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Constraining neutrino non-standard interactions from low energy neutrino experiments

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Based on Refs.[1], [2], [3]

Abstract

The standard three-active neutrino oscillation picture would be modified in the presence of neutrino non-standard interactions (NSIs). In a model-independent manner, I shall review dimension-6 SMEFT operators that can induce such NSIs. Then, by focusing on terrestrial neutrino oscillation experiments Daya Bay, Double Chooz, RENO, T2K, NOvA, as well as T2HK, DUNE, JUNO and JUNO-TAO in the near future, I will discuss their sensitivity to new physics in SMEFT. Results on neutral current NSIs from COHERENT and precision measurements of $N_{\rm eff}$ at both Planck and CMB-S4 will also be discussed.

FROM QM to QFT

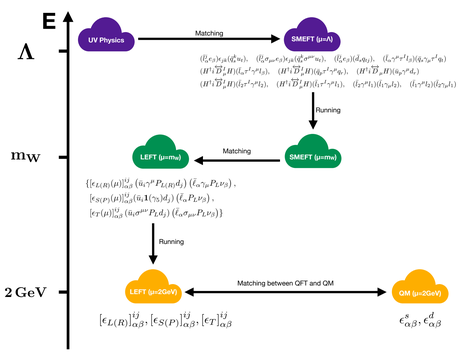
For neutrino oscillation experiments, neutrinos of different flavors at production and detection are usually parameterized in the following form in the quantum mechanical (QM) formalism:

$$|\nu^s_\alpha\rangle = \frac{(1+\epsilon^s)_{\alpha\gamma}}{N^s_\alpha}|\nu_\gamma\rangle,\ \langle\nu^d_\beta| = \langle\nu_\gamma|\frac{(1+\epsilon^d)_{\gamma\beta}}{N^d_\beta},$$

where ϵ^s and ϵ^d parameterize effects of new physics. On the other hand, since neutrino oscillation experiments are very low-energy ones, the system can also be parameterized in the quantum-field-theory (QFT) formalism as follows:

$$\begin{aligned}\mathcal{L}_{\rm CC} \supset -\frac{2V_{ud}}{v^2}\Big\{&[1+\epsilon_L]^{ij}_{\alpha\beta}\left(\bar u_i\gamma^\mu P_L d_j\right)\left(\bar\ell_\alpha\gamma_\mu P_L\nu_\beta\right)+[\epsilon_R]^{ij}_{\alpha\beta}\left(\bar u_i\gamma^\mu P_R d_j\right)\left(\bar\ell_\alpha\gamma_\mu P_L\nu_\beta\right)\\&+\frac{1}{2}[\epsilon_S]^{ij}_{\alpha\beta}\left(\bar u_i d_j\right)\left(\bar\ell_\alpha P_L\nu_\beta\right)-\frac{1}{2}[\epsilon_P]^{ij}_{\alpha\beta}\left(\bar u_i\gamma_5 d_j\right)\left(\bar\ell_\alpha P_L\nu_\beta\right)\\&+\frac{1}{4}[\epsilon_T]^{ij}_{\alpha\beta}\left(\bar u_i\sigma^{\mu\nu}P_L d_j\right)\left(\bar\ell_\alpha\sigma_{\mu\nu}P_L\nu_\beta\right)+{\rm h.c.}\Big\},\end{aligned}$$

where $\epsilon_{L,R,S,P,T}$ encode effects of new physics and "CC" stands for charge-current neutrino non-standard interactions (NSIs). To connect the parameters in the QM and the QFT formalisms, a consistent matching can be obtained following the procedure outlined in Ref.[4]. Once the connection is obtained, one can then readily connect NSIs in the QFT formalism to, for example, the Standard Model Effective Field Theory (SMEFT) through matching and running as depicted in the following graph:



In this way, constraints on ϵ^s and ϵ^d in the QM formalism can be translated onto those of the Wilson coefficients in the SMEFT, or equivalently, the UV scale.

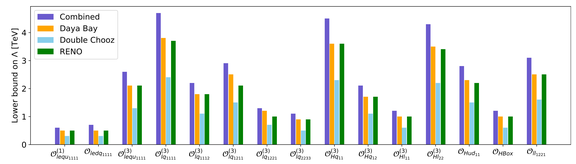
On the other hand, for Neutral-Current (NC) NSIs, we consider contact interactions between neutrinos and electrons, neutrinos and photons, as well as neutrino self-interactions in the EFT framework. All possible operators up to dimension-7 are listed in the table below:

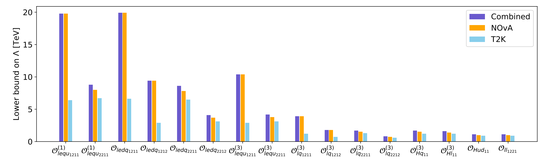
Dimensions	Operators	Wilson coefficients
dimension-5	$\mathcal{O}^{(5)}_1 = \frac{c}{8\pi}\left(\bar\nu_\beta\sigma^{\mu\nu}P_L\nu_\alpha\right)F_{\mu\nu}$	$C^{(5)}_1$
dimension-6	$\mathcal{O}^{(6)}_{1,f} = \left(\bar\nu_\beta\gamma_\mu P_L\nu_\alpha\right)\left(\bar f\gamma^\mu f\right)$	$C^{(6)}_{1,f}$
	$\mathcal{O}^{(6)}_{2,f} = \left(\bar\nu_\beta\gamma_\mu P_L\nu_\alpha\right)\left(\bar f\gamma^\mu\gamma_5 f\right)$	$C^{(6)}_{2,f}$
	$\mathcal{O}^{(6)}_3 = \left(\overline{\nu^c}_\beta P_L\nu_\alpha\right)\left(\overline{\nu^c}_{\beta'}P_L\nu_{\alpha'}\right)^\clubsuit$	$C^{(6)}_3$
	$\mathcal{O}^{(6)}_4 = \left(\bar\nu_\beta\gamma_\mu P_L\nu_\alpha\right)\left(\bar\nu_{\beta'}\gamma_\mu P_L\nu_{\alpha'}\right)^\clubsuit$	$C^{(6)}_4$
	$\mathcal{O}^{(6)}_5 = \left(\overline{\nu^c}_\beta\sigma^{\mu\nu}P_L\nu_\alpha\right)\left(\overline{\nu^c}_{\beta'}\sigma^{\mu\nu}P_L\nu_{\alpha'}\right)^\clubsuit$	$C^{(6)}_5$
dimension-7	$\mathcal{O}^{(7)}_1 = \frac{\alpha}{12\pi}\left(\bar\nu_\beta P_L\nu_\alpha\right)F^{\mu\nu}F_{\mu\nu}$	$C^{(7)}_1$
	$\mathcal{O}^{(7)}_2 = \frac{\alpha}{8\pi}\left(\bar\nu_\beta P_L\nu_\alpha\right)F^{\mu\nu}\tilde F_{\mu\nu}$	$C^{(7)}_2$
	$\mathcal{O}^{(7)}_{5,f} = m_f\left(\bar\nu_\beta P_L\nu_\alpha\right)\left(\bar f f\right)$	$C^{(7)}_{5,f}$
	$\mathcal{O}^{(7)}_{6,f} = m_f\left(\bar\nu_\beta P_L\nu_\alpha\right)\left(\bar f i\gamma_5 f\right)$	$C^{(7)}_{6,f}$
	$\mathcal{O}^{(7)}_{7,f} = m_f\left(\bar\nu_\beta\sigma^{\mu\nu}P_L\nu_\alpha\right)\left(\bar f\sigma_{\mu\nu}f\right)$	$C^{(7)}_{7,f}$
	$\mathcal{O}^{(7)}_{8,f} = \left(\bar\nu_\beta i\overleftrightarrow{\partial}_\mu P_L\nu_\alpha\right)\left(\bar f\gamma^\mu f\right)$	$C^{(7)}_{8,f}$
	$\mathcal{O}^{(7)}_{9,f} = \left(\bar\nu_\beta i\overleftrightarrow{\partial}_\mu P_L\nu_\alpha\right)\left(\bar f\gamma^\mu\gamma_5 f\right)$	$C^{(7)}_{9,f}$
	$\mathcal{O}^{(7)}_{10,f} = \partial_\mu\left(\bar\nu_\beta\sigma^{\mu\nu}P_L\nu_\alpha\right)\left(\bar f\gamma_\nu f\right)$	$C^{(7)}_{10,f}$
	$\mathcal{O}^{(7)}_{11,f} = \partial_\mu\left(\bar\nu_\beta\sigma^{\mu\nu}P_L\nu_\alpha\right)\left(\bar f\gamma_\nu\gamma_5 f\right)$	$C^{(7)}_{11,f}$

Each type of interactions in the table above could affect neutrino decoupling in the early Universe, thus altering the prediction of $N_{\rm eff}$. Since $N_{\rm eff}$ has been precisely measured by Planck as well as CMB-S4 in the future at the percent level, these operators would be constrained from precision measurements of $N_{\rm eff}$.

Results: CC NSIs

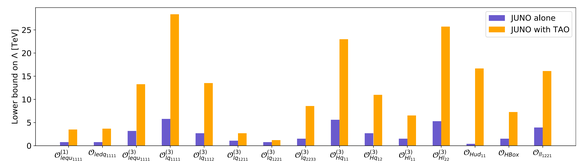
Constraints for current neutrino oscillation experiments Daya Bay, Double Chooz, RENO, T2K and NOvA are summarized below with their Wilson coefficients fixed at one and considering only one operator to dominate at a time [1]. Note that the upper bound on Λ from reactor type experiments is at most ~5 TeV, while for accelerator ones, it is about 20 TeV. However, as can be seen from the horizontal axis, these two types of experiments are actually probing different subsets of the SMEFT dimension-6 operators, implying the complementarity between them and suggesting that one exploit the ability of different experiments in searching for BSM physics.

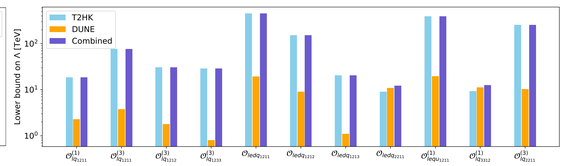




Similarly, we show our results from future neutrino oscillation experiments JUNO, JUNO-TAO, T2HK and DUNE [2]. We stress that with the configuration summarized in [2], we find that T2HK would be sensitive to new physics around the O(100)TeV scale, while it is about 25 TeV for JUNO-TAO and DUNE. We point out that in each configuration, the near detector will play a very significant role in exploring new physics above the weak scale. Once again, the complementarity among these experiments is seen from the plots below.

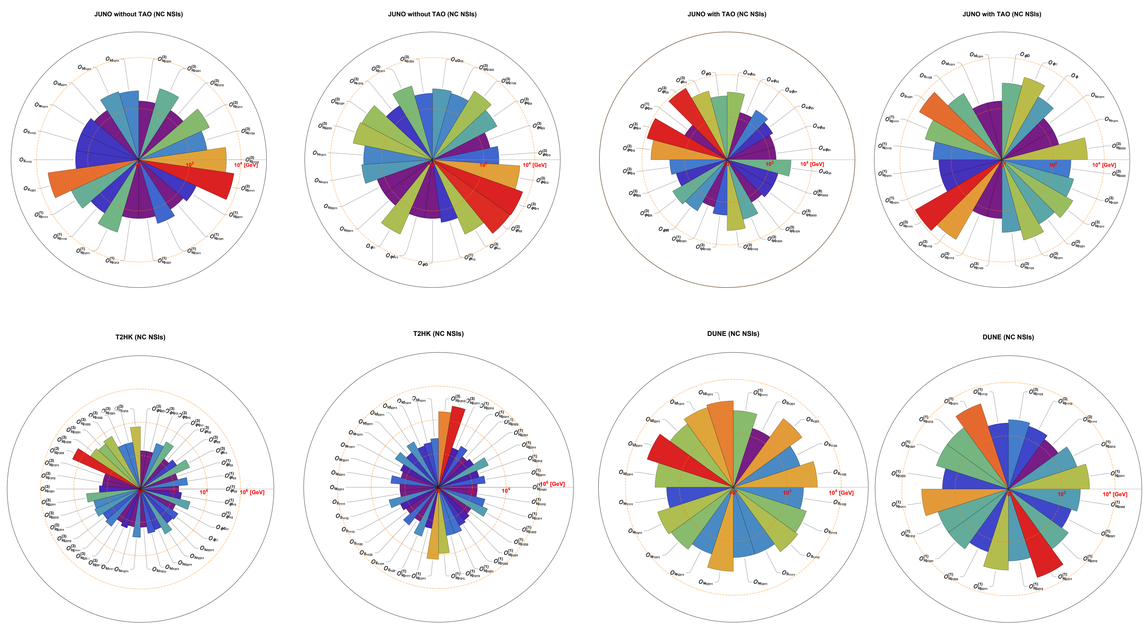
The dimension-6 operators shown in these plots would be the most stringently constrained ones from future experiments. For the constraints on all dimension-6 SMEFT operators, please visit the summary Github page at SMEFT_NSIs.





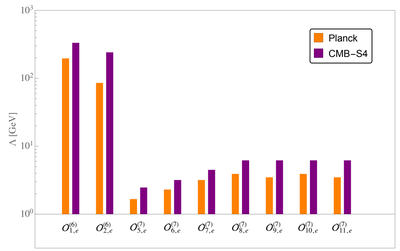
Results: NC NSIs

Due to the very long baseline of future neutrino oscillation experiments like DUNE and T2HK, matter effects, which can also be induced by NC NSIs, will become significant for neutrino production, detection and propagation. Understanding NC NSIs would be essential to correctly interpret the experimental results. Assuming the standard three-active neutrino picture for neutrino oscillation, we study constraints on these NC NSIs from future neutrino experiments and summarize our results below [2]:

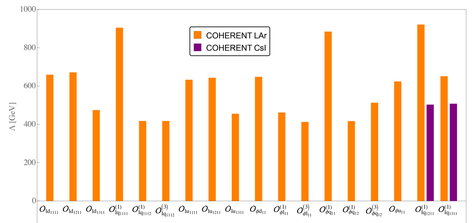


Results: NC NSIs - - continued

On the other hand, NC NSIs can also modify the cross section of coherent elastic neutrino-nucleus scattering as well as $N_{\rm eff}$ in the early Universe during neutrino decoupling. We show our results below [2,3].



Results on operators listed in previous table from precision measurements of $N_{\rm eff}$. For comparison with previous results from various experiments that are sensitive to NC NSIs, see our discussion in Ref.[3]. We point it out that comparable or even stronger bounds can be obtained from precision $N_{\rm eff}$.



Constraints on SMEFT dimension-6 operators from the COHERENT experiment with the CsI and the LAr detector respectively. Note that both the number of constrained operators and the lower bounds on Λ increase with the LAr detector.

Conclusions

1. Current reactor and accelerator type neutrino experiments are already sensitive to new physics at ~ 5 TeV and ~ 20 TeV, they are complementary to each other in probing different subsets of SMEFT operators.
2. JUNO, JUNO-TAO, T2HK and DUNE would extend above bounds to around the O(10-100) TeV.
3. Precision measurements of $N_{\rm eff}$ from Planck and CMB-S4 put stringent constraints on NC NSIs, dimension-6 neutrino-electron contact interactions are most stringently constrained to be above O(100GeV). Results on dimension-7 operators are mostly firstly obtained from our work.
4. CEvNS events already constraint new physics to be above ~1TeV scale with the LAr detector. We expect this bound to be improved with more events in the future.

References

[1] *JHEP* 03 (2021) 019 • e-Print: 2011.14292 [hep-ph]
[2] e-Print: 2106.15800 [hep-ph]
[3] *JHEP* 05 (2021) 058 • e-Print: 2101.10475 [hep-ph]
[4] *JHEP* 11 (2020) 048 • e-Print: 1910.02971 [hep-ph]

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