Article

Joint neutrino oscillation analysis from the T2K and NOvA experiments

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The NOvA Collaboration* & The T2K Collaboration*

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NPC – Journal Club

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This Paper

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Abstract

The landmark discovery that neutrinos have mass and can change type (or flavour) as they propagate—a process called neutrino oscillation[1–6]—has opened up a rich array of theoretical and experimental questions being actively pursued today. Neutrino oscillation remains the most powerful experimental tool for addressing many of these questions, including whether neutrinos violate charge-parity (CP) symmetry, which has possible connections to the unexplained preponderance of matter over antimatter in the Universe[7–11]. Oscillation measurements also probe the mass-squared differences between the different neutrino mass states (Δm^2), whether there are two light states and a heavier one (normal ordering) or vice versa (inverted ordering), and the structure of neutrino mass and flavour mixing[12]. Here we carry out the first joint analysis of datasets from NOvA[13] and T2K[14], the two currently operating long-baseline neutrino oscillation experiments (hundreds of kilometres of neutrino travel distance), taking advantage of our complementary experimental designs and setting new constraints on several neutrino sector parameters. This analysis provides new precision on the Δm^2_{32} mass difference, finding $2.43^{+0.04}_{-0.03} \times 10^{-3}$ eV^2 in the normal ordering and $-2.48^{+0.03}_{-0.04} \times 10^{-3}$ eV^2 in the inverted ordering, as well as a 3σ interval on δ_{CP} of [−1.38π, 0.30π] in the normal ordering and [−0.92π, −0.04π] in the inverted ordering. The data show no strong preference for either mass ordering, but notably, if inverted ordering were assumed true within the three-flavour mixing model, then our results would provide evidence of CP symmetry violation in the lepton sector.

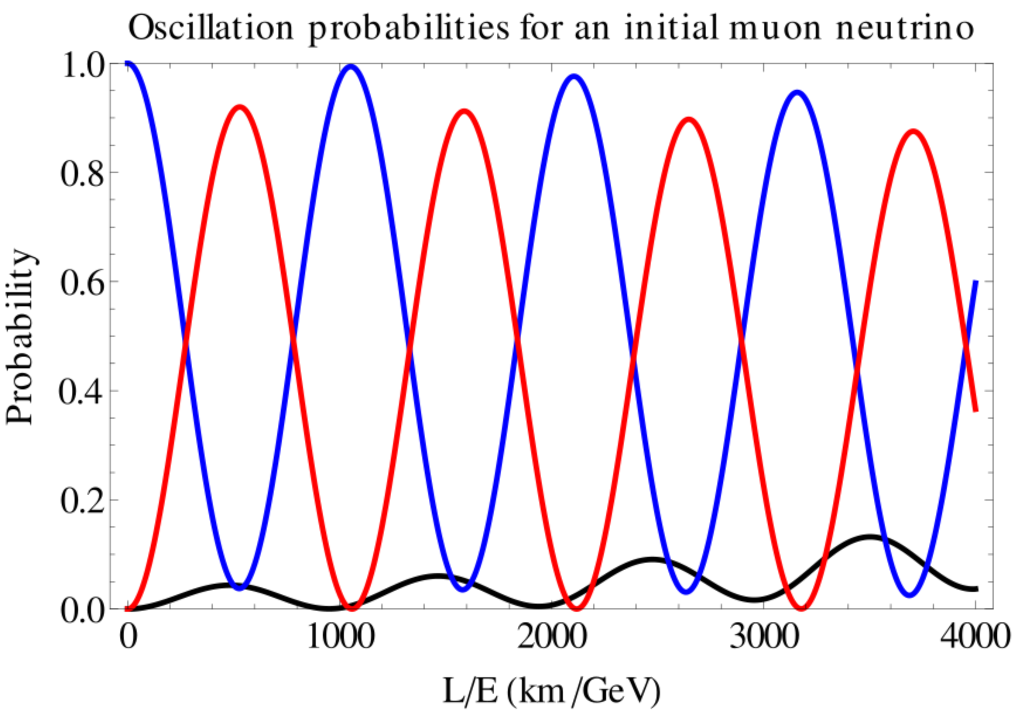
- ✓ First joint analysis of its kind
- ✓ Successful demonstration of cooperation between experiments
- ✓ Presents world-class precision on some of the neutrino oscillation parameters

Main Article and Results

Neutrino Oscillations

The standard model of particle physics, extended to include neutrino mass, describes three-flavour eigenstates of neutrinos (ν_e, ν_μ, ν_τ) that are related to three mass eigenstates (ν_1, ν_2, ν_3) by the 3 × 3 complex Pontecorvo–Maki–Nakagawa–Sakata unitary mixing matrix U_{PMNS} (refs. 15–17). This mixing, together with non-zero neutrino mass, allows for the phenomenon of neutrino oscillation, in which, during propagation, the flavour content of a neutrino evolves at a rate that depends on neutrino mass-squared splittings ($\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$) and the U_{PMNS} matrix elements. Apart from these oscillation parameters, the rate depends on neutrino energy E_ν and neutrino propagation distance L (baseline). Although experiments studying this process in recent decades have provided insights into the details of neutrino masses and mixings[12], many open questions remain.

Wikipedia



$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} \doteq \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

$$U = R_{23} S_{13} R_{12} \doteq \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{-\imath\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{+\imath\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$c_{ij} = \cos(\theta_{ij}) \qquad s_{ij} = \sin(\theta_{ij}) \qquad \delta = \delta_{CP}$$

Neutrino Oscillations: What's Missing

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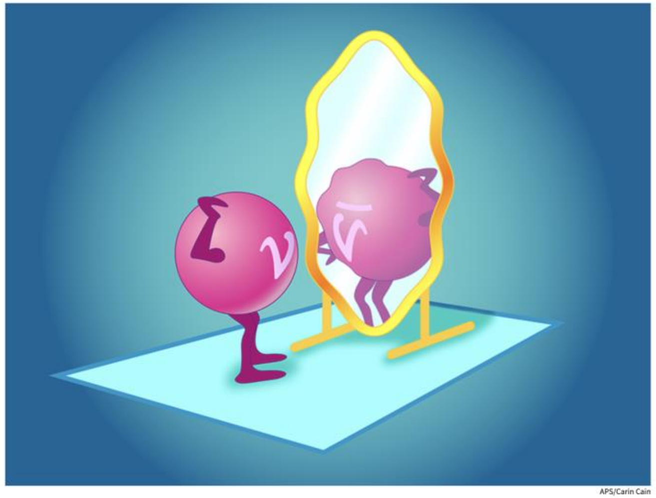

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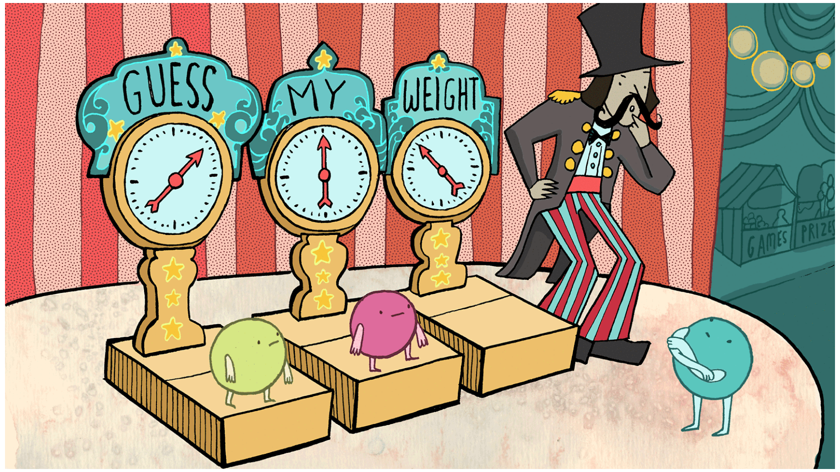

Artwork by Sandbox Studio, Chicago with Corinne Mucha

Is there Charge-Parity violation in the Lepton sector?

Which neutrino is the heaviest?

Why a Joint T2K and NOvA Fit?

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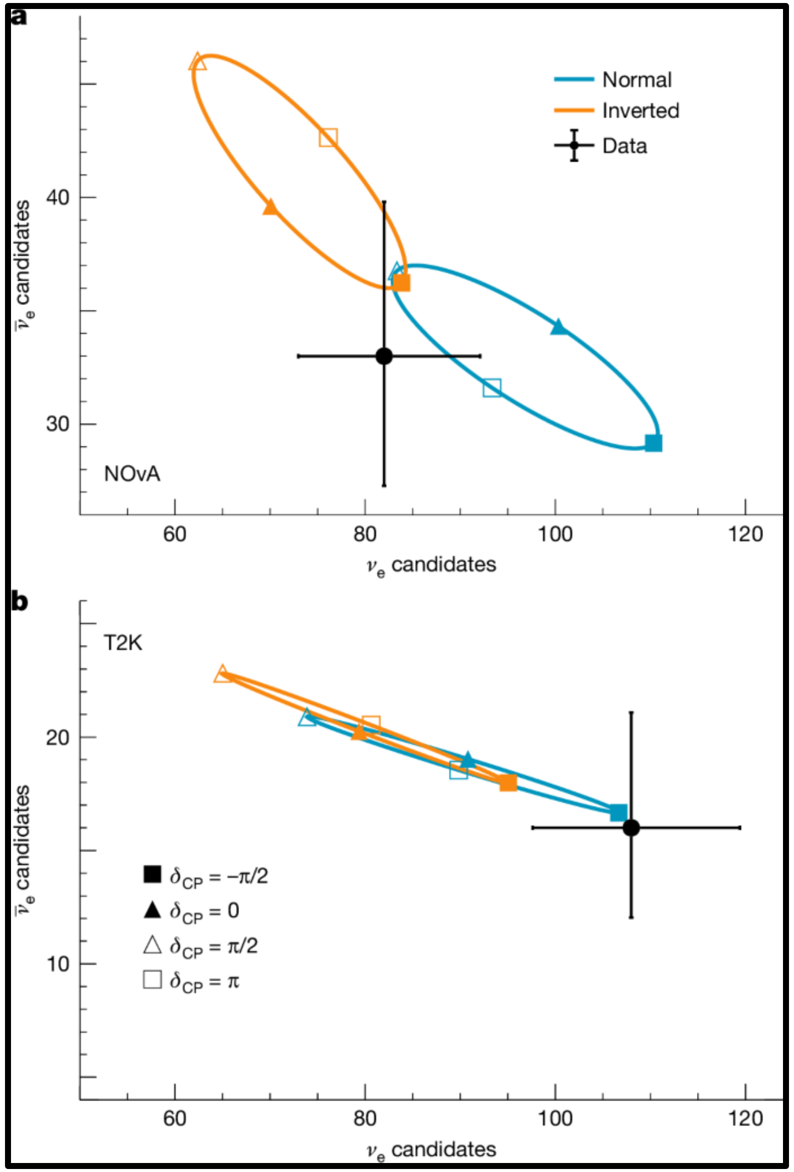


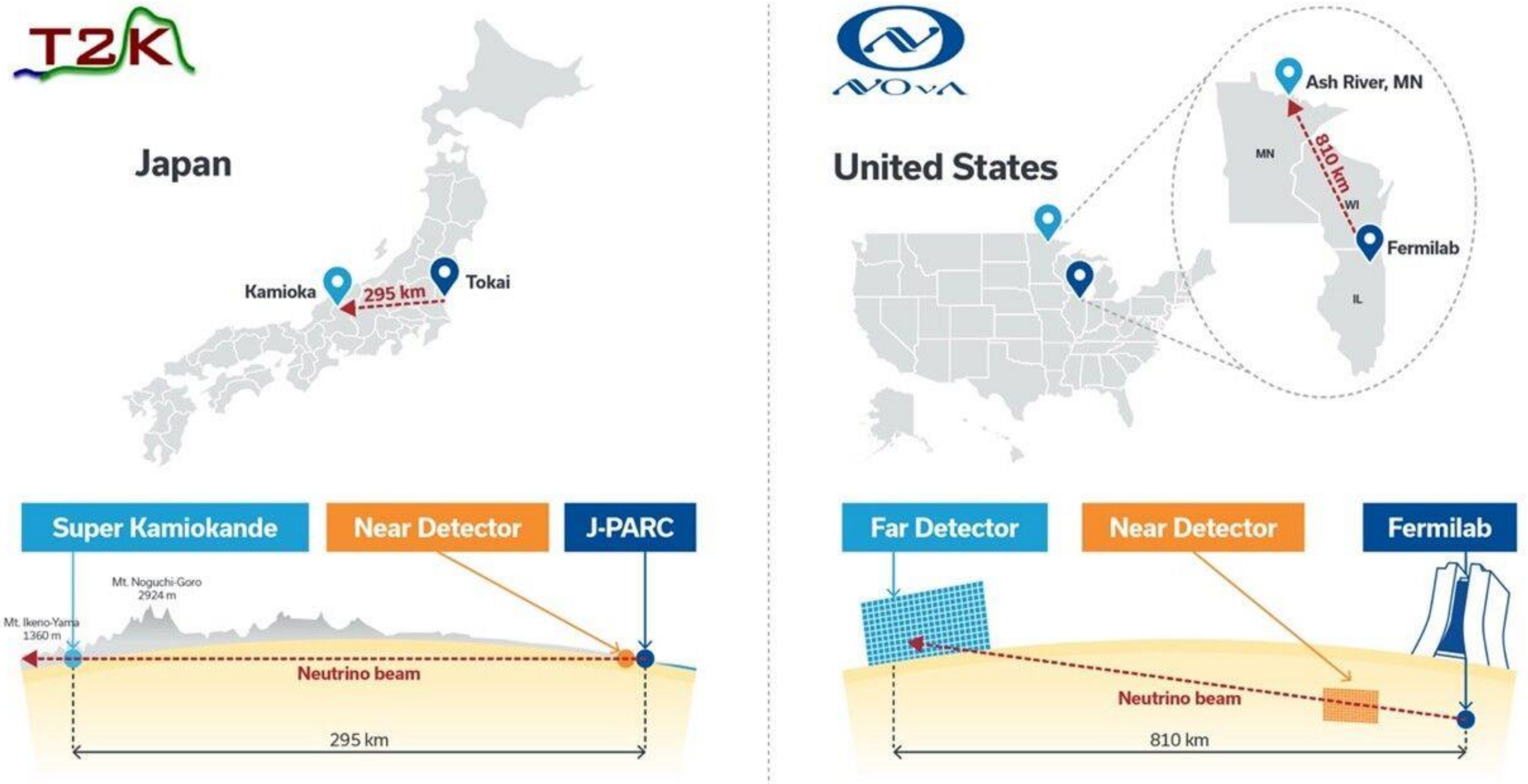
Fig. 1 | The impact of mass ordering and δ_{CP} on event rates. a,b, A bi-event plot that shows experimental sensitivity to neutrino mass ordering and δ_{CP}, with panels representing the NOvA (**a**) and T2K (**b**) cases. Black points with 1σ Poisson statistical error bars show the total number of ν_e and $\bar{\nu}_e$ candidates selected in the far detectors. The oval parametric curves trace out predicted numbers of events under the normal (blue) or inverted (orange) mass ordering assumption as the parameter δ_{CP} varies from $-\pi$ to π. Four specific δ_{CP} values are labelled for reference. All other oscillation parameters are kept fixed in this graphic, set to their most probable values from the joint analysis (Extended Data Table 3).

Fig. 1

NOvA: great mass ordering resolution

T2K: stronger CP-symmetry separation

T2K & NOvA



https://j-parc.jp/c/en/press-release/2025/10/23001631.html

Extended Data Table 3 | NOvA+T2K measurements of oscillation parameters

Parameter	Normal Ordering	Inverted Ordering
$\lvert\Delta m^2_{32}\rvert$	$2.43^{+0.04}_{-0.03}$	$2.48^{+0.04}_{-0.03}$
$\sin^2\theta_{23}$	$0.561^{+0.021}_{-0.039}$ and $0.470^{+0.016\,a}_{-0.008}$	$0.563^{+0.021}_{-0.039}$
δ_{CP}	$-0.87\pi^{+0.35\pi}_{-0.21\pi}$	$-0.47\pi^{+0.17\pi}_{-0.15\pi}$
$\sin^2 2\theta_{13}$	0.0855 ± 0.0027	$0.0859^{+0.0027}_{-0.0025}$

Extended Data Table 3

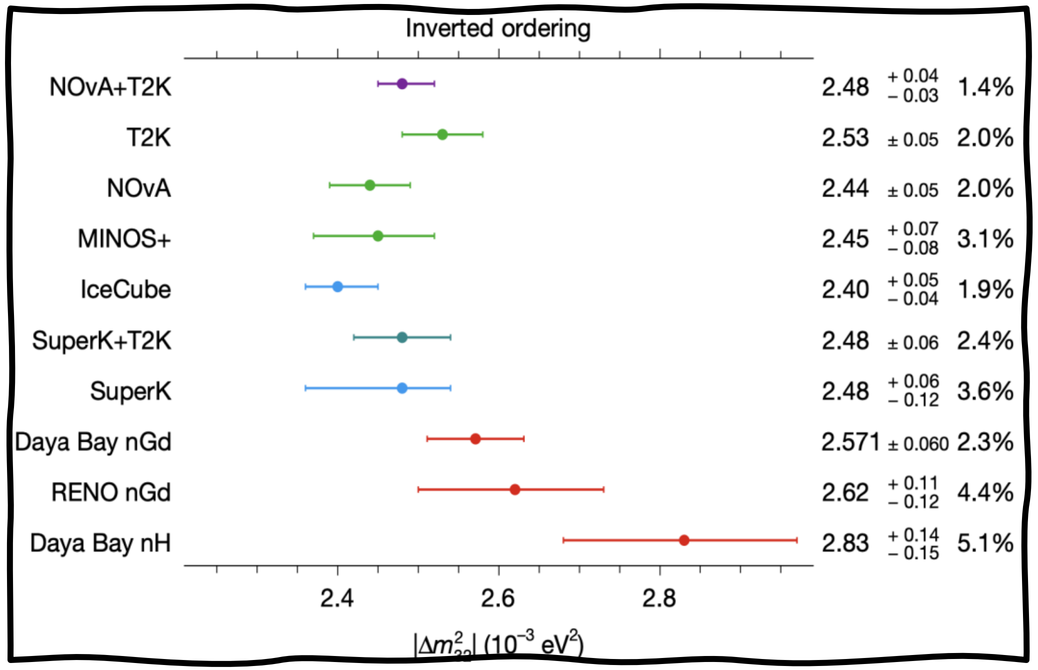


Fig. 2

Results

The joint fit data favors the IO, however at a low significance (Bayes factor of 1.3).

World-leading precision!

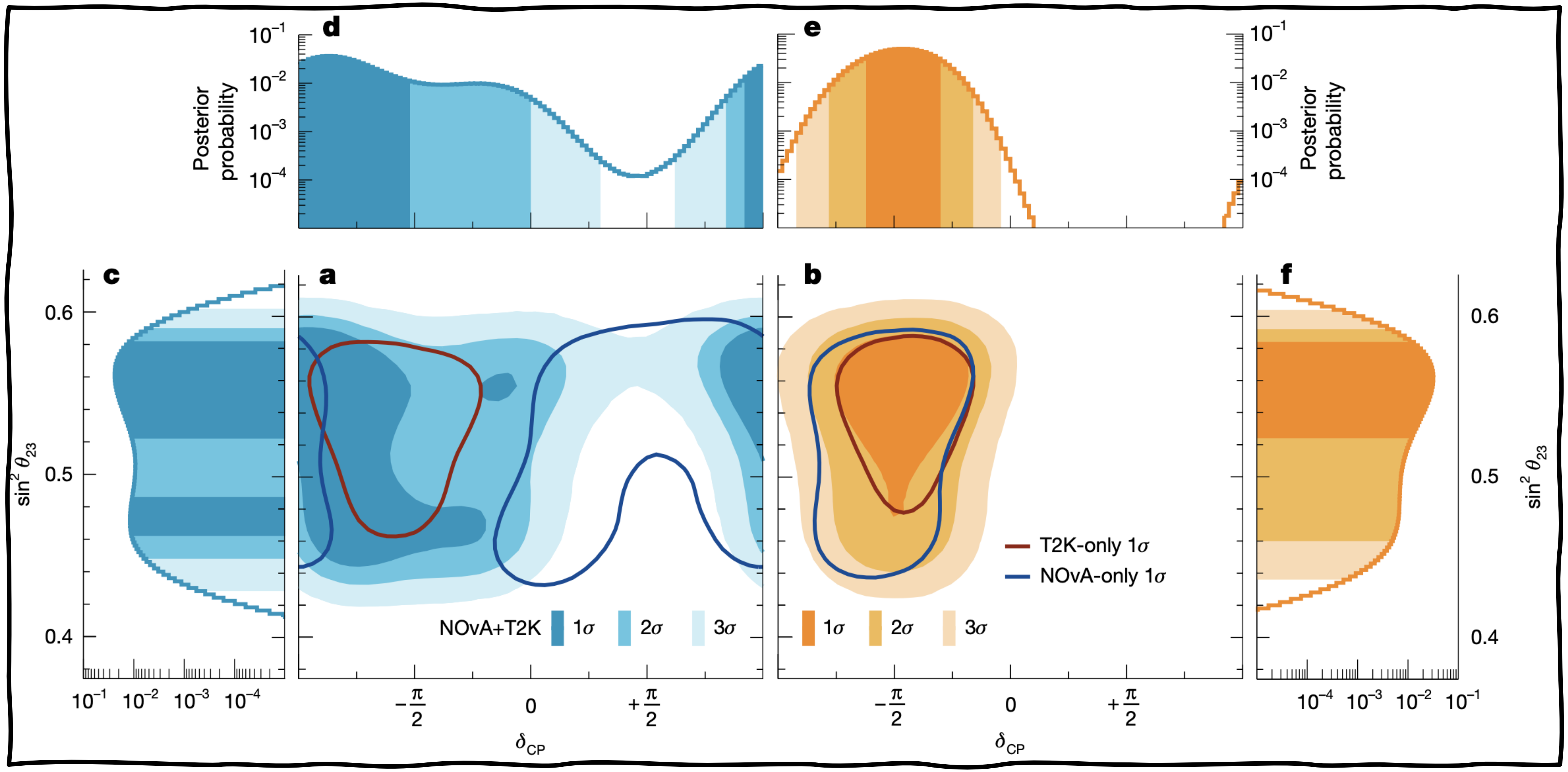


Fig. 3

Results

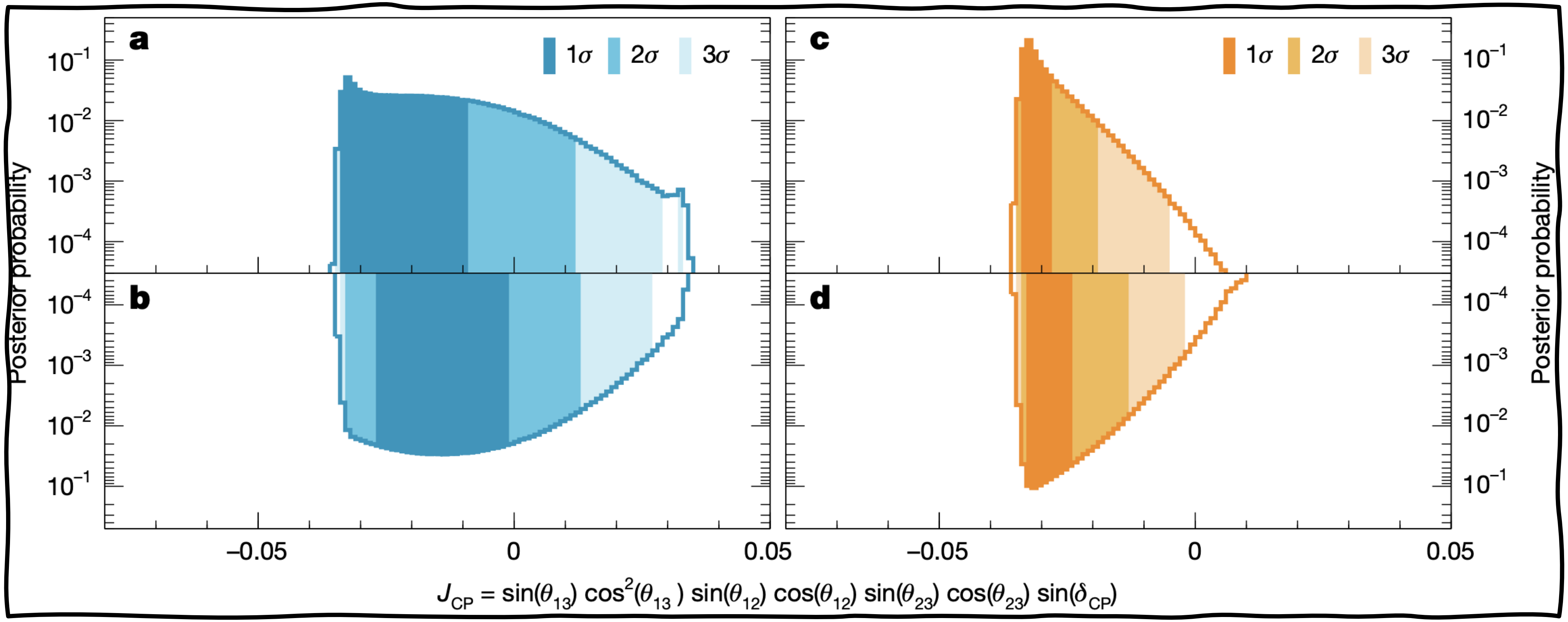


Fig. 4

Results

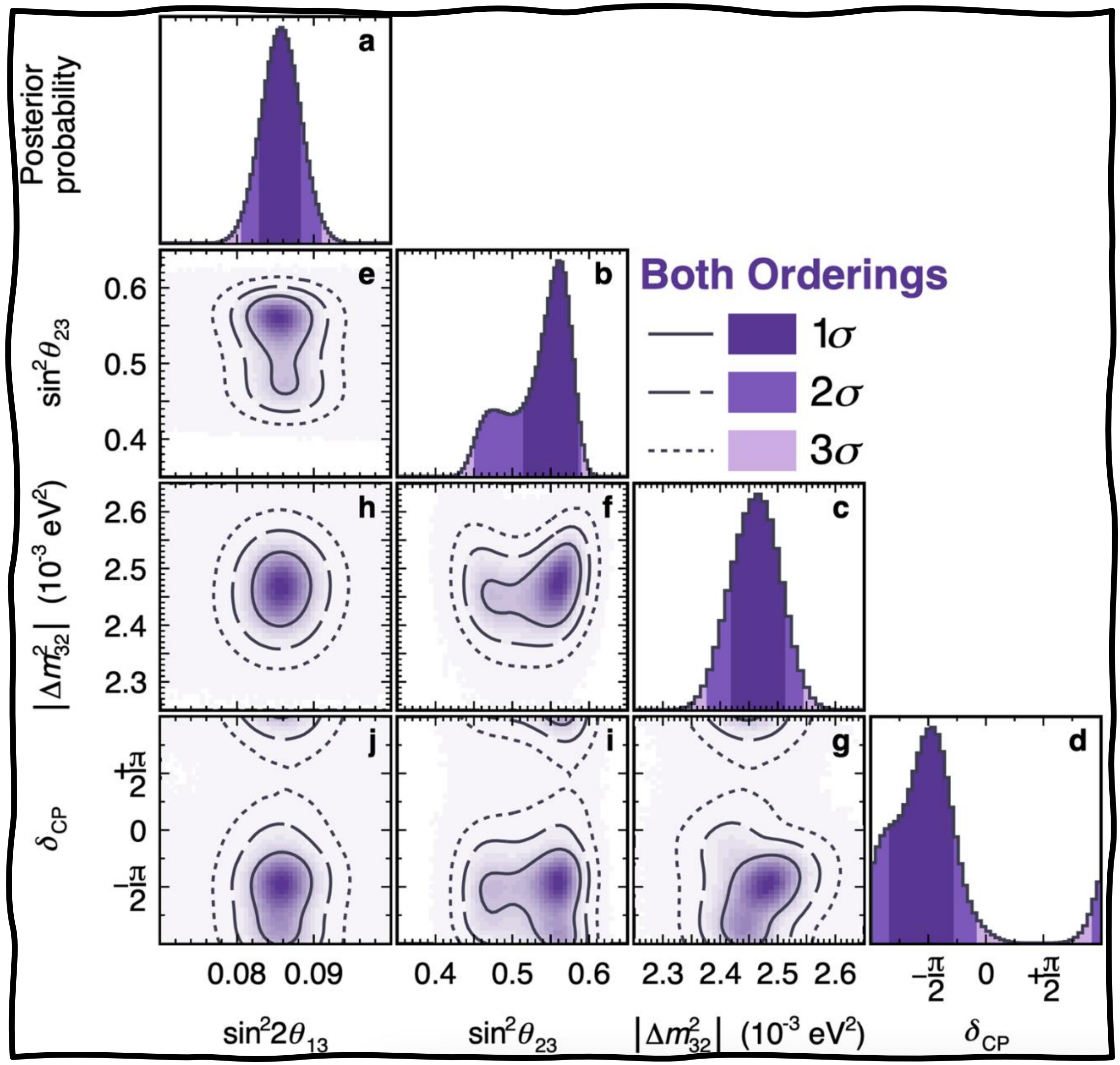
Jarlskog Invariant: captures the "scale" of CP violation

Methods and More

Methods

The analysis uses a Bayesian approach through Markov Chain Monte Carlo (ARIA for NOvA, MaCh3 for T2K) with containerized code to evaluate a joint likelihood over oscillation and nuisance parameters.

Complete integration: combining detector models, energy reconstruction, and uncertainties from both experiments simultaneously.



Extended Data Fig. 6


ONE DOES NOT SIMPLY
ADD NEUTRINOS AND FIT THEM
imgflip.com

Systematics

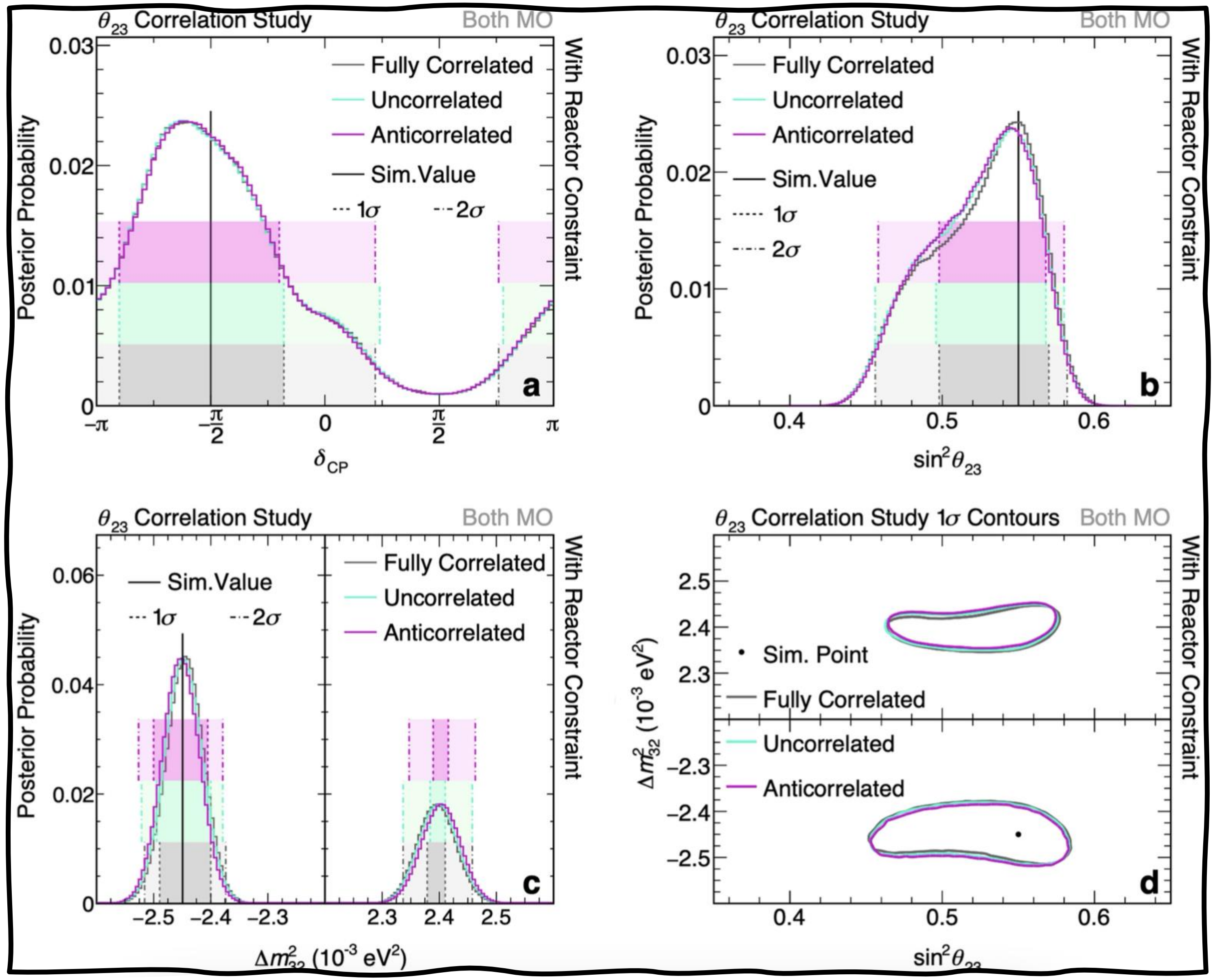
Systematics are carefully treated:

- Flux and detector systematics are largely uncorrelated between the experiments (different beams, near detectors, etc.); left uncorrelated

- Cross-section uncertainties originate from common physics but are implemented in very different models. Could in principle be correlated through a joint model, but for the present study it's left uncorrelated.

Systematics

Extended Data Fig. 1



Largest systematic affecting θ_{23} tested under correlation studies.

Shows no significant bias

What's the worst that could happen?

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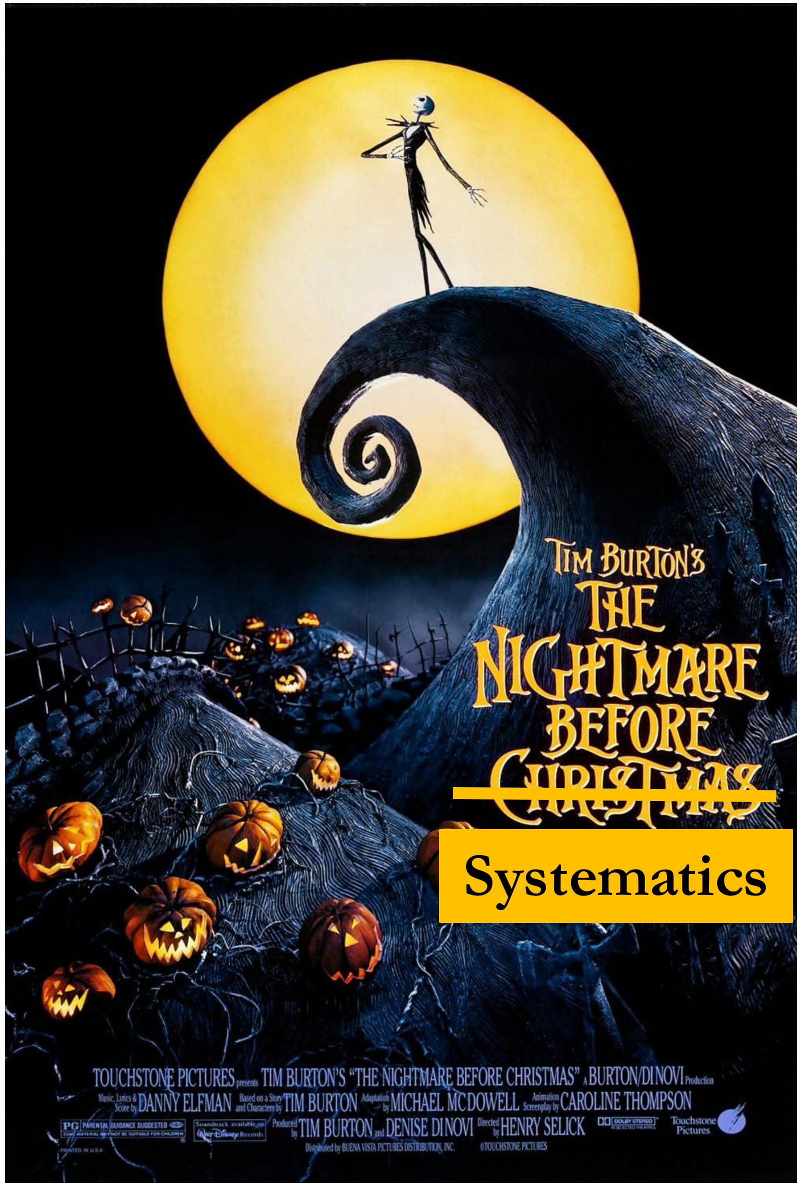

Nightmare parameters

As described in the main text, we study correlations in more extreme situations using the so-called nightmare parameters, which are either artificially constructed parameters or existing parameters with highly inflated uncertainties chosen to be deliberately problematic for the individual analyses. The prior uncertainties of the parameters are set so that they are comparable in impact to the statistical uncertainties on the measurements under study. We carry out this procedure separately for simulated measurements of Δm^2_{32} and θ_{23}. No nightmare study was carried out for δ_{CP} because its total systematic uncertainty compared with the statistical uncertainty is much smaller than for the other two cases.

Nightmare studies:

construct artificial systematic parameters,
or highly inflate existing ones,
and look for their effects...

Methods: Systematics Nightmare

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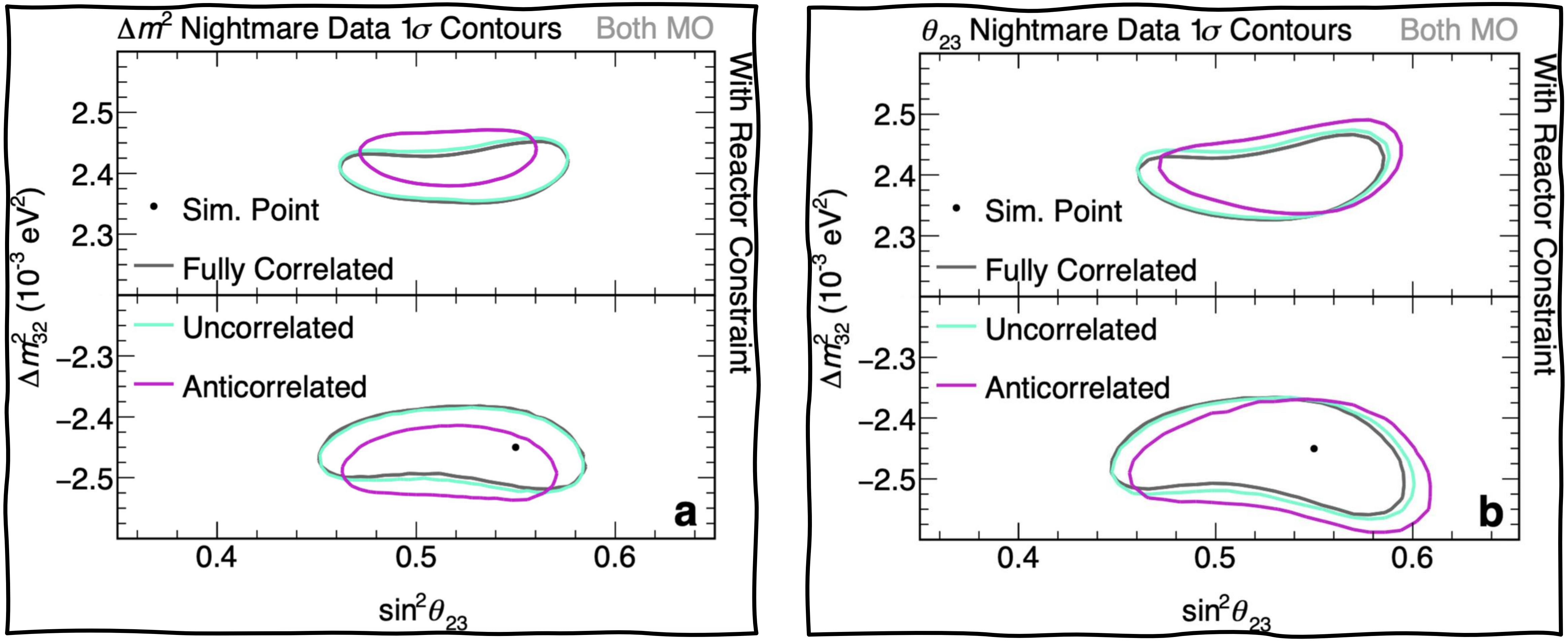

Your Worst Joint Fit Nightmare:

Fully anticorrelated parameters! Thankfully they are not currently present

Conclusions

A pristine collaborative effort between two long-baseline neutrino experiments.

Robust analysis methodology, placing world-leading constraints on the neutrino oscillation parameters at that time.

Do we live in the Inverted (neutrino mass) Ordering World?
Data suggests so…
…. BUT no such statistical significance to call it over yet!