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

Marek Góźdź, Wiesław A. Kamiński and Andrzej Wodecki
Department of Theoretical Physics, Maria Curie-Skłodowska University, Lublin, Poland

The Minimal Supersymmetric Standard Model with gauge mediated supersymmetry breaking and trilinear $R$–parity violation is applied to the description of neutrinoless double beta decay. A detailed study of limits on the parameter space coming from the $B \rightarrow X_s \gamma$ 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 are addressed. We have deduced new limits on the trilinear $R$–parity breaking parameter $\lambda'_{111}$ from the non-observability 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.

PACS numbers: 12.60.Jv,11.30.Er,23.40.Bw

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, has been checked to much less degree. Among them are self-interactions of gauge bosons as well as the Higgs sector, which plays important role for completeness of the model and in many aspects of symmetry breaking. Also many shortcomings of SM, like the big number of free parameters, unresolved question of mass hierarchy, the problem of massive neutrinos and their oscillations, may call for more desirable description of Nature.

In the matter of fact, a number of various models reaching beyond SM’s orthodoxy were proposed. One of the most promising candidate 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 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 unify at some scale $m_{\text{GUT}} \sim 10^{16}$ GeV. As is well known, extrapolations of data from the LEP measurements suggest such behaviour. However, SUSY particles have not been observed in experiments, so supersymmetry has to be broken in low energy regime. The issue how this breaking is realised, 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 ($R$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 large number of free parameters involved, such theory has only marginal predictive power. In contrast, the spontaneous breaking has many virtues added, like the important possibility of dynamical origin of the $R$–parity breaking 4.

Theories of gauge mediated supersymmetry breaking (GMSB) belong to the second kind of approaches and have recently attracted a great deal of attention. They are highly predictive, offer a natural solution to the flavour problem and contain much less free parameters compared to MSSM with SUSY breaking mediated by gravitational interaction 3 6 7 8 9 10 11 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 $M_{SU(3)} \sim 10^5$ GeV. Gauginos and sfermions acquire their masses through interactions with the messenger sector at one– and two–loop levels respectively, resulting in different phenomenology of the low–energy world from the MSSM one. In these models flavour–diagonal sfermions 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 flavour changing neutral currents (FCNC). Moreover, since the soft masses arise as gauge charges squared, the sizeable hierarchy proportional to the gauge quantum numbers appears among the superpartner masses. In this light, recently renewed interest in GMSB [3, 10] is understandable.

The \textit{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 flavour violation, while the bilinear terms generate non-zero vacuum expectation values for sneutrino fields \(\tilde{\nu}_l\), causing neutrino–neutralino and electron–chargino mixing. Thus, approaches with lepton number violation can describe some low-energetic exotic nuclear processes like the neutrinoless double beta decay (0\(\nu\beta\beta\)), known to be very sensitive to some of the \textit{R}–parity violating interactions [13]. Using experimental data about these processes, e.g. bounds on the half-life of neutrino–antineutrino annihilating interactions [15], one can establish stringent limits on the \textit{R}–parity breaking SUSY terms [13, 16, 17, 18, 19, 20].

Supersymmetric models with \textit{R}–parity non-conservation have been extensively discussed in the last decade (see e.g. [13, 14]), and were also used for the study of 0\(\nu\beta\beta\) [15, 16, 17, 18, 19, 20, 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, 18]. Recently the dominance of pion exchange mode based on the double–pion exchange between the decaying neutrons over the two–nucleon mode of 0\(\nu\beta\beta\) was proved [14, 20, 21].

Motivated by the aforementioned features of GMSB models, in this paper we study the \textit{R}–parity breaking phenomenology of MSSM, and use the neutrinoless double beta decay for deducing limits on some non-standard physics parameters. In the previous studies such estimates were performed in the framework of \textit{RMSSM} with supergravity mediated SUSY breaking by means of GUT constraints [13, 14] or additional assumptions relating sfermions and gauginos 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 from CLEO collaboration [22] for 0\(\nu\beta\beta\). As previously, we limit our attention to the trilinear terms only, leaving complete treatment of bilinear and trilinear \textit{R}–parity violating terms in GMSB for subsequent paper.

For reliable extraction of the limits on \textit{R}–parity breaking constant \(\lambda^{(1)}_{11}\) 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, 24], 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 [21], we used it also in our work.

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

\section{II. \textbf{FORMALISM}}

\subsection{A. \textit{R}–parity violation in MSSM}

In this section we briefly outline main features of MSSM and its violation mechanism. Both in the supergravity and in GMSB, the \textit{R}–parity can be explicitly violated by the bilinear [13] and trilinear [14] terms incorporated into the superpotential. Bilinear terms generate non-zero 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 flavour violation. Above features make \textit{RMSSM} models appropriate for the description of 0\(\nu\beta\beta\). Because this process is known to be very sensitive to supersymmetric and \textit{R}–parity breaking parameters, data from the nowadays double beta experiments allow to establish stringent limits on \textit{RMSSM} physics [13, 14, 17, 18, 19, 20, 21, 22, 23].

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

\begin{equation}
W = W_0 + W_R,
\end{equation}

where

\begin{equation}
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
\end{equation}

and

\begin{equation}
W_R = \lambda_{ijk} \hat{L}_i \hat{L}_j \hat{u}_k^c + \lambda'_{ijk} \hat{\bar{L}}_i \hat{\bar{Q}}_j \hat{\bar{d}}_k^c + \lambda''_{ijk} \hat{u}_i^c \hat{\bar{d}}_j^c \hat{\bar{d}}_k^c + \mu_{ij} \hat{L}_j \hat{H}_u
\end{equation}

are the \textit{R}–parity conserving and \textit{R}–parity breaking parts, respectively. Here \(\hat{Q}\) and \(\hat{L}\) denote the quark and lepton \textit{SU}(2) doublet superfields, \(\hat{u}^c\), \(\hat{d}^c\), and \(\hat{e}^c\) the corresponding \textit{SU}(2) singlets and \(\hat{H}_u, \hat{H}_d\) are the Higgs superfields. In the \textit{R}–parity breaking part, the two first 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 follow the usual way and simply set $\lambda_{ijk} = \nu_{ijk} = 0$ 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:

\[- \mathcal{L}_{\text{soft}} = (A_i^U \bar{Q}_i H_u \bar{d}_j^c + A_i^D \bar{Q}_i H_d \bar{u}_j^c + A_i^E \bar{L}_i H_d \bar{e}_j^c + \text{h.c.})
+ B (H_u H_u + \text{h.c.}) + m^2_{H_u} |H_u|^2 + m^2_{H_d} |H_d|^2
+ m^2_{\bar{d}_j} |\bar{d}_j|^2 + m^2_{\bar{u}_j} |\bar{u}_j|^2 + m^2_{\bar{e}_j} |\bar{e}_j|^2
+ \left( \frac{1}{2} M_1 \bar{\psi}_B \psi_B + \frac{1}{2} M_2 \bar{\psi}_W \psi_W + \frac{1}{4} m_3 \bar{\psi}_g \psi_g + \text{h.c.} \right) \]  

and

\[- \mathcal{L}_{\text{soft}}^{R} = \lambda_{ijk} \epsilon_{ijL} \epsilon_{jkR}^c + \lambda'_{ijk} \bar{L}_i \bar{Q}_j \bar{d}_k
+ \lambda_{ijk} \bar{u}_i \bar{d}_j \bar{e}_k + \mu \bar{Q}_j L_i H_u + \mu' \bar{L}_i L_j H_d. \]  

Here, fields with tilde denote the scalar partners of quark and lepton fields, while $\psi_i$ 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 within supersymmetric models. Because of non-zero vev of lowest $S$ and $F$ components of superfield $\Phi$, 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

\[ \left( \begin{array}{c} |\lambda_i S|^2 \\ \lambda_i F \\ |\lambda_i S|^2 \end{array} \right) \]  

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:

\[ m_f = M_i, \]
\[ m_b = M_i \sqrt{1 + \frac{\Lambda_i}{M_i^2}}. \]

Parameter $\Lambda$ 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:

\[ M_{\tilde{G}}(M) = k_i \frac{\alpha_i(M)}{4\pi} \Lambda_G, \]
\[ m_{\tilde{S}}^2(M) = 2 \sum_{i=1}^3 C_i^2 k_i \left( \frac{\alpha_i(M)}{4\pi} \right)^2 \Lambda_S^2, \]

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

\[ \Lambda_G = \sum_{k=1}^{N_k} n_k \frac{F_k}{M_k^2} \left( \frac{F_k}{M_k^2} \right), \]
\[ \Lambda_S^2 = \sum_{k=1}^{N_k} n_k \frac{F_k}{M_k^2} \left( \frac{F_k}{M_k^2} \right), \]  

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 low energy world. In our approach we assumed that the secluded sector consists of a gauge singlet superfield $\tilde{S}$, 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

\[ W = \lambda_i \tilde{S} \Phi_i \Phi_i. \]
with $k$ being the flavour index. In Eqs. (13) and (14) $n_k$ is the doubled Dynkin index of the messenger superfield representation with flavour $k$. Coefficients $C^f_i$ 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:

\[
g(x) = \frac{1}{x^2}[(1 + x) \log(1 + x)] + (x \to -x),
\]

\[
f(x) = \frac{1 + x}{x^2} \left[ \log(1 + x) - 2Li_2 \left( \frac{x}{1 + x} \right) \right] + \frac{1}{2} Li_2 \left( \frac{2x}{1 + x} \right) + (x \to -x).
\]

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

\[
M_{\tilde{\chi}_i}(M) = Nk \frac{\alpha(M)}{4\pi} \lambda g \left( \frac{\Lambda}{M} \right),
\]

\[
m^2_f(M) = 2N \sum_{i=1}^{3} C^f_i k_i \left( \frac{\alpha(M)}{4\pi} \right)^2 \Lambda^2 f \left( \frac{\Lambda}{M} \right) \cdot 1,
\]

where $C^f_1 = Y^2$, $C^f_2 = 3/4$ for $SU(2)_L$ doublets and $0$ for singlets, $C^f_3$ is equal to $4/3$ for $SU(3)_C$ triplets and $0$ for singlets. In (13) $1$ denotes the unit matrix in generation space and guarantees the lack of flavour mixing in soft breaking mass matrices at messenger scale. $N$, the so-called generation index, is given by $N = \sum i N_i n_i$, where $N_i$ means the total number of generations. In this paper we study two cases:

1. a single flavour of $5 + \overline{5}$ representation of $SU(5)$, with $SU(2)_L$ doublets ($l$ and $\overline{l}$), and $SU(3)$ triplets ($q$ and $\overline{q}$);
2. a single flavour of both representations $5 + \overline{5}$ 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 parameters determination

The evolution of all running parameters is realized using Renormalization Group Equations (RGE). The formulae (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.

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, below the mass threshold, where SUSY particles start to contribute, and MSSM RGE above that scale. We admit not to use the full set of RGE appropriate for the MSSM model [28, 29]. 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 $\lambda$’s. In our case the two–loop corrections can also be safely neglected (for a discussion of this problem see [30]). Initially, scale $M_{\text{SUSY}}$ 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 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 [31]. 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 $\mu$ 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 $Q_{\text{min}}$, 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 $\mu$ and $B\mu$ values. Next, all the quantities are running back to $m_Z$ scale. Iterating this procedure one obtains stable values of $\mu$ and $B\mu$ and then low energy spectrum for the considered model. Only four parameters: $\Lambda$, $M$, $\tan\beta \equiv v_u/v_d$ and $\text{sgn}(\mu)$ 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 $\Lambda$ parameter is shown. Other parameters were $\tan\beta = 3$, $M = 500$ TeV, $N = 1$. One sees that the masses of squark and gluino depend heavily on $\Lambda$, while in the case of selectron and neutralino this dependence is much weaker.

D. Restrictions on low energy spectrum

To impose restrictions coming from the present theoretical assumptions and phenomenological data on the resulting spectrum is a non-trivial problem. 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;
4. flavour changing neutral currents (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 $Y_{\text{top}}(m_Z) \sim 1/\sin\beta$. Similarly, other couplings $Y_t$ and $Y_\tau$ “blow up” before the GUT scale for $\tan\beta > 50$ because they are proportional to $1/\cos\beta$ at electroweak scale. Such behaviour 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:

\[
(\mu B)^2 > \left(|\mu|^2 + m_{H_u}^2\right)\left(|\mu|^2 + m_{H_d}^2\right); \\
2B\mu < 2|\mu|^2 + m_{H_u}^2 + m_{H_d}^2.
\]

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 to find combinations of free parameters providing the negative (forbidden) eigenvalues marked in Fig. 2 as “v.e.v.”.

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. \[32, 33, 34, 35, 36, 37\]). Here we consider the $B \to X_s\gamma$ decay only. The effective Hamiltonian for this process reads \[32, 33\]

\[
H_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} K_{ts}K_{tb} \sum_{i=1}^{8} C_i(\mu)P_i(\mu),
\]

FIG. 2: Constraints on GMSB parameter space.
where $K$ is the quark mixing matrix (CKM matrix) and $P_i$ are the relevant operators taken from Ref. [35]. 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 leading order and the next-to-leading order analysis of these interactions were discussed in [32, 36].) In order to costrain 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:

$$R_7 \equiv 1 + \frac{C_7(0)_{\text{extra}}(m_W)}{C_7(0)_{\text{SM}}(m_W)}, \quad (21)$$

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 $C_7(0)_{\text{extra}}$ and $C_7(0)_{\text{SM}}$ can be found e.g. in Ref. [32]. Constraints on allowed values of $R_7$ are induced from the present experimental limits on the branching ratio $\text{BR}(B \to X_s \gamma)$ measured by CLEO collaboration [22]:

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

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

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

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

The additional dependence of $R_7$ on both $\tan \beta$ and $\Lambda$ parameters is shown for positive and negative $\mu$ 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 $\tan \beta$, $\Lambda$, and $\text{sgn}(\mu)$ are explicitly shown. One can see that $\tan \beta$ and $\text{sgn}(\mu)$ do not influence the charged Higgs contribution significantly. Thus, a crucial point in the analysis becomes chargino contribution. Contrary to 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 $\mu$ coupling constant, the chargino impact grows with increasing of $\tan \beta$, while for $\mu < 0$ case one observes opposite behaviour. In this light, behaviour of the surfaces shown in Fig. 3 becomes clear.

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

### III. NEUTRINOLESS DOUBLE BETA DECAY AND LIMITS ON NON-STANDARD PHYSICS

Restrictions imposed on the model by low energy spectrum allow for reliable analysis of exotic nuclear processes, like the neutrinoless double beta decay, and then for deduction of additional constraints imposed on non-standard physics. In this paper we use experimental in-
FIG. 4: Contributions to $C_{\mu}^{\text{MSSM}}$ in GMSB MSSM coming from charged Higgses and charginos for both signs of $\mu$. All parameters as in Fig. 3.
Formation about non-observability 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 (2–nucleon, 1–pion and 2–pion [13, 15]) reads:

$$[T_{1/2}^{0\nu}]^{-1} = G_{01}\left|\eta_T \mathcal{M}_q^{2N} + (\eta_{PS} - \eta_T) \mathcal{M}_f^{2N} + \frac{3}{8} \left(\eta_T + \frac{5}{8}\eta_{PS}\right) \mathcal{M}^{\pi N}\right|^2.$$  

(24)

In this equation $\mathcal{M}_q^{2N}, \mathcal{M}_f^{2N}$ and $\mathcal{M}^{\pi N}$ are matrix elements for the 2$N$, 1$\pi$ and 2$\pi$ channels, respectively.

These matrix elements depend on non-standard physics parameters, involved in description of the neutrinoless double beta decay, and on nuclear structure details of decaying nuclei. (The explicit forms of elements can be found, e.g., in [15, 12].) Our procedure limits the number of free parameters to $\Lambda, M, \tan \beta, \text{sign}(\mu)$, 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–neutron Renormalized Quasiparticle Random Phase Approximation (pn–RQRPA). This approach incorporates the Pauli exclusion principle for fermion pairs [23, 24] and is suitable for studies of nuclear structure aspects of various double beta decay channels in open shell systems. Details of the method and its application to the double beta decay were presented in a number of articles (see, e.g., [9, 19, 21]).

Having both supersymmetric spectrum and nuclear matrix elements, one can extract from Eq. (21) constraints on $R$–parity breaking in GMSB MSSM using experimental information from non-observability of the neutrinoless double beta decay. Such approach is based on comparison of the theoretically obtained half-life for this process, as a function of some free non-standard parameters, with the experimental upper limit for $T_{1/2}$ in the given nucleus.

We start with a presentation of constraints on $\lambda'_{111}$ coming from different channels of $0\nu\beta\beta$. In Ref. [20] the problem of the pion mode has been discussed in details. In Fig. [4] 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. Also the role of various mechanisms leading to SUSY breaking are presented. These data were calculated for $^{76}$Ge nucleus, for which the best experimental limits, coming from the IGEX collaboration, are known [38]. One sees that the SUSY breaking mediated by neutralinos sets more severe limits on $\lambda'_{111}$ than the gluino mechanism.

Further analysis is presented in Fig. [6]. We have included most of the nowadays known experimental data (see [39] and references therein). The interesting thing is, that the combinations $\lambda'_{111}/[(m_{\tilde{q}}/100\text{GeV})^2(m_{\tilde{g}}/100\text{GeV})^{\frac{3}{2}}]$ and $\lambda'_{111}/[(m_{\tilde{\chi}}/100\text{GeV})^2(m_{\tilde{\eta}}/100\text{GeV})^{\frac{3}{2}}]$ remain nearly unchanged within wide range of $\Lambda$'s. This allows us to estimate the lepton number violating constant:

$$\frac{\lambda'_{111}}{(100\text{GeV})^2\sqrt{m_{\tilde{\eta}}/100\text{GeV}}} < 2.75 \cdot 10^{-5}$$  

(25)
FIG. 6: Limits in GMSB MSSM on various combinations of $\lambda_{111}'$ 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 as in Fig. 3.

and

$$\frac{\lambda_{111}'}{(m_{\tilde{q}}/100\text{ GeV})^2 \sqrt{m_{\tilde{g}}/100\text{ GeV}}} < 2.73 \cdot 10^{-3}. \quad (26)$$

These results lower the allowed values in the first case by around 15% (cf. [18]).

We study also constraints coming from different GMSB scenarios in the case of expected sensitivity of planned neutrinoless double beta decays. Two different messenger sector structures are here taken into account: the $5^+5$ representation ($N = 1$) and both, $5^+5$ and $10^+10$, representations ($N = 4$) of $SU(5)$. We include parameters for three new experiments [39, 40]. The GENIUS–MAJORANA-GEM project is expected to reach sensitivity of $T_{1/2} \sim 2.3 \cdot 10^{28}$ y for $^{76}$Ge. The MOON experiment has $T_{1/2} \sim 1.3 \cdot 10^{28}$ y and investigates the $^{100}$Mo nuclei, and the EXO-XMASS experiment will be sensitive to values of the half-life up to around $T_{1/2} \sim 2.2 \cdot 10^{28}$ y 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.

IV. CONCLUSIONS

We have presented an analysis of the current experimental state of neutrinoless double beta decay in the language of gauge mediated Minimal Supersymmetric Standard Model. Combining theoretical, phenomenological, and experimental data we obtained a set of constraints on various non-standard parameters. In particular, 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 $\tan \beta$ and $\Lambda$ up to 400 TeV was presented. Also some preliminary studies related to three
new planned $0\nu\beta\beta$ experiments were performed.