

Snowmass2021 - Letter of Interest

Non-Unitarity of the neutrino mixing matrix

NF Topical Groups:

Primary: (NF3) Beyond the Standard Model

Secondary: (NF2) Sterile neutrinos

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In the precision era of neutrino physics, it is expected that the next generation of long-baseline (LBL) neutrino experiments, such as DUNE [1, 2] and Hyper-Kamiokande, will finally determine the standard oscillation parameters. In particular, one expects that the CP violating phase, δ , will be determined with 5σ precision. In this context, it is extremely relevant to scrutinize the robustness of this determination and ascertain whether we really live in a world with only three neutrinos, or if, on the contrary, more neutrino states exist.

To settle this question one needs to perform unitarity tests of the lepton mixing matrix, that relates the flavor and mass neutrino eigenstates. If more neutrino states exist, then the 3×3 neutrino mixing matrix, will be a submatrix of a larger and complete matrix that includes all the neutrino states. Such a scenario is well-motivated from the theoretical point of view as a test of the seesaw picture. The combination of short and long-baseline neutrino experiments open the opportunity to test for this physics and, at the same time, provide a robust three-neutrino picture if no signal is found.

The Standard Model of particle physics [3–5] was constructed under the hypothesis of a zero neutrino mass. Although this was well-motivated from the experimental observation of parity violation [6, 7], there were theoretical motivations to assume a tiny, but not zero, neutrino mass. One of the main motivations for considering a non-zero neutrino mass was the absence of a basic underlying symmetry that prevents the neutrino from having a mass.

This discussion found its main stream within the well-known seesaw mechanism [8–14]. There are different realizations of these mechanism, particularly the Type-I mechanism naturally requires new heavy neutrinos, also called neutral heavy leptons (NHL). These heavy messengers of neutrino mass generation, expected to be heavier than the Z^0 boson, would not be emitted in most weak decays, leading to a violation of universality. Although they could, they are not likely to be accesible to collider experiments. However, there is also a broad class of low-scale seesaw models [15–18] where the mass of the NHL could be accessible. In any case, the admixture of these states in the charged current weak interactions would affect neutrino oscillations which will be described by a non-unitary neutrino mixing matrix. Deviations from unitarity can be readily parametrized as [19]

$$N = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ \alpha_{21} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} U \quad (1)$$

where U is a unitary matrix that can be described as usual [12, 20, 21]. The triangular matrix encodes the deviation from the non-unitarity for any number of neutrino species (a similar parametrization for the case of $3 + 1$ and $3 + 3$ dimensional mixing was studied in Refs. [22, 23]).

The implications of non-unitarity have been previously studied in electroweak precision observables and in neutrino oscillations [24–36]. The challenges for the future would be the following:

- **Long baseline neutrino experiments** For neutrino oscillation experiments, a non-unitarity mixing matrix implies new CP violating phases. Their interplay with the conventional phase can open a rich phenomenology in LBL neutrino experiments [37, 38] such as DUNE [1, 2].
- **Short baseline neutrino experiments** Important complementary constraints on non-unitarity pa-

rameters can be obtained from these experiments due to the zero-distance effect in non-unitarity. Some important cases would be:

- The Short baseline neutrino program SBN [39, 40] aimed to test the light sterile neutrino hypothesis could also get restrictions on the α_{21} non-unitary parameter [41], at a level competitive with the NOMAD constraint of $|\alpha_{21}|^2 \leq 7 \times 10^{-4}$ at 90 % CL.
- The coherent elastic neutrino-nucleus scattering [42] has been recently measured by the COHERENT collaborations [43]. It is a promising tool in constraining non-standard interactions and it could also be useful to constrain non-unitarity [44].
- Spallation neutron source experiments such as MOMENT could also give constraints on non-unitarity using conventional detectors as has been studied, for example, in Ref. [45]

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