Status of θ_{13} measurements

Zeyuan Yu

Institute of High Energy Physics

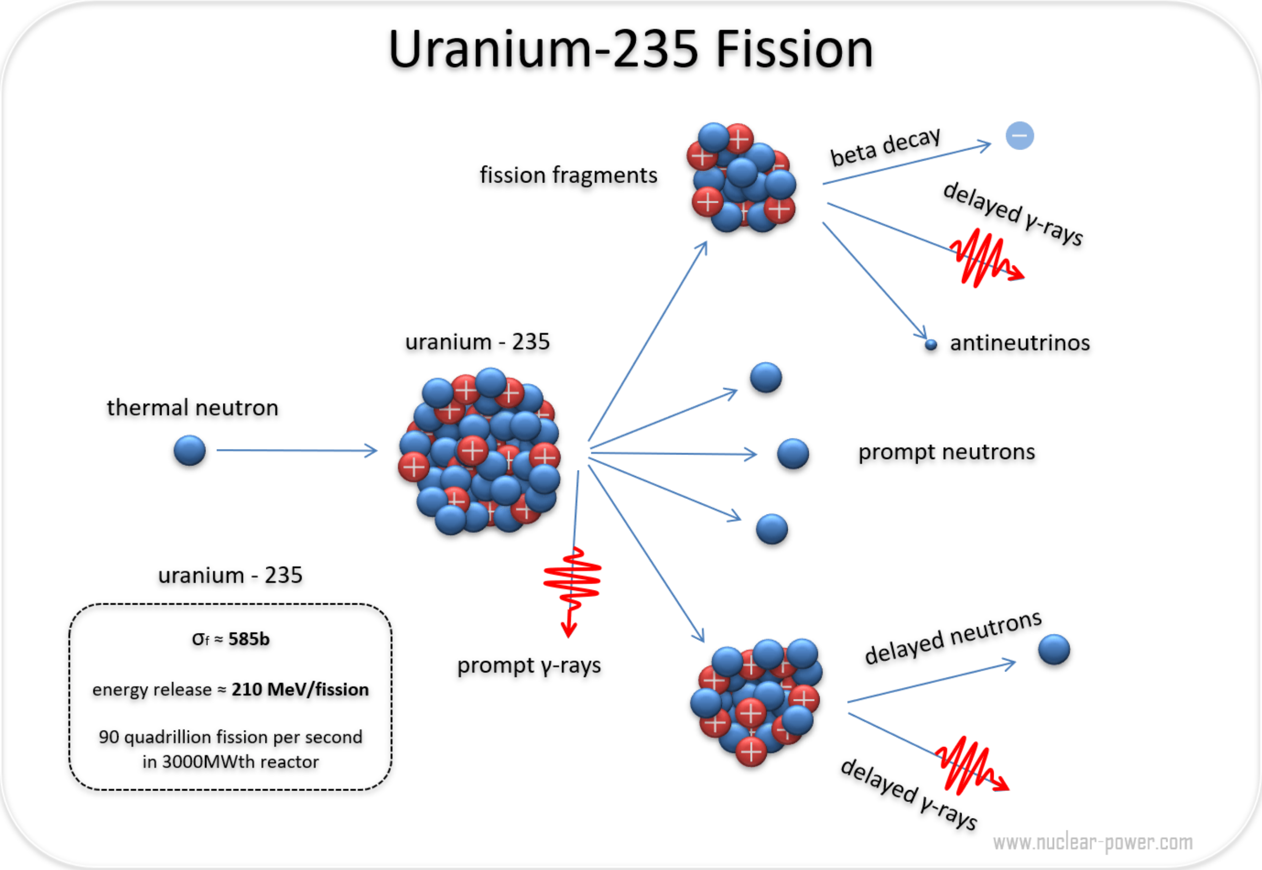
June 17th, 2024

With inputs from Double/Super Chooz, RENO and Daya Bay collaborations

Reactor neutrinos

The strongest artificial neutrino source on the Earth

2×10^{20} ν's per second per GW thermal power, >99.7% from ^{235,238}U and ^{239,241}Pu



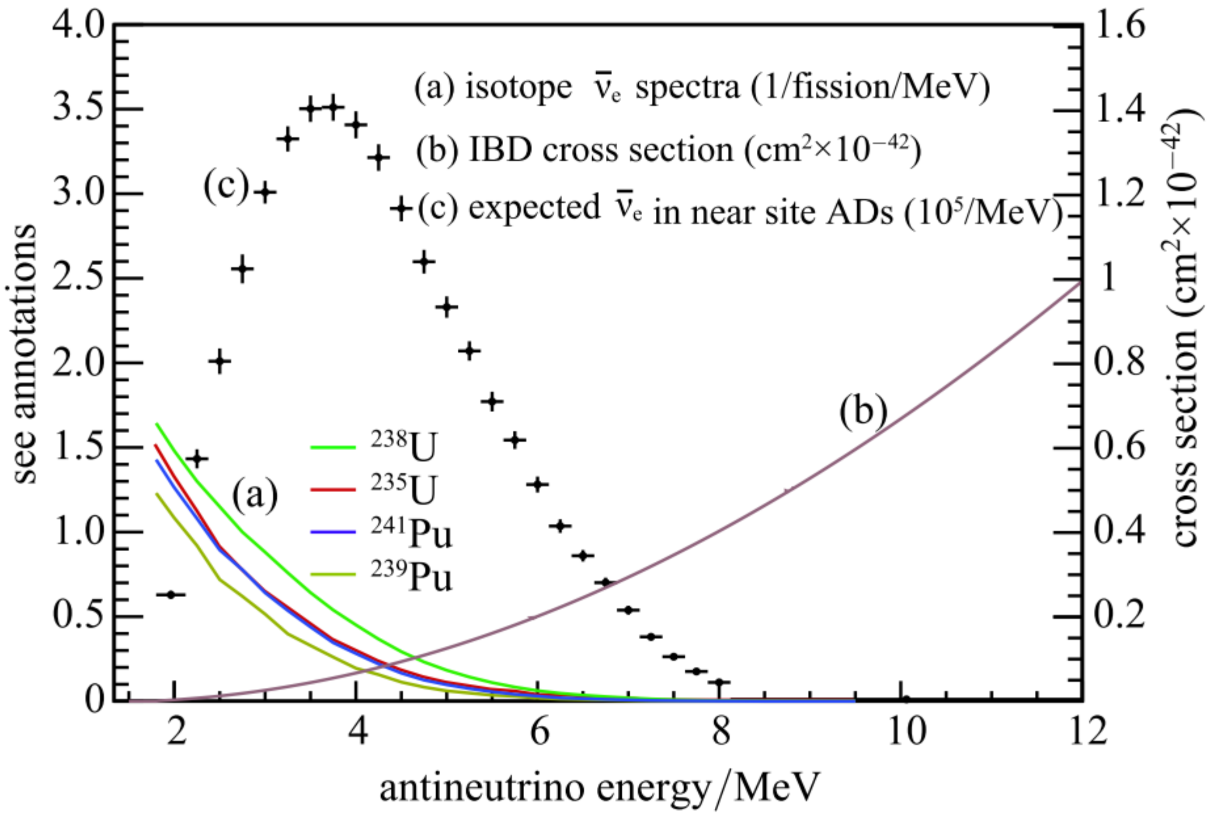
www.nuclear-power.com

Reactor neutrinos

The strongest artificial neutrino source on the Earth

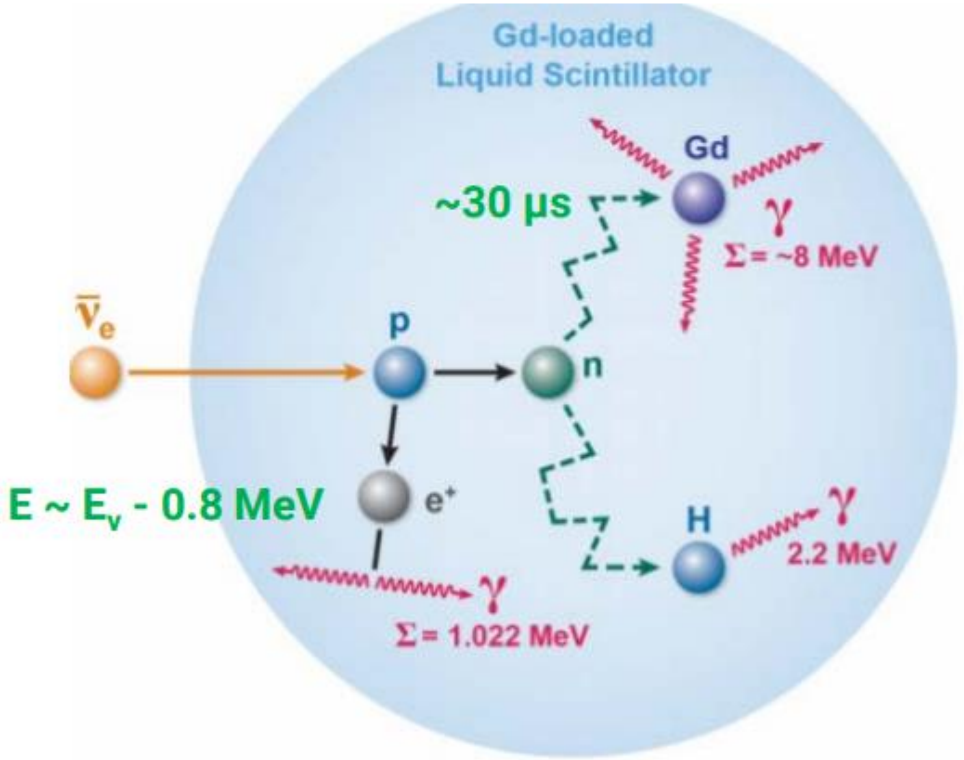
2×10^{20} ν's per second per GW thermal power, >99.7% from ^{235,238}U and ^{239,241}Pu

Easy to detect via the Inverse Beta Decays (IBD)



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

Correlated signals from e$^+$/neutron captures

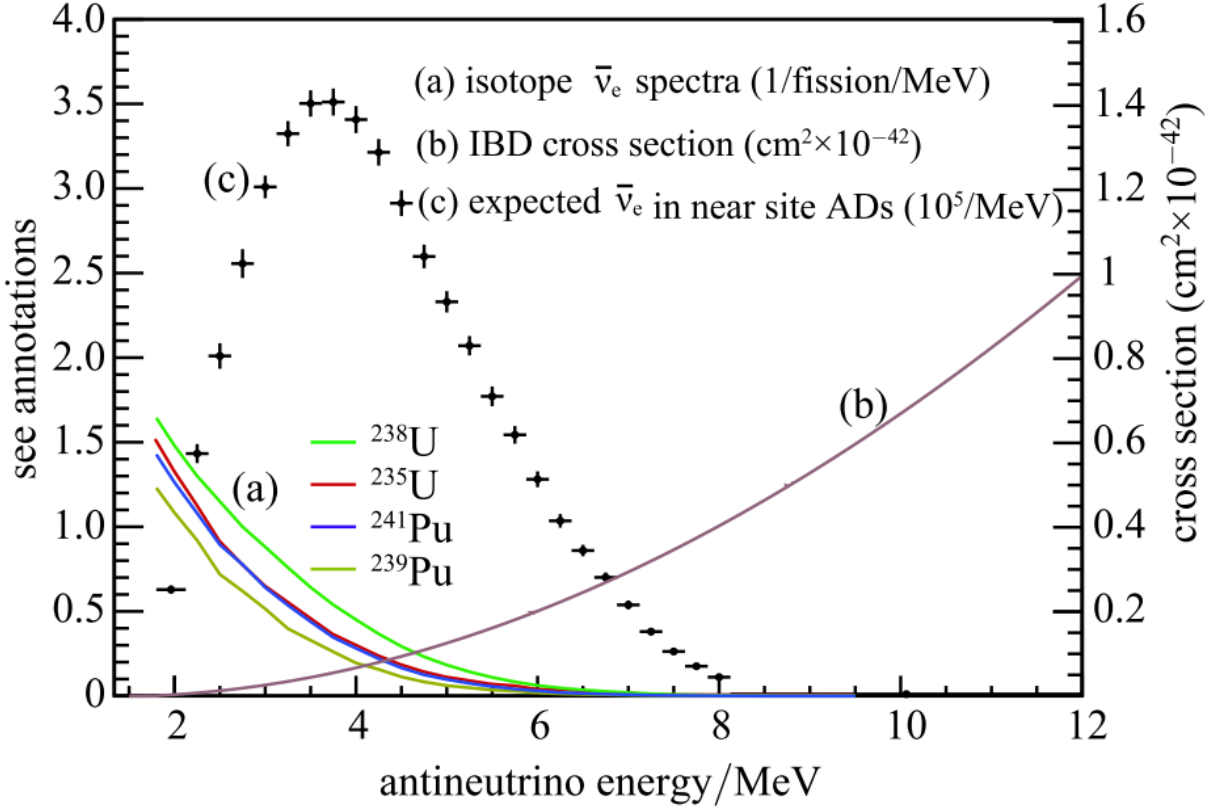


Reactor neutrinos

The strongest artificial neutrino source on the Earth

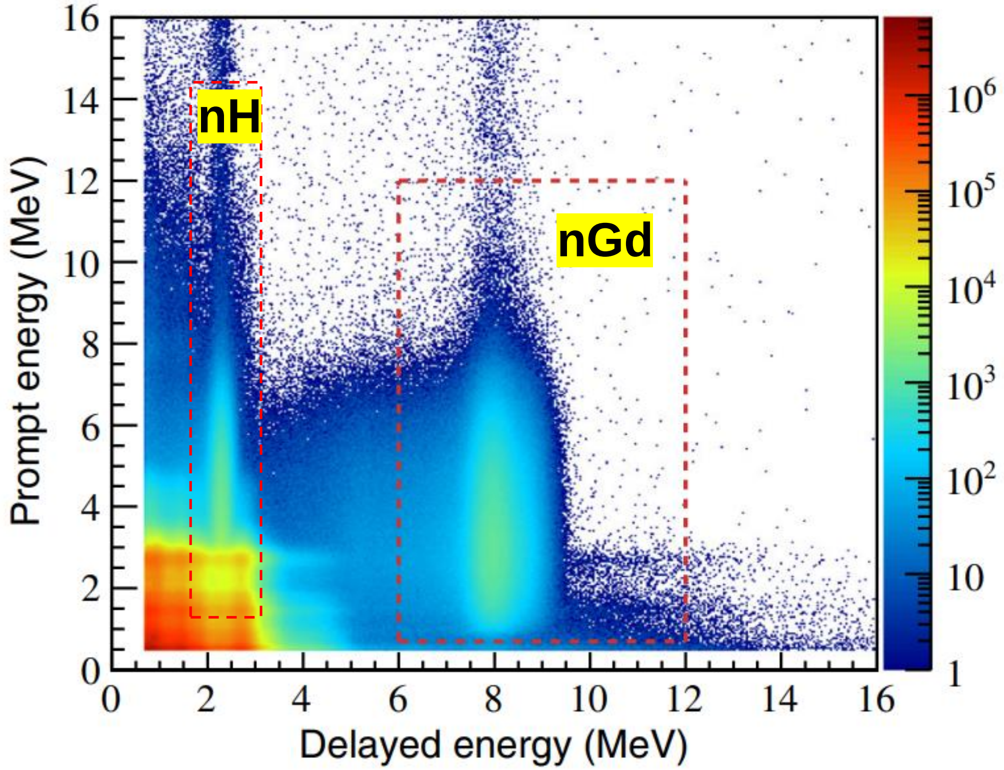
2×10^{20} ν's per second per GW thermal power, >99.7% from $^{235,238}U$ and $^{239,241}Pu$

Easy to detect via the Inverse Beta Decays (IBD)



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

Correlated signals from e^+/neutron captures



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

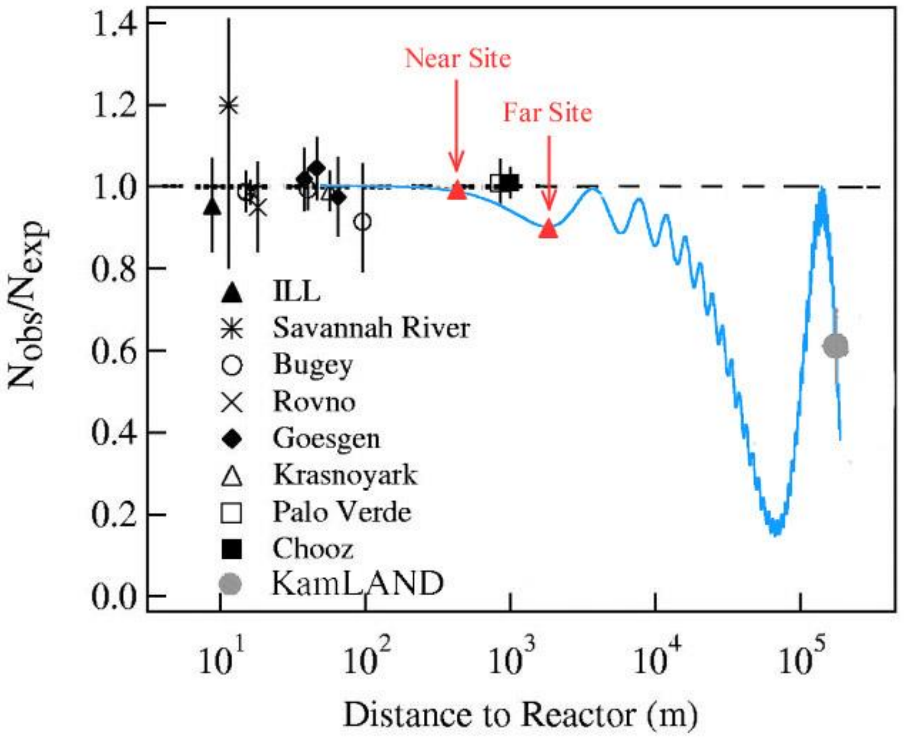
Measure θ_{13} with reactor ν's

Disappearance experiments to measure $\bar{\nu}_e$ survival probabilities

$$P = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} - \sin^2 2\theta_{13}\left(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}\right)$$

No ambiguity, independent of matter effect and δ_{CP}

Place two detectors for a relative measurement, <1% systematics



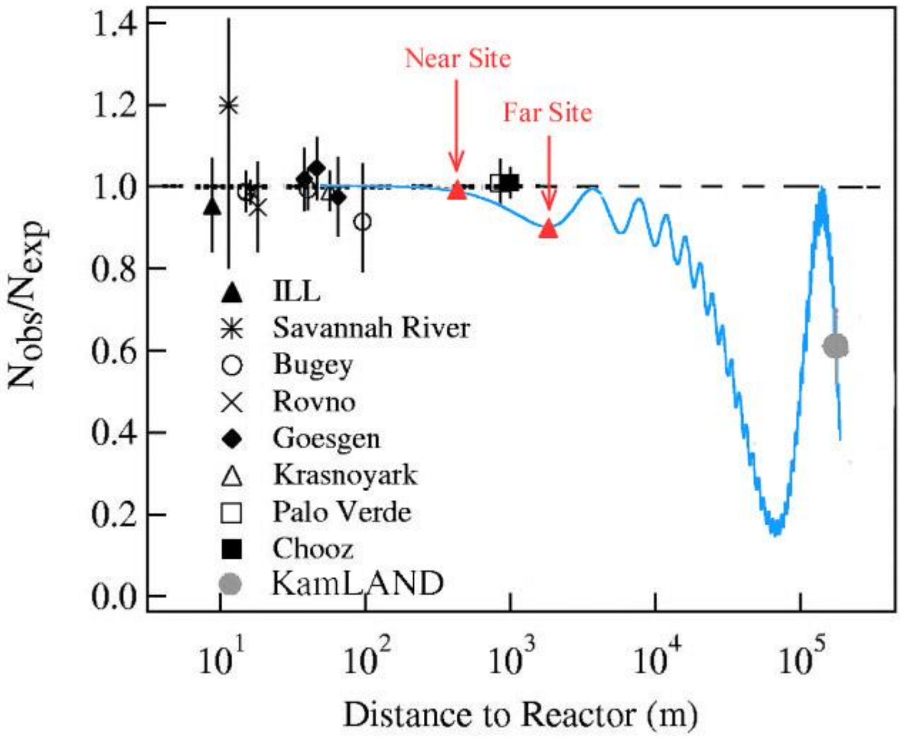
Measure θ_{13} with reactor ν's

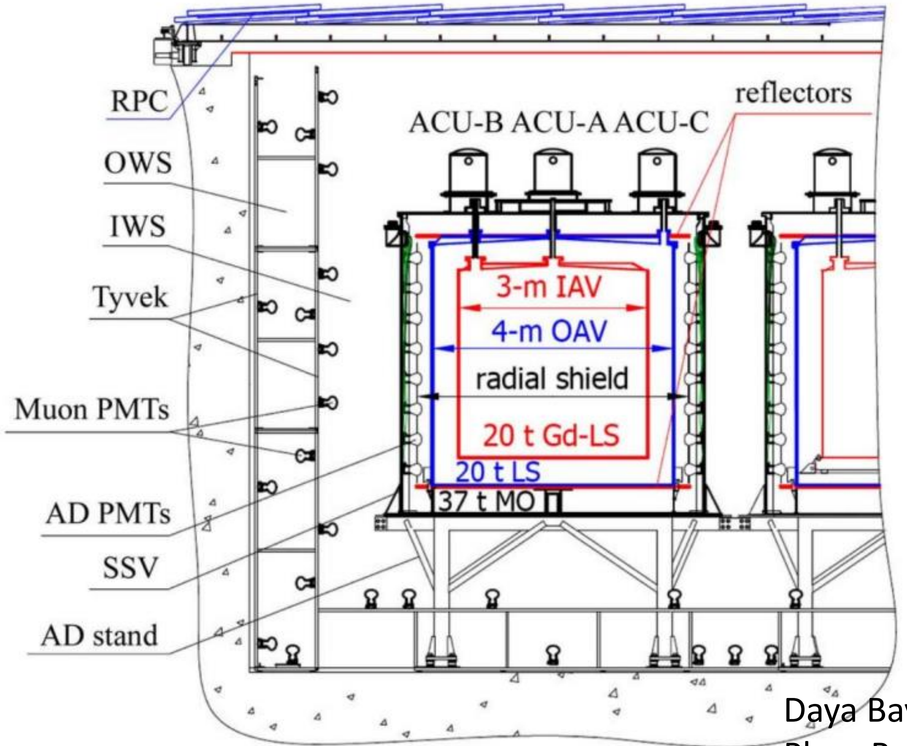
Disappearance experiments to measure $\bar{\nu}_e$ survival probabilities

$$P = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} - \sin^2 2\theta_{13}\left(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}\right)$$

No ambiguity, independent of matter effect and δ_{CP}

Three zones, Gd-LS/LS/oil, naturally define the fiducial volume, good shielding

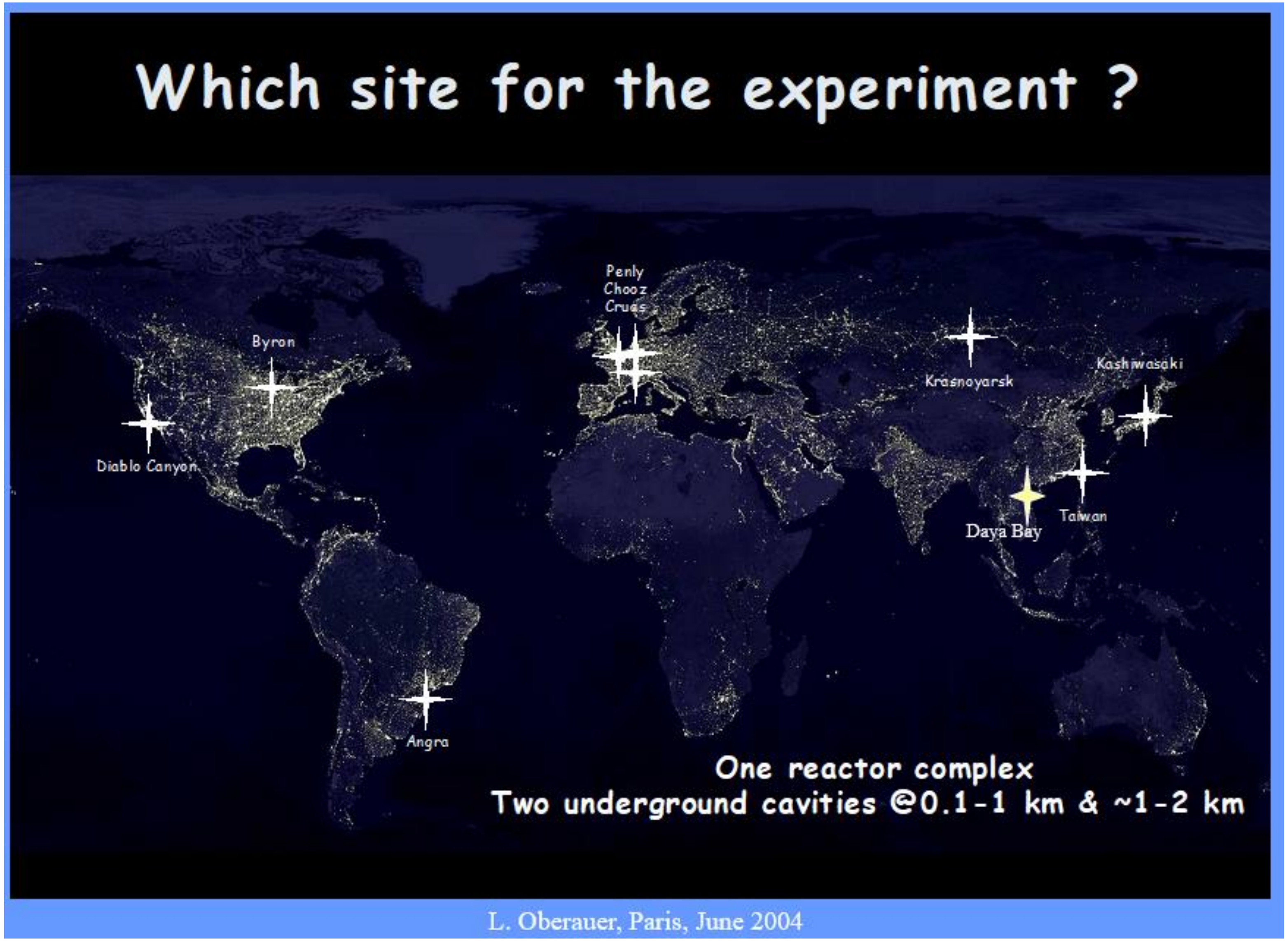




Daya Bay as an example,
Phys. Rev. Lett. 108, 171803

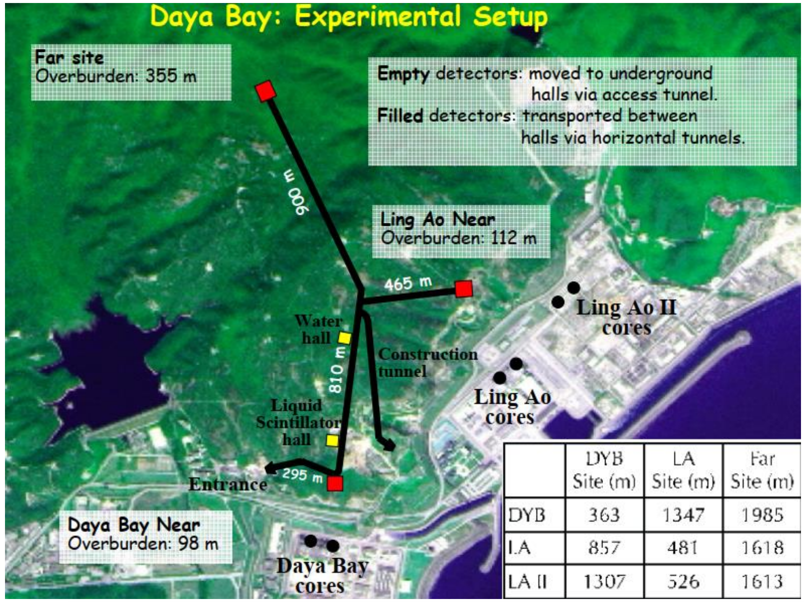
θ_{13} status at Neutrino-2004

Search for θ_{13} with a new reactor experiment is very promising, white paper ready



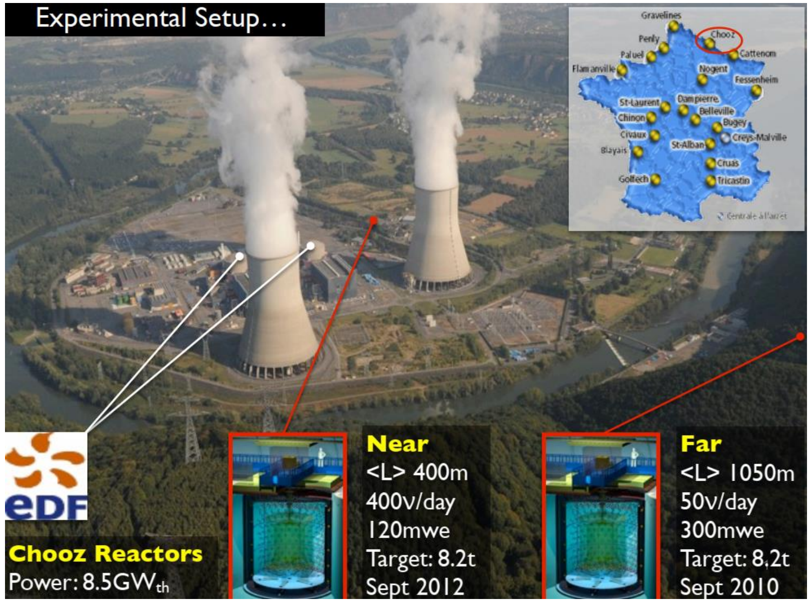
θ_{13} status at Neutrino-2008

Three experiments, Daya Bay, Double Chooz and RENO started construction

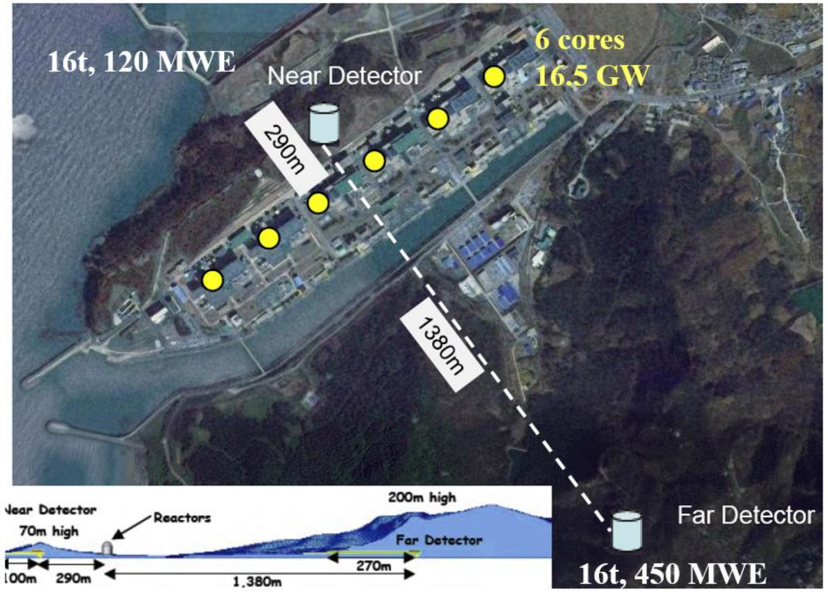


	DYB Site (m)	LA Site (m)	Far Site (m)
DYB	363	1347	1985
LA	857	481	1618
LA II	1307	526	1613

- Daya Bay will reach a sensitivity of ≤ 0.01 for $\sin^2 2\theta_{13}$
- Civil construction has begun
- Subsystem prototypes exist
- Long-lead orders initiated
- Daya Bay is moving forward:
  - Surface Assembly Building - Summer 2008
  - DB Near Hall - installation activities begin early in 2009
  - Assembly of first AD pair - Spring 2009
  - Commission Daya Bay Hall by November 2009
  - LA Near and Far Hall - installation activities begin late in 2009
  - Data taking with all eight detectors in three halls by Dec. 2010



- **Double Chooz Far integration Started in May 08**
- **First goal: measurement of θ_{13}**
  - *2008-09 → Far Detector construction & integration*
  - *Middle 09 → Start of phase I : Far 1 km detector alone*
    $\sin^2(2\theta_{13})$ < 0.06 after 1,5 year (90% C.L.) if no-oscillation
  - *2008-10 → Near Lab Escavation & Near Detector Integration*
  - *2011 → Start of phase II : Both near and far detectors*
    $\sin^2(2\theta_{13})$ < 0.03 after 3 years (90% C.L.) if no-oscillation



- ❑ RENO is suitable for measuring θ_{13} ($\sin^2(2\theta_{13})$ > 0.02)
- ❑ Geological survey and design of access tunnels & detector cavities are completed. Civil construction will begin in early June, 2008.
- ❑ RENO is under construction phase.
- ❑ Data taking is expected to start in early 2010.

Asian Reactor Anti-Neutrino Experiments DAYA BAY and RENO, Christopher White at Nu-2008
Towards θ13: Double Chooz and non-asian efforts, Thierry Lasserre at Nu-2008

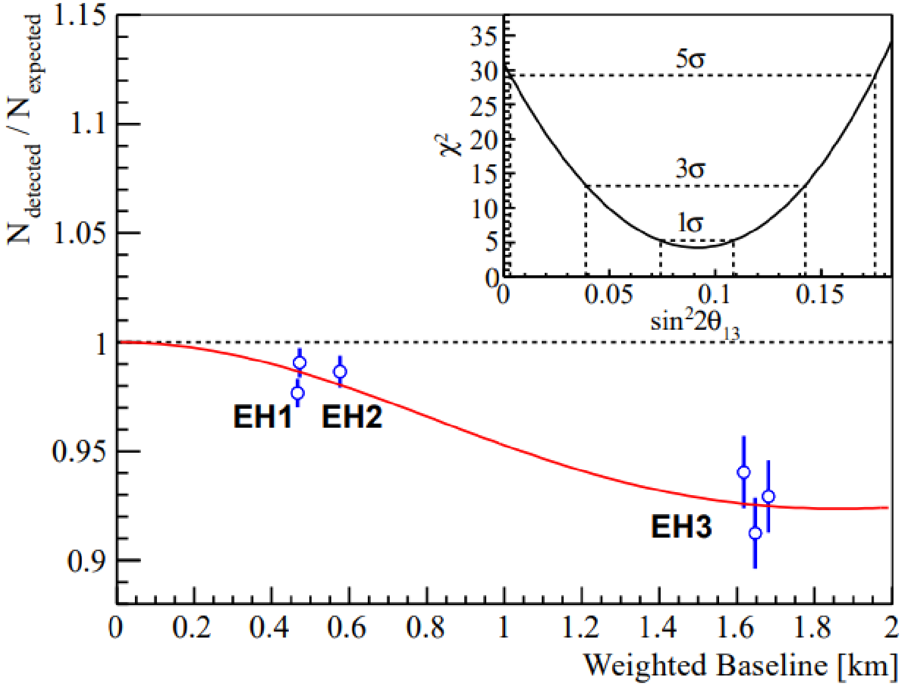
2012: $\theta_{13} \neq 0$! It's relatively large!

Nature is kind to us!

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

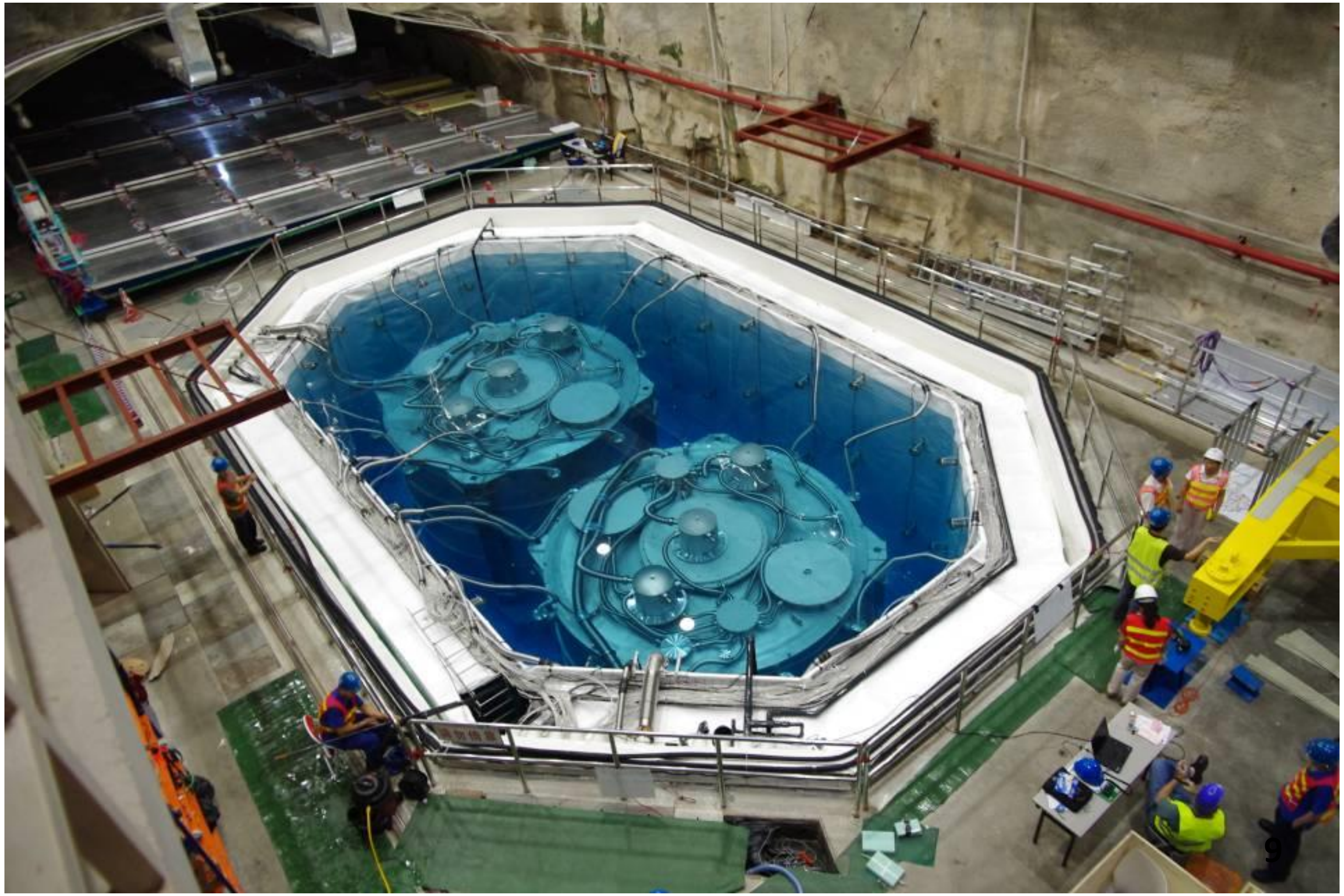
$\sin^2 2\theta_{13} = 0.092 \pm 0.016(\text{stat}) \pm 0.005(\text{syst})$

March 2012, 5.2σ for non-zero $\sin^2 2\theta_{13}$



Daya Bay

Phys.Rev.Lett. 108 (2012) 171803

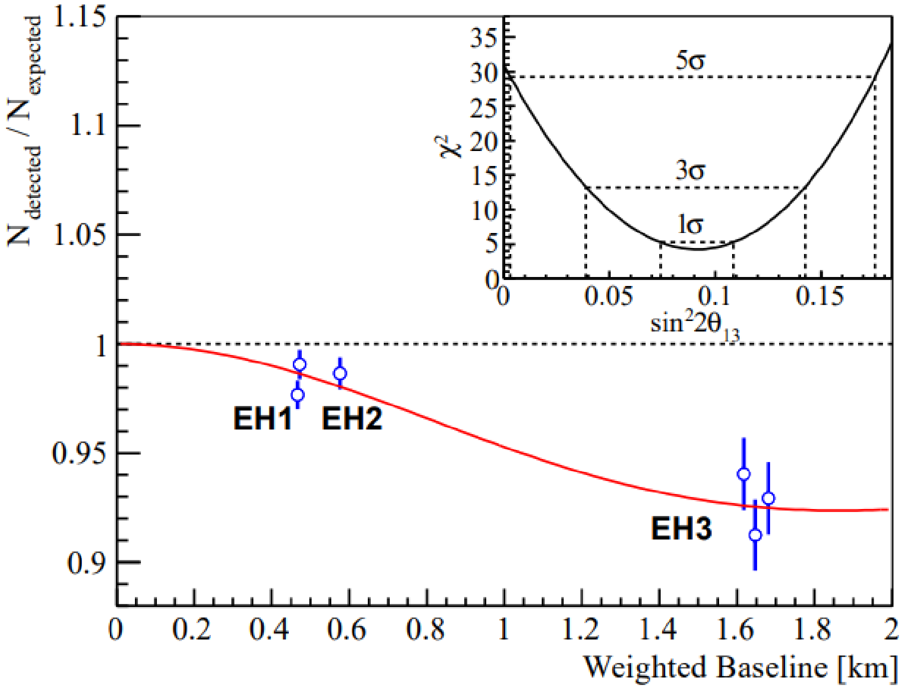


2012: $\theta_{13} \neq 0$! It's relatively large!

Nature is kind to us!

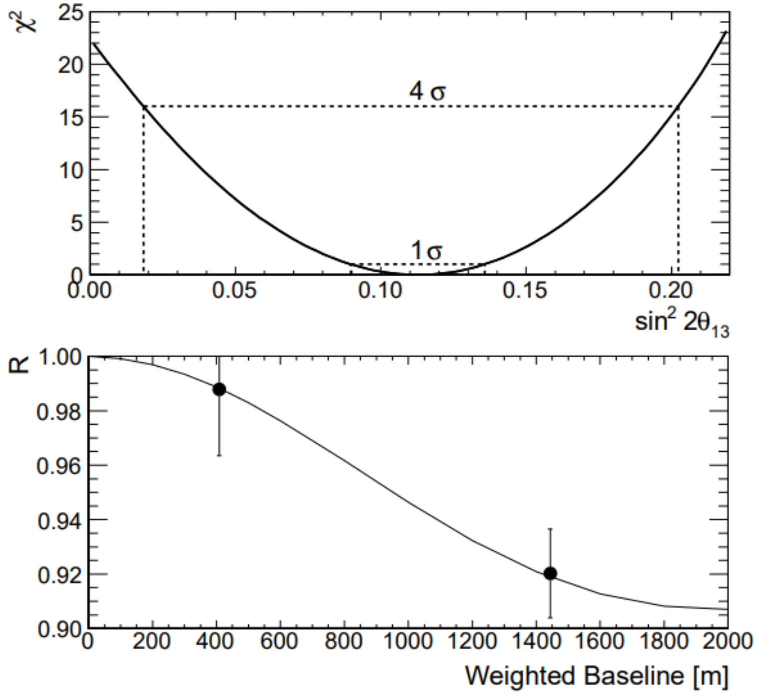
We will be able to know the neutrino mass ordering and δ_{CP} in 2030s

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



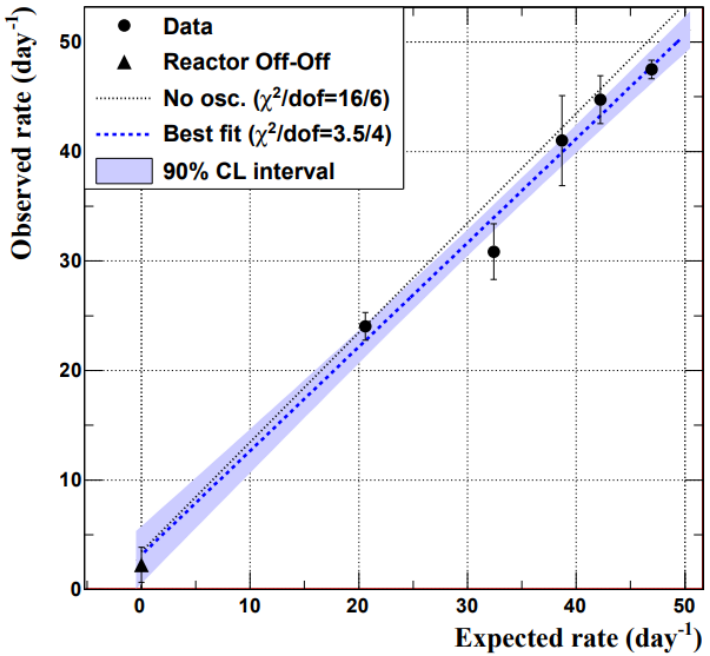
Daya Bay
Phys.Rev.Lett. 108 (2012) 171803

0.113 ± 0.013(stat.) ± 0.019(syst.)
April 2012, 4.9σ



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

0.086 ± 0.041(stat.) ± 0.030(syst.)
Nov. 2011, 94.6% C.L.



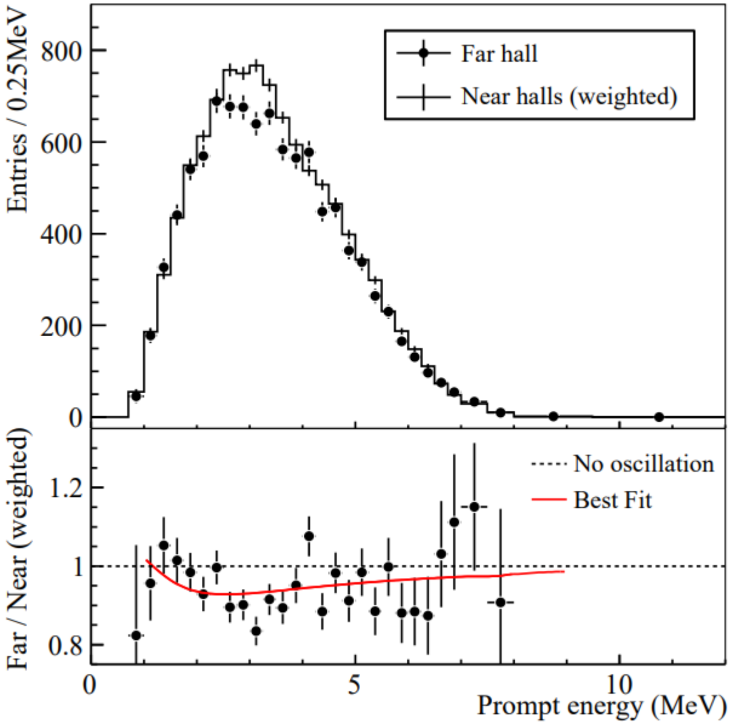
Double Chooz far detector
Phys.Rev.Lett. 108 (2012) 131801

2012: $\theta_{13} \neq 0$! It's relatively large!

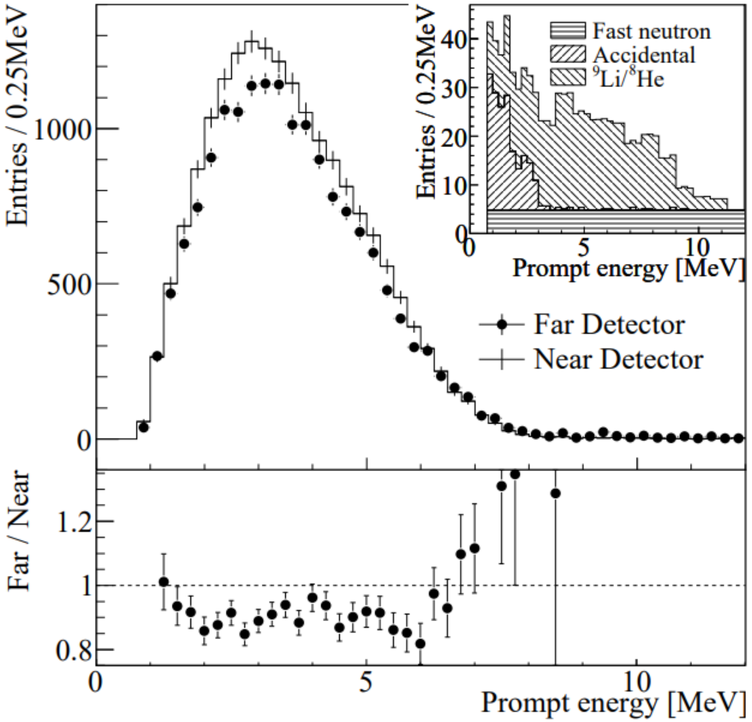
Nature is kind to us!

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

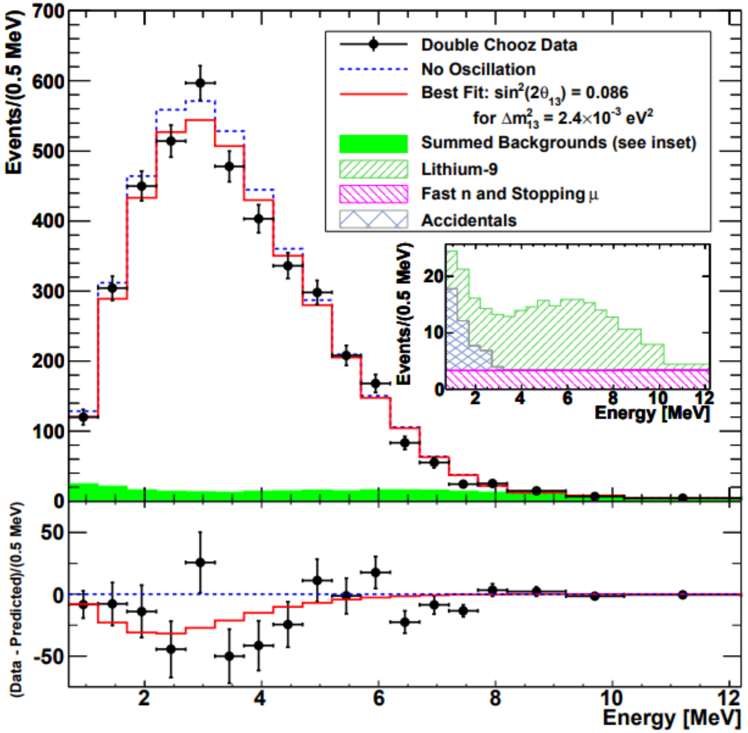
Shape distortions consistent with three-flavor oscillation predictions



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



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



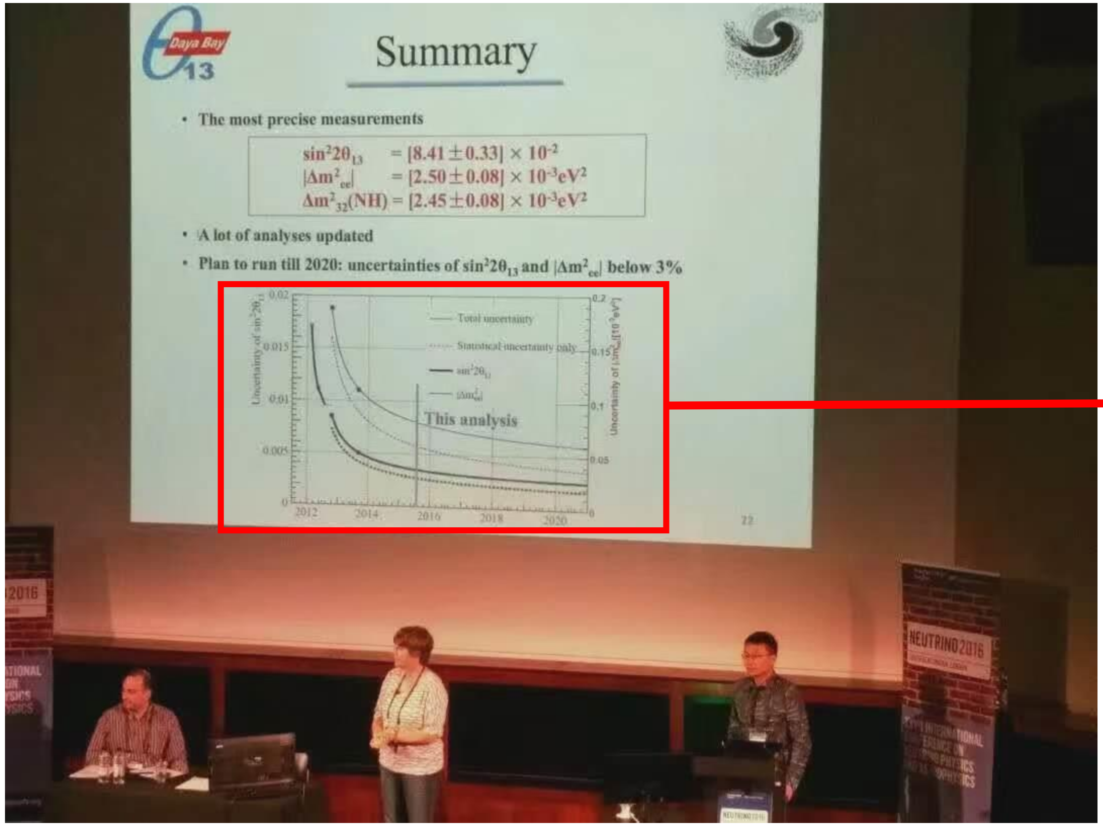
Double Chooz far detector
Phys.Rev.Lett. 108 (2012) 131801

How to improve θ_{13} precision?

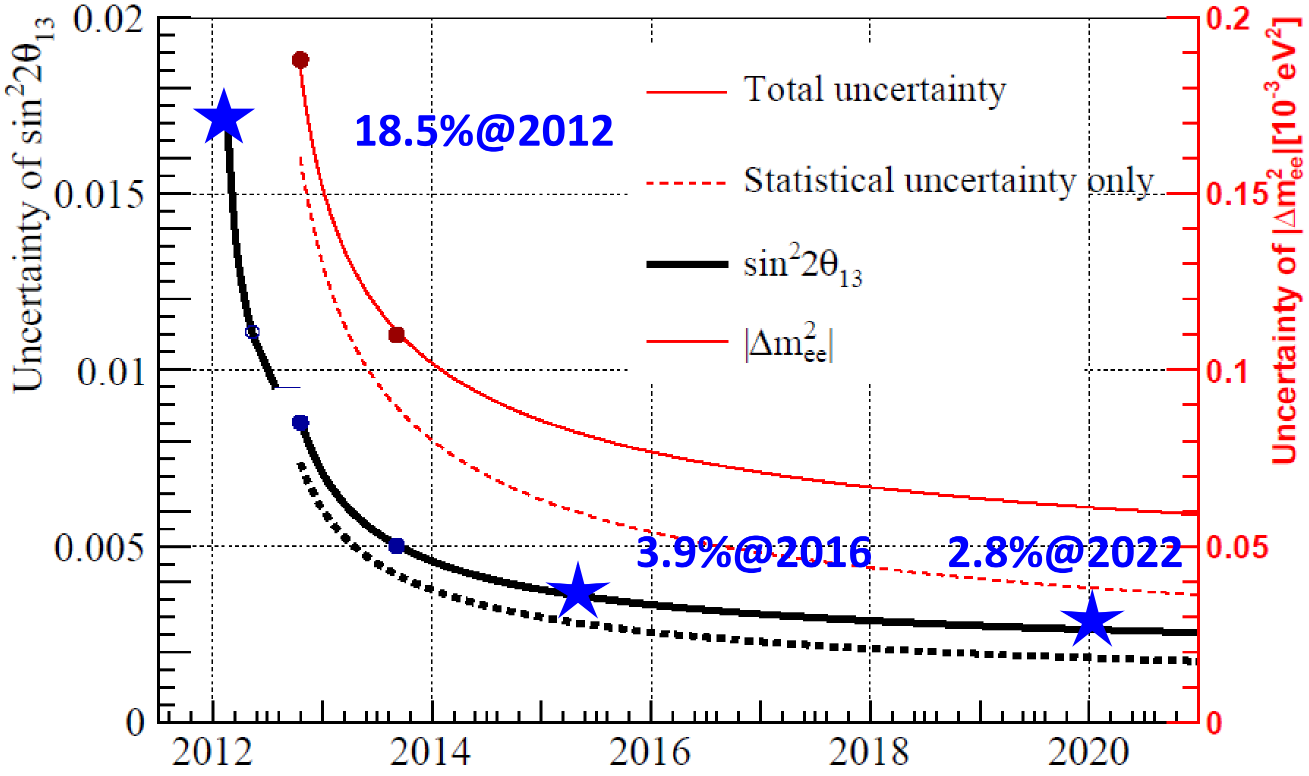
1、 **Accumulate statistics** → Stable data taking, include nH IBDs

2、 **Improve systematics** → Detector identicalness, backgrounds

3、 **Rate+shape analysis** → Accurate energy response model



Daya Bay talk by Zeyuan Yu at Nu-2016



Data sets

Three experiments have stopped data taking

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

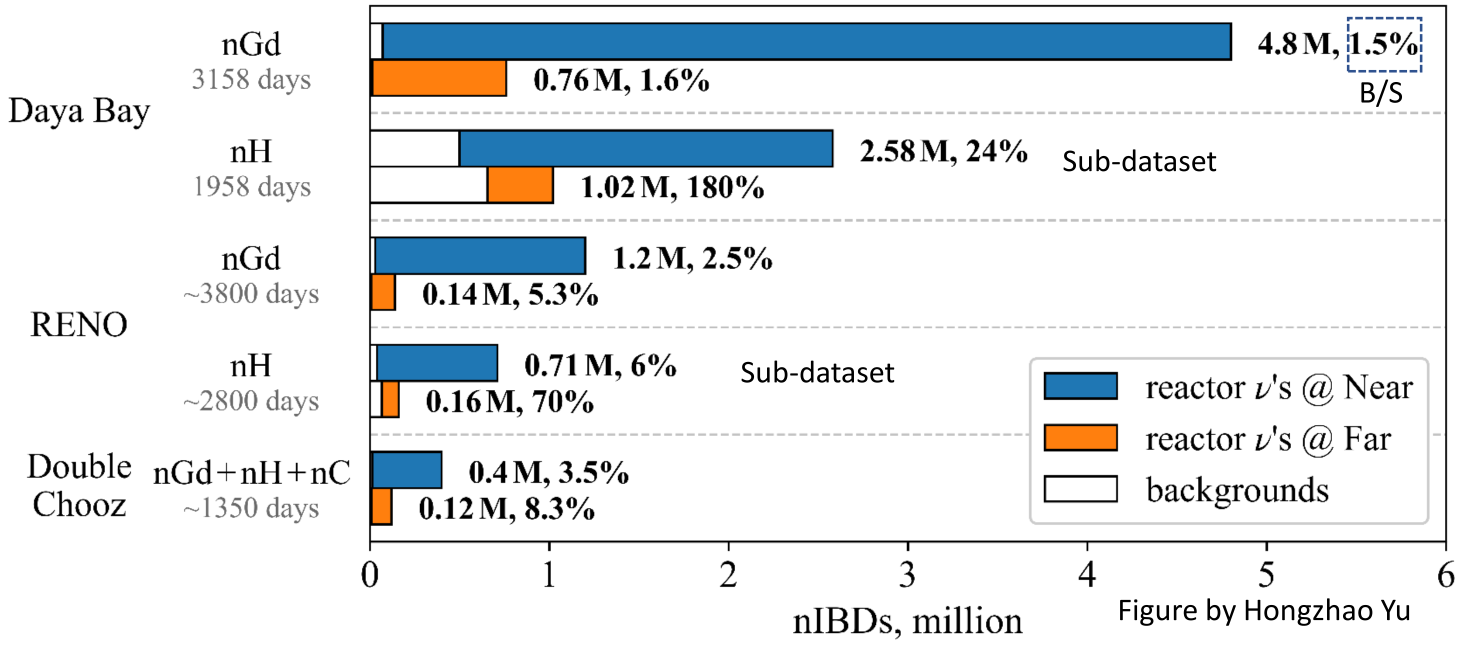


Figure by Hongzhao Yu

Data sets

Three experiments have stopped data taking

Backgrounds and systematics well studied

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

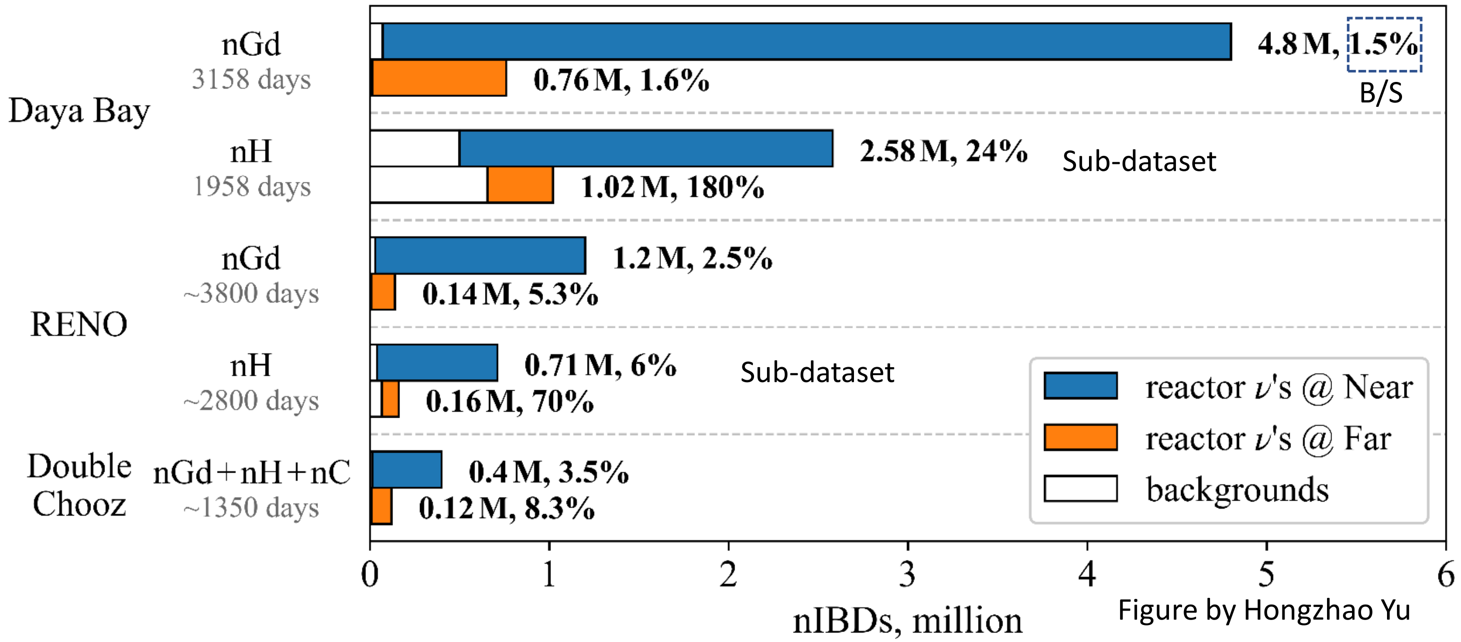
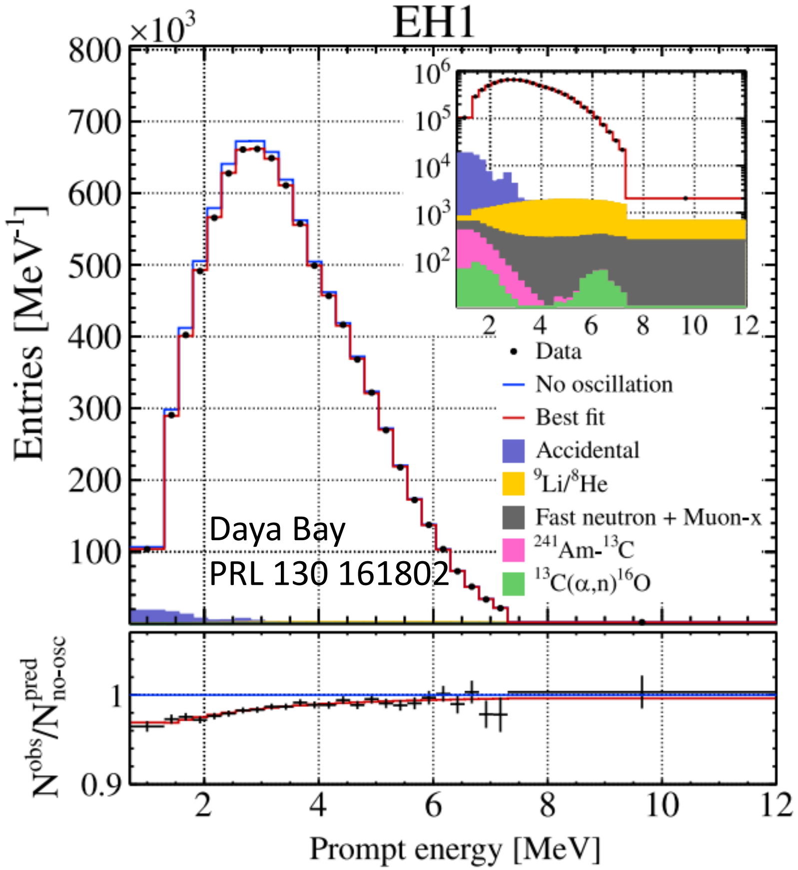


Figure by Hongzhao Yu



Accidentals: measured w/ time off-window

Correlated: $^{9}Li/^{8}He$, cosmogenic and radiogenic neutrons, more crucial

Backgrounds - cosmogenic $^9Li/^8He$

Production yields of $^9Li/^8He$ measured

→ **Good power-law versus muon energies**

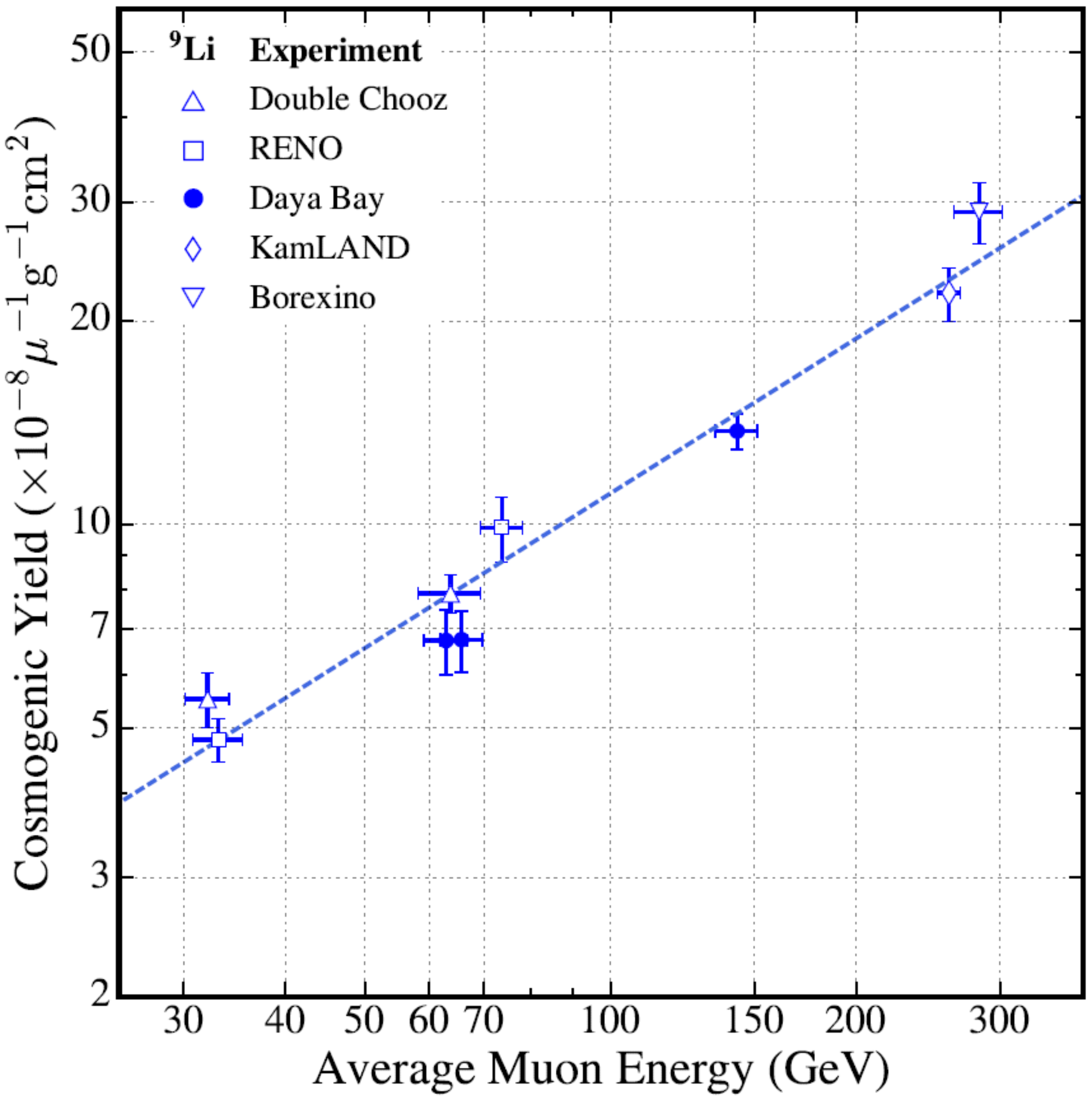
→ **However, unknown $^9Li/^8He$ ratio**

Several methods for the high-rate low-energy-deposit muons

→ Muon-Neutron capture-$^9Li/^8He$ triple coincidence

→ Multiple dimension fitting

→ Reactor-off data (Double Chooz)



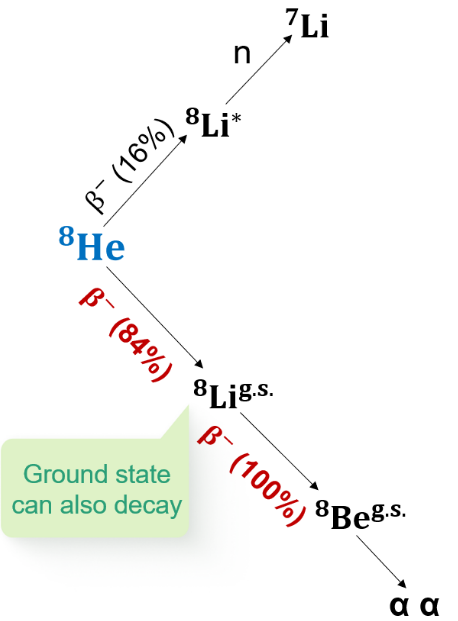
Daya Bay arXiv: 2402.05383, Double Chooz: JHEP 11 (2018) 053, RENO: Phys.Rev.D 106 (2022) 1, 012005

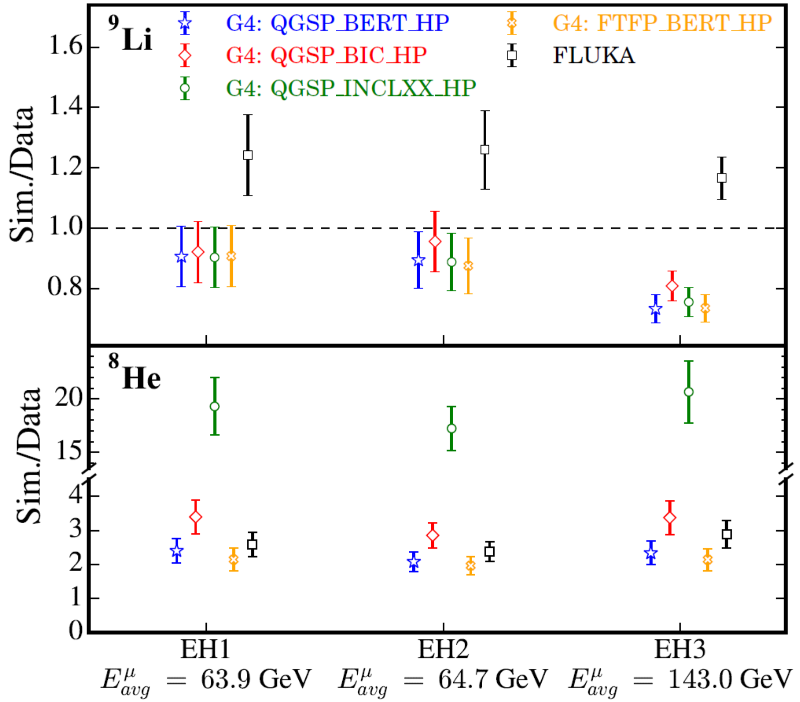
Backgrounds - cosmogenic $^9Li/^8He$

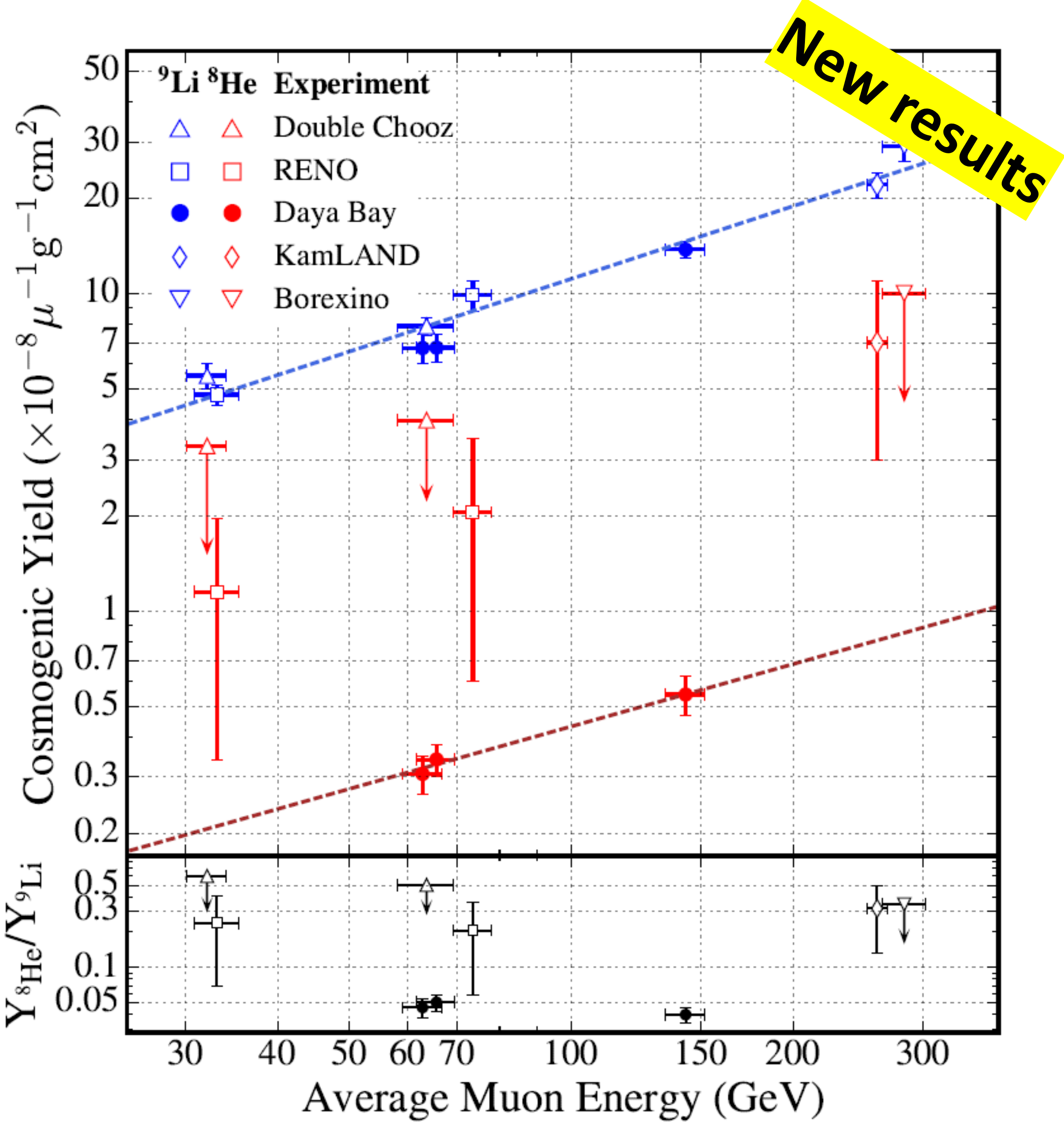
First observation of ^8He at Daya Bay using β cascade decays of ^8He-$^8Li^{g.s.}$

→ **The smallest production yield isotope in LS**

→ Valuable inputs for future experiments





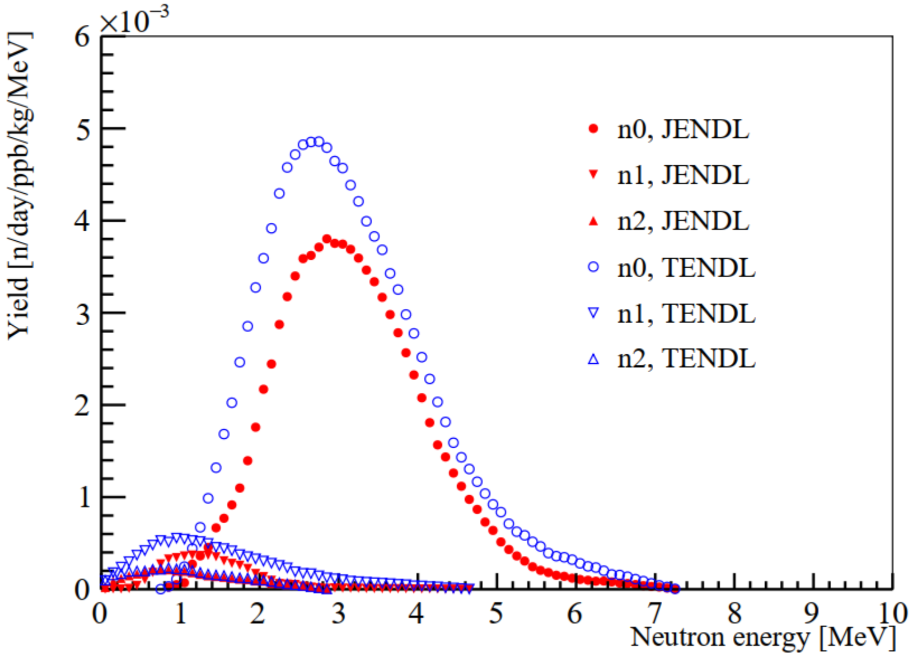


Daya Bay arXiv: 2402.05383, accepted as PRD Letter

Poster from Chengzhuo Yuan (Daya Bay), ID-488

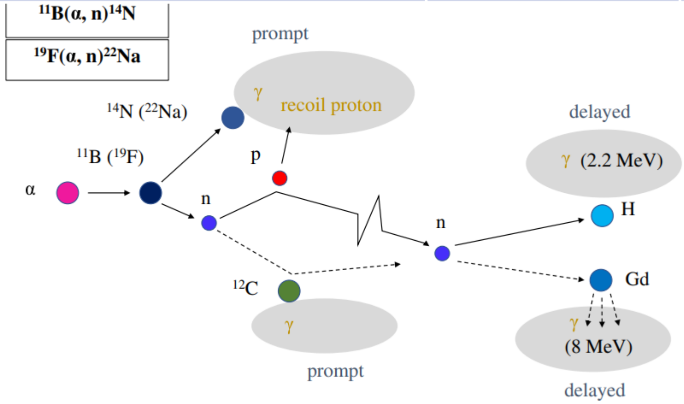
Neutrons from (α,n) reactions and spontaneous fissions

- → **Gd-LS, LS and acrylic**: clean, ^{238}U and ^{232}Th < 0.1 ppb, 1.1% ^{13}C, *O*(0.05) n's/day
- → **PMT glass**: *O*(100) ppb ^{238}U/^{232}Th and 20% boron, *O*(100) n's/day/100kg glass
- → **Negligible for nGd but not for nH** if PMTs not well shielded from LS
  - → Five Daya Bay PMTs were broken to measure the Boron fraction in glass
  - → Also investigated the material screening results, no other non-negligible neutron source



Phys. Rev. D **104**, 092006

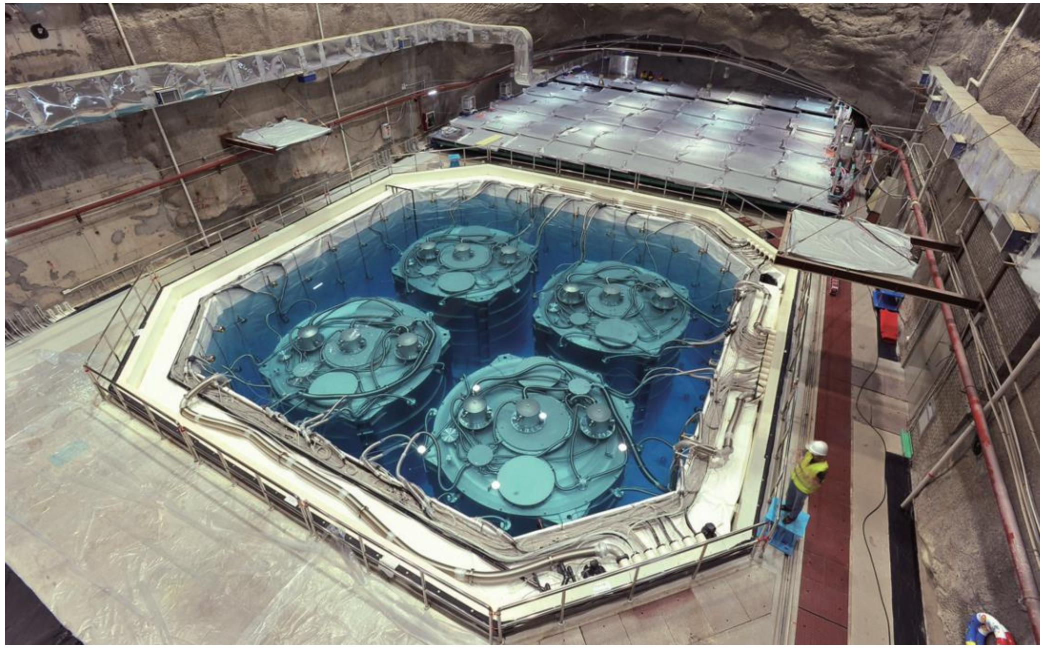
Distance from PMT to LS		Residual bkg in nH
Daya Bay	20 cm	0.2/day/AD
RENO	~50 cm	<10^{-4}/day
Double Chooz	~45 cm	<10^{-4}/day



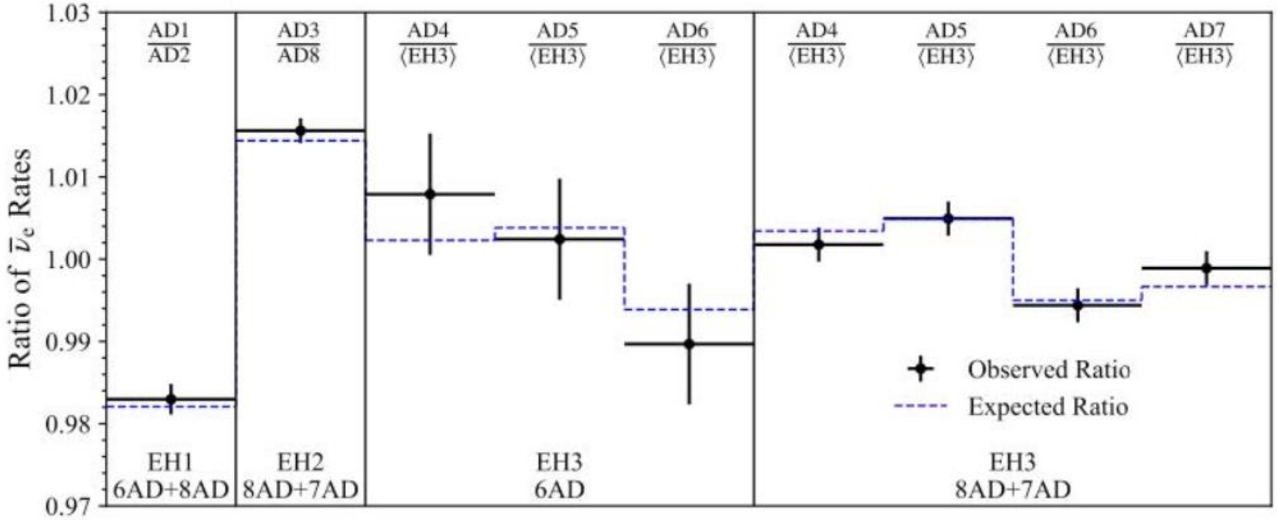
Detector identicalness

Multiple detectors at the same site at Daya Bay enables side-by-side comparison

→ Confirms that systematic errors are under control



IBD measurement agrees with prediction well



Relative differences on energy scales (<0.2%) and Gd capture fractions (<0.1%)

Plots from Kam-Biu Luk's Daya Bay talk at Nu-2022, also refer to Nucl.Instrum.Meth.A 685 (2012) 78-97

Detector energy response

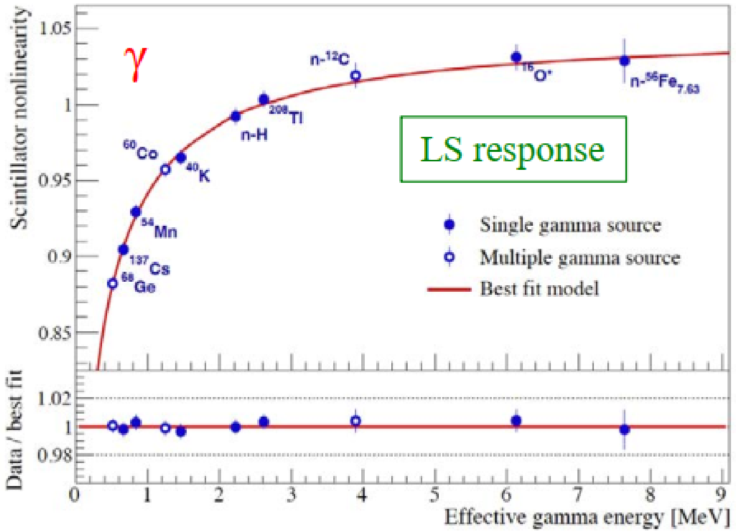
Nonlinear energy response due to quenching and Cherenkov effects

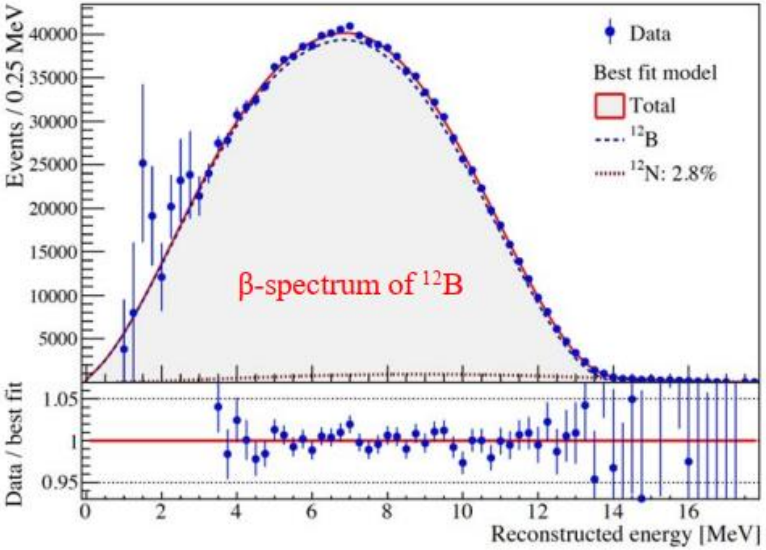
Three experiments obtained 0.5% precision using multiple γ's and ^{12}B spectrum

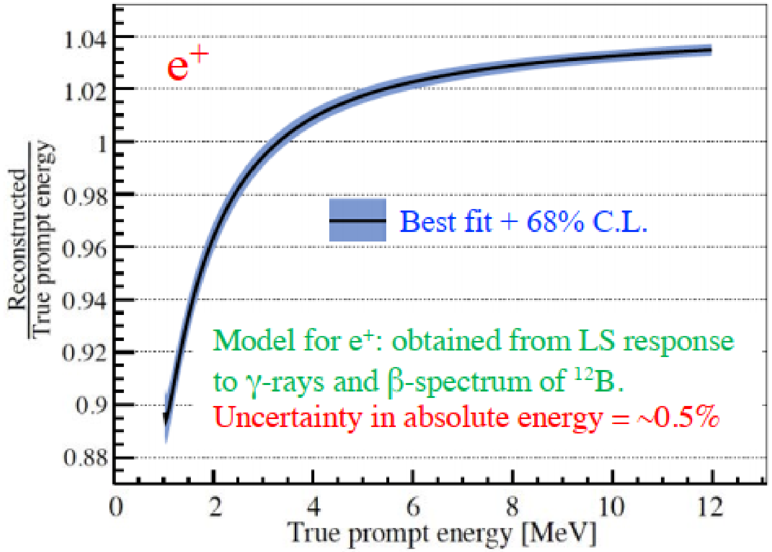
Refer to the ESCAPE before Nu-2018 focused on the calibration strategies in antineutrino experiments

→ More than 10 experiments shared calibration details, better understandings with each other

→ https://www.mpi-hd.mpg.de/escape2018/

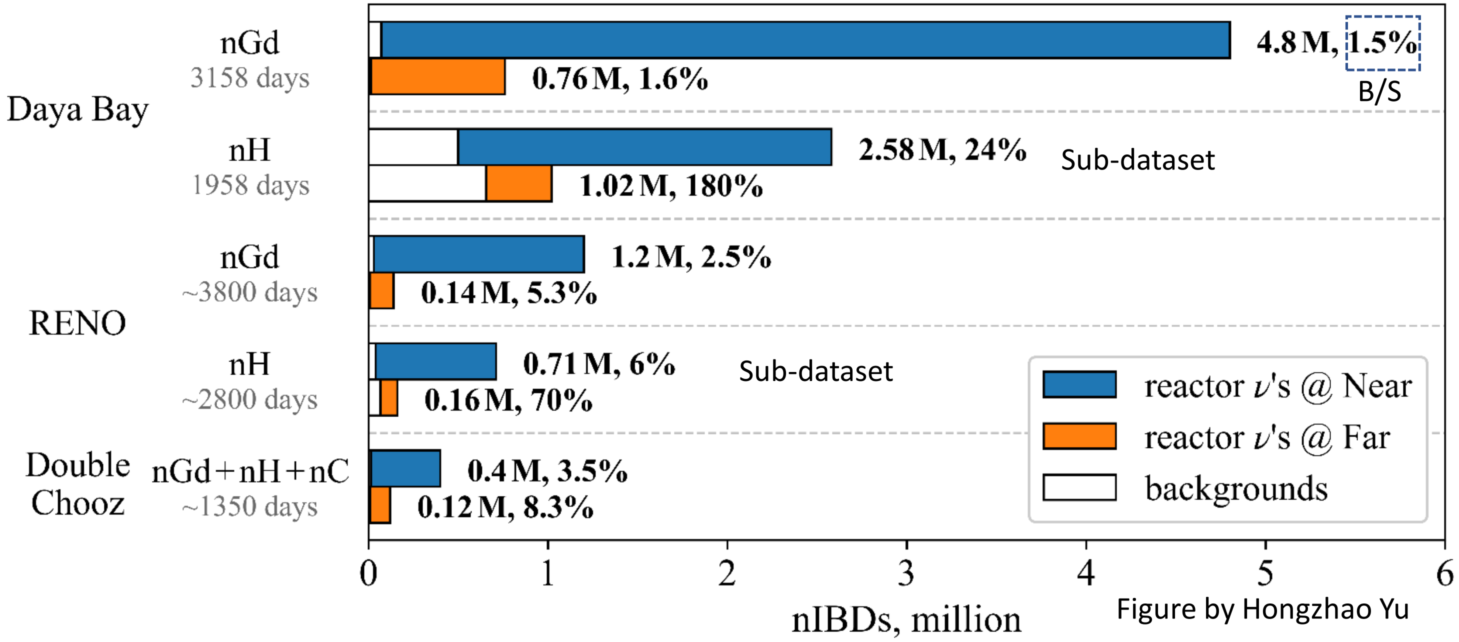






Plots from Kam-Biu Luk's Daya Bay talk at Nu-2022, also refer to Nucl.Instrum.Meth.A 940 (2019) 230-242 and 895 (2018) 48-55

Latest oscillation results



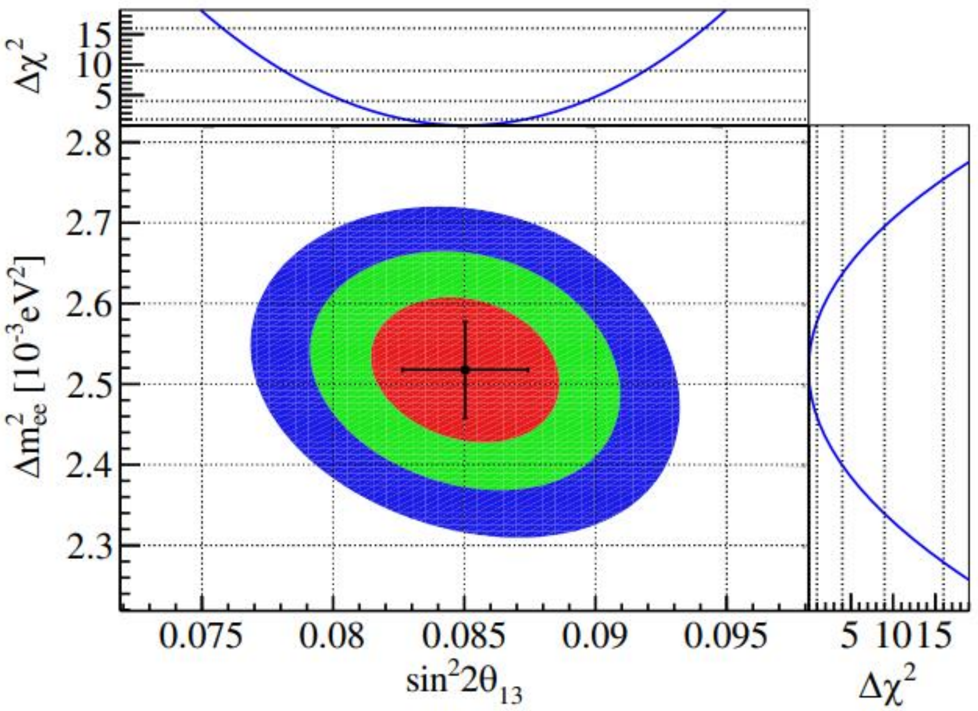
θ_{13} with nGd -- Daya Bay

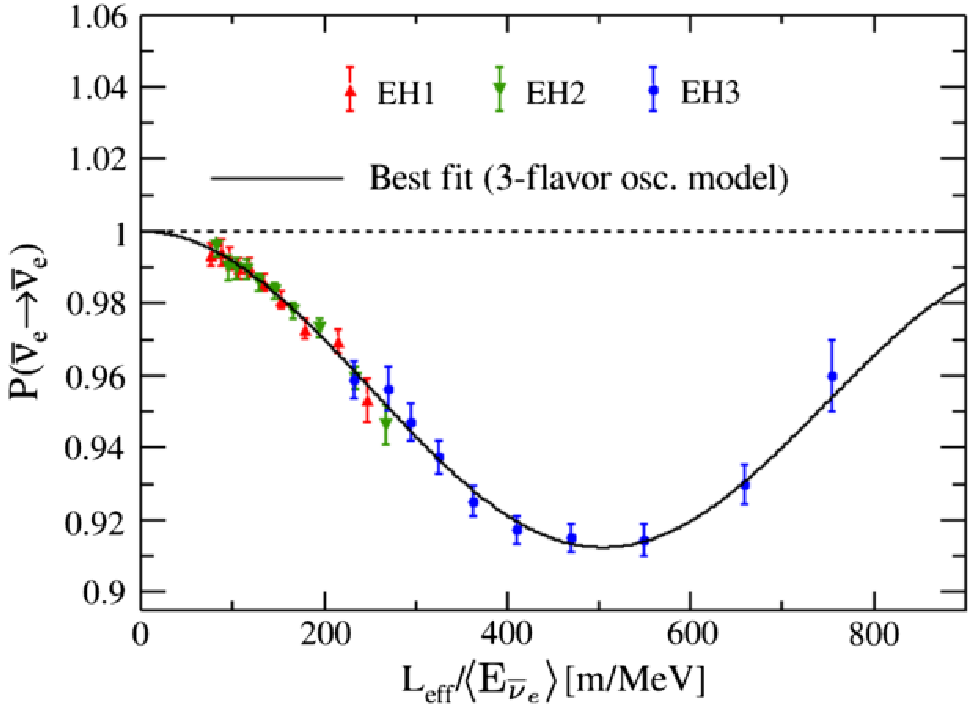
Daya Bay reported the precision measurement with 3158-days full dataset in 2022

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

$\Delta m^2_{32} = 2.466 \pm 0.060$ (NO) $(-2.571 \pm 0.060$ (IO)$) \times 10^{-3}\ eV^2$ **precision 2.4%**

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





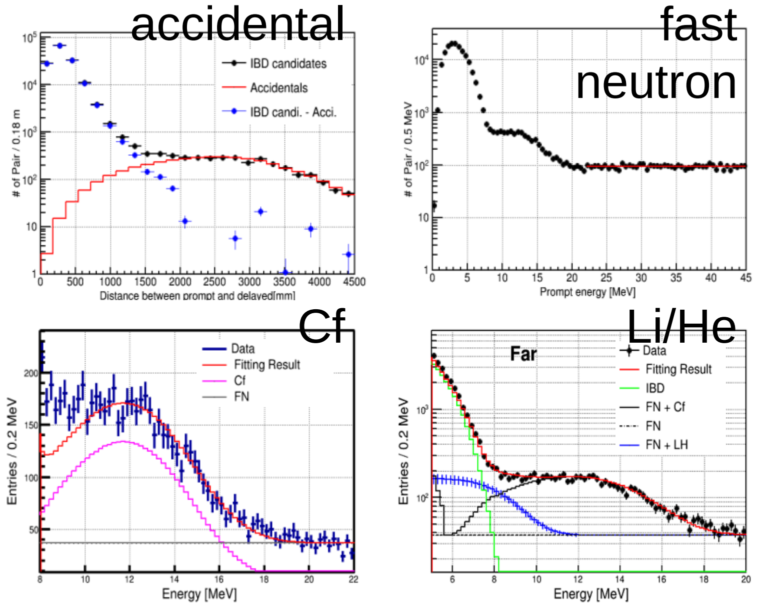
PhysRevLett. 130 161802

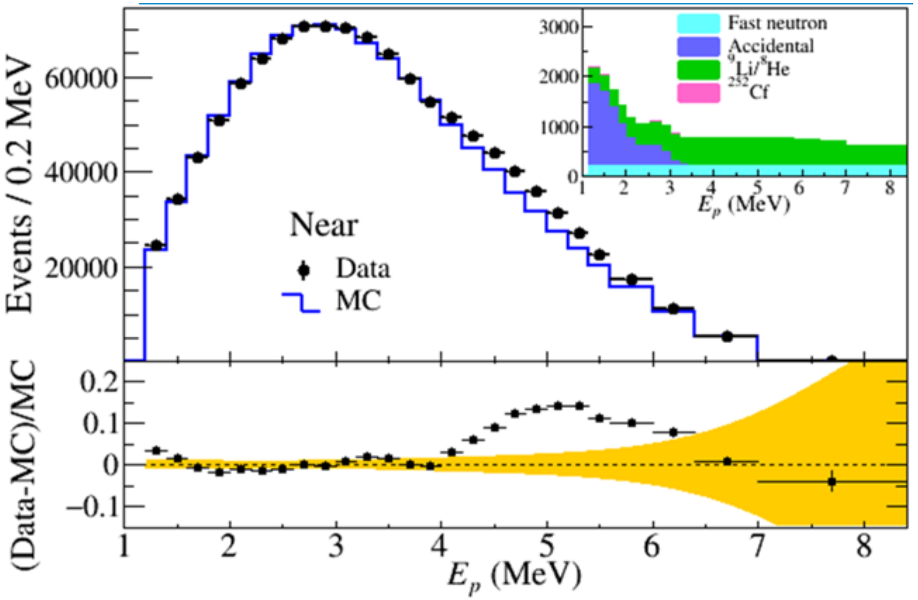
θ_{13} with nGd -- RENO

NEUTRINO 2024

- **1,211,995(144,667) $\bar{\nu}_e$ candidate events** obtained for near(far) in 3800 days
- **Data driven background estimate**
  - 9.08±0.18 (2.06±0.13) events per day
  - 2.5%(5.3%) of IBD signals
- Compare with a reactor model prediction w/ oscillation confirms the 5-MeV bump

New results



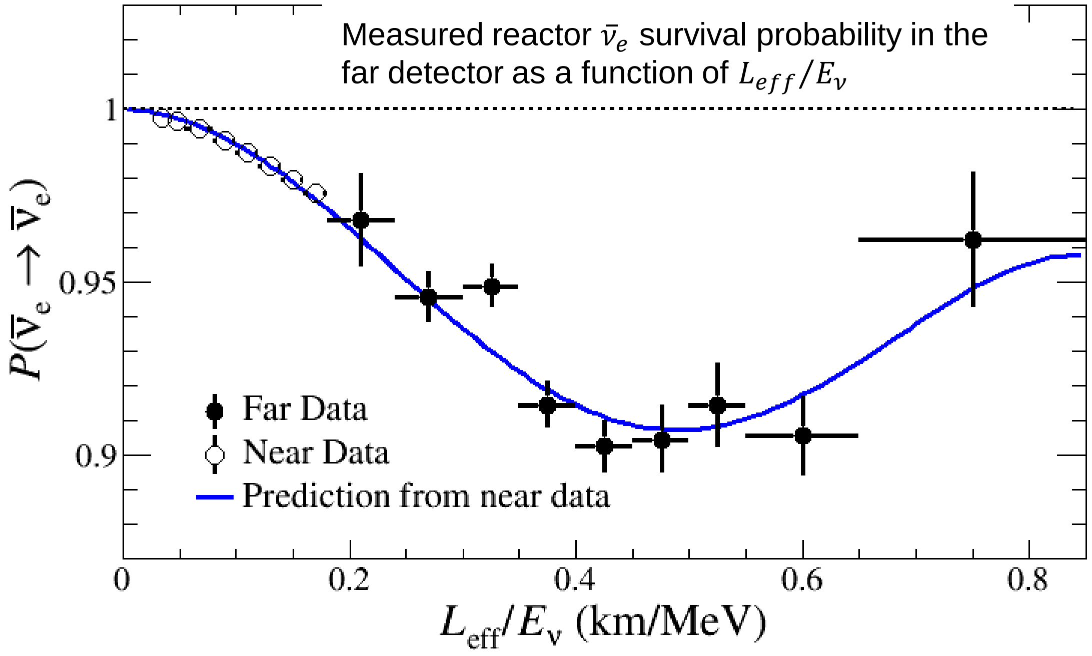


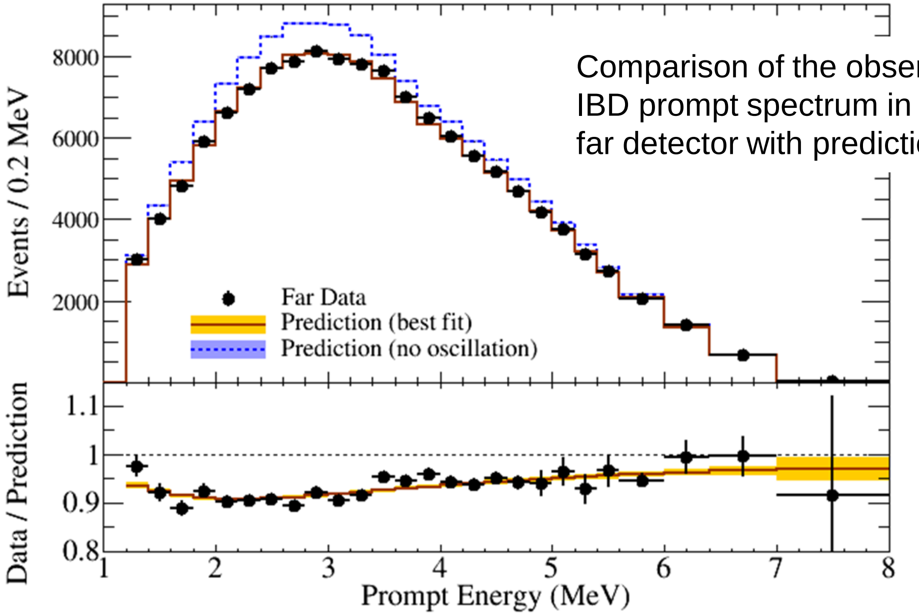
Detector	Near	Far
IBD rate	366.47 ± 0.33	38.70 ± 0.10
after background subtraction	357.39 ± 0.38	36.64 ± 0.16
total background rate	9.08 ± 0.18	2.06 ± 0.13
live time [days]	3307.25	3737.85
accidental rate	2.30 ± 0.02	0.36 ± 0.01
fast neutron rate	1.74 ± 0.01	0.34 ± 0.01
^{252}Cf contamination rate	0.07 ± 0.01	0.34 ± 0.04
^{9}Li/^{8}He rate	4.97 ± 0.17	1.02 ± 0.12

θ_{13} with nGd -- RENO

New results

- **Based on the measured far-to-near ratio of IBD rates and prompt spectra**
  - $\sin^2 2\theta_{13} = 0.0920\,^{+0.0044}_{-0.0042}(stat.)\,^{+0.0041}_{-0.0041}(syst.)$ **precision 6.5%**
  - $\Delta m^2_{ee} = 2.57\,^{+0.10}_{-0.11}(stat.)\,^{+0.05}_{-0.05}(syst.)[\times 10^{-3} eV^2]$ **precision 4.6%**
- (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%





θ_{13} with nH -- Daya Bay

A new θ_{13} measurement with 1958-days data

→ Two independent analyses

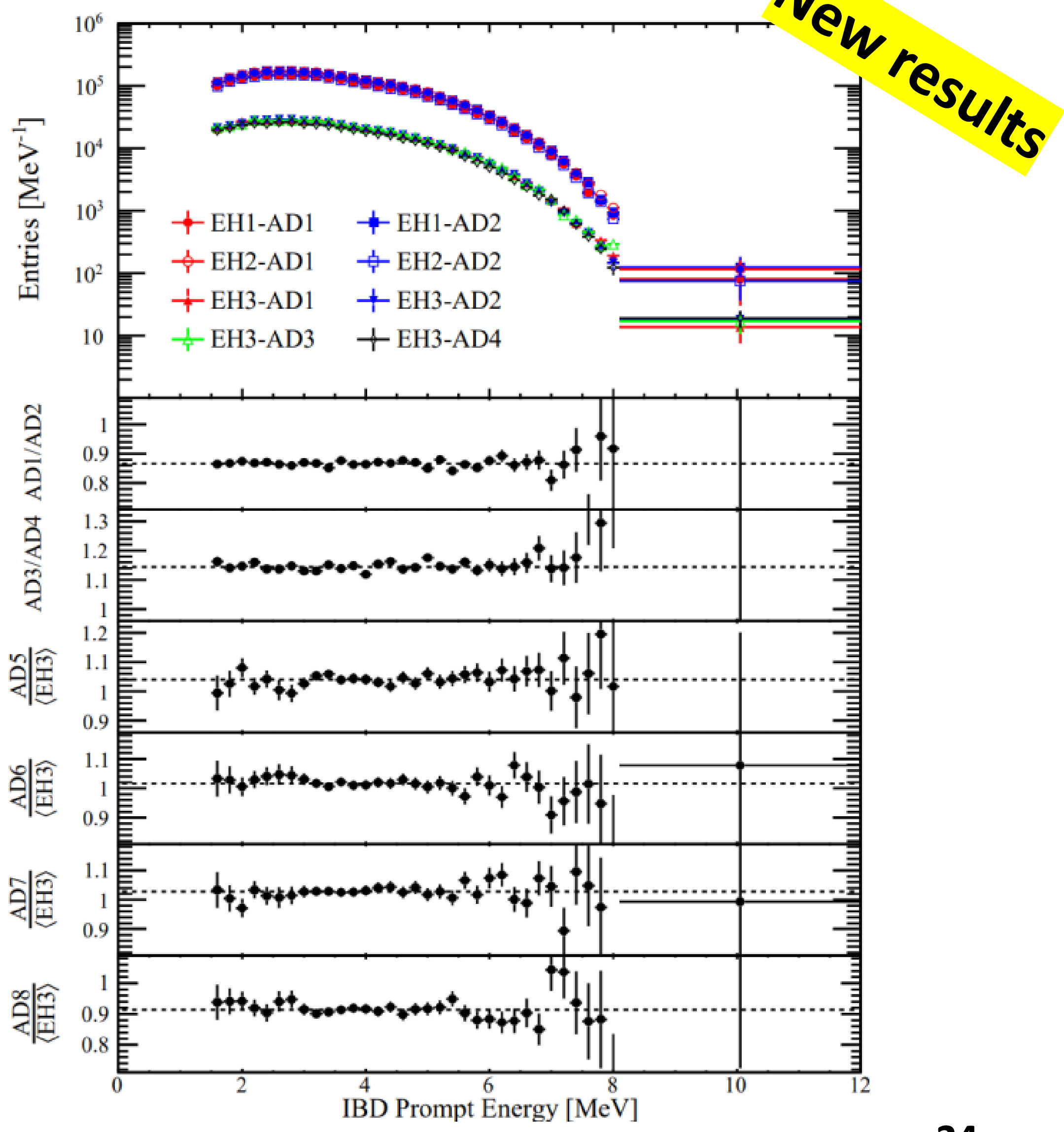
→ Crosschecks on backgrounds, systematics, and fitting codes

→ Identification of radiogenic background

→ Development of energy response matrix

→ Previous publication used 621-days data and rate-only analysis Phys.Rev.D 93 (2016) 7, 072011

	Uncertainty (%)	
	Analysis A	Analysis B
Target protons	0.11	0.11
Prompt energy	0.13	0.13
[1, 1500] μs	0.10	0.10
Delayed energy	0.20	0.24
Coincidence DT	0.20	0.21
Combined (ε)	0.34	0.37



θ_{13} with nH -- Daya Bay

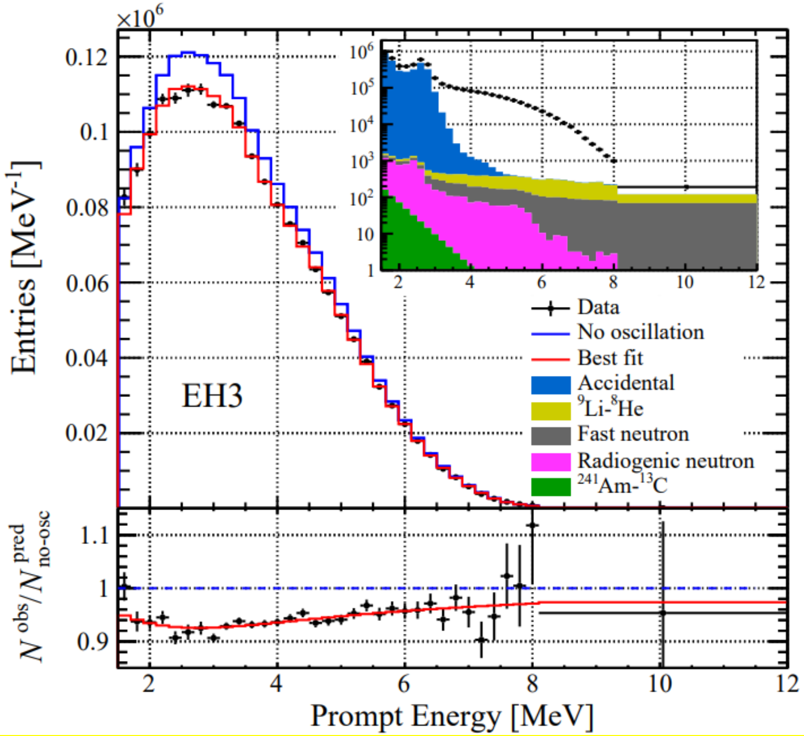
New results

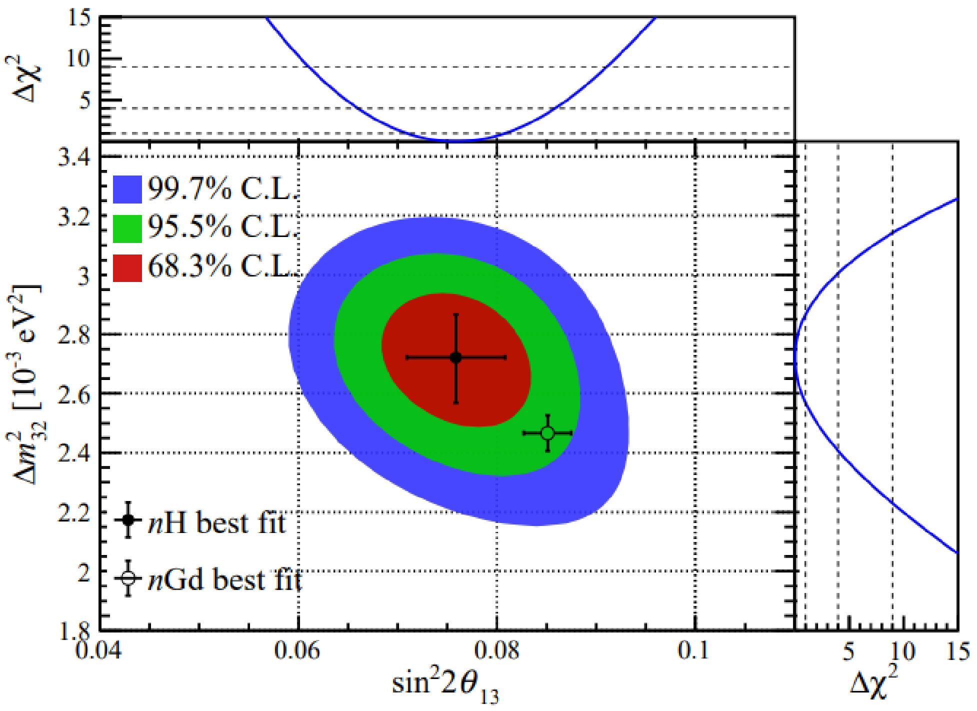
Consistent with nGd results within 2σ

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

$\Delta m^2_{32} = 2.72 \pm_{NO} 0.15\ (-2.83 \pm_{IO} 0.15) \times 10^{-3}\ eV^2$ **precision 5.3%**

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





Poster from Zhiyuan Chen (Daya Bay), ID-321, paper arXiv 2406.01007

θ_{13} with nH -- RENO

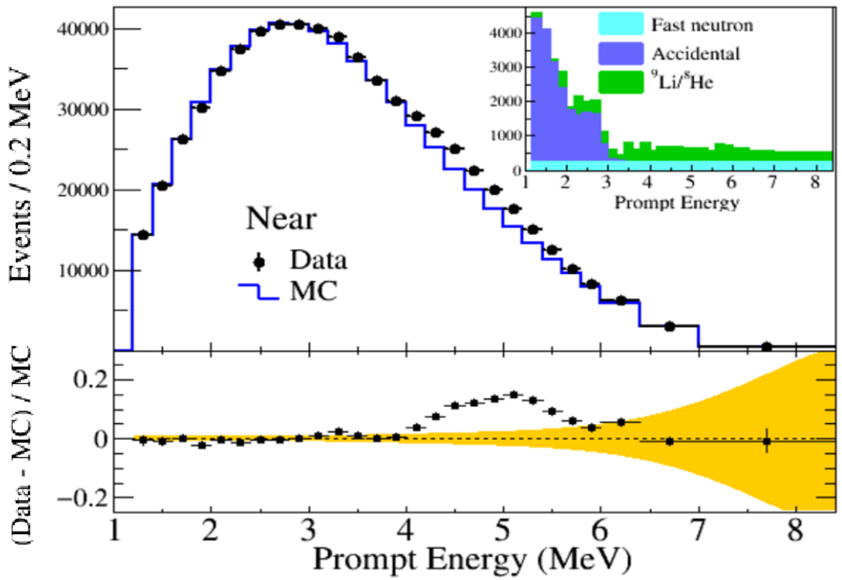
New results

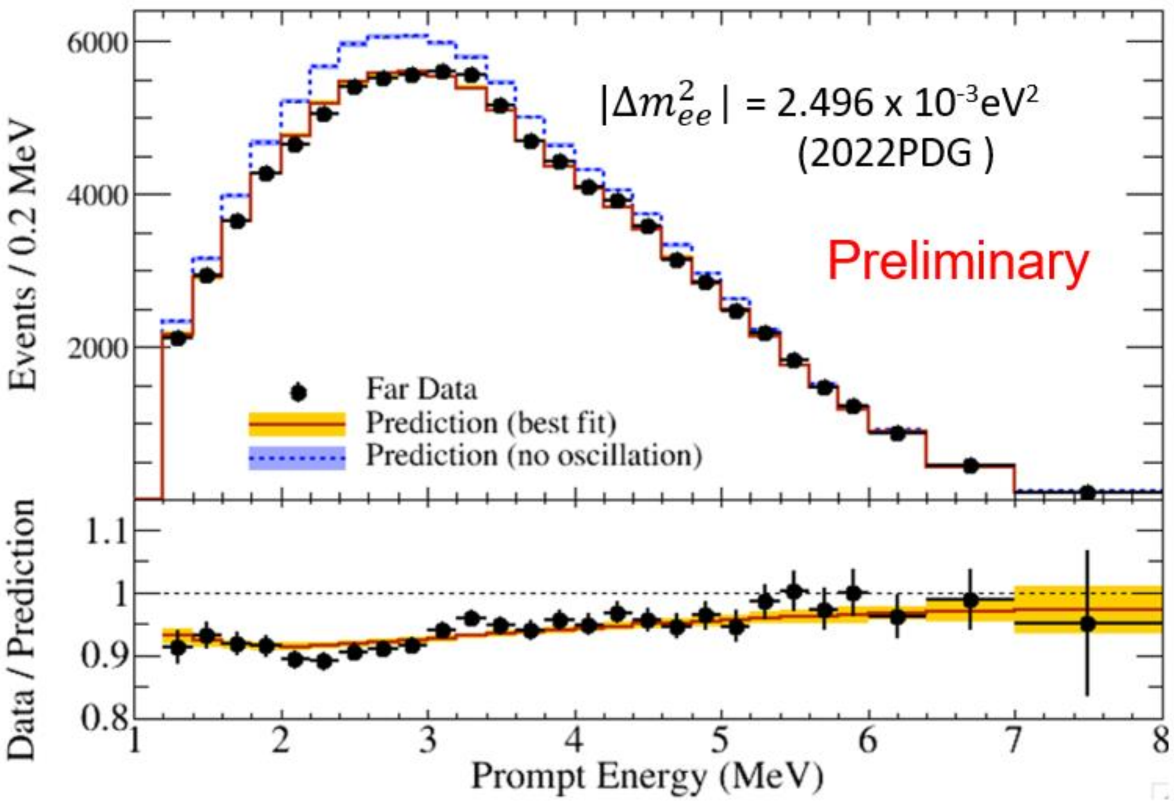
Using nH data set of about 2800 days

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





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

θ_{13} with all captures - Double Chooz

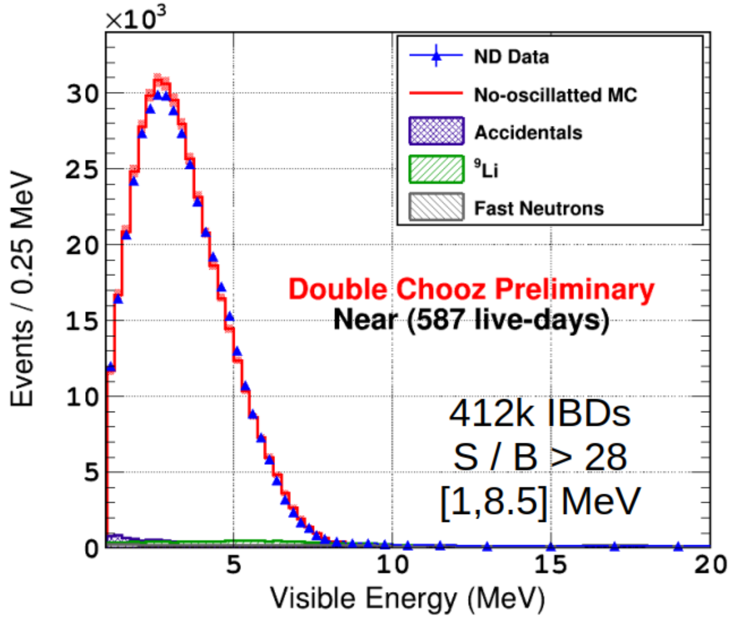
Double Chooz preliminary results with full data set, presented at Nu-2020

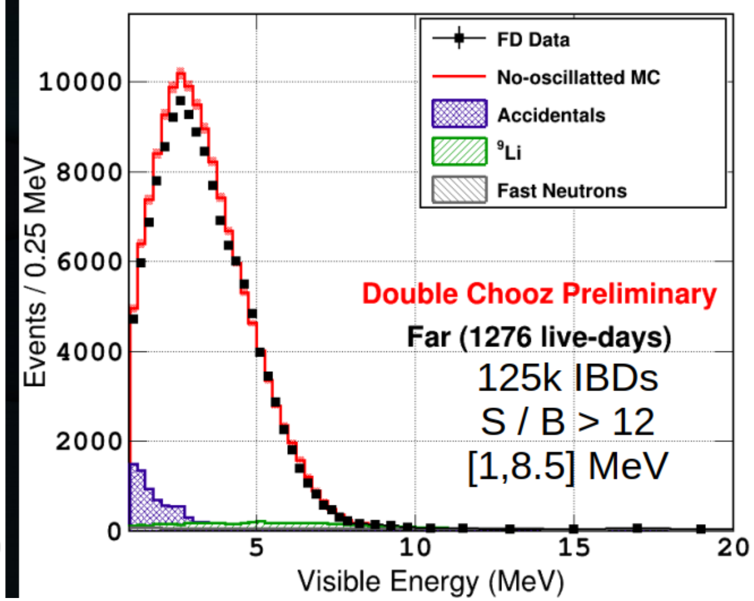
Using ANN to suppress accidental background

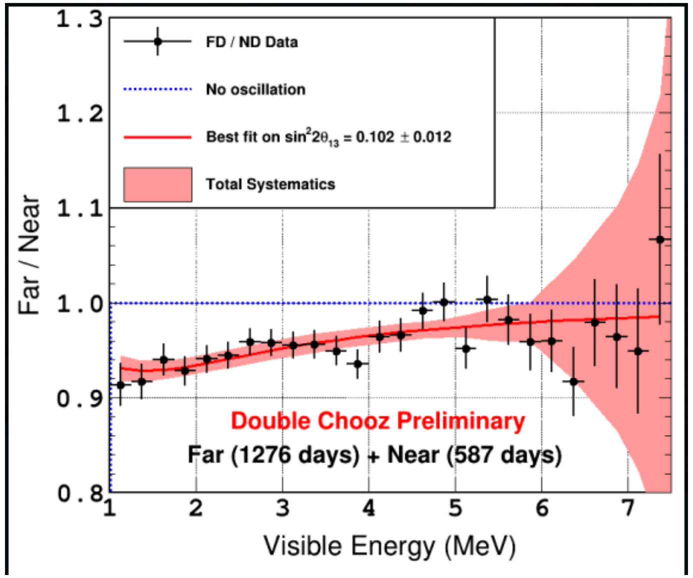
Total neutron capture enhanced the detection efficiency for n-Gd

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 Thiago Bezerra's Double Chooz talk at Nu-2020

Global comparison θ_{13}

Daya Bay leads the precision measurement, nGd+nH gives 2.6% precision

By combining all reactor results, ultimate precision of $\sin^2 2\theta_{13}$: 2.5%

Consistent results from reactor and accelerator experiments

Note: average is error weighted average assuming no correlation

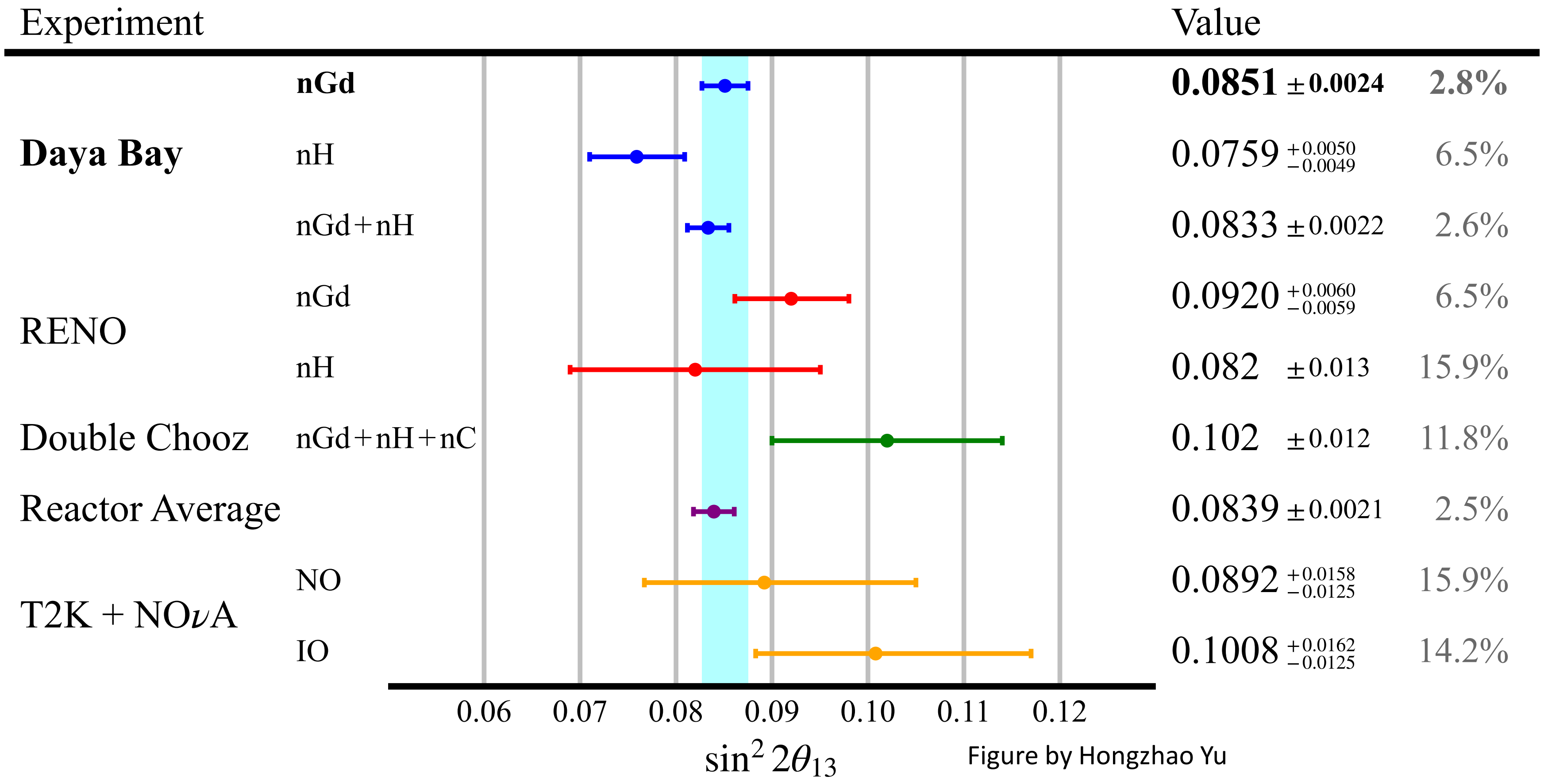


Figure by Hongzhao Yu

Global comparison Δm^2

Consistent results from reactor and accelerator experiments

Reactor weighted average 2% dominated by Daya Bay

Accelerator weighted average 1.5% (SK+T2K) + NOvA + MINOS + IceCube

Note: average is error weighted average assuming no correlation

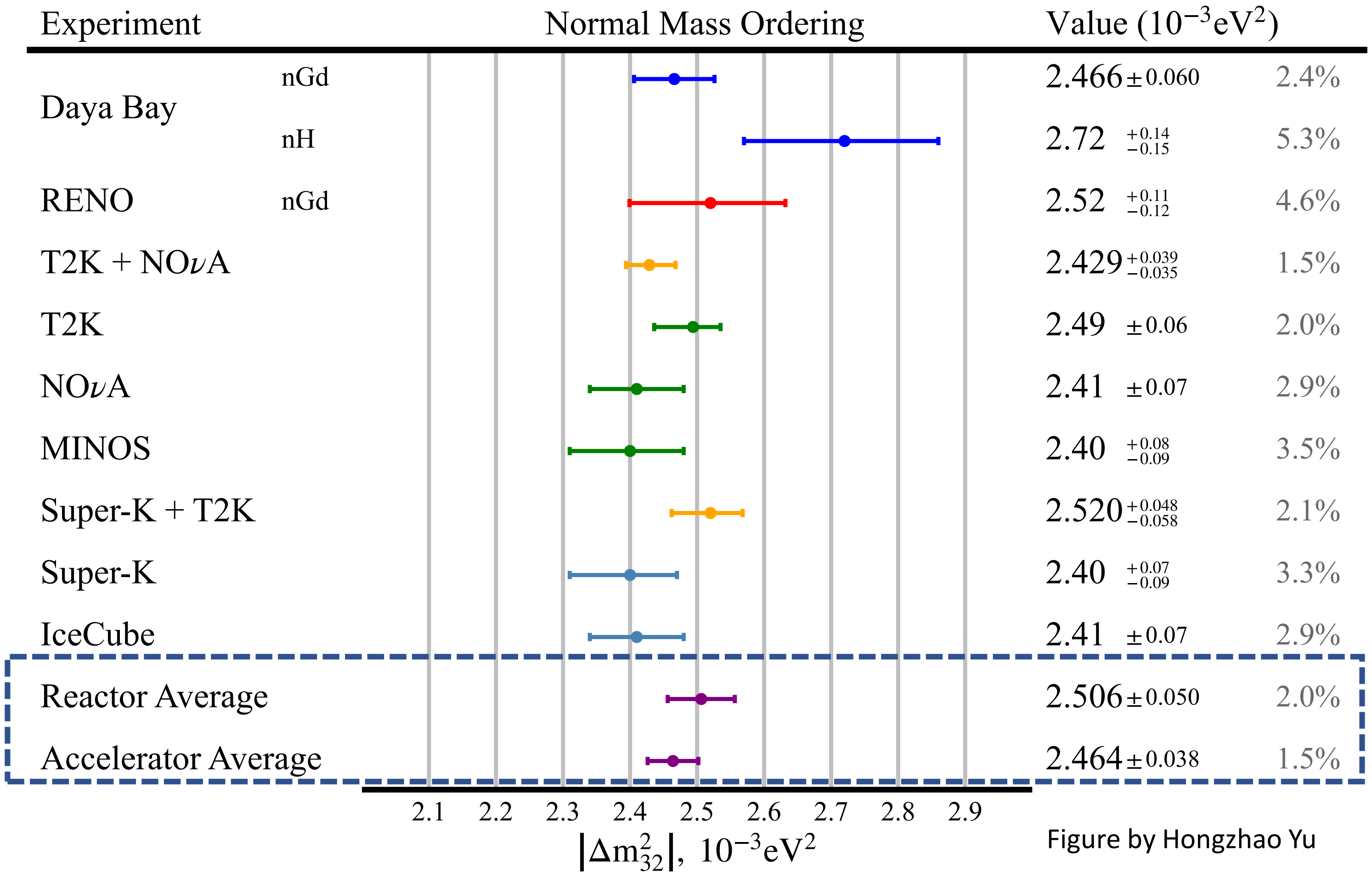


Figure by Hongzhao Yu

Global comparison Δm^2

Consistent results from reactor and accelerator experiments

Normal Ordering slightly preferred (<2σ) from reactor/accelerator averages

Note: average is error weighted average assuming no correlation

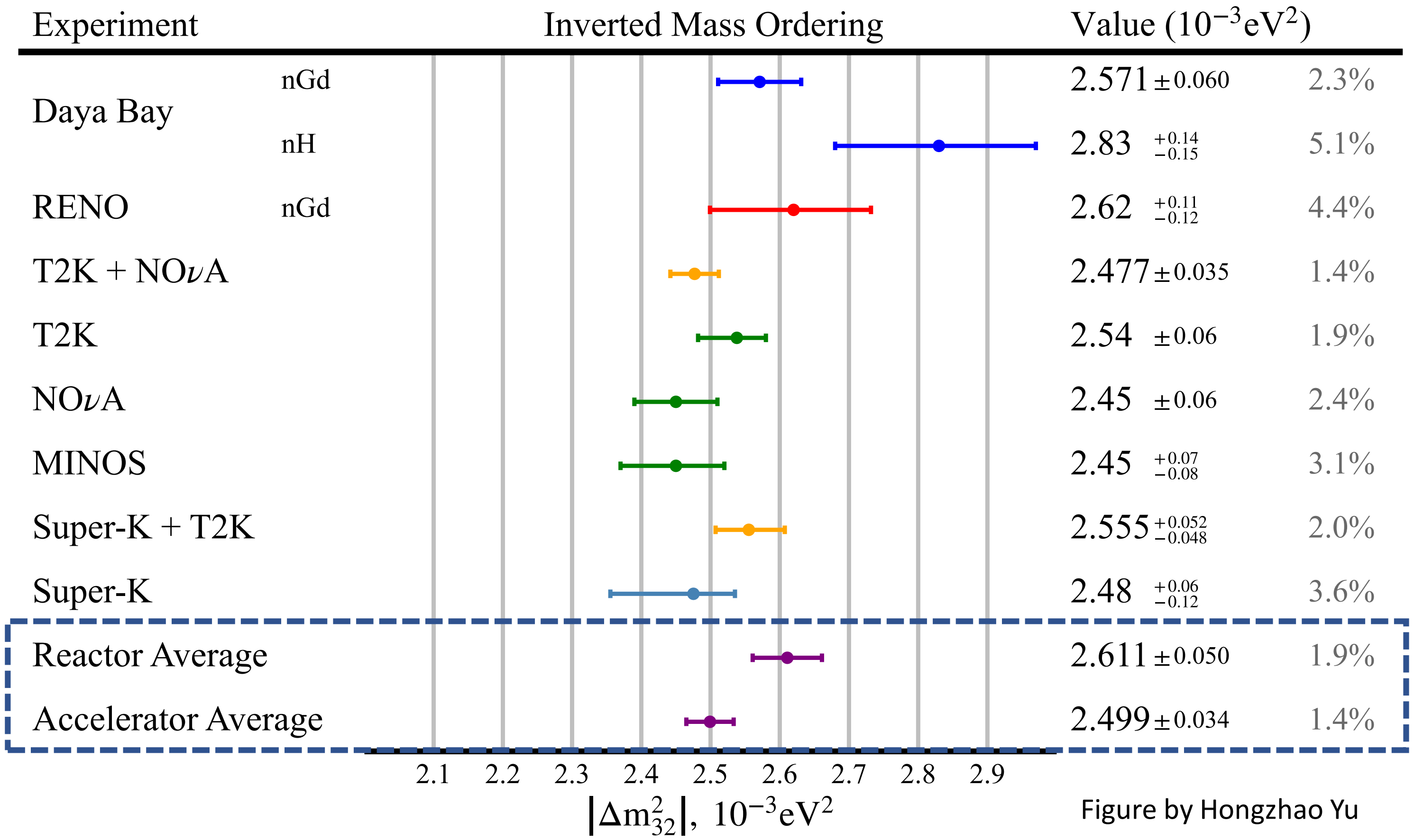
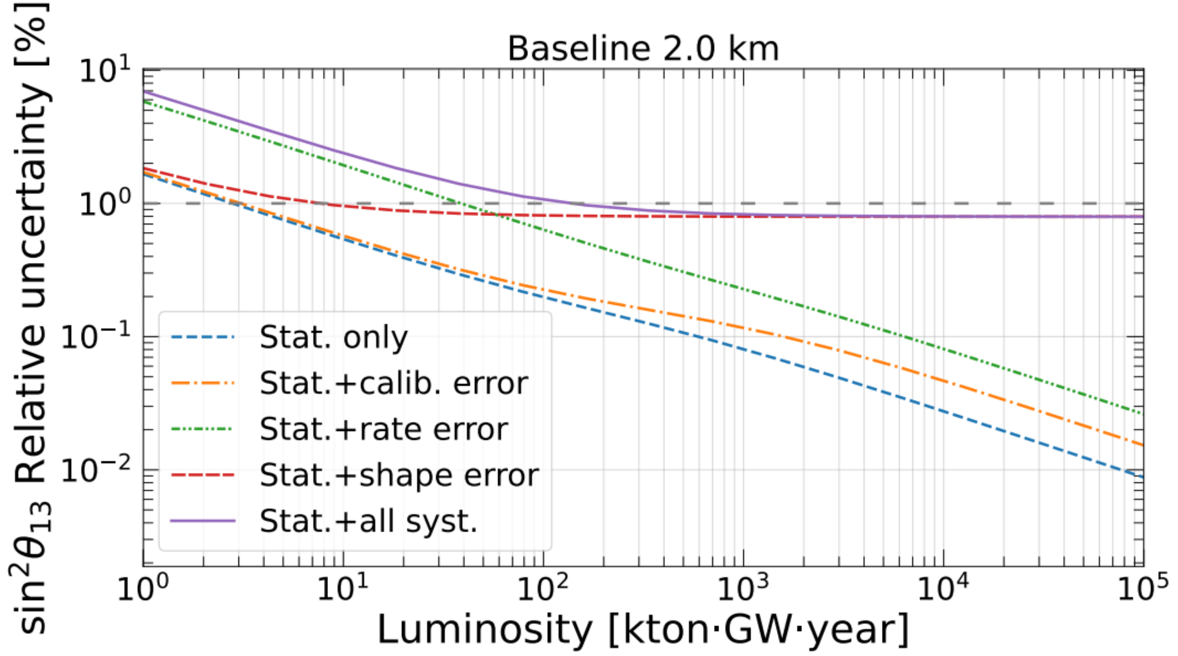


Figure by Hongzhao Yu

1% precision $\sin^2 2\theta_{13}$?

In future, if unitarity test of PMNS matrix is limited by θ_{13}, two ways to improve

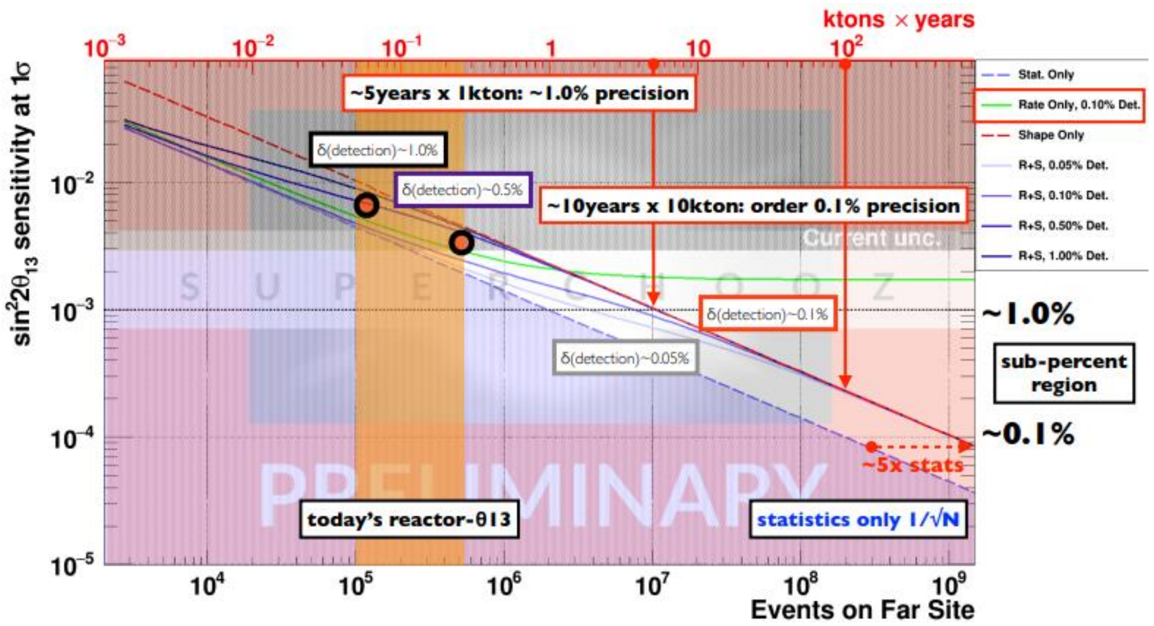
1. **Shape distortion 1kt LS detector at 2.0km baseline**
2. **Rate deficit 10kt LiquidO detector at 1.1km baseline**



Requires 1% shape uncertainty and 0.5% energy scale

Fulfilled by inputs of TAO and intensive calibration

JHEP, 2023, 03: 072

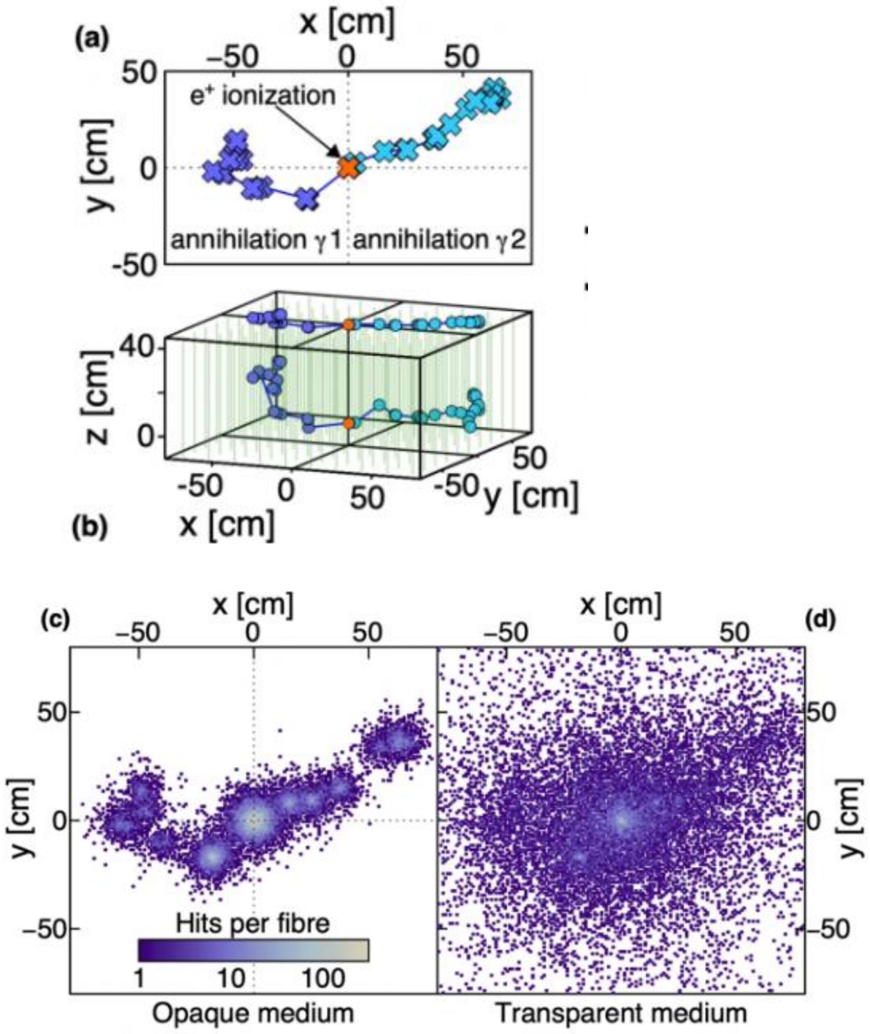


Super Chooz: LiquidO to suppress bkgs.

https://zenodo.org/doi/10.5281/zenodo.7504161

Poster from Raphaël Gazzini, ID-635

Under ongoing experimental demonstration & exploration via the CLOUD experiment



Summary

1. Daya Bay, RENO, and Double Chooz all stopped data taking

→ Well controlled systematics (< 0.2%), in total more than 1 million IBDs at far sites

→ Almost equal contributions from systematics and statistics in oscillation parameters

→ Side-by-side comparison at Daya Bay verified the systematics control

2. Daya Bay leads the precision measurement of $\sin^2 2\theta_{13}$ and $|\Delta m^2_{32}|$ in reactor side

2.1 Reactor experiments average: $\sin^2 2\theta_{13} = 0.0839 \pm 0.0021$, 2.5% precision

→ The most precisely measured mixing angle up to Nu-2024

2.2 Reactor experiments average: $\Delta m^2_{32} = (2.51[-2.61] \pm 0.05) * 10^{-3}$ eV^2 , 2% precision

→ Slightly prefer normal mass ordering by comparing with accelerator results

3. Working on final results

→ Full nH data set in Daya Bay and RENO, final results from Double Chooz

4. <1% precision of $\sin^2 2\theta_{13}$ achievable using either shape distortion or rate deficit

Note: average is error weighted average assuming no correlation

Posters

Daya Bay,

1、Daya Bay oscillation results with neutron capture by hydrogen, Zhiyuan Chen, ID-321

2、Reactor neutrino flux and spectrum measurements with Daya Bay full data set, Yang Han, ID-236

3、Neutron Capture Cross Section Measurement on Carbon, Yuchin Cheng *et al*, ID-486

4、Seasonal Variation of Muon Rates Using Full Dataset, Bangzheng Ma, ID-291

5、First measurement of the yield of ^{8}He isotopes produced in LS, Chengzhuo Yuan, ID-488

Super Chooz,

1、The SuperChooz project: a LiquidO-based neutrino oscillation experiment,Raphaël Gazzini, ID-635

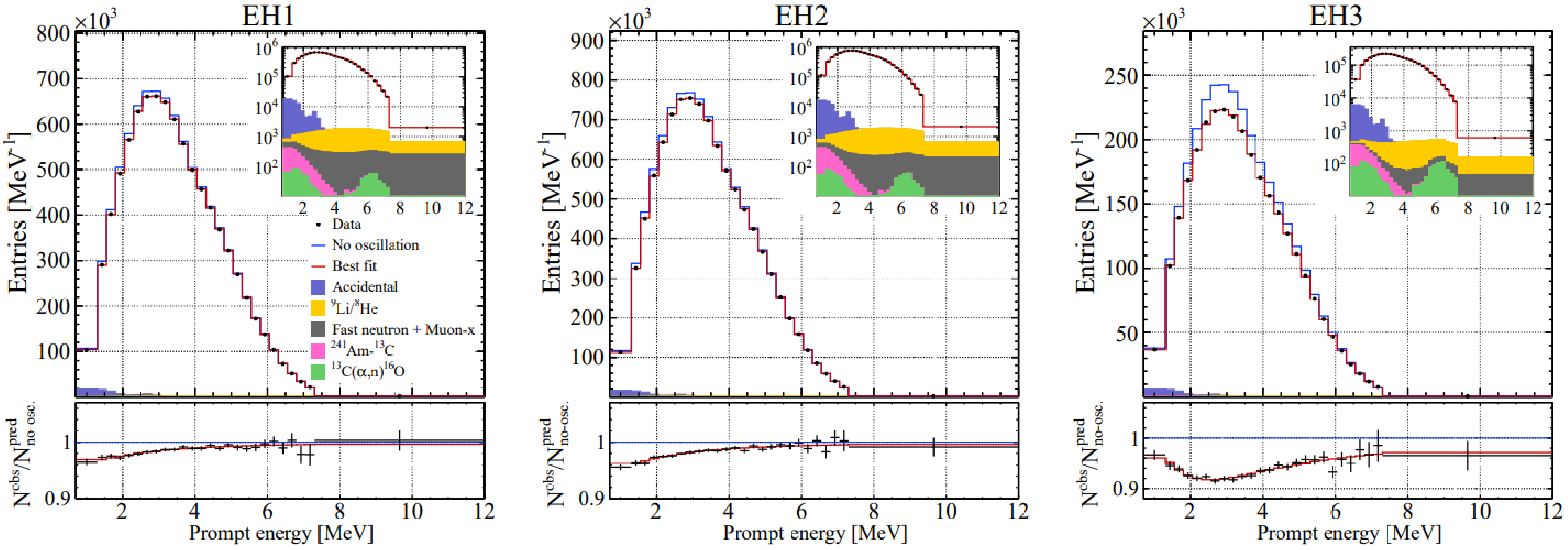
GRAZIE 谢谢 THANKS

Backup

Experiment	Reference
Daya Bay nGd	Phys. Rev. Lett. **130,** 161802 (2023)
Daya Bay nH	arXiv:2406.01007
RENO nGd	Provided by RENO for this talk
RENO nH	Provided by RENO for this talk
Double Chooz	Neutrino 2020 talk
T2K	Eur. Phys. J. C **83,** 782 (2023)
NOvA	Phys. Rev. D **106,** 032004 (2022) arXiv:2311.07835
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)

Backup

Measured prompt energy spectra at Daya Bay



PhysRevLett. 130 161802

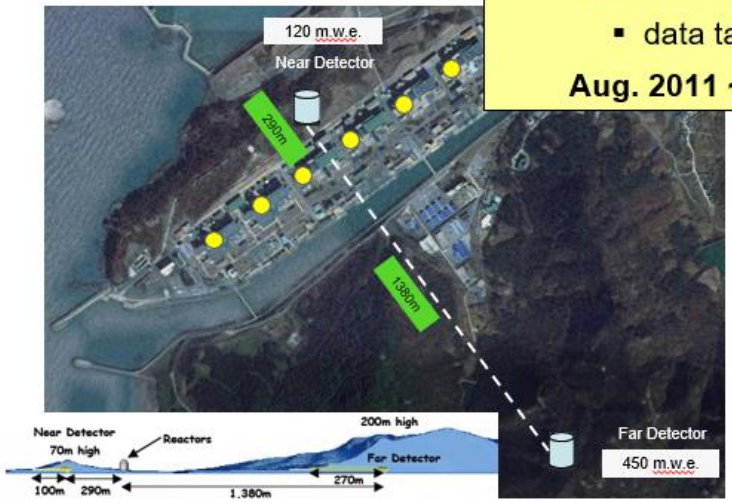
Slides provided by RENO

RENO

- Reactor Experiment for Neutrino Oscillation
- The RENO experiment has precisely measured the amplitude and frequency of reactor antineutrino oscillation at Hanbit Nuclear Power Plant.
- Data taking : Aug. 2011 ~ Mar. 2023 (corresponding to ~3800[d] live time)

- Total cost : **$10M**
- Start of project : **2006**
- data taking :

Aug. 2011 ~ Mar. 2023

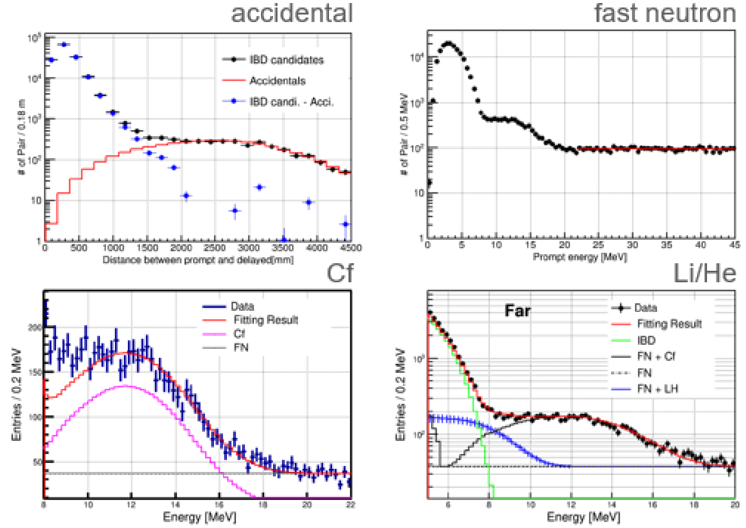


period	live time	result
Aug. 2011 ~ Feb. 2018	2200 [days]	2018 PRL
Aug. 2011 ~ Mar. 2023	3800 [days]	new

Slides provided by RENO

IBD Candidate Sample & Background Estimation (n-Gd)

- By applying selection criteria, 1,211,995(144,667) $\bar{\nu}_e$ candidate events were obtained for near(far).
- The remaining background rates and spectral shapes are obtained from control data samples.
- The total background rates are estimated to be 9.08±0.18(2.06±0.13) events per day for near(far) detectors, which corresponds to 2.5%(5.3%) of the total background fraction.

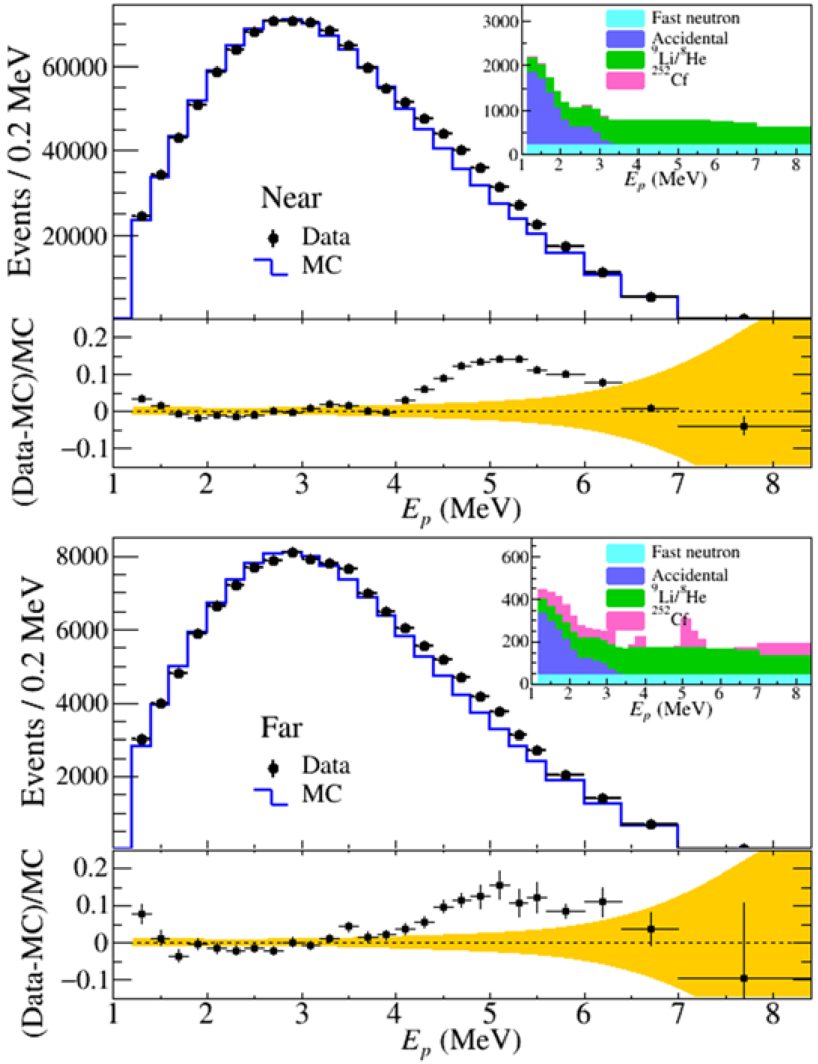


Detector	Near	Far
IBD rate	366.47 ± 0.33	38.70 ± 0.10
after background subtraction	357.39 ± 0.38	36.64 ± 0.16
total background rate	9.08 ± 0.18	2.06 ± 0.13
live time [days]	3307.25	3737.85
accidental rate	2.30 ± 0.02	0.36 ± 0.01
fast neutron rate	1.74 ± 0.01	0.34 ± 0.01
^{252}Cf contamination rate	0.07 ± 0.01	0.34 ± 0.04
^{9}Li/^{8}He rate	4.97 ± 0.17	1.02 ± 0.12

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

IBD Spectrum (n-Gd)

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



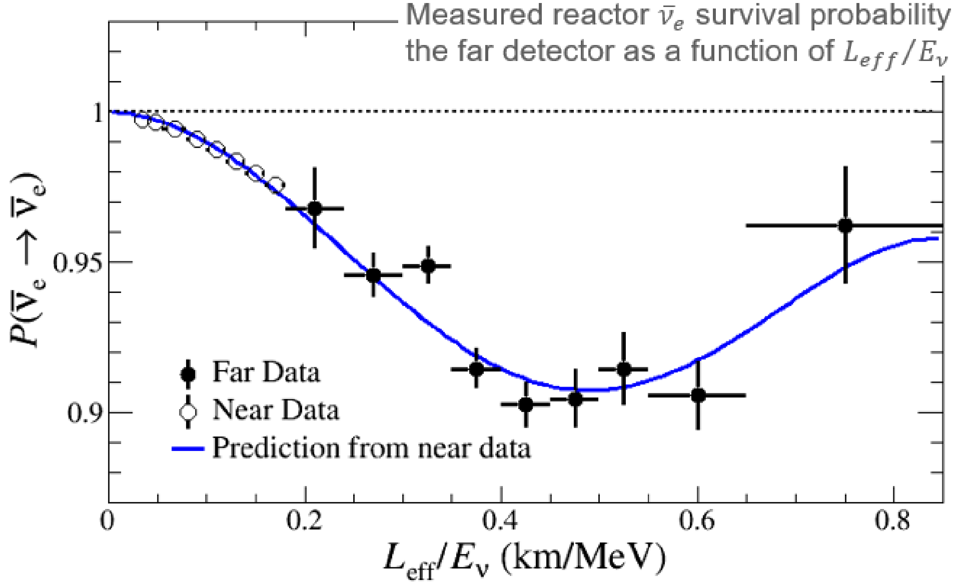
Slides provided by RENO

Oscillation Measurement (n-Gd)

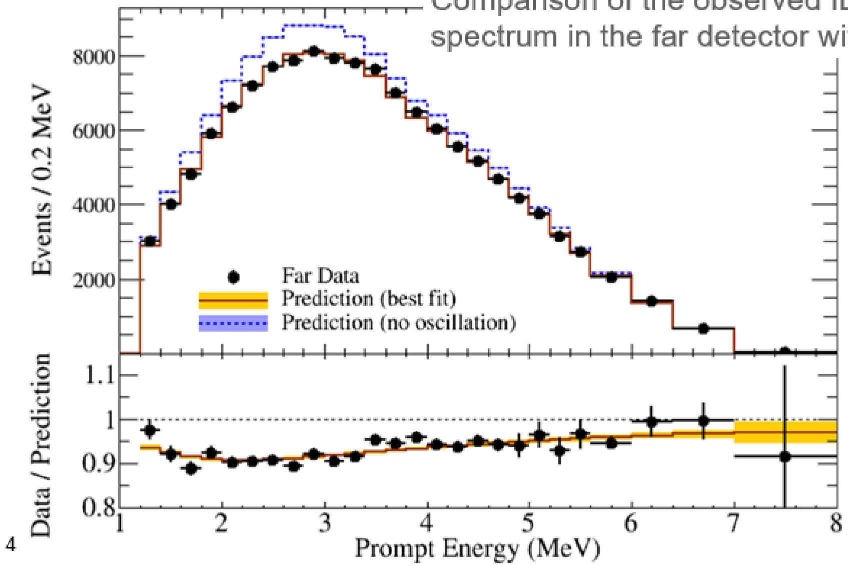
- Based on the measured far-to-near ratio of prompt spectra from the 3800[d] sample, we obtain the following final result.
  - $\sin^2 2\theta_{13} = 0.0920 {}^{+0.0044}_{-0.0042} (stat.) {}^{+0.0041}_{-0.0041} (syst.)$
  - $\Delta m^2_{ee} = 2.57 {}^{+0.10}_{-0.11} (stat.) {}^{+0.05}_{-0.05} (syst.) [\times 10^{-3} eV^2]$

→ preparing publication

- (reference) 2200[d] result published at 2018
  - $\sin^2 2\theta_{13} = 0.0896 \pm 0.0048 (stat.) \pm 0.0047 (syst.)$
  - $\Delta m^2_{ee} = 2.68 \pm 0.12 (stat.) \pm 0.07 (syst.) [\times 10^{-3} eV^2]$



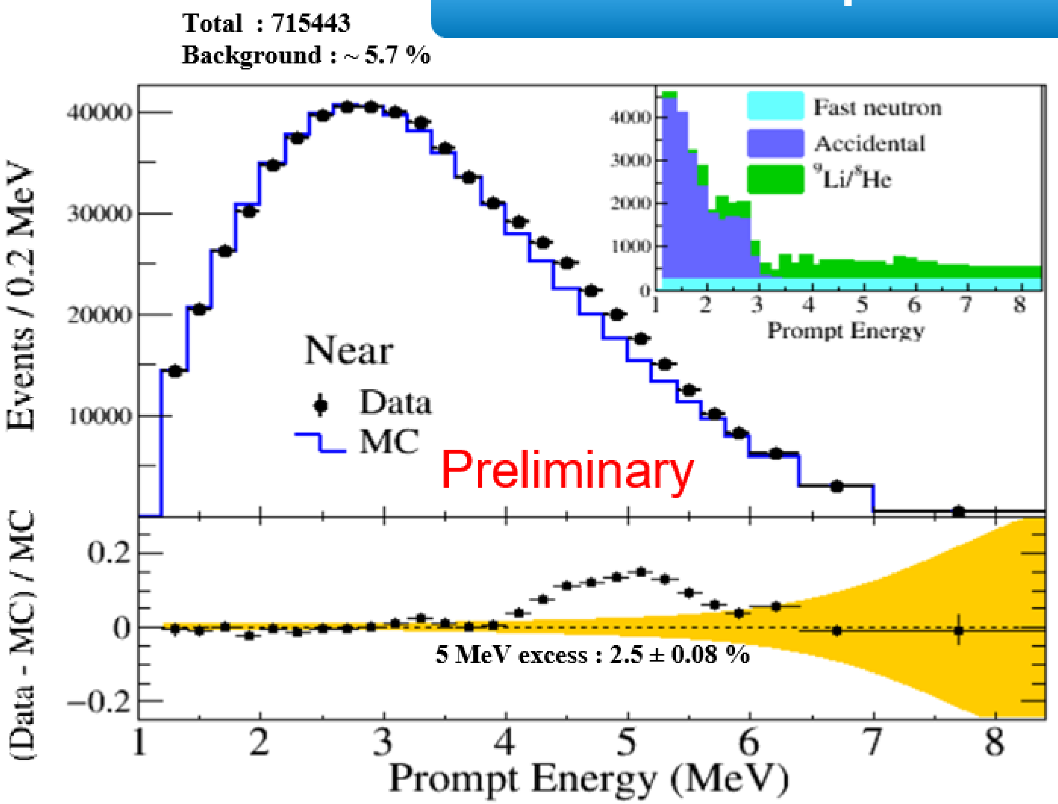
Measured reactor $\bar{\nu}_e$ survival probability in the far detector as a function of L_{eff}/E_ν

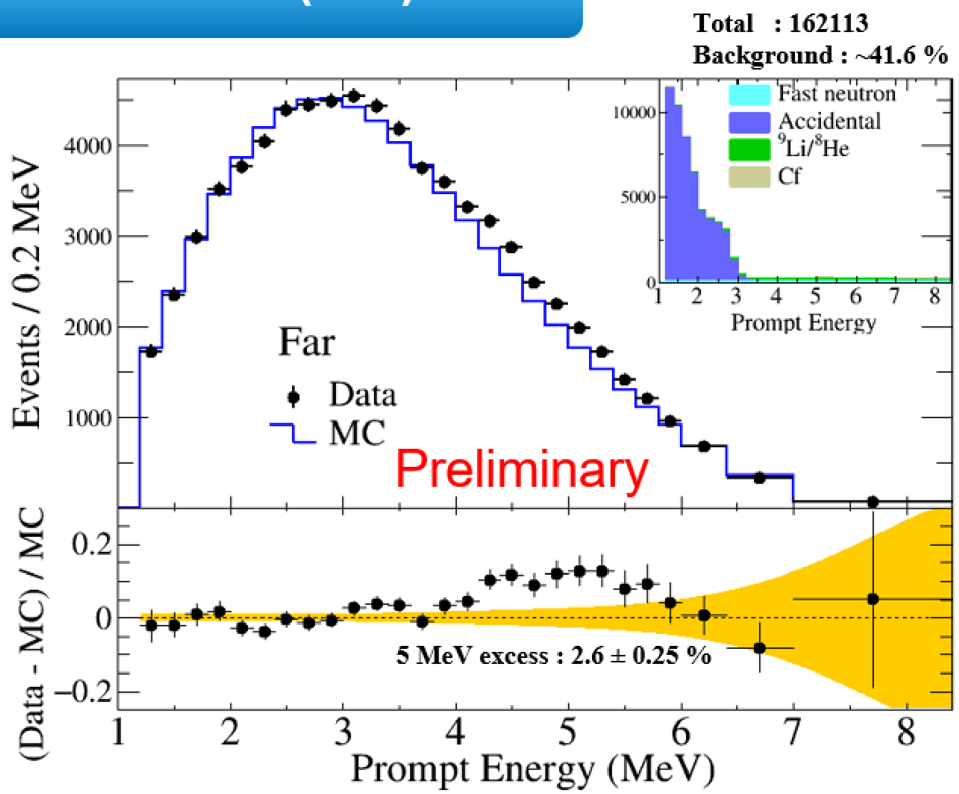


Comparison of the observed IBD prompt spectrum in the far detector with prediction

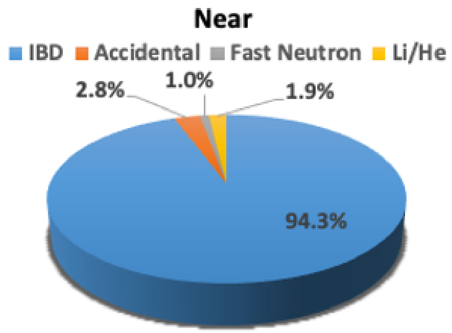
Slides provided by RENO

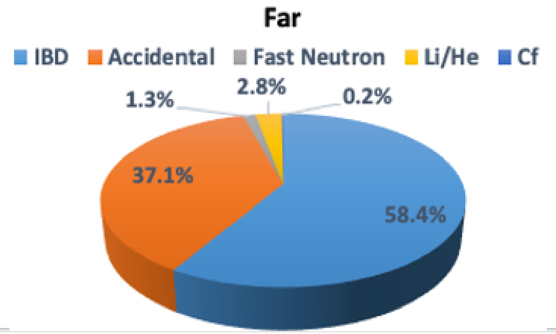
Final Sample of IBD Candidates (n-H)





	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





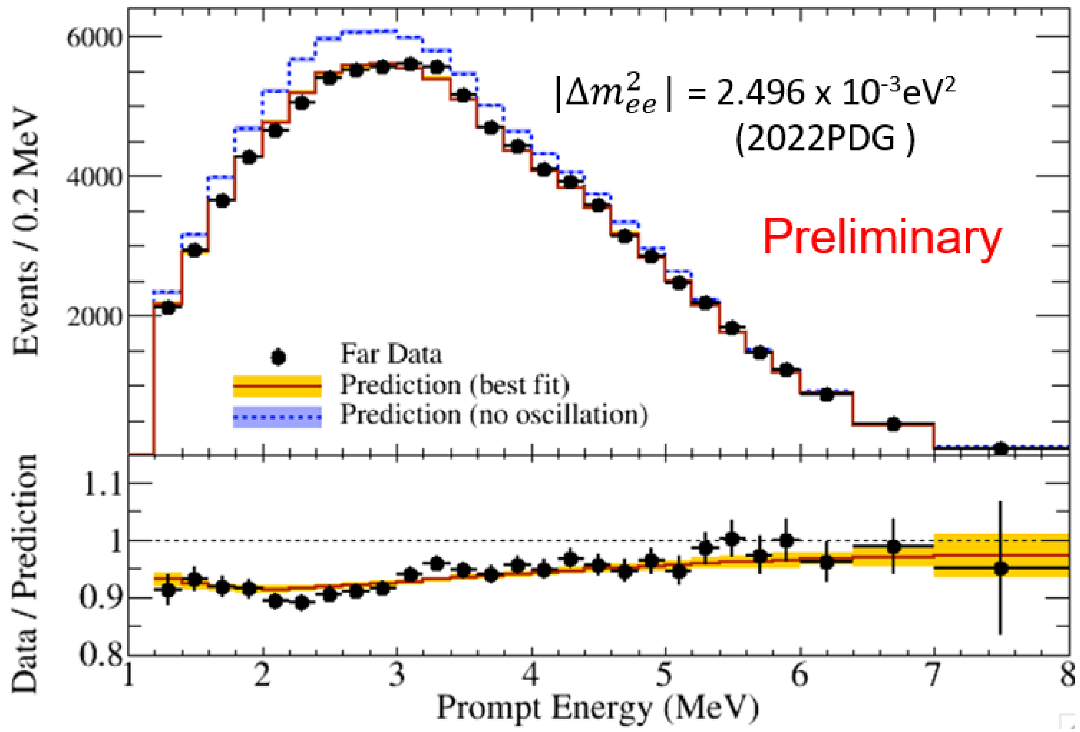
Slides provided by RENO

θ_{13} Measurement (n-H)

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

JHEP(2019) : 1500days n-H result → $\sin^2(2\theta_{13}) = 0.086 \pm 0.008(\text{stat.}) \pm 0.014(\text{syst.})$

PRL(2018) : 2200days n-Gd result → $\sin^2(2\theta_{13}) = 0.0896 \pm 0.0048(\text{stat.}) \pm 0.0047(\text{syst.})$



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

nGd(2200d) + nH(2800d) combined result

$$Correlation = \frac{\sigma^{n-H}_{correlated} \cdot \sigma^{n-Gd}_{correlated}}{\sigma^{n-H}_{tot} \cdot \sigma^{n-Gd}_{tot}}$$

	Uncertainty fraction (%)	Correlation
Statistical	38.0	0
Reactor	19.7	1
Detector	21.3	0.1
Total background	22.8	0
Combined	101.8	0.1

Combined result Error weighted mean (nGd+nH)

(No correlated) → 0.0871 ± 0.0064(tot.)

(apply correlation) → 0.0871 ± 0.0040(stat.) ± 0.0045(syst.)

[± 0.0060(tot.)]