The unitarity of neutrino mixing in light of atmospheric and reactor oscillation data

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Neutrino mixing **UNITARITY** is…

- Postulated in the three-flavour oscillation picture
- Violated in several neutrino mass generation models
- Possible to constrain using neutrinos alone [1-3]

The **NON-UNITARITY** manifests as…

flavour states — mass states

$$|\nu_\alpha\rangle = \frac{1}{\sqrt{(NN^\dagger)_{\alpha\alpha}}}\sum_{i=1}^{3} N^*_{\alpha i}|\nu_i\rangle$$

$$N = \begin{pmatrix} |N_{e1}| & |N_{e2}|e^{i\phi_{e2}} & |N_{e3}|e^{i\phi_{e3}} \\ |N_{\mu1}| & |N_{\mu2}| & |N_{\mu3}| \\ |N_{\tau1}| & |N_{\tau2}|e^{i\phi_{\tau2}} & |N_{\tau3}|e^{i\phi_{\tau3}} \end{pmatrix}$$

generic mixing matrix N with unconstrained elements [2]

$$NN^\dagger \neq \mathbb{I},\ N^\dagger N \neq \mathbb{I}$$

THIS STUDY asks…

How can we constrain N using atmospheric + reactor neutrino data?

&

How much do the systematic uncertainties impact the constraints?

not included for atmospheric neutrinos in previous global fits!

METHODS

1. Compute modified oscillations

"Standard Model" "non-unitary" Hamiltonian baseline

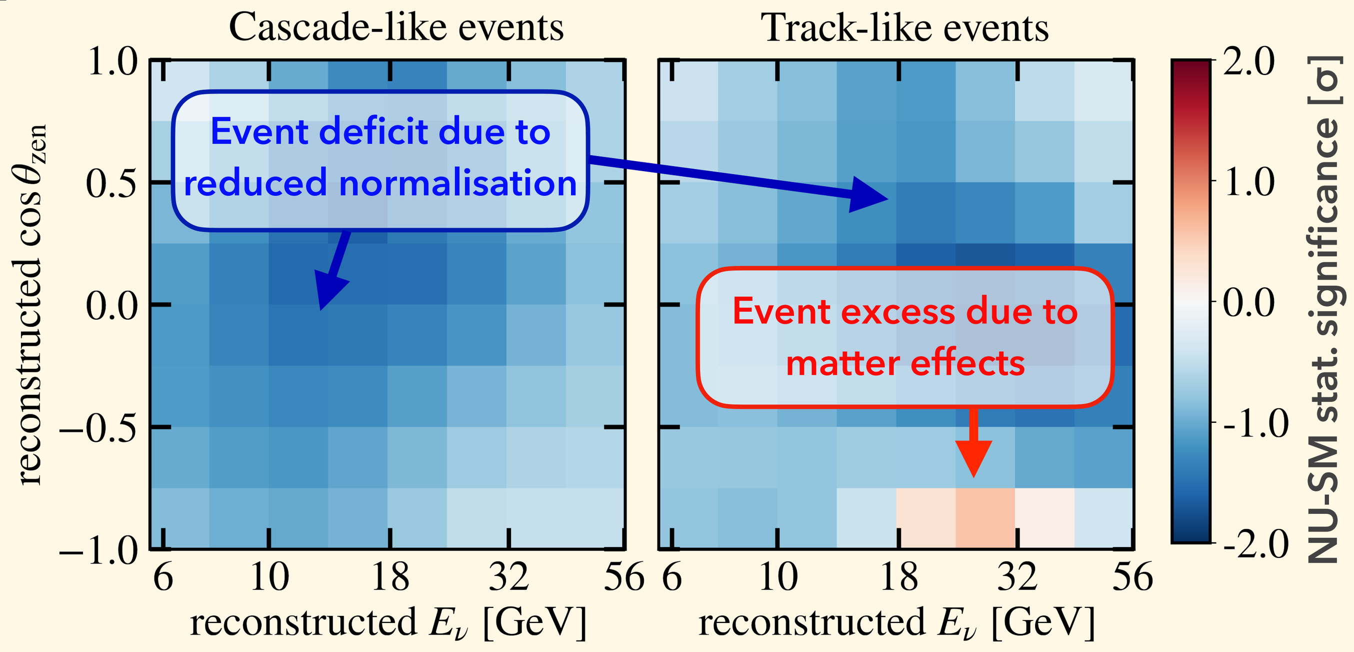
$$P^{\mathrm{SM}}_{\alpha\beta} \rightarrow P^{\mathrm{NU}}_{\alpha\beta}(E,L) = \frac{|(Ne^{-iHL}N^\dagger)_{\beta\alpha}|^2}{(NN^\dagger)_{\alpha\alpha}(NN^\dagger)_{\beta\beta}}$$

Take into account:

- matter effects with CC and NC potentials
- flux and cross section normalisations under non-unitarity

2. Produce expected event templates in detectors

Ex.: impact of $(NN^\dagger)_{\mu\mu} = 0.9$ on the IceCube-DeepCore 3y public Monte Carlo [4]



3. Contrast NU model with public data and perform a global Bayesian fit

- Test statistic: $\chi^2 \rightarrow$ log-likelihood
- Fit for $|N_{\alpha i}|$, $\phi_{\alpha i}$, Δm^2_{ij}, and $\mathcal{O}(10)$ systematic uncertainty parameters
- Algorithm: nested sampling (ULTRANEST)[5]

Current constraints

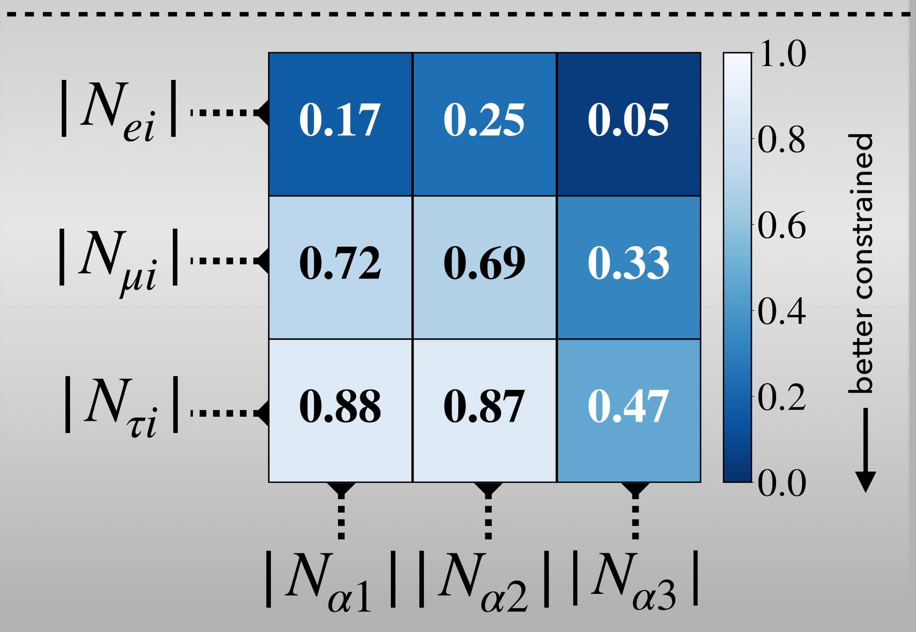
- IceCube-DeepCore: 3 years [4]
- Daya Bay: 3158 days [6]
- KamLAND: 5 years [7]

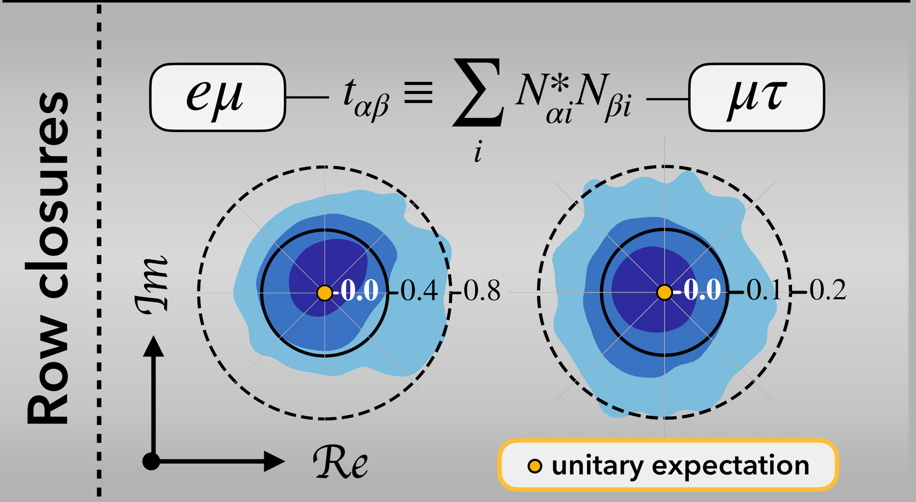
Future projections

- IceCube-Upgrade: 3 years [8]
- Daya Bay: 3158 days [6]
- JUNO: 6 years [9]

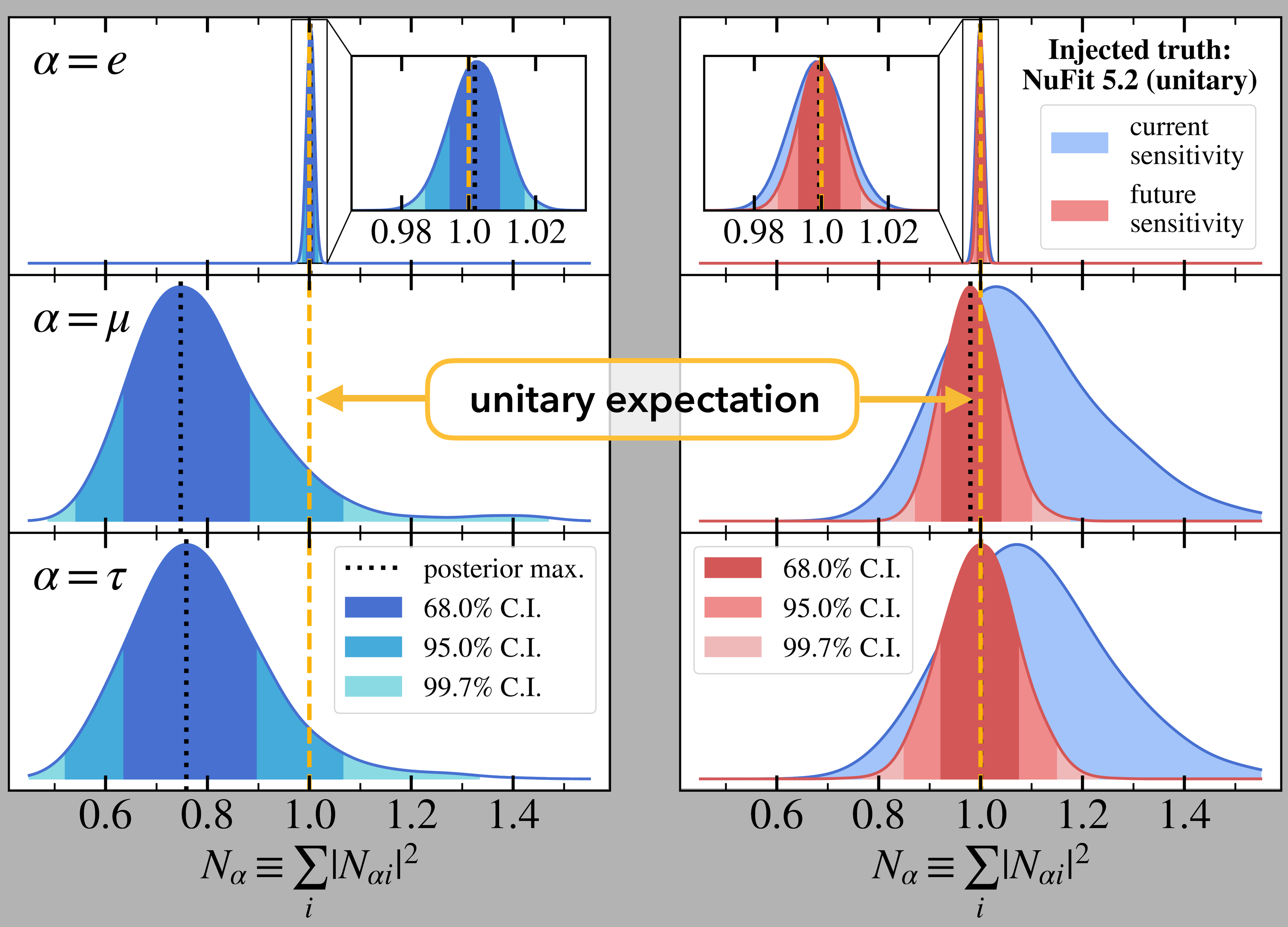
RESULTS

Matrix elements: 3σ range width

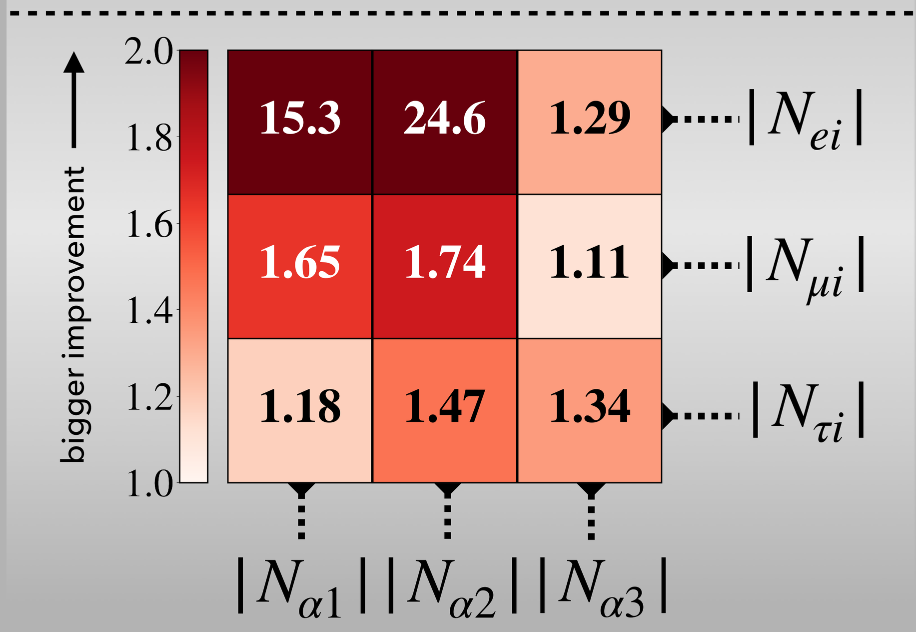


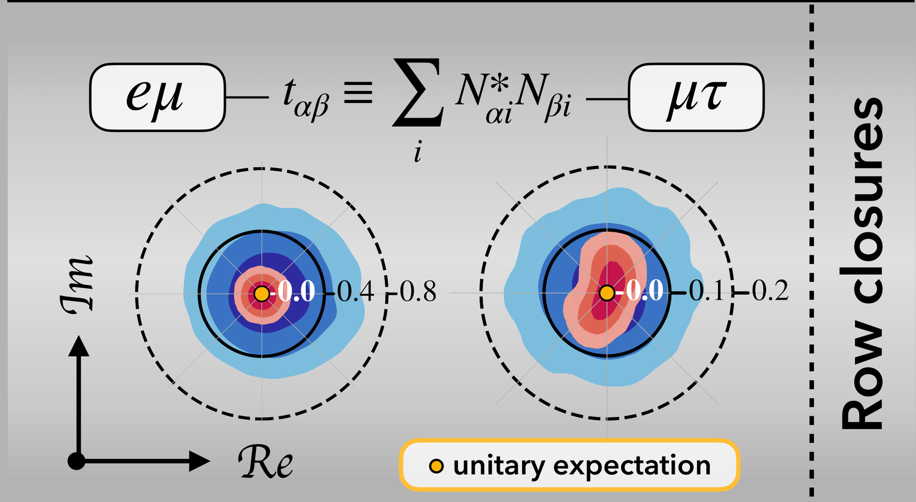


Row normalisations, N_α



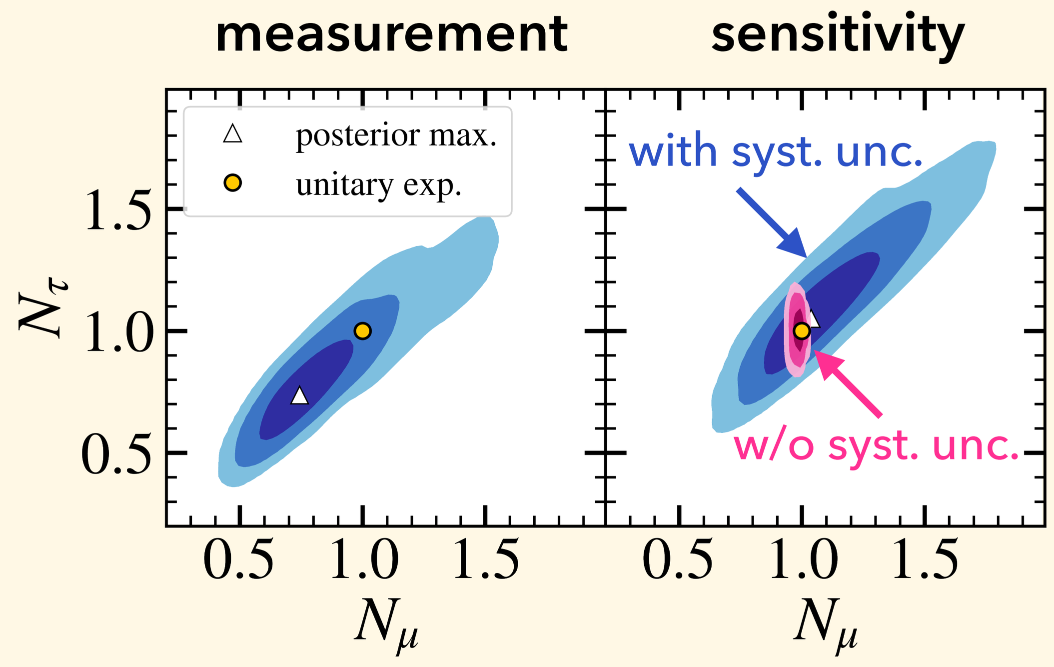
Matrix elements: 3σ range improvement factor





IMPACT OF ATMOSPHERIC NEUTRINO SYSTEMATICS

- Our results indicate $N_\mu, N_\tau < 1$ with **strong correlations** in the posteriors:
- These correlations occur due to coupling to the atmospheric neutrino flux uncertainties.



TAKE-AWAY

A combined analysis of atmospheric and reactor neutrino data finds results **consistent with unitarity at 1.3σ*** and reveals the **critical impact of the atmospheric neutrino systematic uncertainties** on the non-unitarity measurement.

*considering row normalisations

[1] S. Parke, M. Ross-Lonergan, Phys. Rev. D 93, 113009 (2016).
[2] S. Ellis, K. Kelly, S. Li, JHEP12 (2020) 068.
[3] P. Denton, J. Gehrlein, JHEP 06 (2022) 135.
[4] IceCube Collaboration, Three-year high-statistics neutrino oscillation samples, DOI:10.21234/ac23-ra43 (2019).
[5] J. Buchner, Stat. Comput. 26, 383–392 (2016).
[6] Daya Bay Collaboration, Phys. Rev. Lett. 130, 161802 (2023).
[7] KamLAND Collaboration, Phys. Rev. Lett. 100, 221803 (2008).
[8] IceCube Collaboration IceCube Upgrade Neutrino Monte Carlo Simulation, DOI:10.21234/qfz1-yh02 (2020).
[9] JUNO Collaboration, Chinese Phys. C 46 123001 (2022).