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# Effective *R*-parity violation from supersymmetry breaking

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We present a scenario in which Yukawa-like *R*-parity violating (RPV) couplings are naturally suppressed. In our model, RPV is assumed to originate from the SUSY breaking mechanism and then transmitted into the SUSY Lagrangian only through soft SUSY breaking operators in the scalar potential. The RPV Yukawa-like operators of the superpotential, conventionally parametrized by the couplings $\lambda$, $\lambda'$ and $\lambda''$, are then generated through loops containing the SUSY scalars, the gauginos and the soft RPV interactions and are, therefore, manifest as effective operators with a typical strength of $O(10^{-3})$.

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One of the unresolved puzzles associated with supersymmetric (SUSY) theories is whether or not $R$ parity ($R_P$) is conserved in the SUSY Lagrangian. On the one hand, a general SUSY theory allows the existence of $R$-parity violating (RPV) trilinear operators in the superpotential whose strength is naturally of $O(1)$. On the other hand, experimental searches for RPV interactions yield null results, which seem to indicate that such RPV couplings, if they exist, are much smaller than $O(1)$ as long as the typical SUSY mass scale is not much larger than the electroweak scale. The question then arises: why are the RPV Yukawa-like interactions so suppressed wherever they can emerge?

In this paper we propose a way for generating RPV Yukawa-like effective operators, with a structure similar to the ones which may appear in the superpotential (i.e., the usual $\lambda$, $\lambda'$ and $\lambda''$ type RPV operators) [1], however, with a typical strength $\ll O(1)$. We assume that the superpotential conserves $R_P$ and that RPV "leaks" into the SUSY Lagrangian through the mechanism that breaks supersymmetry. In particular, in this scenario the only place where RPV interactions show up is in the scalar potential—in the form of three-scalar "soft" operators. Being soft, such scalar RPV operators cannot renormalize the Yukawa-like RPV operators and, so, *the latter remain zero at all scales*. Such a nonvanishing low-energy RPV soft operator will, however, generate an effective RPV Yukawa-like interaction through loops involving the soft interactions (for a related work see [2]). In general, one expects that these effective RPV interactions will show additional patterns (compared to the "regular" $\lambda$, $\lambda'$ and $\lambda''$ ones) due to their explicit dependence on the particles that run in the loops.

To illustrate how the new effective RPV couplings are generated, assume that $R_P$ is violated in the Lagrangian *only* through the pure leptonic (lepton number violating) soft SUSY breaking operators:

$$\Delta V^{soft}_{R_P,\not{L}} = \epsilon_{ab}\frac{1}{2}a_{ijk}\tilde{L}^a_i\tilde{L}^b_j\tilde{E}^c_k + \text{H.c.}, \qquad (1)$$

where $\tilde{L}(\tilde{E}^c)$ are the scalar components of the leptonic SU(2) doublet (charged singlet) supermultiplets $\hat{L}(\hat{E}^c)$, respectively, $\tilde{L}=(\tilde{\nu}_L,\tilde{e}_L)$ and $\tilde{E}^c=\tilde{e}_R$. Also, $a_{ijk}=-a_{jik}$, due to the SU(2) indices $a$, $b$.

This obviously means that in our framework the superpotential conserves $R_P$, i.e., $\lambda$, $\lambda'$ and $\lambda''$ as well as the bilinear RPV terms ($\mu_i\hat{L}_i\hat{H}_u$) are absent. For example, $\lambda_{ijk}\to 0$ in

$$\Delta W_{R_P,\not{L}} = \frac{1}{2}\epsilon_{ab}\lambda_{ijk}\hat{L}^a_i\hat{L}^b_j\hat{E}^c_k + \text{H.c.} \qquad (2)$$

In order to realize this scenario, let us suppose that SUSY breaking occurs spontaneously in a hidden sector at the intermediate scale $\Lambda\sim 10^{10}$–$10^{11}$ GeV, described by the $R_P$-conserving Fayet-O'Raifearartaigh superpotential:

$$W = m_{12}\hat{\Phi}_1\hat{\Phi}_2 + g\hat{\Phi}_3(\hat{\Phi}_2^2 - M^2), \qquad (3)$$

where $m_{12}\sim M\sim\Lambda$ and under $R_P$ the chiral superfields in Eq. (3) transform as $\hat{\Phi}_1,\hat{\Phi}_2,\hat{\Phi}_3 \to -\hat{\Phi}_1,-\hat{\Phi}_2,\hat{\Phi}_3$. SUSY breaking can then be triggered by the vacuum expectation values (VEV's) of the auxiliary $F$ term ($F_{\Phi_i}$) of $\hat{\Phi}_1,\hat{\Phi}_2,\hat{\Phi}_3$. We choose the minimum of the potential in this model to lie at $A_{\Phi_1}=A_{\Phi_3}=0$, $A_{\Phi_2}=M\sqrt{1-m_{12}^2/(2g^2M^2)}$, which satisfies $F_{\Phi_1}=m_{12}A_{\Phi_2}$, $F_{\Phi_2}=0$ and $F_{\Phi_3}=g(A^2_{\Phi_2}-M^2)$.

Supergravity mediation of SUSY breaking can then be parametrized by the following $R_P$-conserving superpotential:

$$\frac{1}{M_{Pl}}\int d^2\theta[\hat{\Phi}_1\hat{L}\hat{L}\hat{E}^c + \hat{\Phi}_2\hat{L}\hat{L}\hat{E}^c] + \text{H.c.}, \qquad (4)$$

which will spontaneously break $R_P$ and induce the soft operator in Eq. (1) with $a\sim F_{\Phi_1}/M_{Pl}\sim\Lambda^2/M_{Pl}\sim m_W$ for $m_{12}\sim M\sim\Lambda$. The superpotential in Eq. (4) will also generate the operators $\propto\lambda$ in Eq. (2) with an extremely suppressed coupling: $\lambda\propto A_{\Phi_2}/M_{Pl}\sim\Lambda/M_{Pl}\sim 10^{-9}$–$10^{-8}$ at the high scale, essentially causing the soft operator in Eq. (1) to be the only source for RPV in this model. Alternative mechanisms for the generation of RPV were suggested in [3].

In general, other operators which couple the hidden sector superfields $\hat{\Phi}_1,\hat{\Phi}_2,\hat{\Phi}_3$ to the observable sector can be constructed, which will generate an RPV $\mu$-like term as well as

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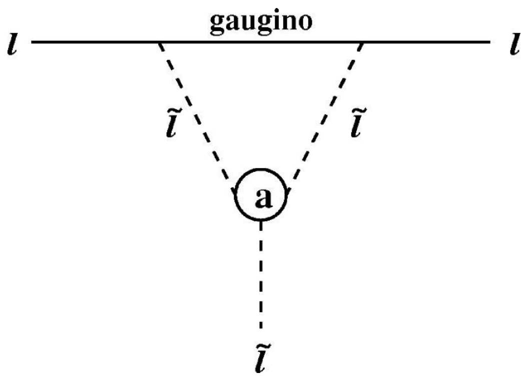


FIG. 1. A typical one-loop diagram that generates an effective λ-like operator similar to Eq. (2). $\tilde{\ell}$ is either a charged slepton or a sneutrino and $\ell$ is a lepton or a neutrino. $a$ is the trilinear soft breaking coupling defined in Eq. (1).

a soft bilinear term $B_i\tilde{L}_iH_u$ (for a somewhat similar example see e.g., [4]. One can always rotate away the $\mu_i$ term at the high scale by a field redefinition. In the absence of the Yukawa-like trilinear terms, $\mu_i$ will remain zero at all scales at the one loop order (see [5]). The $B_i$'s can also be rotated away at the high scale; however, even if they are zero at the high scale they will be radiatively (one-loop) generated by the non-zero soft trilinear $a$ term in Eq. (1) and evolved down to the electroweak (EW) scale through the RGE. Since for $\lambda\to 0$ and $\mu_i\to 0$ the RGE for $B_i$ takes a relatively simple form [5], $B_i(M_Z)$ can be easily estimated. In the leading logarithm we get

$$B_i(M_Z)\sim -\frac{1}{16\pi^2}h_\tau(M_Z)\mu(M_Z)a_{i33}(M_Z)\ln\left(\frac{M_{Pl}^2}{M_Z^2}\right), \tag{5}$$

where $h_\tau$ is the $\tau$ Yukawa coupling and $\mu$ is the usual $\mu$ term ($\mu\hat{H}_u\hat{H}_d$).

Let us now define the effective RPV terms which are generated at one-loop through the soft operator in Eq. (1) via diagrams of the type shown in Fig. 1 as follows:

$$\begin{aligned}\mathcal{L}_{R_P}^{eff}\equiv \frac{1}{2}\left(\frac{a_{ijk}}{16\pi^2}\right)&[\tilde{\nu}_{Li}\overline{e_k}(A_{L,ijk}L+A_{R,ijk}R)e_j\\&+B_{L,ijk}\tilde{\nu}_{Li}\overline{\nu_k}L\nu_j+C_{L,ijk}\tilde{e}_{Lj}\overline{e_k}L\nu_i+D_{L,ijk}\tilde{e}_{Rk}\overline{\nu_i^c}Le_j\\&-(i\to j)]+\text{H.c.},\end{aligned} \tag{6}$$

where $i,j,k$ are generation indices and $L(R)\equiv(1-(+)\gamma_5)/2$. Note that the customary RPV operators in Eq. (2) are obtained by setting: $A_{R,ijk}=B_{L,ijk}=0$, $A_{L,ijk}=C_{L,ijk}=D_{L,ijk}=1$ GeV$^{-1}$ and $a_{ijk}=16\pi^2\lambda_{ijk}$ GeV.

The particles running in the loop diagrams for each of the form factors in Eq. (6) are (i) $\tilde{e}_L\tilde{e}_R\chi_n^0$ for the $\tilde{\nu}_{Li}\overline{e_k}e_j$ term, where $\chi_n^0$ are the four neutralinos ($n=1-4$), (ii) $\tilde{e}_L\tilde{e}_R\chi_m$ for the $\tilde{\nu}_{Li}\overline{\nu_k}\nu_j$ term, where $\chi_m$ are the two charginos ($m=1,2$), (iii) $\tilde{e}_R\tilde{\nu}_L\chi_n^0$ for the $\tilde{e}_{Lj}\overline{e_k}\nu_i$ term and (iv) both $\tilde{e}_L\tilde{\nu}_L\chi_n^0$ and $\tilde{e}_L\tilde{\nu}_L\chi^m$ for the $\tilde{e}_{Rk}\overline{\nu_i^c}e_j$ term.

Calculating these loop diagrams we find that $B_{L,ijk}\propto m_\nu$, i.e., no $\tilde{\nu}\overline{\nu}\nu$ term in the limit of zero neutrino masses. Also, $A_{R,ijk}\ll A_{L,ijk}$ since $A_{R,ijk}$ is proportional to the leptonic Yukawa couplings. Thus, neglecting terms which are proportional to the external lepton masses and to the leptonic Yukawa couplings we find

$$A_{L,ijk}=\frac{e^2}{s_Wc_W^2}\sum_{n=1}^4 m_{\chi_n^0}\mathcal{C}_0^{a(n,ijk)}Z_N^{1n}(Z_N^{1n}s_W+Z_N^{2n}c_W),$$

$$C_{L,ijk}=-\frac{e^2}{s_Wc_W^2}\sum_{n=1}^4 m_{\chi_n^0}\mathcal{C}_0^{c(n,ijk)}Z_N^{1n}(Z_N^{1n}s_W-Z_N^{2n}c_W),$$

$$\begin{aligned}D_{L,ijk}=\frac{e^2}{2s_W^2c_W^2}\Bigg\{&\sum_{n=1}^4 m_{\chi_n^0}\mathcal{C}_0^{d1(n,ijk)}[(Z_N^{1n})^2s_W^2-(Z_N^{2n})^2c_W^2]\\&+\sum_{m=1}^2 2c_W^2m_{\chi_m}\mathcal{C}_0^{d2(m,ijk)}Z_{1m}^+Z_{1m}^-\Bigg\},\end{aligned} \tag{7}$$

where $Z_N^{ij}$ and $Z_{ij}^+$, $Z_{ij}^-$ are the matrices that diagonalize the neutralino and chargino mass matrices, respectively, as defined in [6], $s_W(c_W)$ is the sine (cosine) of the weak mixing angle $\theta_W$, and $\mathcal{C}_0^{a(n,ijk)}$, $\mathcal{C}_0^{c(n,ijk)}$, $\mathcal{C}_0^{d1(n,ijk)}$, $\mathcal{C}_0^{d2(n,ijk)}$ are the three-point loop integrals defined via

$$\mathcal{C}_0(m_1^2,m_2^2,m_3^2,p_1^2,p_2^2,p_3^2)\equiv\int\frac{d^4q}{i\pi^2}\frac{1}{[q^2-m_1^2][(q+p_1)^2-m_2^2][(q-p_3)^2-m_3^2]}, \tag{8}$$

and

$$\begin{aligned}\mathcal{C}_0^{a(n,ijk)}&\equiv\mathcal{C}_0(m_{\chi_n^0}^2,m_{\tilde{e}_{kR}}^2,m_{\tilde{e}_{jL}}^2,m_{e_k}^2,m_{\tilde{\nu}_{iL}}^2,m_{e_j}^2),\\ \mathcal{C}_0^{c(n,ijk)}&\equiv\mathcal{C}_0(m_{\chi_n^0}^2,m_{\tilde{e}_{kR}}^2,m_{\tilde{\nu}_{iL}}^2,m_{e_k}^2,m_{\tilde{e}_{jL}}^2,m_{\nu_i}^2),\\ \mathcal{C}_0^{d1(n,ijk)}&\equiv\mathcal{C}_0(m_{\chi_n^0}^2,m_{\tilde{\nu}_{iL}}^2,m_{\tilde{e}_{jL}}^2,m_{\nu_i}^2,m_{\tilde{e}_{kR}}^2,m_{e_j}^2),\\ \mathcal{C}_0^{d2(m,ijk)}&\equiv\mathcal{C}_0(m_{\chi_m}^2,m_{\tilde{e}_{iL}}^2,m_{\tilde{\nu}_{jL}}^2,m_{\nu_i}^2,m_{\tilde{e}_{kR}}^2,m_{e_j}^2).\end{aligned} \tag{9}$$

Since the soft RPV trilinear $a$ term in Eq. (1) generates the soft RPV bilinear term $B_i$ through the RGE [see (6)], an

TABLE I. Values for the effective RPV form factors $A_{L,ijk}$, $C_{L,ijk}$ and $D_{L,ijk}$ within the Snowmass 2001 benchmark points SPS1, SPS2, SPS4 and SPS5 of the mSUGRA parameter space [6].

| Effective coupling (GeV$^{-1}$) | SPS1 | SPS2 | SPS4 | SPS5 |
|---|---|---|---|---|
| $\lvert A_{L,ijk}\rvert\times10^4$ | 3.5–3.6 | 0.08 | 0.8–1.3 | 2.5–2.6 |
| $\lvert C_{L,ijk}\rvert\times10^4$ | 3.4–3.5 | 0.08 | 0.7–1.1 | 2.5–2.6 |
| $\lvert D_{L,ijk}\rvert\times10^4$ | 6.8 | 0.3 | 2.0–2.6 | 5.2–5.3 |

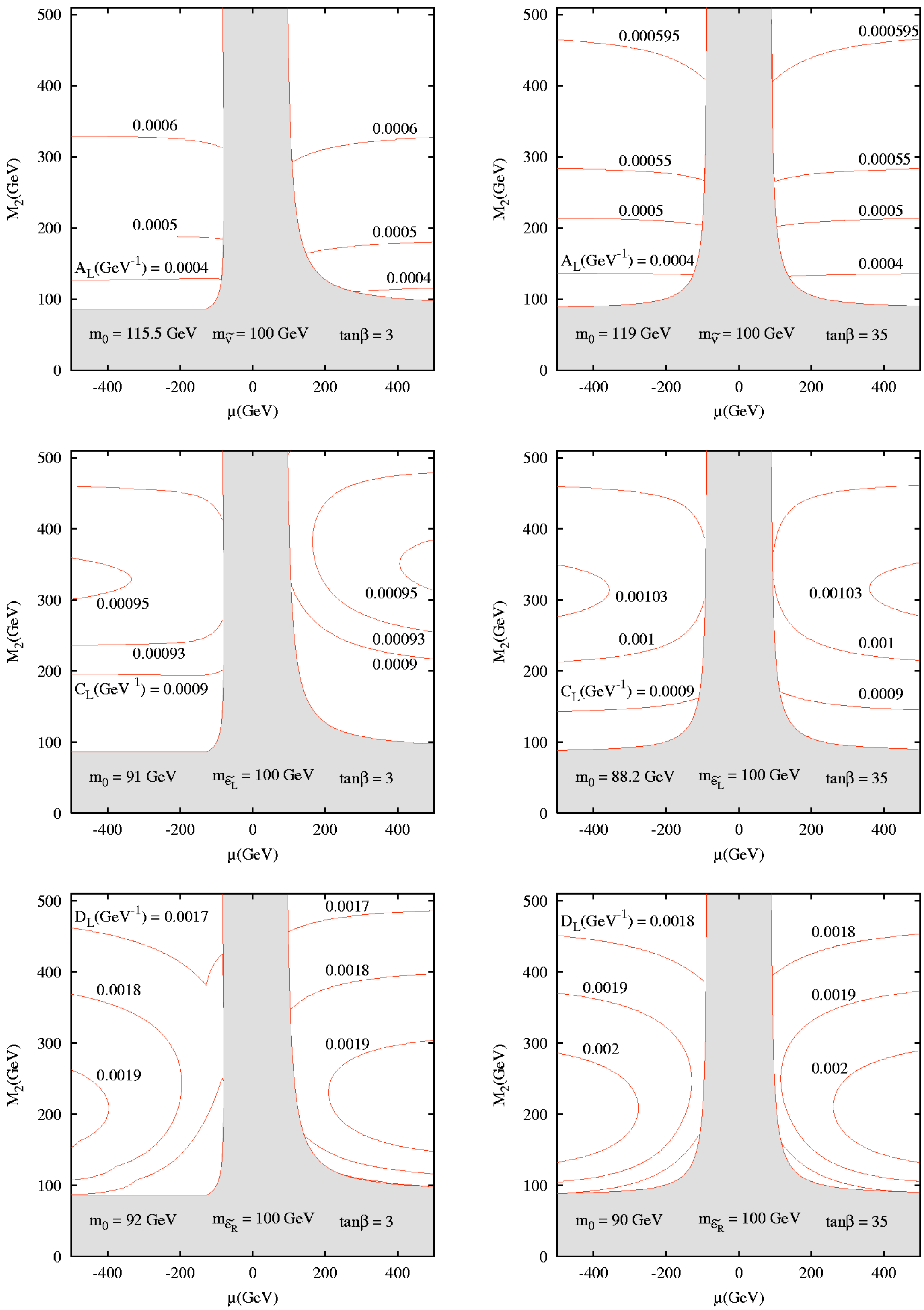


FIG. 2. Contours of the RPV effective form factors $A_L$, $C_L$ and $D_L$ (in GeV$^{-1}$) in the ($\mu$-$M_2$) plane for $\tan\beta=3$ (left panel) and $\tan\beta=35$ (right panel). The shaded region in each figure is disallowed by the lighter chargino and the lightest neutralino mass bounds from LEP2 ($m_{\chi_1^\pm}>87$ GeV and $m_{\chi_1^0}>23$ GeV) corresponding to the *R*-parity violating scenario [8]. See also text.

effective $\tilde{l}ll$ interaction ($l$ for lepton and $\tilde{l}$ for slepton) of the type (7) can also arise from slepton–Higgs boson mixing ($\propto B_i/B_0$, where $B_0$ is the $R_P$-conserving soft bilinear term) followed by the Higgs boson couplings to leptons ($\propto h_l^{jk}$, where $h_l^{jk}$ is the Higgs boson–$l_j l_k$ Yukawa coupling). The contribution of this diagram to the $\tilde{l}ll$ coupling is therefore $\propto h_l^{jk}\times B_i/B_0$, and can be easily estimated when all tree-level low energy SUSY mass parameters are assumed to be of the same size, i.e., $\sqrt{B_0(M_Z)} \sim \mu(M_Z) \sim a_{ijk}(M_Z) \sim M_{SUSY}$. Thus, from Eq. (5) it is clear that $h_l^{jk} \times (B_i/B_0) \sim (h_l^{jk} h_\tau / 16\pi^2) \times \ln(M_{Pl}^2/M_Z^2)$. For $j \neq k$ and for $j=k=1,2$ this effect is negligible, while for $j=k=3$ (couplings involving the $\tau$) we have $\tilde{l} l_3 l_3 \sim (h_\tau^2/16\pi^2) \times \ln(M_{Pl}^2/M_Z^2)$, which gives $\tilde{l} l_3 l_3 \sim 10^{-4}$ for $\tan^2\beta \sim O(10)$ and $\tilde{l} l_3 l_3 \sim 10^{-2}$ if $\tan^2\beta \sim O(1000)$. This effect will be studied in further detail in [9].

In Table I we give a sample of our numerical results for the three effective RPV couplings in Eq. (7), corresponding to the ''Snowmass 2001'' benchmark points SPS1, SPS2, SPS4 and SPS5 of the minimal SUperGRAvity (mSUGRA) scenario [7]. The ranges of values in Table I for each effective operator are due to slight differences in the slepton masses for different generations $i,j,k$. We see that the SPS1 and SPS5 scenarios give the largest effective couplings, of the order of $10^{-4}$–$10^{-3}$ if $a_{ijk} \sim 16\pi^2$ GeV $\sim 150$ GeV.

Let us also evaluate the effective RPV form factors $A_{L,ijk}$, $C_{L,ijk}$ and $D_{L,ijk}$ in a low energy SUSY framework where the SUSY parameter space is defined at the electroweak scale. In particular, in the most general case $A_{L,ijk}$, $C_{L,ijk}$ and $D_{L,ijk}$ depend on $\tan\beta$, the $R_P$ conserving bilinear Higgs boson mass term $\mu$, the three gaugino mass parameters $M_1$, $M_2$ and $M_3 = m_{\tilde{g}}$ ($m_{\tilde{g}}$ is the gluino mass) and the slepton masses. For simplicity, we assume the grand unified theory (GUT) relationship between the SU(3), SU(2) and U(1) gaugino mass parameters, namely, $M_2 = (\alpha_2/\alpha_3) m_{\tilde{g}}$ and $M_1 = (5/3)\tan^2\theta_W M_2$, where $m_{\tilde{g}}$ is taken to be a free parameter. We further assume that all the charged sleptons and the sneutrinos get a universal contribution, $m_0$, to their masses at the electroweak scale. Thus, the masses of the charged sleptons and the sneutrino are given by (including the usual D-term contributions)

$$m_{\tilde{e}_R}^2 = m_0^2 - \sin^2\theta_W m_Z^2 \cos 2\beta \tag{10}$$

$$m_{\tilde{e}_L}^2 = m_0^2 - (1/2 - \sin^2\theta_W) m_Z^2 \cos 2\beta \tag{11}$$

$$m_{\tilde{\nu}_L}^2 = m_0^2 + \frac{1}{2} m_Z^2 \cos 2\beta. \tag{12}$$

Under these conditions, our relevant low-energy SUSY parameter space is reduced to four parameters: $\tan\beta$, $\mu$, $m_{\tilde{g}}$ and $m_0$.

Using the above SUSY parameter space, in Fig. 2 we show contour plots of our effective RPV couplings $A_L$, $C_L$ and $D_L$ (in GeV$^{-1}$) in the $\mu$-$M_2$ plane ($M_2$ is fixed by $m_{\tilde{g}}$ due to the GUT relation mentioned above), for two discrete choices of $\tan\beta$, namely, $\tan\beta = 3$ and 35. It should be noted that the numbers corresponding to a particular effective operator are flavor blind since we have assumed a universal contribution to the soft scalar masses. We can see from Fig. 2 that for slepton masses of 100 GeV (the values of $m_0$ in each of the plots are chosen to give slepton masses of 100 GeV) and if $a_{ijk} \sim 16\pi^2$ GeV and $|\mu|$ as well as $M_2$ are of the order of several hundred GeV, then the $\tilde{\nu} ee$, $\tilde{e}_L e \nu$ and $\tilde{e}_R \nu^c e$ effective couplings in Eq. (6) range between $4 \times 10^{-4}$–$2 \times 10^{-3}$, where the $\tilde{e}_R \nu^c e$ effective coupling is the largest of the three.

The existing upper bounds on $\lambda_{ijk}$ (see, e.g., Allanach *et al.* in [1]) are larger than the expected values of our effective couplings if the trilinear soft breaking RPV coupling $a_{ijk}$ is of the order of the electroweak mass scale. We note that in the general case of soft lepton number violation, the scalar potential may also contain the RPV soft operator $\epsilon_{ab} a'_{ijk} \tilde{L}_i^a \tilde{Q}_j^b \tilde{D}_k^c$, in which case both $\lambda$-like and $\lambda'$-like RPV interactions may be effectively loop generated. Then, the more stringent limits on the $\lambda\lambda'$ coupling products can be applied to constrain our scenario. This will be investigated in a future work [9].

Finally, in our model the soft RPV $a$ term in Eq. (1) gives rise to a neutrino mass only at the two-loop level (see [2]), or equivalently, as an effective ''tree-level'' neutrino mass which is generated by the sneutrino VEVs ($v_i$) and is $\propto v_i^2$. Since $v_i \propto B_i / M_{SUSY}$ [10] and since in our model $B_i$ is a one-loop quantity, clearly this also is essentially a two-loop effect. Similarly, ''one-loop'' neutrino masses involving two vertices of our effective $\lambda$'s are essentially a three-loop effect.

To summarize, we have postulated that RPV can emerge in the hidden sector through the same mechanism that breaks SUSY and then transmitted to the SUSY dynamics at some high energy scale, only in the form of soft operators. A viable hidden sector model that gives rise to softly broken RPV was presented.

In this scenario Yukawa-like RPV operators are generated only through loops involving the RPV soft interactions. Such effective Yukawa-like RPV interactions are similar (albeit richer) in structure to the conventional $\lambda$, $\lambda'$ and $\lambda''$ ones which, in most RPV scenarios, are added *ad hoc* in the superpotential.

We have shown that this framework naturally explains the smallness and, therefore, the present non-observability of RPV interactions in low and high energy processes. The implications of our effective RPV scenario to the $\lambda'$ and $\lambda''$-type couplings, as well as to bilinear RPV, will be detailed in [9].

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