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TeV Lepton Number Violation: From Neutrinoless Double β-Decay to the LHC

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We analyze the sensitivity of next-generation tonne-scale neutrinoless double β-decay ($0\nu\beta\beta$) experiments and searches for same-sign di-electrons plus jets at the Large Hadron Collider to TeV scale lepton number violating interactions. Taking into account previously unaccounted for physics and detector backgrounds at the LHC, renormalization group evolution, and long-range contributions to $0\nu\beta\beta$ nuclear matrix elements, we find that the reach of tonne-scale $0\nu\beta\beta$ generally exceeds that of the LHC for a class of simplified models. However, for a range of heavy particle masses near the TeV scale, the high luminosity LHC and tonne-scale $0\nu\beta\beta$ may provide complementary probes.

Total lepton number (L) is a conserved quantum number at the classical level in the Standard Model (SM) of particle physics, yet it is not conserved in many scenarios for physics beyond the Standard Model (BSM). Experimentally, the observation of neutrinoless double beta-decay ($0\nu\beta\beta$-decay) of atomic nuclei would provide direct evidence for lepton number violation (LNV). This observation would also indicate the existence of a Majorana mass term for the lightest neutrinos[1], consistent with the prediction of the see-saw mechanism[2–6].

Recent results from the EXO[7], GERDA[8], and KamLand-ZEN[9, 10] experiments have placed stringent upper limits on the $0\nu\beta\beta$-decay half lives ($T_{1/2}^{0\nu\beta\beta}$) of ^{76}Ge and ^{136}Xe on the order of a few times 10^{25} years. When interpreted in terms of the exchange of light Majorana neutrinos, these limits imply an upper bound of order 100-400 meV on the $0\nu\beta\beta$-decay effective mass $m_{\beta\beta}$, depending on the value of the nuclear matrix element employed in this extraction [63]. The next generation of "tonne scale" $0\nu\beta\beta$-decay searches aim for half life sensitivities of order $\gtrsim 10^{27}$ years, with a corresponding $m_{\beta\beta}$ sensitivity on the order of tens of meV, consistent with expectations based on the inverted hierarchy (IH) for the light neutrino mass spectrum. In this interpretive framework, a null result would imply that either neutrinos are Majorana particles with a mass spectrum in the normal hierarchy (NH) or that they are Dirac fermions.

It is possible that neutrino oscillation studies may determine the neutrino mass hierarchy before the next generation $0\nu\beta\beta$-decay searches reach their goal sensitivity. Should the hierarchy turn out to be normal, a null result from the tonne-scale $0\nu\beta\beta$-decay experiments would not be surprising. However, alternate decay mechanisms could still lead to observation of a signal in the next generation searches, even if the light neutrino spectrum follows the NH and the value of $m_{\beta\beta}$ is experimentally inaccessible. These mechanisms include radiative neutrino mass scenarios[11] and the TeV-scale see-saw mechanism[12–18][64]. In these scenarios, the LNV interactions may involve particles whose masses are of order one TeV and whose exchange generates short range interactions that lead to $0\nu\beta\beta$-decay. Straightforward arguments indicate that the resulting $0\nu\beta\beta$-decay half-life can be of order 10^{27} yr or shorter, comparable to expectations based on the three light Majorana exchange mechanism and the IH[19]. The associated light Majorana masses may nevertheless follow the NH with $m_{\beta\beta}$ well below the meV scale.

How might one experimentally distinguish the TeV LNV scenario for $0\nu\beta\beta$-decay from the more conventional paradigm based solely on the exchange of light Majorana neutrinos? One possibility is to analyze experiments that search for charged lepton flavor violation, as discussed in Ref. [19]. Another, perhaps more direct, means is to search for the LNV interactions in high energy collider experiments (see, *e.g.* [20–40]).

This possibility has recently been explored by the authors of Refs. [41, 42], who utilized a simplified model framework to analyze the relative sensitivities of tonne-scale $0\nu\beta\beta$-decay experiments and searches for LNV signals at the CERN Large Hadron Collider. These authors performed a systematic classification of simplified models that one may map onto more complete theories, such as R-parity violating supersymmetry. They find that in a broad range of cases the LHC with 300 fb^{-1} of integrated luminosity (corresponding to the end of Run II) would achieve substantially greater reach for TeV-scale LNV interactions than would the tonne-scale $0\nu\beta\beta$-decay searches[65]. If verified, the prospective LHC exclusion of TeV scale LNV in the simplified model context would contrast sharply with conclusions based on Type I see-saw models, where the $0\nu\beta\beta$-decay reach can exceed that of the LHC for sufficiently small active-sterile neutrino mixing angles (see, *e.g.*, [31]).

In what follows, we revisit the analysis of Refs. [41, 42] and find that their conclusions regarding the LHC reach may be overly optimistic. We consider three aspects of the LHC and $0\nu\beta\beta$-decay physics not included in Refs. [41, 42] but that should be taken into account in any analysis of the LHC/$0\nu\beta\beta$-decay interplay: (a) the impact of SM and detector backgrounds on the significance

σ(**fb**)	**Signal**	**Backgrounds**									$\frac{\mathbf{S}}{\sqrt{\mathbf{S+B}}}$ ($\sqrt{\mathbf{fb}}$)
		Diboson			Charge Flip		Jet Fake				
		$\mathrm{W^-W^-}$+2j	$\mathrm{W^-Z}$+2j	ZZ+2j	Z/γ^*+2j	$t\bar{t}$	$t\bar{t}$	$\bar{t}$+3j	W^-+3j	4j	
Before Cuts	0.142	0.541	6.682	0.628	903.16	68.2	6.7	0.45	15.09	362.352	0.0038
Signal Selection	0.091	0.358	4.66	0.435	721.7	28.9	2.37	0.22	11.73	72.03	0.0031
H_T(jets) > 650 GeV	0.054	0.04	0.187	0.015	5.6	0.266	0.025	0.0003	0.102	0.027	0.0213
$m_{\ell_1\ell_2}$ > 130 GeV	0.039	0.029	0.105	0.008	0.163	0.127	0.024	3x10^{-4}	0.101	0.027	0.0493
$\not{E}_T$ < 40 GeV	0.036	0.005	0.036	0.007	0.126	0.014	0.005	3x10^{-5}	0.03	0.017	0.0684
$(\eta_{j_{1,2}} - \eta_{\ell_{1,2}})_{max} < 2.2$	0.033	0.003	0.022	0.005	0.093	0.009	0.004	2x10^{-5}	0.019	0.011	0.0738

TABLE I: Cut-flow designed for optimizing signal relative to background. Note: kinematic cuts are not commutative.

of an LHC LNV signal; (b) running of the corresponding LNV effective operators from the TeV scale to the low-energy scale relevant to $0\nu\beta\beta$-decay; and (c) long-distance contributions to the $0\nu\beta\beta$-decay nuclear matrix element (NME). For the specific model realization considered here (see below), the impacts of these considerations are, respectively, to (a) degrade the significance of the LHC LNV signal for a given choice of LNV model parameters; (b) reduce the strength of the $0\nu\beta\beta$-decay amplitude relative to the inferred value of parameters at the high scale; and (c) enhance the NME. We then find that for a limited range of heavy particle masses, existing $0\nu\beta\beta$-decay searches and Run II of the LHC may have comparable sensitivities to TeV scale LNV, depending on the values of the $0\nu\beta\beta$-decay nuclear and hadronic matrix elements. Accumulation of additional data with the high-luminosity phase of the LHC would be necessary to achieve a reach comparable to the tonne-scale $0\nu\beta\beta$-decay searches. More generally, our results highlight the importance of incorporating all three considerations (a-c) when assessing the relative reaches of $0\nu\beta\beta$-decay and the LHC, a practice that has not always been implemented in previous work on this topic.

To be concrete, we focus on one of the simplified models yielding the greatest LHC reach according to Refs. [41, 42]. The model includes a scalar doublet S transforming as $(1, 2, 1)$ under $\mathrm{SU(3)}_C\times\mathrm{SU(2)}_L\times\mathrm{U(1)}_Y$ and a Majorana fermion F that transforms as a SM gauge singlet. The interaction Lagrangian is

$$\mathcal{L}_{\mathrm{INT}} = g_1 \bar{Q}_i^\alpha d^\alpha S_i + g_2 \epsilon^{ij} \bar{L}_i F S_j^* + \mathrm{h.c.} \quad , \qquad (1)$$

where L and Q are first generation left-handed lepton and quark doublets, respectively; d is the right-handed down quark; and Roman and Greek indices correspond to $\mathrm{SU(2)}_L$ and $\mathrm{SU(3)}_C$ components, respectively. In high energy proton-proton collisions, the interaction (1) will generate a final state with a same sign (SS) di-electron pair along with two high-p_T jets. When either the S or F appears as an s-channel resonance, the corresponding cross section will be enhanced. For the low-energy $0\nu\beta\beta$-decay process, one may integrate out the heavy degrees of freedom, yielding the dimension-nine LNV interaction:

$$\mathcal{L}_{\mathrm{LNV}}^{\mathrm{eff}} = \frac{C_1}{\Lambda^5}\mathcal{O}_1 + \mathrm{h.c.} \quad , \quad \mathcal{O}_1 = \bar{Q}\tau^+ d\bar{Q}\tau^+ d\bar{L}L^C \quad , \qquad (2)$$

where L^C is the lepton doublet charge conjugate field, τ^+ is the isospin raising operator, $C_1 = g_1^2 g_2^2$ and $\Lambda^5 = M_S^4 M_F$.

We have implemented the model (1) in Madgraph and generated events with Madevent [43] for pp collisions at 14 TeV, carrying out showering, jet matching, and hadronization with Pythia [44] and detector simulation with PGS. The dominant backgrounds involve (a) "charge flip", wherein one lepton from a SM opposite sign (OS) di-electron pair transfers most of its p_T to an electron of the opposite sign through conversion and (b) a high-p_T jet is registered as an electron in the electromagnetic calorimeter ("jet fake"). Subdominant backgrounds include diboson (WW, WZ, ZZ) plus jets. The charge flip background from the various aforementioned sources was derived by binning events in pseudo-rapidity (η) and applying the η-dependent charge-flip probabilities as measured by ATLAS [45]. For the jet-fake background, we applied a medium jet-fake probability of 2×10^{-4} [45, 46] times a combinatoric factor associated with the number of jet-fakes in an event with N jets.

After imposing a set of basic selection cuts ($p_{T_{j,b,\ell^\pm}} >$ 20 GeV, $|\eta_j| < 2.8$, $|\eta_{\ell^\pm}| < 2.5$) we find that additional cuts on H_T(jets), the scalar sum of all jet p_T, the dilepton invariant mass, and missing energy $\not{E}_T$ are highly effective in reducing the background while maintaining the signal. A set of cuts that optimizes the significance $S/\sqrt{S+B}$ is given in Table I. The signal indicated is generated for $M_S = M_F = 1$ TeV and $g_1 = g_2 = 0.176$, corresponding to a $0\nu\beta\beta$-decay rate consistent with the present GERDA upper bound (see below).

In order to translate the sensitivity to the parameters that enter the high energy process to the $0\nu\beta\beta$-decay rate, we evolve the operator $\mathcal{O}_1$ to the GeV scale using the renormalization group. We include only QCD corrections, known to be particularly important for $0\nu\beta\beta$-decay [47, 48], and run from the scale $\mu = \Lambda$ to $\mu = 1$ GeV. Under this evolution,

$\mathcal{O}_1$ will mix with three additional operators: $\mathcal{O}_2 = \bar{Q}\sigma_{\mu\nu}\tau^+ d\bar{Q}\sigma^{\mu\nu}\tau^+ d\bar{L}L^C$, $\mathcal{O}_3 = \bar{Q}T^A\tau^+ d\bar{Q}T^A\tau^+ d\bar{L}L^C$, and $\mathcal{O}_4 = \bar{Q}\sigma_{\mu\nu}T^A\tau^+ d\bar{Q}\sigma^{\mu\nu}T^A\tau^+ d\bar{L}L^C$, where T^A $A = 1, \cdots 8$ denote the $\mathrm{SU}(3)_C$ generators in the fundamental representation. The corresponding anomalous dimension matrix is

$$\gamma^T = \frac{\alpha_s}{2\pi}\begin{pmatrix} -8 & 0 & 0 & -32/3 \\ 0 & -8/3 & 2/9 & 0 \\ 0 & -48 & 1 & -20 \\ -1 & 0 & -5/12 & -19/3 \end{pmatrix} \quad . \tag{3}$$

The Wilson coefficients $C^T = (C_1, \cdots, C_4)$ then evolve according to $dC/d\ln\mu = \gamma^T C$. Under this evolution, we find, for example, that if only $C_1(\mu = \Lambda)$ is non-vanishing at the high scale, then the magnitude of the Wilson coefficients $C_j(\mu = 1~\mathrm{GeV})$ are: $C_1 = 0.203C_1(\Lambda)$, $C_2 = -0.007C_1(\Lambda)$, $C_3 = 0.266C_1(\Lambda)$, and $C_4 = -0.055C_1(\Lambda)$.

For μ below ~ 1 GeV, use of quark degrees of freedom is no longer appropriate, so one must match the operators $\mathcal{O}_j$ onto operators built from hadronic degrees of freedom[49]. To that end, we follow Ref. [50] and exploit the transformation properties of the $\mathcal{O}_j$ under $\mathrm{SU}(2)_L\times\mathrm{SU}(2)_R$ chiral symmetry. It is convenient to Fierz transform $\mathcal{O}_{3,4}$ to forms in which all quark blinears are color singlets, leading to an effective coefficient of $\mathcal{O}_1$ given by

$$C_{\mathrm{eff}} \approx C_1(1~\mathrm{GeV}) - \frac{5}{12}C_3(1~\mathrm{GeV}) = 0.092C_1(\Lambda) \tag{4}$$

where we have omitted the negligible contributions from $C_{2,4}(1~\mathrm{GeV})$. Using the notation of Ref. [50] we note that the part of $\mathcal{O}_1$ relevant to the decay process is

$$\mathcal{L}^{\mathrm{eff}}_{\mathrm{LNV}} = \frac{C_{\mathrm{eff}}}{2\Lambda^5}\left(\mathcal{O}^{++}_{2+} - \mathcal{O}^{++}_{2-}\right)\bar{e}_L e^c_R \; + \mathrm{h.c.} \quad , \tag{5}$$

where $e^c_R \equiv (e_L)^C$ and

$$\mathcal{O}^{ab}_{2\pm} = \bar{q}_R\tau^a q_L\bar{q}_R\tau^b q_L \pm \bar{q}_L\tau^a q_R\bar{q}_L\tau^b q_R \tag{6}$$

with $q^T_{L,R} = (u,d)_{L,R}$. Since $\mathcal{O}^{++}_{2-}$ is parity-odd and the $0\nu\beta\beta$-decay processes of experimental interest involve $0^+ \to 0^+$ transitions, we retain only the $\mathcal{O}^{++}_{2+}$ part of (5).

At the hadronic level, $\mathcal{O}^{++}_{2+}\bar{e}_L e^c_R$ matches onto the two pion-two electron operator

$$\frac{C_{\mathrm{eff}}}{\Lambda}\mathcal{O}^{++}_{2+}\bar{e}_L e^c_R + \mathrm{h.c.} \to \frac{C_{\mathrm{eff}}\Lambda^2_H F^2_\pi}{2\Lambda^5}\pi^-\pi^-\bar{e}_L e^c_R + \mathrm{h.c.}\,, \tag{7}$$

where $F_\pi = 92.2 \pm 0.2$ MeV is the pion decay constant [51] and Λ_H is a mass scale associated with hadronic matrix elements of the four quark operator $\mathcal{O}^{++}_{2+}$. Using the vacuum saturation and factorization approximation, we estimate the latter to be $\Lambda_H = m^2_\pi/(m_u + m_d) \approx 2.74$ GeV for $m_{\pi^+} = 139$ MeV and $m_u + m_d = 7$ MeV [52]. While this approximation is subject to theoretical uncertainties, it provides a reasonable guide to the magnitude of the hadronic matrix elements. We account for this uncertainty below.

The effective pion-electron interaction in Eq. (7) leads to a long-range contribution to the $0\nu\beta\beta$ amplitude[50]. Following Ref. [50] we then obtain the following result for the decay rate:

$$\begin{aligned} \frac{1}{T_{1/2}} &= G_{01}\left(\frac{\mathrm{TeV}}{m_e}\right)^2\left(\frac{\Lambda_H}{\mathrm{TeV}}\right)^4\left(\frac{1}{18}\right)\left(\frac{v}{\mathrm{TeV}}\right)^8 \\ &\quad\times\left(\frac{1}{g_A\cos\theta_C}\right)^4|M_0|^2\left[\frac{C^2_{\mathrm{eff}}}{(\Lambda/\mathrm{TeV})^{10}}\right] \quad , \\ G_{01} &= (G_F\cos\theta_C)^4\left(\frac{\hbar c}{R}\right)^2\left(\frac{m^2_e\, g^4_A}{32\pi^5\hbar\ln 2}\right)I(E_{\beta\beta}) \quad , \end{aligned} \tag{8}$$

with θ_C being the Cabibbo angle, $v = 246$ GeV the Higgs vacuum expectation value, g_A the nucleon axial vector coupling, $I(E_{\beta\beta})$ the electron phase space integral

$$\int_{m+e}^{E_{\beta\beta}-m_e} dE_1 F(Z+2,E_1)F(Z+2,E_2)p_1E_1p_2E_2 \quad , \tag{9}$$

$E_2 = E_{\beta\beta} - E_1$, and $F(Z+2, E_{1,2})$ being factors that account for distortion of the electron wave functions in the field of the final state nucleus. The NME is given by

$$M_0 = \langle\Psi_f|\sum_{i,j}\frac{R}{\rho_{ij}}\left[F_1\vec{\sigma}_i\cdot\vec{\sigma}_j + F_2T_{ij}\right]\tau^+_i\tau^+_j\,|\Psi_i\rangle \tag{10}$$

where $T_{ij} = 3\vec{\sigma}_i\cdot\hat{\rho}_{ij}\vec{\sigma}_j\cdot\hat{\rho}_{ij} - \vec{\sigma}_i\cdot\vec{\sigma}_j$, $R = r_0A^{1/3}$, $\vec{\rho}_{ij}$ is the separation between nucleons i and j, and the functions $F_{1,2}(|\vec{\rho}_{ij}|)$ are given in Ref. [50]. We have normalized the rate to the conventionally-used factor G_{01} that contains quantities associated with the SM weak interaction (such as g_A), even though the LNV mechanism here involves no SM gauge bosons. The rate (8) is, in fact, insensitive to g_A and the debate over its "quenching" in nuclei[53–59].

Values for M_0 have been computed using the quasiparticle random phase approximation (QRPA) in Ref. [49] for a variety of isotopes. For illustrative purposes, we consider the $0\nu\beta\beta$-decay of ^{76}Ge, for which the authors of Ref. [49] give $M_0 = -1.99$. We emphasize, however, that both the hadronic matching scale Λ_H and the NME M_0 are presently subject to considerable theoretical uncertainties. In the case of $0\nu\beta\beta$-decay mediated by the exchange of light Majorana neutrinos, for example, NME computations obtained using the nuclear shell model are typically a factor of two smaller than those obtained using QRPA. In order to illustrate the impact of both sources of uncertainty, we show results for two different values the product $M_0\Lambda^2_H$ that differ by a factor of two.

To illustrate the present and prospective reach of $0\nu\beta\beta$-decay and LHC searches, we first show in Fig. 1 the significance of a possible LHC observation, assuming C_1/Λ^5 has the maximum value consistent with the present GERDA limit for ^{76}Ge ($T_{1/2}$ <3×10^{25} yr) as implied by Eq. (8). We see that non-observation with

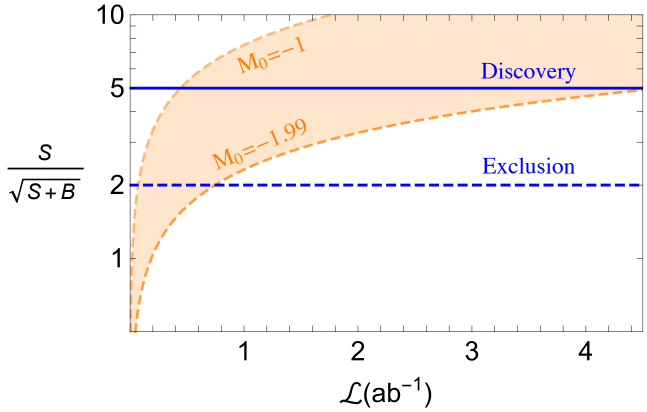

FIG. 1: Significance of a LHC e$^-$e$^-$ + di-jet signal as a function of integrated luminosity assuming the maximum C_1/Λ^5 consistent with the GERDA $0\nu\beta\beta$ half-life limit. Upper and lower curves correspond to values of the NME $M_0 = -1.0$ and -1.99, respectively.

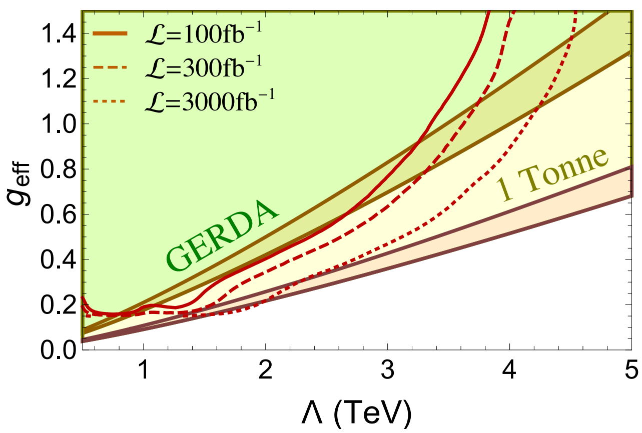

FIG. 2: Present and future reach of $0\nu\beta\beta$ and LHC searches for the TeV LNV interaction (1) as functions of the effective coupling $g_{\rm eff}$ and mass scale Λ (see text). Present GERDA exclusion and future tonne-scale $0\nu\beta\beta$ sensitivity are indicated by upper and lower shaded regions, respectively. Darker shaded bands indicate impact of varying $M_0\Lambda_H^2$ by a factor of two. LHC exclusion reach for representative integrated luminosities are indicated by the solid, dashed, and dotted lines.

~ 735 fb^{-1} (~ 70 fb^{-1}) would imply exclusion at a level consistent with the present GERDA limit assuming the larger (smaller) value of $M_0\Lambda_H^2$. The corresponding requirement for discovery $S/\sqrt{S+B} \geq 5$ is $\gtrsim$4.6 ab^{-1} ($\gtrsim$ 435 fb^{-1}). It is striking that a factor of two difference in $M_0\Lambda_H^2$, when translated into an upper bound on C_1/Λ^5, implies an order of magnitude difference in the luminosity needed for LHC exclusion or discovery. The exclusion and discovery reaches for both the LHC and a future, one-ton $0\nu\beta\beta$-decay as functions of Λ and an effective coupling $g_{\rm eff} = C_1(\Lambda)^{1/4}$ are shown Figs. 2 and

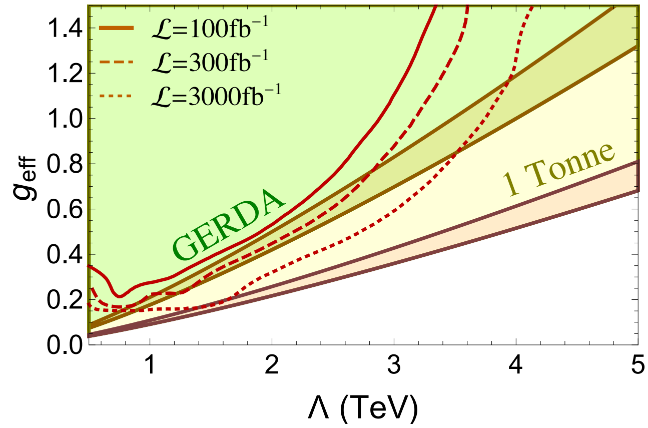

FIG. 3: Same as Fig. 2 but giving LHC discovery reach.

3, respectively. We use a prospective ^{76}Ge sensitivity of $T_{1/2} = 6\times 10^{27}$ yr[60]. We also show the present GERDA exclusion for reference. The darker shaded bands at the lower edges of each $0\nu\beta\beta$-decay exclusion and future sensitivity regions indicate the impact of varying $M_0\Lambda_H^2$ by a factor of two. From Fig. 2 we observe that with $\gtrsim$ 100 fb^{-1} the LHC would begin to extend the present GERDA exclusion for Λ in the vicinity of 1.4 TeV for the larger value of $|M_0|\Lambda_H^2$ and for a broader range of masses assuming the smaller value. As indicated by Fig. 3, the opportunities for discovery with 300 fb^{-1} appear more limited, even under the assumption of the smaller nuclear and hadronic matrix elements. However, the high luminosity phase of the LHC with 3 ab^{-1} could open the possibility for discovery over a range of masses that depends on the value of $M_0\Lambda_H^2$.

From the standpoint of the LHC, this conclusion is not as optimistic as obtained in Refs. [41, 42], as the reach of the tonne-scale $0\nu\beta\beta$-decay experiments appears to exceed that of the high-luminosity LHC over nearly the entire range of parameter space considered within this simplified model framework. We expect that our findings regarding the importance of jet-fake and charge flip backgrounds, QCD running, and long-range NME contributions to generalize to other simplified models as well as to full theories of LNV. It is, nevertheless, interesting to compare the prospects for both $0\nu\beta\beta$-decay and the LHC, as observation of a signal in both experiments is possible and would point to the existence of TeV scale LNV interactions.

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[64] The presence of an additional “sterile” neutrino that

mixes with the three "active" neutrinos could yield a value of $m_{\beta\beta}$ within reach of the tone-scale searches

[65] This conclusion assumes less than three signal events with 300 fb^{-1}.