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Neutrinoless double beta decay in effective field theory and simplified models

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Abstract: In light of recent advancements that enable a more robust description of the neutrinoless double beta ($0\nu\beta\beta$) decay using effective field theoretic techniques, we revisit the outlook for the sensitivity of current- and next-generation $0\nu\beta\beta$ decay experiments. We focus in particular on interpreting projected experimental sensitivity in terms of masses and interaction strengths of new particles in simplified models that can be imbedded in ultraviolet-complete scenarios, such as extended gauge and grand unified theories. As part of the Snowmass 2021 exercises, we investigate also the complementary to direct searches for such states at high momentum transfer experiments like the Large Hadron Collider and proposed successor colliders.

Topical Groups:

- ■ (NF2) Sterile neutrinos
- ■ (NF3) Beyond the Standard Model
- ■ (TF11) Theory of neutrino physics
- ■ (RF4) Baryon and Lepton Number Violating Processes

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Introduction: the interplay between $0\nu\beta\beta$ and the high energy frontier

Due to implications for the Majorana nature of neutrinos, grand unification, and the universe's cosmological history, searches for lepton number violation (LNV) remain one of the top priorities in particle physics [1, 2]. To this end, the neutrinoless double beta decay ($0\nu\beta\beta$) process is one of the most sensitive and robust probes of LNV. Current experimental limits on $0\nu\beta\beta$ half lives are at the level of 10^{26} years [3–7] and next-generation, ton-scale experiments aim for one or two order-of-magnitudes improvements [8–17]. Although the measurement of a positive signal in upcoming experiments would be a major breakthrough, showing that neutrinos are Majorana particles [18–20] and that LN is not conserved, it would not necessarily pinpoint the source (or sources) of LNV nor the underlying cause(s) for suppressed neutrino masses. In fact, disentangling all possible mechanisms using $0\nu\beta\beta$ observables alone would be a very challenging, if at all possible, task [21], making it important to consider LNV signatures in other experimental probes alongside $0\nu\beta\beta$.

Although other probes are unlikely to be sensitive enough if $0\nu\beta\beta$ is generated by a Seesaw mechanism originating at a high scale, say $\Lambda \sim 10^{15}$ GeV, there are observables that become complementary to $0\nu\beta\beta$ when LNV occurs at scales as low as $\Lambda \sim 1 - 100$ TeV or even the electroweak scale. Numerous scenarios of beyond-the-standard-model (BSM) physics exist that introduce LNV at such low scales, in which case it becomes possible to see signals in energy-frontier experiments, such as colliders and beam dump facilities [22,23]. Any observation of LNV at colliders would greatly aid in determining the fundamental origin of LNV. It is therefore important to consider the complementarity of $0\nu\beta\beta$ and energy-frontier experiments.

In the case of $0\nu\beta\beta$, sources of LNV are most conveniently described in an effective field theory (EFT) framework in which the Standard Model (SM) is supplemented by gauge-invariant, higher dimensional operators. As long as all new fields are heavy compared to the electroweak scale, this framework allows one to determine in a semi-model-independent way the impact of LNV in BSM scenarios at low energies. Such a framework in the context of the SMEFT has been developed in Refs. [24–27], which has been extended to include light sterile neutrinos (here light means any mass below the electroweak scale) [28]. On the other hand, for TeV-scale LNV, collider analyses usually consider specific BSM models as an EFT description breaks down for $\sqrt{s} \sim \Lambda \sim$ TeV.

To bridge the gap between these approaches we will consider several well-motivated simplified models of neutrino masses and LNV, and, by using the framework of [25–28], assess their impact on the $0\nu\beta\beta$ process. Although numerous analyses combining $0\nu\beta\beta$ and collider probes exist, see for example Refs. [22,29–33], the description of $0\nu\beta\beta$ can be improved. We intend to take advantage of the systematic EFT approach to provide a survey of simplified models that can readily be imbedded in ultraviolet-complete scenarios, such as extended gauge and grand unified theories. In this Letter of Interest for the 2021 Snowmass process, we briefly review the EFT framework of Refs. [25–28] and discuss some of the simplified models as well as their connection to high-energy experiments.

An effective field theory framework for low-energy $0\nu\beta\beta$ decay

The EFT framework [25–28] starts at the LNV scale, $\Lambda \gg m_W$, where heavy BSM fields can be integrated out and parametrized by LNV operators of dimension $d = 5$, 7, and 9 that contain SM fields and possibly sterile neutrinos. These operators are evolved to the electroweak scale, where heavy SM fields are integrated out, and then to the QCD scale, $\Lambda_\chi \sim 1$ GeV. Here the quark-level theory is matched onto Chiral EFT, extended to include hadronic LNV interactions. The resulting chiral Lagrangian is used to derive a LNV potential between nucleons, which provides the starting point for nuclear many-body computations of nuclear $0\nu\beta\beta$ matrix elements (MEs). The end product is an expression for the $0\nu\beta\beta$ decay rate in terms of Wilson coefficients at the scale Λ, hadronic MEs, and nuclear MEs. The MEs come with significant theoretical uncertainties. The framework allows one to estimate the impact of these uncertainties. The main goal of the proposed work is to perform the above mentioned matching and evolution for several simplified BSM models.

Simplified models with LNV and their collider tests

The canonical, high-scale Type I Seesaw mechanism [34–40], which is characterized by the existence of right-handed (RH) neutrinos with GUT-scale, RH Majorana masses, is a leading, well-motivated explanation for the lightness of active neutrinos. At the same time, there exist scenarios of comparable or simpler complexity [41], including scenarios without sterile neutrinos [40, 42–45], and more so with increasing complexity [46]. Due to the lack of guidance from both data and theory, it is important to take a broad approach to potential LNV in nature. We consider the following simplified models with TeV-scale states that are testable at energy-frontier experiments.

Phenomenological Type I Seesaw Model: Like the canonical Type I Seesaw mechanism, this model is characterized by at least two RH neutrinos with RH Majorana masses. However, in order to minimize any flavor-model dependence, the masses and mixing of active and sterile neutrinos are decoupled. As a benefit, manifestations of the Inverse and Linear Type I Seesaws [47–52] are possible. Extensive searches at collider experiments have been conducted focusing particularly on the same-sign dilepton $\ell_i^{\pm}\ell_j^{\pm}$ and trilepton $\ell_i\ell_j\ell_k$ signatures [53–55].

Minimal Left-Right Symmetric Model: Nature's distinction between LH and RH fields may be due to the spontaneous breaking of an exact parity symmetry at high energy scales, a scenario known as the Left-Right Symmetric Model (LRSM) [56–60]. The LRSM extends the SM by an $SU(2)_R$ gauge symmetry and predicts new gauge bosons, fermions, and scalars that may be accessible at the TeV-scale. Direct searches at colliders generally rule out lighter masses [61–64]. A common phenomenological limit, known as the minimal LRSM (mLRSM), decouples the theory's scalar sector, leaving behind only the new gauge fields and heavy Majorana neutrinos that can couple directly to the new bosons.

Type I+II Seesaw Model: The LRSM contains an enlarged gauge sector that reduces to the SM gauge sector after the spontaneous breaking of left-right symmetry. During this process, LH Majorana masses for LH neutrinos and RH Majorana masses for RH neutrinos are generated. This in turn triggers the so-called Type I+II Seesaw mechanism [34–40, 40, 42–45], which is characterized by heavy Majorana neutrinos (Type I) and exotically charged Higgs bosons (Type II). Direct searches for doubly charged Higgs bosons rule out masses below a few hundred GeV [65, 66]. In contrast to the mLRSM, it is possible to decouple the gauge fields, leaving behind only those fields that are responsible for light neutrino masses.

Type I+III Seesaw Model: Whether or not the SM forces ultimately come together under a grand unified theory (GUT) remains an open question in particle physics. Despite their potential, the viability of GUTs has historically been challenged by the absence of proton decay. More recently, however, it has been shown [67–69] that such limitations can be naturally resolved by extending the minimal $SU(5)$ GUT by a new lepton multiplet charged under $SU(2)_L$. In doing so, the Type I+III Seesaw mechanism, which is characterized by heavy Majorana neutrinos (Type I) and charged and neutral vector-like leptons (Type III), is triggered. Despite this motivation, searches for such leptons rule out masses below 800 GeV [70, 71].

Leptoquarks: Leptoquarks are hypothetical particles that couple quarks to leptons. They appear in various extensions of the SM, and recently gained renewed interest in the context of the tension between the SM and experiment in semileptonic B decays [72, 73]. In addition, leptoquarks could be responsible for the generation of the Majorana masses of the neutrinos [74, 75], which, in some cases, can be achieved at the same time as addressing the B anomalies [76–78]. We will therefore consider simplified leptoquark models that involve one type of leptoquark along with left-handed Majorana masses and sterile neutrinos.

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