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Abstract

We briefly review lepton flavor violating Z decays at GigaZ as a probe of supersymmetry, focusing on Z → l_i l_j in two representative supersymmetric models: the minimal supersymmetric model without R-parity and the supersymmetric seesaw model. We conclude that under current experimental constraints from LEP and l_i → l_j , these rare decays can still be enhanced to reach the sensitivity of GigaZ. Therefore, supersymmetry can be probed via these decays at GigaZ.

Full Text

Preamble

Lepton Flavor Violating Z-boson Decays at GigaZ as a Probe of Supersymmetry

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Abstract

We briefly review the potential of lepton flavor violating Z-decays at GigaZ to probe supersymmetry, focusing on $Z \to \ell_i \ell_j$ in two representative supersymmetric models: the minimal supersymmetric model without R-parity and the supersymmetric seesaw model. We conclude that under current experimental constraints from LEP and $\ell_i \to \ell_j \gamma$, these rare decays can still be enhanced to reach the sensitivity of GigaZ. Therefore, supersymmetry can be probed via these decays at GigaZ.

Keywords: Z-decay, GigaZ, supersymmetry
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Introduction

The primary task of particle physics in the current Large Hadron Collider (LHC) era is to probe new physics beyond the Standard Model. While the LHC is a powerful discovery machine due to its high energy, it is not ideal for precision tests of theories because of its substantial QCD background. If new physics appears at the TeV scale, as speculated and expected by most theorists, the LHC will undoubtedly unveil it, and the proposed International Linear Collider (ILC) will then take on the task of performing precision tests of such new physics.

At the ILC, the GigaZ option is expected to produce more than 10^9 Z-bosons [**?**] and will play an important role in probing new physics related to the Z-boson. One sensitive probe is through flavor-changing neutral-current (FCNC) Z-boson decays $Z \to \ell_i \bar{\ell}_j$, which are suppressed to unobservably small levels in the Standard Model (SM) but could be greatly enhanced in new physics models such as supersymmetry [**?**].

In this review, we recapitulate studies on the decays $Z \to \ell_i \bar{\ell}_j$ in the R-parity violating minimal supersymmetric model (RPV-MSSM) [**?**, **?**] and the supersymmetric seesaw model [**?**]. In Section II we delineate the study in RPV-MSSM, in Section III we elucidate the study in the supersymmetric seesaw model, and finally a summary is given in Section IV.

II. Lepton Flavor Violating Z-Decay in RPV-MSSM

In the MSSM, the R-violating interactions are given by

$$W_{\not R} = \lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_k^c + \frac{1}{2}\epsilon_{abd} U_a^c D_b^c D_d^c + \mu_i L_i H_2,$$

where i, j, k are generation indices, c denotes charge conjugation, a, b and 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. These interactions have rich phenomenology that has been studied intensively [**?**], and a list of bounds is summarized in [**?**].

Lepton flavor violating (LFV) processes, which are extremely suppressed in the SM, may be greatly enhanced by these R-violating interactions since both λ and λ' couplings can contribute. Such R-violating effects in the decays $Z \to \ell_i \bar{\ell}_j$ and $\ell_i \to \ell_j \gamma$ were studied in [**?**, **?**, **?**]. Taking the presence of λ'_{ijk} as an example, the LFV interactions $\ell_i \bar{\ell}_j V$ $(V = \gamma, Z)$ can be induced at loop level by exchanging a squark $\tilde{u}_j$ or $\tilde{d}_k$, as shown in [Figure 1: see original paper].

The relevant constraints come from $\ell_i \to \ell_j \gamma$ [**?**]:

$$\text{BR}(\mu \to e\gamma) < 1.2\times10^{-11}, \quad \text{BR}(\tau \to e\gamma) < 1.1\times10^{-7}, \quad \text{BR}(\tau \to \mu\gamma) < 4.5\times10^{-8},$$

and the LEP bounds on $Z \to \ell_i \bar{\ell}_j$ [**?**]:

$$\text{BR}(Z \to \mu e) < 1.7\times10^{-6}, \quad \text{BR}(Z \to \tau e) < 9.8\times10^{-6}, \quad \text{BR}(Z \to \tau\mu) < 1.2\times10^{-5}.$$

The possible sensitivity of GigaZ to LFV decays of the Z-boson could reach [?]:

$$\mathrm{BR}(Z \to \mu e) \sim 2.0{\times}10^{-9}, \quad \mathrm{BR}(Z \to \tau e) \sim \kappa{\times}6.5{\times}10^{-8}, \quad \mathrm{BR}(Z \to \tau\mu) \sim \kappa{\times}2.2{\times}10^{-8},$$

with the factor κ ranging from 0.2 to 1.0. In [Figure 2: see original paper] we take $\kappa = 1.0$ to show the sensitivity of GigaZ in RPV-MSSM compared with the bounds from $\ell_i \to \ell_j\gamma$ and the Z-decays at LEP. We see that under current experimental constraints, the LFV Z-decays can still be enhanced to the sensitivity of GigaZ. This implies that GigaZ can further strengthen the bounds on the relevant R-violating couplings in case of non-observation.

III. Lepton Flavor Violating Z-Decays in Supersymmetric Seesaw Model

The seesaw mechanism [?] can be realized in supersymmetric models by introducing right-handed neutrino superfields with heavy Majorana masses [?]. In such a framework, the flavor diagonality of sleptons is usually assumed at the Planck scale, but flavor mixings at the weak scale are inevitably generated through renormalization group equations since there is no symmetry to protect flavor diagonality. Such flavor mixings of sleptons generated at the weak scale are proportional to neutrino Yukawa couplings, which may be as large as the top quark Yukawa coupling due to the seesaw mechanism, and are enhanced by a large factor $\log(M_P^2/M^2)$ (where M_P is the Planck scale and M is the neutrino Majorana mass). Therefore, the popular mSUGRA with seesaw mechanism predicts large flavor mixings of sleptons at the weak scale.

With the right-handed neutrino superfields ν_R, the superpotential contains the terms

$$W_\nu = -\frac{1}{2}\nu_R^c M \nu_R^c + \nu_R^c y_\nu L \cdot H_2,$$

where M and y_ν are matrices in flavor space, L and H_2 denote the left-handed lepton doublet and the Higgs doublet with hypercharge -1 and $+1$, respectively. The mass matrix of the charged sleptons is given by

$$\mathcal{M}_{\tilde{\ell}}^2 = \begin{pmatrix} \mathcal{M}_{LL}^2 & \mathcal{M}_{LR}^2 \\ \mathcal{M}_{LR}^{2\dagger} & \mathcal{M}_{RR}^2 \end{pmatrix},$$

where

$$\mathcal{M}_{LL}^2 = m_{\tilde{L}}^2 + m_\ell^2 + m_Z^2 \cos 2\beta \left(-\frac{1}{2} + \sin^2\theta_W\right)\mathbf{1},$$

$$\mathcal{M}_{RR}^2 = m_{\tilde{R}}^2 + m_\ell^2 - m_Z^2 \cos 2\beta \sin^2\theta_W \mathbf{1},$$

$$\mathcal{M}_{LR}^2 = A_\ell v \cos\beta - m_\ell \mu \tan\beta,$$

with $\mathbf{1}$ being the unit 3×3 matrix in generation space.

Since the right-handed sneutrinos have masses as large as the heavy Majorana neutrinos, their contributions to LFV processes can be ignored. Thus, only the left-handed sneutrinos need to be taken into account, whose mass matrix is given by

$$\mathcal{M}_{\tilde{\nu}}^2 = m_{\tilde{L}}^2 + \frac{1}{2} m_Z^2 \cos 2\beta \mathbf{1}.$$

We assume universal soft-breaking parameters at the Planck scale: $m_{\tilde{L}} = m_{\tilde{R}} = m_0 \mathbf{1}$, $A_\ell = A_0 y_\ell$, $A_\nu = A_0 y_\nu$. Since y_ℓ and y_ν cannot be diagonalized simultaneously in general, it is usually assumed that y_ℓ is flavor diagonal but y_ν is not. In this basis the mass matrix of the charged sleptons is flavor diagonal at the Planck scale. However, when evolving down through renormalization equations to the weak scale, such flavor diagonality is broken:

$$\delta(m_{\tilde{L}}^2)_{IJ} \simeq -\frac{1}{8\pi^2}(3m_0^2 + A_0^2)(y_\nu^\dagger y_\nu)_{IJ} \ln \frac{M_P}{M},$$

$$\delta(m_{\tilde{R}}^2)_{IJ} \simeq 0, \quad \delta(A_\ell)_{IJ} \simeq -\frac{3}{16\pi^2} A_0 (y_\ell^\dagger y_\nu)_{IJ} \ln \frac{M_P}{M},$$

where $y_0 \equiv y(M_P)$. Therefore, both the charged sleptons and the left-handed sneutrinos have mixings in flavor space. The flavor mixing of the charged sleptons induces the FCNC couplings $\tilde{\chi}^0 \ell_I \tilde{\ell}_J$ and $Z \tilde{\ell}_I \tilde{\ell}_J$, while the flavor mixing of left-handed sneutrinos induces the charged-current flavor-changing couplings $\tilde{\chi}^\pm \ell_I \tilde{\nu}_J$. These flavor-changing couplings contribute to the FCNC Z-decays $Z \to \ell_i \bar{\ell}_j$, as shown in [Figure 3: see original paper].

With constraints from current neutrino oscillation experiments and introducing two right-handed neutrinos with masses $M_1 = 10^{13}$ GeV and $M_2 \simeq 10^{15}$ GeV, the branching ratios of $Z \to \ell_i \bar{\ell}_j$ and $\ell_i \to \ell_j \gamma$ versus the common scalar mass m_0 are shown in [Figure 4: see original paper]. We see that the branching ratio of $Z \to \tau\mu$ can reach 10^{-8} in the supersymmetric seesaw model. With the current upper bound $\mathrm{BR}(\tau \to \mu\gamma) < 4.5 \times 10^{-8}$ shown in Eq. (4), $Z \to \tau\mu$ with a branching ratio $\sim 10^{-8}$ is allowed. Since the GigaZ sensitivity for $Z \to \tau\mu$ is at 10^{-8}, as shown in Eq. (10), $Z \to \tau\mu$ may be accessible at GigaZ and thus may serve as a probe of the supersymmetric seesaw model.

Note that while the above lepton flavor violating Z-decays serve as a clean probe of new physics at GigaZ, the FCNC decay modes into quarks such as $Z \to b\bar{s}$ may also be sensitive to new physics. In the SM, $Z \to b\bar{s}$ has a branching ratio of $\sim 10^{-8}$ [**?**], which could be greatly enhanced in new physics models [**?**].

IV. Conclusion

From our study of lepton flavor violating Z-decays $Z \to \ell_i \ell_j$ in the R-parity violating minimal supersymmetric model and the supersymmetric seesaw model, we conclude that under current experimental constraints from LEP and $\ell_i \to \ell_j \gamma$, these decays can reach the sensitivity of GigaZ. Therefore, supersymmetric models can be probed via these decays at GigaZ.

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[1] J. A. Aguilar-Saavedra, et al., hep-ph/0106315.
[2] J. Cao, L. Wu, J. M. Yang, Nucl. Phys. B 829, 370 (2010).
[3] M. A. Mughal, M. Sadiq and K. Ahmed, Phys. Lett. B 417, 87 (1998);
[4] J. Cao, Z. Xiong, J. M. Yang, Eur. Phys. Jour. C 32, 245 (2004);
[5] J. Hisano, T. Moroi, K.Tobe, M. Yamaguchi, Phys. Lett. B 357, 579 (1995); Phys. Rev. D 53, 2442 (1996); Phys. Lett. B 391, 341 (1997); M. Frank and H. Hamidian, Phys. Rev. D 54, 6790 (1996); J. Hisano, et al., Phys. Rev. D 58, 116010 (1998); J. Hisano, D. Nomura, T. Yanagida Phys. Lett. B 437, 351 (1998); J. Hisano, D. Nomura, Phys. Rev. D 59, 116005 (1999); G.K. Leontaros, N.D. Ttracas,Phys. Lett. B 431, 90 (1998); W. Buchmuller, D. Delepine, F. Vissani, Phys. Lett. B 459, 171 (1999); J. Cao, et al., Phys. Rev. D 59, 095001 (1999); S. F. King, M. Oliveira, Phys. Rev. D 60, 035003 (1999); J. Ellis, et al., Eur. Phys. Jour. C 14, 319 (2000); J. L. Feng, Y. Nir, Y. Shadmi, Phys. Rev. D 61, 113005 (2000); W. Buchmuller, D. Delepine, L.T. Handoko, Nucl. Phys. B 576, 445 (2000); J. Sato, K. Tobe, Phys. Rev. D 63, 116010 (2001); J. Sato, K. Tobe, T. Yanagita,Phys. Lett. B 498, 189 (2001); J. A. Casas, A. Ibarra, Nucl. Phys. B 618, 171 (2001); D. F. Carvalho, M.E. Gomez, S. Khalil, JHEP 0107, 001 (2001); J. I. Illana, T. Riemann, Phys. Rev. D 63, 053004 (2001); D. F. Carvalho, M. E. Gomez, J. C. Romao, Phys. Rev. D 65, 093013 (2002); D. Atwood, et al., Phys. Rev. D 66, 093005 (2002); J. I. Illana, M. Masip, Phys. Rev. D 67, 035004 (2003). A. Gemintern, et al., Phys. Rev. D 67, 115012 (2003); M. C. Chen, K. T. Mahanthappa Phys. Rev. D 70, 113013 (2004); E. Arganda, M. J. Herrero, Phys. Rev. D 73, 055003(2006)
[6] See, e.g., V. Barger, G. F. Giudice and T. Han, Phys. Rev. D 40, 2978 (1989); K. Agashe, M. Graesser, Phys. Rev. D 54, 4445 (1996); F. Zwirner, Phys. Lett. B 132, 103 (1983); R. N. Mohapatra, Phys. Rev. D 34, 3457 (1986); M. Hirsch, H. Kleingrothaus, S. G. Kovalenko, Phys. Rev. Lett. 75, 17 (1995); K. S. Babu, R. N. Mohapatra, Phys. Rev. Lett. 75, 2276 (1995); D. E. Kaplan, hep-ph/9703347; J. Jang, J. K. Kim, J. S. Lee, Phys. Rev. D 55, 7296 (1997); G. Bhattacharyya, A. Raychaudhuri,Phys. Rev. D 57, 3837 (1998); J. M. Yang, B.-L. Young, X. Zhang, Phys. Rev. D 58, 055001 (1998); J. M. Yang, Eur. Phys. Jour. C 20, 553 (2001); D. Atwood, et al., Phys. Rev. D 66, 093005 (2002); G. Eilam, et al., Phys. Lett. B 510, 227 (2001); G. Bhattacharyya, J. Ellis, K. Sridhar, Mod. Phys. Lett. A 10, 1583 (1995); Z. Heng et al., Phys. Rev. D 79, 094029 (2009); J. Erler, J. L. Feng, N. Polonsky, Phys. Rev. Lett. 78, 3063 (1997); A. Datta, et al., Phys. Rev. D 56, 3107 (1997); R. J. Oakes et al., Phys. Rev. D 57, 534 (1998); M. Chemtob and G. Moreau, Phys. Rev. D 59, 116012 (1999); P. Chiappetta et al., Phys. Rev. D 61, 115008 (2000); J. L. Feng, J. F. Gunion, T. Han, Phys. Rev. D 58, 071701 (1998); S. Bar-Shalom, G. Eilam, A. Soni,Phys. Rev. Lett. 80, 4629 (1998); Phys. Rev. D 59, 055012 (1999); B.C. Allanach et al., Phys. Lett. B 420, 307 (1998); E. Perez, Y. Sirois, H. Dreiner,

hep-ph/9703444; K. Hikasa, J. M. Yang, B.-L. Young, Phys. Rev. D 60, 114041 (1999); P. Li et al., Eur. Phys. Jour. C 51, 163 (2007); K. J. Abraham et al., Phys. Rev. D 63, 034011 (2001); Phys. Lett. B 514, 72 (2001). A. Belyaev et al., JHEP 0409, 012 (2004); J. Cao et al., arXiv:0812.1698 [hep-ph].
[7] For a review of current bounds, see, e.g., M. Chemtob, Prog. Part. Nucl. Phys. 54, 71 (2005); R. Barbier et al., Phys. Rept. 420, 1 (2005).
[8] M. Chaichian and K. Huitu, Phys. Lett. B 384, 157 (1996).
[9] M. Ahmed et al. [MEGA Collaboration], Phys. Rev. D 65, 112002 (2002); K. Abe et al. [Belle Collaboration], Phys. Rev. Lett. 92, 171802 (2004).
[10] R. Akers et al. [OPAL Collaboration], Z. Phys. C 67, 555 (1995); P. Abreu et al. [DELPHI Collaboration], Z. Phys. C 73, 243 (1997).
[11] G. Wilson, talks at DESY-ECFA LC Workshops in Frascati, 1998 and Oxford, 1999
[12] T. Yanagida, Prog. Theor. Phys. 64, 1103 (1980), R.N. Mohapatra and G. Senjanovic, Phys. Rev. Lett. 44 (1980) 912.
[13] J. Hisano, T. Moroi, K. Tobe and M. Yamaguchi, Phys. Lett. B357 (1995) 579, Phys. Lett. B391 (1997) 341; Phys. Rev. D53 (1996) 2442; J. Hisano and D. Nomura, Phys. Rev. D59 (1999) 116005; J. Hisano et. al., Phys. Rev. D58 (1998) 116010; J. Hisano, D. Nomura, and T. Yanagida, Phys. Lett. B437 (1998) 351. J.A. Casas and A. Ibarra, Nucl. Phys. B618 (2001)
[14] G. Eilam, Nucl. Phys. Proc. Suppl. 116, 306 (2003); M. Clements, et al., Phys. Rev. D 27, 570 (1983); V. Ganapathi, et al., PRD27, 579 (1983); W. S. Hou, et al., Phys. Rev. Lett. 57, 1406 (1986); J. Bernaben, et al., Phys. Rev. Lett. 57, 1514 (1986).
[15] C. Busch, Nucl. Phys. B 319, 15 (1989); W. S. Hou and R. G. Stuart, Phys. Lett. B 226, 122 (1989); B. Grzadkowski, J. F. Gunion and P. Krawczyk, Phys. Lett. B 268, 106 (1991); B. Mukhopadhyaya and A. Raychaudhuri, Phys. Rev. D 39, 280 (1989); M. J. Duncan, Phys. Rev. D 31, 1139 (1985); F. Gabbiani, J. H. Kim and A. Masiero, Phys. Lett. B 214, 398 (1988); M. Chemtob and G. Moreau, Phys. Rev. D 59, 116012 (1999); W. Buchm, M. Gronau, Phys. Lett. B 220, 641 (1989); G. T. Park and T. K. Kuo, Phys. Rev. D 42, 3879 (1990); M. A. Perez and M. A. Soriano, Phys. Rev. D 46, 284 (1992); J Roldan, F. J. Botella and J. Vidal, Phys. Lett. B 283, 389 (1992); X. L. Wang, G. R. Lu and Z. J. Xiao, Phys. Rev. D 51, 4992 (1995); C. X. Yue, H. Li, H. Zong, Nucl. Phys. B 650, 290 (2003); R. Mohanta, Phys. Rev. D 71, 114013 (2005); X.-F. Han, L. Wang, J. M. Yang, Phys. Rev. D 78, 075017 (2008).

Note: Figure translations are in progress. See original paper for figures.