Minimal supersymmetric standard model with gauge mediated supersymmetry breaking and neutrinoless double β decay

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The minimal supersymmetric standard model with gauge mediated supersymmetry breaking and trilinear R-parity violation is applied to the description of neutrinoless double β decay. A detailed study of limits on the parameter space coming from the $B \to X_s \gamma$ processes by using the recent CLEO results is performed. The importance of two-nucleon and pion-exchange realizations of $0\nu\beta\beta$ decay together with gluino and neutralino contributions to this process is addressed. We have deduced new limits on the trilinear R-parity breaking parameter λ'_{111} from the nonobservability of $0\nu\beta\beta$ in several medium and heavy open-shell nuclei for different gauge mediated breaking scenarios. In general, they are stronger than those known from other analyses. Also some studies with respect to the future $0\nu\beta\beta$ projects are presented.

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I. INTRODUCTION

During recent years, a lot of work has been devoted to test the standard model (SM) of elementary particles. The best tested are interactions between gauge bosons and matter, and in this sector the SM description turns out to be very accurate. Other sectors, however, have been checked to much less degree. Among them are self-interactions of gauge bosons as well as the Higgs sector, which plays an important role for completeness of the model and in many aspects of symmetry breaking. Also, many shortcomings of SM, such as the big number of free parameters, unresolved question of mass hierarchy, and the problem of massive neutrinos and their oscillations, may call for more desirable description of nature.

As a matter of fact, a number of various models reaching beyond SM's orthodoxy were proposed. One of the most promising candidates is the supersymmetric extension of SM called minimal supersymmetric standard model (MSSM). It is based on the concept of supersymmetry (SUSY) and, despite the lack of direct experimental evidence at the moment, is supported by many theoretical arguments accompanied with the hope that SUSY is the relevant description of our world above 1 TeV scale. One of the main facts supporting MSSM is that incorporating SUSY in SM causes all the gauge couplings to unify at some scale $m_{GUT} \sim 10^{16}$ GeV. As is well known, extrapolations of data from the LEP measurements suggest such behavior. However, SUSY particles have not been observed in experiments, so supersymmetry has to be broken in the low-energy regime. The issue of how this breaking is realized is the least understood question of the theory.

The most widely studied version of SUSY conserves the so-called R parity. The R parity is a multiplicative quantity defined as $R=(-1)^{2S+3B+L}$, where B and L are the baryon and lepton numbers, and S is the spin of corresponding particle. As a consequence, processes which do violate lepton or baryon number are strictly forbidden unless the symmetry is broken. Moreover, SUSY particles are pair produced and the lightest one is stable.

The origin of R-parity conservation is not based on any fundamental principle, so this property of MSSM is an *ad hoc* hypothesis and therefore some extensions of the model, allowing the violation of R parity, were discussed in literature. These modifications can be classified either as explicitly R-parity broken MSSM ($\not{R}$MSSM) approaches [1] or as formalisms with spontaneous breaking of this symmetry [2]. In the first class of models the R-violating interactions are consistent with both gauge invariance and SUSY [3], while the second ones provide the simplest way for R-parity violating effects conserving at low energy the baryon number [4]. The explicit R-parity breaking leads to well-defined phenomenological consequences, but due to a large number of free parameters involved, such theory has only marginal predictive power. In contrast, the spontaneous breaking has many virtues added, such as the important possibility of dynamical origin of the R-parity breaking [4].

One of the most popular models discussed in literature is the supergravity mediated SUSY breaking (SUGRA MSSM models). The soft breaking terms are generated in these models at m_{GUT}, or even the Planck scale, and then transmitted to the low-energy sector by gravitational interactions. However, there is a problem related to the flavor symmetry, which, due to high energies and radiative corrections, is permanently broken. It is therefore desirable to lower the scale of SUSY breaking. It is achieved in the so-called gauge mediated supersymmetry breaking (GMSB), which has recently attracted a great deal of attention. These models are highly predictive, offer a natural solution to the flavor problem, and contain much less free parameters compared to MSSM with SUSY breaking mediated by gravitational interaction [5–12]. In GMSB models supersymmetry breaking is transmitted to the superpartners of quarks, leptons, and gauge bosons via the usual $SU(3)\times SU(2)\times U(1)$ gauge interactions and occurs at the scale $M_{SUSY} \sim 10^5$ GeV, so there is no problem with the flavor symmetry. Besides, one can construct a renormalizable model with dynamical SUSY breaking, where all the param-

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eters can, in principle, be calculated. For example, gauginos and sfermions acquire their masses through interactions with the messenger sector at one- and two-loop levels, respectively. Since in GMSB the messenger sector consists of gauge bosons and matter fields of SM and some grand unified theory (GUT), all the soft masses are related to gauge couplings. This results in more restrictive phenomenology of the low-energy world than the SUGRA MSSM one. In these models flavor-diagonal sfermion mass matrices are induced in a rather low-energy scale, and therefore they supply us with a very natural mechanism of suppressing, unobserved in experiments, flavor changing neutral currents (FCNC). Moreover, since the soft masses arise as gauge charges squared, the sizable hierarchy proportional to the gauge quantum numbers appears among the superpartner masses.

The main practical difference between GMSB and SUGRA is that in GMSB the renormalization group evolution is performed to much lower energy. Besides, interactions with the messenger sector lead to certain corrections to gauge coupling's values and the low-energy mass spectrum. What is more, gravitino, usually heavy in SUGRA, becomes the lightest SUSY particle (LSP) in GMSB. Since it is a $\frac{3}{2}$-spin particle, its $\pm\frac{1}{2}$-spin projections contribute to phenomenology through weak interactions.

Among other scenarios there are anomaly and gaugino mediated SUSY breaking. In the first approach conformal anomalies mediate SUSY breaking, but such formalism produces tachyonic sleptons, which means that their mass squared becomes negative at tree level. The gaugino mediated scenario is the least known. It assumes our world to be more than $3+1$ dimensional; such possibility emerges from the string theory and is being discussed extensively in the literature, but is beyond the scope of the present paper. Having this in mind, GMSB scenario appears as the most natural and convenient framework. In this light, recently renewed interest in GMSB [9,10] is understandable.

The R parity in MSSM can be explicitly violated by the presence of bilinear [13] and trilinear [14] terms in the superpotential. The trilinear terms lead to lepton number and flavor violation, while the bilinear terms generate nonzero vacuum expectation values for sneutrino fields $\langle\tilde{\nu}_l\rangle$, causing neutrino-neutralino and electron-chargino mixing. Thus, approaches with lepton number violation can describe some low-energetic exotic nuclear processes such as the neutrinoless double β decay $(0\nu\beta\beta)$, known to be very sensitive to some of the R-parity violating interactions [15]. Using experimental data of these processes, e.g., bounds on the half-life of neutrinoless double β decay, one can establish stringent limits on the R-parity breaking SUSY [15–19].

Supersymmetric models with R-parity nonconservation have been extensively discussed in the last decade (see, e.g., Refs. [13,14]), and were also used for the study of $0\nu\beta\beta$ (for the first time in Ref. [20], see also Refs. [15–19,21]). The older calculations were concentrated on the conventional two-nucleon mode of $0\nu\beta\beta$, in which direct interaction between quarks of the two decaying neutrons causes the process [15,17]. Recently, the dominance of pion-exchange mode based on the double-pion exchange between the decaying neutrons over the two-nucleon one was proved [19,21,22].

Motivated by the aforementioned features of GMSB models, we study in this paper the R-parity breaking phenomenology of MSSM, and use the neutrinoless double β decay for deducing limits on some nonstandard physics parameters. In the previous studies such estimates were performed in the framework of $\not{R}$MSSM with supergravity mediated SUSY breaking by means of GUT constraints [17,19] or additional assumptions relating sfermion and gaugino masses [15,16]. We will show that one can find quantitatively new constraints [18] within GMSB models. In this paper we study this problem using up-to-date experimental data on the $B \to X_s\gamma$ process from CLEO Collaboration [36] and apply it to $0\nu\beta\beta$. As previously, we limit our attention to the trilinear terms only, leaving complete treatment of bilinear and trilinear R-parity violating terms in GMSB for a subsequent paper.

For reliable extraction of the limits on R-parity breaking constant λ'_{111} from the best presently available experimental lower limit on the half-life of $0\nu\beta\beta$, it is necessary to determine other SUSY parameters, e.g., masses of SUSY particles, within a proper SUSY scenario, and to evaluate corresponding nuclear matrix elements. Because at present the renormalized quasiparticle random phase approximation (RQRPA) [23,37], which takes to some extent the Pauli exclusion principle into account, is the main method commonly used in calculations of the $0\nu\beta\beta$ nuclear matrix elements [22], we also used it in our work.

Our paper is organized as follows. In Sec. II the necessary theory is developed. We also discuss to some extent the gauge mediated supersymmetry breaking mechanism of the neutrinoless double β decay. Section III contains the results and analysis of constraints imposed on supersymmetric parameters by nonobservation of $0\nu\beta\beta$ in germanium ^{76}Ge, for which the best experimental limit on the half-life is known. In this section we also demonstrate differences between the neutralino and gluino mechanisms in the neutrinoless double β decay. Finally, summary and concluding remarks can be found in Sec. IV.

II. FORMALISM

A. *R*-parity violation in MSSM

In this section we briefly outline the main features of MSSM and its violation mechanism. Both in the supergravity and in GMSB, the R parity can be explicitly violated by the bilinear [13] and trilinear [14] terms incorporated into the superpotential. Bilinear terms generate nonzero vacuum expectation values for the sneutrino fields $\langle\tilde{\nu}_L\rangle$, causing neutrino-neutralino and electron-chargino mixing. Trilinear terms lead to the lepton number and flavor violation. The above features make $\not{R}$MSSM models appropriate for the description of $0\nu\beta\beta$. Because this process is known to be very sensitive to supersymmetric and R-parity breaking parameters, data from the nowadays double β experiments allow one to establish stringent limits on $\not{R}$MSSM physics [15–19,21,22,24].

The complete superpotential W of the model can be written in the form

$$W = W_0 + W_{\not R}, \tag{1}$$

where

$$W_0 = h_{ij}^U \hat{Q}_i \hat{H}_u \hat{u}_j^c + h_{ij}^D \hat{Q}_i \hat{H}_d \hat{d}_j^c + h_{ij}^E \hat{L}_i \hat{H}_d \hat{e}_j^c + \mu \hat{H}_d \hat{H}_u \tag{2}$$

and

$$W_{\not R} = \lambda_{ijk} \hat{L}_i \hat{L}_j \hat{u}_k^c + \lambda'_{ijk} \hat{L}_i \hat{Q}_j \hat{d}_k^c + \lambda''_{ijk} \hat{u}_i^c \hat{d}_j^c \hat{d}_k^c + \mu_j \hat{L}_j \hat{H}_u \tag{3}$$

are the R-parity conserving and R-parity breaking parts, respectively. Here $\hat{Q}$ and $\hat{L}$ denote the quark and lepton SU(2) doublet superfields, $\hat{u}^c, \hat{d}^c$, and $\hat{e}^c$ are the corresponding SU(2) singlets, and $\hat{H}_u$, $\hat{H}_d$ are the Higgs superfields. In the R–parity breaking part (3), the first two terms are lepton number violating, while the third violates the baryon number conservation. The presence of these terms simultaneously would cause unsuppressed proton decay, and therefore we follow the usual way and simply set $\lambda_{ijk} = \lambda''_{ijk} = 0$ in order to avoid such possibility.

In the low-energy world supersymmetry is obviously broken, and usually one supplies the theory with the "soft" breaking terms, being another source of R-parity violation:

$$\begin{aligned} -\mathcal{L}_{soft} = {} & (A_{ij}^U \tilde{Q}_i H_u \tilde{u}_j^c + A_{ij}^D \tilde{Q}_i H_d \tilde{d}_j^c + A_{ij}^E \tilde{L}_i H_d \tilde{e}_j^c + \text{H.c.}) \\ & + B\mu (H_d H_u + \text{H.c.}) + m_{H_d}^2 |H_d|^2 + m_{H_u}^2 |H_u|^2 + m_{\tilde{L}}^2 |\tilde{L}|^2 \\ & + m_{\tilde{e}^c}^2 |\tilde{e}^c|^2 + m_{\tilde{Q}}^2 |\tilde{Q}|^2 + m_{\tilde{u}^c}^2 |\tilde{u}^c|^2 + m_{\tilde{d}^c}^2 |\tilde{d}^c|^2 \\ & + \left(\tfrac{1}{2} M_1 \overline{\psi_B} \psi_B + \tfrac{1}{2} M_2 \overline{\psi_W^a} \psi_W^a + \tfrac{1}{2} m_{\tilde{g}} \overline{\psi_g^a} \psi_g^a + \text{H.c.} \right) \end{aligned} \tag{4}$$

and

$$\begin{aligned} -\mathcal{L}_{soft}^{\not R} = {} & \tilde{\lambda}_{ijk} \tilde{L}_i \tilde{L}_j \tilde{u}_c^k + \tilde{\lambda}'_{ijk} \tilde{L}_i \tilde{Q}_j \tilde{d}_k^c + \tilde{\lambda}''_{ijk} \tilde{u}_i^c \tilde{d}_j^c \tilde{d}_k^c + \tilde{\mu}_{2j}^2 \tilde{L}_j \hat{H}_u \\ & + \tilde{\mu}_{1j}^2 \tilde{L}_j \hat{H}_d . \end{aligned} \tag{5}$$

Here, fields with tilde denote the scalar partners of quark and lepton fields, while ψ_i are the spin-$\frac{1}{2}$ partners of gauge bosons.

To describe $0\nu\beta\beta$ process within supersymmetric models one needs an explicit form of the appropriate Lagrangian. It can be obtained using the standard procedure of extracting Lagrangian from superpotential $W_{\not R}$. After some computation one gets

$$\begin{aligned} \mathcal{L}_{\lambda'_{111}} = -\lambda'_{111} \Bigg[& (\overline{u_L}, \overline{d_L}) \begin{pmatrix} e_R^c \\ -\nu_R^c \end{pmatrix} \tilde{d}_R^* + (\overline{e_L}, \overline{\nu_L}) d_R \begin{pmatrix} \tilde{u}_L^* \\ -\tilde{d}_L^* \end{pmatrix} \\ & + (\overline{u_L}, \overline{d_L}) d_R \begin{pmatrix} \tilde{e}_L^* \\ -\tilde{\nu}_L^* \end{pmatrix} + \text{H.c.} \Bigg]. \end{aligned} \tag{6}$$

Applying the formalism described in detail in, e.g., Refs. [15,19], one ends up with the effective Lagrangian

$$\mathcal{L}_{eff}^{\Delta L_e = 2} = \frac{G_F^2}{2m_p} \overline{e}(1+\gamma_5) e^c \left[\eta_{PS} \, J_{PS} J_{PS} - \frac{1}{4} \eta_T \, J_T^{\mu\nu} J_{T\mu\nu} \right], \tag{7}$$

where the color singlet hadronic currents are $J_{PS} = \overline{u^\alpha}(1+\gamma_5) d_\alpha$ and $J_T^{\mu\nu} = u^{-\alpha} \sigma^{\mu\nu} (1+\gamma_5) d_\alpha$, with α being the color index and $\sigma^{\mu\nu} = (i/2)[\gamma^\mu, \gamma^\nu]$. The effective lepton number violating parameters η_{PS} and η_T in Eq. (7) accumulate fundamental parameters of MSSM, including gluino, squarks, neutralinos, selectron, and proton masses, and neutralino, gauge, and Yukawa couplings in proper combinations. Their explicit forms, obtained with a proper treatment of the color currents in the Lagrangian, can be found in Ref. [19]. These parameters are rather complicated functions of supersymmetric masses and coupling constants which are, in general, free quantities limited by experimental data or theoretical considerations only. In the following section we describe our procedure of how to obtain values of most of them in the GMSB MSSM model.

B. GMSB MSSM and procedure for finding supersymmetric parameters

Supersymmetry breaking in GMSB models occurs in the so-called hidden (or secluded) sector. It is a well-known fact that the detailed structure of this sector does not change the phenomenology of the low-energy world. In our approach we assumed that the secluded sector consists of a gauge singlet superfield $\hat{S}$, whose lowest S and F components acquire vacuum expectation values (vev).

Supersymmetry breaking is communicated to the visible world via the so-called messenger sector. The interaction among superfields of the secluded and messenger sectors is described by the superpotential

$$W = \lambda_i \hat{S} \Phi_i \overline{\Phi_i}, \tag{8}$$

where Φ_i and $\overline{\Phi_i}$ denote appropriate messenger superfields. Because of nonzero vev of the lowest S and F components of superfield $\hat{S}$, fermionic components of messenger superfields gain Dirac masses $M_i = \lambda_i S$ and determine in this way the messenger scale M. Simultaneously mass matrices of their scalar superpartners

$$\begin{pmatrix} |\lambda_i S|^2 & \lambda_i F \\ \lambda_i^* F^* & |\lambda_i S|^2 \end{pmatrix} \tag{9}$$

have eigenvalues $|\lambda_i S|^2 \pm |\lambda_i F|$.

It is easy to see that vev of S generates masses for fermionic and bosonic components of messenger superfields, while vev of F destroys degeneration of these masses, which results in supersymmetry breaking. Defining $F_i \equiv \lambda_i F$ one can introduce a new parameter $\Lambda_i \equiv F_i / S$ measuring the fermion-boson mass splitting:

$$m_f = M_i,$$

$$m_b = M_i \sqrt{1 \pm \frac{\Lambda_i}{M_i}}. \tag{10}$$

Parameter Λ and messenger scale M are in the following treated as free parameters of the model.

Messenger superfields transmit SUSY breaking to the visible sector. It is realized through loops containing insertions of S and results in gaugino and scalar masses at M scale:

$$M_{\tilde{\lambda}_i}(M) = k_i \frac{\alpha_i(M)}{4\pi} \Lambda_G, \tag{11}$$

$$m^2_{\tilde{f}}(M) = 2 \sum_{i=1}^{3} C_i^{\tilde{f}} k_i \left(\frac{\alpha_i(M)}{4\pi} \right)^2 \Lambda_S^2, \tag{12}$$

where $i = 1,2,3$ is the gauge group index, and

$$\Lambda_G = \sum_{k=1}^{N_g} n_k \frac{F_k}{M_k} g\left(\frac{F_k}{M_k^2} \right), \tag{13}$$

$$\Lambda_S^2 = \sum_{k=1}^{N_g} n_k \frac{F_k}{M_k^2} f\left(\frac{F_k}{M_k^2} \right), \tag{14}$$

with k being the flavor index. In Eqs. (13) and (14) n_k is the doubled Dynkin index of the messenger superfield representation with flavor k. Coefficients $C_i^{\tilde{f}}$ are the quadratic Casimir operators of sfermions. For d-dimensional representation of SU(d) their eigenvalues are $C = (d^2-1)/2d$. In the case of $U(1)$ group $C = Y^2 = (Q - T_3)^2$. It follows that coefficients k_i are equal to $5/3$, 1, and 1 for SU(3), SU(2), and U(1), respectively. The normalization here is conventional and assures that all $k_i \alpha_i$ meet at the GUT scale. Finally, the functions f and g have the following forms:

$$g(x) = \frac{1}{x^2}[(1+x)\log_{10}(1+x)] + (x \to -x), \tag{15}$$

$$f(x) = \frac{1+x}{x^2}\left[\log_{10}(1+x) - 2Li_2\left(\frac{x}{1+x} \right) + \frac{1}{2} Li_2\left(\frac{2x}{1+x} \right) \right] + (x \to -x). \tag{16}$$

The minimal model of GMSB considered in this paper contains only one messenger field flavor. Thus, dropping flavor indices, one can write

$$M_{\tilde{\lambda}_i}(M) = N k_i \frac{\alpha_i(M)}{4\pi} \Lambda g\left(\frac{\Lambda}{M} \right), \tag{17}$$

$$m^2_{\tilde{f}}(M) = 2N \textstyle\sum_{i=1}^{3} C_i^{\tilde{f}} k_i \left(\frac{\alpha_i(M)}{4\pi} \right)^2 \Lambda^2 f\left(\frac{\Lambda}{M} \right) \cdot \mathbf{1}, \tag{18}$$

where $C_1^{\tilde{f}} = Y^2$, $C_2^{\tilde{f}} = 3/4$ for SU(2)$_L$ doublets and 0 for singlets, $C_3^{\tilde{f}}$ is equal to $4/3$ for SU(3)$_C$ triplets and 0 for singlets. In Eq. (18) $\mathbf{1}$ denotes the unit matrix in generation space and guarantees the lack of flavor mixing in soft breaking mass matrices at messenger scale. N, the so-called generation index, is given by $N=$&txtsum;$_{i=1}^{N_g}\, n_i$, where N_g means the total number of generations. In this paper we study the following two cases: (1) A single flavor of $5+\bar{5}$ representation of SU(5), with SU(2)$_L$ doublets (l and $\tilde{l}$) and SU(3) triplets (q and $\tilde{q}$)and (2) A single flavor of both representations $5+\bar{5}$ and $10+\overline{10}$ of SU(5) group. In case (1) N is equal to 1, while in case (2) $N = 1+3 = 4$, because for $10+\overline{10}$ representation of SU(5) the doubled Dynkin index is 3.

C. Renormalization group equations and parameter determination

The evolution of all running parameters is realized using renormalization group equations (RGE). The formulas (17) and (18) may therefore serve as boundary conditions for evolution of soft parameters at the electroweak scale. Our procedure resulting in low-energy spectrum of SUGRA and GMSB MSSM models and its application to the description of $0\nu\beta\beta$ decay can be found in our previous papers [18,19], so here we only sketch its most important features. The main difference between GMSB and SUGRA is that we evolve now all the parameters between m_Z and $M \ll m_{GUT}$. Besides, due to new interactions with the messenger sector, the mass matrices are constructed in a different way, which gives gluino as LSP and results in further corrections.

At the beginning, one evolves all gauge and Yukawa couplings for three generations up to the messenger scale M. We use the one-loop standard model RGE [25] below the mass threshold, where SUSY particles start to contribute, and the MSSM RGE [26] above that scale. We admit not to use the full set of RGE appropriate for the $R\!\!\!/$MSSM model [27,28]. The influence of R-parity breaking constants on other quantities running from the messenger to the electroweak scale is marginal due to the smallness of λ's. In our case the two-loop corrections can also be safely neglected (for a discussion of this problem see Ref. [29]). Initially, scale M_{SUSY} is taken to be equal to 1 TeV, but it is dynamically modified during running of relevant masses. In the next step we construct the gaugino and sfermion soft mass matrices using Eqs. (17) and (18), and perform RGE evolution of all the quantities back to m_Z scale. During this run, $m^2_{H_u}$ reaches a negative value causing dynamical electroweak symmetry breaking (EWSB). It is well known that proper treatment of this mechanism needs minimizing of the full one-loop Higgs effective potential [30]. On the other hand, appropriate corrections contain functions of particle mass eigenstates generated by EWSB mixing. Thus, as the first approximation, we minimize the tree-level Higgs potential parameters μ and $B\mu$ which are crucial for further analysis.

Having all needed mass parameters at electroweak scale, one can evolve all other quantities to some scale Q_{min}, which is optimal for minimization of the one-loop corrected Higgs potential. At this scale, defined as the geometric mean of stop masses, minimization procedure results in μ and $B\mu$ values.

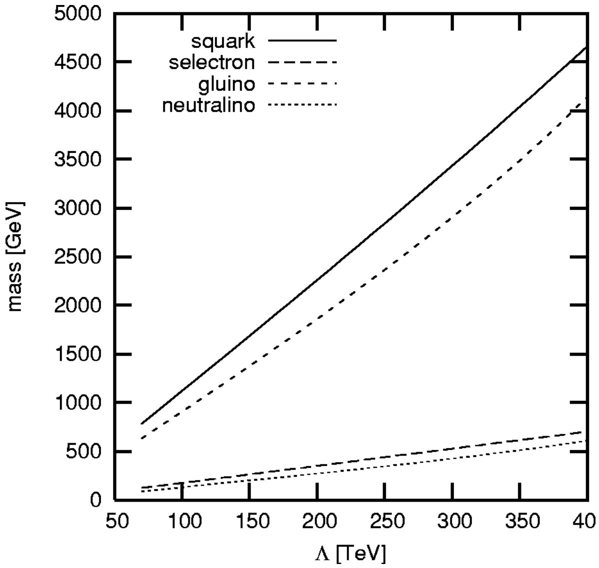

FIG. 1. Sample RGE evolution of sparticle masses in GMSB MSSM and their dependence on Λ.

Next, all the quantities are running back to the m_Z scale. Iterating this procedure one obtains stable values of μ and $B\mu$ and then the low-energy spectrum for the considered model. Only four parameters Λ, M, $\tan\beta \equiv v_u/v_d$, and $\mathrm{sgn}(\mu)$ remain free. The quantities v_u and v_d are vev's of $\hat{H}_u$ and $\hat{H}_d$, respectively.

In Fig. 1 a sample evolution of sparticle masses versus the Λ parameter is shown. Other parameters were $\tan\beta=3$, $M=500$ TeV, and $N=1$. One sees that the masses of squark and gluino depend heavily on Λ, while in the case of selectron and neutralino this dependence is much weaker.

D. Restrictions on low-energy spectrum

It is a nontrivial problem to impose restrictions coming from the present theoretical assumptions and phenomenological data on the resulting spectrum. We would like to obtain limits on physics beyond SM induced by $0\nu\beta\beta$ experiments, consistent with constraints coming from (1) finite values of Yukawa couplings at the GUT scale; (2) proper treatment of electroweak symmetry breaking; (3) requirement of physically acceptable mass eigenvalues at low energies; and (4) FCNC phenomenology.

Below, we will briefly discuss these sources of additional constraints.

The first requirement comes from the RGE evolution procedure. It is well known that running of the Yukawa couplings is sensitive to initial (i.e., at the electroweak scale) values determined by $\tan\beta$. For very small $\tan\beta$ (<1.8) the top Yukawa coupling may "explode" before reaching the GUT scale. It follows from the fact that $Y_{top}(m_Z) \sim 1/\sin\beta$. Similarly, other couplings Y_b and Y_τ "blow up" before the GUT scale for $\tan\beta > 50$ because they are proportional to $1/\cos\beta$ at electroweak scale. Such behavior of the Yukawa couplings limits the range of $\tan\beta$ to the interval 2–50.

Another theoretical constraint is imposed by the EWSB mechanism. In order to obtain a stable minimum of the scalar potential, the following conditions must hold:

$$(\mu B)^2 > (|\mu|^2 + m_{H_u}^2)(|\mu|^2 + m_{H_d}^2),$$

$$2B\mu < 2|\mu|^2 + m_{H_u}^2 + m_{H_d}^2. \tag{19}$$

They are always checked in our procedure during RGE running, and points which do not fulfill these conditions are rejected (see Fig. 2, points marked "EWSB"). Next restriction comes from the requirement of positive eigenvalues of mass matrices squared at the electroweak scale, and allows one to find combinations of free parameters providing the negative (forbidden) eigenvalues marked in Fig. 2 as "vev."

The most interesting set of constraints has its source in the FCNC phenomenology. Such processes, strongly experimentally suppressed, limit upper values of different entries of the sfermion mass matrices at low energies (cf. Refs. [31–35,38]). Here we consider the $B \to X_s \gamma$ decay only. The effective Hamiltonian for this process reads [31,34]

$$H_{\mathrm{eff}} = -\frac{4G_F}{\sqrt{2}} K_{ts}^* K_{tb} \sum_{i=1}^{8} C_i(\mu) P_i(\mu), \tag{20}$$

where K is the quark mixing matrix and P_i are the relevant operators taken from Ref. [34]. Among the Wilson coefficients $C_i(\mu)$ two, C_7 and C_8, are the most important for the analysis of impact of the SM and MSSM interactions. (The

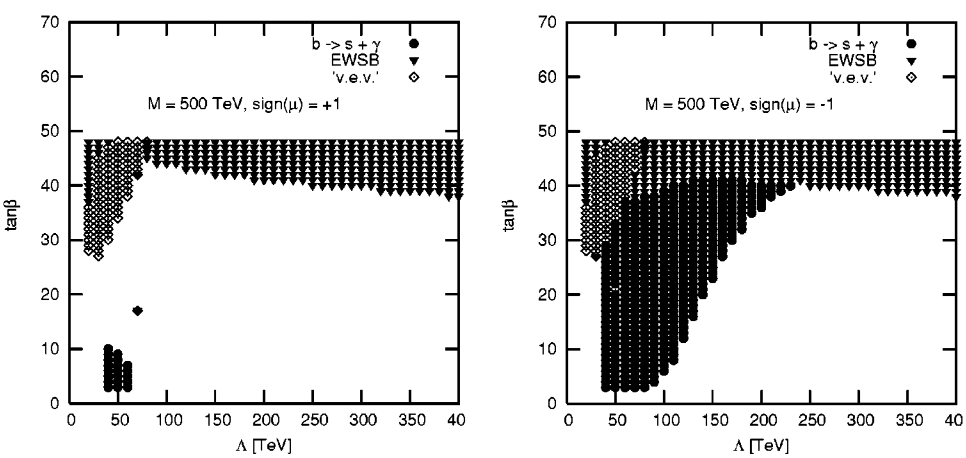

FIG. 2. Constraints on GMSB parameter space.

leading order and the next-to-leading order analyses of these interactions were discussed in Refs. [31,35].) In order to constrain the low-energy spectrum of supersymmetric models using FCNC processes, it is a common practice to define the parameter R_7, which measures the extra (MSSM) contributions to the $B \to X_s \gamma$ decay:

$$R_7 \equiv 1 + \frac{C_7^{(0)extra}(m_W)}{C_7^{(0)SM}(m_W)}, \tag{21}$$

where the index (0) stands for the leading order Wilson coefficients and the superscript *extra* indicates SUSY (charged Higgs, chargino, neutralino, and gluino) contributions. Explicit expressions for $C_7^{(0)extra}$ and $C_7^{(0)SM}$ can be found, e.g., in Ref. [31]. Constraints on allowed values of R_7 are induced from the present experimental limits on the branching ratio $\mathrm{BR}(B \to X_s \gamma)$ measured by CLEO Collaboration [36]:

$$\mathrm{BR}(B \to X_s \gamma) = (3.21 \pm 0.43_{stat} \pm 0.27_{syst}) \times 10^{-4}. \tag{22}$$

The theoretical dependence of $\mathrm{BR}(B \to X_s \gamma)$ on R_7 confronted with such experimental data allows one to make the following estimate:

$$-6.6 < R_7 < -4.4 \quad \text{or} \quad 0.0 < R_7 < 1.3. \tag{23}$$

Using the above restriction, one can exclude certain values of supersymmetric parameters, which result in the R_7 coefficient outside the allowed region (23). In Fig. 2 such points are marked as "$b \to s + \gamma$."

Looking in Fig. 2 one sees that the constraints deduced from the FCNC phenomenology are very sensitive to the sign of μ. The same behavior was also observed in the SUGRA MSSM model (see, e.g., Ref. [19]), which is mainly due to the sensitivity of charged Higgs and chargino contributions to R_7 on the sign of the μ parameter.

The additional dependence of R_7 on both $\tan\beta$ and Λ parameters is shown for positive and negative μ in Fig. 3. In the case $\mu > 0$ the parameter R_7 grows up for smaller values of $\tan\beta$ and behaves in opposite manner for $\mu < 0$. Moreover, in the latter case R_7 is, in general, bigger, which results in more stringent restrictions. More detailed analysis is presented in Fig. 4, where the most important impacts to R_7 for different choices of $\tan\beta$, Λ, and $\mathrm{sgn}(\mu)$ are explicitly shown. One can see that $\tan\beta$ and $\mathrm{sgn}(\mu)$ do not influence the charged Higgs contribution significantly. Thus, a crucial point in the analysis becomes chargino contribution. Contrary to the SUGRA MSSM case [19] the magnitude of chargino influence on R_7 is almost equal to the influence coming from charged Higgses. For positive values of the μ coupling constant, the chargino impact grows with increasing $\tan\beta$, while for the $\mu < 0$ case one observes opposite behavior. In this light, behavior of the surfaces shown in Fig. 3 becomes clear.

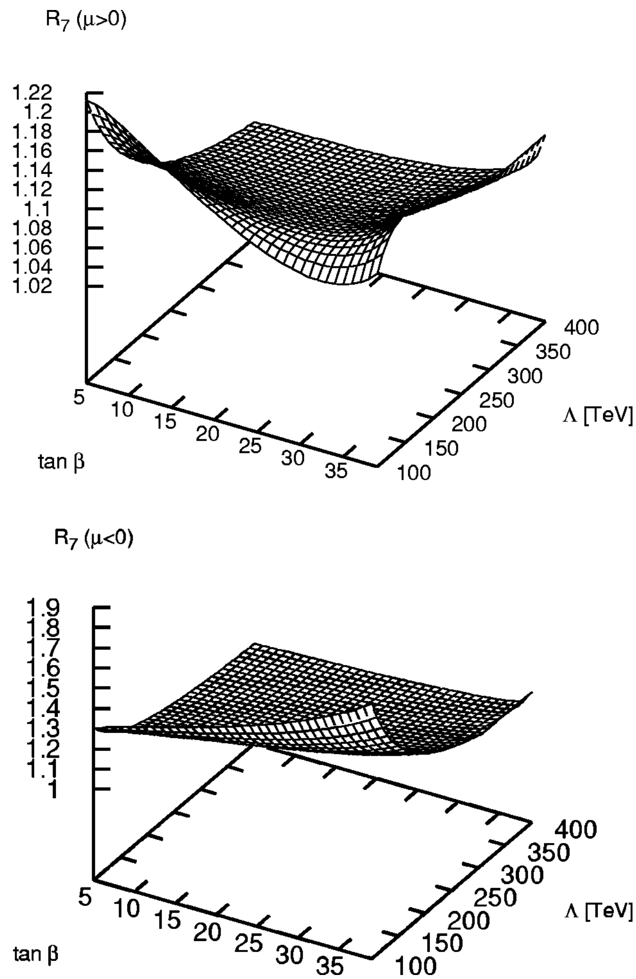

FIG. 3. R_7 parameter in GMSB MSSM for both signs of μ. The scan is performed over Λ and $\tan\beta$, with $M = 500$ TeV and $N = 1$.

III. NEUTRINOLESS DOUBLE β DECAY AND LIMITS ON NONSTANDARD PHYSICS

Restrictions imposed on the model by low-energy spectrum allow for a reliable analysis of exotic nuclear processes, such as the neutrinoless double β decay, and then for deduction of additional constraints imposed on nonstandard physics. In this paper we use experimental information about nonobservability of the $0\nu\beta\beta$ decay in different nuclei to extract stringent limits on R-parity breaking.

The half-life of the process, taking into account all three possible types of hadronization (two-nucleon, one-pion, and two-pion [15,19]) reads

$$[T_{1/2}^{0\nu}]^{-1} = G_{01}\Big| \eta_T \mathcal{M}_{\tilde{q}}^{2N} + (\eta_{PS} - \eta_T)\mathcal{M}_{\tilde{f}}^{2N} + \frac{3}{8}\Big(\eta_T + \frac{5}{8}\eta_{PS}\Big)\mathcal{M}^{\pi N}\Big|^2. \tag{24}$$

In this equation $\mathcal{M}_{\tilde{q}}^{2N}, \mathcal{M}_{\tilde{f}}^{2N}$, and $\mathcal{M}^{\pi N}$ are matrix elements for the $2N$, 1π, and 2π channels, respectively. These matrix elements depend on nonstandard physics parameters, involved in description of the neutrinoless double β decay, and on nuclear structure details of decaying nuclei. (The explicit

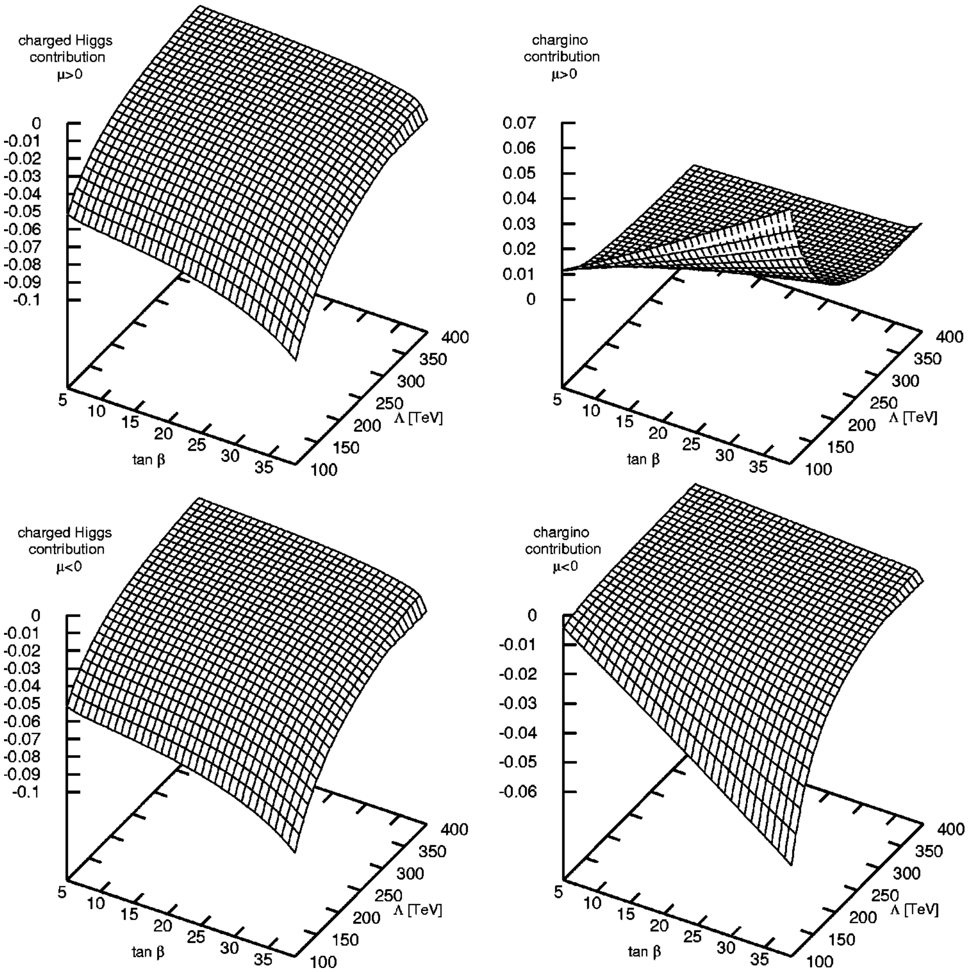

FIG. 4. Contribution to $C_7^{(0)MSSM}$ in GMSB MSSM coming from charged Higgses and charginos for both signs of μ. All parameters are as in Fig. 3.

forms of elements (24) can be found, e.g., in Refs. [15,19].) Our procedure limits the number of free parameters to Λ, M, tan β, sgn(μ), and N only. As the loop diagrams with messenger fields do not affect the A-terms considerably, we can equal the common soft SUSY breaking parameter A_0 to 0 at the M scale.

Following well established procedure, the nuclear matrix elements in question were calculated within the proton-

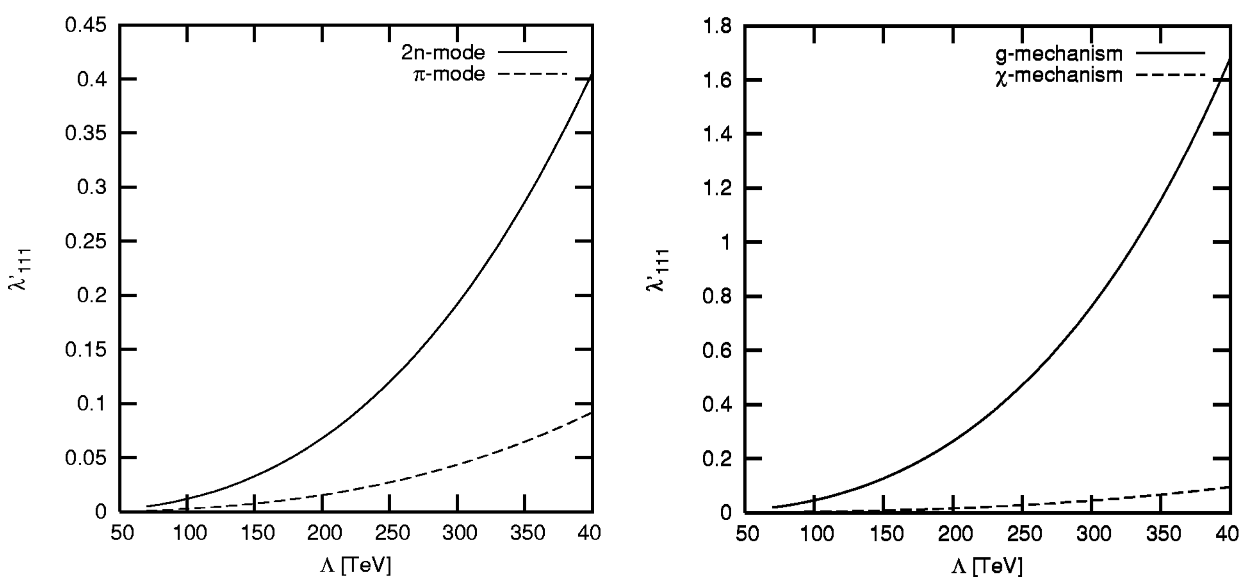

FIG. 5. Contributions to λ'_{111} coming from two-nucleon and pion-exchange modes of $0\nu\beta\beta$ in ^{76}Ge as well as gluino and neutralino mechanism of SUSY breaking. All parameters are as in Fig. 3 except tan β=3 and $\mu>0$.

neutron RQRPA (pn-RQRPA). This approach incorporates the Pauli exclusion principle for fermion pairs [23,37] and is suitable for studies of nuclear structure aspects of various double β decay channels in open-shell systems. Details of the method and its application to the double β decay were presented in a number of papers (see, e.g., Refs. [9,19,22]).

Having both supersymmetric spectrum and nuclear matrix elements, one can extract from Eq. (24) constraints on *R*-parity breaking in GMSB MSSM using experimental information from nonobservability of the neutrinoless double β decay. Such approach is based on comparison of the theoretically obtained half-life for this process, as a function of some free nonstandard parameters, with the experimental upper limit for $T_{1/2}$ in the given nucleus.

We start with a presentation of constraints on λ'_{111} coming from different channels of $0\nu\beta\beta$. Using the experimental lower limits on the half-life of neutrinoless double β decay for ^{76}Ge, established by IGEX Collaboration [39], we obtained upper limits for λ'_{111} in GMSB MSSM. We have separately taken into account various possibilities. In Ref. [21] the problem of the pion mode has been discussed in detail. In Fig. 5 the upper limits on λ'_{111} coming from nucleon and pion modes of neutrinoless double β decay (upper diagram) and two different possibilities of SUSY GMSB (lower diagram) are presented. The importance of pion-exchange mode is clearly visible. The curve corresponding to the pion mode lies definitely below the line corresponding to the nucleon channel, so the pion mode imposes more stringent restrictions on the coupling constant. One sees that in order to obtain reliable results, both modes should be taken into account. Also, the role of various mechanisms leading to SUSY breaking are presented. The neutralino contribution to GMSB sets much more stringent bounds on λ'_{111} than the gluino one. It is rather difficult to compare these results with analogous discussion in the SUGRA MSSM scenario [19], because of completely different parametrization in these two models. However, one easily sees that the 2*n* mode in GMSB sets much more severe constraints, especially for small Λ's, whereas the gluino contribution in GMSB relaxes the constraints, when compared to SUGRA MSSM. However, the general tendencies remain the same in both approaches, that is, the pion mode and neutralino SUSY breaking are the dominant ones.

Further analysis is presented in Fig. 6. We have included most of the nowadays known experimental data (see Ref. [40] and references therein). Using the lower limits on $T_{1/2}^{0\nu}$ for different nuclei we have obtained upper limits on λ'_{111} and two more quantities. The interesting thing is that the combinations $\lambda'_{111}/[(m_{\tilde{q}}/100\ \mathrm{GeV})^2(m_{\tilde{g}}/100\ \mathrm{GeV})^{1/2}]$ and $\lambda'_{111}/[(m_{\tilde{e}}/100\ \mathrm{GeV})^2(m_{\chi 1}/100\ \mathrm{GeV})^{1/2}]$ remain nearly unchanged within a wide range of Λ's. This allows us to make the following estimation:

$$\frac{\lambda'_{111}}{\left(\dfrac{m_{\tilde{q}}}{100\ \mathrm{GeV}}\right)^2\sqrt{\dfrac{m_{\tilde{g}}}{100\ \mathrm{GeV}}}} < 2.75\times 10^{-5} \qquad (25)$$

and

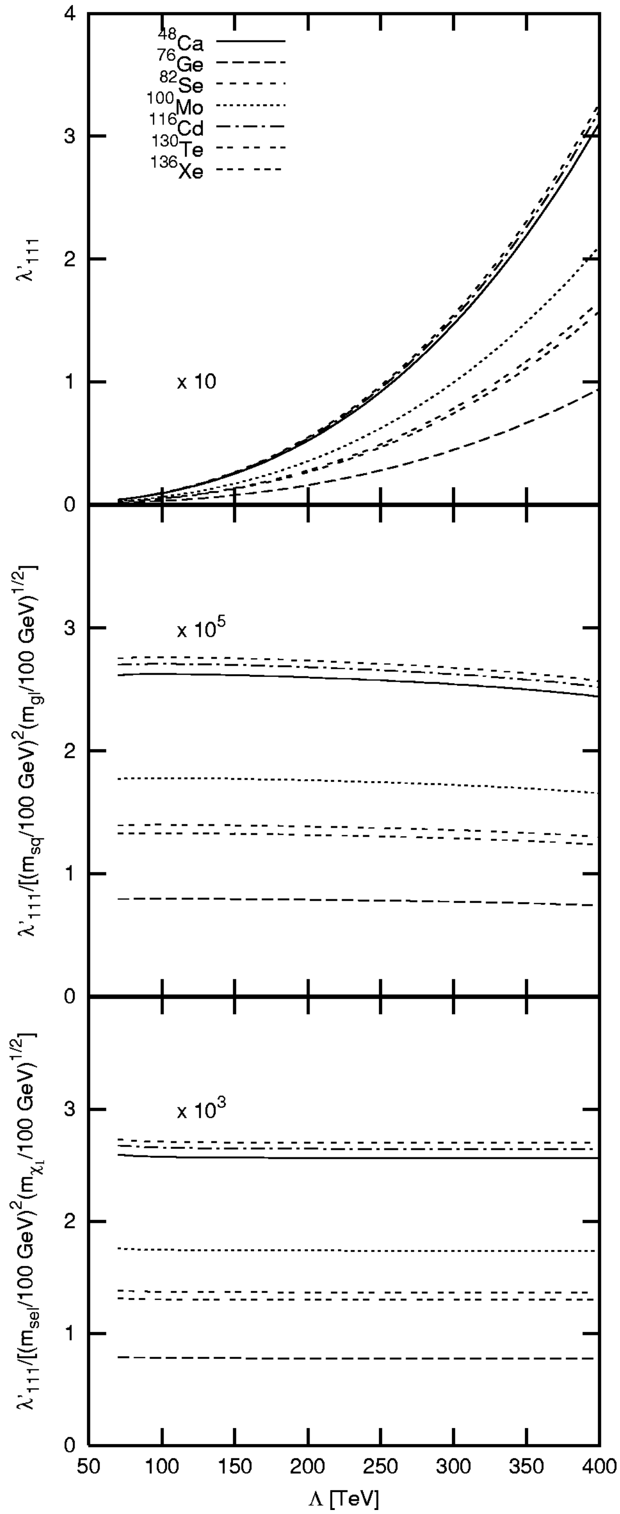

FIG. 6. Limits in GMSB MSSM on various combinations of λ'_{111} and masses of SUSY particles coming from experimental lower bounds on the half-life of $0\nu\beta\beta$ decay in different nuclei. The corresponding nuclear matrix elements have been calculated using pn-RQRPA method and the bag model. Other parameters are as in Fig. 3.

$$\frac{\lambda'_{111}}{\left(\frac{m_{\tilde{e}}}{100\ \text{GeV}}\right)^2\sqrt{\frac{m_{\chi 1}}{100\ \text{GeV}}}} < 2.73 \times 10^{-3}. \qquad (26)$$

These results lower the allowed values in the first case by around 15% when compared to our previous result within the SUGRA MSSM model (cf. Ref. [18]).

We study also constraints coming from different GMSB scenarios in the case of expected sensitivity of planned neutrinoless double β decays. Two different messenger sector structures are taken into account here: the $5+\overline{5}$ representation ($N=1$) and both $5+\overline{5}$ and $10+\overline{10}$ representations ($N=4$) of SU(5). We include parameters for three new experiments [40,41]. The GENIUS-MAJORANA-GEM project is expected to reach sensitivity of $T_{1/2} \sim 2.3 \times 10^{28}$ yr for ^{76}Ge. The MOON experiment has $T_{1/2} \sim 1.3 \times 10^{28}$ yr and investigates the ^{100}Mo nuclei, and the EXO-XMASS experiment will be sensitive to values of the half-life up to around $T_{1/2} \sim 2.2 \times 10^{28}$ yr for ^{136}Xe. The relevant results are presented in Fig. 7. It is worth noting that for $N=4$ the allowed values for the lepton number violating constant are much higher. The most promising results can be expected from the MOON project, which may set the best constraints on the R-parity violating coupling constant.

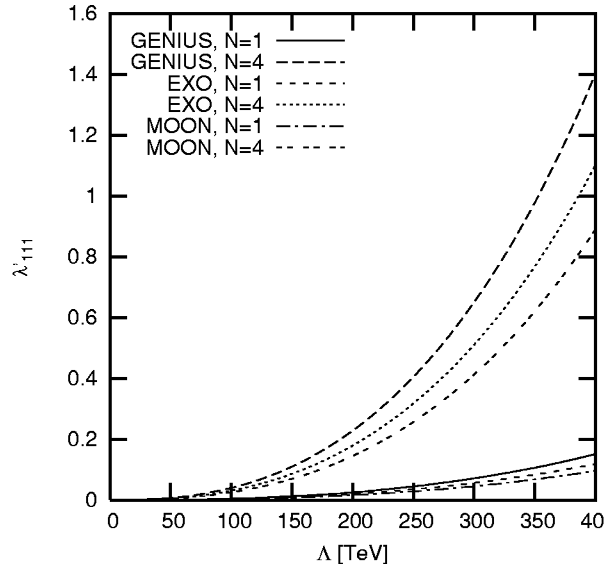

FIG. 7. Limits on λ'_{111} for different structures of messenger sector (see text for details) for planned $0\nu\beta\beta$ experiments. All parameters are in Fig. 5.

IV. CONCLUSIONS

We have presented an analysis of the current experimental state of neutrinoless double β decay in the language of gauge mediated minimal supersymmetric standard model. The GMSB scenario of supersymmetry breaking is a very attractive framework owing to its simplicity, naturalness, high predictive power, and consistency. It has a few free parameters, does not rely on not fully established theory, such as supergravity, does not need extra dimensions, and offers a natural mechanism for flavor violating processes.

Combining theoretical, phenomenological, and experimental data we have obtained a set of constraints on various nonstandard parameters. In particular, we confirmed the importance of pion-exchange channel of $0\nu2\beta$ and neutralino mechanism of GMSB. Also, new upper limits for $\lambda'_{111}/[(m_{\tilde{q}}/100\ \text{GeV})^2(m_{\tilde{g}}/100\ \text{GeV})^{1/2}]$ and $\lambda'_{111}/[(m_{\tilde{e}}/100\ \text{GeV})^2(m_{\chi 1}/100\ \text{GeV})^{1/2}]$ were extracted. A detailed discussion of the Wilson coefficients, the SUSY contributions to it, and its dependence on the whole allowed range of tan β and Λ up to 400 TeV was presented. Also, some preliminary studies related to three new planned $0\nu\beta\beta$ experiments were performed.

The dominance of the pion-exchange mode in $0\nu\beta\beta$ has been recently confirmed on a completely different basis. The authors of Ref. [42], using methods of the effective field theory, showed that this phenomenon is a generic feature of any R-parity violating SUSY model.

ACKNOWLEDGMENTS

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