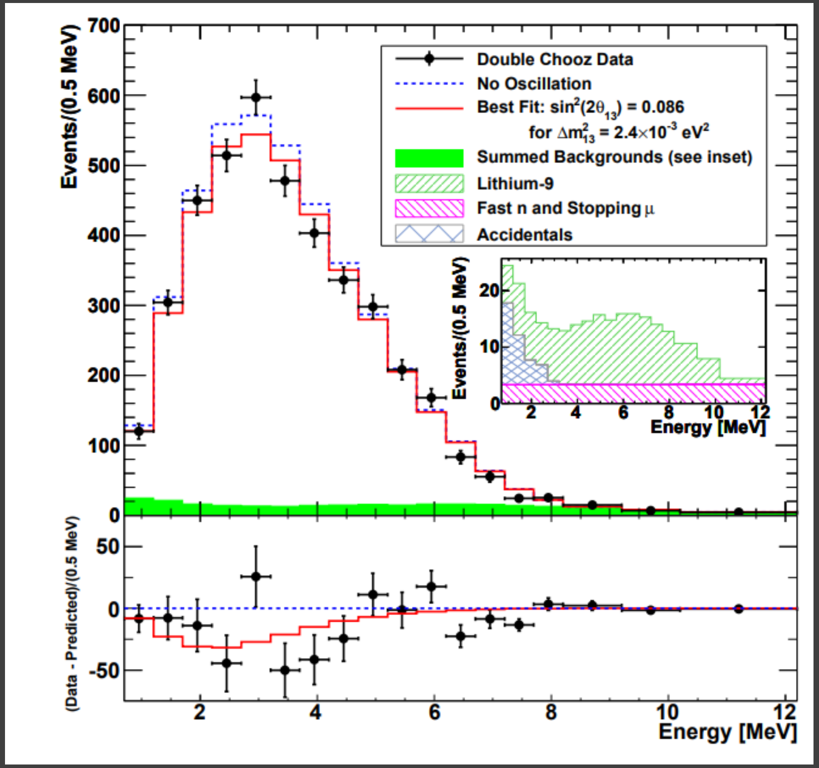
Shape distortions consistent with three-flavor oscillation predictions



Daya Bay, March 2012
Phys.Rev.Lett. 108 (2012) 171803



RENO, April 2012
Phys.Rev.Lett. 108 (2012) 191802

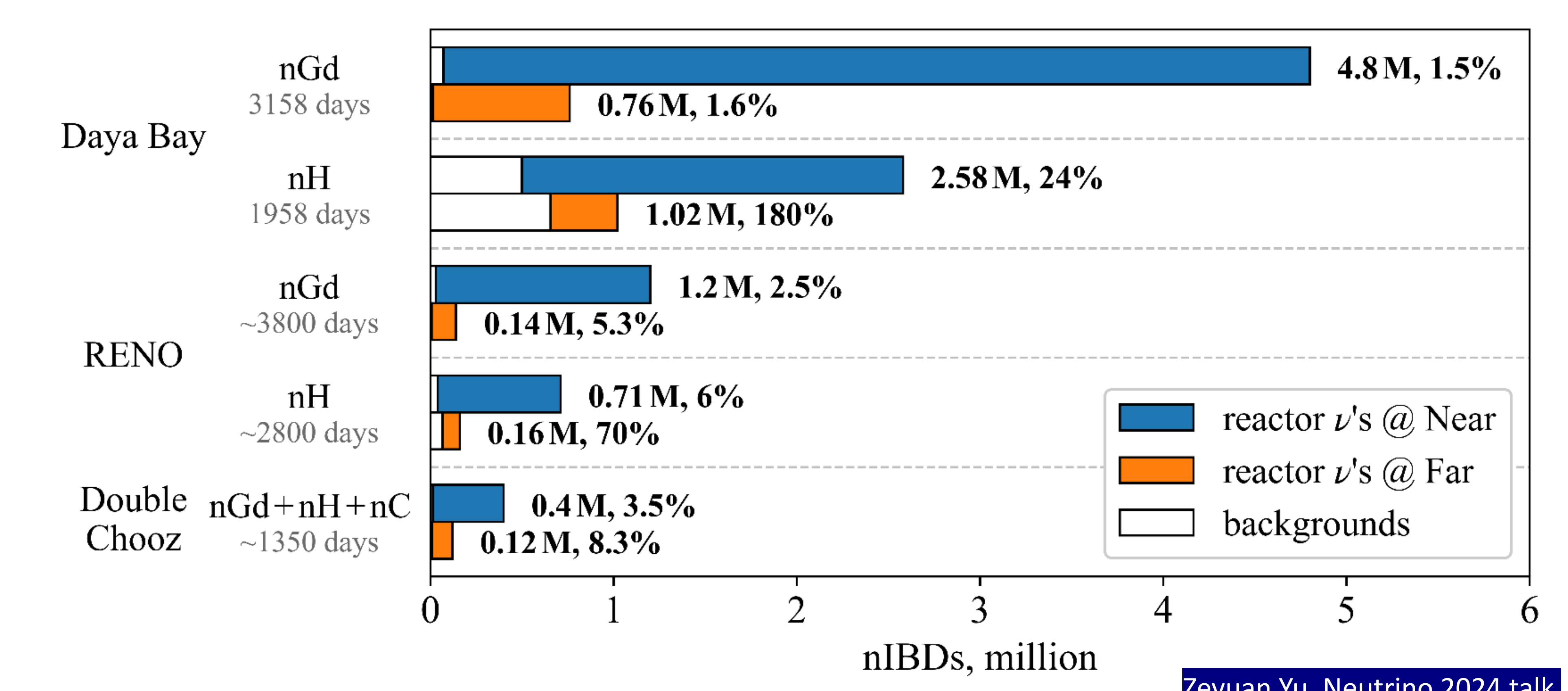


Double Chooz far detector
Phys.Rev.Lett. 108 (2012) 131801

Data Set

- Three experiments are closed
- A door is open for mass ordering and CP violating phase

Daya Bay	Dec. 2011 to Dec. 2020, 3158 days
Double Chooz	Apr. 2011 to Dec. 2017, ~1350 days
RENO	Aug. 2011 to Mar. 2023, ~3800 days



Zeyuan Yu, Neutrino 2024 talk

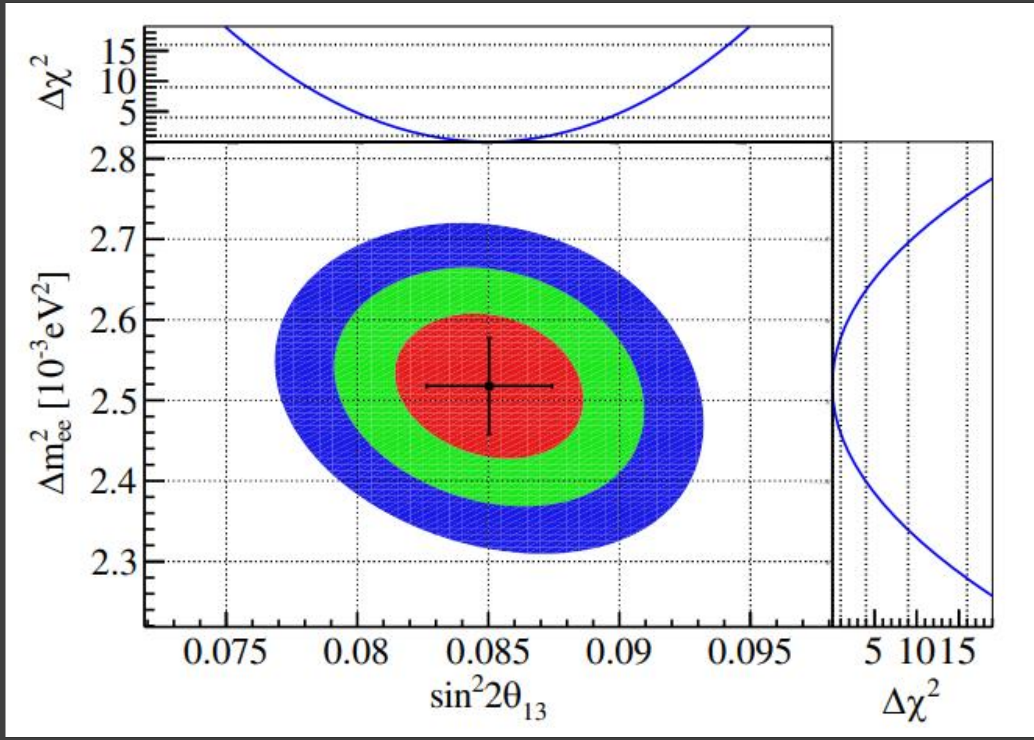
Daya Bay nGd full dataset

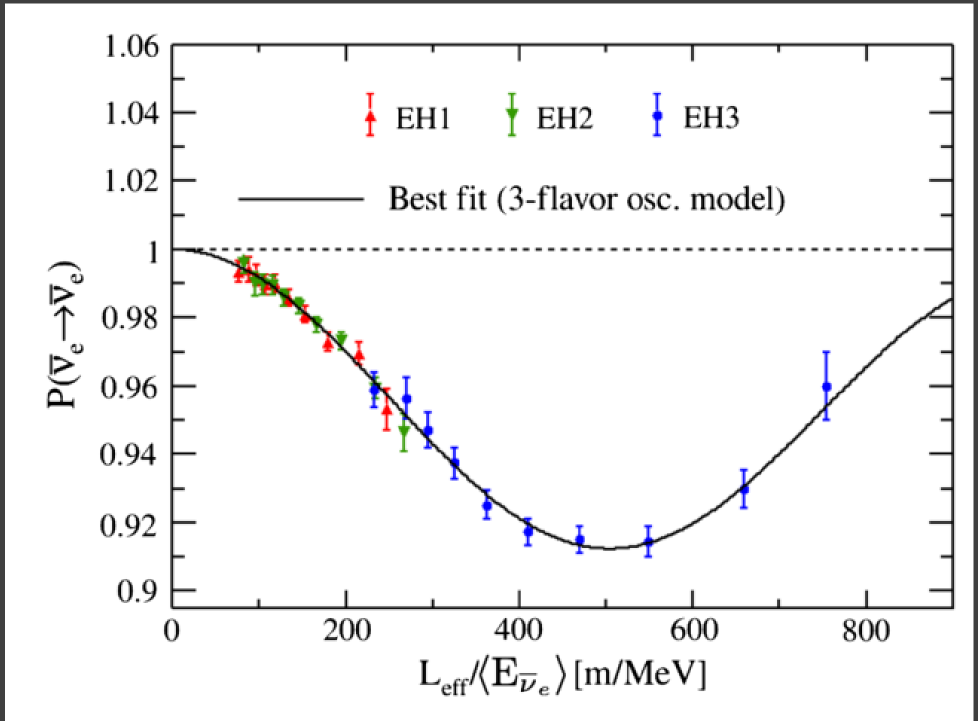
- Daya Bay reported the precision measurement with 3158-days full dataset

  $\sin^2 2\theta_{13} = 0.0851 \pm 0.0024$ precision 2.8%

  $\Delta m^2_{32} = 2.466 \pm 0.060\ (-2.571 \pm 0.060) \times 10^{-3}\ \mathrm{eV}^2$ precision 2.4%

- Systematics, mainly detector differences, contributed about 50% in the total error





PhysRevLett. 130 161802

RENO nGd results with full dataset

From RENO talk @ ICHEP 2024

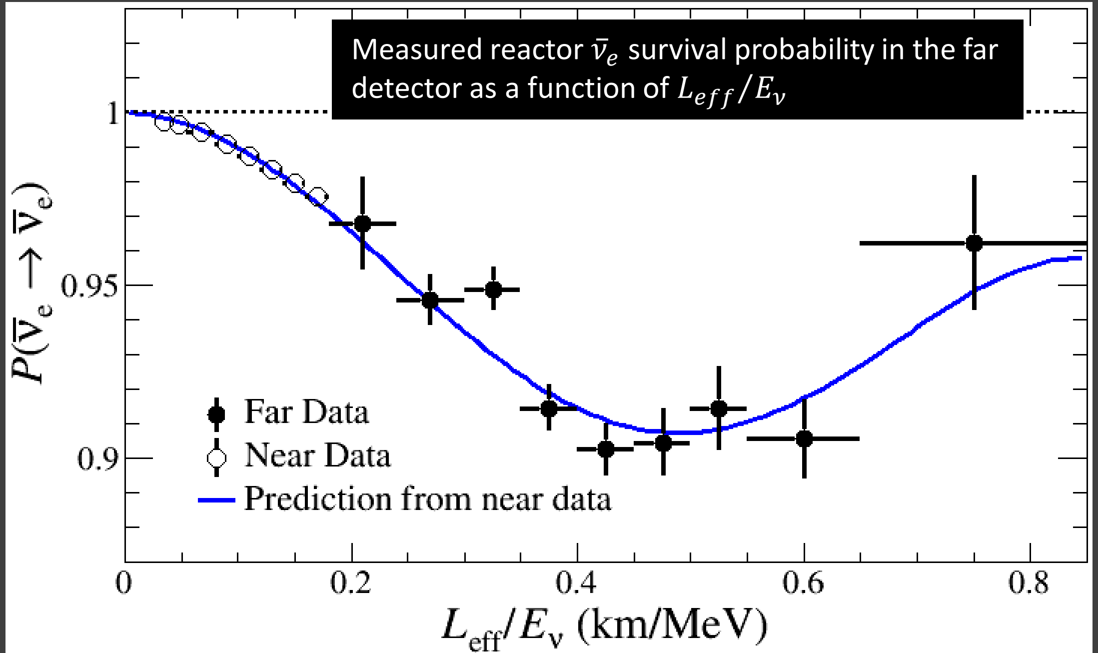
- Results obtained with 3800 days full dataset

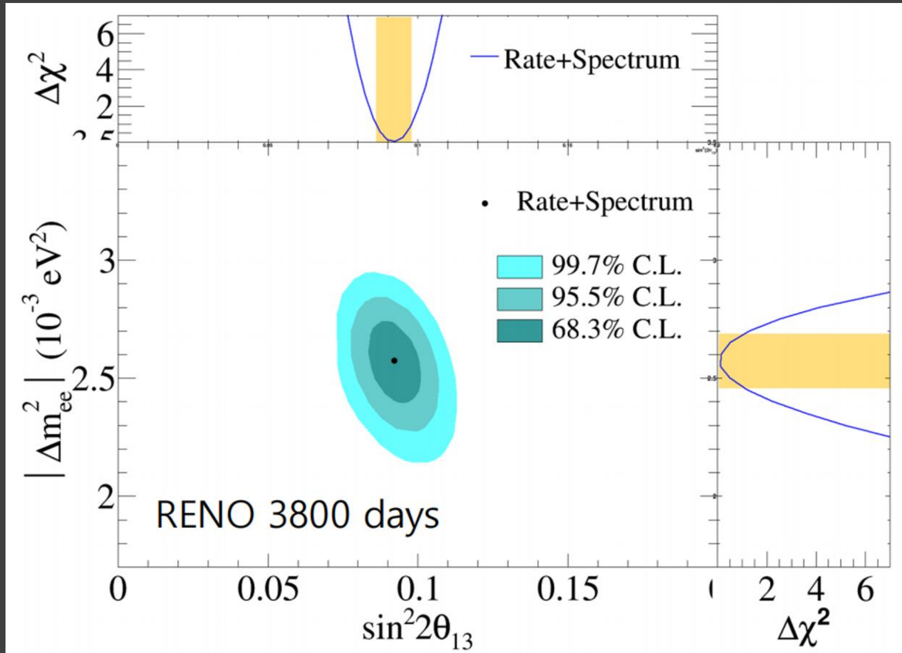
$$\boldsymbol{sin^2 2\theta_{13} = 0.0920\ ^{+0.0044}_{-0.0042}(stat.)\ ^{+0.0041}_{-0.0041}(syst.)}$$ precision 6.4%

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

- (reference) 2200[d] result published at **2018**

  - $sin^2 2\theta_{13} = 0.0896 \pm 0.0048(stat.) \pm 0.0047(syst.)$ precision 7.5%
  - $\Delta m^2_{ee} = 2.68 \pm 0.12(stat.) \pm 0.07(syst.)[\times 10^{-3} eV^2]$ precision 5.2%





Daya Bay nH results

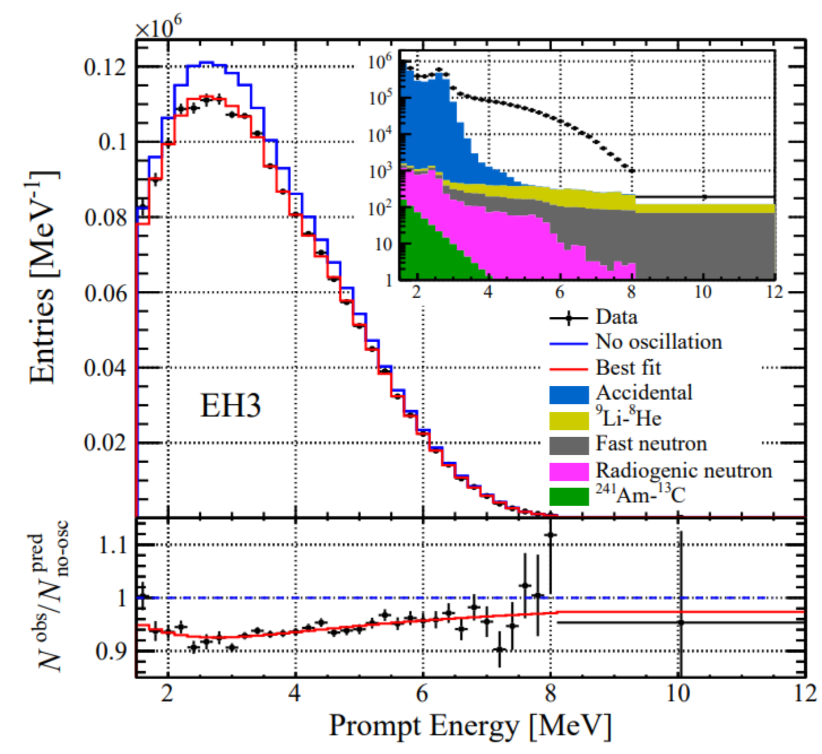
Consistent with nGd results within 2σ with 1958-days nH data

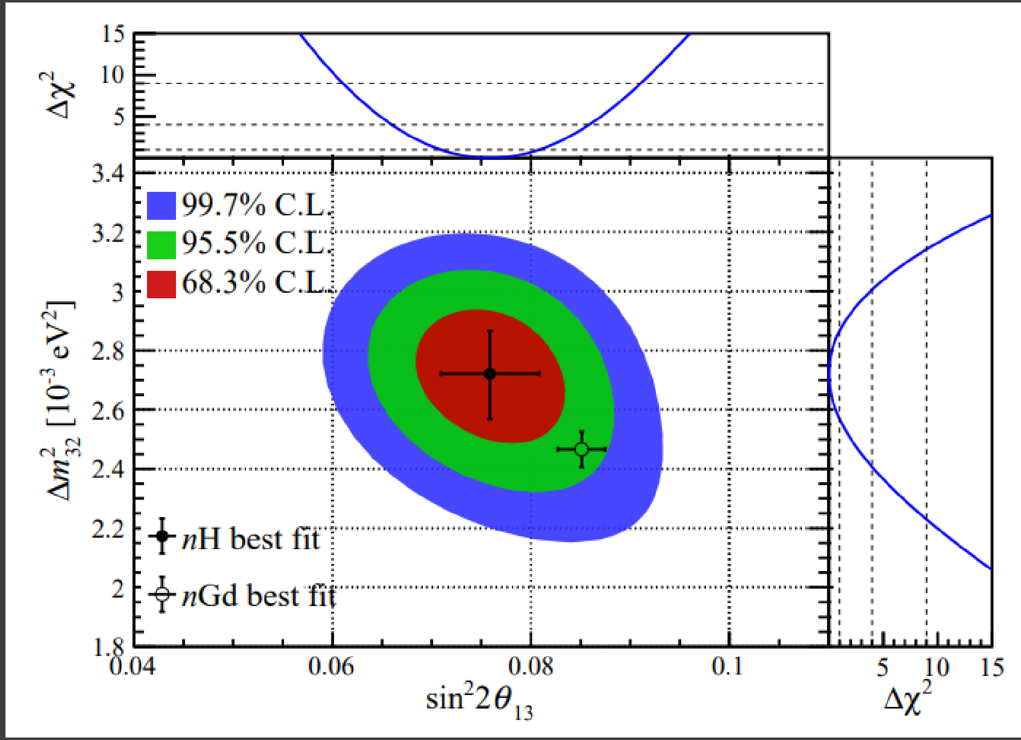
nH analysis on full dataset is ongoing

$\sin^2 2\theta_{13} = 0.0759 \pm 0.005$ precision 6.5%

$\Delta m^2_{32} = 2.72 \pm 0.15\ (-2.83 \pm 0.15) \times 10^{-3}\ \mathrm{eV}^2$ precision 5.3%

Statistics contribute 47% and 64% to the errors of $\sin^2 2\theta_{13}$ and Δm^2_{32}, respectively





arXiv: 2406.01007, accepted by PRL

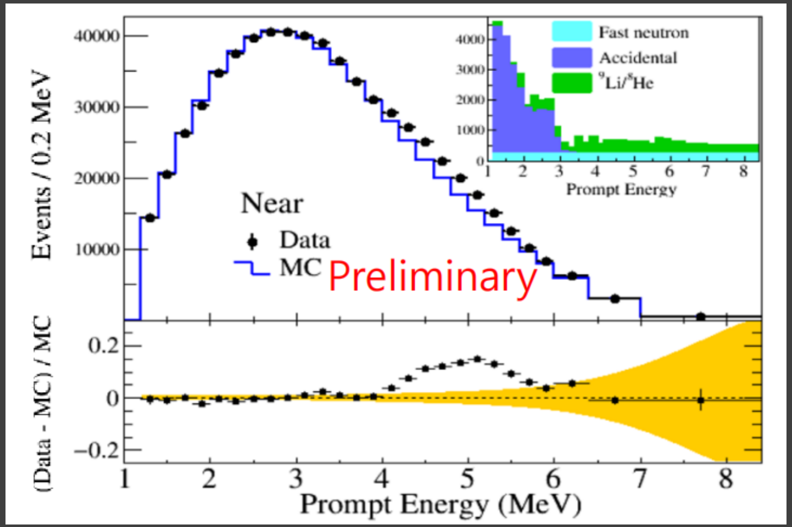
RENO nH results

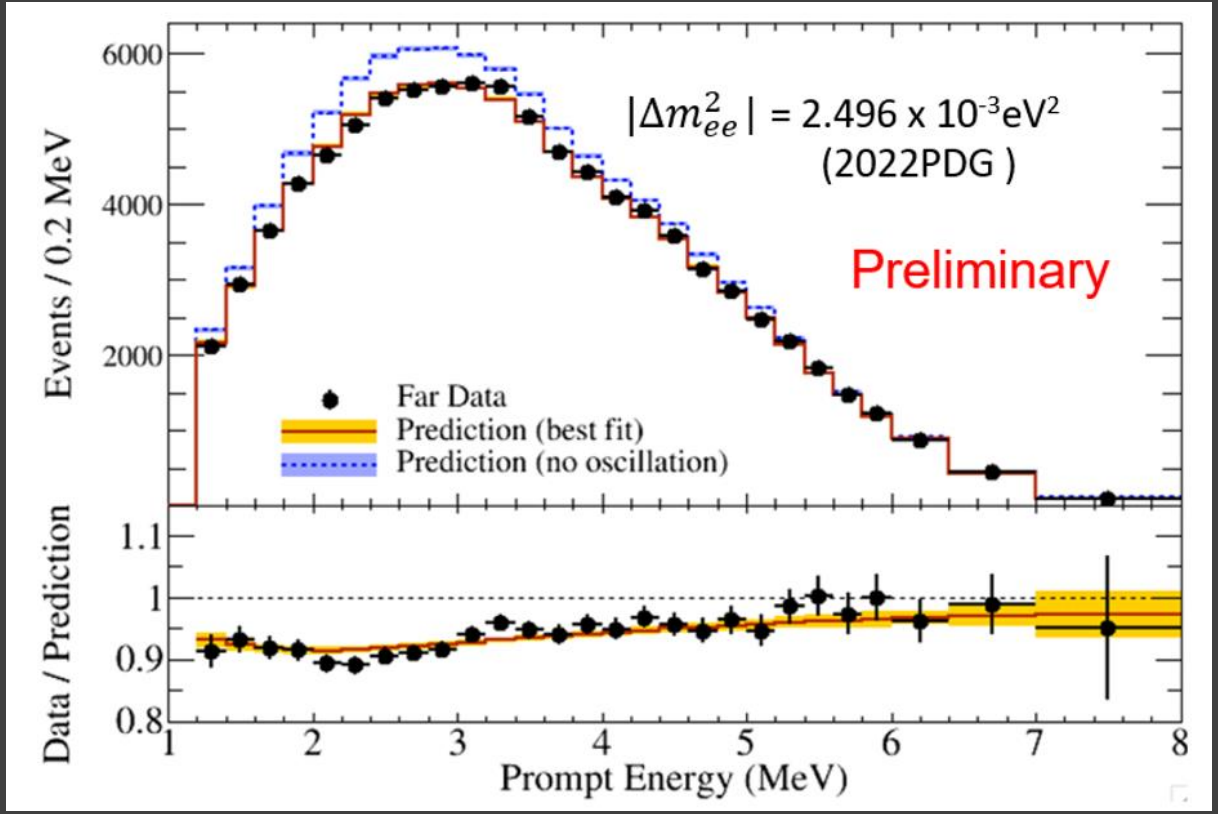
From RENO talk @ ICHEP 2024

- Using 2800[d] n-H sample (full dataset)

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

- [reference] JHEP (2019) 1500 days of nH: $\sin^2 2\theta_{13} = 0.086 \pm 0.008(\text{stat.}) \pm 0.014(\text{syst.})$ precision 18.7%



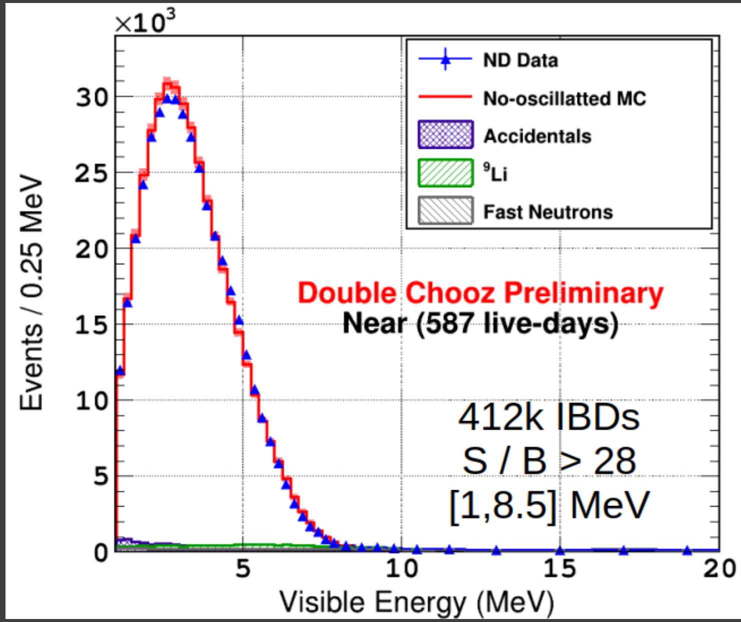


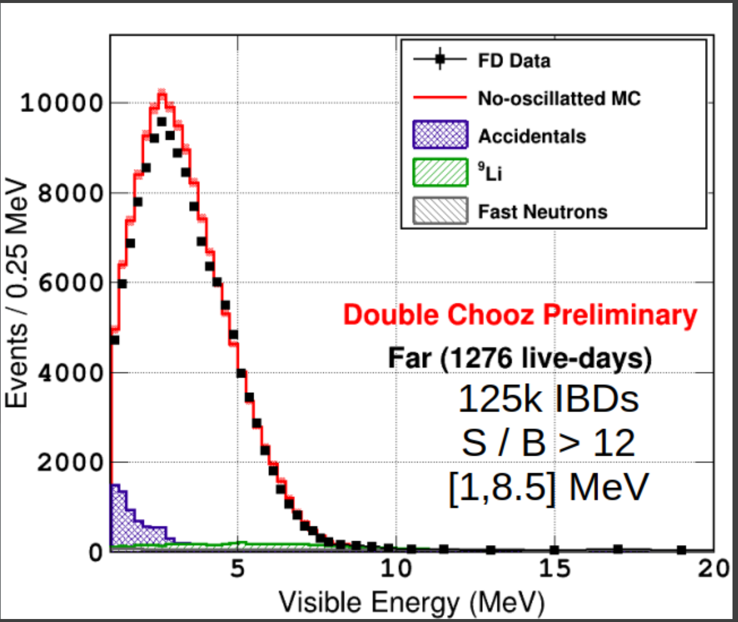
	Near	Far
DAQ live time (days)	2259.298	2653.297
IBD candidates & backgrounds rate	316.67 ± 0.37	61.10 ± 0.15
After background subtraction	298.60 ± 0.62	35.67 ± 0.28
Total background rate	18.06 ± 0.50	25.43 ± 0.24

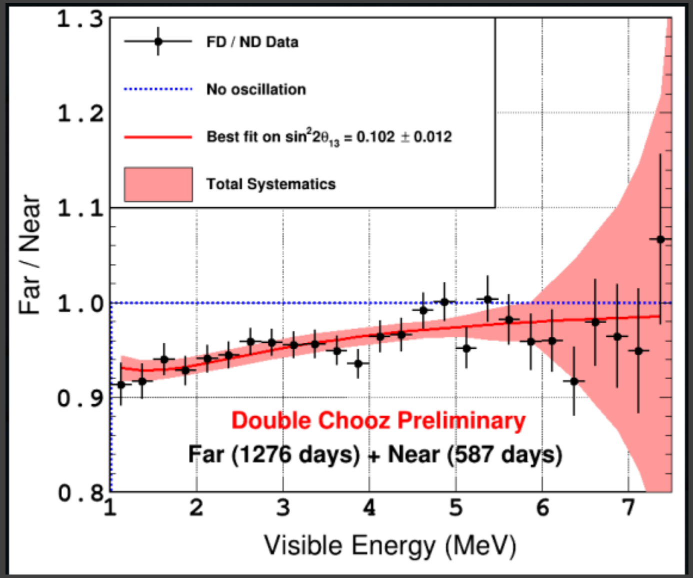
Double Chooz nH+nGd+nC

- Double Chooz preliminary results with full data set, presented at Nu-2020
- Using ANN to suppress accidental background
- Total neutron capture enhanced the detection efficiency for n-Gd
- Plan to finalize by end of 2024

$\sin^2 2\theta_{13} = 0.102 \pm 0.004(\text{stat.}) \pm 0.011(\text{syst.})$ precision 11.8%







Plots from Double Chooz talk at Nu-2020

Comparison of θ_{13} results

- Daya Bay leads the precision measurement, nGd+nH gives 2.6% precision. It can be improved by nH results of full dataset.
- Consistent results from reactor and accelerator experiments

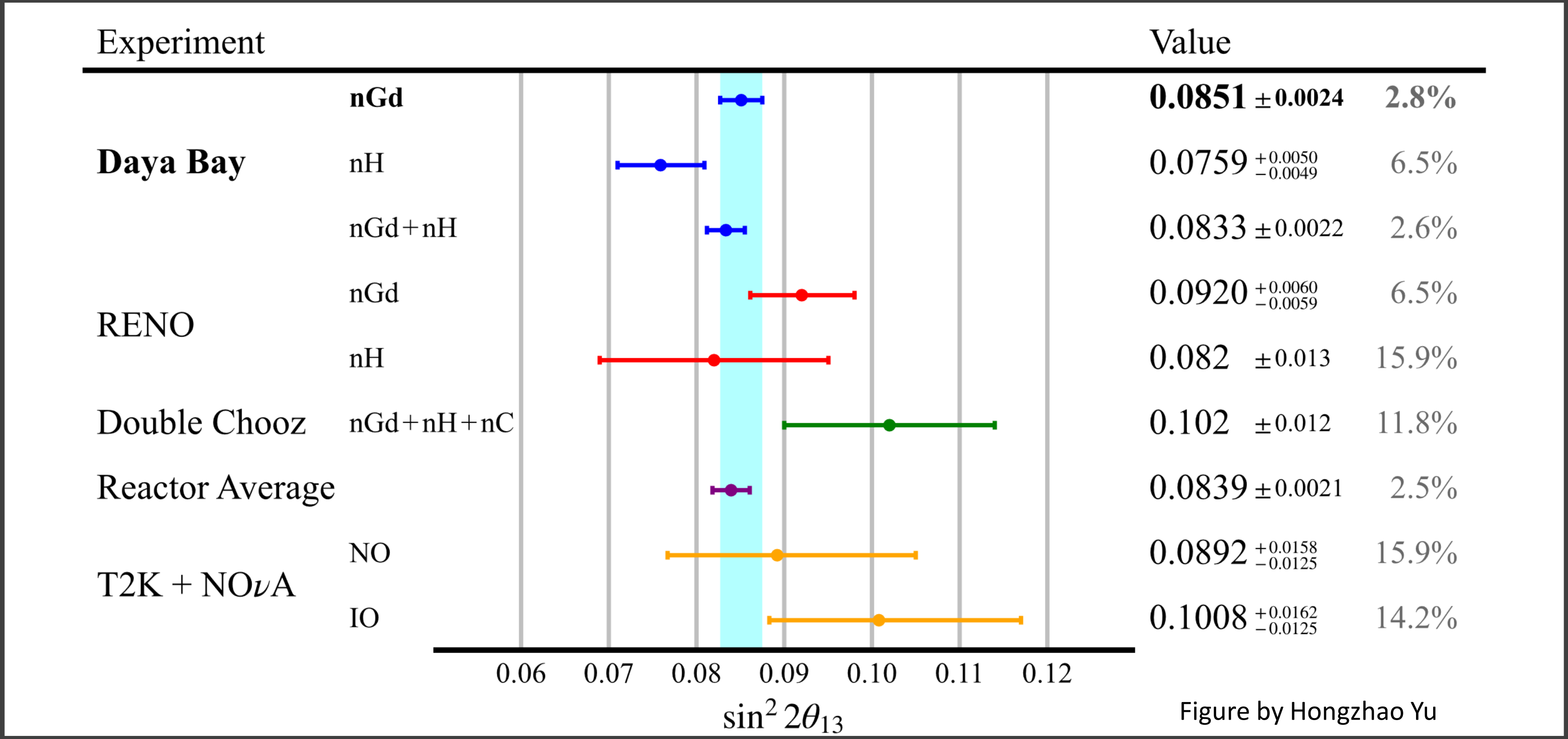
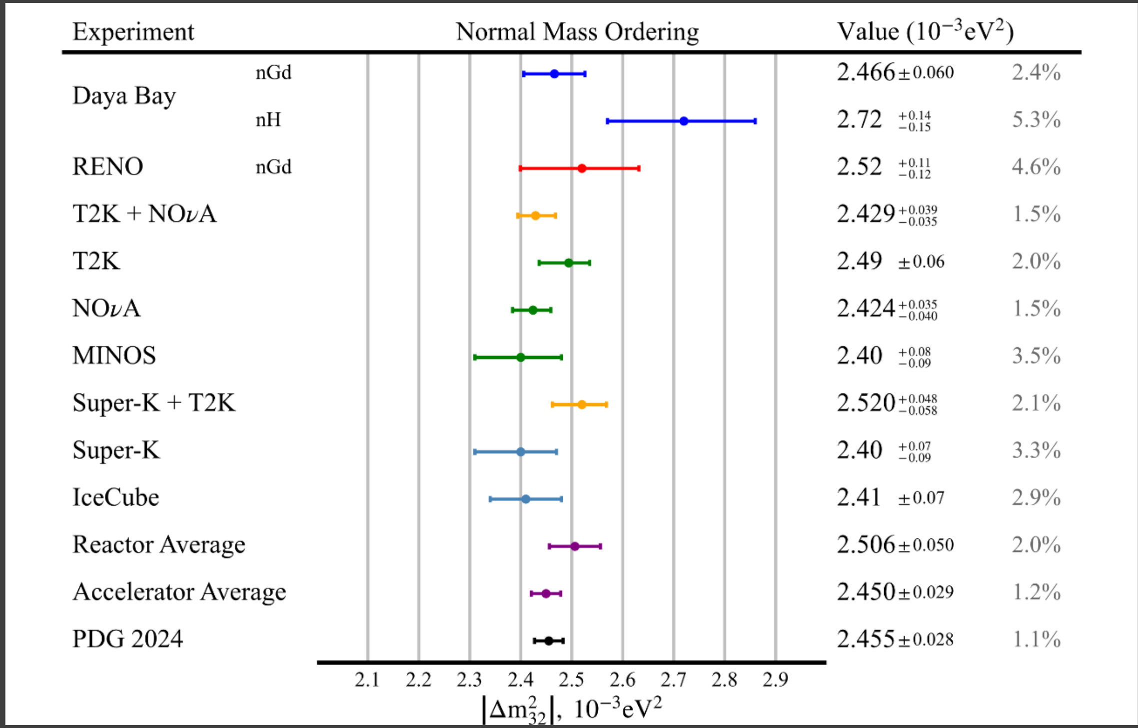


Figure by Hongzhao Yu

Simple weighted average assuming no correlation

Comparison of Δm^2 results

- Consistent results from reactor and accelerator experiments
- Reactor weighted average 2%, dominated by Daya Bay
- Leading results (1.5%) from NOvA
- Normal mass ordering is preferred from checking the discrepancy



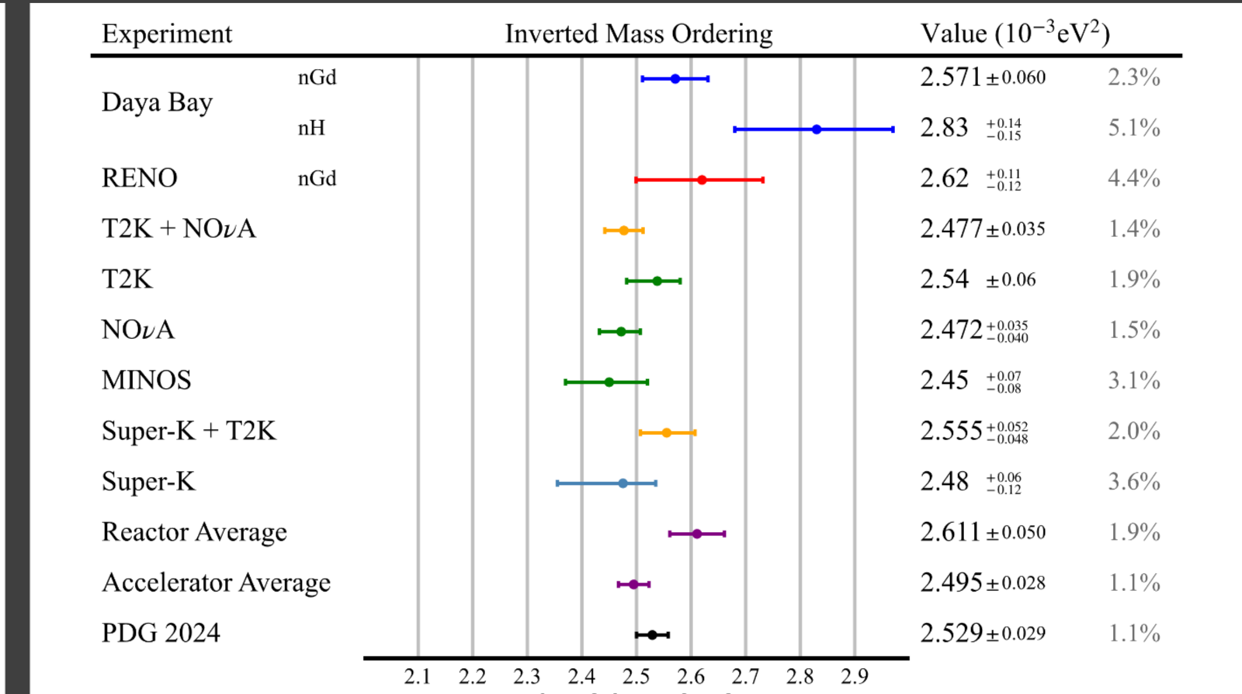


Figure by Hongzhao Yu

Note: average is error weighted assuming no correlation. T2K+NOvA does not include latest NOvA result

Summary

- Reactor neutrinos performed few percent level measurements of
  - $\sin^2 2\theta_{13}$, Δm^2_{31} by Daya Bay, Double Chooz, and RENO
  - $\sin^2 2\theta_{12}$, Δm^2_{21} by KamLAND
- Daya Bay, RENO, and Double Chooz all stopped data taking
  - Near/far relative measurement is a great success to control systematics
  - Leading results are from Daya Bay nGd full dataset
- For future, precisions of Δm^2_{31}, $\sin^2 2\theta_{12}$, and Δm^2_{21} will be improved by JUNO

backup

Experiment	Reference
Daya Bay nGd	Phys. Rev. Lett. **130,** 161802 (2023)
Daya Bay nH	arXiv:2406.01007
RENO nGd and nH	ICHEP 2024 talk
Double Chooz	Neutrino 2020 talk
T2K	Eur. Phys. J. C **83,** 782 (2023)
NOvA	Neutrino 2024 talk
T2K + NOvA	Reports (2024) found at https://indico.fnal.gov/event/62062/ https://kds.kek.jp/event/49811/
MINOS	Phys. Rev. Lett. **125,** 131802 (2020)
Super-K	Phys. Rev. D **109,** 072014 (2024)
Super-K + T2K	arXiv:2405.12488
IceCube	Phys. Rev. D **108,** 012014 (2023)