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Neutrino Masses at the LHC

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Abstract. Neutrinoless double beta decay is the traditional tool to probe Majorana neutrino masses and lepton number violating physics in general. On the other hand, many models incorporating Majorana neutrino masses also predict new states and lepton number violating interactions at the TeV scale that can potentially be probed at the LHC. We provide a brief overview of the pertinent operators and a selection of physics models in order to highlight the interplay between neutrinoless double beta decay and LHC searches.

1. Introduction

Neutrinoless double beta decay ($0\nu\beta\beta$) is the most sensitive tool for probing Majorana neutrino masses. However, while the so-called mass mechanism is certainly the best known example triggering the decay, Majorana neutrino masses are not the only element of beyond Standard Model physics which can induce it. In this proceedings report we highlight possible other mechanisms of $0\nu\beta\beta$ decay where the lepton number violation (LNV) does not directly originate from the exchange of light Majorana neutrinos but rather due to LNV in extensions of the Standard Model. Many of these extensions predict new states and lepton number violating interactions at the TeV scale that can be potentially probed at the LHC. Correlating $0\nu\beta\beta$ with searches at the LHC provides a powerful tool to distinguish between different LNV sources and mechanisms of neutrino mass generation.

In this report, we provide a brief overview of the possible effective operators (c.f. Figure 1) that can trigger $0\nu\beta\beta$ beta decay, and discuss example signatures of lepton number and flavour violation at the LHC. For more details, see the review [1] and references therein.

2. Neutrinoless Double Beta Decay

2.1. Standard Mass Mechanism

Recall that the standard light neutrino exchange of $0\nu\beta\beta$ probes the effective mass $\langle m_\nu \rangle = \sum_j U_{ej}^2 m_j \equiv m_{ee}$, where the sum is over the active light neutrinos. The inverse $0\nu\beta\beta$ half life in a given isotope is then $[T_{1/2}^{0\nu\beta\beta}]^{-1} = |\langle m_\nu \rangle / m_e|^2 G_0 |ME|^2$, where G_0 and $|ME|$ denote the nuclear phase space factor and matrix element, respectively. The non-observation of $0\nu\beta\beta$ in current experiments points to a limit $\langle m_\nu \rangle \lesssim 0.5 - 1.0$ eV.

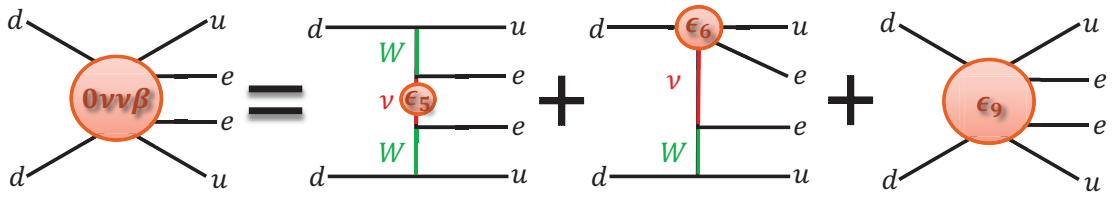

Figure 1. Schematic overview of different contributions to $0\nu\beta\beta$: Standard mass mechanism, long–range 6-dim operator, short–range 9-dim operator.

2.2. Long–Range Contributions

Long–range contributions to $0\nu\beta\beta$ decay involve two effective vertices connected by the exchange of a light neutrino. The general Lagrangian is expressed in terms of effective couplings $\epsilon^{\alpha}_{\beta}$ [2],

$$\mathcal{L} = \frac{G_F}{\sqrt{2}} \left(j^{\mu}_{V-A} J^{\dagger}_{V-A,\mu} + \sum_{\alpha,\beta} \epsilon^{\beta}_{\alpha} j_{\beta} J^{\dagger}_{\alpha} \right), \tag{1}$$

with the hadronic and leptonic currents $J^{\dagger}_{\alpha} = \bar{u}\mathcal{O}_{\alpha}d$ and $j_{\beta} = \bar{e}\mathcal{O}_{\beta}\nu$, respectively. The sum is over all Lorentz-invariant combinations, except for the standard case $\alpha = \beta = (V-A)$, and all currents are scaled relative to the Fermi interaction strength. The individual operators $\mathcal{O}_{\alpha}$ are

$$\mathcal{O}_{V\pm A} = \gamma^{\mu}(1 \pm \gamma_5), \qquad \mathcal{O}_{S\pm P} = (1 \pm \gamma_5), \qquad \mathcal{O}_{T_{\pm}} = \frac{i}{2}[\gamma_{\mu}, \gamma_{\nu}](1 \pm \gamma_5). \tag{2}$$

The interpretation of the effective couplings $\epsilon^{\alpha}_{\beta}$ depends on the specific particle physics model. Assuming the dominance of one of the couplings, the inverse $0\nu\beta\beta$ half life is

$$[T^{0\nu\beta\beta}_{1/2}]^{-1} = |\epsilon^{\beta}_{\alpha}|^2 G_{0k} |ME|^2, \tag{3}$$

where G_{0k} and $|ME|$ denote the corresponding nuclear phase space factor and matrix element, respectively. Current limits on the effective couplings are of the order $\epsilon \lesssim 10^{-9} - 10^{-7}$, depending on the operator [1]. This points to a limit on the scale of LNV physics of $\Lambda_{\mathrm{LNV}} \gtrsim 10^6$ GeV, generating the 6-dimensional operators in (1).

2.3. Short–Range Contributions

Short–range contributions to $0\nu\beta\beta$ decay involve one effect vertex originating from the general Lorentz-invariant Lagrangian [3]

$$\mathcal{L} = \frac{G_F^2}{2m_p} \left(\epsilon_1 JJj + \epsilon_2 J^{\mu\nu} J_{\mu\nu} j + \epsilon_3 J^{\mu} J_{\mu} j + \epsilon_4 J^{\mu} J_{\mu\nu} j^{\nu} + \epsilon_5 J^{\mu} J j_{\mu} \right), \tag{4}$$

consisting of 9-dimensional effective operators, with the hadronic currents $J = \bar{u}(1 \pm \gamma_5)d$, $J^{\mu} = \bar{u}\gamma^{\mu}(1 \pm \gamma_5)d$, $J^{\mu\nu} = \bar{u}\frac{i}{2}[\gamma^{\mu}, \gamma^{\nu}](1 \pm \gamma_5)d$ and the leptonic currents $j = \bar{e}(1 \pm \gamma_5)e^C$, $j^{\mu} = \bar{e}\gamma^{\mu}(1 \pm \gamma_5)e^C$. The $0\nu\beta\beta$ decay rate can be expressed as in (3) with the corresponding phase space factors and matrix elements. Similar to the long-range operators case, current limits on the effective couplings are of the order $\epsilon \lesssim 10^{-9} - 10^{-7}$, depending on the operator [1]. In this case, the scale of LNV physics probed is of the order $\Lambda_{\mathrm{LNV}} \gtrsim 1$ TeV. This hints at the possibility that physics generating these operators can be probed at the LHC as well.

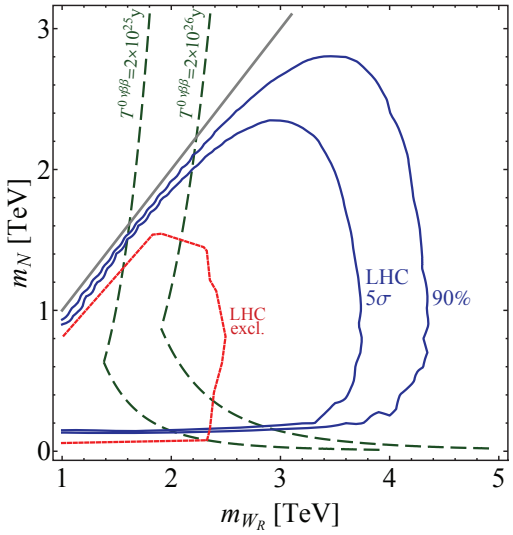

Figure 2. Comparison of LNV event rates at the LHC and in $0\nu\beta\beta$ experiments [9]. The solid blue contours give the signal significances of 5σ and 90% at the LHC with 14 TeV and $\mathcal{L} = 30$ fb^{-1}. The red shaded area is excluded by current LHC searches [10]. The green dashed contours show the sensitivity of current and future $0\nu\beta\beta$ experiments, assuming dominant doubly-charged Higgs or heavy neutrino exchange.

3. Lepton Number Violation at the LHC

3.1. Left-Right Symmetry

As an example of a model incorporating the rich phenomenology of lepton number violation, we briefly discuss the minimal Left-Right symmetric model (LRSM) which extends the Standard Model gauge symmetry to the group $\mathrm{SU}(2)_L \otimes \mathrm{SU}(2)_R \otimes \mathrm{U}(1)_{B-L}$ [4, 5, 6, 7, 8]. Lepton number violation and the presence of right-handed neutrinos are a necessary ingredient. The LRSM accommodates a general Seesaw type I + II neutrino mass matrix.

3.2. Neutrinoless Double Beta Decay

The model provides several mechanisms that contribute to $0\nu\beta\beta$ decay: (i) Standard light neutrino exchange with mass helicity flip; (ii) Long-range light neutrino exchange with right-handed currents; (iii) Short-range heavy right-handed neutrino exchange; (iv) Short-range right-handed doubly-charged triplet Higgs exchange. Each of these contributions can be mapped to one of the effective operators discussed in the previous section. For example, $0\nu\beta\beta$ decay through the exchange of heavy neutrinos with right-handed currents via the right-handed W_R gauge boson corresponds to the effective coupling

$$\epsilon_3^{RR} = \sum_{i=1}^{3} V_{ei}^2 \frac{m_p}{m_{N_i}} \frac{m_{W_L}^4}{m_{W_R}^4}, \tag{5}$$

with the heavy neutrino masses N_i and the mixing matrix between the heavy neutrinos V_{ei}.

3.3. Lepton Number and Flavour Violation at the LHC

In the LRSM, lepton number violation can also be probed via heavy right-handed neutrino exchange leading to the signal $pp \to W_R \to e^{\pm}\mu^{\pm,\mp} + 2$ jets at the LHC [11]. The potential to discover lepton flavour and lepton number violation using this process has been analyzed

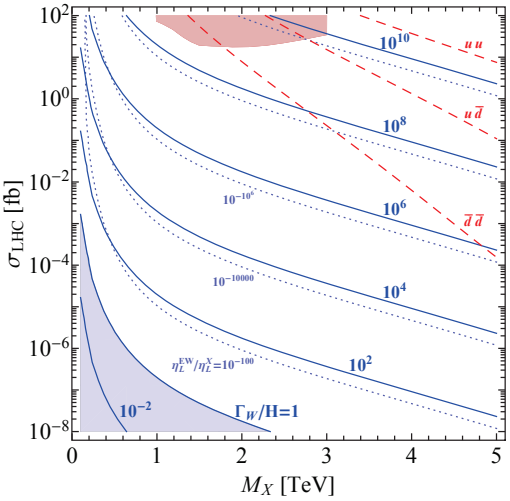

Figure 3. Lepton number washout rate Γ_W/H at $T = M_X$ as a function of the LNV scale M_X and the corresponding LHC cross section $\sigma_{\rm LHC}$ (solid blue contours). The dotted light blue contours denote the lepton asymmetry at the electroweak scale relative to its value at M_X, $\eta_L^{\rm EW}/\eta_L^X$. The red dashed curves are typical cross sections of the process $pp \to l^\pm l^\pm qq$. The shaded region at the top is excluded by recent searches at the LHC.

in [12, 9]. Figure 2 compares the LNV event rate at the LHC with the sensitivity of $0\nu\beta\beta$ experiments. The green dashed contours represent the excluded areas from $0\nu\beta\beta$ searches using nominal values for the current and future sensitivity. In this analysis it was assumed that $0\nu\beta\beta$ is dominated by either heavy neutrino or Higgs triplet exchange. As the contribution from the standard light neutrino exchange is always present, this corresponds to a scenario with a small effective mass $\langle m_\nu \rangle$. Figure 2 provides an example of the potential synergy between LNV searches at the LHC and in $0\nu\beta\beta$ experiments.

3.4. Falsifying Leptogenesis

The observation of lepton number violation at the LHC would not only have important consequences on the physics of $0\nu\beta\beta$ and neutrino mass generation but also on the viability of Leptogenesis models. In the traditional Leptogenesis scenario, the observed baryon asymmetry of the Universe is explained through the generation of a net lepton number asymmetry through the out-of-equilibrium decay of heavy right-handed neutrinos, which is then converted to the matter asymmetry though Standard Model $(B + L)$-violating sphaleron interactions. As part of this mechanism, the generation of a net lepton number asymmetry has to be balanced with necessarily present processes that washout this asymmetry.

Observing any lepton number violating process at the LHC would put a strong lower limit on this washout rate. This relation between general LNV processes at the LHC and the effect on leptogenesis models was discussed in [13]. The minimal rate of washout as a function of the LHC cross section and the scale of lepton number violation (for example observed as a resonance at this mass) is shown in Figure 3. For a washout rate larger than one, the dilution of lepton number is highly effective and a model that generates a lepton number asymmetry above the TeV scale is not a viable scenario to explain the observed baryon asymmetry. As shown in the figure, any observation of LNV at the LHC would correspond to a much larger washout rate, and would therefore strongly constrain Leptogenesis scenarios above the scale M_X. Low scale scenarios, such as resonant Leptogenesis where the lepton asymmetry is generated at scales lower

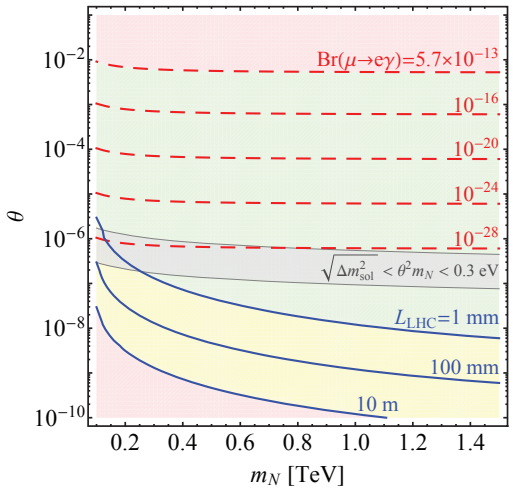

Figure 4. Average decay length of a heavy neutrino as a function of its mass m_N and the light-heavy mixing θ (solid blue contours). The dashed red contours denote $Br(\mu \to e\gamma)$ whereas the grey shaded band corresponds to light neutrino mass scales $m_\nu = \theta^2 m_N$ between $\sqrt{\Delta m^2_{\rm sol}}$ and 0.3 eV within the canonical type-I seesaw mechanism (taken from [14]).

than M_X would not necessarily be constrained.

3.5. Probing Small Yukawa Couplings

While total lepton number violation is considered a smoking gun signal of the Majorana nature of neutrinos, the observed neutrino oscillations already provide clear evidence of individual lepton flavour violation (LFV). Searches for rare processes such as $\mu \to e\gamma$ already put stringent limits on charged lepton flavour violation, which usually prohibits the observation of flavour violation at the LHC. This can be evaded in a scenario where right-handed neutrinos are produced via a Z' portal but which only decay via small flavour violating couplings θ [14]. The LHC process rate is then not suppressed by the small LFV despite unobservably small $\mu \to e\gamma$. The process under consideration is $pp \to Z' \to NN \to e^\pm\mu^\mp + 4\text{j}$, through the resonant production of two heavy neutrinos via a Z' portal. The neutrino N can decay via the channels $\ell^\pm W^\mp$, $\nu_\ell Z$ and $\nu_\ell h$, all of which are suppressed by the small light-heavy neutrino mixing θ. As long as the total neutrino decay width is large enough for decays within the detector, the process rate is not suppressed by the overall mixing strength θ. The decay length of the heavy neutrino is shown in Figure 4 (left), in relation with $Br(\mu \to e\gamma)$. It demonstrates that the canonical Seesaw type I regime with TeV scale neutrinos and small Yukawa couplings $\theta \approx 10^{-6}$ cannot be probed by low energy searches but potentially by the LHC process discussed here.

4. Summary

The Standard Model of particle physics (here defined as including light neutrino masses) has so far evaded all attempts to unambiguously prove it wrong. The discovery of a SM compatible Higgs boson at the LHC provides the most recent and dramatic confirmation of its predictions. Neutrinos provide a natural channel to look for (further) signs beyond the Standard Model as they are still the least understood matter particles; even if the Higgs mechanism of fermion mass generation is confirmed, we do not understand why neutrinos are as light as they are. Of crucial importance in this regard is not only the value of the mass of neutrinos but also their nature: Dirac or Majorana? Neutrinoless double beta decay is the most important observable to probe

for both. In addition, it tests the fundamental symmetry of lepton number. Despite the lack of any signs of new physics, the LHC does and most importantly will provide important information in this regard as it probes models of neutrino mass generation and lepton number violation at the TeV scale. In this report, we briefly highlighted the connection between neutrinoless double beta decay and searches for lepton number and flavour violating processes at the LHC. The observation of lepton number violation at the LHC would have a dramatic impact on aspects of neutrino physics such as Leptogenesis, but even if nothing was to be observed, it would affect our understanding of neutrinoless double beta decay.

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