Single superparticle production via $\gamma\gamma$ collision with explicit R-parity violation

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ABSTRACT

We study the single production of scalar neutrinos or charginos via $\gamma\gamma$ collision in an R-parity ($R_p$) violating supersymmetric model. It may be possible to detect a sneutrino or a chargino at a Linear Collider (LC) in $\gamma\gamma$ operation mode, as a test of supersymmetry and $R_p$-violation. Because of the clean background in LC, stringent constraints on $R_p$ violating parameters can be obtained even if the process cannot be observed at the future Linear Collider.

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I. Introduction

One of the main aims of a Linear Collider (LC) is detecting supersymmetry [1]. Because of its clean background compared with hadron colliders, LC can efficiently probe new physics beyond the Standard Model (SM). In addition to the $e^+e^-$ collider mode, the LC can, with the advent of new collider techniques, produce highly coherent laser beams being back-scattered with high luminosity and efficiency at the $e^+e^-$ colliders [2]. In this paper we will concentrate on $\gamma\gamma$ collisions.

The R-parity ($R_p = (-1)^{3B+L+2S}$, where $B$, $L$ and $S$ denote the baryon number, lepton number and spin), which is introduced to guarantee the $B$- and $L$-conservation automatically, is conserved in the minimal supersymmetric extension of the SM [3]. With the discrete symmetry the lightest supersymmetric particle (LSP) is stable and superparticles can only be pair produced. However, $R_p$ is not necessary in order to forbid fast proton decay [4]. Since in the $R_p$-violating ($R'_p$) models superparticles can be singly produced and neutrinos get masses and mix [5], it is a significant source of new physics. Especially after the first signals for neutrino oscillations from atmospheric neutrinos were observed in Super-Kamiokande [6], $R_p$-violation became a good candidate to explain those experimental results.

The $R_p$-violation will introduce many processes forbidden in the Standard Model. Thus, it is limited by the low energy experiments [8][9]. Since the single production of superparticles is admitted in the $R_p$-violating model, it can lower superparticle production threshold. If Nature favors the $R_p$-violation, then the single production of superparticles may be the first sign of supersymmetry. In this work we will consider the single production of scalar neutrinos and the lightest chargino in $\gamma\gamma$ collisions.

Detection of $R_p$-violation at the lepton colliders has been considered both indirectly [10] and directly by detecting the $R_p$-violating decay of superparticles produced at the lepton colliders [11], and by producing superparticles singly [12]. The single production of scalar neutrinos from $e^+e^-$ collision has been considered in [12], where the $L$-violating parameters $\lambda$ involving light flavors will dominate the process. The processes $e^+e^- \rightarrow \tilde{\nu}, \tilde{\chi}^\pm l^\mp$ were also considered in [12]. However, $\gamma\gamma$ collision could introduce the $R_p$-violating parameters involving heavy flavors. These parameters could be much larger than those involving light flavors with an assumption of family symmetry [13], and also introduce other $L$-violating parameters $\lambda'$ in the processes. A $\gamma\gamma$ resonance can be probed over a wide mass region, even before production in direct $e^+e^-$ collision, which is only sensitive at the center of mass energy (c.m. energy) of colliders. The resonant sneutrino production at Large Hadron Collider (LHC) has already been considered in Ref. [14].

In section 2, the cross section of the process $\gamma\gamma (\rightarrow \tilde{\nu}, \tilde{\chi}^\pm + l^\mp)$ is calculated. In section 3 the signals of the processes

$$\gamma\gamma \rightarrow \tilde{\nu},$$

$$\gamma\gamma \rightarrow \tilde{\chi}^\pm + l^\mp$$

are considered. Our conclusions are given in section 4 and some details of the expressions are listed in the appendix.

2. Production of $\tilde{\nu}$ and $\tilde{\chi}^\pm$ with explicit R-parity violation

All renormalizable supersymmetric $R_p$ interactions can be introduced in the superpotential [3]:

$$W_{R_p} = \frac{1}{2} \lambda_{ij[k]} L_i L_j \tilde{E}_k + \lambda'_{ijk} L_i Q_j D_k + \frac{1}{2} \lambda''_{ij[k]} \tilde{U}_i \tilde{D}_j \tilde{D}_k + \epsilon_i L_i H_u.$$  (2.1)
where $L_i$, $Q_i$ and $H_u$ are SU(2) doublets containing lepton, quark and Higgs superfields respectively, $E_j$ ($\bar{D}_j$, $U_j$) are singlet lepton (down-quark and up-quark) superfields, and $i, j, k$ are generation indices. Square brackets on them denote antisymmetry in the bracketted indices.

We will consider only trilinear terms in this paper. In order to avoid fast proton decay, it is necessary that

$$|<\lambda, \lambda'|\lambda''| < 10^{-10} \left(\frac{\tilde{m}}{100 \text{ GeV}}\right)^2,$$

where $\tilde{m}$ is the mass of a squark or a slepton. We will consider only the $L$-violating terms in our calculations. We also assume that the parameters $\lambda$ and $\lambda'$ are real.

One-loop corrections (the ones corresponding to $\lambda$ terms are shown in Fig.1, and contributions from $\lambda'$ terms are similar) to $\gamma\gamma \rightarrow \tilde{\chi}^\mp l^\pm$ can be split into the following components:

$$M = \delta M_s + \delta M_v + \delta M_b,$$

where $\delta M_s$, $\delta M_v$, and $\delta M_b$ are the one-loop amplitudes corresponding to the self-energy, vertex, and box correction diagrams, respectively. Since the proper vertex counterterm should cancel with the counterterms of the external legs in this case, we do not need to deal with the ultraviolet divergence. We simply sum over all (unrenormalized) reducible and irreducible diagrams and the result is finite and gauge invariant.

Thus, we can get the amplitude of $\gamma\gamma \rightarrow \tilde{\chi}^\mp l^-$. Collecting the terms together, we obtain the total cross section for the subprocess $\gamma\gamma \rightarrow \tilde{\chi}^{\pm} l^\mp$:

$$\hat{\sigma}(\hat{s}) = \frac{1}{16\pi s^2} \int_{t^-}^{t^+} dt \sum_{\text{spins}} |M|^2,$$

where $t^\pm = \frac{1}{2} \left[(m_{\tilde{\chi}^\pm}^2 + m_l^2 - \hat{s}) \pm \sqrt{s^2 + m_{\tilde{\chi}^\pm}^2 + m_l^2 - 2sm_{\tilde{\chi}^\pm} - 2sm_l^2 - 2m_{\tilde{\chi}^\pm}^2 m_l^2}\right]$, and the bar over summation means averaging over initial spins. In order to obtain the observable cross section of single chargino production via $\gamma\gamma$ fusion in an $e^+e^-$ collider, we need to fold the cross

Figure 1: Feynman diagrams of $\gamma\gamma \rightarrow \tilde{\chi}^- \tau^+$. Here (a) are self-energy diagrams, (b) vertex diagrams, and (c) box, quartic interaction and triangle diagrams.
section of $\gamma\gamma \rightarrow \tilde{\chi}^\pm l^\tau$ with the photon luminosity,

$$\sigma(s) = \int_{(m_{\tilde{\chi}^\pm} + m_l)/\sqrt{s}}^{x_{max}} \frac{dz}{dz} \frac{dL_{\gamma\gamma}}{dz} \hat{\sigma}(\hat{s}),$$

(2.5)

where $\hat{s} = z^2 s$, $\sqrt{s}$ and $\sqrt{\hat{s}}$ are the $e^+e^-$ and $\gamma\gamma$ c.m. energies respectively. $\frac{dL_{\gamma\gamma}}{dz}$ is the photon luminosity, which is defined as [3]

$$\frac{dL_{\gamma\gamma}}{dz} = 2z \int_{x_{min}/x_{max}}^{x_{max}} \frac{dx}{x} F_{\gamma/e}(x) F_{\gamma/e}(z^2/x),$$

(2.6)

where the energy spectrum of the back-scattered photon is given by [3]

$$F_{\gamma/e}(x) = \frac{1}{D(\xi)} [1 - x + \frac{1}{1 - x} - \frac{4x}{\xi (1 - x)} + \frac{4x^2}{\xi^2 (1 - x)^2}],$$

(2.7)

and [15] $\xi = 4.8$, $x_{max} = 0.83$ and $D(\xi) = 1.8$.

3. Numerical results

Let us first consider the production of sneutrinos. The cross section will only depend on the $R_p$ couplings and masses of sneutrinos, but not on the other sparticle masses. With an assumption of family symmetry discussed in [13], $R_p$-violating couplings involving heavy flavors will be larger than those involving light flavors. Thus, we will consider mainly couplings $\lambda_{23i}$, $\lambda'_2 2i$, $\lambda'_2 2i$, and $\lambda'_{23j}$. These are also experimentally least bounded. The productions of $\tilde{\nu}_2$ and $\tilde{\nu}_3$ differ qualitatively. In the case of $\tilde{\nu}_2$, the production via both $\lambda$ and $\lambda'$ terms are important, since either $\tau$-lepton or $b$-quark can circulate in the loop. In the case of $\tilde{\nu}_3$ only $\lambda'$ term with $b$-quark in the loop is significant.

We plot in Fig. 2 cross sections for the single production of $\tilde{\nu}_2$ and $\tilde{\nu}_3$, using the largest allowed values of the relevant couplings, as well as using the close to smallest values observable for the couplings. In Fig. 2 (a), we show the cross section of $e^+e^- \rightarrow \gamma\gamma \rightarrow \tilde{\nu}_2$ for c.m. energy 500 GeV. The solid line corresponds to $\lambda_{233} = 0.1$ and the dashed line to $\lambda_{233} = 0.01$, respectively. It can be seen that the cross section is still 0.005 fb for $m_{\tilde{\nu}} = 400$ GeV with $\lambda_{233} = 0.1$, which is almost the present upper limit for $\lambda_{233}$ [4]. Even with a much smaller $R_p$-violating coupling, $\lambda_{233} = 0.01$, the sneutrino production cross section for sneutrinos lighter than 95 GeV[1] remains above 0.002 fb (corresponding to one event per year with the luminosity 500 fb$^{-1}$ at c.m. energy 500 GeV). Similarly, in Fig. 2 (b), we plot the cross section of $e^+e^- \rightarrow \gamma\gamma \rightarrow \tilde{\nu}_2$ with the coupling $\lambda'_{233} = 0.15$ (present upper limit), corresponding to the solid line, and $\lambda'_{233} = 0.03$ corresponding to the dashed line. If $m_{\tilde{\nu}} = 90$ GeV and $\lambda'_{233} = 0.15$, a few tens of events are produced per year with 500 fb$^{-1}$ luminosity. The cross section remains above 0.002 fb with $\lambda'_{233} = 0.15$ for $m_{\tilde{\nu}}$ less than 400 GeV. In Fig. 2 (c), we plot the cross section of $e^+e^- \rightarrow \gamma\gamma \rightarrow \tilde{\nu}_3$ as a function of the sneutrino $\tilde{\nu}_3$ mass for c.m. energy 500 GeV with the coupling of $\lambda'_{333} = 0.45$ (present limit). Since $\lambda'_{333}$ can be much larger than $\lambda'_{233}$, the cross section of $\tilde{\nu}_3$ production could be larger within the present limits.

Next we consider the possible single production of charginos with $R_p$ couplings. We assume here the minimal supergravity (mSUGRA) model, where we take as our reference point $m_0 = 100$ GeV, $A_0 = -100$ GeV, $\tan\beta = 3$ and sign$(\mu) = +$. The masses of sneutrinos and charginos increase when we change $m_{1/2}$ from 100 GeV to 500 GeV, see Table 1. Increasing $m_0$ would

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1The present lower limits for sneutrino masses are $m_{\tilde{\nu}_2} > 84$ GeV and $m_{\tilde{\nu}_3} > 86$ GeV [15].
increase the masses of stau and sneutrino and at the same time decrease the cross section to an unobservable level.

We plot the cross section of $\gamma\gamma \rightarrow \tilde{\chi}_1^{\pm}l^\mp$ as a function of the chargino mass $m_{\tilde{\chi}_1^{\pm}}$ for the c.m. energy 500 GeV in Figs. 3. In Fig. 3 (a) we have $l = \mu$ and $\lambda_{233} = 0.1$ and in Fig. 3 (b) $l = \mu$ and $\lambda'_{233} = 0.15$. In Fig. 3 (c) $l = \tau$ and $\lambda'_{333} = 0.45$. It is seen in the cases (a) and (c) that with the luminosity 500 fb$^{-1}$ at least one chargino $\tilde{\chi}_1^{\pm}$ is produced if $m_{\tilde{\chi}_1^{\pm}} \lesssim 200$ GeV. Compared with the cross section of pair production of charginos and neutralinos at the lepton colliders, the results are smaller if the charginos are light. However, the single production of charginos can lower the threshold of production and can provide us with a possible way to detect heavier charginos at lepton colliders.

In order to detect the signal events, the decays of sneutrinos and charginos are of prime importance. In the following we consider the possible decay modes.

Decay of sneutrinos. We consider here two essentially different possibilities for the sneutrino decay: it may be that the LSP, in which case the $R_\mu$ decays dominate, or it may be that one or more of the neutralinos and charginos are lighter than the sneutrino.

If a sneutrino is the LSP, it will decay through $R_\mu$-violating terms. Assuming only one nonvanishing $R_\mu$ violating coupling, we can conclude from the diagrams in Fig. 1 that there are no nondiagonal decays of sneutrinos if a sneutrino has been produced. However, the decays with even small nondiagonal couplings may be experimentally important, since they induce flavor-changing decay modes and thus provide spectacular final states.

With nonzero $\lambda_{233}$ coupling, the sneutrino $\tilde{\nu}_2$ will decay to $\tau^+\tau^-$, and with nonvanishing $\lambda'_{233}$ ($\lambda'_{333}$) coupling, the sneutrino $\tilde{\nu}_2$ ($\tilde{\nu}_3$) will decay to $b\bar{b}$. If the nondiagonal $\lambda_{23i} = \lambda_{32i}$ are also nonvanishing, the decays

$$\tilde{\nu}_2 \rightarrow \tau\mu, \tau e, \tilde{\nu}_3 \rightarrow \tau\mu, \mu e$$

would be possible, or if the nondiagonal couplings $\lambda'_{23i}$ or $\lambda'_{3ij}$ exist, the decay channels

$$\tilde{\nu}_2 \rightarrow b\bar{s}, \bar{b}s, bd, \bar{b}d$$

would be open.

If one of the lightest neutralinos $\tilde{\chi}^{0}_{1,2}$ or the chargino $\tilde{\chi}^{\pm}_{1}$ are lighter than sneutrinos, then the $R_\mu$-conserving decay is also possible. The possible decay channels are as follows:

$$\tilde{\nu}_i \rightarrow \tilde{\chi}^{\pm}_{1}l^{\mp}, \tilde{\nu}_1 \rightarrow \tilde{\chi}^{0}_{1,2}\nu_i. \quad (4.1)$$

If kinematic space admits, sneutrino can also decay as follows

$$\tilde{\nu}_i \rightarrow \bar{e}lW^+. \quad (4.2)$$

In our case, with sparticle masses shown as in Table 1, only the decays in (4.1) are allowed. In Figs. 4 and 5, we show the branching ratios of the sneutrinos with parameters $\lambda_{23i}$ and $\lambda'_{33i}$ (with $\lambda'_{32i}$) dominating, respectively. (The branching ratio of sneutrinos with parameters $\lambda_{233}$ and $\lambda'_{222}$ dominating will be the same as in Fig. 5). We can see from the figures that the $R_\mu$-violating decay of sneutrinos will be important for $\lambda_{23i} = \lambda_{23} = 0.1$, and even dominate when $\lambda'_{333}$ ($\lambda'_{322}$) = 0.45.

If it turns out that the Higgs boson mass is close to the sneutrino mass, and $m_h \lesssim 2m_W$, the sneutrino cannot be distinguished from the Higgs boson. To see this explicitly, we have plotted in Fig. 6 the $\sigma \times Br(\gamma\gamma \rightarrow h \rightarrow b\bar{b}, \tau\tau, ss)$. The cross section for the $b\bar{b}$ final state for a 100 GeV Higgs boson is more than 10 fb and for the $\tau\tau$ final state is around 0.7 fb, which are both larger
than the sneutrino production cross section. If the $h$ and $\tilde{\nu}_i$ masses are clearly different, or if the Higgs mass is above $2m_W$ (in which case it decays dominantly to a pair of gauge bosons) the situation changes, and $\tau^+\tau^-$ or $bb$ would provide good signals of $\tilde{\nu}_{2,3}$. In the case of nondiagonal decay modes there is no background from the Higgs decay. Thus, it is worth emphasizing that for similar mass sneutrinos and the Higgs boson, the sneutrino decay modes $\tilde{\nu} \rightarrow \tau \mu, \tau e, bs$ are essential in order to detect sneutrinos.

However, we need consider other decay modes if the $R_p$-violating parameters are very small. In Fig. 4, we can see that $\tilde{\nu} \rightarrow \tilde{\chi}^0_1 + \nu$ will dominate if we take $\lambda_{233} = 0.01$. In this case, we should detect $\tilde{\chi}^0_1$ with its $R_p$-violating decay. From the $\lambda$ terms, $\tilde{\chi}^0_1 \rightarrow 2l + \nu$ will dominate, and in the $\lambda'$ case, we have $\tilde{\chi}^0_1 \rightarrow 2 \text{jets} + (\nu, \text{lepton})$, as shown in Fig.7 (a).

**Decay of charginos $\tilde{\chi}^+_{1}$.** The lightest chargino can decay directly to sneutrinos or sleptons if it is heavier than the corresponding thresholds. In our case, chargino decay to the lightest neutralino and $W$ boson (real or virtual) will dominate with chargino mass below 200 GeV, as shown in Fig. 7 (b). Combined with the neutralino decay (shown in Fig. 7), the chargino $\tilde{\chi}^+_{1}$, which is produced with other lepton, could be detected at the LC with multi-lepton signals.

4. Conclusion

We have studied the single production and decay of sneutrino and the lightest chargino in $\gamma\gamma$ collisions. The cross section for the production of sneutrinos with mass below 400 GeV in the future LC experiments with c.m. energy 500 GeV is above 0.005 fb with $\lambda_{233} = 0.1$ and 0.05 fb with $\lambda'_{333} = 0.45$, allowed by experimental limits. If we cannot find any signals from the experiments, we could improve the present upper bounds on $\lambda$ and $\lambda'$ or exclude sneutrino with mass below 400 GeV.

The single production of charginos in photon colliders through $R_p$ violating couplings is observable only if sneutrino and stau are light. The nondiagonal decay channels are important for detection. The cross section for the processes are at the observable level when the chargino is lighter than 200 GeV assuming the present $R_p$-violating limits.

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Appendix

A. Loop integrals:
We adopt the definitions of two-, three-, and four-point one-loop Passarino-Veltman integral functions of reference [18][19]. The integral functions are defined as follows:

The two-point integrals are:

\[
\{B_0; B_\mu; B_{\mu\nu}\}(p, m_1, m_2) = \frac{(2\pi\mu)^{4-n}}{i\pi^2} \int d^nq \frac{\{1; q_\mu; q_{\mu\nu}\}}{[q^2 - m_1^2][(q + p)^2 - m_2^2]}, \tag{A.a.1}
\]

The function \(B_\mu\) should be proportional to \(p_\mu\):

\[
B_\mu(p, m_1, m_2) = p_\mu B_1(p, m_1, m_2) \tag{A.a.2}
\]

Similarly we get:

\[
B_{\mu\nu} = p_\mu p_\nu B_{21} + g_{\mu
u} B_{22} \tag{A.a.3}
\]

We denote \(\bar{B}_0 = B_0 - \Delta\), \(\bar{B}_1 = B_1 + \frac{1}{3}\Delta\) and \(\bar{B}_{21} = B_{21} - \frac{1}{3}\Delta\). with \(\Delta = \frac{2}{\epsilon} - \gamma + \log(4\pi)\), \(\epsilon = 4 - n\). \(\mu\) is the scale parameter. The three-point and four-point integrals can be obtained similarly.

The numerical calculation of the vector and tensor loop integral functions can be traced back to the four scalar loop integrals \(A_0, B_0, C_0\) and \(D_0\) in Ref. [18], [19] and the references therein.

B. Sparticle masses

The supersymmetric parameters which we use in our calculations are shown in the following table as well as the resulting sparticle masses:

**Table 1** We take here \(m_0 = 100\) GeV, \(A_0 = -100\) GeV, \(\tan \beta = 3\) and \(\text{sign}(\mu) = +\). The masses are given in GeV units.

| \(m_{1/2}\) | \(m_{\tilde{t}_1}\) | \(m_{\tilde{t}_2}\) | \(m_{\tilde{\tau}_2}\) | \(m_{\tilde{\rho}}\) | \(m_{\tilde{\chi}_1^0}\) | \(m_{\tilde{\chi}_1^\pm}\sim m_{\tilde{\chi}_2^0}\) |
|------|------|------|------|------|------|------|
| 200  | 515  | 179  | 163  | 78   | 140  |
| 250  | 613  | 208  | 195  | 100  | 185  |
| 260  | 633  | 214  | 201  | 105  | 194  |
| 300  | 713  | 239  | 228  | 122  | 229  |
| 350  | 815  | 271  | 261  | 144  | 273  |
| 400  | 917  | 304  | 295  | 166  | 316  |
| 450  | 1021 | 337  | 329  | 187  | 359  |
| 500  | 1125 | 371  | 364  | 208  | 402  |
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Figure 2: As a function of the mass of the produced sneutrino, the cross section of (a) $e^+e^- \rightarrow \gamma\gamma \rightarrow \tilde{\nu}_2$, where the solid line corresponds to $\lambda_{233} = 0.1$, and the dashed line to $\lambda_{233} = 0.01$, (b) $e^+e^- \rightarrow \gamma\gamma \rightarrow \tilde{\nu}_2$, where the solid line corresponds to $\lambda'_{233} = 0.15$ and dashed line to $\lambda'_{233} = 0.03$, and (c) $e^+e^- \rightarrow \gamma\gamma \rightarrow \tilde{\nu}_3$, where $\lambda'_{333} = 0.45$. 
Figure 3: As a function of the mass of the chargino $\tilde{\chi}^\pm$, the cross section of $e^+e^- \to \gamma \gamma \to \tilde{\chi}^\pm \tilde{\chi}^\mp$ at c.m. energy $E_{cm} = 500$ GeV with (a) $l = \mu$ and $\lambda_{233} = 0.1$, (b) $l = \mu$ and $\lambda'_{233} = 0.15$, and (c) $l = \tau$ and $\lambda'_{333} = 0.45$. The horizontal line corresponds to one event with 500 fb$^{-1}$. 
Figure 4: Branching ratios of sneutrino $\tilde{\nu}_2$ with (a) $\lambda_{233} = 0.1$ and with (b) $\lambda_{233} = 0.01$.

Figure 5: Branching ratios of sneutrino $\tilde{\nu}_3$ with (a) $\lambda'_{333} = \lambda'_{332} = \lambda'_{323} = 0.45$ and with (b) $\lambda'_{333} = \lambda'_{332} = \lambda'_{323} = 0.1$. 
Figure 6: As a function of the Higgs mass, $\sigma(\gamma\gamma \rightarrow h^0) \times BR(f\bar{f})$, where $f = b, \tau$ or $s$, as denoted in the figure.

Figure 7: (a) Branching ratio of neutralino $\tilde{\chi}_1^0$ via $\lambda'$ terms. (b) Branching ratio of chargino $\tilde{\chi}_1^\pm$, with $\lambda'_{333} = \lambda'_{322} = 0.45$. 