R-parity Violating Radiative Photino Decay in Supersymmetric Models

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It has been shown that unless the tri-linear R-parity violating coupling $\lambda_{i33}$ ($i = 1, 2$) is small enough ($\lambda_{i33} < 10^{-2}$ for MSSM and $10^{-3}$ for GMSB model), the partial decay width of photino decaying into 'photon + $\nu_{e,\mu}$', both in supergravity motivated (MSSM) and gauge mediated (GMSB) supersymmetric models are larger than the partial decay width of photino decaying into 'photon + goldstino' in R-parity conserving GMSB model including one loop supersymmetric QED correction.

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Confirmation of neutrino oscillation by Superkamiokande experiment \[1\] leads to the conclusion of non-zero neutrino mass. In Minimal Supersymmetric version of Standard Model either Supergravity motivated (we refer it as MSSM) \[2\] or Gauge mediated (which we refer as GMSB) \[3\], this feature of non-zero neutrino mass is realized through R-parity violation in the theory. Supersymmetric models with R parity violation opens up a plethora of new signals or can mimic the signals of R-parity conserving models. In the present work, we have computed such loop induced photino decays \[4\] $\tilde{\gamma} \to \gamma \nu_i$, $\tilde{\gamma} \to \gamma \nu_\mu$ via R-parity violation. The qualitative nature of both these processes are same and the quantitative difference arises due to the difference in respective R-parity violating couplings. Keeping this feature in view, in the following, we represent both the decays as $\tilde{\gamma} \to \gamma \nu_i$ (where $i = e, \mu$) and the decay amplitude of both the processes will be evaluated just by replacing the respective R-parity violating coupling. Furthermore, we have neglected the decay process $\tilde{\gamma} \to \gamma \nu_\tau$ as it is much suppressed compared to the other two processes. This is precisely because $\tilde{\gamma} \to \gamma \nu_i$ decays involve heaviest $\tau$ lepton in the loop whereas $\tilde{\gamma} \to \gamma \nu_\tau$ decay involves $e$ and $\mu$ leptons. The decay $\tilde{\gamma} \to \gamma \nu_i$ mimics the signal of $\tilde{\gamma} \to \gamma \tilde{G}$ in R-parity conserving GMSB model where $\tilde{\gamma}$ is the Next to Lightest Supersymmetric Particle (NLSP). Both these decay process, $\tilde{\gamma} \to \gamma \nu_i$ and $\tilde{\gamma} \to \gamma \tilde{G}$, give rise to the same final state $"\gamma + \not{E}\"$. We have also considered one loop supersymmetric QED correction of the decay $\tilde{\gamma} \to \gamma \tilde{G}$. There is not much enhancement in the partial decay width due to this correction and we find that the partial decay width of $\tilde{\gamma} \to \gamma \nu_i$ decay process is larger than the $\tilde{\gamma} \to \gamma \tilde{G}$ decay, unless the trilinear $\lambda_{33}$ (where $i = 1, 2$) coupling is too small. Fur-
thermore, if R parity is violated, there will be possible three body photino decay ($\tilde{\gamma} \rightarrow fff$) and it has been shown\(^5\) that non-observation of such signal put a stringent constraint on the trilinear R-parity violating coupling $< 10^{-5}$, through the comparison between the partial decay width of $\tilde{\gamma} \rightarrow \gamma \tilde{G}$ with $\tilde{\gamma} \rightarrow fff$. A recent analysis\(^6\) in this path has been done through the inclusion of bi-linear R-parity violating term and it has been shown that the branching ratio of $\tilde{\chi}_1^0 \rightarrow \nu \gamma$ decay can have a maximum value of about 5-10%. In the present work, we find that the tri-linear R-parity violating $\lambda_{i33}$ coupling alone give rise to a larger partial decay width of the decay process $\tilde{\gamma} \rightarrow \gamma \nu_i$ compared to the one loop supersymmetric QED corrected decay process $\tilde{\gamma} \rightarrow \gamma \tilde{G}$, unless the value of $\lambda_{i33}$ is too low. Thus, if R-parity is violated, ambiguity arises to interpret the observed signal ”$\gamma + \mathcal{E}$” or ”$\gamma \gamma + \mathcal{E}$” etc.\(^7\),\(^8\) as a low energy signature of R-parity conserving GMSB model in an unambiguous way. Some other complementary signal in collider experiment should be needed which when taken into account with the ”photon + missing energy” signal could lead us to confirm any of these models. Before going into the details, we like to mention the followings: First, although, in general, lightest neutralino $\tilde{\chi}_1^0$ is an admixture of the neutral gauginos and neutral Higgsinos, however, the present state of knowledge leads to the fact that the $\tilde{\gamma}$ component is dominated over the largest region of allowed parameter space\(^9\). The relevant mixing factor arises due to general consideration of $\tilde{\chi}_1^0$ structure will modify equally all the decays discussed in the present work. Second, we discard any photino-lepton-slepton off diagonal coupling in the present work.

To compute one loop supersymmetric QED correction to the decay of
\( \tilde{\gamma} \to \gamma \tilde{G} \) in R-parity conserving GMSB model, we consider the following goldstino-lepton-slepton interaction Lagrangian \[10\]

\[ L = -ie_{gL} \sqrt{2} [\bar{e}_L \tilde{e}_L \tilde{G} + \tilde{G} \bar{e}_L^* e_L] + ie_{gR} \sqrt{2} [\bar{e}_R \tilde{e}_R \tilde{G} + \tilde{G} \bar{e}_R^* e_R] \tag{1} \]

where

\[ e_{gL} = \frac{m_{\tilde{e}_L}^2 - m_e^2}{d}, e_{gR} = \frac{m_{\tilde{e}_R}^2 - m_e^2}{d}, d = \sqrt{\frac{3}{4\pi}} M_{susy}^2 \tag{2} \]

In the above expressions \( m_{\tilde{e}_L}, m_{\tilde{e}_R} \) are the masses of the left-slepton and right-slepton and \( M_{susy} \) is the supersymmetry breaking scale parametrized in terms of parameter \( d \). In GMSB model, masses of left-slepton and right-slepton are wide apart primarily due to their different representation under SU(2) gauge group and since \( m_{\tilde{e}_L} >> m_{\tilde{e}_R} \) we have discarded the contribution due to \( m_{\tilde{e}_L} \). Furthermore, we ignored any non-degeneracy in right-slepton masses and \( m_{\tilde{e}_R} \) represents mass of the right-selectron. The one loop supersymmetric QED corrected diagrams of the decay \( \tilde{\gamma}(q) \to \gamma(p_2)\tilde{G}(p_1) \) is generated due to slepton-lepton particles in the loop. The squark-quark induced loop diagrams are neglected since \( m_{\tilde{q}} >> m_{\tilde{t}} \). Neglecting lepton masses as well compared to selectron mass, we obtain the following matrix element

\[ -iM_{loop} = i \left( \frac{2e^2}{16d^2} \right) m_{\tilde{e}_R}^2 A \bar{u}(p_1) \gamma^\rho u(q) \epsilon_\rho^* \] \tag{3}

where

\[ A = -\frac{3}{2} \ln(1 + p - 2p^2) + \frac{p}{18} + \frac{143}{60} p^2 \tag{4} \]

and \( p = \frac{m_\gamma}{m_{\tilde{e}_R}^2} \) where \( m_\gamma \) is the mass of the photino. It is to be noted that as \( p \to 0 \), still there is a non-zero contribution to the loop correction due to the presence of the second term in the right-hand side of Eqn.(4), which
shows non-decoupling effect of the above process. This is basically due to the proportionality of the coupling of the Goldstino-lepton-slepton term in the lagrangian with the slepton mass squared.

The relevant part of the Lagrangian required to calculate tree level $\tilde{\gamma}(q) \rightarrow \gamma(p_2)\tilde{G}(p_1)$ is given by [11]

$$L = \frac{1}{2d} \partial_\mu \tilde{\gamma} \gamma^{\mu}[\gamma^\nu, \gamma^\rho] \tilde{G} \partial_\nu A_\rho + h.c. \quad (5)$$

and the tree level matrix element comes out as

$$-iM_{Tree} = \frac{3m_{\tilde{\gamma}}^2}{2d} \bar{u}(p_1)\gamma^\rho u(q)\epsilon^*_{\rho}(p_2) \quad (6)$$

The total matrix element $M_{total}(= \text{tree level} + \text{one loop})$ of the decay process $\tilde{\gamma} \rightarrow \gamma\tilde{G}$ can be written as

$$M_{total} = M_{tree}(1 + \Delta) = \frac{3m_{\tilde{\gamma}}^2}{2d} (1 + \frac{e^2}{12\pi^2} \frac{m_{\tilde{e}_R}^2}{m_{\tilde{\gamma}}^2} A) \bar{u}(p_1)\gamma^\rho u(q)\epsilon^*_{\rho}(p_2) \quad (7)$$

where $\Delta = \frac{M_{\text{loop}}}{M_{\text{tree}}}$ is the enhancement factor. For a typical mass value of $m_{\tilde{\gamma}} = 80 \text{ GeV}$ and $m_{\tilde{e}_R} = 100 \text{ GeV}$ which are allowed in GMSB model, we found the enhancement in $M_{total}$ due to one loop correction is $\Delta \sim 6 \times 10^{-3}$ for three generations of leptons. For higher values of photino and right-selectron masses the correction becomes more and more insignificant. Thus, we find that the enhancement due to the one loop supersymmetric QED correction of the decay $\tilde{\gamma} \rightarrow \gamma\tilde{G}$ is insignificant compared to its tree level decay mode.

Next, we consider the one loop decay of $\tilde{\gamma} \rightarrow \gamma\nu_i$ in MSSM induced by the tri-linear R-parity violating $\lambda_{i33}$ coupling. The relevant diagrams are obtained by replacing goldstino field of the previous process by the $\nu_i$ field with R parity violating $\lambda_{i33}$ coupling, however, unlike the previous case, there
is a chirality flip in the internal lepton(s) line(s) due to Yukawa type nature of the R-parity violating interactions, and therefore, we cannot neglect lepton mass in this case. We have considered heaviest \( \tau \) lepton contribution only and as we have considered photino-lepton-slepton flavour diagonal coupling, the other particle circulating in the loop is \( \tilde{\tau}_R \). Furthermore, we have ignored any non-degeneracy between \( m_{\tilde{\tau}_L} \) and \( m_{\tilde{\tau}_R} \) and we have also ignored \( \lambda' \) coupling induced \( d - \bar{d} \) interactions by considering \( m_{\tilde{d}} >> m_{\tilde{\tau}_R} \).

We consider the following R-parity violating trilinear interaction,

\[
L_{R_p} = \frac{\lambda_{333}}{2}[\tilde{\tau}_L \nu_i L \tilde{\tau}_R + (\tilde{\tau}_R)^* (\nu_i L)^c \tau_L] + h.c. \quad (8)
\]

The squared matrix element of the process \( \tilde{\gamma} \to \gamma \nu_i \) comes out as

\[
|M|^2_{\text{MSSM}} = 16Q^2[2A^2 - B_1^2(A_1 + C)(B + C) - 2AB_1(B + C)] \quad (9)
\]

where

\[
Q = \frac{(\lambda_{333} \alpha)}{4\sqrt{2\pi}} \left( \frac{m_{\tau}}{m_{\tilde{\tau}}^2} \right) m_{\tilde{\gamma}}^2 \quad (10)
\]

\[
A = \frac{t}{t - 1} \ln t - \ln t - 1 \quad (11)
\]

\[
A_1 = \frac{2}{1 - t} (t \ln t + 1 - t) - 1 + \frac{2}{(1 - t)^2} \left( \frac{t^2}{4} - \frac{1}{4} - \frac{t^2}{2} \ln t \right) \quad (12)
\]

\[
B = \frac{t}{1 - t} \ln t + 1 \quad (13)
\]

\[
B_1 = \frac{3}{t - 1} \quad (14)
\]

\[
C = \frac{1}{(1 - t)^2} \left[ t(1 - \frac{t}{2}) \ln t + (t - \frac{1}{4}) - \frac{3t^2}{4} \right] \quad (15)
\]

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and \( t = \frac{m_\tau^2}{m_{\tilde{\tau}}^2} \). Neglecting higher powers of \( t \), we obtain a simpler expression for \( |M|_{MSSM}^2 \) as

\[
|M|_{MSSM}^2 = 16Q^2[2(1 + \ln t)^2 + \frac{9}{2} \ln t + \frac{45}{16}]
\]  

(16)

The partial decay width comes out as

\[
\Gamma_{R_p}^{MSSM} = \frac{1}{16\pi} |M|_{MSSM}^2 \frac{1}{m_{\tilde{\gamma}}}
\]  

(17)

The partial decay width \( \Gamma(\tilde{\gamma} \rightarrow \gamma \tilde{G}) \) in R-parity conserving GMSB model at the tree level is given by [12]

\[
\Gamma(\tilde{\gamma} \rightarrow \gamma \tilde{G})^{GMSB} = \frac{m_{\tilde{\gamma}}^5}{6M_{\text{Susy}}^4}
\]  

(18)

and for the previous choice of photino mass and \( M = 150 \text{ TeV} \), the partial decay width comes out as \( \Gamma(\tilde{\gamma} \rightarrow \gamma \tilde{G})^{GMSB} \sim 0.10 \times 10^{-11} \) whereas \( \Gamma_{R_p}^{MSSM} \sim 0.17 \times 10^{-7} \times \lambda_{33}^2 \) for \( m_{\tilde{\tau}} = 200 \text{ GeV} \), \( m_{\tilde{\gamma}} = 100 \text{ GeV} \). Thus, unless \( \lambda_{33} \) is very small \( (< 10^{-2}) \), \( \Gamma(\tilde{\gamma} \rightarrow \gamma \nu_i)^{MSSM} \rangle > \Gamma(\tilde{\gamma} \rightarrow \gamma \tilde{G})^{GMSB} \). Such a value of \( \lambda_{33} \) is well within the present upper bounds: \( \lambda_{233} < 0.09 \left( \frac{m_{\tilde{\tau}}}{100 \text{ GeV}} \right) \), \( \lambda_{133} < 0.24 \left( \frac{m_{\tilde{\tau}}}{100 \text{ GeV}} \right) \) [13].

Similar result is also obtained in case of GMSB model including R-parity violation. The squared matrix element in this case is given by

\[
|M|_{GMSB}^2 = 4 \left( \frac{\lambda_{33} a}{4\sqrt{2}\pi} \right)^2 t_1[2(1 + \ln t_1)^2 + \frac{9}{2} \ln t_1 + \frac{45}{16} \frac{m_{\tilde{\gamma}}^2}{m_{\tilde{\tau}}^2}]
\]  

(19)

\[+ \text{terms containing } m_{\tilde{\ell}_L} \]  

(20)

where \( t_1 = \frac{m_\tau^2}{m_{\tilde{\tau}}^2} \) and as before we have neglected higher powers of \( t_1 \). We can also neglect left-slepton contribution in the above expression since \( m_{\tilde{\ell}_L} >> m_{\tilde{\tau}} \) in GMSB model. The partial decay width comes out as

\[
\Gamma_{R_p}^{GMSB} = \frac{1}{16\pi} |M|_{GMSB}^2 \frac{1}{m_{\tilde{\gamma}}}
\]  

(21)
For a typical choice of model parameters, $m_{\tilde{\gamma}} = 80 \text{ GeV}$, $m_{\tilde{\tau}_R} = 100 \text{ GeV}$ we obtain, $\Gamma_{R_{\text{p}}}^{\text{GMSB}} = 0.21 \times 10^{-7} \times \lambda_{i33}^2$. Hence, as before, unless $\lambda_{i33} < 10^{-3}$, the partial decay width of R-parity violating photino decay ($\tilde{\gamma} \rightarrow \gamma \nu_i$) in GMSB model is larger than the R-parity conserving photino decay ($\tilde{\gamma} \rightarrow \gamma \tilde{G}$) mode.

In summary, we have calculated partial decay width of one loop radiative photino decay ($\tilde{\gamma} \rightarrow \gamma \nu_i$) (where $i = e, \mu$) both in MSSM as well as GMSB models due to tri-linear R-parity violating interactions. We have also computed one loop supersymmetric QED corrected amplitude of the decay process $\tilde{\gamma} \rightarrow \gamma \tilde{G}$ in R-parity conserving GMSB model. We found that for a typical choice of model parameters the enhancement due to this correction, $\Delta(=\frac{M_{\text{loop}}}{M_{\text{tree}}})$ is of the order of $6 \times 10^{-3}$ for three generations of leptons. We have compared the one loop QED corrected partial decay width of the decay $\tilde{\gamma} \rightarrow \gamma \tilde{G}$ with the R-parity violating $\tilde{\gamma} \rightarrow \gamma \nu_i$ decay for both MSSM and GMSB models and we found that unless the tri-linear R-parity violating $\lambda_{i33}$ (where $i = 1, 2$) coupling is small enough ($\lambda_{i33} < 10^{-2}$ for MSSM and $10^{-3}$ for GMSB model), the partial decay width of this loop induced process is larger than the photino decay $\tilde{\gamma} \rightarrow \gamma \tilde{G}$ in R-parity conserving GMSB model. The upshot of this analysis leads to a crucial position to interpret the collider signal ”photon + missing energy” as a signature of R-parity conserving GMSB model in an unambiguous way.

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