Snowmass2021 - Letter of Interest

Constraints on Non-Standard Neutrino Interactions Utilizing Copulas

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

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Abstract: Neutrino non-standard interactions (NSI) with the first generation of standard model fermions can span a parameter space of large dimension and exhibit degeneracies that cannot be broken by a single class of experiment. Global analyses are therefore necessary to constrain or discover NSIs and new physics, and oscillation experiments, together with neutrino scattering experiments, can merge their observations into a highly informational dataset to address this problem. In order to perform a global fit combining several datasets, we adopted a novel approach using a copula method which combines posterior information from different experiments with a large, generalized set of NSI parameters. Using this new technique, we plan to analyze multidimensional parameter spaces of complex NSIs, models with light mediators, and NSIs with sterile neutrinos, to name a few. We plan to make our analysis codes publicly available so that the formalism of this new approach can be easily disseminated.

The need for a global analysis of the complete set of NSIs: NSIs are a popular effective field theory framework for exploring new physics beyond the standard model (BSM) in the neutrino sector[1–3]. In the context of neutrino scattering experiments and neutrino oscillations, in the limit where any new gauge fields that mediate NSI are much heavier than the characteristic momentum transfer q^2, they are a convenient expression of the effective operators that arise in BSM extensions. NSIs with the first generation of standard model fermions can span a parameter space of large dimension and exhibit degeneracies that cannot be broken by a single class of experiment. Oscillation experiments, together with neutrino scattering experiments, can merge their observations into a highly informational dataset to combat this problem. In this sense, the existing and upcoming neutrino oscillation and neutrino scattering experiments should be thought of as a unified experimental program, working together to understand NSI and new physics in general.

In most of the existing works that performed statistical analyses of NSI, it has been common practice to either consider a large family of NSI but only vary one or two of them at a time in the likelihood fit (Ref.[4], for example), or reparameterize the NSI down to a more phenomenological and pragmatically manageable subset based on model assumptions (for example, in Refs.[5–7]). This is usually done for (i) the sake of model simplicity and (ii) computational limitations with regard to the dimensionality of the fit. Scenarios in which more than two NSI are nonzero at once, albeit complex, have no good reason to be prohibited by nature and a larger NSI parameter space is warranted to provide generalized constraints. Additionally, degeneracies among the NSI parameters arise due to transformations that leave the oscillation Hamiltonian and scattering cross sections invariant. The full space of these degeneracies as they show up in a likelihood analysis are not fully explored if only a small subset of NSI parameters are activated.

One may perform a generalized NSI analysis by considering a complete set of flavor conserving and non-conserving neutrino interactions, for example, with a heavy vector mediator;

$$\mathcal{L}_{NSI} = -2\sqrt{2}G_F \sum_{f,\alpha,\beta} \left[\epsilon^{f,L}_{\alpha\beta} (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta)(\bar{f}\gamma_\mu P_L f) + \epsilon^{f,R}_{\alpha\beta} (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta)(\bar{f}\gamma_\mu P_R f) \right] \tag{1}$$

Ongoing and upcoming neutrino experiments are sensitive to these NSI or to particular subsets of them. Oscillation experiments, such as DUNE and Hyper-K, will be sensitive to all NSI parameters $\epsilon^{f,L(R)}_{\alpha\beta}$ in the NSI Lagrangian through their inclusion in the Earth's matter potential that gives rise to the Wolfenstein neutrino oscillations and MSW effects. Experiments measuring coherent elastic neutrino-nucleus scattering (CEνNS), such as COHERENT, CCM will have direct access to just the quark NSI $\epsilon^{q,V}_{\alpha\beta} \equiv \epsilon^{q,L}_{\alpha\beta} + \epsilon^{q,R}_{\alpha\beta}$. The electron NSI, $\epsilon^{e,L(R)}_{\alpha\beta}$, can also be measured directly via electron recoils from elastic neutrino-electron scattering (EνES) at solar neutrino experiments such as Borexino, or at any dark matter direct detection experiments, such as XENON1T the next-generation set of detectors with XENONnT, DARWIN. In addition, JSNS^2 will be sensitive to electron NSI.

In the Case of a Large Number of Fit Parameters: With the inclusion of all NSI parameters in Eq. 1, transformations in the NSI that leave the observed data invariant lead to degeneracies in each of the aforementioned experiments. An obvious example are the phenomenologically observable NSI by oscillation experiments; since the electron and quark NSI enter into the Earth's matter potential roughly as the linear combination $\epsilon^{e,V}_{\alpha\beta} + 3\epsilon^{u,V}_{\alpha\beta} + 3\epsilon^{d,V}_{\alpha\beta}$, oscillation experiments cannot isolate sensitivity to the electron or quark NSI on their own. It will take the contribution of CEνNS and EνNS experiments and potentially others to break the degeneracy. By combining data sets together from several experiments that each measure a different aspect of the interaction Lagrangian, we can reduce the degeneracy in a likelihood fit. A computational challenge can then arise when one includes the many model parameters in Eq. 1 into a likelihood fit to data. A solution to this challenge was presented[8] where each experimental dataset is treated in separate Bayesian likelihood analyses. The key idea is the following: The posterior probability distribution over the NSI from one dataset can be used as the prior distribution for the analysis of another dataset. Separating the analysis of the datasets this way offers a “divide and conquer” approach where the analysis of each dataset can be performed in a standalone fashion, permitting a larger number of free parameters per fit, and the posterior information can be carried forward as the prior in the analysis of the next dataset.

The Copula Approach: To pass in one posterior probability distribution over the new physics parameters from one data set as the priors in a fit on another dataset, one may use a copula. In d dimensions, a copula $\mathcal{C}$ is a cumulative distribution fucntion (CDF) $\mathcal{C} : [0,1]^d \to [0,1]$ with uniform marginal distributions. See[9;10] for a review. Sklar's theorem[11] states that for every d-dimensional joint CDF, in our case $\mathcal{F}(\epsilon_1, \ldots, \epsilon_d)$ for NSI parameters $\epsilon_1, \ldots, \epsilon_d$, there exists a d-copula $\mathcal{C}$ such that

$$\mathcal{F}(\epsilon_1, \ldots, \epsilon_d) = \mathcal{C}(F_1(\epsilon_1), \ldots, F_d(\epsilon_d)) \tag{2}$$

where $F_1, \ldots, F_d$ are the marginal distributions of the NSI parameters. From Sklar's theorem one can see that copula functions, in essence, connect the marginal distributions and the joint distribution through a correlation structure. Given absolutely continuous marginal distributions and the joint distribution, the copula function is unique. Pragmatically, one can use a copula to model a wide variety of potentially complex joint distributions. This is precisely the technology suitable for modelling the multidimensional posteriors from one dataset as priors for another dataset.

The relatively many NSI considered in the analysis and multiple experiments being simulated became pragmatically realizable using the copula. We demonstrated that this strategy allows one to scale a global analysis with a potentially large number of model and nuisance parameters, with copulas facilitating the transfer of prior information. This novel “prior-flow” framework we developed can be extended in a straightforward way to include other existing data which would be sensitive to NSI. The Bayesian estimation of posterior probability distributions on the relatively large number of NSI parameters are demonstrated to be tractable. In fact, this technique is easily generalized to cases with few new physics parameters but a large number of nuisance parameters, e.g., parameterizing statistical and systematic experimental uncertainties.

Summary: So far we have performed the global analysis with a set of 18 real valued NSIs utilizing this novel approach. This number of NSI that would ordinarily demand a high computational cost have been treated in an inexpensive way using the “prior-flow” strategy with copulas, a formalism that can be generalized to any global analysis. We plan to extend this analysis to (i) complex NSIs, (ii) NSIs with sterile neutrinos, (iii) NSIs with light mediators and (iv) concrete models with NSIs.

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