Latest results from Daya Bay experiment based on full dataset

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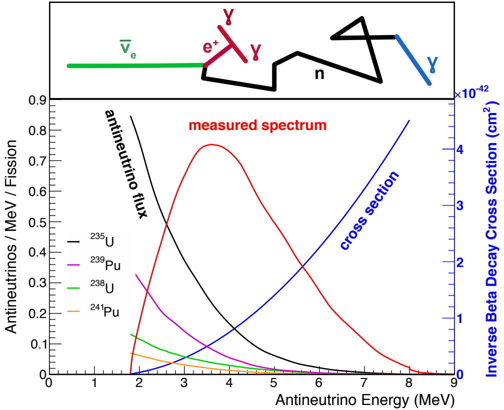
on behalf of the Daya Bay Collaboration

ICPPA-2024

23 October 2024

Neutrinos
Oscillation and etc.

- Neutrino flavor oscillates with distance
$$(\nu_{e,\mu,\tau} \rightarrow \nu_x)$$
- Oscillation can be studied at accelerators, Sun, and nuclear power plants
- Nuclear reactors are the most intensive artificial source of antineutrinos ($10^{20}\ \overline{\nu}_e$/sec/GWt)
- Energies of $\overline{\nu}_e$ is bellow 12 MeV, it allows to measure survival probability of $\overline{\nu}_e$



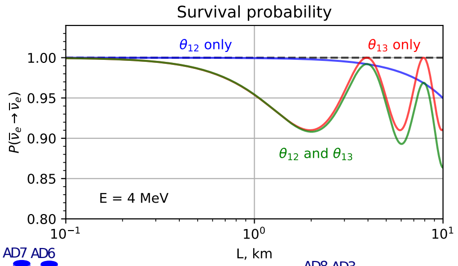
Daya Bay Reactor Antineutrino Experiment

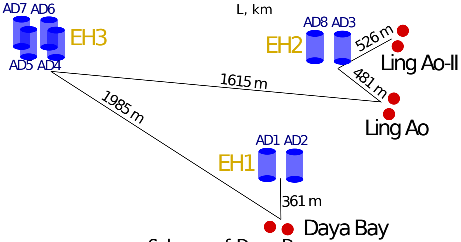
Overview

- Experiment was taking data from December 2011 to December 2020
- It has accumulated $\sim 5 \cdot 10^6$ events
- One of the main goals is precision measurement of $\sin^2 2\theta_{13}$ and Δm^2_{32}
- Search for sterile neutrinos, high energy reactor antineutrinos ($E > 10$ MeV), measurement of ^{235}U and ^{239}Pu spectra

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

$$\Delta m^2_{ee} = \cos^2\theta_{12}\Delta m^2_{31} + \sin^2\theta_{12}\Delta m^2_{32}$$





Schema of Daya Bay

- Liquid scintillator doped with Gd (0.1%)
- 192 8" PMT
- IBD – inverse β-decay

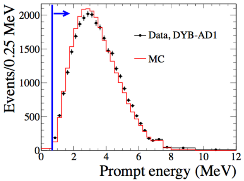
$$\overline{\nu}_e + p \underset{\sim\,80\text{ ns}}{\rightarrow} e^+ + n \text{ (prompt signal)}$$

$$\hookrightarrow +p \overset{\sim\,180\mu s}{\longrightarrow} D + \gamma \text{ (2.2 MeV)}$$

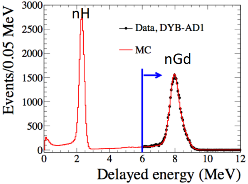
$$\hookrightarrow +Gd \rightarrow Gd^* \quad \text{delayed signal}$$

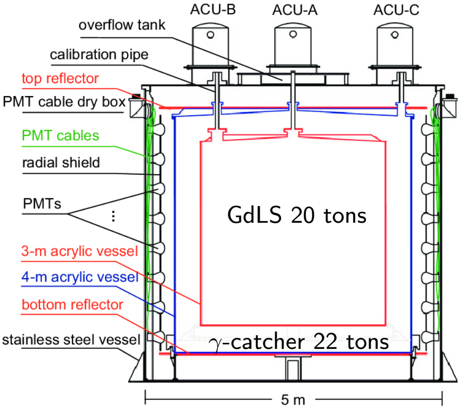
$$\underset{\sim\,30\mu s}{\hookrightarrow} Gd + \gamma \text{ (8 MeV)}$$

Prompt Signal



Delayed Signal

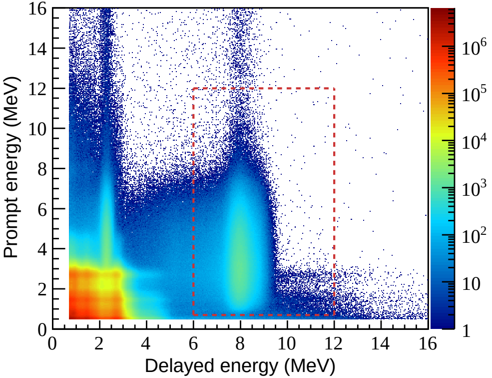




Schema of antineutrino detector (AD)

$$\sigma_E/E = 8.5\%/\sqrt{E[\text{MeV}]}$$

- Veto events that are close in time to muons
- Temporal and spatial coincidence
- Remove spontaneous flashing from PMTs
- Cuts
  - Prompt signal: 0.7 MeV $< E_p <$ 12 MeV
  - Delayed signal: 6 MeV $< E_d <$ 12 MeV
  - Time window: 1 μs $< \Delta t <$ 200 μs
- Multiplicity cut: time-isolated event pairs



Three periods of data taking

- 6 detectors: 0 – 210 days
- 8 detectors: 300 – 1820 days
- 7 detectors: 1850 – 3280 days

$\rightarrow$ 3158 days of operation

	Hall 1	Hall 2	Hall 3
IBD candidates	2 236 810	2 544 895	764 514
ν_e rate [1/day]	1342.29	1191.18	300.57
Background rate [1/day]	21.93	16.20	4.47
Background / Signal ratio, %	**1.63**	**1.36**	**1.58**

Based on data from PRL 130, 161802 (2023)

$$N_{dk}^{IBD} = \sum_b B_b^{dk} + \sum_{kj} C_j^k \sum_t \varepsilon_t^d T_t^d M^d \times$$

Background events

Detector effects

Detector mass and effective live time

$$\times \int\limits_{-1}^{+1} d\cos\theta \int\limits_{E_j^{vis}}^{E_{j+1}^{vis}} dE_{\mathrm{vis}} \frac{d\sigma(E_\nu, \cos\theta)}{d\cos\theta} \frac{dE_\nu(E_{\mathrm{vis}}, \cos\theta)}{dE_{\mathrm{vis}}} \times$$

2D integration

Cross-section

$$\times \sum_r \frac{1}{4\pi \left(L_r^d\right)^2} \sum_c P\left(E_\nu, L_r^d, \Delta m_{32}^2, \sin^2 2\theta_{13}, \ldots\right) \times$$

Distance reactor-detector

Oscillation probability

Spectrum $\overline{\nu}_e$, SNF

and non-equilibrium effect

$$\times \left[\frac{W_{rt}}{\sum\limits_{i'} f_{i'rt} \langle e \rangle_{i'}} \omega(E_\nu) \sum_i f_{irt} S_i\left(E_\nu\right) C_i\left(E_\nu\right) + F_r\left(E_\nu\right)\right]$$

Model of Experiment

Observation

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Model of Experiment

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$$
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\end{aligned}
$$

Background events

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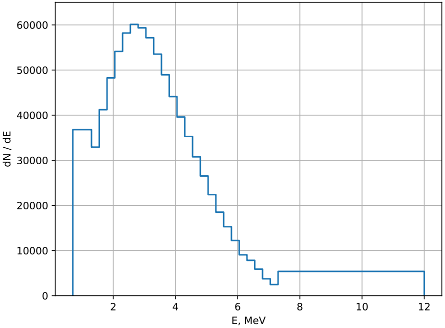
Model of Experiment

Effects and uncertainties

- Effects and systematic are divided into 3 groups:
  - **Background**: ω^{Li}, $N^{bkg}(Li/He)$, $N^{bkg}(AmC)$, $N^{bkg}(C(\alpha,n))$, N^{acc}, $N^{bkg}(\text{fast } n)$, $S(\text{fast } n)$
  - **Reactor**: $E^{fission}$, W_{th}, fission fractions (f), non-equilibrium, spent nuclear fuel (SNF), $\overline{\nu}_e$ spectra uncertainties (Huber-Mueller)
  - **Energy+detector**: σ_E, inner acryl vessel (IAV), non-linearity of liquid scintillator, E_{scale}, ϵ
- $\sim$ 300 nuisance parameters
- Free spectrum of $\overline{\nu}_e \to$ Huber-Mueller model is used as initial



Model of observation from near detector (EH1-AD1) of Daya Bay experiment full data set

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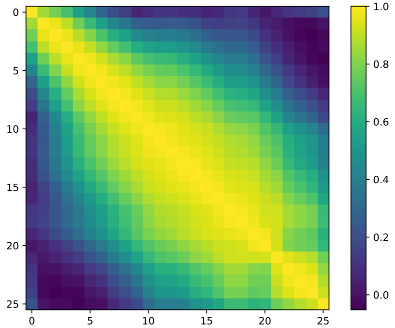
- ~ 300 nuisance parameters
- Free spectrum of $\overline{\nu}_e$ $\rightarrow$ Huber-Mueller model is used as initial



Correlation matrix for
near detector (EH1-AD1) of Daya Bay experiment
full data set

$$\underbrace{0.70,\ 1.30}_{0},\ \underbrace{1.55,\ (\text{step } 0.25)}_{2-24},\ \underbrace{7.30,\ 12.00}_{25}\ \text{MeV}$$

Illustration, the analysis uses a full covariance matrix

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  - **Background**: ω^{Li}, $N^{bkg}(Li/He)$, $N^{bkg}(AmC)$, $N^{bkg}(C(\alpha,n))$, N^{acc}, $N^{bkg}(\text{fast } n)$, $S(\text{fast } n)$
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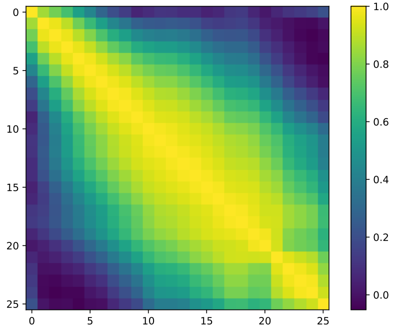

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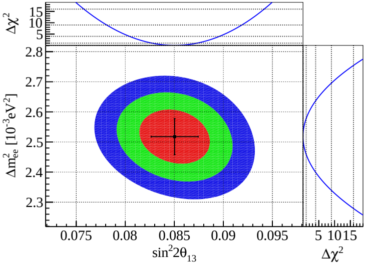
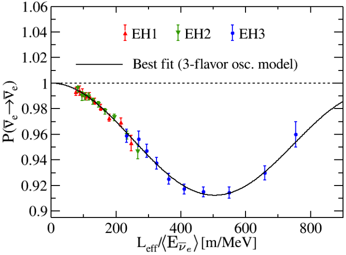
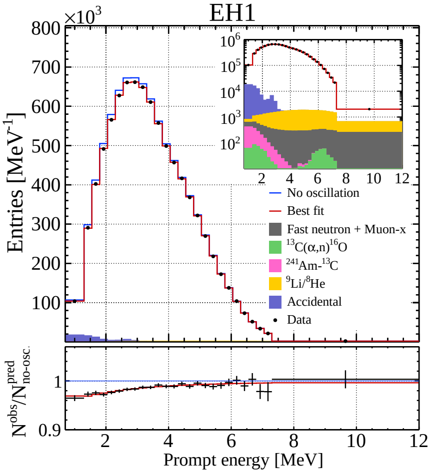
3ν oscillation analysis

Results





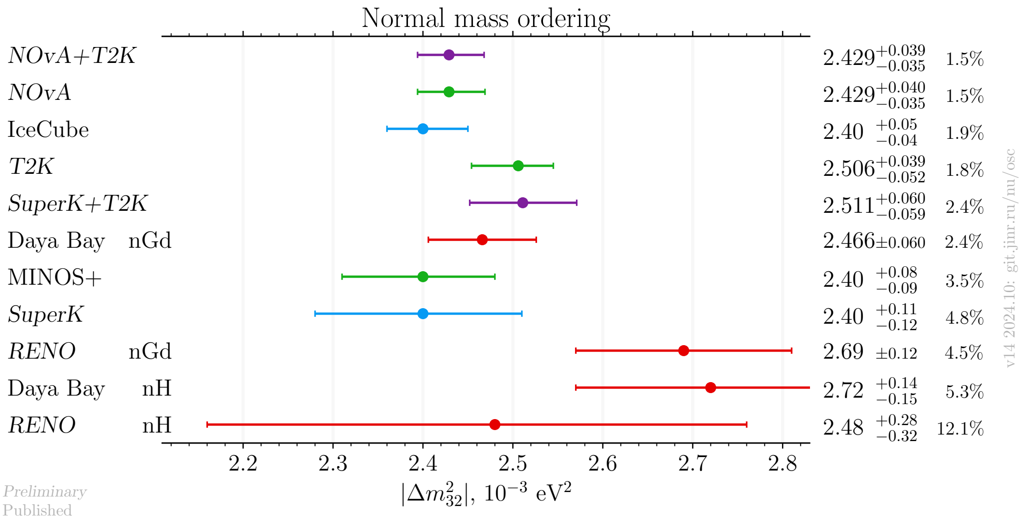


Best fit results:

- $\chi^2/\text{NDF} = 559/517$
- $\sin^2 2\theta_{13} = 0.0851 \pm 0.0024$ (2.8 %)
- $\Delta m^2_{32} = (2.466 \pm 0.060) \times 10^{-3}$ eV^2 NO (2.4 %)
- $\Delta m^2_{32} = -(2.571 \pm 0.060) \times 10^{-3}$ eV^2 IO (2.3 %)

3ν oscillation analysis

Global picture of Δm^2_{32} and $\sin^2 2\theta_{13}$



3ν oscillation analysis

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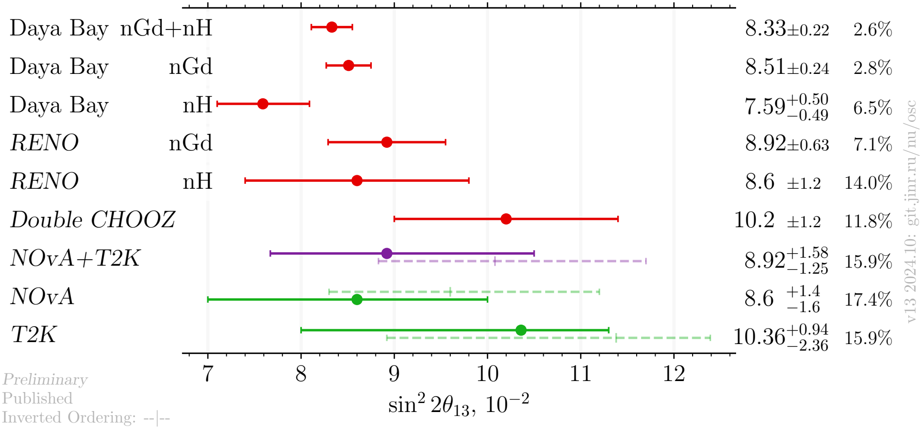
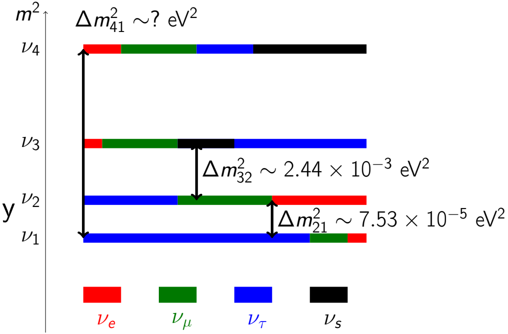


Sterile neutrinos

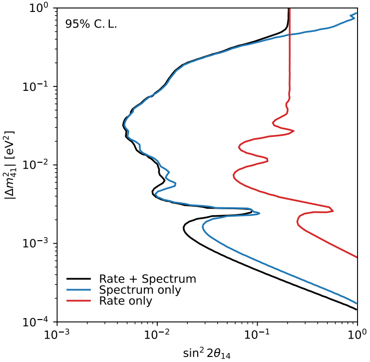
Motivation

Sterile neutrino

- is minimal possible extension of 3ν framework
- one of the possible explanations of deficit of $\overline{\nu}_e$ in the reactor experiments (Reactor Antineutrino Anomaly)
  - Experiments measure overall deficit of $\overline{\nu}_e$ events ($2011 \sim 3\sigma \to 2022 \sim 1\sigma$)
- one of the possible explanations of gallium anomaly
- interacts only gravitationally $\to$ does not affect Z-boson decay into invisible mode
- is a possible dark matter candidate
- is a search for physics beyond the Standard Model



- No significant signal of sterile neutrino was observed (p-value = 0.86)
- Obtained the world leading limits for $\sin^2 2\theta_{14}$: $2 \cdot 10^{-4}$ eV^2 $< \Delta m^2_{41} <$ 0.2 eV^2



Sterile neutrinos

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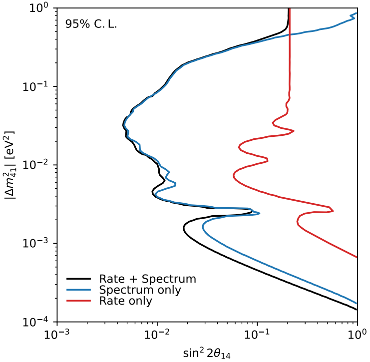

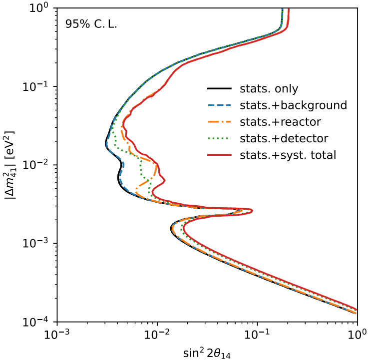

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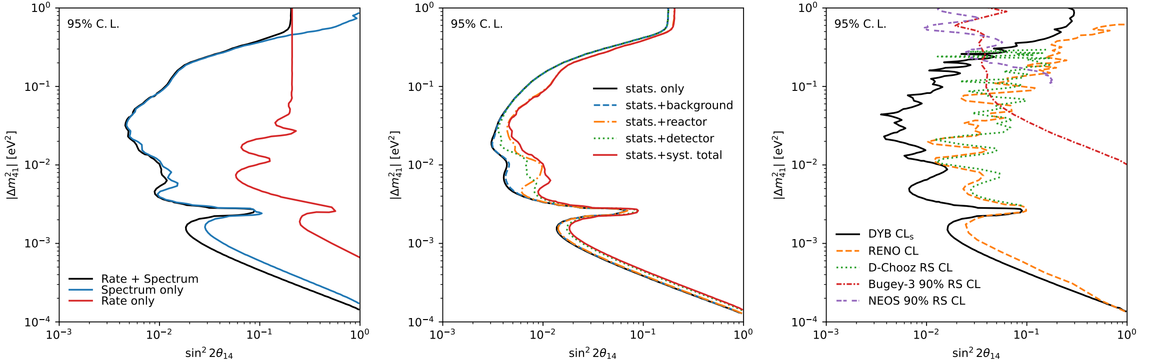


Conclusion

Analysis of full dataset of Daya Bay experiment, one of the largest IBD dataset

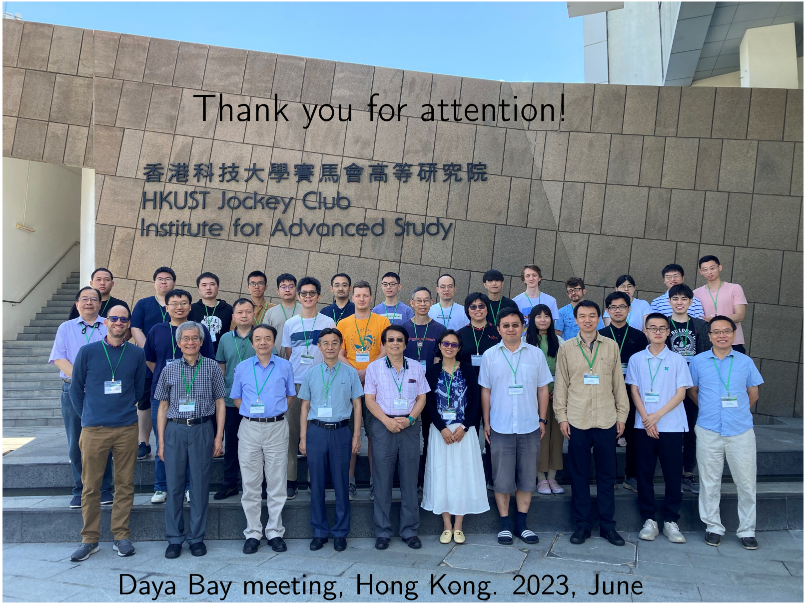
- The most precise measurements of θ_{13} and Δm^2_{32} — PRL 130, 161802 (2023)
- nGd analysis is validated by independent nH analysis
- The world-leading constraints on parameters of sterile neutrinos — PRL 133, 051801 (2024)

Performed but not highlighted in this talk

- Measurement of high energy electron antineutrinos — PRL 129, 041801 (2022)
- Oscillation analysis with capture of neutron on Hydrogen — PRL 133, 151801 (2024)
- Observation of cosmogenic isotopes of ^{8}He — PRD 110, L011101 (2024)

To be performed

- Joint sterile analysis with other experiments
- Other non-oscillation results
- Data preservation


Thank you for attention!
香港科技大學賽馬會高等研究院
HKUST Jockey Club
Institute for Advanced Study
Daya Bay meeting, Hong Kong. 2023, June

- Pontecorvo-Maki-Nakagawa-Sakata matrix – unitary mixing matrix: massive states $\rightarrow$ flavor states
- Parametrized with:
  - $\dfrac{(N_\nu - 1)N_\nu}{2}$ – mixing angles θ_{ij}
  - $\dfrac{(N_\nu - 1)(N_\nu - 2)}{2}$ – physical phases $\delta_{ij}^{\mathrm{CP}}$
- $N_\nu = 3$: $U = U_{23}\widetilde{U}_{13}U_{12}$
- $N_\nu = 4$: $U = U_{34}\widetilde{U}_{24}\widetilde{U}_{14}U_{23}\widetilde{U}_{13}U_{12}$

$$U_{ij} \rightarrow \begin{array}{cc} \begin{array}{c} \mathrm{i} \rightarrow \\ \mathrm{j} \rightarrow \end{array} & \begin{pmatrix} \cos\theta_{ij} & -\sin\theta_{ij} \\ \sin\theta_{ij} & \cos\theta_{ij} \end{pmatrix} \\ & \begin{array}{cc} \uparrow & \uparrow \\ \mathrm{i} & \mathrm{j} \end{array} \end{array}$$

$$\widetilde{U}_{ij} \rightarrow \begin{array}{cc} & \begin{array}{cc} \mathrm{i} & \mathrm{j} \\ \downarrow & \downarrow \end{array} \\ \begin{array}{c} \mathrm{i} \rightarrow \\ \mathrm{j} \rightarrow \end{array} & \begin{pmatrix} \cos\theta_{ij} & \sin\theta_{ij} e^{-i\delta_{ij}^{\mathrm{CP}}} \\ \sin\theta_{ij} e^{i\delta_{ij}^{\mathrm{CP}}} & \cos\theta_{ij} \end{pmatrix} \end{array}$$

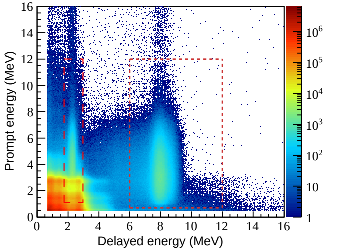
Backup slides

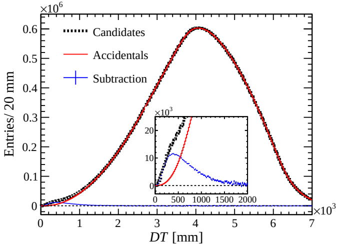
nGd analysis: summary of IBD events and backgrounds

	EH1-AD1	EH1-AD2	EH2-AD1	EH2-AD2	EH3-AD1	EH3-AD2	EH3-AD3	EH3-AD4
ν_e candidates	794335	1442475	1328301	1216594	194949	195469	193334	180762
DAQ live time [days]	1535.111	2686.110	2689.880	2502.816	2689.156	2689.156	2689.531	2501.7441
$\varepsilon_\mu \cdot \varepsilon_m$	0.7743	0.7716	0.8127	0.8105	0.9513	0.9514	0.9512	0.9513
Accidentals [1/day]	7.11 ± 0.01	6.76 ± 0.01	5.00 ± 0.00	4.85 ± 0.01	0.80 ± 0.00	0.77 ± 0.00	0.79 ± 0.00	0.66 ± 0.00
Fast n + muon-x [1/day]	0.83 ± 0.17	0.96 ± 0.19	0.56 ± 0.11	0.56 ± 0.11	0.05 ± 0.01	0.05 ± 0.01	0.05 ± 0.01	0.05 ± 0.01
^{9}Li/^{8}He [1/day]	2.92 ± 0.78	2.92 ± 0.78	2.45 ± 0.57	2.45 ± 0.57	0.26 ± 0.04	0.26 ± 0.04	0.26 ± 0.04	0.26 ± 0.04
AmC [1/day]	0.16 ± 0.07	0.13 ± 0.03	0.12 ± 0.05	0.11 ± 0.05	0.04 ± 0.02	0.04 ± 0.02	0.04 ± 0.02	0.03 ± 0.01
Alpha-N [1/day]	0.08 ± 0.04	0.06 ± 0.03	0.04 ± 0.02	0.06 ± 0.03	0.04 ± 0.02	0.04 ± 0.02	0.03 ± 0.02	0.04 ± 0.02
ν_e rate [1/day]	657.16 ± 1.10	685.13 ± 1.0	599.47 ± 0.78	591.71 ± 0.79	75.02 ± 0.18	75.21 ± 0.18	74.41 ± 0.18	74.93 ± 0.18

PRL 130, 161802 (2023)

- Veto events that are close in time to muons
- Temporal and spatial coincidence
- Remove spontaneous flashing from PMTs
- Cuts
  - Prompt signal: 1.5 MeV $< E_p <$ 12 MeV
  - Delayed signal: $2.2 - 3\sigma$ MeV $< E_d < 2.2 + 3\sigma$ MeV
  - Time window: 1μs$< \Delta t < 1500\mu$s, $\delta r + \delta t/[600\ \mu\text{s/m}] < 1$ m
- Multiplicity cut: time-isolated event pairs





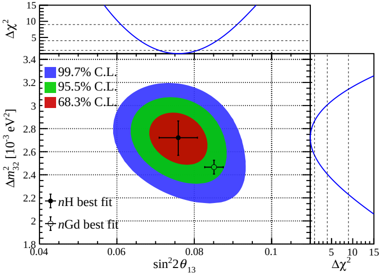
Three periods of data taking:

- 6AD: 0 – 210 days
- 8AD: 300 – 1820 days
- 7AD: 1850 – 2080 days

$\rightarrow$ 1958 days of operation

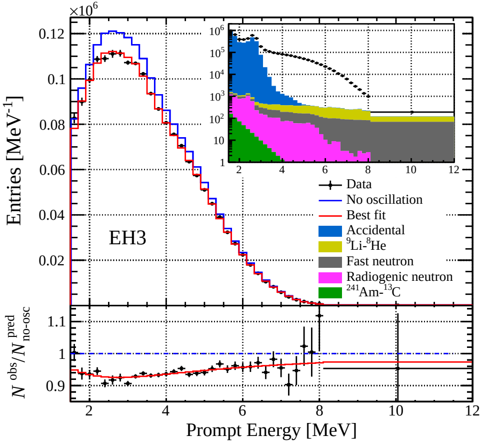
	EH1	EH2	EH3
ν_e candidates	1293120	1288314	1022130
ν_e rate [1/day]	1055.85	939.00	236.85
Background rate [1/day]	247.52	222.92	421.10
Background / Signal ratio, %	**23.44**	**23.74**	**177.79**

Based on data from PRL 133, 151801 (2024)



Best fit results:

- $\chi^2/\mathrm{NDF} = 256.7/236$
- $\sin^2 2\theta_{13} = 0.0759^{0.0050}_{-0.0049}$ (6.5 %)
- $\Delta m^2_{32} = (2.75 \pm 0.14) \times 10^{-3}$ eV^2 NO (5.1 %)
- $\Delta m^2_{32} = -(2.85 \pm 0.14) \times 10^{-3}$ eV^2 IO (4.9 %)
- nGd+nH $\sin^2 2\theta_{13} = 0.0833 \pm 0.0022$ (2.6 %)

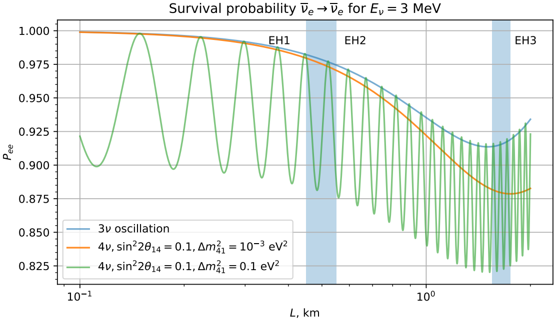


- PMNS matrix describes 3ν oscillation
- Extended matrix describes 4ν oscillation

$$\begin{bmatrix} V_{e1} & V_{e2} & V_{e3} \\ V_{\mu 1} & V_{\mu 2} & V_{\mu 3} \\ V_{\tau 1} & V_{\tau 2} & V_{\tau 3} \end{bmatrix}$$

$$\sin^2 2\theta_{12} = 0.8510$$
$$\sin^2 2\theta_{13} = 0.0856$$
$$\sin^2 \theta_{23} = 0.5432$$
$$\sin^2 2\theta_{14} = 0.1$$

$$\begin{bmatrix} V_{e1} & V_{e2} & V_{e3} & V_{e4} \\ V_{\mu 1} & V_{\mu 2} & V_{\mu 3} & V_{\mu 4} \\ V_{\tau 1} & V_{\tau 2} & V_{\tau 3} & V_{\tau 4} \\ V_{s1} & V_{s2} & V_{s3} & V_{s4} \end{bmatrix}$$



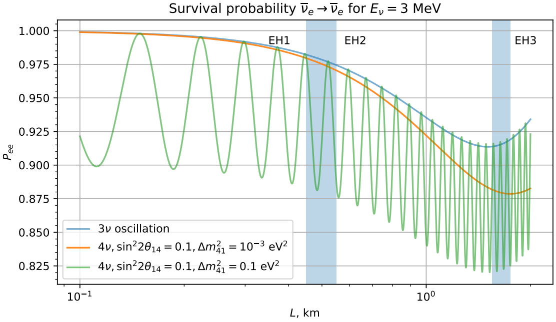
- Survival probability (vacuum)

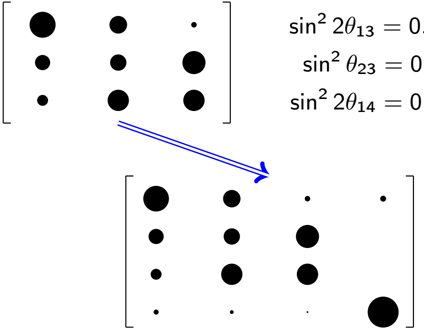
$$P_{ee} = 1 - 4 \sum_{j>i}^{N_\nu = 4} |U_{ei}|^2 |U_{ej}|^2 \sin^2\left(\frac{\Delta m^2_{ji}}{4E_\nu} L\right)$$

Backup slides

Sterile neutrinos: oscillation

- PMNS matrix describes 3ν oscillation
- Extended matrix describes 4ν oscillation





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Backup slides

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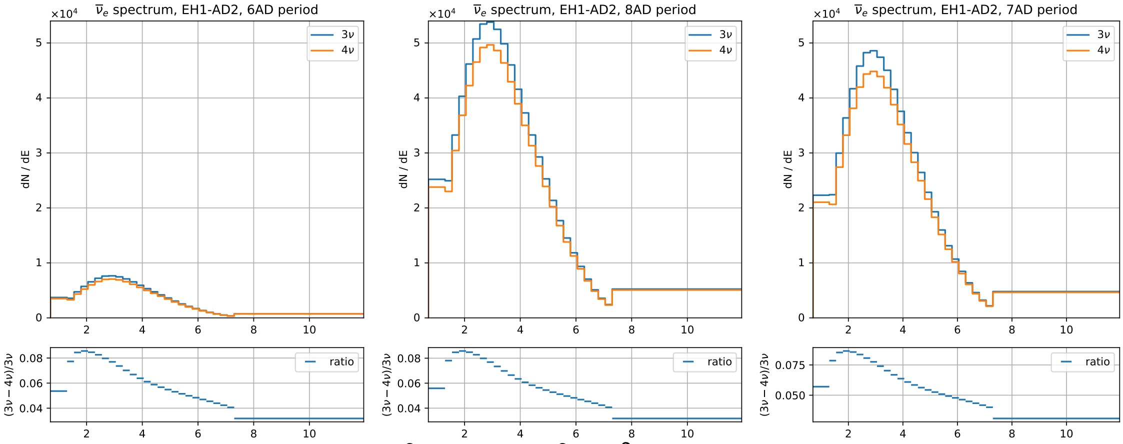
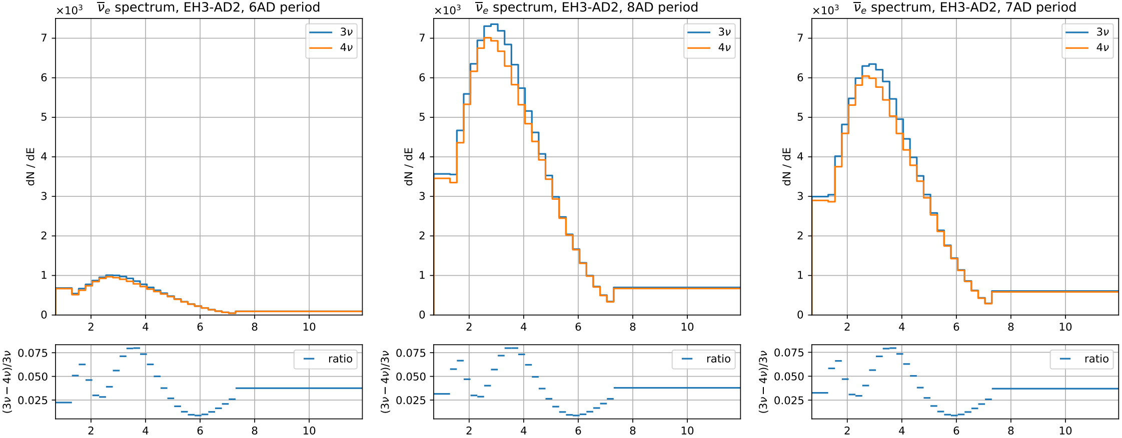


$$\Delta m^2_{41} = 0.01\ \text{eV}^2,\ \sin^2 2\theta_{14} = 0.1$$

Simultaneous fit of the data of the near, far halls, and periods

Backup slides

Sterile neutrinos: oscillation



$$\Delta m^2_{41} = 0.01\ \mathrm{eV}^2,\ \sin^2 2\theta_{14} = 0.1$$

Simultaneous fit of the data of the near, far halls, and periods

Minimization parameters

$N^{\mathbf{global}} = 1 \pm 0.05$
$\Delta m^2_{32} = (2.453 \pm 0.034) \times 10^{-3}$ eV^2
$\sin^2 2\theta_{13} = 0.0853$ – free

- H_0 – 3ν oscillation
  H_1 – 4ν oscillation
- For each point of grid of parameters of interests $(\sin^2 2\theta_{14},\ \Delta m^2_{41})$

$$\Delta\chi^2 = \chi^2_{4\nu}(\sin^2 2\theta_{14}, \Delta m^2_{41} \text{ are fixed}) - \chi^2_{3\nu}$$

$$CL_b = P(\Delta\chi^2 \geq \Delta\chi^2_{obs} | 3\nu)$$

$$CL_{s+b} = P(\Delta\chi^2 \geq \Delta\chi^2_{obs} | 4\nu)$$

$$CL_s = \frac{CL_{b+s}}{CL_b}$$

- Calculation of limits could be speed up with Gaussian approximation

NIMA, 827, 63-78, (2016)

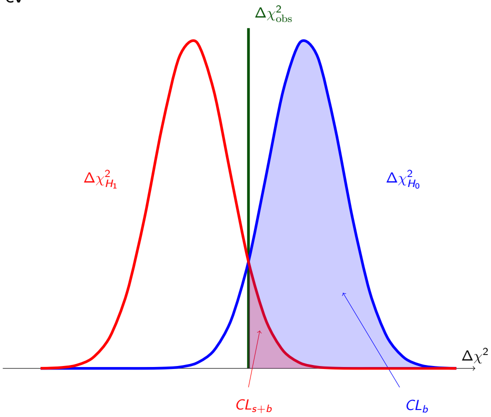


Illustration of CL_s method

- H_0 – 4ν oscillation with fixed values of $(\Delta m^2_{41}, \sin^2 2\theta_{14})$
  H_1 – 4ν oscillation with free values of $(\Delta m^2_{41}, \sin^2 2\theta_{14})$
- For each point of $(\Delta m^2_{41}, \sin^2 2\theta_{41})$ generate MC data
- Each MC sample is obtained by $\chi^2_{H_0}$ and $\chi^2_{H_1}$
- Calculate $\Delta\chi^2 = \chi^2_{H_0} - \chi^2_{H_1}$ histogram
- Calculate $\Delta\chi^2$(DATA)
- Obtain p-value