Review of θ_{13} measurements and latest results from Daya Bay

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On behalf of the Daya Bay collaboration

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中国物理学会高能物理分会第十四届全国粒子物理学术会议（2024）

Neutrino Oscillation: 2004 to 2024

	Value (3σ C.L.)	Source
$\sin^2\theta_{12}$	$0.3^{+0.09}_{-0.07}$	Solar + KamLAND
$\sin^2\theta_{23}$	≈ 0.5	Atmospherics + K2K
$\sin^2\theta_{13}$	< 0.066	CHOOZ
Δm^2_{21}	$6.9^{+2.6}_{-1.5} \times 10^{-5}$ eV^2	Solar + KamLAND
$\lvert\Delta m^2_{32}\rvert$	$2^{+1.2}_{-0.9} \times 10^{-3}$ eV^2	Atmospherics + K2K
δ_{CP}	/	/

2004

2024

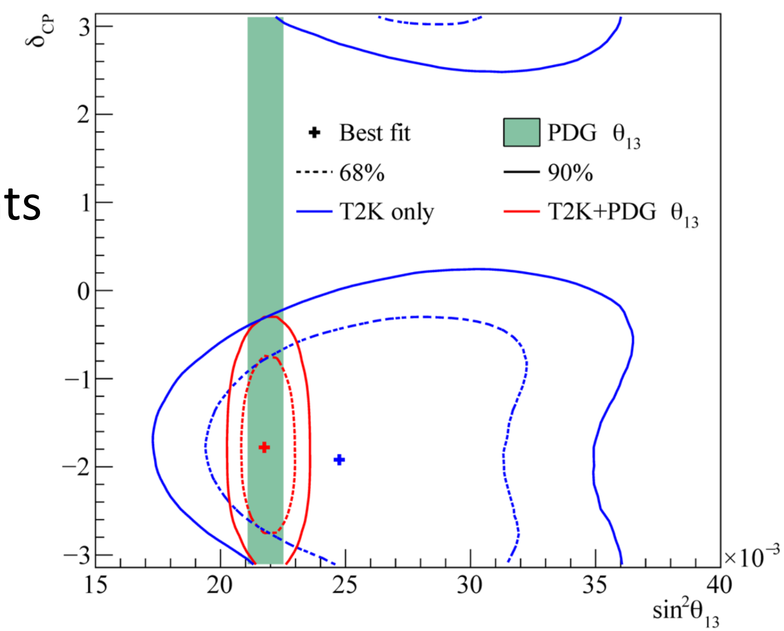
	Value (1σ)	Source
$\sin^2\theta_{12}$	0.307 ± 0.013	Solar + KamLAND
$\sin^2\theta_{23}$	$0.454^{+0.019}_{-0.016}$ or $0.568^{+0.016}_{-0.021}$	Atmospherics + Accelerators
$\sin^2\theta_{13}$	$(2.19 \pm 0.07) \times 10^{-2}$	Daya Bay + RENO + D-Chooz
Δm^2_{21}	$(7.53 \pm 0.18) \times 10^{-5}$ eV^2	Solar + KamLAND
Δm^2_{32}	$(2.455 \pm 0.028) \times 10^{-3}$ eV^2 (NO) $-(2.529 \pm 0.029) \times 10^{-3}$ eV^2 (IO)	Atmospherics + Accelerators
δ_{CP}	/	T2K + NOνA + SuperK

Why $\boldsymbol{\theta}_{13}$ Matters

- The dominant terms in determining δ_{CP} , Neutrino Mass Ordering, and θ_{23} octant are all directly related to θ_{13}
- Jarlskog invariant $J_v = \sin\theta_{13}\cos^2\theta_{13}\sin\theta_{12}\cos\theta_{12}\sin\theta_{23}\cos\theta_{23}\sin\delta_{CP}$

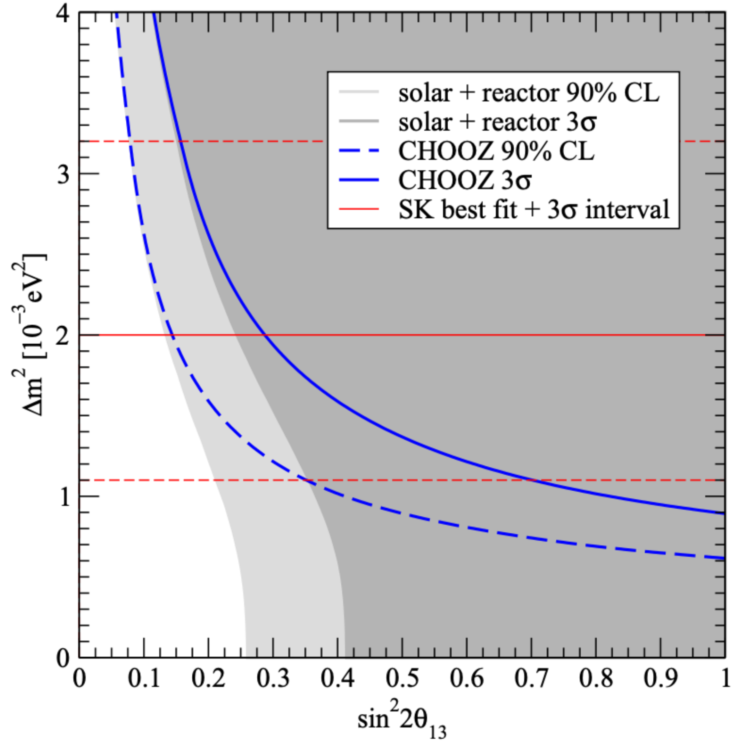
- Improved measurements by reactor experiments can break θ_{13} - δ_{CP} degeneracy in Long Baseline experiments and greatly improves their sensitivity
- Opening the possibility of a role of neutrino oscillations in explaining the **matter-antimatter asymmetry** in the Universe

T2K: *Eur. Phys. J. C* 83 (2023) 9, 782



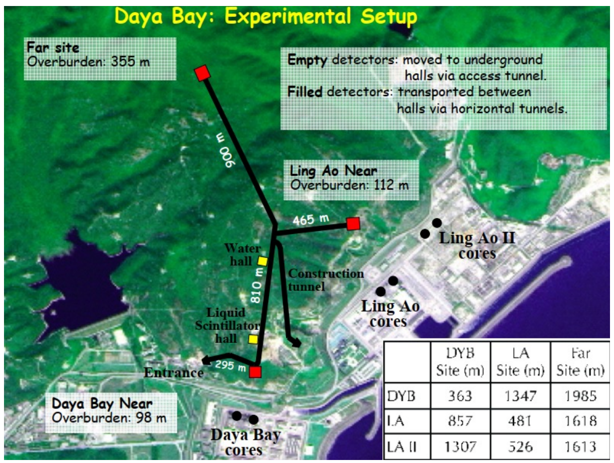
θ_{13} Status at 2004

- White paper ready:
  - WHITE PAPER REPORT on Using Nuclear Reactors to Search for a value of θ_{13}, hep-ex/0402041



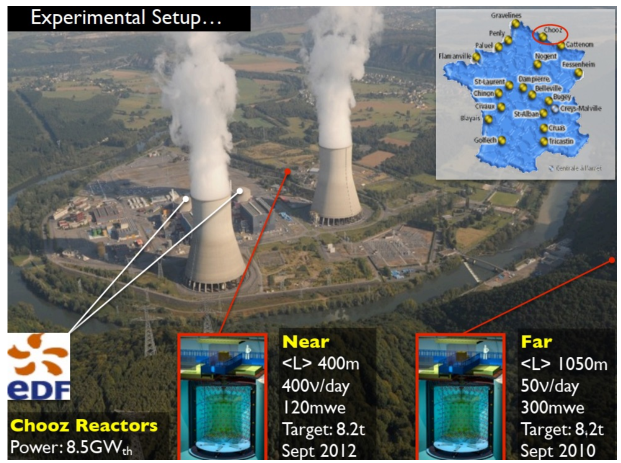
θ_{13} Status at 2008

Daya Bay

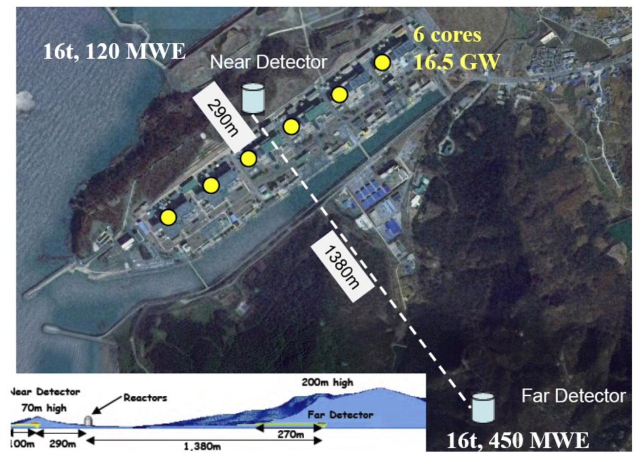


	DYB Site (m)	LA Site (m)	Far Site (m)
DYB	363	1347	1985
LA	857	481	1618
LA II	1307	526	1613

Double Chooz

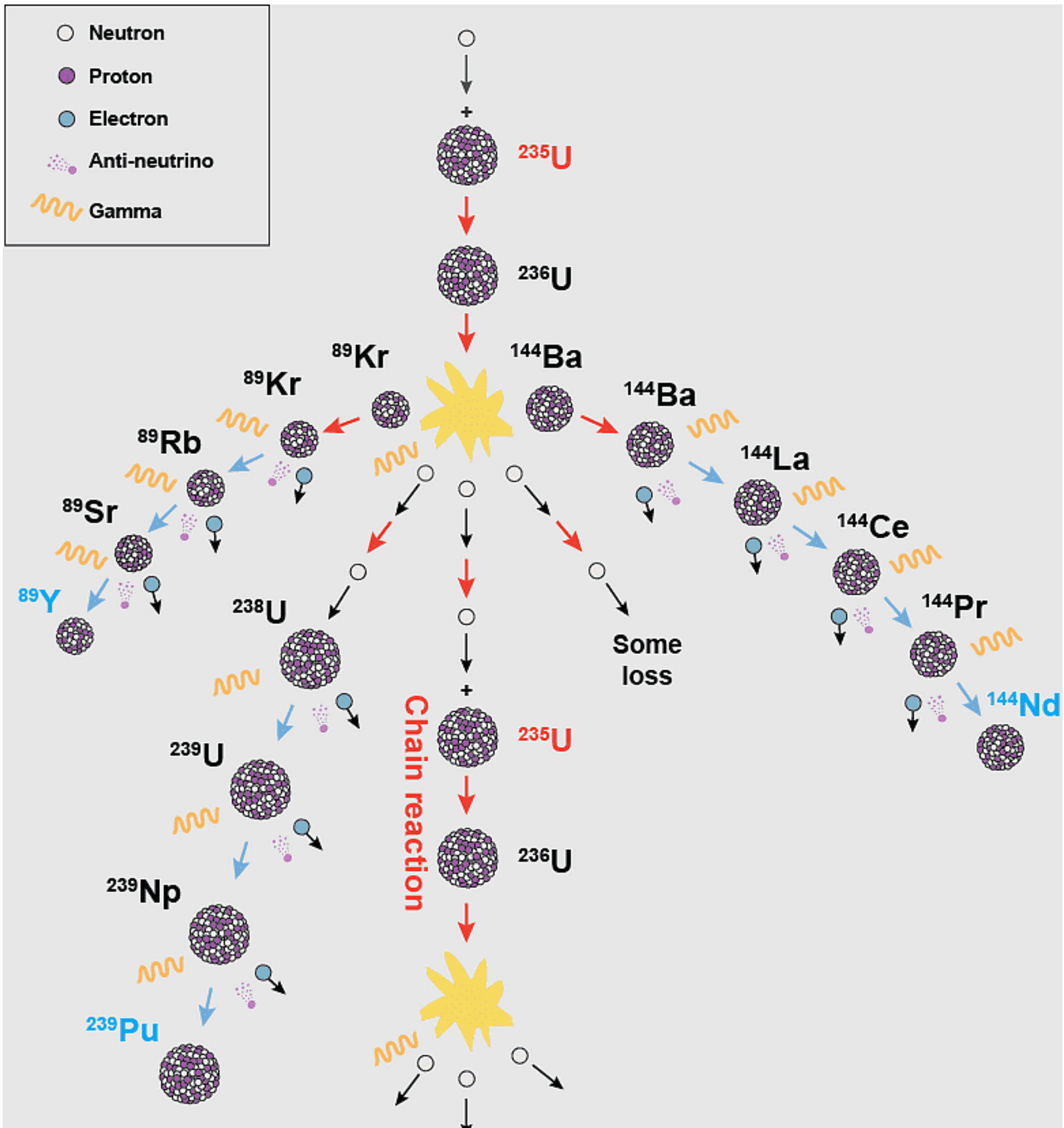


RENO



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

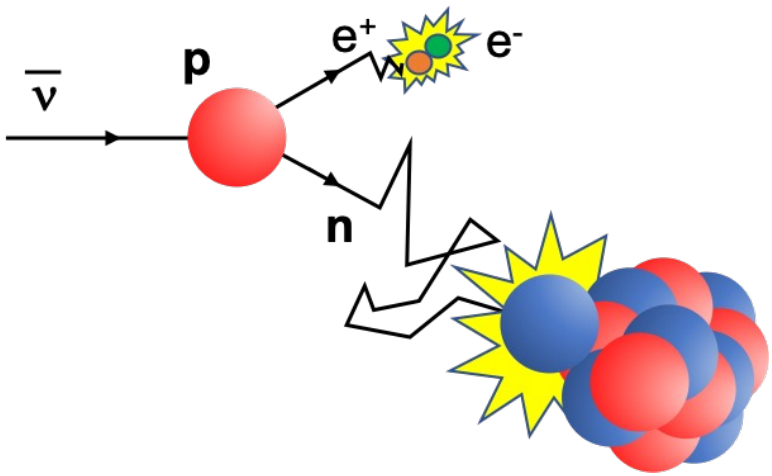
Reactor Neutrinos



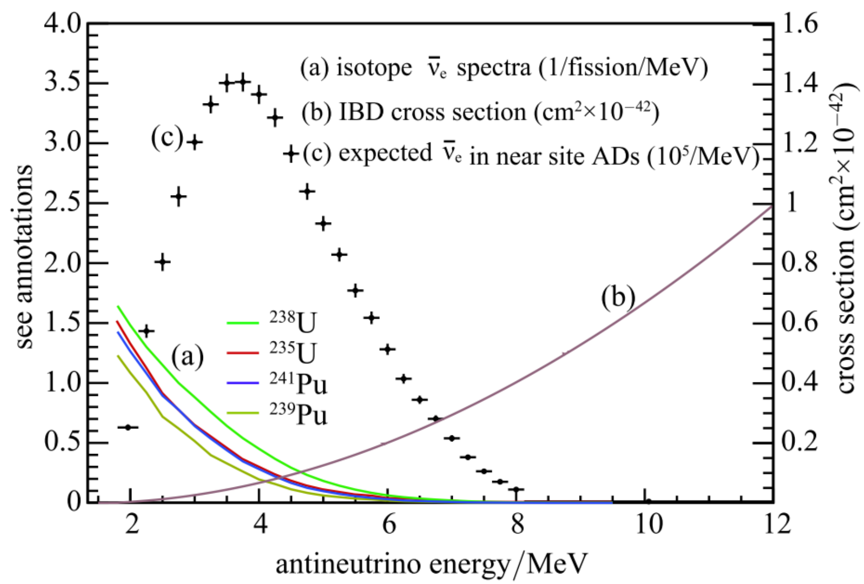
- The strongest artificial neutrino source on the Earth
- 2×10^{20} ν's per second per GW thermal power, >99.7% from ^{235,238}U and ^{239,241}Pu

Detecting Reactor Neutrinos

- Easy to detect via the Inverse Beta Decays (IBD)
  - Well distinguished prompt-delayed pair signature
  - **Prompt** positron deposits energy and annihilation
  - **Delayed** neutron capture (Δt: ~30/200 μs for nGd/nH)



Capture on hydrogen → nH
Capture on gadolinium → nGd



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

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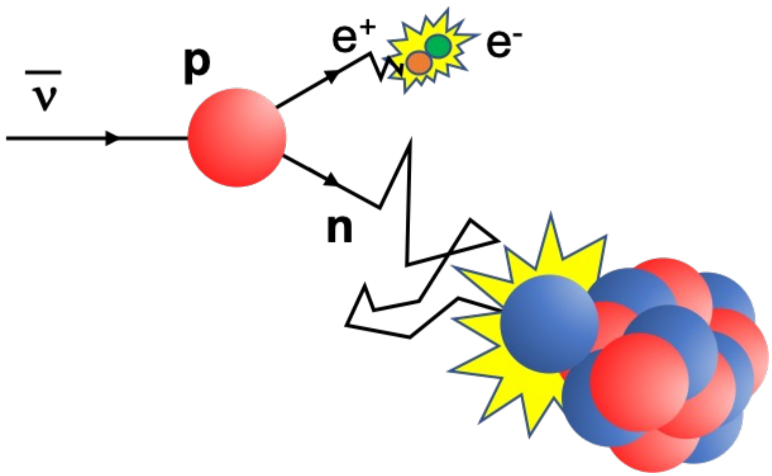

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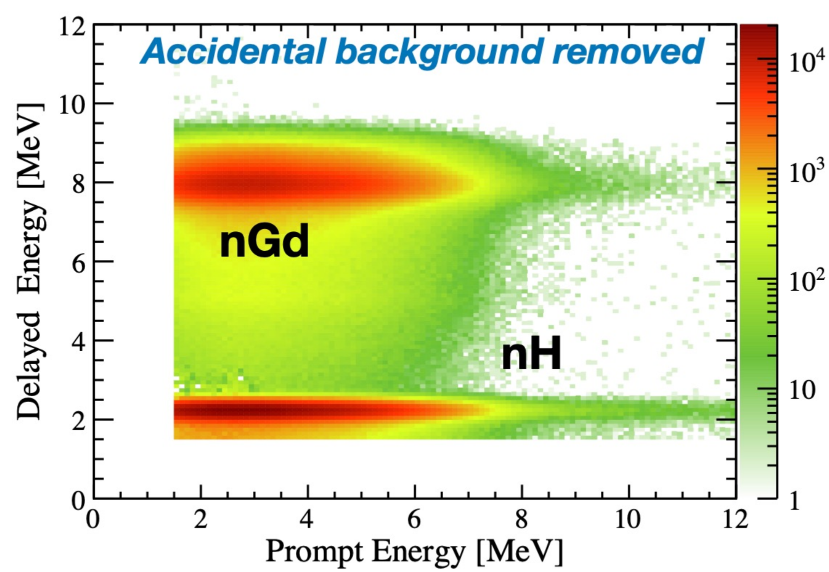
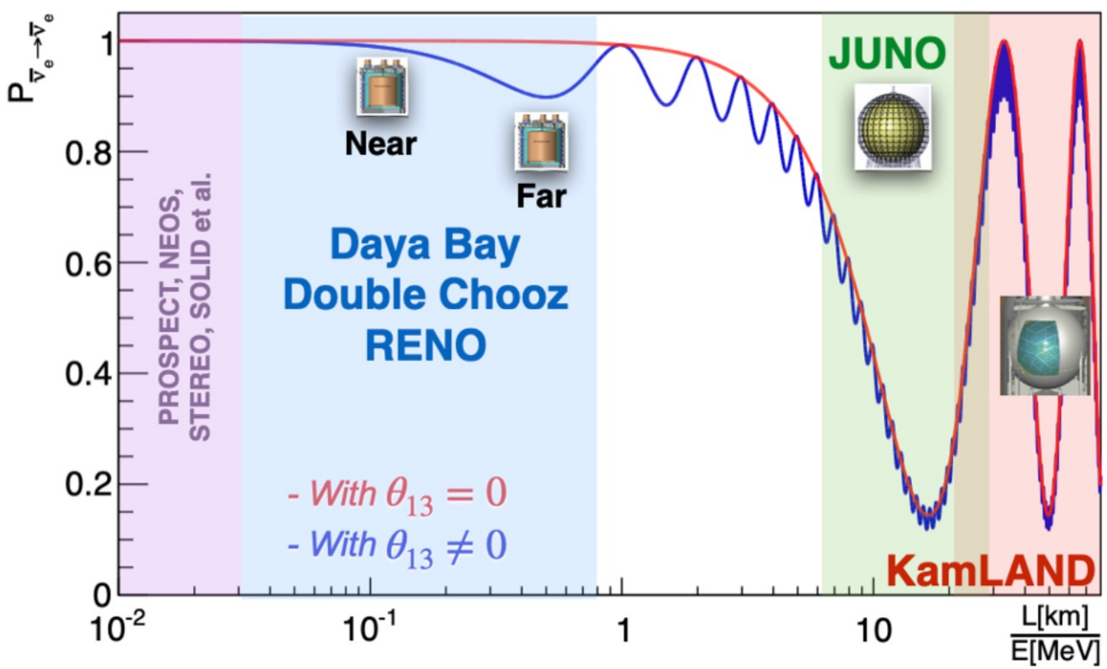


Measuring $\boldsymbol{\theta}_{13}$ with Reactor $\overline{\boldsymbol{\nu}}_{\boldsymbol{e}}$

- Disappearance experiments to measure $\overline{\boldsymbol{\nu}}_{\boldsymbol{e}}$ survival probabilities

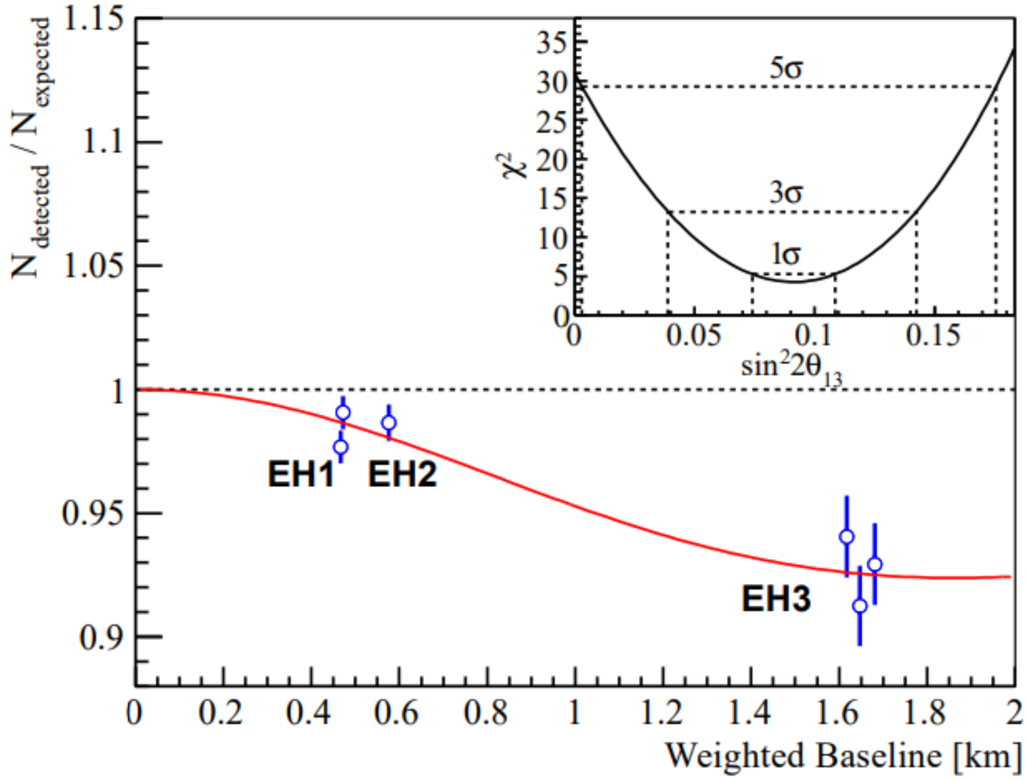
$$P = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} - \sin^2 2\theta_{13}\left(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}\right)$$

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



First shot in 2012

- Daya Bay firstly excluded θ=0 in 2012 with 5.2σ significance
  - **$\sin^2 2\theta_{13} = 0.092 \pm 0.016(\text{stat}) \pm 0.005(\text{syst})$**
  - Phys. Rev. Lett. 108 (2012) 171803



First shot in 2012

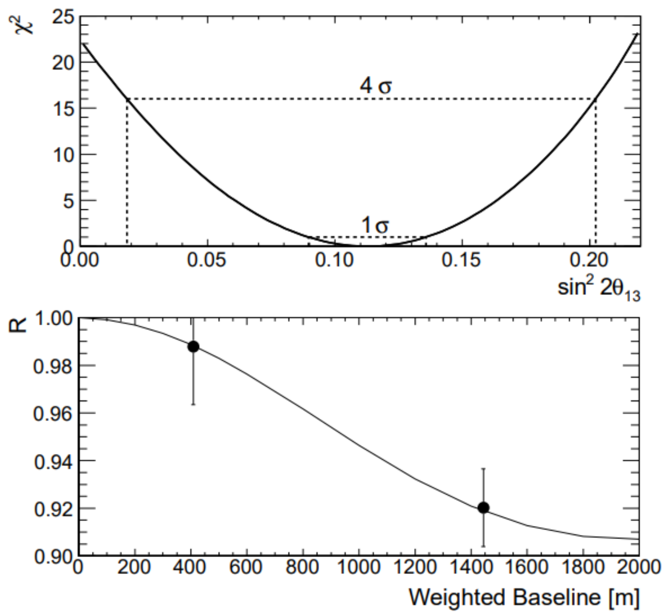
Confirming Daya Bay's observation

RENO

Phys. Rev. Lett. 108 (2012) 191802

0.113 ± 0.013(stat.) ± 0.019(syst.)

April 2012, 4.9σ

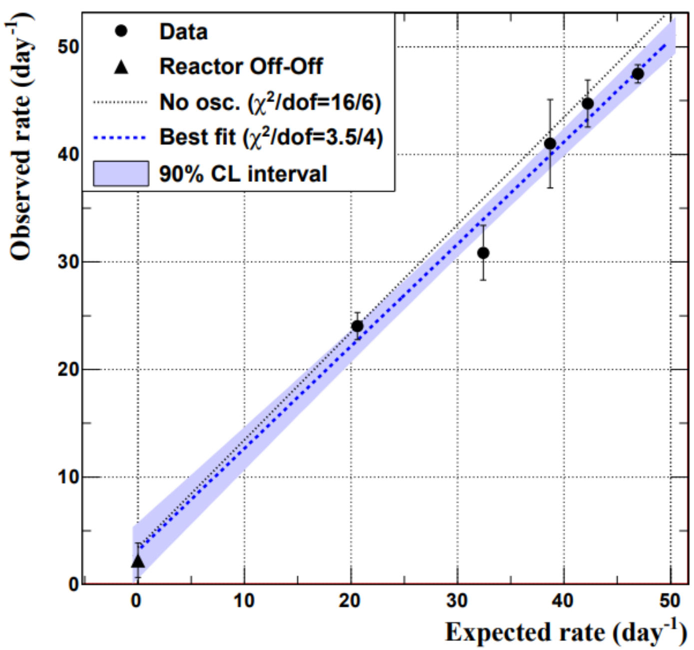


Double Chooz far detector

Phys. Rev. Lett. 108 (2012) 131801

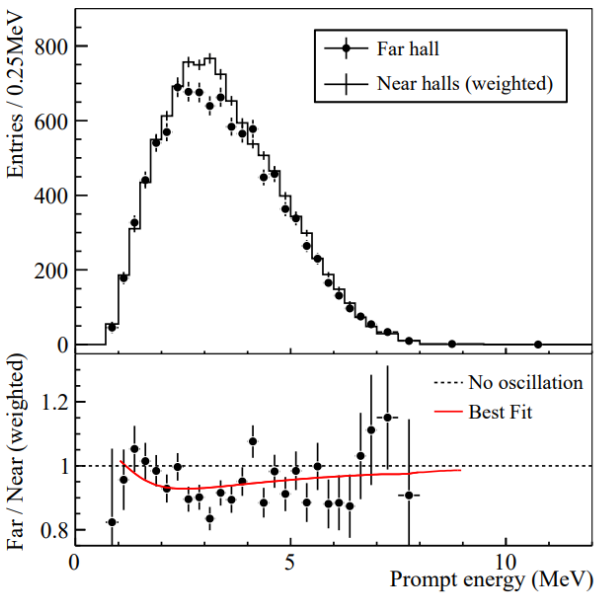
0.086 ± 0.041(stat.) ± 0.030(syst.)

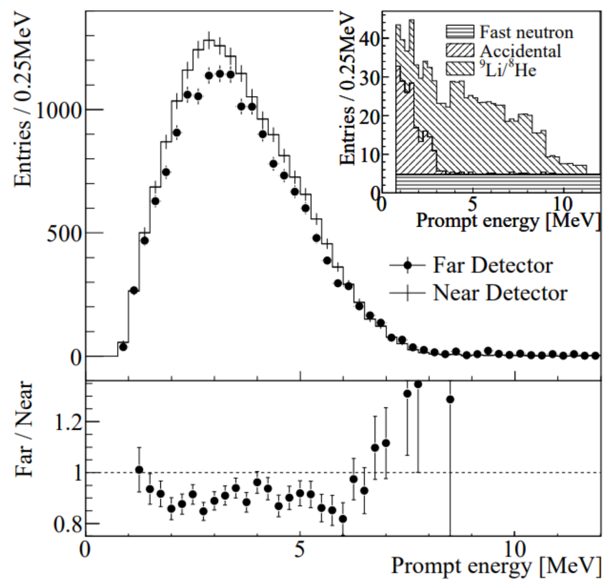
Nov. 2011, 94.6% C.L.

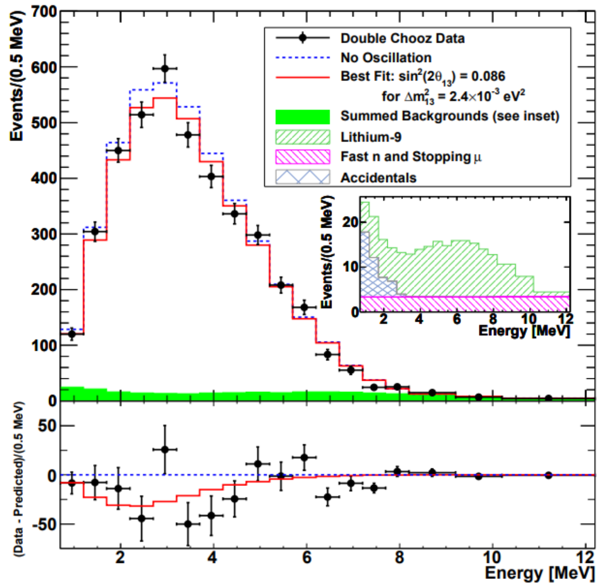


First shot in 2012

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

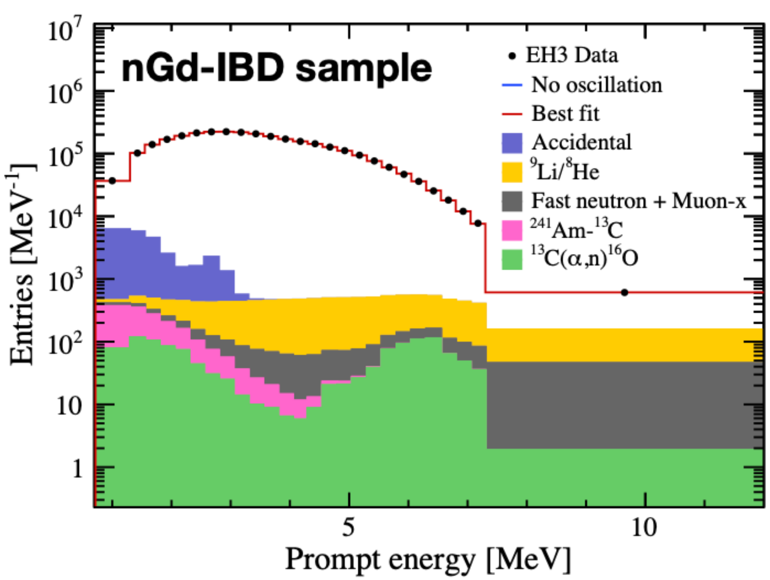
Double Chooz far detector
Phys.Rev.Lett. 108 (2012) 131801

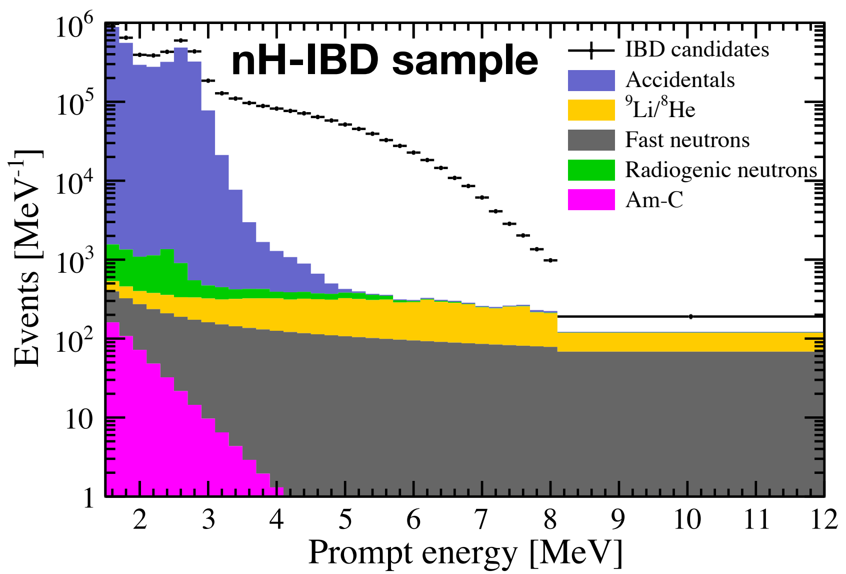
Precision improvement

- Data statistics
  - Stable data taking, include nH IBDs
  - Daya Bay: Dec. 2011 to Dec. 2020, 3158 days
    - 8 detectors, total thermal power up to 17.4 GW
  - Double Chooz: Apr. 2011 to Dec. 2017, ~1350 days
    - 2 detectors, total thermal power up to 8.5 GW
  - RENO: Aug. 2011 to Mar. 2023, ~3800 days
    - 2 detectors, total thermal power up to 16 GW
- Systematics uncertainty
  - Selection efficiencies, backgrounds
  - Data-driven evaluation also depends on the statistical
- Spectral measurement
  - Increase number of points for energy/baseline measurement
    - Need energy response model ($E_\nu \rightarrow E_p$)

Backgrounds

- Signal + backgrounds for **Daya Bay's far site**
- Accidental background
    - Largest contribution for both nH and nGd but with negligible uncertainty
- $^9Li/^8He$: largest background uncertainty for both nH and nGd
- New background for nH: radiogenic neutron background

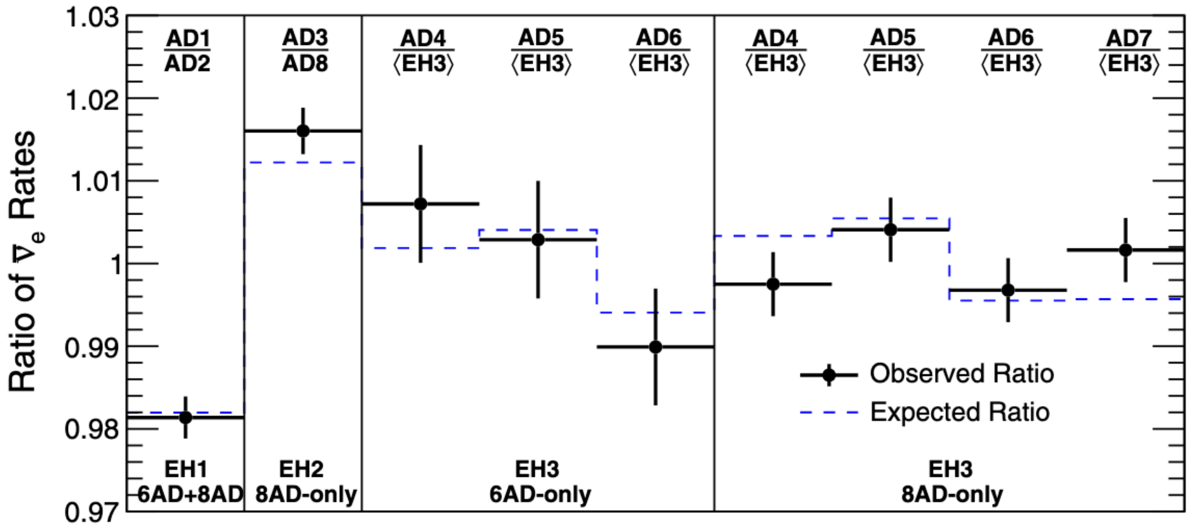




Detector Identicalness

- Multiple detectors at the same site at Daya Bay enables side-by-side comparison
- Confirming that systematic errors are under control

nGd-IBD sample
PRD 95, 072006 (2017)

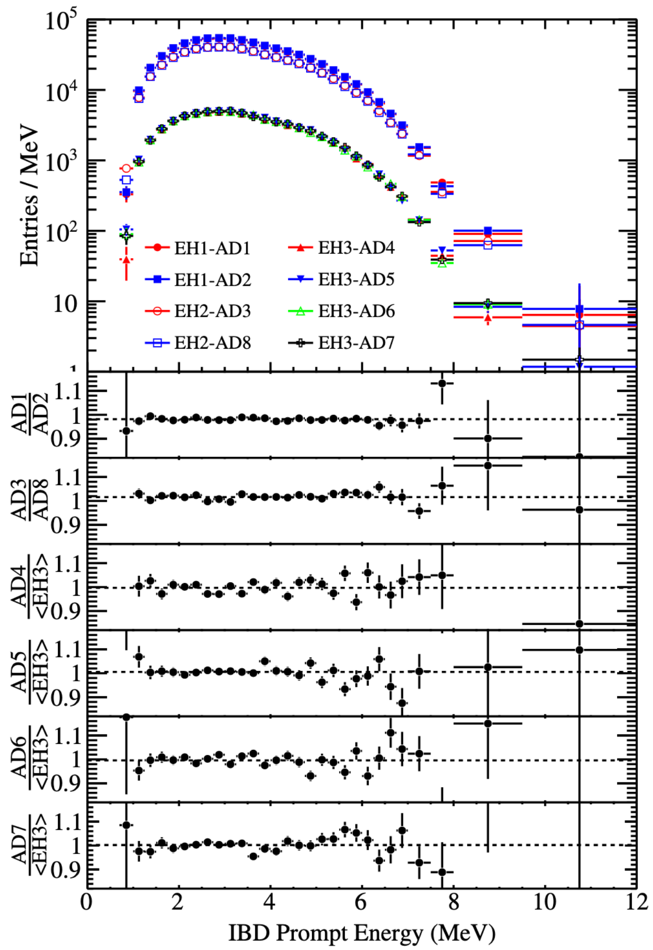


IBD measurement agrees with prediction well

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

Detector Identicalness

Also good identicalness for IBD spectrum

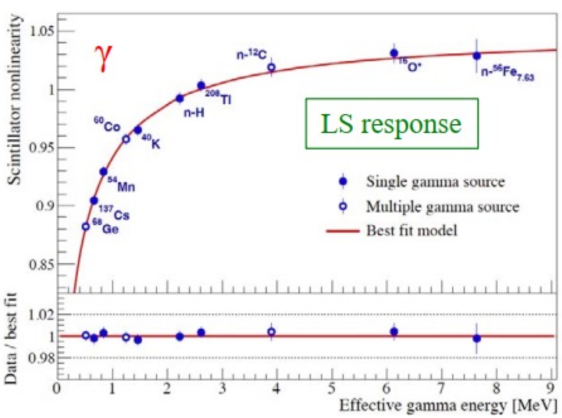


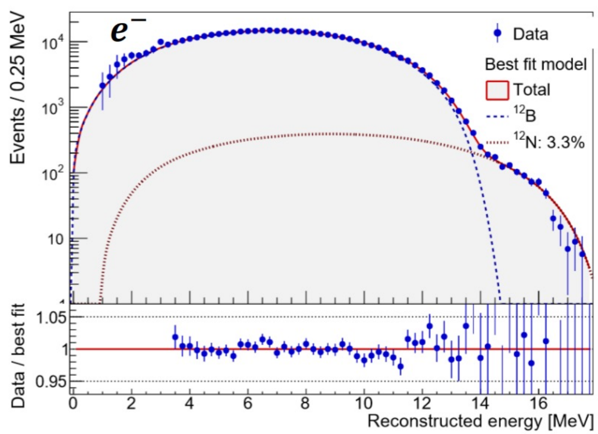
nGd-IBD sample
PRD 95, 072006 (2017)

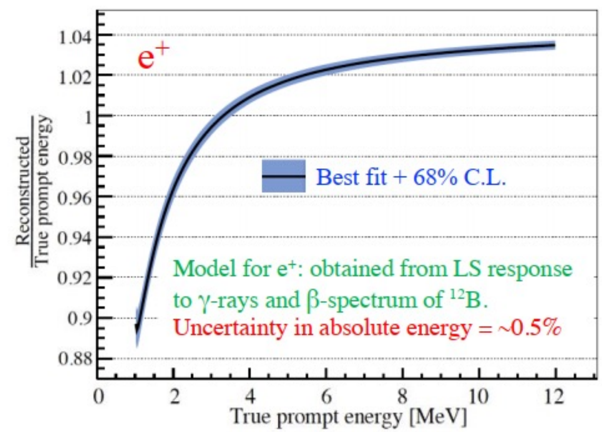
Relative differences on energy scales (<0.2%) and Gd capture fractions (<0.1%)

Energy Response Model

- Nonlinear energy response
  - Quenching (Birks constant) and Cherenkov effects
  - Readout electronics (FADC correction)
- 0.5% precision using multiple γ's and ^{12}B spectrum





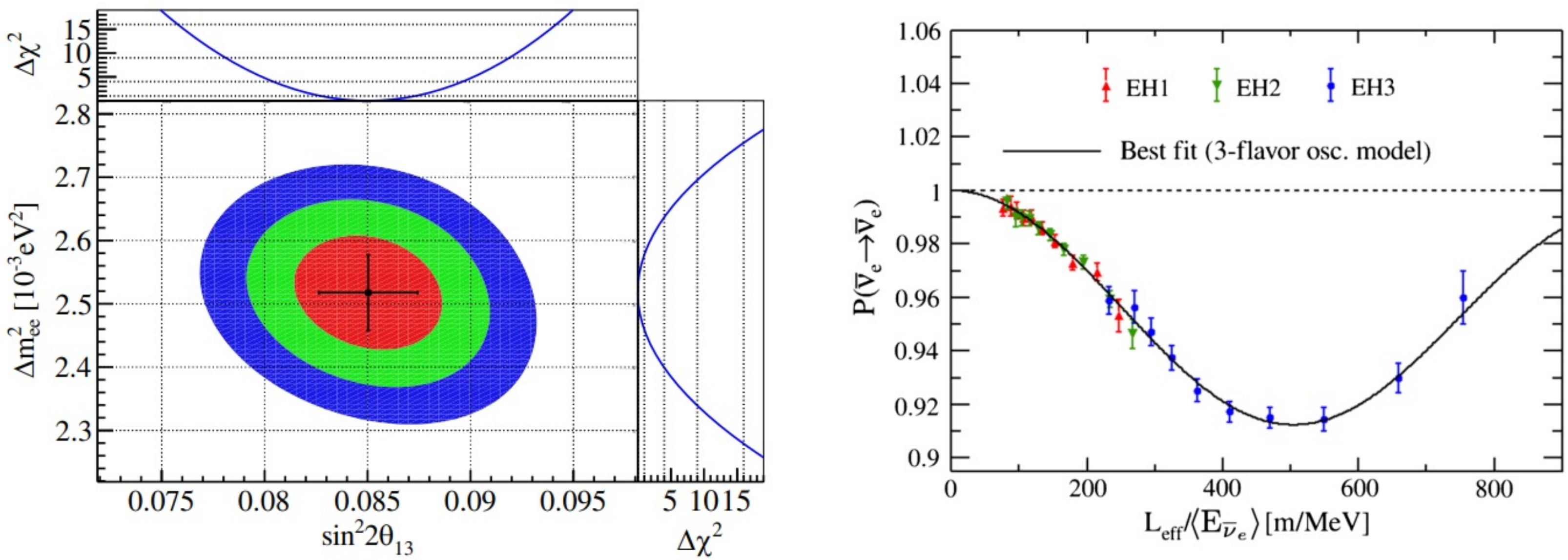


Nucl. Instrum. Meth. A 940 (2019) 230-242 and 895 (2018) 48-55

θ_{13} with nGd: Daya Bay

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

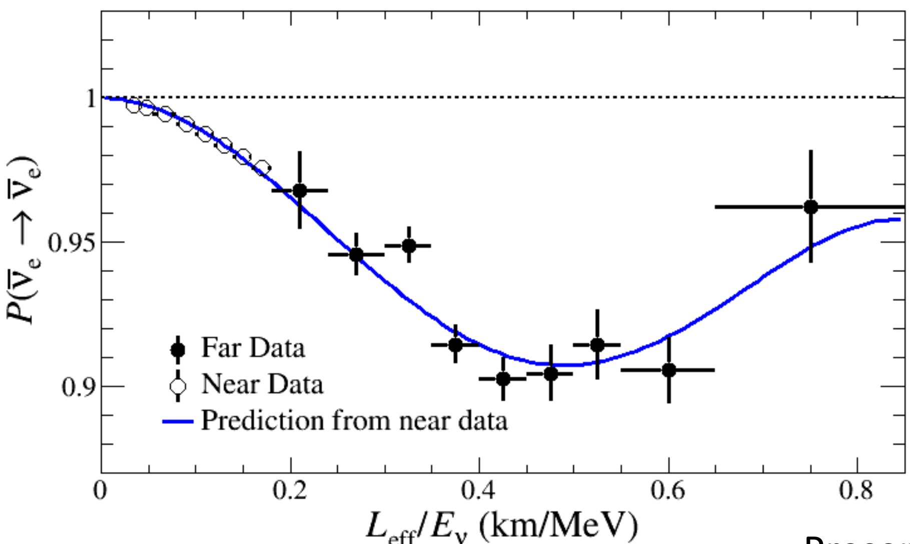
- $\sin^2 2\theta_{13} = 0.0851 \pm 0.0024$ precision 2.8%
- $\Delta m^2_{32} = 2.466 \pm 0.060\ (-2.571 \pm 0.060) \times 10^{-3}\ \mathrm{eV}^2$ precision 2.4%
    - Systematic uncertainty contributed about 50% in total

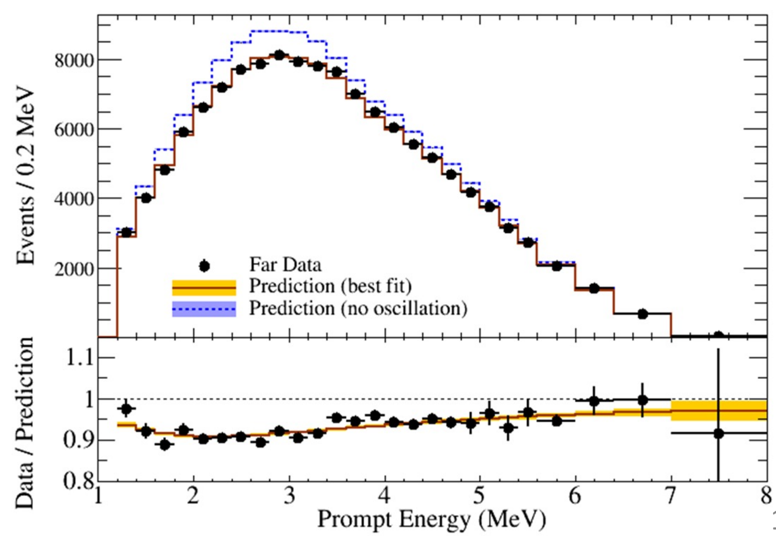


PhysRevLett. 130 161802

θ_{13} Measurement with nGd at RENO

- Based on the measured far-to-near ratio of IBD rates and prompt spectra
  - $\sin^2 2\theta_{13} = 0.0920\ ^{+0.0044}_{-0.0042}\,(\mathrm{stat.})\ ^{+0.0041}_{-0.0041}\,(\mathrm{syst.})$ precision 6.5%
  - $\Delta m^2_{ee} = 2.57\ ^{+0.10}_{-0.11}\,(\mathrm{stat.})\ ^{+0.05}_{-0.05}\,(\mathrm{syst.})[\times 10^{-3}\,\mathrm{eV}^2]$ precision 4.6%
- [Reference] 2200-days result published at 2018
  - $\sin^2 2\theta_{13} = 0.0896 \pm 0.0048(\mathrm{stat.}) \pm 0.0047(\mathrm{syst.})$ precision 7.5%
  - $\Delta m^2_{ee} = 2.68 \pm 0.12(\mathrm{stat.}) \pm 0.07(\mathrm{syst.})[\times 10^{-3}\,\mathrm{eV}^2]$ precision 5.2%

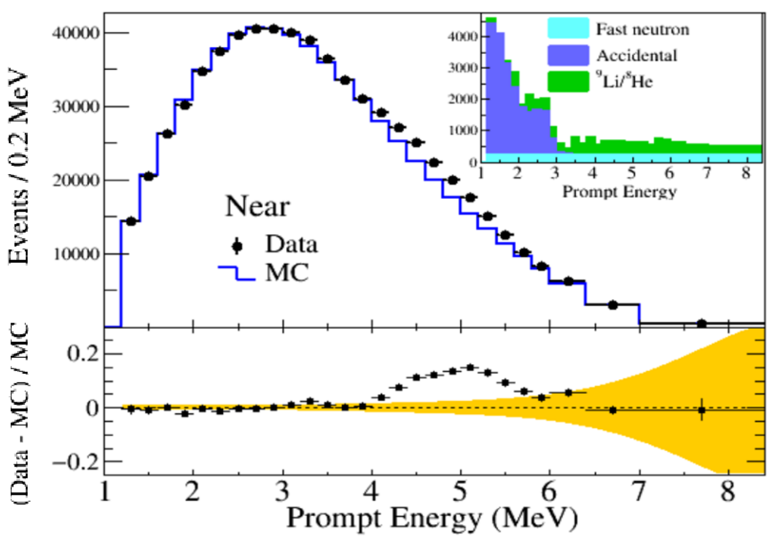


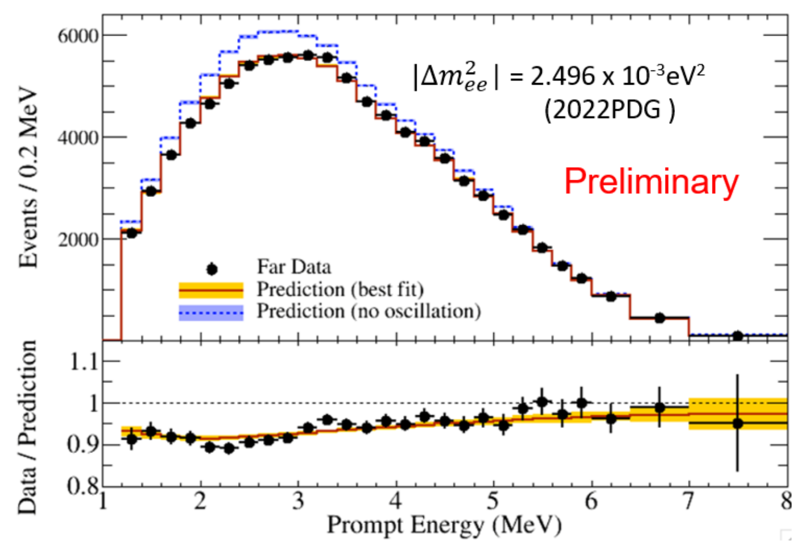


Presented at Nu-2024 and ICHEP2024

$\boldsymbol{\theta}_{13}$ Measurement with nH at RENO

- 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%





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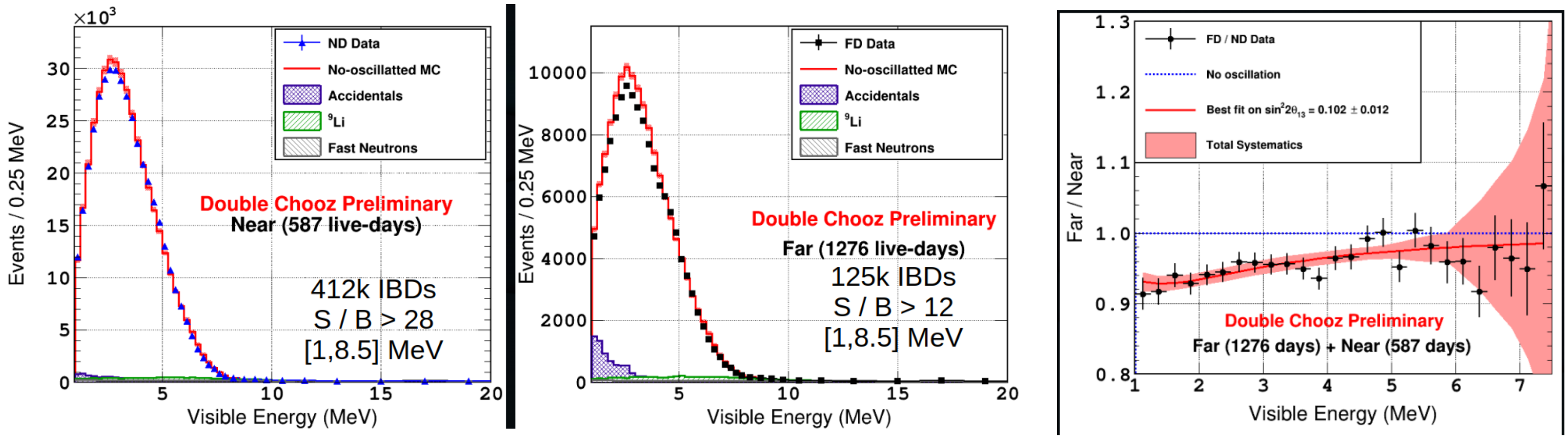
θ_{13} Measurement at Double Chooz

- 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 nGd
  - 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%
  - Compared to 13.3% precision in 2020 [*Nat. Phys.* **16**, 558–564 (2020)]

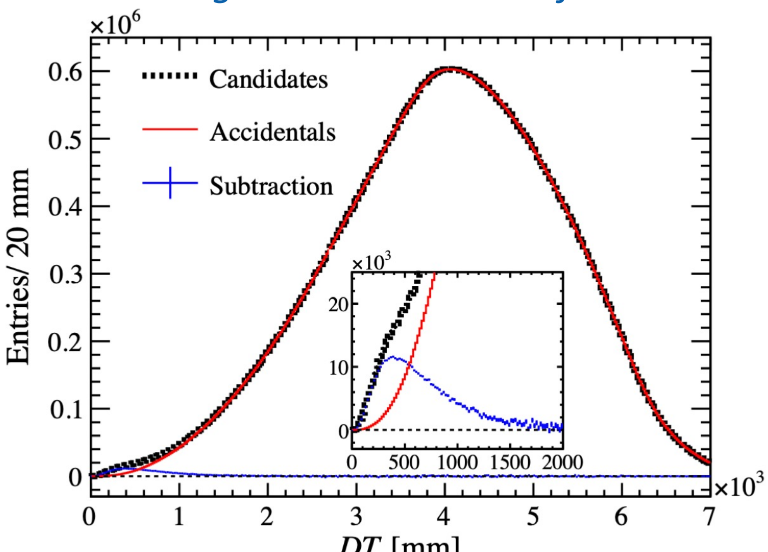


Plots from Thiago Bezerra's Double Chooz talk at Nu-2020

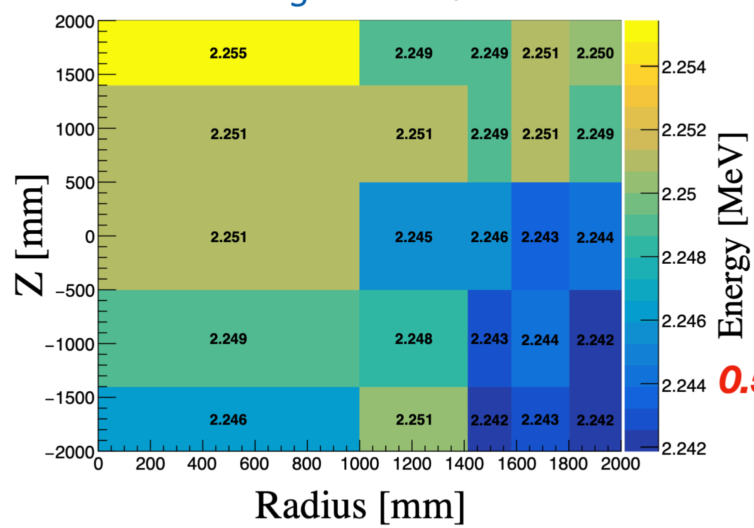
Latest nH Measurement at Daya Bay

- New nH oscillation result in arXiv:2406.01007 released on June 3, 2024
  → Previous DYB nH result: PRD 93, 072011 (2016)
    - Two independent analyses giving consistent result
    - 3.1 times more statistics (2/3 of the full data set)
    - Improvements in candidate selection, backgrounds and efficiencies, calibration…

Combining distance and time for selection



- *Energy scale difference among ADs ≲ 0.3%*
- *… among voxels ≲ 0.5%*

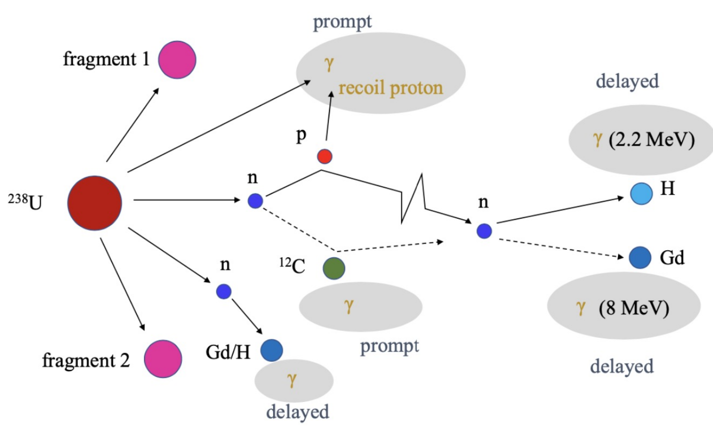


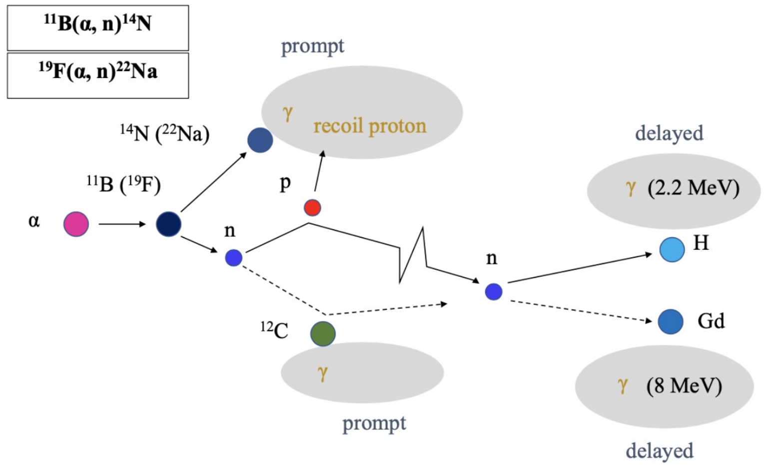
0.5% Z-axis range

Latest nH Measurement at Daya Bay

Neutrons from (α,n) reactions and spontaneous fissions

- **Gd-LS/LS/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 at Tsinghua to measure the Boron fraction in glass
  - Also investigated the material screening results, no other non-negligible neutron source





Phys. Rev. D **104**, 092006 and arXiv:2406.01007

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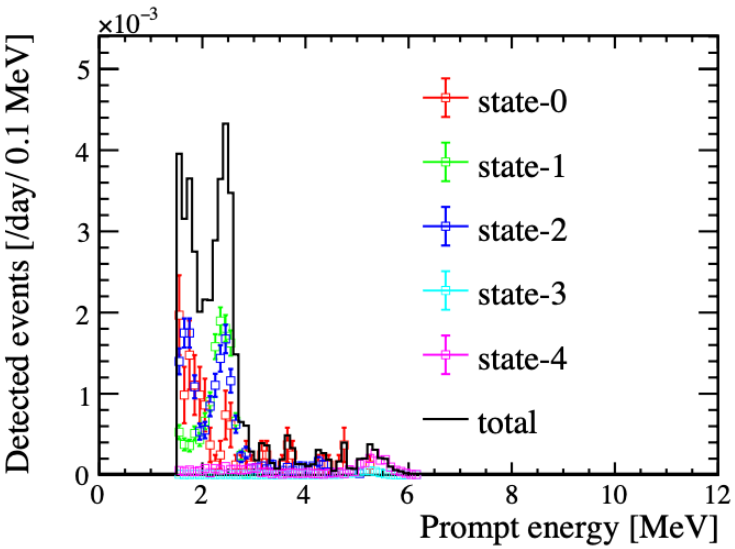
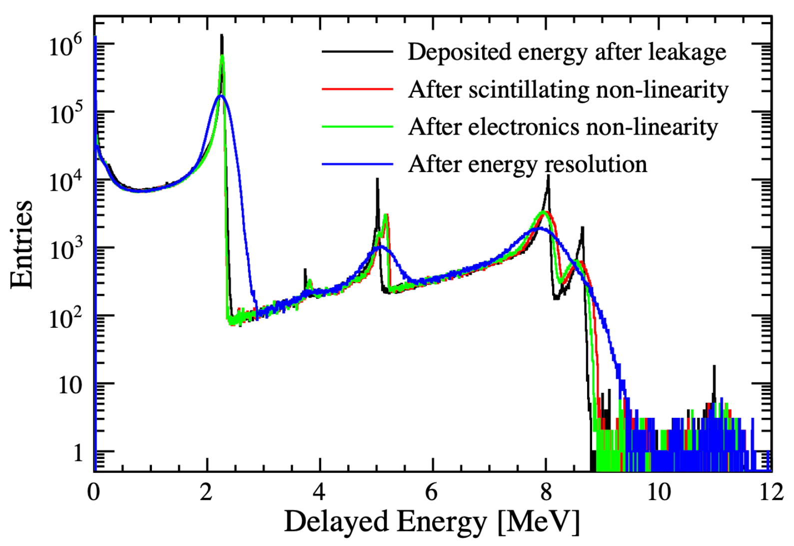
Distance from PMT to LS		Residual bkg in nH
Daya Bay	20 cm	0.2/day/AD
RENO	~50 cm	$<10^{-4}$/day
Double Chooz	~45 cm	$<10^{-4}$/day



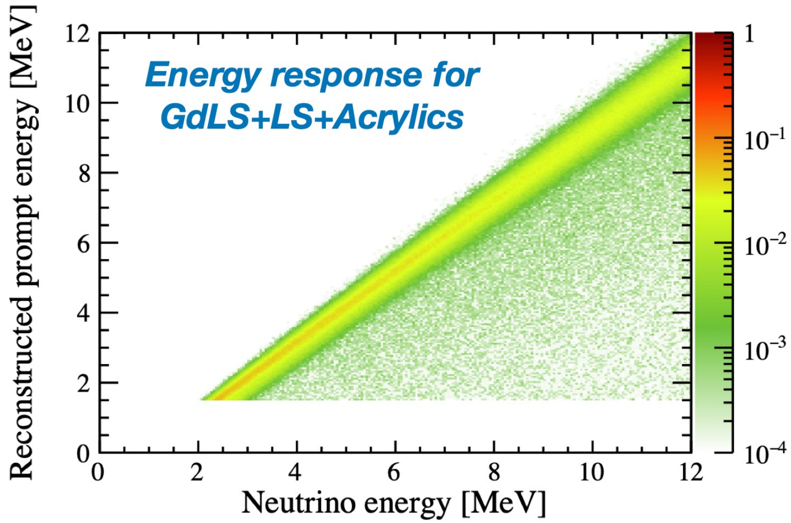
Latest nH Measurement at Daya Bay

- **New energy response model**
  - **Enable the first rate + shape analysis with nH-only sample**
  - Purpose: prediction of IBD spectrum and uncertainty study
  - Adding the non-linearities on deposited energy on step-by-step basis
  - Able to adjust each effect and study the resulted uncertainty

Simulated IBDs in LS volume

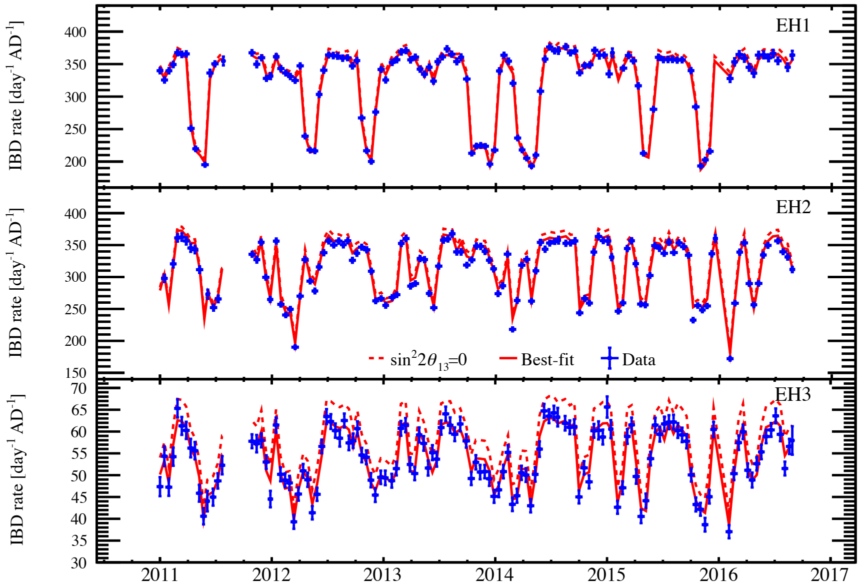


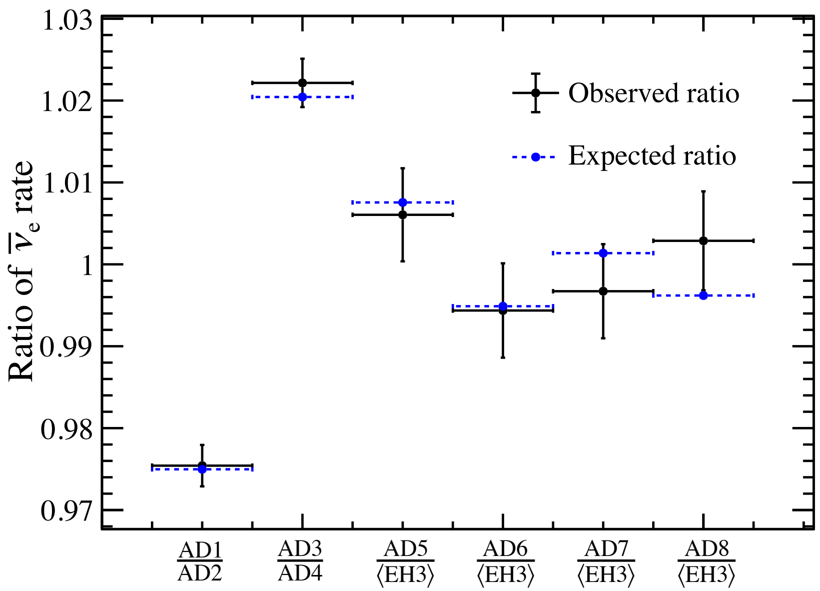
Adjusting Non-uniformities in Monte-Carlo according to Data



Latest nH Measurement at Daya Bay

- The identicalness among ADs is examined and used to evaluate the AD-uncorrelated uncertainties
- The total systematic uncertainty benefits from the larger statistics and new control techniques
    - Reduced from 0.57% to 0.34% in this result





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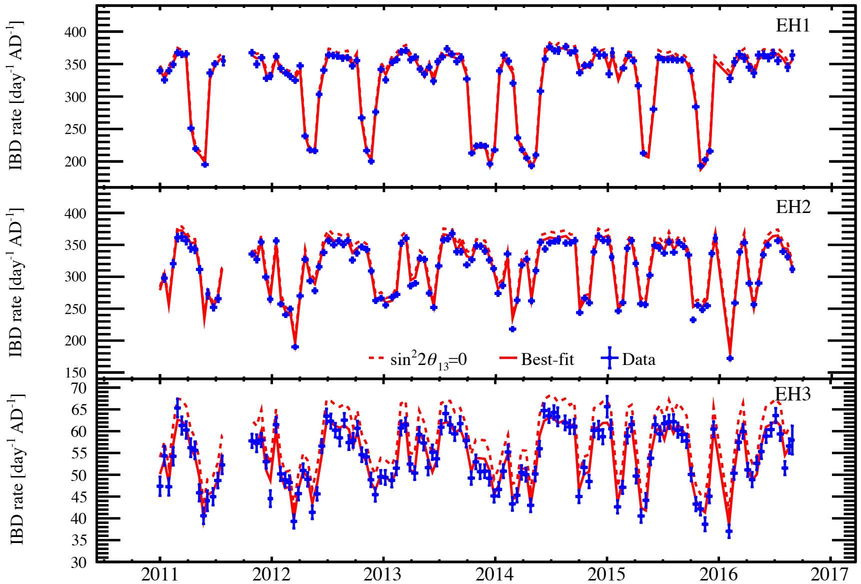
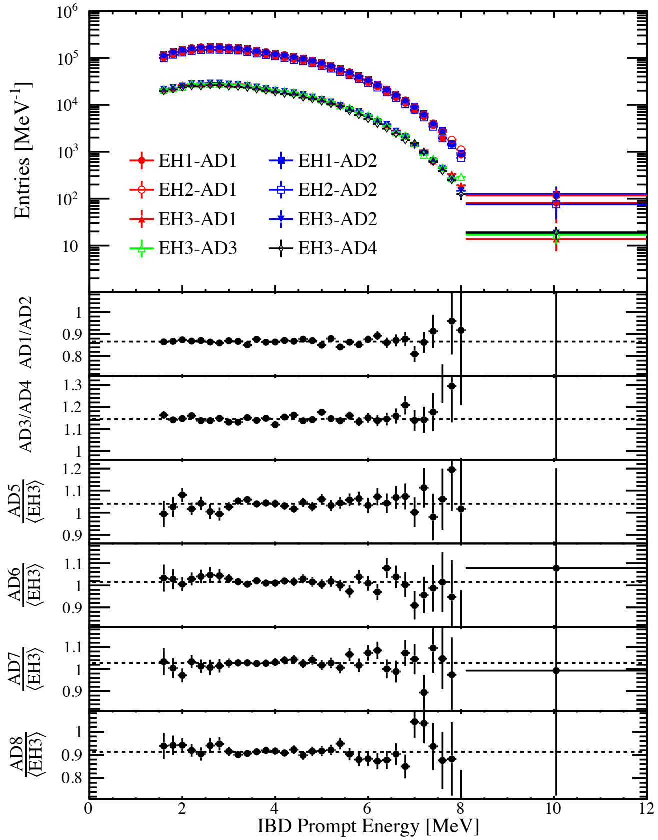
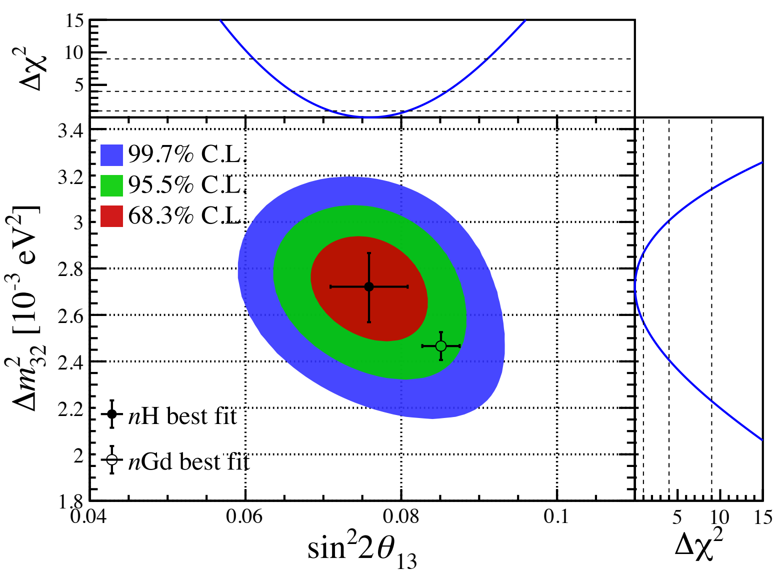
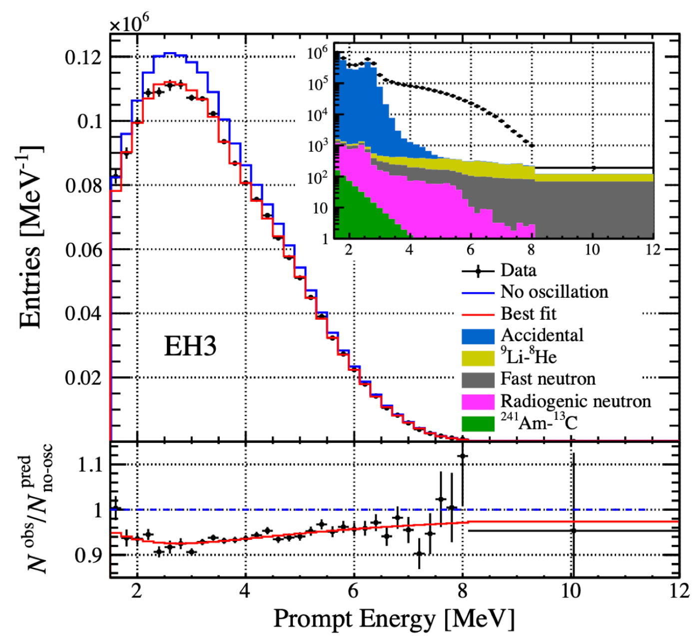




Latest nH Measurement at Daya Bay

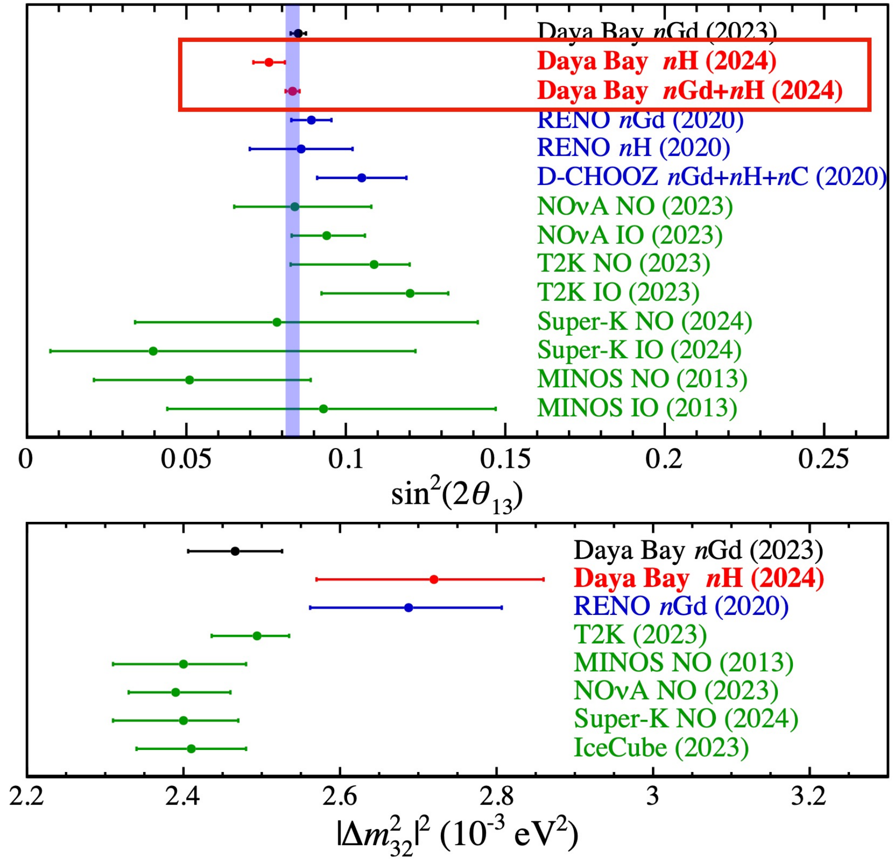
- The results with rate+shape analysis yield:
  - $\sin^2 2\theta_{13} = 0.0759^{+0.0050}_{-0.0049}$
    - From previous 15.5% precision to 6.6%
  - $\Delta m^2_{32} = 2.72^{+0.14}_{-0.15} \times 10^{-3}\ \mathrm{eV}^2$ [NO], $-2.83^{+0.15}_{-0.14} \times 10^{-3}\ \mathrm{eV}^2$ [IO]
- nGd+nH combined result for $\sin^2 2\theta_{13}$: 0.0833 ± 0.0022





Global Comparison

- **Daya Bay's nH measurement provides a $\sin^2 2\theta_{13}$ precision surpassed only by Daya Bay's nGd result**
  - Statistical uncertainty accounts for about 46% of the total
  - 8% improvement in nGd+nH result compared to nGd-only
- **nGd+nH leads to a precision measurement of $\sin^2 2\theta_{13}$, 2.6% precision**



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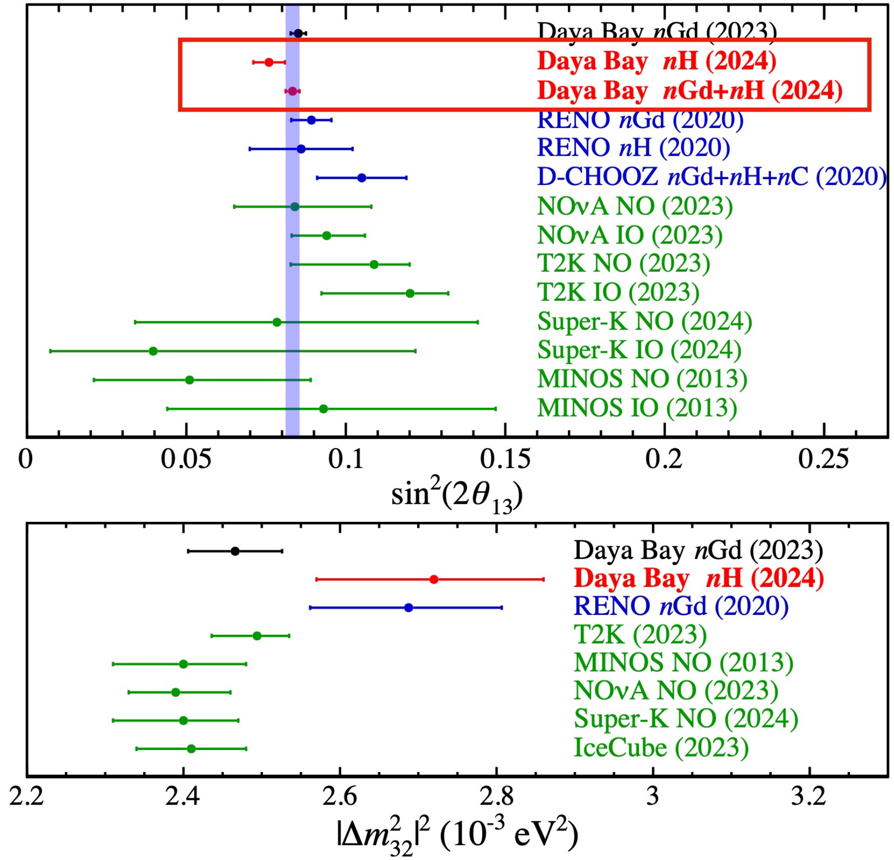
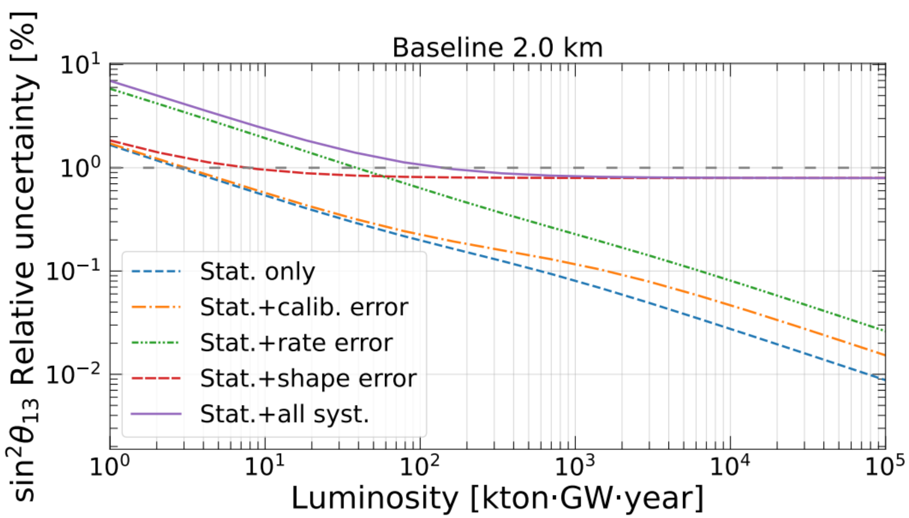
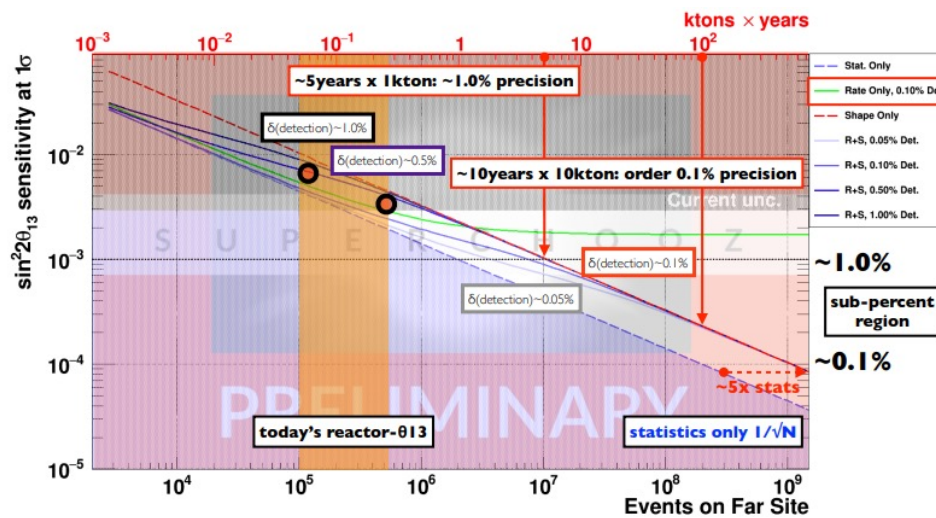
Consistent results from reactor and accelerator experiments



Improve Precision in $\sin^2 2\theta_{13}$ to <1%

- Two ways to improve $\sin^2 2\theta_{13}$ precision to <1%
- 1. Shape distortion 4kt LS detector at 2.0 km baseline
- 2. Rate deficit 10kt LiquidO detector at 1.1 km 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.

Summary

- Daya Bay, RENO, and Double Chooz all stopped data taking
  - Almost equal contributions from systematics and statistics
  - Side-by-side comparison at Daya Bay validated the systematics control
- Daya Bay leads the precision measurement of $\sin^2 2\theta_{13}$
  - and $|\Delta m^2_{32}|$ in reactor side
- Expecting more results
  - Full nH data set in Daya Bay and RENO, final results from Double Chooz
- In the future, precision improvement of $\sin^2 2\theta_{13}$ to <1% using either shape distortion or rate deficit is possible

谢谢！

Backup

Double Chooz's full data set

Detector	Run Time (days)	Factor To Nature Physics Dataset
Far Alone (Reactor-ON)	481.12	1.00
Far Alone (Reactor-OFF)	7.57	1.00
Far (Reactor-ON)	868.11	**2.26**
Near (Reactor-ON)	788.73	**2.28**
Far (Reactor-OFF)	23.54	**NEW**
Near (Reactor-OFF)	23.12	**NEW**

Double Chooz's full data set