Lepton flavor-changing processes in R-parity violating MSSM: Z —> l(i) anti-l(j) and gamma gamma —> l(i) anti-l(j) under new bounds from l(i) —> l(j) gamma postprint

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Lepton Flavor-Changing Processes in R-Parity Violating MSSM: Z → _ī_j and $\gamma\gamma$ → _ī_j under New Bounds from $\ell_i \to \ell_j\gamma$

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Abstract

We examine lepton flavor-changing processes in R-parity violating MSSM. First, we update constraints on relevant R-violating couplings using the latest data on rare decays $\ell_i \to \ell_j\gamma$. Then we calculate the processes Z → _ī_j and $\gamma\gamma$ → _ī_j. We find that the updated constraints are much stronger than previous ones. Even with these updated constraints, R-violating couplings can still enhance the rates of these processes to reach the sensitivity of GigaZ and photon-photon collision options at the ILC.

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Introduction

The Minimal Supersymmetric Standard Model (MSSM) is a popular extension of the Standard Model (SM). In this model, R-parity invariance, defined by R = (-1)^{2S+3B+L} for a field with spin S, baryon number B, and lepton number L, is often imposed on the Lagrangian to maintain separate conservation of baryon and lepton numbers. Although R-parity plays a crucial role in MSSM phenomenology (e.g., forbidding proton decay and providing a dark matter candidate), it is not required by any fundamental principle such as gauge invariance, and there is no compelling theoretical motivation for it. The most general MSSM superpotential consistent with SM gauge symmetry and supersymmetry contains R-violating interactions [1]:

$$\mathcal{W}_R = \lambda_{ijk} L_i L_j E^c_k + \lambda'_{ijk} L_i Q_j D^c_k + \lambda''_{ijk} \epsilon_{abd} U^c_a U^c_b D^c_d + \mu_i L_i H_2$$

where i, j, k are generation indices, c denotes charge conjugation, a, b, d are color indices with ϵ{abd} *being the totally antisymmetric tensor,* H_2 *is the Higgs doublet chiral superfield, and* L_i*(*Q_i*) and* E_i*(*U_i*,* D_i*) are the left-handed lepton (quark) doublet and right-handed lepton (quark) singlet chiral superfields. The dimensionless coefficients* λ{ijk} (antisymmetric in i and j) and λ' *{ijk} are L-violating couplings, while* λ'' {ijk} (antisymmetric in j and k) are B-violating couplings. The phenomenology of R-parity breaking supersymmetry has been intensively studied in various processes [2, 3], yielding constraints on these couplings [4].

Lepton flavor-changing (LFC) processes, searched for in various experiments [5-7], provide sensitive probes of new physics because they are extremely suppressed in the SM but can be greatly enhanced in new physics models like supersymmetry [8]. In R-parity breaking supersymmetry, these rare processes may receive large enhancements since both λ and λ' couplings can contribute. Such enhancements have been considered in decays $\ell_i \to \ell_j\gamma$ [9], μ-e conversion in nuclei [10], dilepton productions p̄p/pp → $\mathrm{e}^{\pm\mu}$ + X [11], $\mathrm{e}^{+\mathrm{e}}$- → _ī_j [12], and Z → $\mathrm{e}^{\pm\mu}$ [13].

Since GigaZ and photon-photon collision options at the ILC can precisely measure LFC processes Z → _ī_j and $\gamma\gamma$ → _ī_j (i ≠ j and ℓ_i = e, μ, τ), we study these processes in R-violating MSSM. Noting that experimental upper bounds on LFC τ decays have become more stringent recently [6], we first update constraints on relevant R-violating couplings from latest measurements of $\ell_i \to \ell_j\gamma$. Then, using these updated bounds, we calculate Z → _ī_j and $\gamma\gamma$ → _ī_j to determine if they can reach the sensitivity of GigaZ and ILC photon-photon collision options.

The paper is organized as follows. Section II describes calculations for Z → _ī_j and $\gamma\gamma$ → _ī_j. Section III presents numerical results and discussions. Finally, Section IV draws conclusions.

II. Calculations

In four-component Dirac notation, the L-violating interaction Lagrangian is (using λ' _{ijk} as an example):

$$\mathcal{L}_{\lambda'} = \lambda'_{ijk}\left[(\tilde{d}_{kR})^*(\nu_{iL})^c d_{jL} + (\tilde{d}_{kR})^*(\ell_{iL})^c u_{jL}\right] + \text{h.c.}$$

LFC interactions _ī_jV (V = γ, Z) are induced at loop level by exchanging squarks $\tilde{u}$_j or $\tilde{d}$_kR, as shown in Fig. 1.

For decays $\ell_i \to \ell_j\gamma$, we take $\mu \to$ eγ as an example. The gauge-invariant amplitude is:

$$\mathcal{M}(\mu \to e\gamma) = 2A\bar{u}(p_e)P_R(2\epsilon \cdot p_\mu - \not{\epsilon}\not{p}_\mu)u(p_\mu)$$

where A is given by (assuming degenerate squark masses):

$$A = \frac{ie\lambda'_{1jk}\lambda'_{2jk}}{16\pi^2}\left[f_1(x) + f_2(x)\right]$$

with

$$\begin{aligned} f_1(x) &= \frac{2x^2 + 5x - 1}{6(x-1)^3} - \frac{x^2 \ln x}{(x-1)^4} \\ f_2(x) &= \frac{x^2 - 5x - 2}{6(x-1)^3} + \frac{x \ln x}{(x-1)^4} \end{aligned}$$

where x = m_{$\tilde{q}$}$^{2/\mathrm{m_q}}$2.

The branching ratio is:

$$\mathrm{Br}(\mu \to e\gamma) = \frac{48\pi^3\alpha}{G_F^2 m_\mu^2}|A|^2$$

For Z → _ī_j decays, we calculate rates numerically using the effective vertex from Appendix A. According to the effective vertex method [14], external legs can be on-shell or off-shell, making the vertex applicable to any relevant process. Equations (3)-(6) can be obtained from the Appendix A vertex with both leptons on-shell.

For $\gamma\gamma$ → _ī_j, besides Figs. 2(a,b) induced by the Appendix A vertex, additional diagrams in Figs. 2(c-i) contribute. Their amplitude expressions are given in Appendix B. These amplitudes contain Passarino-Veltman one-loop functions calculated using LoopTools [26]. We verified gauge invariance and ultraviolet cancellation.

Since photon beams in $\gamma\gamma$ collisions are generated by backward Compton scattering of incident electrons and laser beams, event rates are obtained by convolving the $\gamma\gamma$ collision cross section with the photon beam luminosity distribution:

$$\sigma_{e^+e^- \to \ell_i \ell_j} = \int d\sqrt{s_{\gamma\gamma}} \frac{d\mathcal{L}_{\gamma\gamma}}{d\sqrt{s_{\gamma\gamma}}} \sigma_{\gamma\gamma \to \ell_i \ell_j}(s_{\gamma\gamma}) \equiv L_{e^+e^-} \hat{\sigma}_{\gamma\gamma \to \ell_i \ell_j}(s)$$

where d$\mathcal{L}$*{γγ}/d*$\sqrt{s_{\gamma\gamma}}$ *is the photon-beam luminosity distribution and* σ{γγ → _ī_j} is the $\gamma\gamma$ → _ī_j cross section. In the optimum case [15]:

$$\hat{\sigma}_{\gamma\gamma \to \ell_i \ell_j}(s) = \int_{2m_\ell/\sqrt{s}}^{x_{\max}} dz\, 2z \hat{\sigma}_{\gamma\gamma \to \ell_i \ell_j}(s_{\gamma\gamma} = z^2 s) \int_{z^2/x_{\max}}^{x_{\max}} \frac{dx}{x} F_{\gamma/e}(x) F_{\gamma/e}(z^2/x)$$

where F_{γ/e} is the back-scattered photon energy spectrum for unpolarized initial electron and laser beams:

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

with

$$D(\xi) = \left(1 - \frac{4}{\xi} - \frac{8}{\xi^2}\right)\ln(1+\xi) + \frac{1}{2} + \frac{8}{\xi} - \frac{1}{2(1+\xi)^2}$$

Here ξ = 4E_eE_0/m_e^2 (E_e is incident electron energy and E_0 is initial laser photon energy) and x = E/E_0 with E being the scattered photon energy along the initial electron direction.

III. Numerical Results and Discussions

We use SM parameters [16]: m_μ = 0.106 GeV, m_τ = 1.777 GeV, m_b = 4.2 GeV, α = 1/137, sin^2θ_W = 0.223. The top quark mass is taken as the CDF value m_t = 172.3 GeV [17]. Relevant SUSY parameters are squark masses and R-parity violating couplings listed in Table I.

The strongest squark mass bound comes from Tevatron. For example, in R-conserving minimal supergravity with $A_0 = 0$, $\mu < 0$, tanβ = 5, CDF gives a 392 GeV bound at 95% C.L. for degenerate gluinos and squarks [18]. However, this bound may not apply to R-violating scenarios because SUSY signals differ significantly. The most robust bounds come from LEP, giving m_{$\tilde{q}$,$\tilde{\ell}$} 100 GeV [19]. We assume minimal R-violating couplings: for each process, only the two relevant couplings (not summed over family indices) are present.

Latest $\ell_i \to \ell_j\gamma$ data [7] are: Br($\mu \to$ eγ) < 1.2 × 10^{-11} Br($\tau \to$ eγ) < 1.1 × 10^{-11} Br($\tau \to \mu\gamma$) < 4.5 × 10^{-11}

We use these to update L-violating coupling bounds. Table I compares new and old bounds for m_{$\tilde{q}$} = 100 GeV (heavier squarks weaken the bounds). The new bounds are much stronger. Since λ' *{i33}*λ' {j33} bounds are weakest, we focus on these in our numerical calculations.

Neutrino masses could also constrain λ' couplings, especially λ' _{i33} [20], but these depend on additional parameters like squark mixings and slepton masses. With small mixings and appropriate signs, cancellations between one- and two-loop effects can avoid these constraints. Since our focus is LFC process sensitivity to λ' couplings, which is independent of these additional parameters, we do not include neutrino mass constraints.

TABLE I: Upper bounds on L-violating couplings for m_{$\tilde{q}$} = 100 GeV from $\ell_i \to \ell_j\gamma$ data [7], compared with previous bounds [4].

[Table content would be inserted here]

LEP limits on Z → _ī_j are [21, 22]: Br(Z → eμ) < 1.7 × 10^{-6} Br(Z → eτ) < 9.8 × 10^{-6} Br(Z → $\mu\tau$) < 1.2 × 10^{-5}

These LEP bounds are compared with $\ell_i \to \ell_j\gamma$ bounds in Fig. 3. The Z-decay coupling bounds are weaker than radiative decay bounds. LEP Z-decay bounds were also studied in [10]; our results are consistent.

FIG. 3 [Figure 3: see original paper]: L-violating coupling bounds versus squark mass. Solid, dashed, and dotted curves show bounds on λ‘*{133}*λ’ {233}, λ’ *{133}*λ ‘{333}, and λ’ *{233}*λ’ {333}. Also shown are 2σ sensitivity from Z decays at GigaZ and 3σ sensitivity from $\gamma\gamma$ collisions at √s = 500 GeV with luminosity 3.45 × 10^2 fb^{-1}. For e(μ)-τ final states at ILC, the sum over k is implied for λ’ *{i3k}*λ’ {j3k} with m_{$\tilde{q}$} = 200 GeV.

GigaZ sensitivity to LFC Z decays could reach [23] with $\kappa = 0.2$–1.0. Fig. 3 uses $\kappa = 1.0$. Unlike the R-conserving case where only Z → $\mu\tau$ is accessible at GigaZ [8], R-violating couplings allowed by $\ell_i \to \ell_j\gamma$ can enhance all _ī*j channels to GigaZ sensitivity. Thus GigaZ can strengthen bounds on* λ’ {i33}λ’ _{j33} if no signal is observed. These bounds depend only on squark mass, unlike neutrino mass constraints.

For $\gamma\gamma$ collisions in Fig. 3, we fix $\xi = 4.8$, D(ξ) = 1.83, x_max = 0.83 [15]. Since couplings relevant to $\gamma\gamma \to$ _ī_j are tightly constrained by $\mu \to e\gamma$, we only show channels with final-state taus: $\gamma\gamma \to e\bar{\tau}$, $\mu\bar{\tau}$. Backgrounds from $\gamma\gamma \to \tau^{+\tau}$- are reduced by cuts [13]: |cosθ_ | < 0.9 and $p_T^\ell > 20$ GeV (= e, μ). With these cuts, backgrounds from $\gamma\gamma \to \tau^{\text{-}\nu e\bar{\nu}\tau e}$+, $\gamma\gamma \to$ W^{+W}- → e^{+e}-$\tau^{+\tau}$-, and $\gamma\gamma \to$ e^{+e}-$\tau^{+\tau}$- at √s = 500 GeV are suppressed to 9.7 fb, 1.0 fb, and 2.4 fb, respectively (see Table I of [13]). For 3σ observation with 3.45 × 10^2 fb^{-1} integrated luminosity [24], $\gamma\gamma \to e\bar{\tau}$, $\mu\bar{\tau}$ rates after cuts must exceed 2.5 fb [13]. Fig. 3 shows that current $\ell_i \to \ell_j\gamma$ bounds still allow large enough couplings to enhance $\gamma\gamma \to e\bar{\tau}$, $\mu\bar{\tau}$ to 3σ sensitivity.

Figure 4 shows $\gamma\gamma \to$ _ī_j cross sections versus ILC center-of-mass energy √s. Cross sections decrease with increasing energy, similar to R-conserving MSSM results [13].

LFC processes also constrain λ‘*{i31}*λ’ {j31} and λ’ *{i32}*λ’ {j32}, with bounds similar to those in Fig. 3. These bounds from Z → _ī_j at GigaZ are generally stronger than neutrino mass constraints [20].

IV. Conclusion

We evaluated lepton flavor-changing processes in R-parity violating MSSM. Using latest $\ell_i \to \ell_j\gamma$ data, we updated constraints on relevant R-violating couplings. We then calculated Z → _ī_j and $\gamma\gamma \to$ _ī_j processes. Despite stronger updated constraints, R-violating couplings can still enhance these processes to reach GigaZ and ILC photon-photon collision sensitivity. Thus GigaZ and ILC photon-photon collisions can either observe these λ ‘-induced LFC processes or further strengthen λ’ coupling bounds in case of non-observation.

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Appendix A: Effective Vertex γ(Z) Expressions

We list L-violating contributions to the effective vertex γ(Z)-ℓ_i-ℓ_j. Other vertices are similar with appropriate momentum and mass replacements. The γ(Z)-e-μ vertex is:

$$\Gamma_{\gamma(Z)e\mu} = \Gamma^{\tilde{u}_L}_{\gamma(Z)e\mu} + \Gamma^{\tilde{d}_R}_{\gamma(Z)e\mu}$$

where the terms denote L-violating loop contributions from exchanging squarks $\tilde{u}^j_L$ and $\tilde{d}^k_R$.

[The original text contains severely corrupted LaTeX for the full vertex expressions. The amplitude would be expressed in terms of Passarino-Veltman functions B_i and C_i with proper Dirac matrix structure and projection operators.]

Appendix B: $\gamma\gamma \to$ _ī_j Amplitude Expressions

Amplitudes for diagrams in Fig. 2(a-i) are given by expressions involving Passarino-Veltman functions D_i. The general structure includes contributions from effective vertices and box diagrams, with proper gauge invariance and UV cancellation verified.

[The original text contains severely corrupted LaTeX for the full amplitude expressions. The complete formulas would involve loop functions D_1 through D_6 with appropriate momentum routing and spinor contractions.]

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