New tau neutrino oscillation and scattering constraints on unitarity violation

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in collaboration with Peter B. Denton
(appears tonight on the arxiv!)

(Non)-Unitarity

- global neutrino oscillation analysis assumed **unitarity** of 3×3 mixing matrix

- many new physics scenarios predict **non-unitarity matrix**, for example models with heavy, sterile neutrinos

$\Rightarrow$ testable 3×3 matrix is not unitary but a submatrix of a larger unitary matrix

$$\begin{pmatrix} \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} & \begin{matrix} \cdots & U_{eN} \\ \cdots & U_{\mu N} \\ \cdots & U_{\tau N} \end{matrix} \\ \begin{matrix} \vdots & \vdots & \vdots \\ U_{s_n 1} & U_{s_n 2} & U_{s_n 3} \end{matrix} & \begin{matrix} \ddots & \vdots \\ \cdots & U_{s_n N} \end{matrix} \end{pmatrix}$$

What are the constraints on the leptonic mixing matrix without assuming unitarity?

(see also Stephen's talk yesterday)

Non-unitarity

- depending on mass scale of the steriles $\rightarrow$ different phenomenology at oscillation experiments
  - $m_4 \lesssim \mathcal{O}$(eV): oscillations can be resolved at experiments
  - $m_4 \in$[10 eV-15 MeV]: sterile oscillations are too fast to be resolved at experiments $\rightarrow$ averaged out oscillations
  - $m_4 \gtrsim$ 40 MeV: steriles are too heavy to be produced in neutrino beams
- focus on $m_4 \in$[10 eV-15 MeV] scenario here

  (see also Jacobo's talk yesterday, BSM talks on Friday for sterile pheno)

Effects of unitarity violation [Denton, Gehrlein '21]

- on oscillation probability

$$P_{\alpha\beta}(E,L) = \frac{|\sum_{i=1}^{acc} U_{\alpha i}^* e^{iP_i L} U_{\beta i}|^2}{(UU^\dagger)_{\alpha\alpha}(UU^\dagger)_{\beta\beta}},$$

- on CC cross section and flux

$$\sigma_\alpha^{CC} = \sigma_\alpha^{CC,SM}(UU^\dagger)_{\alpha\alpha}, \qquad \frac{d\phi_\alpha^{CC}}{dE} = \frac{d\phi_\alpha^{CC,SM}}{dE}(UU^\dagger)_{\alpha\alpha}.$$

Effects of unitarity violation [Denton, Gehrlein '21]

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- on NC cross section

$$\sigma_i^{NC}=\sigma^{NC,SM}\sum_{j=1}^{acc}|(U^\dagger U)_{ij}|^2\,,$$

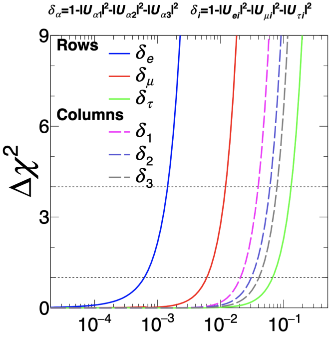
where $(U^\dagger U)_{ij}=\sum_{\alpha=e}^{\tau}U^*_{\alpha i}U_{\alpha j}$ summed over all active flavors in the flavor basis

$$\sigma_\beta^{NC}=\sigma^{NC,SM}|(UU^\dagger)_{\beta\beta}|^2\,,$$

summed over all accessible mass states

Non-unitarity analysis

Recent analysis by [Hu, Ling, Tang, Wang '19] , see also [Ellis, Kelly, Li '19, Parke, Ross-Lonergan' 16]



deviations from unitarity well constrained for electron and muon row normalizations $\leftrightarrow$ constraint on tau row normalization rather weak

Non-unitarity analysis: Tau row

- tau row mostly informed from muon neutrino disappearance experiments, and tau appearance experiments
- **more tau neutrino data sets available in literature!**
- in [Denton, Gehrlein '21] pioneer use of **new** tau data sets for non-unitarity studies
- focus on tau row only $\rightarrow$ use priors on electron and muon row matrix elements from studies in literature

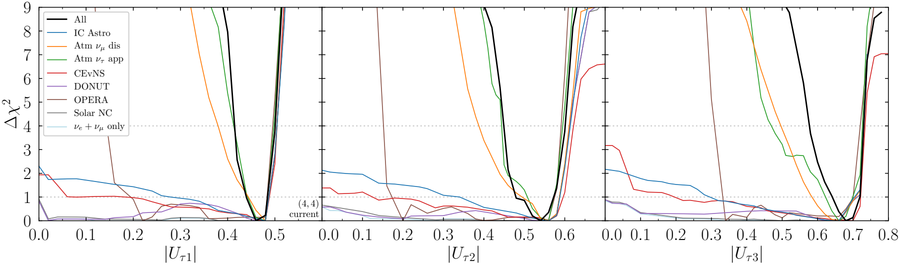
$\Rightarrow$ derive **novel** results on tau row matrix elements and tau row normalization

Tau data sets: current [Denton, Gehrlein '21]

- Atmospheric ν_μ disappearance (DeepCore, SuperK, IceCube)
- Long baseline ν_τ appearance data (OPERA)
- **new:** ν_τ CC scattering data from DOnuT
- **new:** Atmospheric ν_τ appearance (IceCube, SuperK)
- **new:** Astrophysical ν_τ appearance (IceCube)
- **new:** NC data from SNO
- **new:** NC data from CEvNS

Results: current data [Denton, Gehrlein '21]

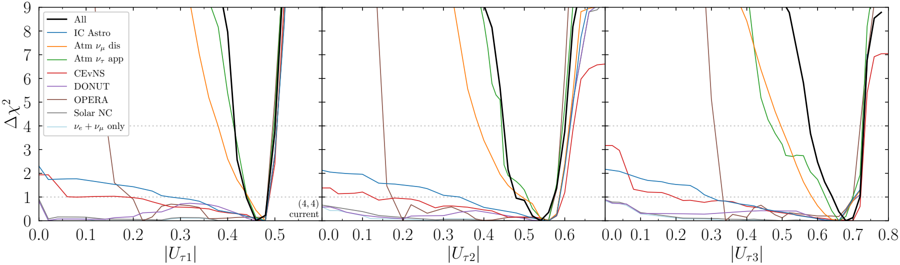
most impactful constraints: atmospheric ν_μ disappearance, atmospheric ν_τ appearance, long baseline ν_τ appearance data



[Denton, Gehrlein '21]

Results: current data [Denton, Gehrlein ’21]

less impactful constraints: NC data from SNO, NC data from CEvNS, ν_τ CC scattering data from DOnuT, astrophysical ν_τ appearance



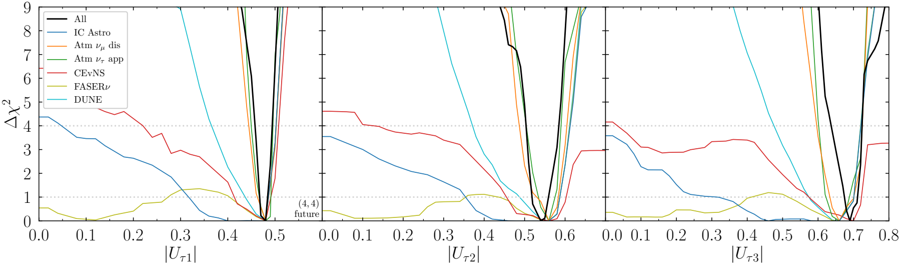
[Denton, Gehrlein ’21]

Results: future data [Denton, Gehrlein '21]

- assume that future results are compatible with unitarity 3×3 mixing matrix
- Atmospheric ν_μ disappearance (HyperK, KM3NeT/ORCA)
- Long baseline ν_τ appearance data (DUNE)
- **new:** ν_τ CC scattering data from FASERnu
- **new:** Atmospheric ν_τ appearance (KM3NeT/ORCA, HyperK)
- **new:** Astrophysical ν_τ appearance (IceCube-Gen2)
- **new:** NC data from CEvNS (assume 5x more data)

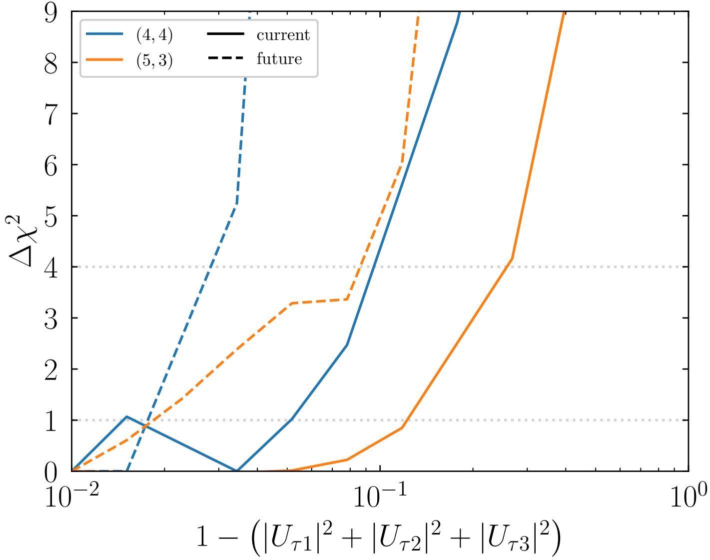
Results: future data [Denton, Gehrlein '21]

most impactful constraints: Atmospheric ν_μ disappearance, atmospheric ν_τ appearance, long baseline tau appearance data, NC scattering data CEvNS

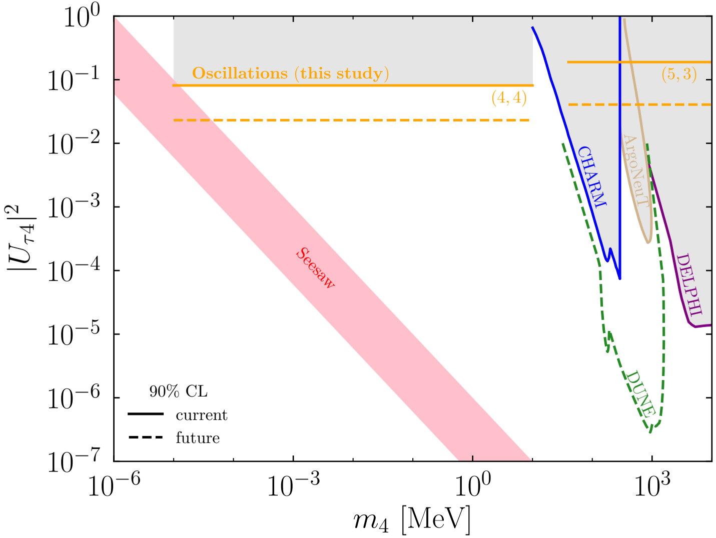


[Denton, Gehrlein '21]

Results: tau row normalization [Denton, Gehrlein '21]



Results: comparison to direct searches [Denton, Gehrlein '21]



[Denton, Gehrlein '21]

Summary & Conclusions

- introduced new, previously overlooked tau neutrino data sets
- derived constraints on tau row matrix elements and tau row normalization with current data as well as forecasted prospects
- complementary constraints to direct searches
- tau row in better shape than previously assumed in the literature

  $\Rightarrow$ in the future the tau row can be measured potentially as well as the muon row!

Thank you for your attention!

[Art work by symmetry magazine]

Backup: Analytical expressions [Denton, Gehrlein '19]

- NOMAD

$$\tilde{P}(\nu_\mu \to \nu_\tau) = \left| \sum_{i=1}^{acc} U_{\mu i}^* U_{\tau i} \right|^2 - 2\Re \left(\sum_{j=heavy}^{acc} U_{\mu j}^* U_{\tau j} \sum_{i=1}^{3} U_{\mu i} U_{\tau i}^* \right) ,$$

- CEvNS

$$n_{NC}^{CEvNS} = \sigma^{NC,SM} \sum_{\alpha=e}^{\mu} \phi_\alpha^{\mathrm{SM}}$$

$$\sum_{\beta=e}^{\tau} \left[\left| \sum_{i=1}^{acc} U_{\alpha i}^* U_{\beta i} \right|^2 - 2\Re \left(\sum_{j=heavy}^{acc} U_{\alpha j}^* U_{\beta j} \sum_{i=1}^{3} U_{\alpha i} U_{\beta i}^* \right) \right] (UU^\dagger)_{\beta\beta} ,$$

Backup: Analytical expressions [Denton, Gehrlein '19]

- Astrophysical tau appearance

$$n_{\nu_\alpha}^{theo} = \sigma_\alpha^{CC,SM}(UU^\dagger)_{\alpha\alpha} \times \phi_p(\xi(UU^\dagger)_{ee}P_{e\alpha} + (1-\xi)(UU^\dagger)_{\mu\mu}P_{\mu\alpha})$$

- compare

$$\left(\frac{\phi_{\nu_\tau}}{\phi_{track}}\right)^{meas}$$

to theory prediction

Backup: Results in (5,3) case [Denton, Gehrlein '21]