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Radiative Neutrino Masses from LNV SMEFT operators: Beyond Cutoff Regularisation

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Beyond the three types of conventional tree-level seesaw mechanisms and their low-scale variants, the generation of light neutrino masses radiatively via quantum loop corrections leads to naturally loop-suppressed small neutrino masses. The three types of seesaw mechanisms can be identified with the only three minimal realisations of the single LNV operator at dimension-5. At the nonrenormalizable level, lepton number violating (LNV) interactions can only occur at odd dimensions in the Standard Model Effective Field Theory (SMEFT). Therefore, the radiative models for neutrino mass generation can correspond to realisation of odd higher dimensional LNV SMEFT operators at tree-level. Consequently, a comprehensive exploration of odd higher dimensional LNV SMEFT operator gives a systematic and power way to capture classes of radiative neutrino mass models in a model independent manner. In this proceeding, we discuss how in some cases the naive cutoff based approach of estimating loop neutrino masses arising from higher dimensional LNV SMEFT operators can break down and how employing dimensional regularisation based approaches can lead to a much more reliable results.

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1. Introduction

At the nonrenormalizable level, lepton number violating (LNV) interactions occur in the Standard Model Effective Field Theory (SMEFT) at odd dimensions [1]. The three types of conventional tree-level seesaw mechanisms for light neutrino mass generation can be identified with the only three minimal realisations of the dimension-5 Weinberg operator. Therefore, many of the models beyond the SM realising radiative neutrino masses can be identified with tree-level realisations of higher odd-dimensional LNV SMEFT operators, which can induce the Weinberg operator (or similar operators at odd higher dimensions involving two lepton doublets accompanied by an even number of SM Higgs fields) at a higher loop order. Consequently, a dimension-by-dimension exploration of odd-dimensional LNV SMEFT operators provides a powerful approach to organise and explore the radiative models for neutrino mass generation beyond the Standard Model (SM).

The dimension-7 LNV SMEFT operators present the next higher dimensional LNV interactions after the Weinberg operators, with 12 independent operators [2–4]. Recently, in Ref. [5], a comprehensive phenomenological survey was presented for these operators in the context of a wide range of observables, e.g., the neutrinoless double beta decay, the LNV LHC searches, the rare meson decays, the coherent elastic neutrino nucleus scattering, long baseline oscillation experiments, the magnetic moment observables, etc., at the tree-level. The different possible tree-level UV completions have been explored in the literature for subset of these dimension-7 operators in various contexts [6–19]. In Ref. [20], a complete exhaustive list of all the tree-level UV completions of the LNV dimension-7 SMEFT operators with only two heavy new physics fields was recently worked out. The LNV dimension-7 SMEFT operators have been long studied in the context of loop-level neutrino mass generation in a model-independent way. Most of these studies mainly used cutoff regularization based estimates supplemented by naive dimensional analysis to approximate the loop-level neutrino masses, see e.g. [21–23]. In such an approach, the loop momentum integrals are regulated by this single cut-off scale, corresponding to a heavy new physics scale Λ. Taking a UV complete tree-level UV model examples, it was shown in Ref. [20], that this naive cut-off based approach can over-estimate the loop neutrino masses when the new heavy degrees of freedom present a large hierarchy in the masses or when the leading order contribution is absent because of a cancellation caused by relative signs of couplings in the loop. A simple dimensional regularization based prescription employing the method of regions is proposed in Ref. [20], which can consistently avoid these issues. Furthermore, a more robust approach is provided by renormalization group (RG) improved perturbation theory [24]. Recently, in Refs . [4, 25, 26], the full RG equations for dimension-7 LNV operators at one-loop order have been worked out. In Ref [27], it was more recently shown that inclusion of these running effects together with additional hard UV matching contributions can completely alter the tree level predictions for LNV observables.

2. Dimensional regularization based approach for hierarchical new physics scales

According to the EFT power counting formula [24], the insertion of a d dimensional effective operator inside a Feynman graph corresponding to an observable with effective momentum scale p should lead to a contribution of the order $\mathcal{A} \propto (p/\Lambda)^{d-d_s}$, where Λ is the heavy scale and d_s

is the space-time dimension. For loop diagrams, the integrated loop momentum k can take any value ranging between $-\infty \leq k \leq +\infty$ and consequently the expansion in k/Λ can break down in general. However, the overall power counting formula remains valid, as can be understood by considering a general loop integral in the low-energy effective theory (where the heavy scales are already integrated out) of the form,

$$I = \int_k d^{d_s} k \frac{(k^2)^a}{(k^2 - m^2)^b} . \tag{1}$$

For a given d_s, a, and b, an integration contour can be chosen such that the integral vanishes sufficiently fast in the limit $k \to \infty$, and the contour at infinity gives no contribution. The integrand is then obtained by summing over the residues at the poles corresponding to the denominators of the integrand. Since the poles can only depend on the light masses and external momenta in the EFT, there are no compensating factors of Λ in the numerator. Therefore, Λ should appear only due to the EFT vertex factor. In general, by design, an EFT cannot capture the hard region behaviour of a loop integral of a complete UV theory. Instead, it can only capture the soft region behaviour of the loop integral corresponding to the case $m \sim p \sim k \ll M$, where M is the heavy mass-scale in the EFT. The hard region of the loop integral $m \sim p \ll k \sim M$, which can depend non-locally M (e.g., powers of M in the numerator), must be provided while matching the complete UV theory to the EFT, sometimes called the Matching contribution. Such a contribution can lead to a different dependence on the mass scales, contrary to the naive power counting formula expectation from just using the EFT. Following this argument, in the presence of two hierarchical heavy new physics scales in the full theory, a two-step matching is clearly necessary. A relevant, simplified formalism based on the method of regions and the general results that can be derived for one- and two-loop cases of LNV dimension-7 SMEFT operators is presented in Ref. [20]. Another subtlety that can arise when estimating loop contributions from an effective higher-dimensional EFT operator is the cancellation of loop contributions due to the relative signs of couplings involving the light degrees of freedom. For instance, in the SM, the up and down couplings to the Higgs boson come with a relative negative sign, which can lead to cancellation effects for loop diagrams involving charged Higgs bosons, causing the sub-leading contributions (from the EFT power counting) to dominate, see e.g., [28]. While the above results are not totally unexpected, they can have profound implications for the phenomenology of the higher-dimensional LNV SMEFT operators. In particular, a mass hierarchy between the heavy new physics degrees of freedom can open up parts of the parameter space that were previously thought to be excluded due to the overestimation of light neutrino masses.

3. Renormalisation group improved EFT approach

The discussion so far has mainly focused on the estimation of the loop-level neutrino masses to the effective higher-dimensional LNV SMEFT operator while still performing only a tree-level computation for the LNV observables. It was shown recently in Ref. [27], using the full RG equations for the LNV dimension-7 SMEFT operators derived in Refs. [4, 25, 26], that a one-loop-level computation of the LNV observables in the EFT can alter the tree-level constraints and predictions in the bottom-up and the top-down approaches, respectively. Let us consider the case where, in a full theory, one starts with a vanishing tree-level contribution for the dimension-5 Weinberg operator and only tree-level contributions arising at a higher dimensional level, e.g., dimension-7. Because of the mixing between the different dimension-7 operators among themselves and with the dimension-5 Weinberg operator via the Higgs mass term in the unbroken SM phase, loop-level dimension-5 contributions will be induced as the SMEFT operators are run down using RGEs from the new physics scale to the electroweak scale. This can be seen from the generic set of RGEs up to $O(\Lambda^{-3})$ given by

$$\dot{C}^5 = \gamma^{(5,5)} C^5 + \hat{\gamma}^{(5,5)} C^5 C^5 C^5 + \gamma_i^{(5,6)} C^5 C_i^6 + \gamma_i^{(5,7)} C_i^7, \tag{2}$$

$$\dot{C}_i^7 = \gamma_{ij}^{(7,7)} C_j^7 + \gamma_i^{(7,5)} C^5 C^5 C^5 + \gamma_{ij}^{(7,6)} C^5 C_j^6, \tag{3}$$

where C^d denotes the d-dimensional mass-dimensionful Wilson coefficients corresponding to the d-dimensional SMEFT operator O^d. The dots denote the rate of change with respect to the logarithm of the scale, and the different γ's correspond to the tensors of anomalous dimensions. As shown in Ref. [27], it turns out that the loop-induced dimension-5 contributions can compete for dominance with the tree-level dimension-7 contributions in the computation of the LNV observable rates and in some cases can completely dominate them. Furthermore, for a full UV-complete model, loop-level matching contributions to the dimension-5 operator can also be very important and dominant. As a consequence, the tree-level constraints and predictions for LNV observables, often used in the previous literature, can change drastically.

4. Conclusions

The systematic study of odd-dimensional LNV SMEFT operators provides a robust framework for exploring the radiative light neutrino mass generation mechanism beyond tree-level see-saw mechanisms systematically. Naive cutoff regularization based approach of estimating the loop neutrino masses from the effective operators can break down in the presence of hierarchy between the heavy new physics scales or cancellations. Dimensional regularization can be used to consistently capture these effects, thereby opening up the parameter space that was previously thought to be excluded by the overestimation of light neutrino masses, in the presence of a hierarchy between the heavy new physics mass scales. Finally, for a robust and accurate prediction of LNV observables using the EFT framework, often-ignored loop-level effects are crucial and significantly alter the landscape of existing tree-level constraints.

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