Snowmass2021 - Letter of Interest

A comprehensive EFT global fit in the neutrino oscillation experiments

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Abstract

This Letter of Interest (LOI) proposes to systematically study the physics beyond the standard model (BSM) in the neutrino oscillation experiments within the standard model Effective Field Theory (SMEFT) framework. Thus, the analysis of the data can capture large classes of models, where the new degrees of freedom have masses well above the relevant energy for the experiment. Moreover, it allows to compare several experiments in a unified framework and in a systematic way. The approach will be applied to several short- and long baseline neutrino experiments, for which the results can be included in the GLoBES-EFT package, or equivalent pieces of software so that both theorists and experimentalists can directly use the outcome.

NF Topical Groups: (check all that apply ☐/■)
■ (NF1) Neutrino oscillations
☐ (NF2) Sterile neutrinos
■ (NF3) Beyond the Standard Model
☐ (NF4) Neutrinos from natural sources
■ (NF5) Neutrino properties
☐ (NF6) Neutrino cross sections
☐ (NF7) Applications
■ (TF11) Theory of neutrino physics
☐ (NF9) Artificial neutrino sources
☐ (NF10) Neutrino detectors

TF Topical Groups: (check all that apply ☐/■)
☐ (TF01) String theory, quantum gravity, black holes
■ (TF02) Effective field theory techniques
☐ (TF03) CFT and formal QFT
☐ (TF04) Scattering amplitudes
☐ (TF05) Lattice gauge theory
☐ (TF06) Theory techniques for precision physics
☐ (TF07) Collider phenomenology
■ (TF08) BSM model building
☐ (TF09) Astro-particle physics & cosmology
☐ (TF10) Quantum Information Science
■ (TF11) Theory of neutrino physics

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Introduction: After several decades of neutrino oscillation experiments currently most standard neutrino parameters are over-constrained by several measurements. Hence, one can use this wealth to explore new physics beyond the neutrino masses and mixings. Traditionally the BSM searches in the neutrino sector are done through the so-called **non-standard interactions** (NSI), a generic feature of theories of neutrino mass generation, that may have important phenomenological implications [1–25]. The new physics (NP) at the production, detection and propagation of neutrinos is parametrized by the effective couplings $\epsilon^{s,d,m}$, respectively. However, there has been little emphasis on connecting these couplings to parameters of concrete ultraviolet (UV) models. As shown in Ref [26], there are several limitations in the literature when this traditional approach is used: 1) For some production/detection processes there is no matching between $\epsilon^{s,d}$ and the Wilson coefficients of a well-defined and systematic framework of EFT; 2) The $\epsilon^{s,m,d}$ in the traditional approach are usually assumed to be independent of each other, while in reality there are certain correlations between the production, propagation and detection processes which need to be considered in a careful study. On the other hand, full attention has not been paid to such issues as: i) Power counting of NSI effects; ii) Extraction of the mixing angles in the presence of general new physics; iii) Comparison between the sensitivity of oscillation and other experiments. A systematic EFT analysis of new physics using different neutrino experiments is missing in the literature. Also, there has been little emphasis on connecting the new physics results from neutrino oscillation experiments and other precision experiments, such as nuclear beta transitions, meson decays, Drell-Yan production at the **LHC**, etc. (see e.g. [26–31]). This is clearly an aspect to be improved, since one of the main advantages of the EFT approach is that it provides general results that any model builder can later use.

This Letter of Interest proposes to use neutrino oscillation experiments as tools for beyond the SM searches. A systematic **EFT** approach to neutrino oscillations is proposed in Ref. [32], focusing on short-baseline reactor neutrino experiments Daya Bay and RENO. The general formalism can be readily applied to experiments with longer baselines, where one should calculate different neutrino production and detection processes in the presence of EFT. To do this, one needs to go to higher neutrino energy and enter the quasi-elastic regime, for which these calculations will be a lot more complicated. Therefore, this is a necessary but very challenging part of this program. The main tasks are: (i) development of the theoretical framework to systematically describe new physics in oscillation experiments; (ii) calculating process dependent production and detection amplitudes of neutrinos in the presence of new CC and NC interactions; (iii) calculating the general formulas of neutrino oscillation probabilities for each process.

Search strategy: The plan is to study constraints on the Standard Model Effective Field Theory (**SMEFT**) [33, 34] from neutrino **oscillation experiments**. The advantage of this approach is its generality and efficiency. The analysis of experimental data is done once and for all, and its outcome can be applied to a plethora of specific new physics scenarios in a straightforward way. In this spirit, all effective operators of a given order in the EFT counting must be kept in the analysis simultaneously, and numerical results must be provided including correlations. However, the current constraints in the literature are not available in the model-independent form where all 4-fermion operators are present simultaneously, hence, it has never been considered before. There are advantages in embedding NSI in a solid EFT:

- **First**, consistent EFTs come with an expansion parameter, and the Lagrangian, amplitudes, and observables can be systematically constructed order by order in that expansion. This allows one to compare different NSI effects in neutrino oscillations, and unambiguously identify the leading order contributions.
- **Second**, EFTs may predict correlations between the magnitude of effects in oscillation and in other precision experiments.
- **Third**, sensitivities of the different precision probes can be meaningfully compared.

From an EFT point of view, the most general Lagrangian describing new physics above the electroweak scale is the SMEFT Lagrangian. It features the same particle content and the same local symmetries as the SM, but augments the latter by adding new higher dimensional operators. At smaller neutrino energies (below the W boson mass), the SMEFT Lagrangian reduces to the one of weak effective field theory (WEFT), in which the electroweak gauge bosons, the Higgs boson, and the top quark are integrated out. The WEFT

Wilson coefficients can be matched onto the parameters of the SMEFT at a scale $\mu \sim m_W$, where the matching is given in [32]. It is desirable to incorporate a right-handed neutrino in the EFT framework as well, and that will lead to additional rich phenomenology [31]. For each experiment, one needs calculate the probability of oscillation at the leading order in the parameters of the WEFT. Hence by measuring the Wilson Coefficients at low energy it is possible to derive constraints on the parameters of the higher dimensional SMEFT interactions at $\mu \gg m_W$, where these bounds can be translated into constraints to various ultraviolet (UV) complete models and can be compared to SMEFT constraints from other sources.

Example Experiments: The goal is to derive constraints on the corresponding SMEFT parameters using the most recent data from current and future Long-baseline accelerator experiments MINOS [35], T2K [36] and DUNE [37] (see [38]), the atmospheric experiments IceCube [39] and Super-Kamiokande [40] and finally the solar neutrino data. The global analysis can be done using GLoBES [41] or equivalent pieces of software, and software packages will be prepared based on these results, which will become public. In order to perform a global fit, we also plan to apply the recently developed novel approach using a copula method which combines posterior information from different experiments with a large, generalized set of NSI parameters [42].

Impact: The EFT studies in this project can be translated into constraints on masses and couplings of a large class of BSM theories which will be useful to model builders who will thus have an easy way of comparing their predictions to data. The developed software packages will be public so both theorists and experimentalists can use it for future studies.

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