# Large Hadron Collider probe of supersymmetric neutrinoless double beta decay mechanism

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In the minimal supersymmetric extension to the Standard Model, a non-zero lepton number violating coupling $\lambda'_{111}$ predicts both neutrinoless double beta decay and resonant single slepton production at the LHC. We show that, in this case, if neutrinoless double beta decay is discovered in the next generation of experiments, there exist good prospects to observe single slepton production at the LHC. Neutrinoless double beta decay could otherwise result from a different source (such as a non-zero Majorana neutrino mass). Resonant single slepton production at the LHC can therefore discriminate between the $\lambda'_{111}$ neutrinoless double beta decay mechanism and others.

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Neutrinoless double beta decay ($0\nu\beta\beta$) corresponds to an atomic nucleus changing two of its neutrons into protons, while emitting two electrons. At the quark level, the $0\nu\beta\beta$ process corresponds to the simultaneous transition of two down quarks (in different neutrons) into two up-quarks and two electrons, but *without* associated production of any neutrinos. Thus, the $0\nu\beta\beta$ process is lepton number violating (LNV). $0\nu\beta\beta$ has so far not been observed; the most stringent lower limit on the $^{76}$Ge $0\nu\beta\beta$ half life was measured in the Heidelberg-Moscow experiment [1, 2] to be

$$T_{1/2}^{0\nu\beta\beta}(^{76}\mathrm{Ge}) \ \geq \ 1.9 \cdot 10^{25}\mathrm{yrs}. \qquad (1)$$

Coverage by a couple of additional orders of magnitude is expected by planned experiments in the coming years [3, 4]. The Standard Model conserves lepton number and so predicts a zero rate for this process. A discovery of a non-zero rate would then prompt the question: what beyond the Standard Model physics is responsible for it? In this letter, we discuss two leading possibilities, Majorana neutrino masses and supersymmetric particle exchange, pointing out how data from the Large Hadron Collider (LHC) can favor or disfavor the latter possibility.

The experimental observations of neutrino oscillations has lead to the realization that at least two of the three known neutrinos have masses [5]. Thus, the Standard Model, which predicts zero neutrino mass, must be augmented in some way to account for such masses. Neutrino masses may or may not induce $0\nu\beta\beta$ depending on

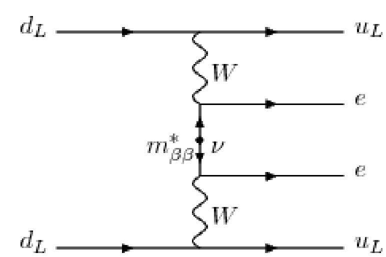


FIG. 1: Majorana neutrino mass induced neutrinoless double beta decay hard sub-process.

whether they are Majorana or Dirac masses, respectively. A Lagrangian for a LNV Majorana neutrino mass is

$$\mathcal{L}_M = \frac{1}{2} m_{\beta\beta} \overline{\nu^c} \nu + h.c., \qquad (2)$$

where $\nu$ is the neutrino originating from the left-handed first generation lepton electroweak doublet, and the $c$ superscript denotes charge conjugation. A Feynman diagram for the induced $0\nu\beta\beta$ is shown in Fig. 1. It leads to an inverse half-life of

$$\left[T_{1/2}^{0\nu\beta\beta}(^{76}\mathrm{Ge})\right]^{-1} = G_{01} \left| \frac{m_{\beta\beta}}{m_e} M_\nu \right|^2, \qquad (3)$$

where $G_{01} = 7.93\ 10^{-15}\mathrm{yr}^{-1}$ [6] is a precisely calculable phase space factor, $m_e$ is the electron mass and $M_\nu$ denotes the nuclear matrix element (NME) for the process in Fig. 1. We shall use $M_\nu = 2.8$ [7] for $^{76}$Ge, but it should be noted that the uncertainty in the theoretical prediction of such nuclear matrix elements could be as large as a factor of 3. Eq. 3 then implies that, assuming $0\nu\beta\beta$ is due solely to a Majorana neutrino mass,

$$\frac{m_{\beta\beta}}{460\mathrm{meV}} \ = \ \left( \frac{1.9 \cdot 10^{25}\mathrm{yr}}{T_{1/2}^{0\nu\beta\beta}(^{76}\mathrm{Ge})(\mathrm{min})} \right)^{1/2}. \qquad (4)$$

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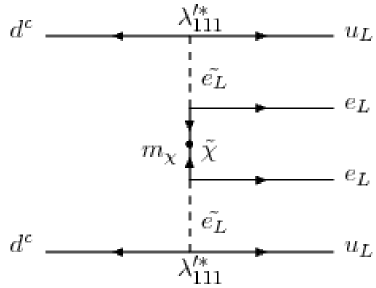


FIG. 2: Example Feynman diagram leading to neutrinoless double beta decay, mediated by supersymmetric particles. Several other such tree-level diagrams are taken into account.

Several other possibilities of LNV processes that induce $0\nu\beta\beta$ have been discussed in the literature, including one attractive alternative where it is mediated by the exchange of sparticles in supersymmetric models with R-parity violation [8, 9, 10, 11, 12]. We shall focus on this possibility in this letter.

The superpotential term

$$W = \lambda'_{111}\hat{L}\hat{Q}\hat{D}^c \tag{5}$$

may induce $0\nu\beta\beta$ and is allowed by the gauge symmetries of the minimal supersymmetric standard model. $\hat{Q}$, $\hat{L}_i$ and $\hat{D}^c$ denote the superfield containing left-handed quark doublet, left-handed lepton doublet and charge conjugated right-handed down quark fields respectively (all being of the first generation). Typically, one imposes a discrete symmetry on the model in order to maintain proton stability. Such a symmetry may allow for the presence of the term in Eq. 5 (for example baryon triality) or ban it, as in the case of $R-$parity [13]. We shall consider the former possibility here.

The interaction in Eq. 5 mediates $0\nu\beta\beta$ by processes such as the one shown in Fig. 2. Following the notation of [8], the effective Lagrangian with $\lambda'_{111}$ in the direct $R-$parity violating $0\nu\beta\beta$ process involving exchange of three supersymmetric (SUSY) particles is

$$\mathcal{L}^{eff,\,\Delta L_e=2}_{\lambda'_{111}\lambda'_{111}}(x) = \frac{G_F^2}{2}m_p^{-1}[\bar{e}(1+\gamma_5)e^c] \times\Big[\eta(J_{PS}J_{PS} - \frac{1}{4}J_T^{\mu\nu}J_{T\mu\nu}) + \eta' J_{PS}J_{PS}\Big], \tag{6}$$

where

$$\eta = a\frac{\lambda'^2_{111}}{G_F^2}\frac{m_P}{\Lambda^5_{SUSY}},\;\; \eta' = b\frac{\lambda'^2_{111}}{G_F^2}\frac{m_P}{\Lambda^5_{SUSY}}. \tag{7}$$

In the above expressions, $J_{PS}$ and $J_T^{\mu\nu}$ are the pseudoscalar and tensor quark currents respectively. The coefficients $a, b$ include factors coming from gauge couplings and mass matrix rotations, and $\Lambda_{SUSY}$ is the approximate mass scale of the sparticles being exchanged.

| $M^{2N}_{\tilde{g}}$ | $M^{2N}_{\tilde{f}}$ | $M^{1\pi}$ | $M^{2\pi}$ |
|---|---|---|---|
| 283 [8] | 13.2 [8] | -18.2 [9] | -601 [9] |

TABLE I: Nuclear matrix elements of $^{76}$Ge used. For model details of the NME calculations, we refer readers to the literature.

The inverse half-life generated by $\lambda'_{111}$ is

$$\left[T^{0\nu\beta\beta}_{1/2}(^{76}\mathrm{Ge})\right]^{-1} = G_{01}\left|M_{\lambda'_{111}}\right|^2, \tag{8}$$

where $M_{\lambda'_{111}}$ denotes the relevant matrix element, obtained from Refs. [8, 9, 10, 11, 12], and is given by

$$M_{\lambda'_{111}} = \eta M^{2N}_{\tilde{g}} + \eta' M^{2N}_{\tilde{f}} + \Big(\eta + \frac{5}{8}\eta'\Big)\big(\frac{4}{3}M^{1\pi} + M^{2\pi}\big), \tag{9}$$

with $M^{2N}_{\tilde{g},\tilde{f}}$ and $M^{1\pi,2\pi}$ denote NME contributions from 2 nucleon lepton decay and pion exchange modes respectively. The numerical values of the NMEs we shall use are displayed in table I. We refer interested readers to [14] for a more detailed discussion.

The experimental lower bound in Eq. 1 then leads to the approximate limit [8, 9]

$$|\lambda'_{111}| \lesssim 5\cdot 10^{-4}\Big(\frac{\Lambda_{SUSY}}{100\mathrm{GeV}}\Big)^{2.5}. \tag{10}$$

Couplings such as Eq. 5 also lead to loop-level Majorana left-handed neutrino masses [15]

$$m_{\beta\beta} \simeq \frac{3m_d}{8\pi^2}\frac{\lambda'^2_{111}m^2_{\tilde{d}_{LR}}}{m^2_{\tilde{d}_{LL}} - m^2_{\tilde{d}_{RR}}}\ln\Big(\frac{m^2_{\tilde{d}_{LL}}}{m^2_{\tilde{d}_{RR}}}\Big), \tag{11}$$

where $m_d$ is the down quark mass, while $m^2_{\tilde{d}_{LL,LR,RR}}$ are entries in the first generation down squark mass squared matrix. Thus there is potentially an additional contribution to $0\nu\beta\beta$ from the induced neutrino mass in Eq. 11. Through the parameter space that we consider $|M_{\lambda'_{111}}|/|M_{m_{\beta\beta}}| > 20$, where $M_{m_{\beta\beta}} \equiv m_{\beta\beta}M_\nu/m_e$, and so we may neglect the contribution coming from induced Majorana neutrino masses.

We pick an illustrative scheme of supersymmetry breaking: the so-called mSUGRA assumption. The following set of parameters is defined: $M_0 = [40, 1000]$ GeV, $M_{1/2} = [40, 1000]$ GeV, $A_0 = 0$ $\tan\beta = 10$, $\mathrm{sgn}\mu = +1$, where $M_0$, $M_{1/2}$ and $A_0$ are the universal scalar, gaugino, and trilinear soft SUSY breaking parameters defined at the electroweak gauge coupling unification scale $M_X \sim 2.0\cdot 10^{16}$GeV, $\tan\beta$ is the ratio of the Higgs vacuum expectation values $v_u/v_d$, and $\mathrm{sgn}\mu$ is the sign of the bilinear Higgs parameter in the superpotential.

For large enough $\lambda'_{111}$, resonant production of a single slepton of the first generation[1] may be observed at the

[1] We will refer to this process simply as 'single slepton production' unless specified otherwise.

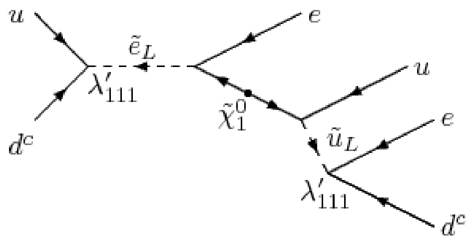


FIG. 3: Example of single selectron production at the LHC, followed by subsequent cascade decay.

LHC. Neglecting finite width effects, the color and spin-averaged parton total cross section of a single slepton production is [16]

$$\hat{\sigma} \;=\; \frac{\pi}{12\hat{s}}|\lambda'_{111}|^2\delta(1-\frac{m^2_{\tilde{l}}}{\hat{s}}), \tag{12}$$

where $\hat{s}$ is the partonic center of mass energy, and $m_{\tilde{l}}$ is the mass of the resonant slepton. Including effects from parton distribution functions, we find that the total cross section for $\sigma(pp \rightarrow \tilde{l}) \propto |\lambda'_{111}|^2/m^3_{\tilde{l}}$ to a good approximation in the parameter region of interest.

At low slepton masses, the stringent bound in Eq. 10 from $0\nu\beta\beta$ renders such a process unobservable at the LHC. We believe that this has precluded any study of single slepton production of the *first* generation at the LHC via $\lambda'_{111}$. However, from eq. (10), we see that, applying the bound on $\lambda'_{111}$ coming from non-observation of $0\nu\beta\beta$, $\sigma < c\Lambda^2_{SUSY}$ where $c$ is a constant, and so at higher values of the supersymmetric masses, larger cross-sections may be allowed due to a much larger allowable $\lambda'_{111}$. It is this possibility that we exploit here.

A closely related process, LHC second generation slepton production, followed by decay into like-sign di-muon pairs, was studied in Ref. [17]. Such a process is predicted by the superpotential term $\lambda'_{211}\hat{L}_2\hat{Q}\hat{D}^c$, where $L_2$ is a chiral superfield containing the second generation left-handed lepton doublet. $\lambda'_{211}$ does not predict $0\nu\beta\beta$ and so it may take a somewhat larger value than $\lambda'_{111}$ for a given set of supersymmetric particle masses. LHC detectors do not have wildly differing acceptances and efficiencies for electrons as compared with muons, and so we use the results of Ref. [17] (which does not include detector effects anyway) as an estimate for the search reach for first generation single slepton production, followed by decay into like-sign electrons, by simply making the replacements $\lambda'_{211} \rightarrow \lambda'_{111}$ and $\mu \rightarrow e$. A Feynman diagram leading to our signal (like-sign di-electron pairs and two hard jets, with no missing energy) is shown in Fig. 3.

Like Ref. [17], we assume 10 fb$^{-1}$ of LHC integrated luminosity at a centre of mass energy of 14 TeV. Fig. 4 shows regions of the $M_0 - M_{1/2}$ plane where single slepton production may be observed via like-sign electrons plus two jets, including backgrounds from both the Standard Model and from sparticle pair production. The cuts are as in Ref. [17]. In the white region, single slepton production by $\lambda'_{111}$ could not be observed without

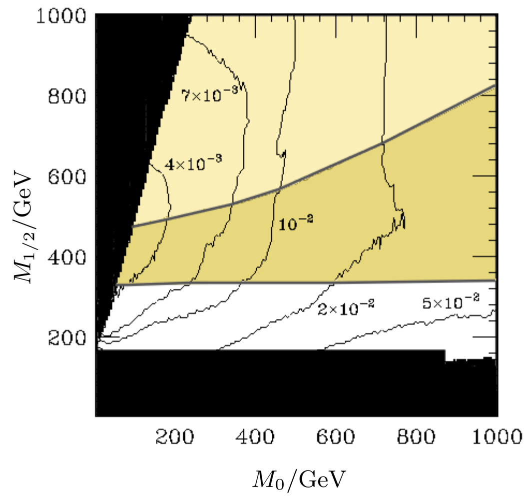


FIG. 4: mSUGRA parameter space in which single slepton production may be observed at the LHC for $\tan\beta = 10$, $A_0 = 0$ and 10fb$^{-1}$ of integrated luminosity. In the top left-hand black triangle, the stau is the LSP, a case not covered by this analysis. The bottom black region is ruled out by direct search constraints. The labelled contours are extracted from Ref. [17], and show the search reach given by the labelled value of $\lambda'_{111}$. The white, dark-shaded and light-shaded regions show that observation of single slepton production at the $5\sigma$ level would imply $T^{0\nu\beta\beta}_{1/2}(^{76}\mathrm{Ge}) < 1.9 \cdot 10^{25}$yrs, $100 > T^{0\nu\beta\beta}_{1/2}(^{76}\mathrm{Ge})/10^{25}\mathrm{yrs} > 1.9$ and $T^{0\nu\beta\beta}_{1/2}(^{76}\mathrm{Ge}) > 1 \times 10^{27}$yrs, respectively.

violating the current bound upon $T^{0\nu\beta\beta}_{1/2}(^{76}\mathrm{Ge})$. The darker shaded region shows where the observation of single slepton production at $5\sigma$ above background implies that $0\nu\beta\beta$ is within the reach of the next generation of experiments, which should be able to probe $T^{0\nu\beta\beta}_{1/2}(^{76}\mathrm{Ge}) < 1 \times 10^{27}$yrs [3, 4]. Conversely, if $0\nu\beta\beta$ is discovered by the next generation of experiments, we should expect single slepton production to be observable and test the $\lambda'_{111}$ hypothesis. We do not expect $A_0$ or $\tan\beta$ to affect the shape of the regions much, since they have a negligible effect on the selectron mass and the couplings in the relevant Feynman diagrams. In the light shaded (upper) region, a $5\sigma$ single slepton discovery at the LHC implies that the next generation of experiments would not be able to observe $0\nu\beta\beta$. Conversely, if $0\nu\beta\beta$ is within reach of the next generation of experiments, the LHC would see single slepton production signal in this region at greater than $5\sigma$ significance.

We show in Fig. 5 the variation of the discovery reach of $\lambda'_{111}$ with $M_0$ along the line $M_{1/2} = 300$ GeV $+ 0.6M_0$ in Fig. 4. Above the dotted light line, single slepton production will be observed at the LHC. We see from the figure that for nearly all of the parameter space where $0\nu\beta\beta$ can be measured by the next generation of experiments, the LHC would provide a confirmation of the supersymmetric origin of the signal by observing single slepton production at the $5\sigma$ level.

In summary, we have discussed the interplay between

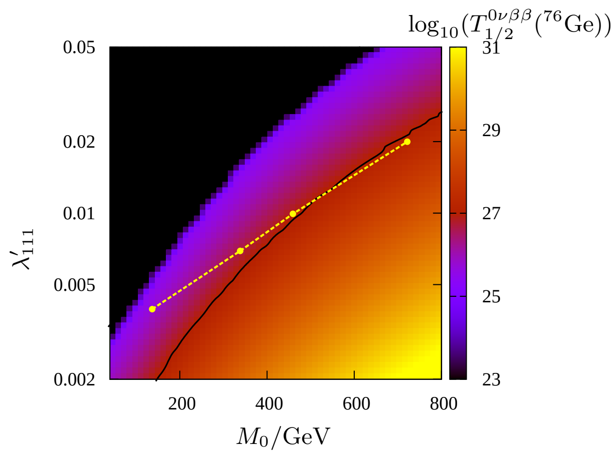


FIG. 5: Comparison of $T^{0\nu\beta\beta}_{1/2}(^{76}\text{Ge})$ and single slepton discovery reach as a function of $\lambda'_{111}$ along the mSUGRA slope $M_{1/2} = 300$ GeV $+ 0.6M_0$, with $A_0 = 0$, $\tan\beta = 10$ and $\text{sgn}\mu = 1$. The black region on the top left corner is ruled out by $0\nu\beta\beta$. The region above the solid black line is accessible in near future $0\nu\beta\beta$ experiments, whereas the light dotted line shows the lower limit of $\lambda'_{111}$ for single slepton production to be discoverable at the LHC.

neutrinoless double beta decay and single slepton production at the LHC in $R-$parity violating supersymmetry. Should neutrinoless double beta decay be observed in the next round of experiments, one would like to interpret which physics would lead to the observation. We have considered the exchange of supersymmetric particles via the lepton number violating interaction in Eq. 5. The observation of single slepton production could discriminate between this possibility and others (for example a Majorana neutrino mass). Fig. 4 shows that much of the parameter space allowed by $0\nu\beta\beta$ in simple models of supersymmetry breaking predicts observable single slepton production at the LHC. It also shows that if the next round of experiments observe the $0\nu\beta\beta$ process, the LHC has a very good chance of observing single slepton production with only 10 fb$^{-1}$ of integrated luminosity, assuming that $0\nu\beta\beta$ is induced by a $\lambda'_{111}$ coupling. Conversely, non-observation of single slepton production could then discriminate against the $\lambda'_{111}$ mechanism. In general, one may enquire whether *both* Majorana neutrino masses and $\lambda'_{111}$ contribute simultaneously and non-negligibly to $0\nu\beta\beta$. Detailed LHC measurements of the kinematics in single slepton production would constrain the mSUGRA parameters, and the total cross-section could then give information about the size of $|\lambda'_{111}|$. The LHC information could be combined to predict an associated inverse $T^{0\nu\beta\beta}_{1/2}(^{76}\text{Ge})$ coming from $\lambda'_{111}$, which could be compared with the experimental measurement of $T^{0\nu\beta\beta}_{1/2}(^{76}\text{Ge})$ in order to see if additional contributions were necessary. It will be interesting in future studies to see how accurate such an inference could be, assuming matrix element uncertainties can be kept under control.

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