# Overview of precise measurements of reactor neutrino oscillation parameters

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COUSP, May 8, 2024

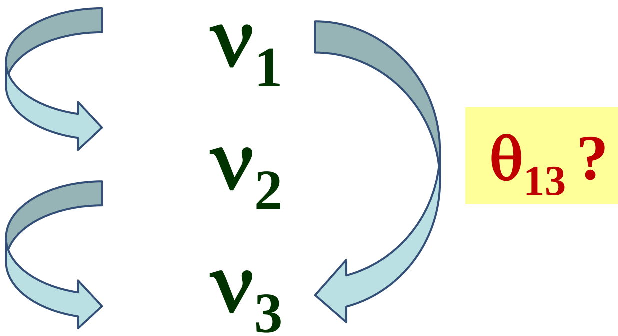
# $\theta_{13}$ for neutrino oscillation

- Neutrino mixing matrix:

$$U=\begin{pmatrix}1&0&0\\0&c_{23}&s_{23}\\0&-s_{23}&c_{23}\end{pmatrix}\begin{pmatrix}c_{13}&0&s_{13}e^{-i\delta_{CP}}\\0&1&0\\-s_{13}e^{i\delta_{CP}}&0&c_{13}\end{pmatrix}\begin{pmatrix}c_{12}&s_{12}&0\\-s_{12}&c_{12}&0\\0&0&1\end{pmatrix}\begin{pmatrix}e^{i\eta_1}&0&0\\0&e^{i\eta_2}&0\\0&0&1\end{pmatrix}$$

**Solar ν Oscillation**
**$\sin^2 2\theta_{12} \sim 0.9$**

**Atm. ν Oscillation**
**$\sin^2 2\theta_{23} \sim 1$**




- Key to complete the picture of the neutrino oscillation; a fundamental parameter of the standard model (SM)
- Important for future neutrino experiments: mass ordering and CP phase $\delta_{CP}$
- Search for new physics beyond SM; test of leptonic unitarity

# $\theta_{13}$ measurement in the past

- Palo Verde & Chooz: no signal

$\sin^2 2\theta_{13} < 0.12$ @ 90%C.L.
if $\Delta m^2_{23} = 0.0024\ eV^2$

- T2K: 2.5 σ over background

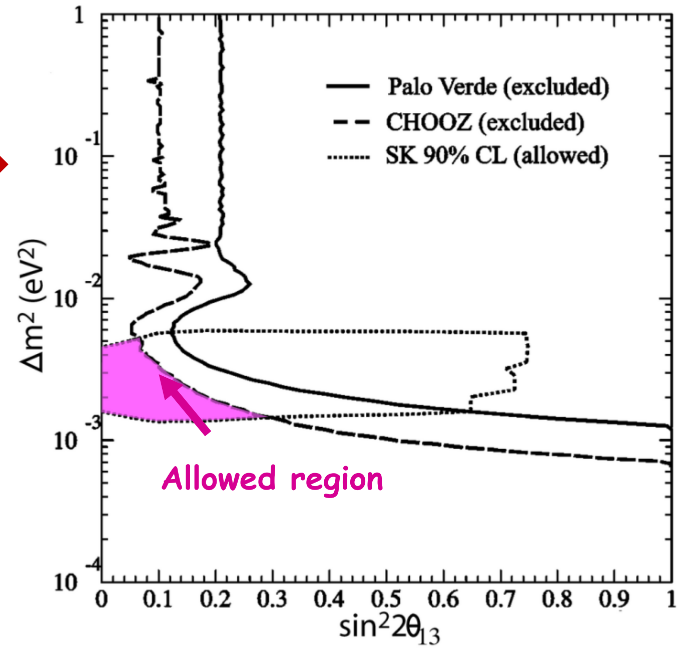
$0.03 < \sin^2 2\theta_{13} < 0.28$ @ 90%C.L. for NO
$0.04 < \sin^2 2\theta_{13} < 0.34$ @ 90%C.L. for IO

- MINOS: 1.7 σ over background

$0 < \sin^2 2\theta_{13} < 0.12$ @ 90%C.L. NO
$0 < \sin^2 2\theta_{13} < 0.19$ @ 90%C.L. IO

- Double Chooz: 1.7 σ

$\sin^2 2\theta_{13} = 0.086 \pm 0.041(stat.) \pm 0.030(sys.)$



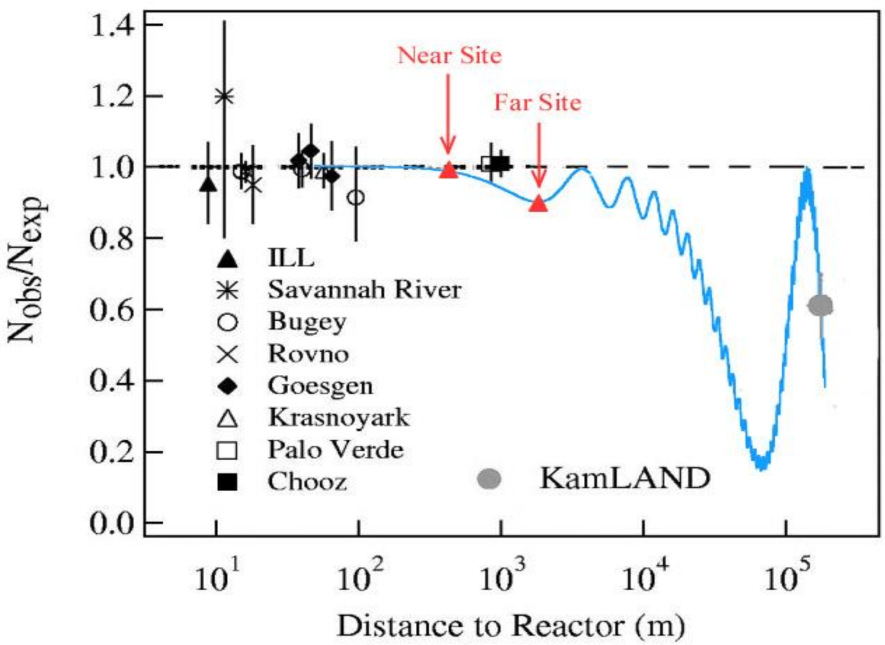

From Yifang' report in 2012

# Challenges for $\theta_{13}$ measurement

- **Reactor antineutrino survival probability:**

$$P_{sur} = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} - \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{13} + \sin^2\theta_{12}\sin^2\Delta_{32})$$

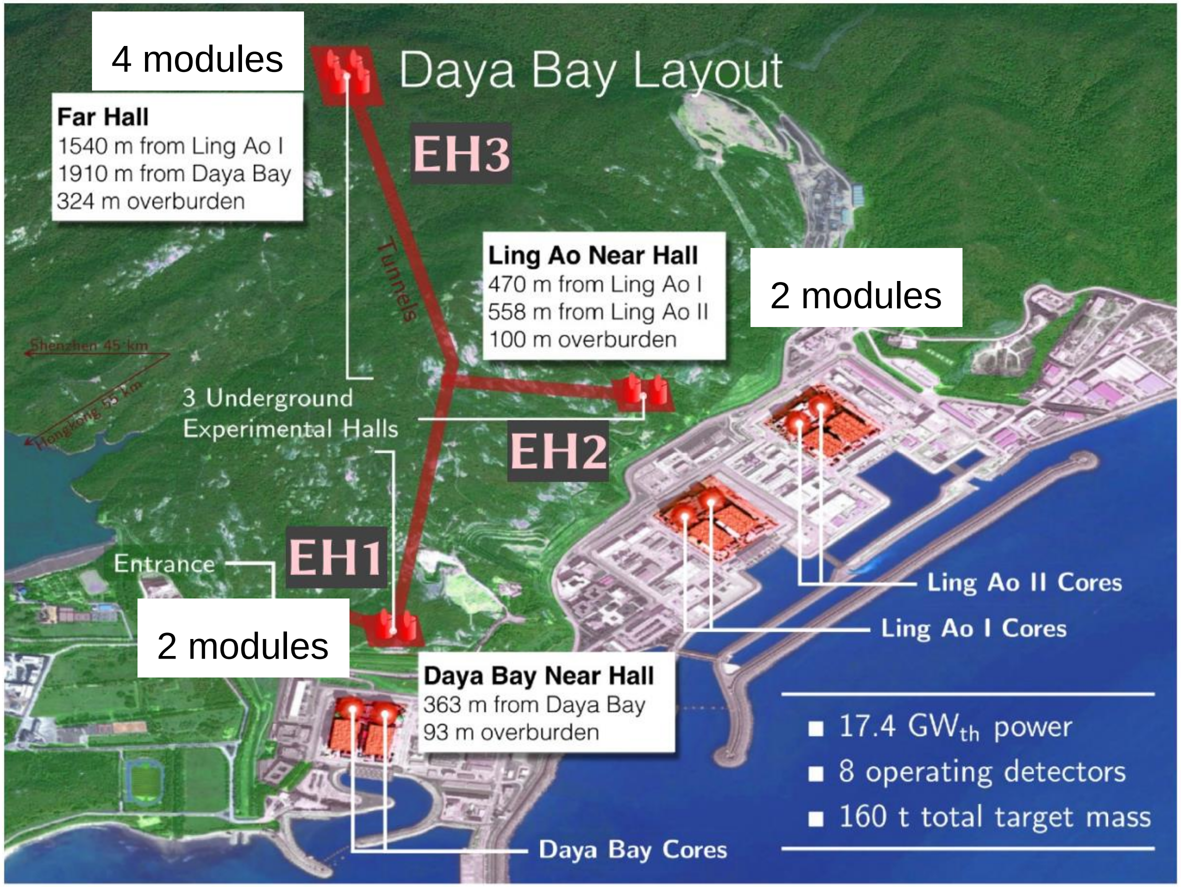
$$\Delta_{ij} = \Delta m^2_{ij}\frac{L}{4E}$$




- **Rate deficit by $\theta_{13}$ ~ 5%**
- **Precision of past experiments ~ 4%:**
  - Reactor related ~ 3%
  - Detection related ~ 2%
  - Background ~ 2%

**Same order of magnitude with rate deficit**

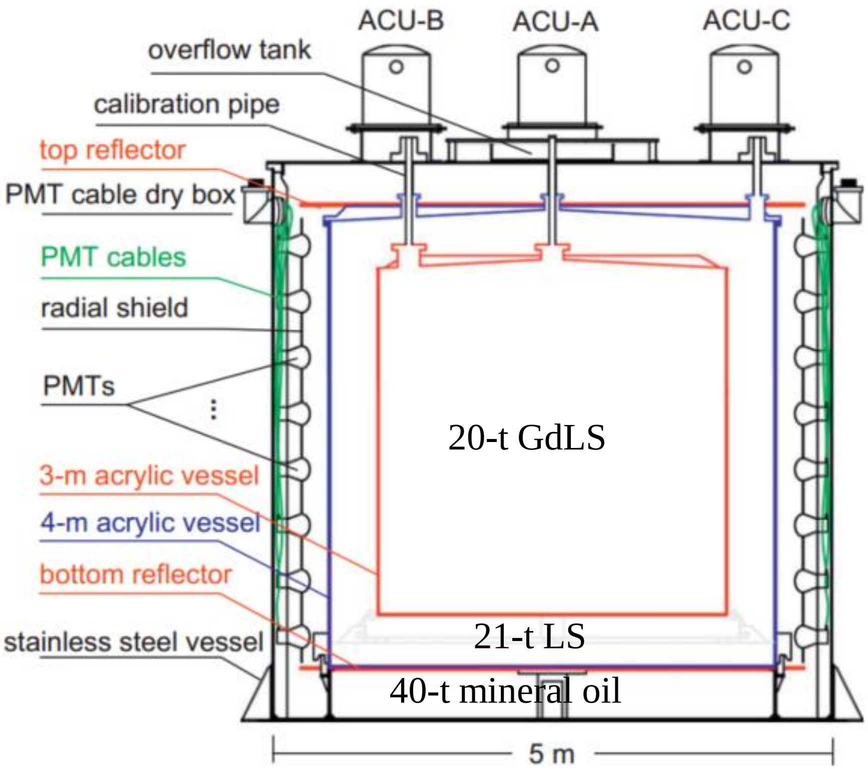
# Daya Bay experiment: concept




- Relative measurement (far over near) to cancel correlated systematic errors
- Multiple modules to reduce uncorrelated systematic errors
- Sensitivity goal of $\sin^2 2\theta_{13}$: 0.01 @ 90% C.L.

# Daya Bay: antineutrino detector (AD)

NIM A773 (2015) 8; NIM A811 (2016) 133




- 0.1% Gd-loaded liquid scintillator (GdLS) as target
- liquid scintillator (LS) as gamma catcher
- mineral oil (MO) as shielding

prompt, delayed

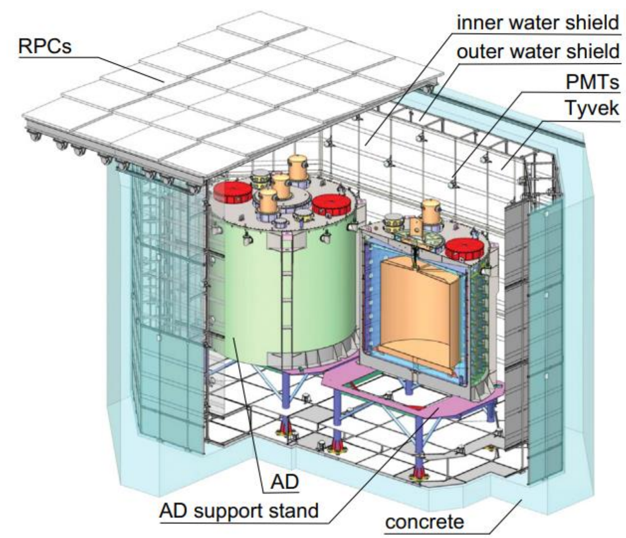
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

~180 μs: $\rightarrow + p \rightarrow d + \gamma\ (2.2\ \text{MeV})$

~30 μs for 0.1% Gd: $\rightarrow + Gd \rightarrow Gd^*$

$\hookrightarrow Gd + \gamma\text{'s}\ (\sim 8\ \text{MeV})$

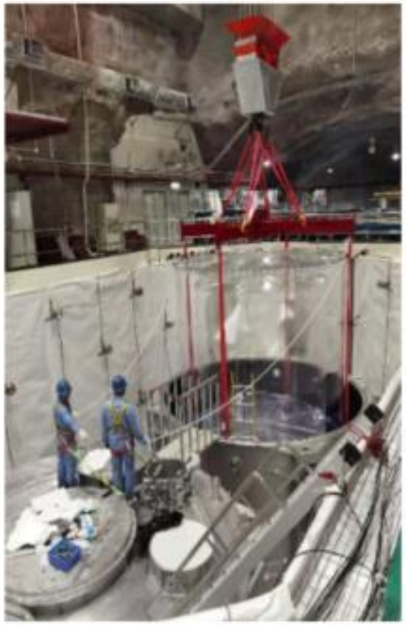
- Detect inverse β-decay reaction (IBD)




- Water pools provide shielding against cosmic-ray muons, secondary neutrons
- Providing a muon veto system via detection of Cherenkov light

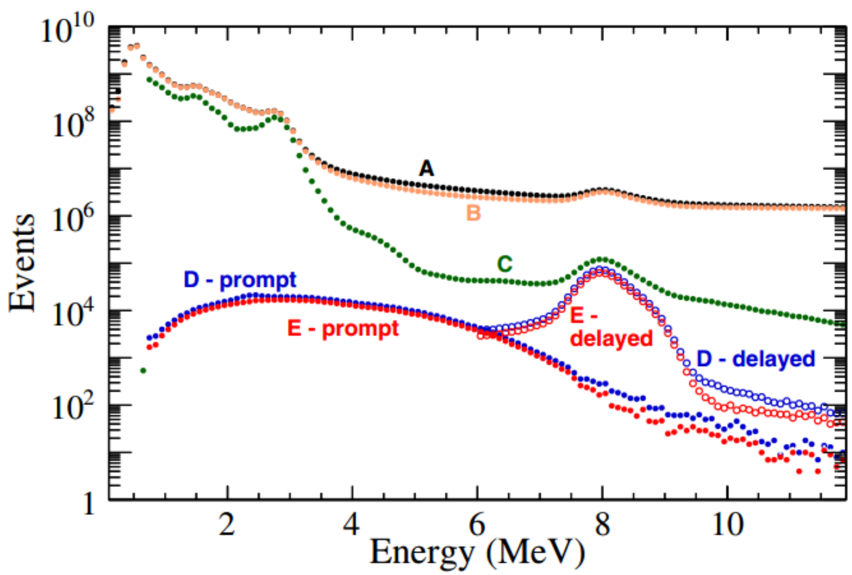
# Daya Bay: history of operation

- Detector commissioning on 15 August 2011
- Collection of physics data began on 24 Dec 2011
- Collection of physics data ended on 12 Dec 2020
- Decommissioning: 12 Dec 2020 – 31 Aug 2021

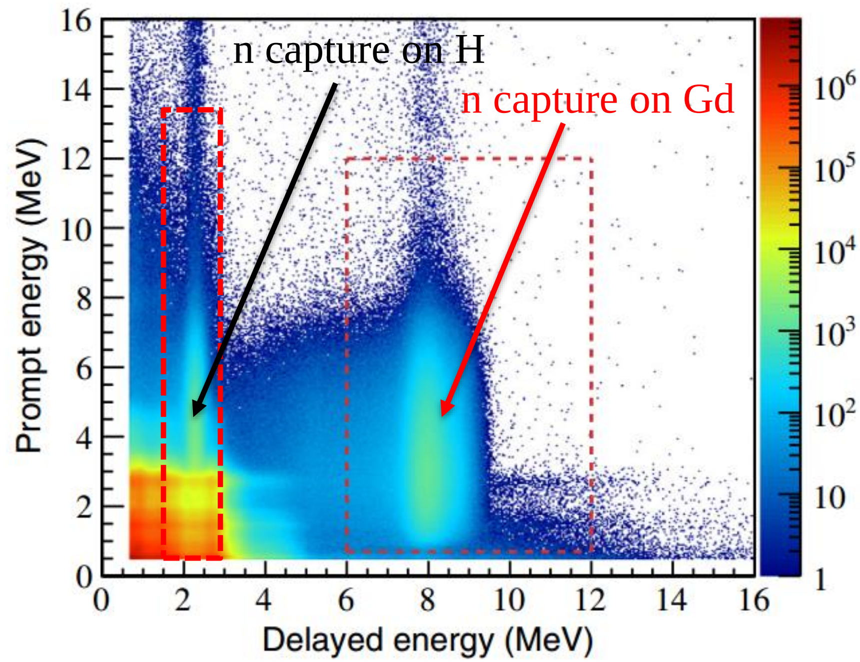


# Daya Bay: IBD candidate selection

- Remove flashing PMT events
- Veto muon events
- Require 0.7 MeV < $E_{prompt}$ < 12 MeV, 6 MeV < $E_{delayed}$ < 12 MeV
- Neutron capture time: 1 μs < Δt < 200 μs
- Multiplicity cut: select time-isolated energy pairs




From DYB, PRD 95, 072006 (2017)



# Daya Bay: efficiency and uncertainty

## Detection efficiency

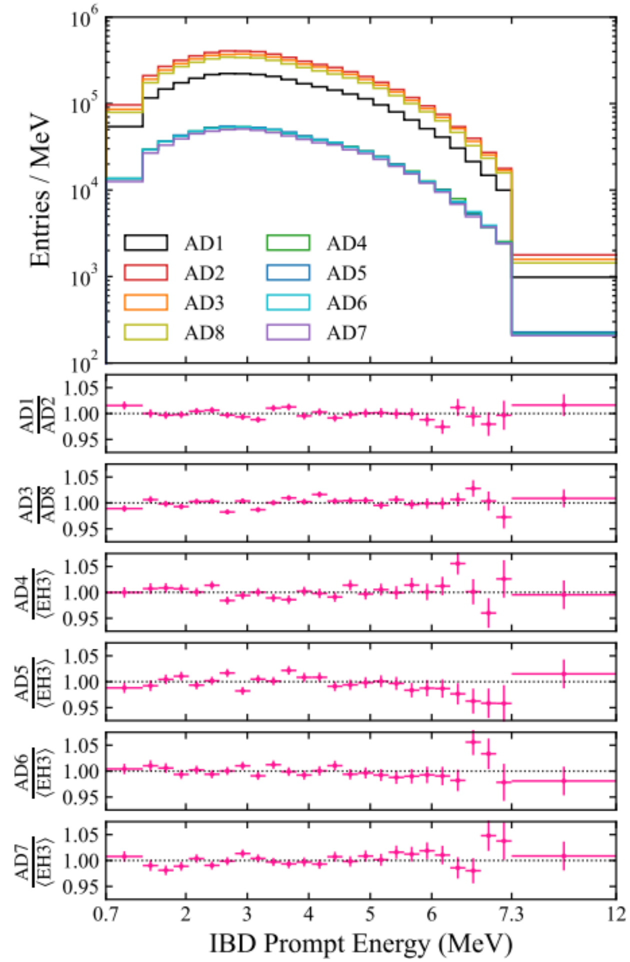
| | Efficiency | Correlated | Uncorrelated |
|---|---|---|---|
| Target protons | - | 0.92% | 0.03% |
| Flasher cut | 99.98% | 0.01% | 0.01% |
| Delayed energy cut | 92.7% | 0.97% | 0.08% |
| Prompt energy cut | 99.8% | 0.10% | 0.01% |
| Multiplicity cut | | 0.02% | 0.01% |
| Capture time cut | 98.7% | 0.12% | 0.01% |
| Gd capture fraction | 84.2% | 0.95% | 0.10% |
| Spill in | 104.9% | 1.00% | 0.02% |
| Live time | - | 0.002% | 0.01% |
| Combined | 80.6% | 1.93% | 0.13% |

## Reactor-related

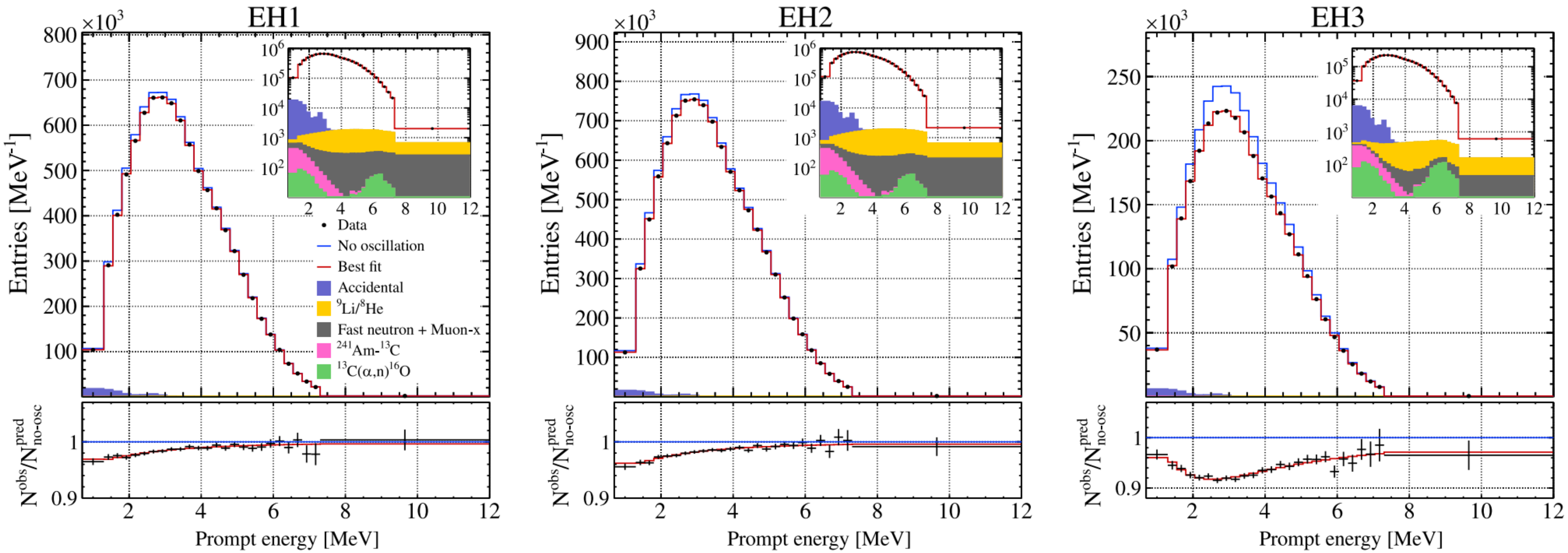
| correlated | | uncorrelated | |
|---|---|---|---|
| energy/fission | 0.2% | power | 0.5% |
| IBD reaction/fission | 3% | fission fraction | 0.6% |
| | | spent fuel | 0.3% |
| combined | 3% | combined | 0.8% |

From DYB, PRD 95, 072006 (2017)

## Side-by-side comparison



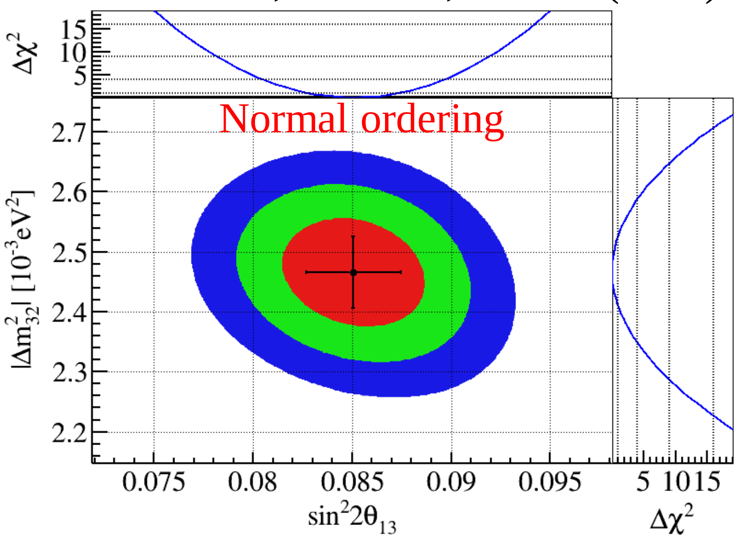
# Daya Bay: signal & background




| | EH1/2 | | EH3 | |
|---|---|---|---|---|
| | B/S | ΔB/S | B/S | ΔB/S |
| **Accidentals** | **~1.4%** | **<0.01%** | **~4.5%** | **~0.04%** |
| **Fast neutron** | **~0.14%** | **~0.08%** | **~0.06%** | **~0.06%** |
| **$^8$He/$^9$Li** | **~0.4%** | **~0.2%** | **~0.2%** | **~0.15%** |
| **Am-C** | **~0.03%** | **~0.03%** | **~0.28%** | **~0.28%** |
| **$^{13}$C(α,n)$^{16}$O** | **~0.01%** | **<0.01%** | **~0.04%** | **~0.02%** |
| **Sum** | **1.9%** | **0.22%** | **5.1%** | **0.3%** |

# Daya Bay: latest oscillation results

DYB, PRL 130, 161802 (2023)




**Best-fit results:**

$$\sin^2 2\theta_{13} = 0.0851^{+0.0024}_{-0.0024}$$

**(2.8% precision)**

**Normal ordering (NO):**

$$\Delta m^2_{32} = +(2.466^{+0.060}_{-0.060}) \times 10^{-3}\mathrm{eV}^2$$

**(2.4% precision)**

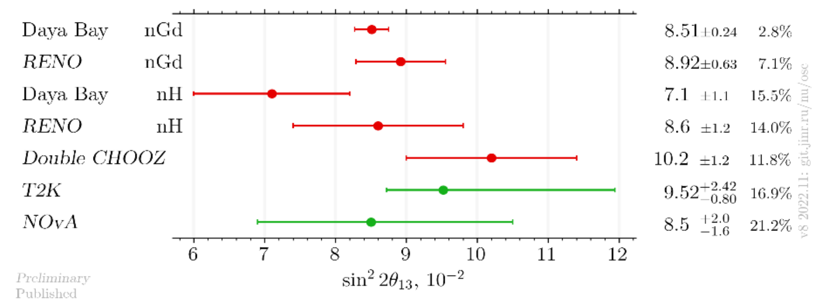
**Inverted ordering (IO):**

$$\Delta m^2_{32} = -(2.571^{+0.060}_{-0.060}) \times 10^{-3}\mathrm{eV}^2$$

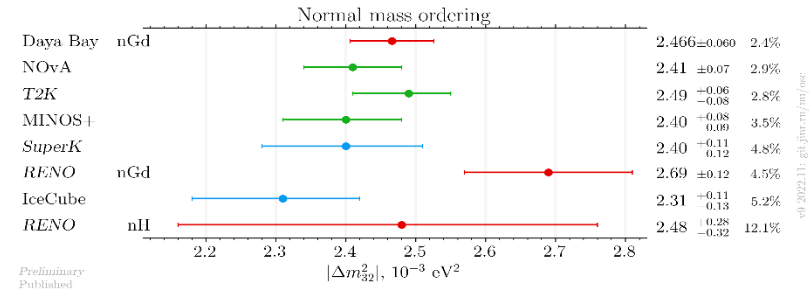
**(2.3% precision)**

$\chi^2/\mathrm{ndf} = 559/518$

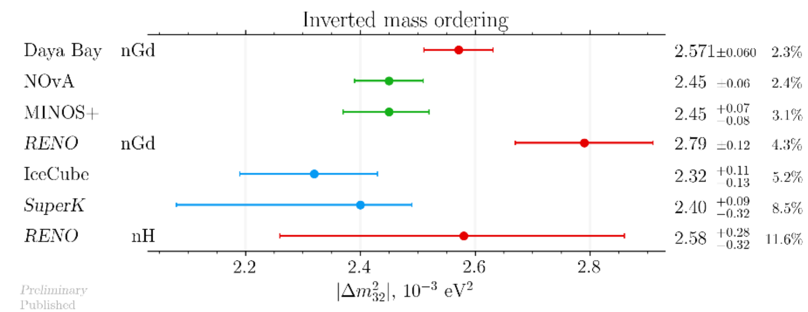
**$\sin^2 2\theta_{13}$**




**$\Delta m^2_{32}$ (NO)**




**$\Delta m^2_{32}$ (IO)**



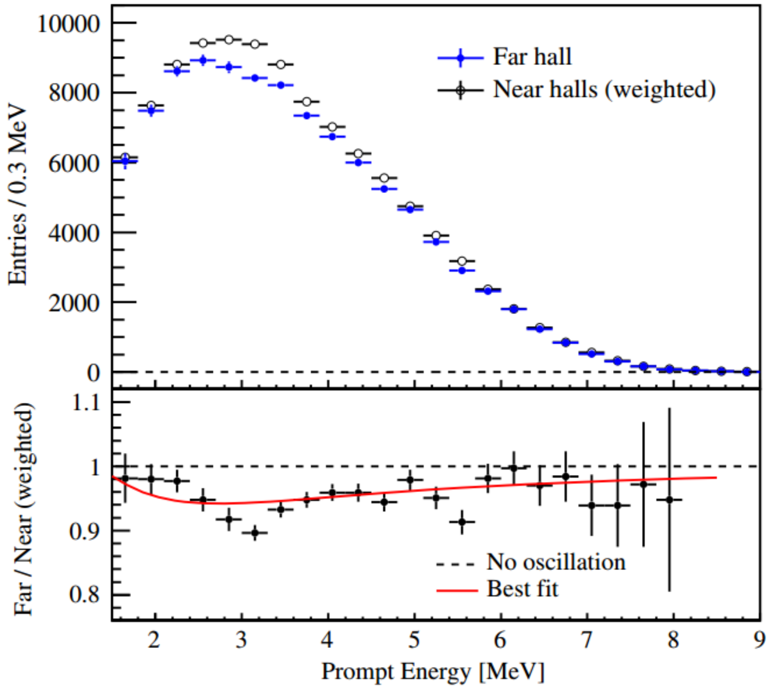
# Daya Bay: neutron capture on H

- Oscillation analysis via neutron capture on H provides powerful cross check
  - Statistically independent on neutron capture via Gd
- Secondary precise results in the world in the next twenty years

- Latest results using 621-days data:

$$\sin^2 2\theta_{13} = 0.071 \pm 0.011$$
$$\chi^2/NDF = 6.3/6$$

- Updated results with larger statistics exploiting rate deficit and shape distortion are under way
- Combined analysis of nGd and nH is in process



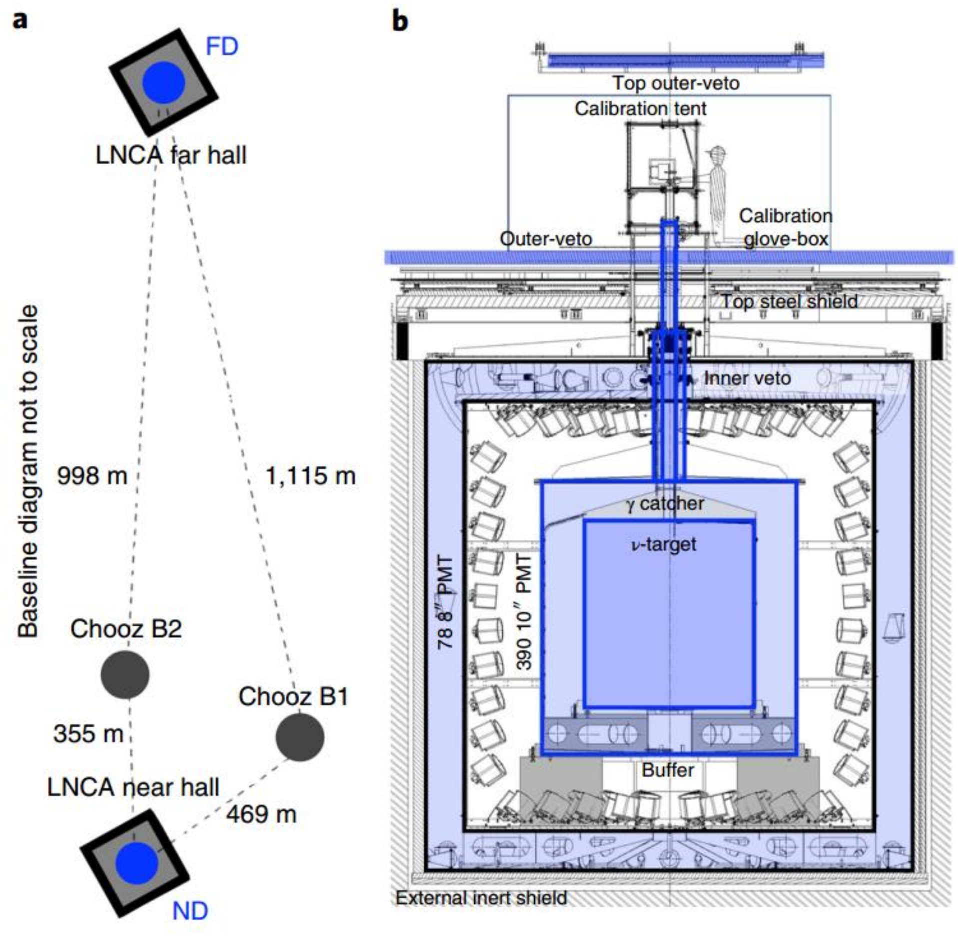

From DYB, PRD 93, 072011 (2016)

# Double Chooz

- Relative measurement
- Reactor power ~ 8.5 $GW_{th}$
- Baseline for far hall ~ 1050 m
- Overburden: near ~ 30 m, far ~ 100 m
- Only one modular in each hall
- Reactor-off mode (17 days): constrain bkg. better
- Analysis with nH, nC an nGd
- Best-fit with full data set:

$$\sin^2 2\theta_{13} = 0.105 \pm 0.014$$
$$\chi^2/NDF = 182/112$$

**(13% precision)**




From Double Chooz, Nat. Phys. 16, 558 (2020)

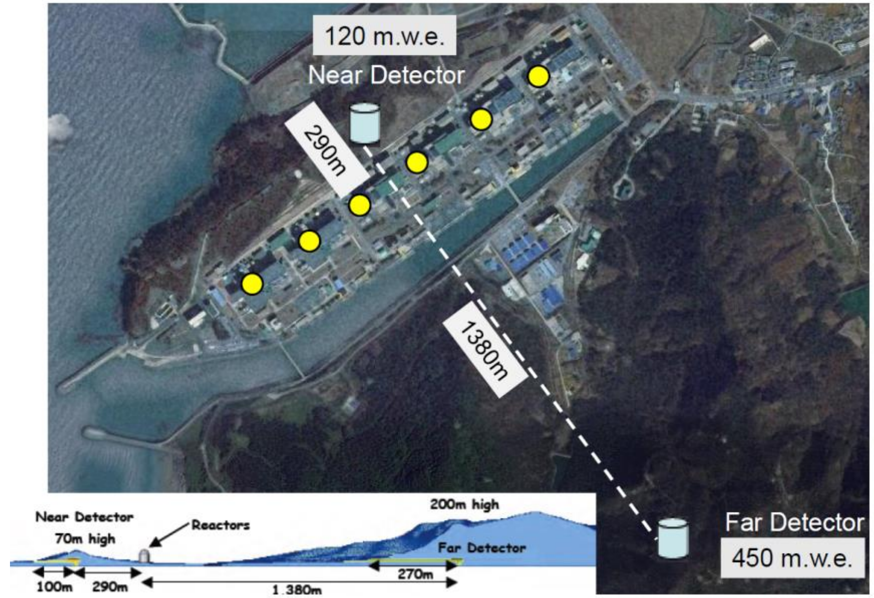
# RENO

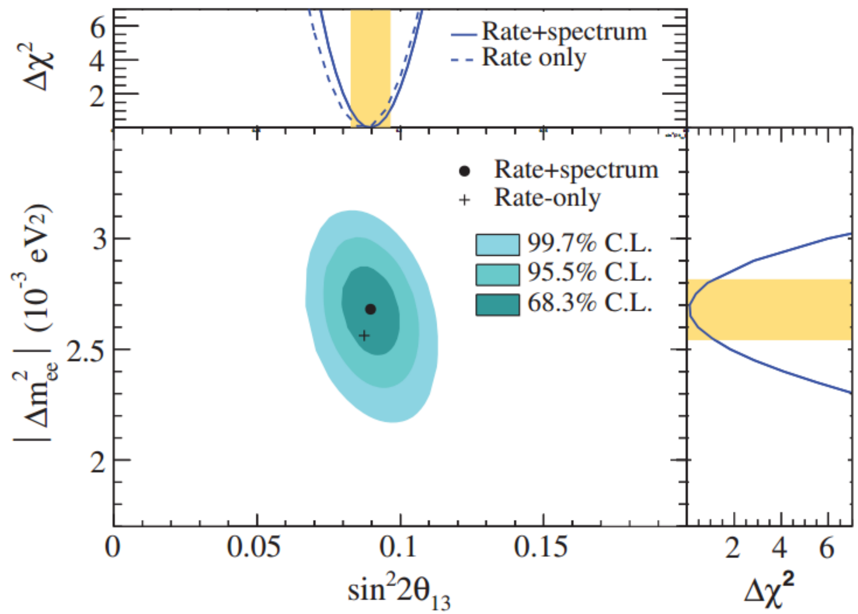
From RENO, PRL 121, 201801 (2018)

- Relative measurement
- Reactor power ~ 16.5 $GW_{th}$
- Baseline for far hall ~ 1380 m
- Overburden: near ~ 120 m, far ~ 450 m
- Only one modular in each hall
- Three optically coupled volumes
- Best-fit with full data set:

$$\sin^2 2\theta_{13} = 0.0896 \pm 0.0068$$
$$\chi^2/\mathrm{NDF} = 47.4/66$$

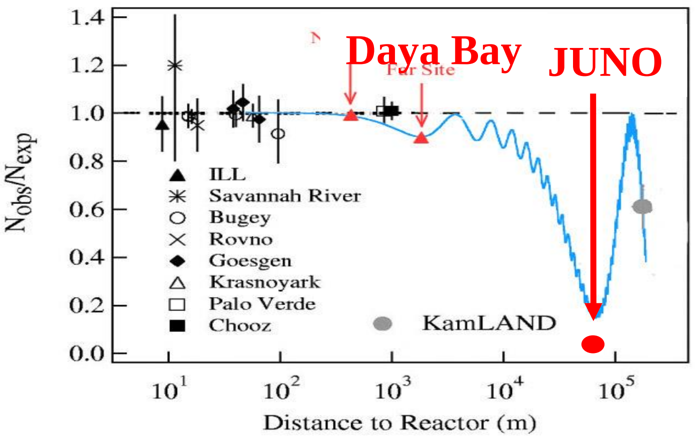
**(7.6% precision)**

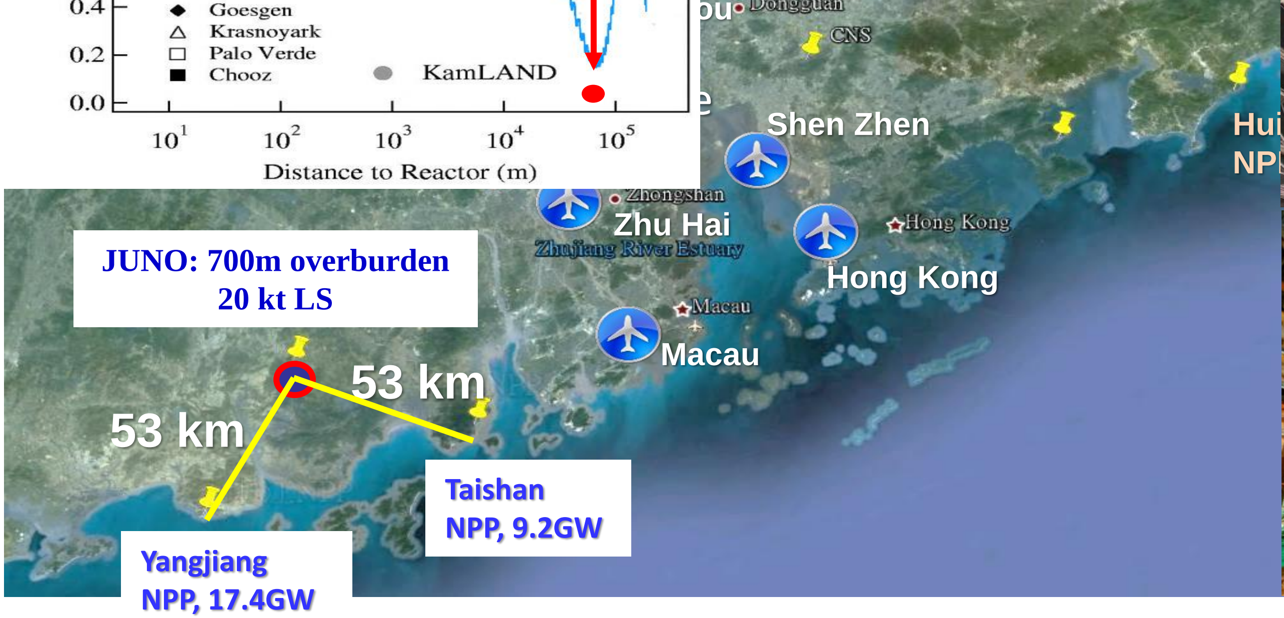


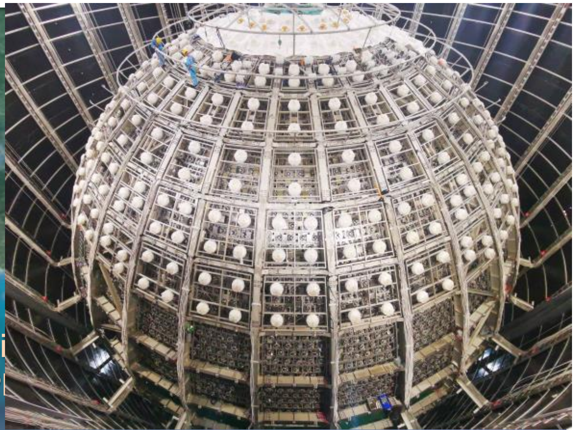



# Future measurement: JUNO

- Mian goal: determine neutrino mass ordering



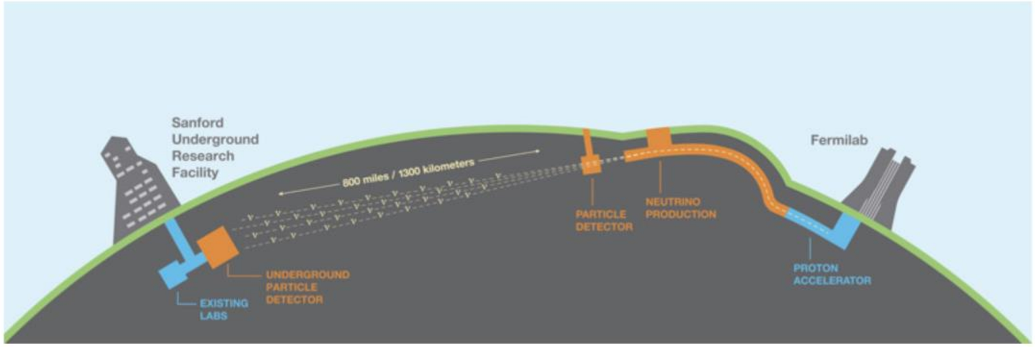
| | Central Value | PDG2020 | 100 days | 6 years | 20 years |
|---|---|---|---|---|---|
| $\sin^2\theta_{13}$ | 0.0218 | ±0.0007 (3.2%) | ±0.010 (47.9%) | ±0.0026 (12.1%) | ±0.0016 (7.3%) |

From JUNO, CPC 46, 123001 (2022)

# Future measurement: DUNE

From DUNE, JINST 15, T08008 (2020)

- Detect accelerator neutrino
- Liquid argon TPC
- 40 kton fiducial mass
- Baseline: 1300 km



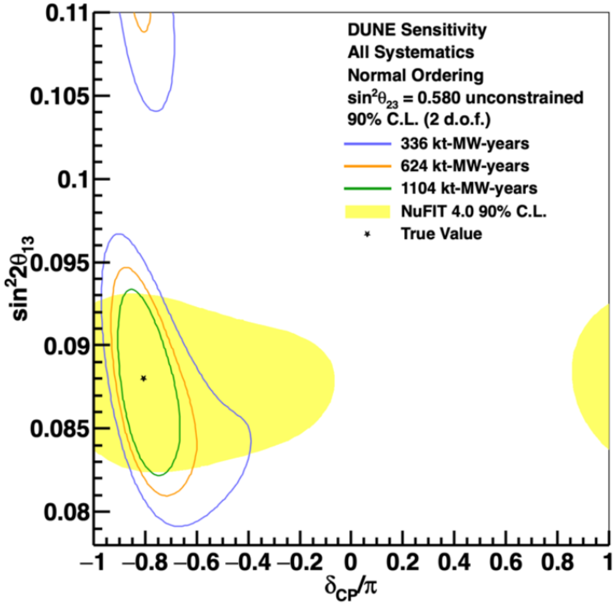

**Goal:**

a) Measure $\delta_{CP}$

b) Determine neutrino mass ordering

c) Measure other oscillation parameters including $\theta_{13}$ with precision similar to the reactor neutrino experiments

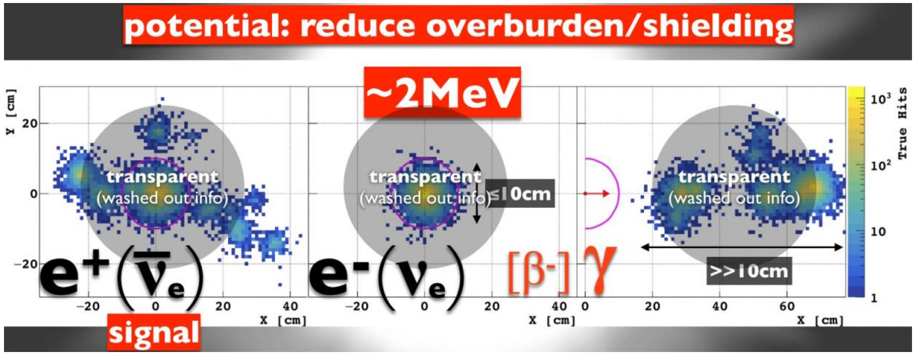
**(~6.3% precision@1104 kt·MW·years)**

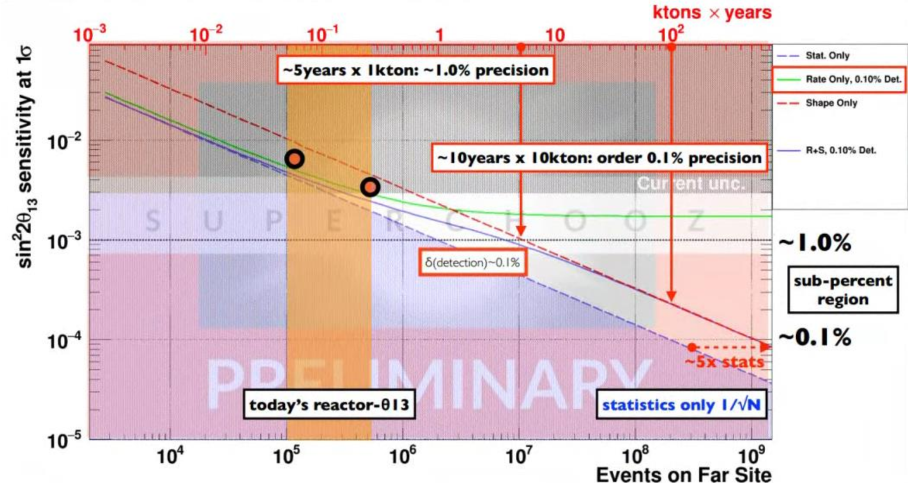



From arXiv:2203.06100 (2022)

# Future measurement: SuperChooz

- **Invitation of sub-percent precise measurement:**
  - ➢ Unitarity test of PMNS matrix
  - ➢ Reduce phase space of other experiments: 0$\nu$bb, $\delta_{CP}$, …
- **LiquidO detector**
  - ➢ Vertex reconstruction ~ 1 cm
  - ➢ PID: $e^+$, $e^-$, $\gamma$
  - ➢ Tracking, directional
- **Thermal power ~ 8.4 GW**
- **Near-far measurement**
- **Under exploration**

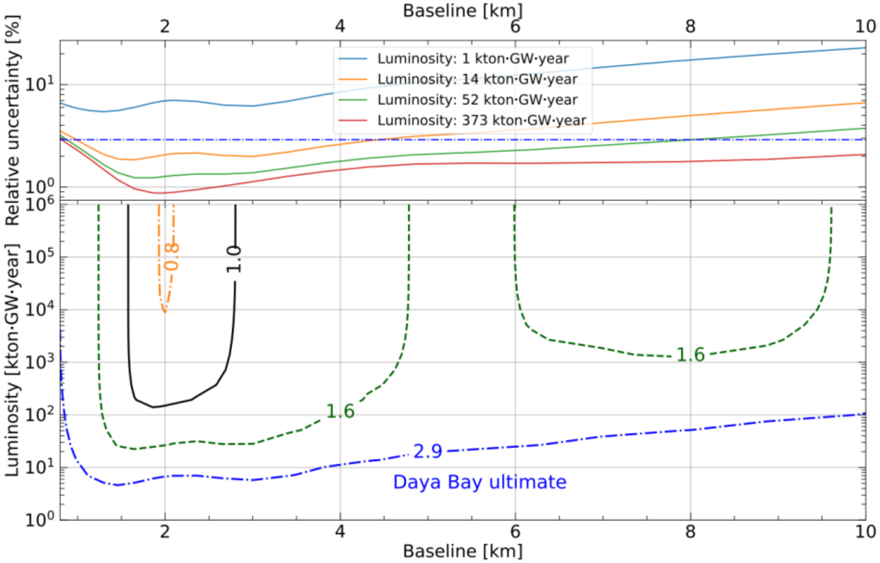


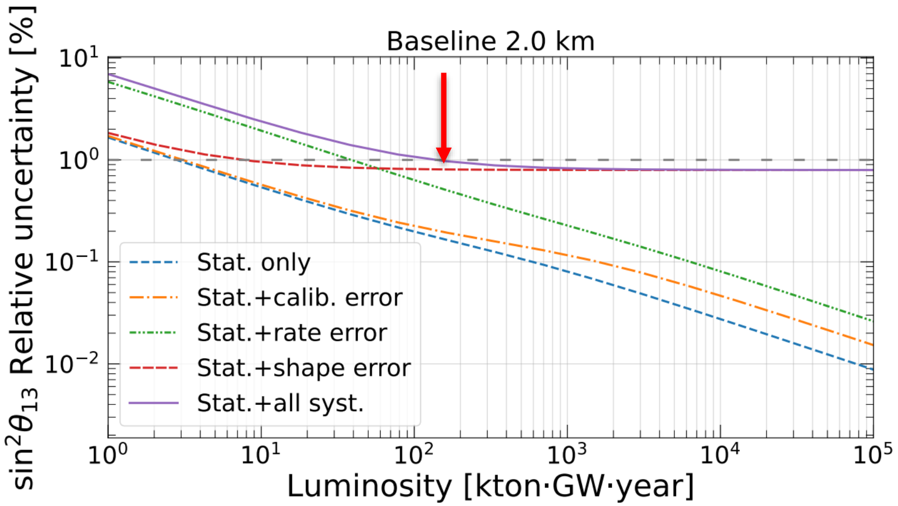




From A. Cabrera, Neutrino2022

# Future measurement: others

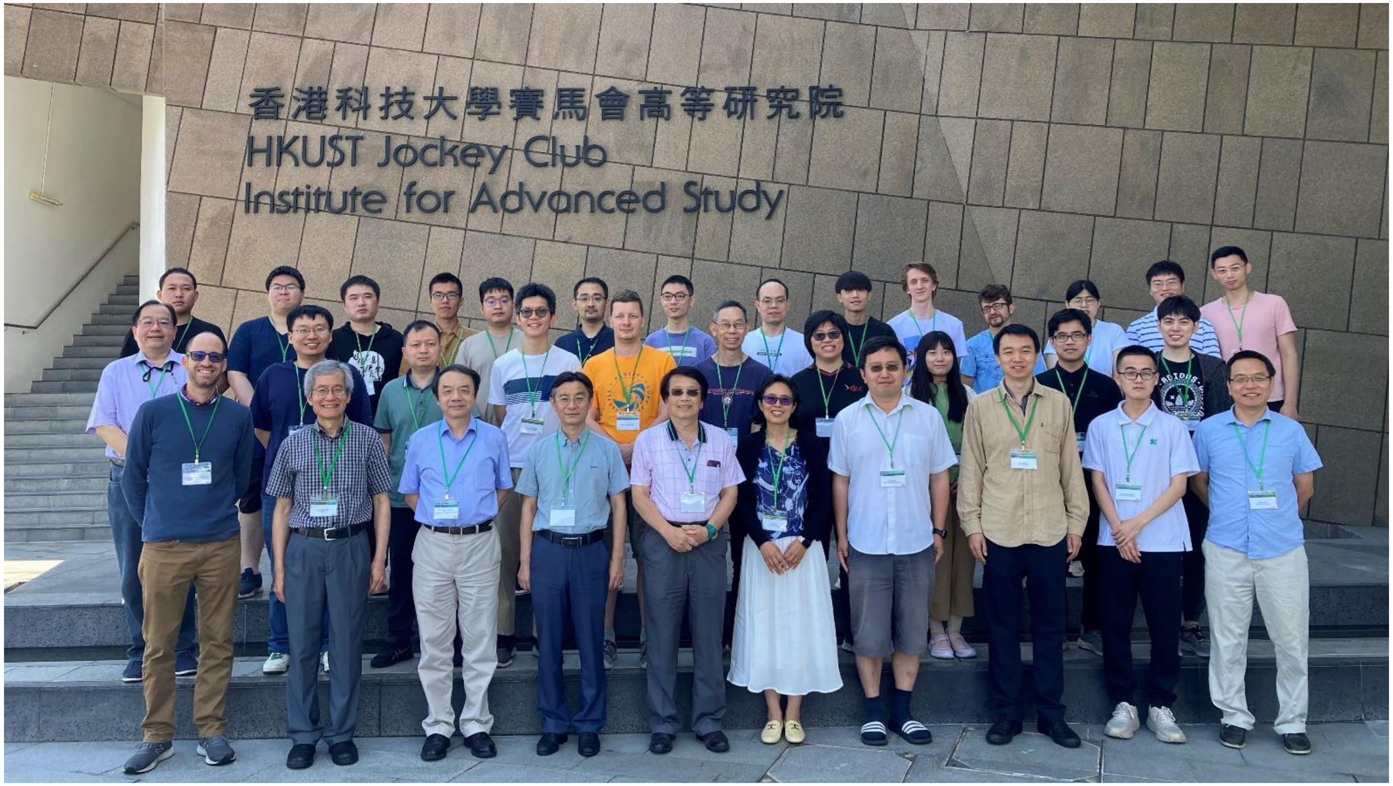
- Single detector
- Liquid scintillator
- Baseline ~ 2 km
  - ➢ Offset the baseline from the oscillation maximum
- Luminosity ~ 150 kton·GW·year
  - ➢ Mass ~ 4 ktons
  - ➢ Reactor power ~ 9.2 GW
  - ➢ Data taking ~ 4 years
- Energy resolution ~ 10%
- Shape error is dominated




From J. N. Zhang and J. Cao, JHEP 03 (2023), 072

# The Daya Bay collaboration

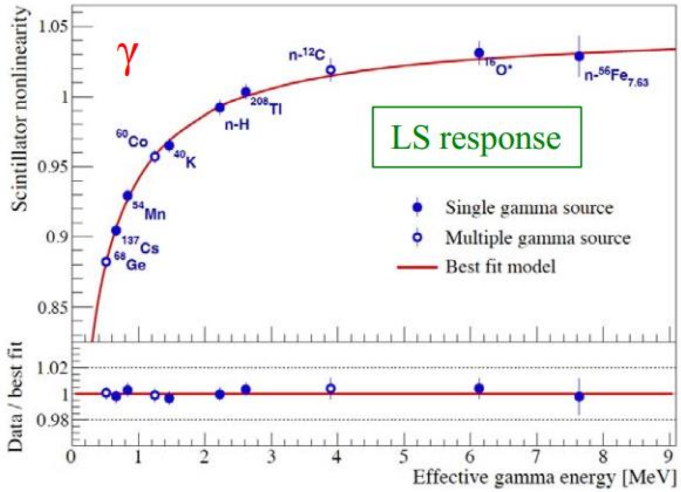


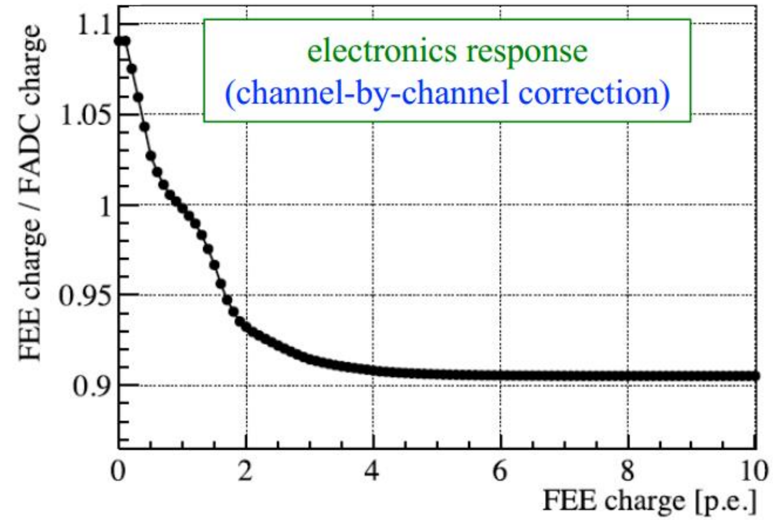

# Thank you!

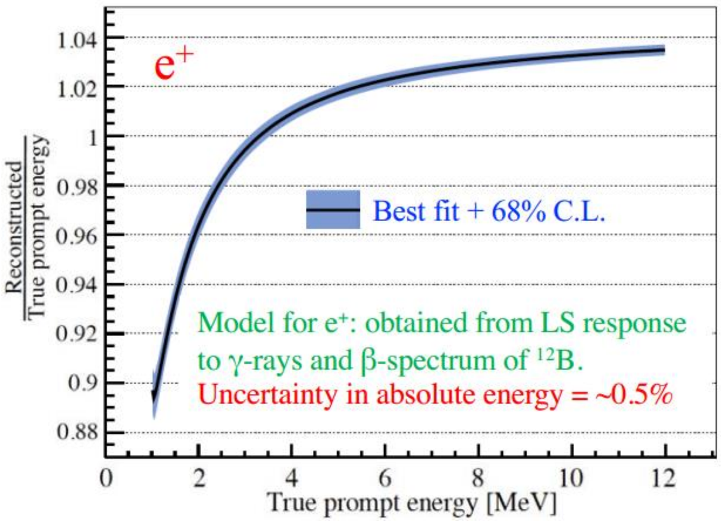
# Backup

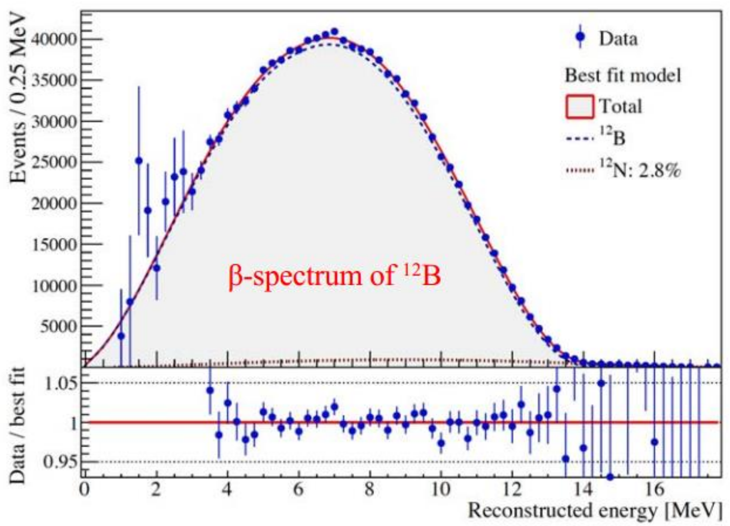
# Daya Bay: energy calibration

NIM A**940** (2019) 230



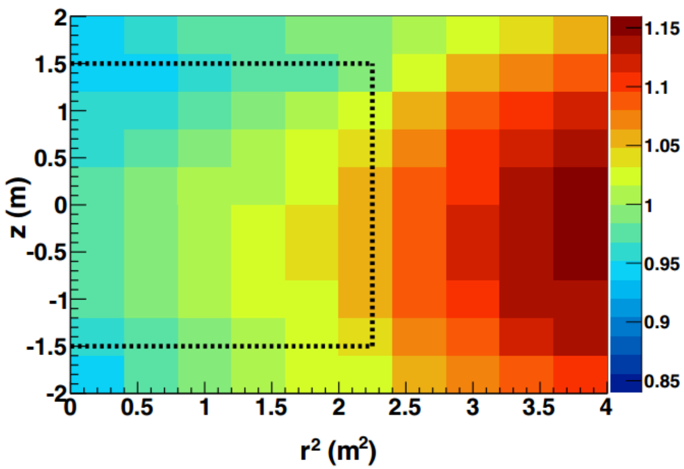



# Daya Bay: event reconstruction

- **Reconstruction of event energy:**

$$E_{\text{rec}} = \left( \sum_i \frac{Q_i}{\bar{Q}_i^{\text{SPE}}(t)} \right) \frac{f_{\text{act}}(t)}{N^{\text{PE}}(t)} f_{\text{pos}}(\mathbf{r}_{\text{rec}}, t),$$

- **Non-uniformity of energy response**



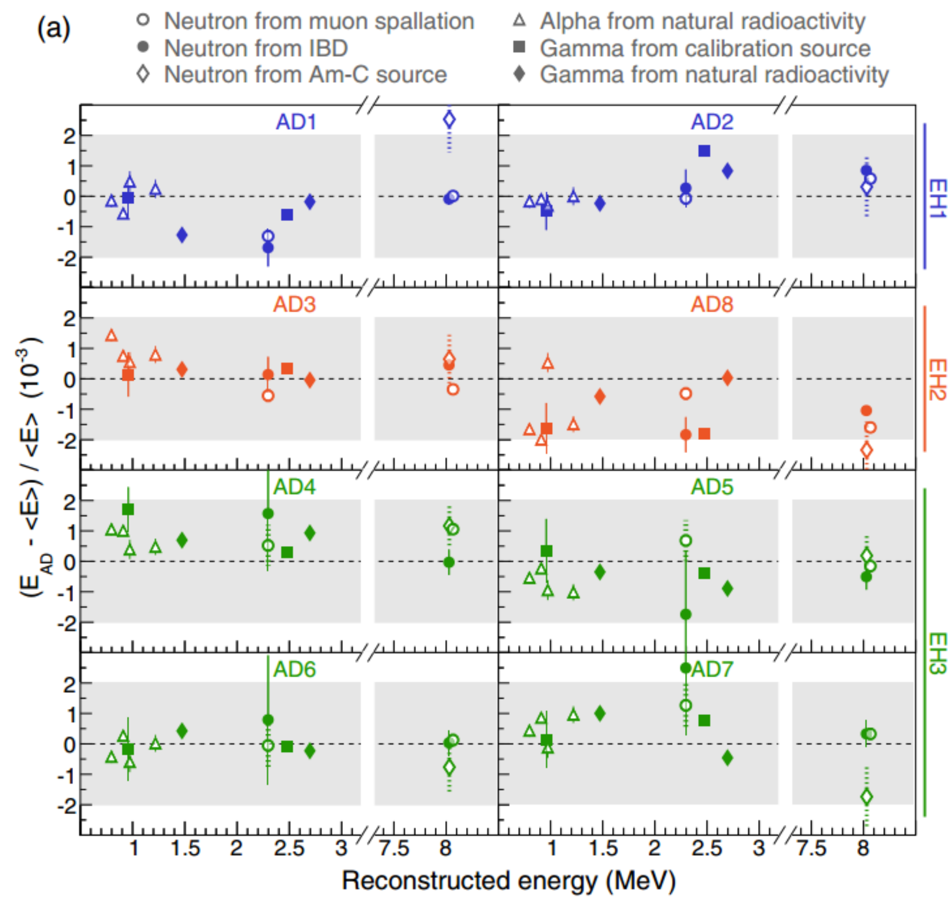

- **Energy resolution:**

$$\frac{\sigma_E}{E_{\text{rec}}} = \sqrt{a^2 + \frac{b^2}{E_{\text{rec}}} + \frac{c^2}{E_{\text{rec}}^2}}.$$

a = 0.016, b = 0.081 $\text{MeV}^{1/2}$, and c = 0.026 MeV

~ 8.7% @ 1 MeV

- **Study of relative energy scale error**




From DYB, PRD 2017