Radiative generation of R-parity violating Yukawa-like interactions from supersymmetry breaking

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ABSTRACT

Yukawa-like R-parity violating (RPV) couplings are generated as effective operators with a typical strength of $\mathcal{O}(10^{-3})$ through loops involving the scalars, the gauginos and the soft supersymmetry breaking RPV interactions. Neutrino masses and other phenomenological implications of such a scenario are discussed.

1. Introduction

In general, the SUSY Lagrangian can have Yukawa-like trilinear R-parity violating interactions \([1]\) with a strength of $\mathcal{O}(1)$. However, strong constraints have been derived on these couplings from various experimental searches which suggest that as long as the masses of the superpartners are in the range of a TeV or less then these RPV couplings should be much smaller than $\mathcal{O}(1)$. In this talk I describe a scenario of generating RPV violating Yukawa-like effective operators, whose structures are similar to the ones conventionally parametrized by $\lambda$, $\lambda'$ and $\lambda''$ in the superpotential but with a strength typically much less than $\mathcal{O}(1)$ \([2]\). We start with the assumption that the superpotential conserves R-parity and that RPV is introduced in the SUSY Lagrangian through the “soft” trilinear scalar operators which break supersymmetry. These soft scalar trilinear RPV operators cannot renormalize the Yukawa-like RPV operators and keep the latter zero at all scales. However, such a non-vanishing low-energy RPV soft operator can generate an effective Yukawa-like RPV interaction at the one-loop level involving the soft interaction and the gauginos and the scalars which run in the loop. This way one expects that in general these effective RPV interactions will show additional patterns (compared to the $\lambda$, $\lambda'$ and $\lambda''$ ones) due to their explicit dependence on the particles running in the loops.

2. R-parity violating effective operators

Let us assume for the purpose of illustration that R-parity is violated in the Lagrangian only through the pure leptonic (lepton number violating) soft SUSY breaking operators:

$$
\Delta V_{R_P,\mathcal{F}}^{\text{soft}} = \epsilon_{ab} \frac{1}{2} a_{ijk} \tilde{L}^a_i \tilde{L}^b_j \tilde{E}^c_k + \text{h.c.},
$$

where $\tilde{L}(\tilde{E}^c)$ are the scalar components of the leptonic SU(2) doublet(charged singlet) supermultiplets $\tilde{L}(\tilde{E}^c)$, 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 means that in our framework the superpotential conserves $R_P$. For example, there is no such term like $\epsilon^{ab}_{\lambda ijk} L^a_i \tilde{L}^b_j \tilde{E}^c_k / 2$ in the superpotential.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure1.png}
\caption{A typical one-loop diagram generating an effective $\lambda$-like operator. $\tilde{\ell}$ 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 (1).}
\end{figure}

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

$$L^\text{eff}_{R_P} \equiv \frac{1}{2} \left( \frac{a_{ijk}}{16\pi^2} \right) [\nu_{Li} \tilde{\nu} \bar{e}^c_k (A_{L,ijk} L + A_{R,ijk} R) e_j + B_{L,ijk} \bar{\nu}_{Li} \nu_k L \nu_j$$

$$+ C_{L,ijk} \bar{\nu}_{Lj} \tilde{e} \bar{\nu}^c_k L \nu_i + D_{L,ijk} \bar{\nu}_{Rk} \tilde{\nu} \bar{e}^c_i L \nu_j - (i \rightarrow j)] + h.c.,$$

where $i, j, k$ are generation indices and $L(R) \equiv (1 - (+) \gamma_5) / 2$ are the chirality projection operators.

We find that $B_{L,ijk} \propto m_\nu$, i.e., no $\tilde{\nu} \tilde{\nu} \nu$ 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 and we neglect them. The expressions for the remaining form factors $A_{L,ijk}$, $C_{L,ijk}$ and $D_{L,ijk}$ can be found in Ref. [2].

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

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

where $m_{12} \sim M \sim \Lambda$ and under $R_P$, $\hat{\Phi}_1, \hat{\Phi}_2, \hat{\Phi}_3 \rightarrow -\hat{\Phi}_1, -\hat{\Phi}_2, \hat{\Phi}_3$. SUSY breaking is triggered by the vacuum expectation values (VEV’s) of the auxiliary F-term $(F_{\Phi_i})$ of $\hat{\Phi}_1, \hat{\Phi}_2, \hat{\Phi}_3$. Supergravity mediation of SUSY breaking can then be parametrized by the following $R_P$-conserving superpotential [2]:

$$\frac{1}{M_{Pl}} \int d^2\theta \left[ \hat{\Phi}_1 \hat{L} \hat{\bar{L}} \hat{E}^c + \hat{\Phi}_2 \hat{L} \hat{\bar{L}} \hat{E}^c \right] + h.c.,$$

which will spontaneously break $R_P$ and induce the soft operator in (1) with $a \sim m_W$. The superpotential in (1) will also generate the operators $\propto \lambda$ with an extremely suppressed coupling: $\lambda \sim 10^{-9} - 10^{-8}$ at the high scale, essentially causing the soft operator in (1) to be the only source for RPV in this model.
One should also note that the lepton number violating soft bilinear term $B_i \bar{L}_i H_u$ will be radiatively (one-loop) generated [2] by the non-zero soft trilinear $a$ term in [1]. In the leading log and in the limit of vanishing $\lambda$ and $\mu$ (bilinear RPV terms in the superpotential),

$$B_i(M_Z) \sim - \frac{1}{16\pi^2} h_\tau(M_Z) \mu(M_Z) a_{i33}(M_Z) \ln \left( \frac{M^2_P}{M_Z^2} \right)$$

(5)

where $h_\tau$ is the $\tau$ Yukawa coupling and $\mu$ is the Higgsino mass parameter ($\mu \hat{H}_u \hat{H}_d$). R-parity violation only by soft terms has also been discussed recently in Ref. [3].

3. Some numerical results

Table 1: 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. Taken from Ref. [2].

| Effective form factor (GeV$^{-1}$) | SPS1  | SPS2  | SPS4  | SPS5  |
|-----------------------------------|-------|-------|-------|-------|
| $|A_{L,ijk}| \times 10^4$          | 3.5 - 3.6 | 0.08  | 0.8 - 1.3 | 2.5 - 2.6 |
| $|C_{L,ijk}| \times 10^4$          | 3.4 - 3.5 | 0.08  | 0.7 - 1.1 | 2.5 - 2.6 |
| $|D_{L,ijk}| \times 10^4$          | 6.8    | 0.3   | 2.0 - 2.6 | 5.2 - 5.3 |

In Table I we give a sample of our numerical results for the three effective RPV form factors, corresponding to the “Snowmass 2001” benchmark points SPS1, SPS2, SPS4 and SPS5 of the mSUGRA scenario [2]. 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. The existing upper bounds [4] on $\lambda_{ijk}$ are larger than the expected values of our effective couplings if $a_{ijk}$ is of the order of the electroweak mass scale.

![Figure 2](image-url): Momentum dependence of the form factor $|A_L(q^2)|$ for two different values of the scalar masses ($m_0$) in the loop. All masses are in GeV.
One should also note that the form factors are momentum dependent. In Fig. 2 we have shown the momentum (q) dependence of the form factor |A_L(q^2)|. From this figure we see a large enhancement at a value of q where the sleptons inside the loop can be produced on-shell. This is one of the very interesting features of this scenario and could possibly be tested, for example, by the process $e^+e^- \rightarrow \tau^+\tau^-$ through an s-channel $\tilde{\nu}_\mu$ exchange. If such an enhancement is observed in $e^+e^- \rightarrow \tau^+\tau^-$, then one should also be able to detect the on-shell production of a pair of sleptons that run in the loop, i.e., $e^+e^- \rightarrow \tilde{l}\tilde{l}$.

Another interesting way to test this scenario is to look at the ratio of the two partial decay widths $\Gamma(\tilde{\nu}_\tau \rightarrow \mu^+\mu^-)$ and $\Gamma(\tilde{\mu}_L \rightarrow \tilde{\nu}_\tau\mu^-)$. In our scenario this ratio is given by (neglecting the lepton mass)

$$\frac{\Gamma(\tilde{\nu}_\tau \rightarrow \mu^+\mu^-)}{\Gamma(\tilde{\mu}_L \rightarrow \tilde{\nu}_\tau\mu^-)} = \left(\frac{|A_{L,322}|^2}{|C_{L,322}|^2}\right)^2,$$

whereas for the conventional tree level RPV $\lambda$-type coupling this ratio is given by $m_{\tilde{\nu}_\tau}/m_{\tilde{\mu}_L}$.

The measurement of this ratio of the two partial decay widths as a function of the mass ratio $m_{\tilde{\nu}_\tau}/m_{\tilde{\mu}_L}$ can help us understand the underlying scenario.

Let us now briefly discuss the generation of neutrino mass in our model. The soft RPV $a$-term in $\lambda$ gives rise to a neutrino mass only at the two-loop level (see [4]), 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 $v_i \propto B_i/M_{\text{SUSY}}$ [5] and 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 in fact coming from three-loop diagrams.

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