Search for a sub-eV sterile neutrino using Daya Bay's full dataset

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(On behalf of the Daya Bay collaboration)

Introduction

➢ Why do we consider sterile neutrino?

- Very generic extension of Standard Model.
  can be leftover of extended gauge multiplet
- Useful phenomenological tool.
  - can explain neutrino masses (seesaw mechanism, $m_4 \sim 10^{15}\text{GeV}$)
  - can explain cosmic baryon asymmetry (leptogenesis, $m_4 \gg 100\text{ GeV}$)
  - can explain dark matter ($m_4 \sim \text{keV}$)
  - can explain oscillation anomalies ($m_4 \sim \text{eV}$)

➢ The simplest sterile neutrino model:

In the minimal "3+1" extension of the three-neutrino model, considering one sterile neutrino in addition to the three active neutrinos, the flavor eigenstates ν_α $(\alpha = e, \mu, \tau, s)$ are related to the four mass eigenstates $\nu_i (i = 1,2,3,4)$ as:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix},$$

where U is a unitary 4 × 4 mixing matrix. The matrix is in general parameterized by six mixing angles θ_{ij} and four CP-violating phases δ_i. The survival oscillation probability of the electron anti-neutrino is:

$$P_{\overline{\nu}_e \to \overline{\nu}_e}(L, E) = 1 - 4 \sum_{j>i}^{4} |U_{ei}|^2 |U_{ej}|^2$$

Where $\Delta_{ji} \approx 1.267\ \Delta m^2_{ji}[\text{eV}^2] L[\text{m}]/E[\text{MeV}]$.

➢ Why is it "sterile"?

- Precision measurements of the Z-boson width are consistent with three light neutrino species participating in the weak interaction.
- How to detect it?
  Via neutrino oscillation

The Daya Bay Experiment

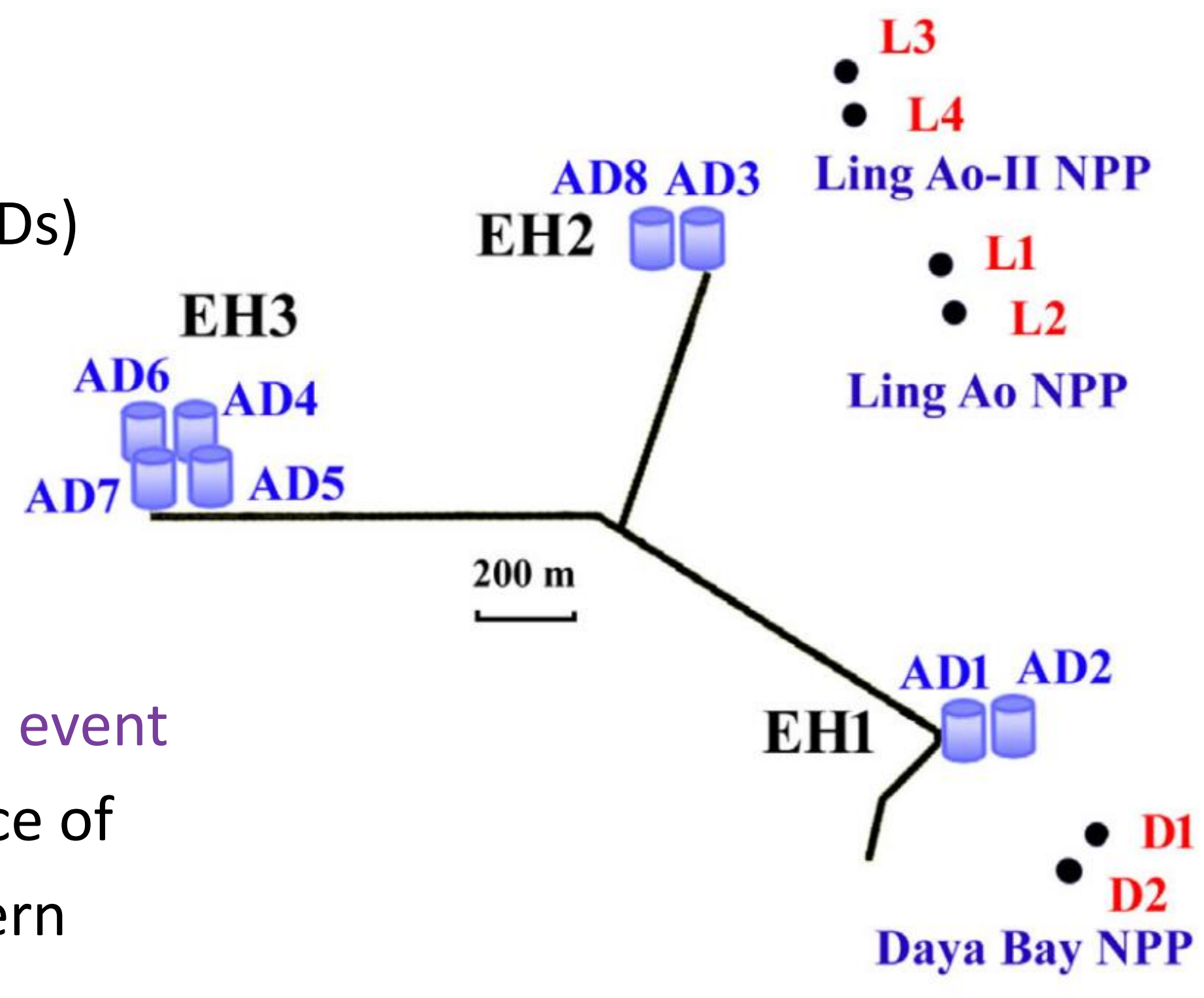
➢ Setup:

- 6 reactor cores
- 8 identical antineutrino detectors (ADs)
  - 4 ADs are in near halls (EH1, EH2)
  - 4 ADs are in far halls (EH3)

Near-Far relative measurement

➢ Possible hint of a sterile neutrino:

- A deficit of the electron-antineutrino event rate, accompanied by the dependence of the energy-spectrum distortion pattern (change the shape) on the distance between source and detector



Layout of the Daya Bay experiment

Analysis improvement and model test

➢ Full dataset of the Daya Bay experiment:

- IBD Candidates: $\bar{\nu}_e$ candidates identified as inverse beta-decay interactions followed by neutron-capture on gadolinium

Item	Previous result	Full dataset
Detector operation time	1230 days	3158 days
IBD Candidates	2.5×10^6	5.6×10^6
Average background-to-signal ratio	~1.7%	~1.5%

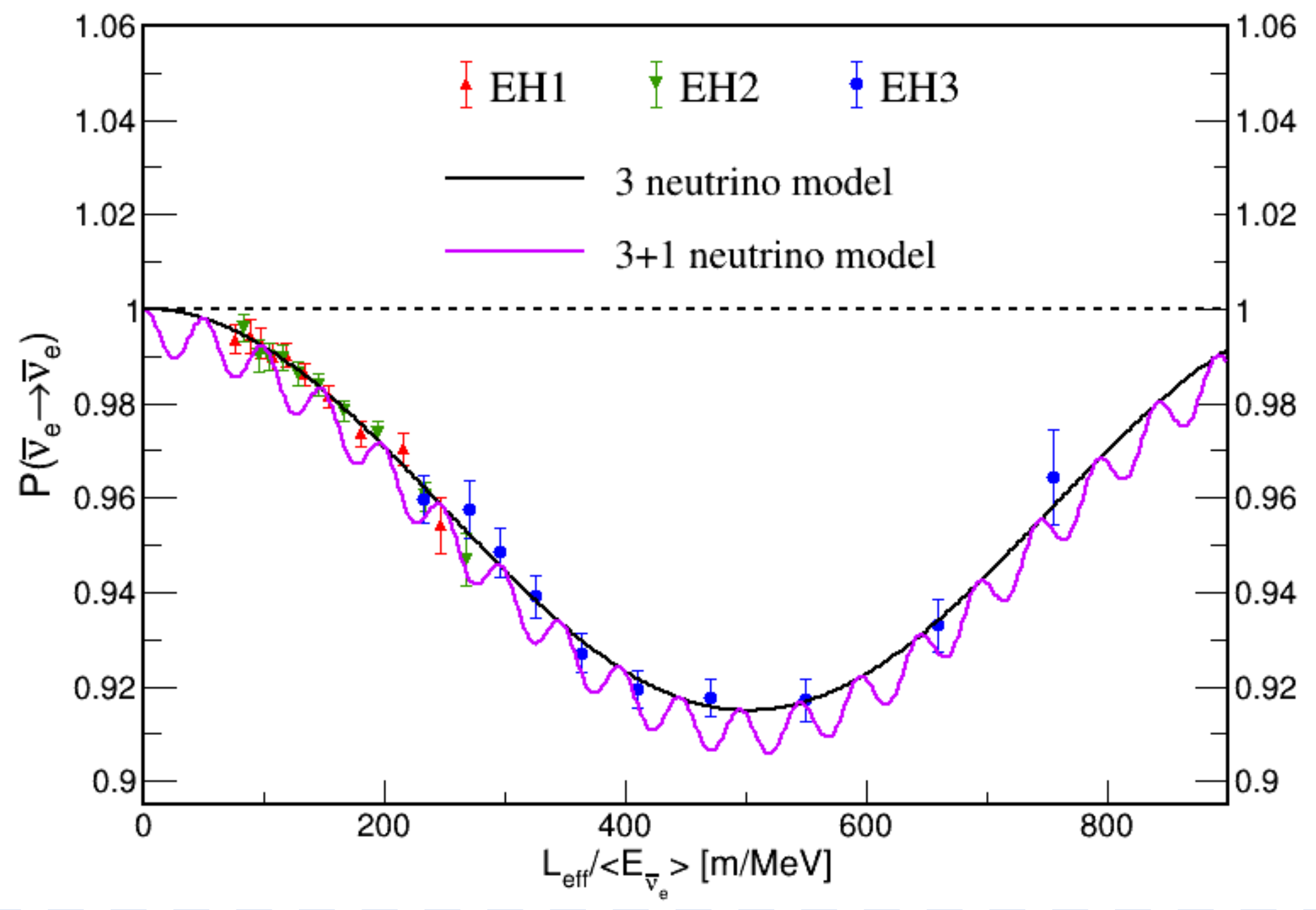
➢ Major Improvements of the systematic uncertainties:

Comparing with previous result,

- The ^{9}Li/^{8}He background is estimated using a new multi-dimensional fitting method, the relative uncertainty is reduced **from ~ 35% to <25%**.
- The channel-wise electronics nonlinearity is recalibrated using an FADC readout system;
  The energy response model is constrained with new calibration data;
  Uncertainty of the energy response model improved **from ~ 1% to <0.5%** for prompt energies larger than 2 MeV.

➢ Comparison of the data and model:

- The survival probability v.s baseline (L) over neutrino energy ($E_{\overline{\nu}_e}$)
- The Data is compared with 3 neutrino model (3ν) and (3+1) neutrino model (4ν).
- The data used effective baseline and average neutrino energy.



➢ Hypothesis test of the standard 3-neutrino model

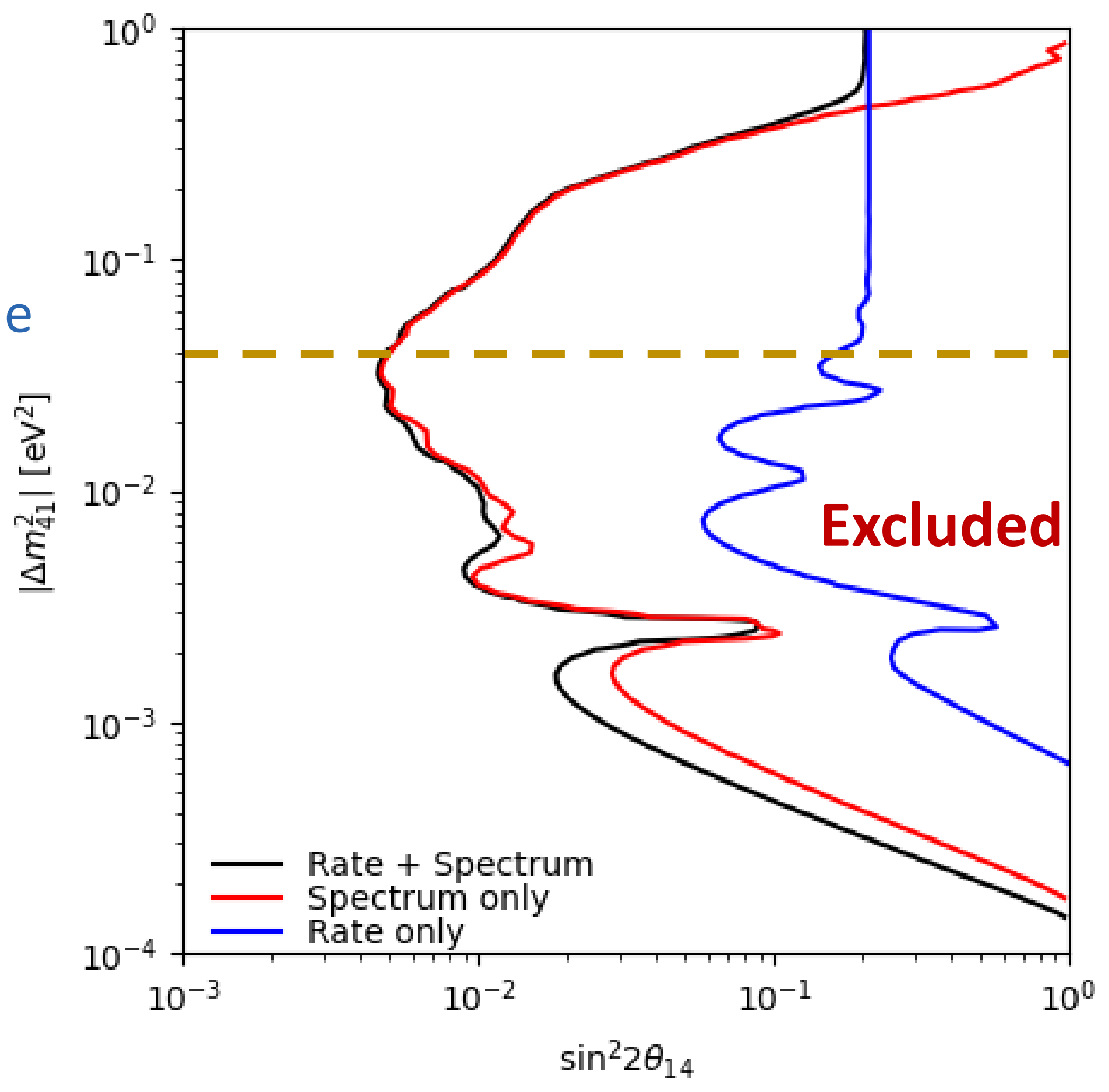
- Test statistic: $\Delta\chi^2 = \chi^2_{3\nu} - \chi^2_{4\nu}$,
- $\Delta\chi^2$ value for the data is compared with $\Delta\chi^2$ distribution generated by Monte Carlo samples under the 3ν oscillation hypothesis including statistical and systematic variations.
- **p-Value = 0.86**

**The data are consistent with the three-neutrino prediction.
No sterile neutrino signal is found.**

Sensitivity analysis

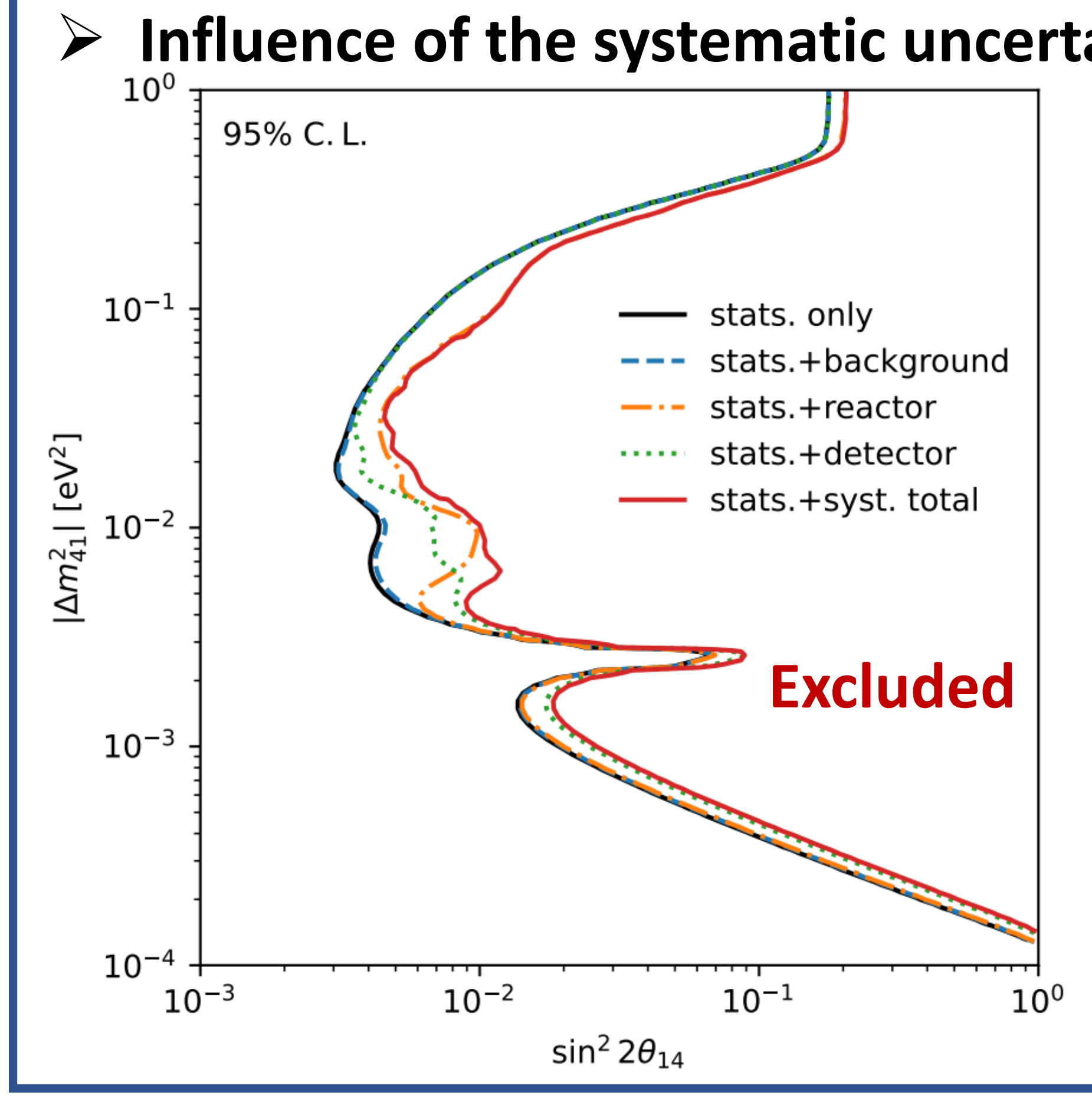
➢ Constraint of the energy spectrum and event rate

- Sensitivity is dominated by relative comparison of spectra among experimental halls.
- The event rates also contribute to the sensitivity:
  - The absolute measurements between the data and model mainly influence the high $|\Delta m^2_{41}|$ region ($\gtrsim 4 \times 10^{-2}\ \text{eV}^2$).
  - The relative comparison mainly influence the low $|\Delta m^2_{41}|$ region ($\lesssim 4 \times 10^{-2}\ \text{eV}^2$).



- The parameter space to the right of the contours is excluded.

➢ Influence of the systematic uncertainties (Unc.):

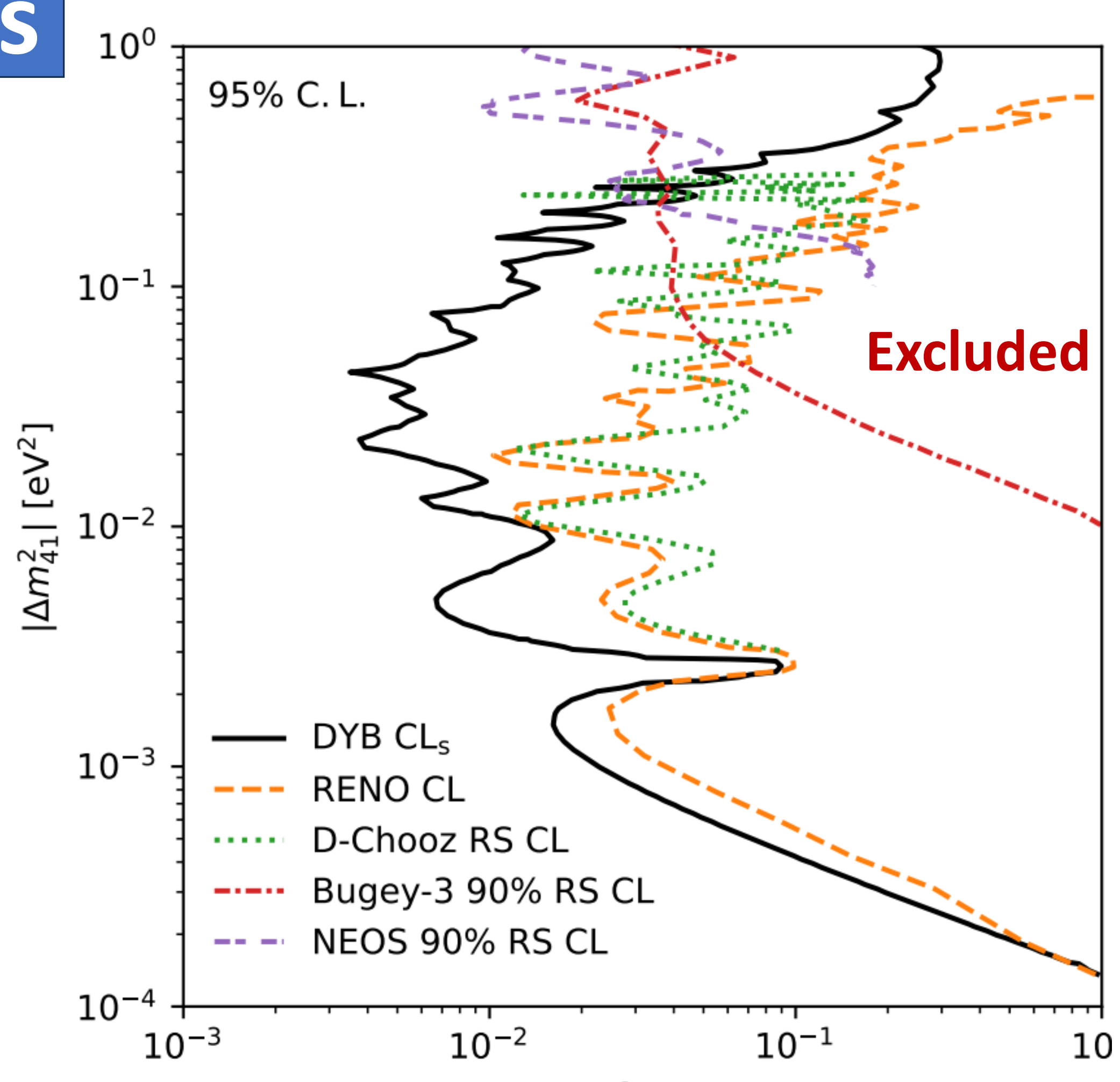


- The systematic uncertainties are split into three groups:

Systematic Unc. group	Influence on the sensitivity
Background related	negligible effect
Reactor related	$\lvert\Delta m^2_{41}\rvert \gtrsim 4 \times 10^{-3}\text{eV}^2$
Detector related	$\lvert\Delta m^2_{41}\rvert \lesssim 3 \times 10^{-2}\text{eV}^2$

Exclusion contours

- Exclusion contour with **Gaussian CL$_s$ method** is shown and compared with other reactor experiments.
  - The contour that results from applying the raster scan (RS) method to the Daya Bay data is consistent with the one obtained using the CL$_s$ method.
- We also released the contour obtained with the **Feldman-Cousins** method.



The world's most stringent limits on the sterile-active neutrino mixing parameter $\boldsymbol{sin^2 2\theta_{14}}$ were obtained in the region of $\boldsymbol{2 \times 10^{-4}\text{eV}^2 \lesssim |\Delta m^2_{41}| \lesssim 0.2\text{eV}^2}$.

Details are shown in the paper: arXiv:2404.01687 [hep-ex]