Published by Institute of Physics Publishing for SISSA

Received: *February 23, 2006*
Revised: *June 27, 2006*
Accepted: *July 26, 2006*
Published: *August 23, 2006*

Generation mixing of sneutrinos in heavier chargino decay

Midori Obara

Institute of High Energy Physics, Chinese Academy of Sciences
P.O. Box 918, Beijing 100049, China
E-mail: midori@mail.ihep.ac.cn

Noriyuki Oshimo

Department of Physics, Ochanomizu University
Tokyo, 112-8610, Japan
E-mail: oshimo@phys.ocha.ac.jp

Abstract: The heavier chargino decay could yield two charged leptons of different generations, owing to generation mixing of sneutrinos. We discuss the possibility of producing e and μ through this process in near future collider experiments. The analyses are made systematically in the supersymmetric extension of the standard model without assuming a specific scenario for the mixing. Production of the heavier chargino is evaluated in e^+e^- collisions. In the parameter region consistent with nonobservation of the radiative μ decay, sizable parts lead to a detectable branching ratio for the generation-changing decay of the heavier chargino.

Keywords: Supersymmetric Standard Model, Supersymmetry Phenomenology.

Contents

1. Introduction

The mixing of generations for quarks or leptons is one of the topics which have been studied actively in particle physics. Examining various phenomena experimentally, generation-changing interactions for the quarks are now understood rather well. On the other hand, there were before few phenomena available for investigating the lepton generation mixing. However, neutrino oscillations, which were controversial until recently, are now established [1], providing information on generation-changing interactions for the leptons. We have now data on the mixings of both quarks and leptons, which can help us to understand underlying theories predicting the generation mixings.

The generation mixing may also be observed for squarks and sleptons whose existence is predicted by the supersymmetric extension of the standard model. Through loop contributions such mixings could indirectly affect various processes, which have been already studied extensively [2]. For instance, it is known that the masses of the squarks or the sleptons with the same weak isospin must be almost degenerate, unless the mixing is suppressed. If the squarks and sleptons are detected in near future experiments, it will become possible to measure their generation-changing interactions directly. Then, another important clue to theories for the generation mixings can be obtained. Possible such a process worth being examined is the production of a pair of charged leptons belonging to different generations in e^+e^- collisions, which is induced by the slepton generation mixing. In particular, a pair of τ and μ or a pair of τ and e could be produced at detectable rates [3, 4].

In this paper, we study the generation-changing process producing a pair of e and μ by the heavier chargino decay, which is due to the sneutrino generation mixing. Without assuming a specific scenario for the generation mixing, we explore parameter space searching for the region which leads to a detectable decay rate. In order to estimate the heavier chargino production, the cross section is evaluated for the process in which a pair of different charginos are created in e^+e^- annihilation. Differently from the other charged lepton pairs, the possibility of detecting e and μ has not been discussed much in the literature, since nonobservation of the radiative decay $\mu \to e\gamma$ may imply a small production rate. Furthermore, the previous analyses were made under certain scenarios for the generation mixings, except for the work by Porod and Majerotto [4]. By model-independent analyses, however, it has been shown recently in the pair production of the sneutrinos at e^+e^- colliders [5] that the sneutrino decays into charged leptons and lighter charginos could yield e and μ at a detectable rate. The same generation-changing interactions may also induce the heavier chargino decay into a lighter chargino and a pair of e and μ, which is mediated by the sneutrinos. If the sneutrinos are lighter than the heavier chargino and heavier than the lighter chargino, this decay process is composed of two successive two-body decays. The decay rate could be nonnegligible. It will be shown that the branching ratio has a detectable value in sizable regions of the parameter space consistent with the radiative μ decay. Since the heavier chargino is expected to be copiously produced at e^+e^- colliders or hadron colliders, the decay will provide a phenomenon for studying generation-changing interactions.

This paper is organized as follows. In section 2, the interactions relevant to our discussions are summarized. In section 3, we calculate the generation-changing decay width as well as the total width of the chargino. In section 4, we make numerical analyses for the branching ratio of the heavier chargino decay. The cross section of the chargino production is also computed. Some discussions are made in section 5. In appendices A and B, we give the formulae for the width of the radiative charged lepton decay and the cross section of the chargino pair production in e^+e^- annihilation, respectively.

2. Generation mixing and interactions

The interactions of charged leptons, sneutrinos, and charginos do not conserve generically the generation number. This nonconservation arises from the generation mixings in the mass matrix M_l for the charged leptons l_α and the mass-squared matrix $\tilde{M}_\nu^2$ for the sneutrinos $\tilde{\nu}_a$, with α and a being generation indices. We assume that there is no superfield for the right-handed neutrino at the electroweak energy scale. These matrices are diagonalized to give the mass eigenstates as

$$U_{lR}^\dagger M_l U_{lL} = \mathrm{diag}\left(m_{l_1}, m_{l_2}, m_{l_3}\right), \tag{2.1}$$

$$\tilde{U}_\nu^\dagger \tilde{M}_\nu^2 \tilde{U}_\nu = \mathrm{diag}\left(M_{\tilde{\nu}_1}^2, M_{\tilde{\nu}_2}^2, M_{\tilde{\nu}_3}^2\right), \tag{2.2}$$

where U_{lL}, U_{lR}, and $\tilde{U}_\nu$ stand for 3×3 unitary matrices. The masses of the charged leptons e, μ, and τ are respectively expressed as m_{l_1}, m_{l_2}, and m_{l_3}. For the parameters which describe M_l and $\tilde{M}_\nu^2$, we take the mass eigenvalues and the unitary matrices for the matrix diagonalization. The mass matrix for the charginos ω_i $(i = 1, 2)$ is given by

$$M^- = \begin{pmatrix} \tilde{m}_2 & -gv_1/\sqrt{2} \\ -gv_2/\sqrt{2} & m_H \end{pmatrix}. \tag{2.3}$$

The SU(2) gaugino mass and the Higgsino mass parameter are denoted by $\tilde{m}_2$ and m_H, respectively. The vacuum expectation values of the Higgs bosons with the hypercharges $-1/2$ and $1/2$ are respectively represented by v_1 and v_2, with $\tan\beta = v_2/v_1$. The unitary matrices which diagonalize the chargino mass matrix are expressed by C_R and C_L,

$$C_R^\dagger M^- C_L = \mathrm{diag}\,(m_{\omega_1}, m_{\omega_2})\,, \tag{2.4}$$

taking ω_2 for the heavier chargino. The interaction Lagrangian for the mass eigenstates l_α, $\tilde{\nu}_a$, and ω_i is given by

$$\mathcal{L} = i\frac{g}{\sqrt{2}}\,(V_C)_{a\alpha}\,\tilde{\nu}_a^\dagger\overline{\omega_i}\left[\sqrt{2}C_{R1i}^*\left(\frac{1-\gamma_5}{2}\right) + C_{L2i}^*\frac{m_{l_\alpha}}{\cos\beta M_W}\left(\frac{1+\gamma_5}{2}\right)\right] l_\alpha + \mathrm{H.c.}, \tag{2.5}$$

with $V_C = \tilde{U}_\nu^\dagger U_{lL}$. The generation mixing is described by the 3×3 unitary matrix V_C, which has four physical parameters. For its parameterization, we adopt the same form as the standard one for the Cabibbo-Kobayashi-Maskawa matrix,

$$V_C = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}\mathrm{e}^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}\mathrm{e}^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}\mathrm{e}^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}\mathrm{e}^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}\mathrm{e}^{i\delta} & c_{23}c_{13} \end{pmatrix}, \tag{2.6}$$

with $c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$. The angles θ_{12}, θ_{23}, and θ_{13} can be put in the first quadrant without loss of generality.

The heavier chargino could decay into a charged lepton and a sneutrino by the interaction in eq. (2.5). Another possible mode is the decay into a neutrino and a charged slepton. The neutrinos ν_α are assumed to have Majorana masses. Their mass matrix M_ν is diagonalized by a unitary matrix U_ν,

$$U_\nu^T M_\nu U_\nu = \mathrm{diag}\,(m_{\nu_1}, m_{\nu_2}, m_{\nu_3})\,. \tag{2.7}$$

The charged sleptons consist of three left-handed components and three right-handed ones. The charginos couple to the left-handed components by gauge interactions. On the other hand, the couplings of the charginos to the right-handed components and the mixings of the left-handed components and the right-handed ones are both proportional to the masses of charged leptons. If the small effects by the charged lepton masses are neglected, we have only to take into consideration the left-handed components. Then, the mass-squared matrix $\tilde{M}_l^2$ for the left-handed charged sleptons $\tilde{l}_a$ is diagonalized by the unitary matrix $\tilde{U}_\nu$ in eq. (2.2),

$$\tilde{U}_\nu^\dagger \tilde{M}_l^2 \tilde{U}_\nu = \mathrm{diag}\left(M_{\tilde{l}_1}^2, M_{\tilde{l}_2}^2, M_{\tilde{l}_3}^2\right), \tag{2.8}$$

$$M_{\tilde{l}_a}^2 = M_{\tilde{\nu}_a}^2 - \cos 2\beta M_W^2. \tag{2.9}$$

The interaction Lagrangian for the mass eigenstates ν_α, $\tilde{l}_a$, and ω_i is given by

$$\mathcal{L} = ig\,(V_N)_{a\alpha}\, C_{L1i}\tilde{l}_a^\dagger \overline{\omega_i^c}\left(\frac{1-\gamma_5}{2}\right)\nu_\alpha + \text{H.c.}, \tag{2.10}$$

with $V_N = \tilde{U}_\nu^\dagger U_\nu$. The 3×3 unitary matrix V_N describes the generation mixing. The number of its physical parameters is six, though a definite parameterization is not necessary for our analyses.

The heavier chargino could also decay into a neutralino and a W boson, or a lighter chargino and a Z boson. The mass matrix for the neutralinos χ_n ($n = 1$–4) is given by

$$M^0 = \begin{pmatrix} \tilde{m}_1 & 0 & g'v_1/2 & -g'v_2/2 \\ 0 & \tilde{m}_2 & -gv_1/2 & gv_2/2 \\ g'v_1/2 & -gv_1/2 & 0 & -m_H \\ -g'v_2/2 & gv_2/2 & -m_H & 0 \end{pmatrix}, \tag{2.11}$$

where $\tilde{m}_1$ represents the U(1) gaugino mass. We assume the relation $\tilde{m}_1 = (5/3)\tan^2\theta_W \tilde{m}_2$ which is suggested by the SU(5) grand unified theory. The unitary matrix for diagonalizing M_0 is expressed by N,

$$N^T M^0 N = \text{diag}\,(m_{\chi 1}, m_{\chi 2}, m_{\chi 3}, m_{\chi 4})\,. \tag{2.12}$$

The interaction Lagrangian for the mass eigenstates ω_i, χ_n, and W is given by

$$\mathcal{L} = \frac{g}{\sqrt{2}}\overline{\chi_n}\gamma^\mu\left[G_{Lni}\left(\frac{1-\gamma_5}{2}\right) + G_{Rni}\left(\frac{1+\gamma_5}{2}\right)\right]\omega_i W_\mu^+ + \text{H.c.}, \tag{2.13}$$
$$G_{Lni} = \sqrt{2}N_{2n}^* C_{L1i} + N_{3n}^* C_{L2i}, \quad G_{Rni} = \sqrt{2}N_{2n}C_{R1i} - N_{4n}C_{R2i}.$$

The interaction Lagrangian for the mass eigenstates ω_1, ω_2, and Z is given by

$$\mathcal{L} = \sqrt{g^2 + g'^2}\,\overline{\omega_1}\gamma^\mu\left[F_L\left(\frac{1-\gamma_5}{2}\right) + F_R\left(\frac{1+\gamma_5}{2}\right)\right]\omega_2 Z_\mu + \text{H.c.}, \tag{2.14}$$
$$F_L = -\frac{1}{2}C_{L21}^* C_{L22}, \quad F_R = -\frac{1}{2}C_{R21}^* C_{R22}.$$

We do not take into consideration the two-body decay modes for the heavier chargino yielding a squark or a Higgs boson, assuming that they are not allowed kinematically.

The sneutrinos could decay into a charged lepton and a lighter chargino by the interaction in eq. (2.5). Another possible mode is the decay into a neutrino and a neutralino. The interaction Lagrangian for the mass eigenstates ν_α, $\tilde{\nu}_a$, and χ_n is given by

$$\mathcal{L} = i\frac{g}{\sqrt{2}}\,(V_N)_{a\alpha}\,(-\tan\theta_W N_{1n} + N_{2n})\,\tilde{\nu}_a^\dagger\overline{\chi_n}\left(\frac{1-\gamma_5}{2}\right)\nu_\alpha + \text{H.c.}, \tag{2.15}$$

where V_N has been defined for eq. (2.10).

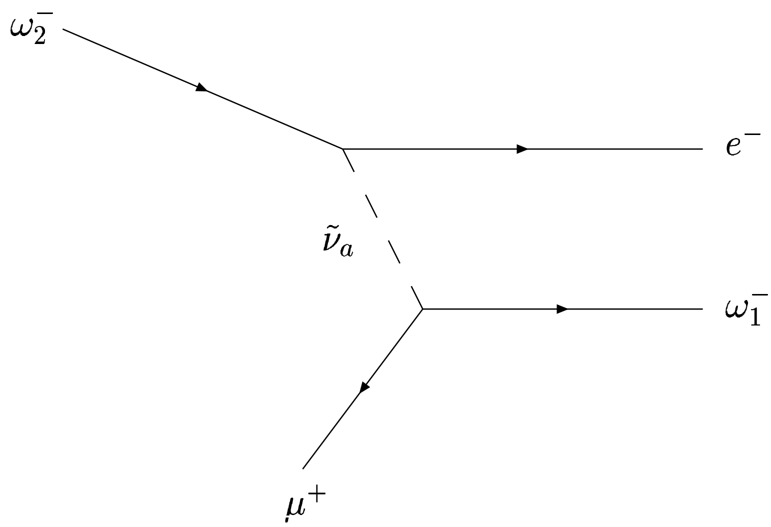

Figure 1: The Feynman diagram for the heavier chargino decay into an electron, a muon, and a lighter chargino.

3. Decay width

The heavier chargino decay could yield two charged leptons belonging to different generations and a lighter chargino by the sneutrino exchanging diagram as shown in figure 1. We assume that the three sneutrino masses are almost degenerate and the chargino masses satisfy the inequality $m_{\omega_2} > M_{\tilde{\nu}_a} > m_{\omega_1}$. Then, the heavier chargino ω_2 can decay into a charged lepton l_α and a sneutrino $\tilde{\nu}_a$, and the sneutrino can decay into a charged lepton l_β and a lighter chargino ω_1. These decay widths are given by

$$\Gamma(\omega_2^- \to l_\alpha^- \tilde{\nu}_a^*) = |(V_C)_{a\alpha}|^2 \tilde{\Gamma}(\omega_2 \to l_\alpha \tilde{\nu}_a), \tag{3.1}$$

$$\Gamma(\tilde{\nu}_a \to l_\beta^- \omega_1^+) = |(V_C)_{a\beta}|^2 \tilde{\Gamma}(\tilde{\nu}_a \to l_\beta \omega_1), \tag{3.2}$$

$$\begin{aligned}\tilde{\Gamma}(\omega_2 \to l_\alpha \tilde{\nu}_a) &= \frac{g^2}{32\pi} m_{\omega_2} \sqrt{\lambda\left(1, \frac{m_{l_\alpha}^2}{m_{\omega_2}^2}, \frac{M_{\tilde{\nu}_a}^2}{m_{\omega_2}^2}\right)} \\ &\quad \left[\left(|C_{R12}|^2 + |C_{L22}|^2 \frac{m_{l_\alpha}^2}{2\cos^2\beta M_W^2}\right)\left(1 + \frac{m_{l_\alpha}^2}{m_{\omega_2}^2} - \frac{M_{\tilde{\nu}_a}^2}{m_{\omega_2}^2}\right)\right. \\ &\quad \left. + \mathrm{Re}[C_{R12} C_{L22}^*] \frac{2\sqrt{2} m_{l_\alpha}^2}{\cos\beta M_W m_{\omega_2}}\right], \\ \tilde{\Gamma}(\tilde{\nu}_a \to l_\beta \omega_1) &= \frac{g^2}{16\pi} M_{\tilde{\nu}_a} \sqrt{\lambda\left(1, \frac{m_{l_\beta}^2}{M_{\tilde{\nu}_a}^2}, \frac{m_{\omega_1}^2}{M_{\tilde{\nu}_a}^2}\right)}\end{aligned}$$

$$\left[\left(|C_{R11}|^2+|C_{L21}|^2\frac{m_{l_\beta}^2}{2\cos^2\beta M_W^2}\right)\left(1-\frac{m_{l_\beta}^2}{M_{\tilde{\nu}_a}^2}-\frac{m_{\omega_1}^2}{M_{\tilde{\nu}_a}^2}\right)\right.$$
$$\left.-\mathrm{Re}[C_{R11}C_{L21}^*]\frac{2\sqrt{2}m_{l_\beta}^2 m_{\omega_1}}{\cos\beta M_W M_{\tilde{\nu}_a}^2}\right],$$

where the function λ is defined as

$$\lambda(a,b,c)=a^2+b^2+c^2-2ab-2bc-2ca. \tag{3.3}$$

The generation-changing decay $\omega_2^- \to l_\alpha^- l_\beta^+ \omega_1^-$ $(\alpha\neq\beta)$ is mediated by all the sneutrinos on mass-shell. Its width is obtained as

$$\Gamma(\omega_2^-\to l_\alpha^- l_\beta^+\omega_1^-)=\sum_{a,b}\frac{(V_C^*)_{a\alpha}(V_C)_{a\beta}(V_C)_{b\alpha}(V_C^*)_{b\beta}}{M_{\tilde{\nu}_a}\Gamma_{\tilde{\nu}_a}+M_{\tilde{\nu}_b}\Gamma_{\tilde{\nu}_b}+i(M_{\tilde{\nu}_a}^2-M_{\tilde{\nu}_b}^2)}$$
$$\left[M_{\tilde{\nu}_a}\tilde{\Gamma}(\omega_2\to l_\alpha\tilde{\nu}_a)\tilde{\Gamma}(\tilde{\nu}_a\to l_\beta\omega_1)+M_{\tilde{\nu}_b}\tilde{\Gamma}(\omega_2\to l_\alpha\tilde{\nu}_b)\tilde{\Gamma}(\tilde{\nu}_b\to l_\beta\omega_1)\right], \tag{3.4}$$

where $\Gamma_{\tilde{\nu}_a}$ denotes the total decay width of the sneutrino $\tilde{\nu}_a$, and the summation for each sneutrino index is done over three generations. The relations $M_{\tilde{\nu}_a}\gg\Gamma_{\tilde{\nu}_a}$ and $|M_{\tilde{\nu}_a}^2-M_{\tilde{\nu}_b}^2|\ll M_{\tilde{\nu}_a}^2\approx M_{\tilde{\nu}_b}^2$ have been taken into account. The total width of the sneutrino is approximately determined by the two-body decays,

$$\Gamma_{\tilde{\nu}_a}=\sum_\alpha\Gamma(\tilde{\nu}_a\to l_\alpha^-\omega_1^+)+\sum_{\alpha,n}\Gamma(\tilde{\nu}_a\to\nu_\alpha\chi_n), \tag{3.5}$$

where the width of $\tilde{\nu}_a\to l_\alpha^-\omega_1^+$ is written in eq. (3.2) and the width of $\tilde{\nu}_a\to\nu_\alpha\chi_n$ is given by

$$\sum_\alpha\Gamma(\tilde{\nu}_a\to\nu_\alpha\chi_n)=\frac{g^2}{32\pi}M_{\tilde{\nu}_a}|-\tan\theta_W N_{1n}+N_{2n}|^2\left(1-\frac{m_{\chi_n}^2}{M_{\tilde{\nu}_a}^2}\right)^2. \tag{3.6}$$

Owing to negligible magnitudes for the neutrino masses, the mixing matrix V_N needs not to be specified for obtaining the total width.

The branching ratio of the generation-changing decay depends on the total width of the heavier chargino. We assume that the squarks and the Higgs bosons are sufficiently heavy not to be produced by two-body decays of the heavier chargino. Then, possible two-body modes are the decays into $l_\alpha\tilde{\nu}_a$, $\nu_\alpha\tilde{l}_a$, $\chi_n W$, and $\omega_1 Z$. The total width of the chargino ω_2 becomes approximately the sum of these widths,

$$\Gamma_{\omega_2}=\sum_{\alpha,a}\Gamma(\omega_2^-\to l_\alpha^-\tilde{\nu}_a^*)+\sum_{\alpha,a}\Gamma(\omega_2^-\to\nu_\alpha^*\tilde{l}_a^-)$$
$$+\sum_n\Gamma(\omega_2^-\to\chi_n W^-)+\Gamma(\omega_2^-\to\omega_1^- Z), \tag{3.7}$$

where the width of $\omega_2^-\to l_\alpha^-\tilde{\nu}_a^*$ is written in eq. (3.1) and the widths of other decay modes are given by

$$\sum_\alpha\Gamma(\omega_2^-\to\nu_\alpha^*\tilde{l}_a^-)=\frac{g^2}{32\pi}m_{\omega_2}|C_{L12}|^2\left(1-\frac{M_{\tilde{l}_a}^2}{m_{\omega_2}^2}\right)^2, \tag{3.8}$$

$$\Gamma(\omega_2^- \to \chi_n W^-) = \frac{g^2}{64\pi} m_{\omega_2} \sqrt{\lambda\left(1, \frac{m_{\chi_n}^2}{m_{\omega_2}^2}, \frac{M_W^2}{m_{\omega_2}^2}\right)}$$
$$\left[\left(|G_{Ln2}|^2 + |G_{Rn2}|^2\right)\left\{1 + \frac{m_{\chi_n}^2}{m_{\omega_2}^2} - 2\frac{M_W^2}{m_{\omega_2}^2} + \left(\frac{m_{\omega_2}}{M_W} - \frac{m_{\chi_n}^2}{m_{\omega_2} M_W}\right)^2\right\}\right.$$
$$\left. -12\mathrm{Re}\left(G_{Ln2} G_{Rn2}^*\right) \frac{m_{\chi_n}}{m_{\omega_2}}\right], \tag{3.9}$$
$$\Gamma(\omega_2^- \to \omega_1^- Z) = \frac{g^2 + g'^2}{32\pi} m_{\omega_2} \sqrt{\lambda\left(1, \frac{m_{\omega_1}^2}{m_{\omega_2}^2}, \frac{M_Z^2}{m_{\omega_2}^2}\right)}$$
$$\left[\left(|F_L|^2 + |F_R|^2\right)\left\{1 + \frac{m_{\omega_1}^2}{m_{\omega_2}^2} - 2\frac{M_Z^2}{m_{\omega_2}^2} + \left(\frac{m_{\omega_2}}{M_Z} - \frac{m_{\omega_1}^2}{m_{\omega_2} M_Z}\right)^2\right\}\right.$$
$$\left. -12\mathrm{Re}\left(F_L F_R^*\right) \frac{m_{\omega_1}}{m_{\omega_2}}\right]. \tag{3.10}$$

The coefficients G_{Ln2}, G_{Rn2}, F_L, and F_R are defined in eqs. (2.13) and (2.14).

The charged lepton can decay into a lighter charged lepton and a photon by exchanging sneutrinos and charginos at the one-loop level by the interactions in eq. (2.5). The width is obtained by applying the general formula of the radiative decay width [6] to the relevant interactions. This result is written in appendix A, which is consistent with the formula in the literature [7]. The radiative charged lepton decay is also induced by the exchanges of charged sleptons and neutralinos. However, this neutralino-loop contribution is affected by additional factors arising from the right-handed charged sleptons, which are not related to the chargino-loop contribution. The correlation between the two types of contribution is uncertain. Furthermore, the neutralino-loop contribution to the radiative decay is generally smaller than the chargino-loop contribution [6]. It could well happen that the neutralino-loop contribution is negligible. Therefore, the interactions in eq. (2.5) may be constrained from the radiative charged lepton decays by comparing the chargino-loop contributions with the experimental bounds.

4. Numerical analyses

We discuss numerically the decay of the heavier chargino $\omega_2^- \to e^- \mu^+ \omega_1^-$. The values of the model parameters which prescribe the branching ratio of this decay mode are constrained by negative results of experimental searches for supersymmetric particles and radiative charged lepton decays [8]. For the parameters $\tilde{m}_2$, m_H, and $\tan\beta$, we take four sets of values listed in table 1, where the resultant mass eigenvalues of the charginos and neutralinos are also given. The mixing matrix V_C and the mass differences between the sneutrinos are crucial parameters. For simplicity, the mixing angles are taken as the same $\theta_{12} = \theta_{23} = \theta_{13}$ ($\equiv \theta$), with the CP violating phase being put at $\delta = \pi/4$, while the masses of the sneutrinos $\tilde{\nu}_1$ and $\tilde{\nu}_3$ are fixed at $M_{\tilde{\nu}_1} = 200\,\mathrm{GeV}$ and $M_{\tilde{\nu}_3} = 198\,\mathrm{GeV}$.

In figure 2, we show contours of the branching ratio in the $M_{\tilde{\nu}_2}$-θ plane for the parameter set (a) in table 1. The solid, dashed, and dotted lines respectively represent the

	(a)	(b)	(c)	(d)
$\tan\beta$	5	5	5	10
$\tilde{m}_2$	200	150	250	200
m_H	-200	-250	-150	-200
m_{ω_1}	166	144	144	159
m_{ω_2}	256	278	278	260
m_{χ_1}	94	72	108	92
m_{χ_2}	164	143	149	158
m_{χ_3}	215	265	166	213
m_{χ_4}	252	271	277	258

Table 1: The parameter values and the resultant masses for the charginos and neutralinos. The unit of mass is GeV.

JHEP08(2006)054

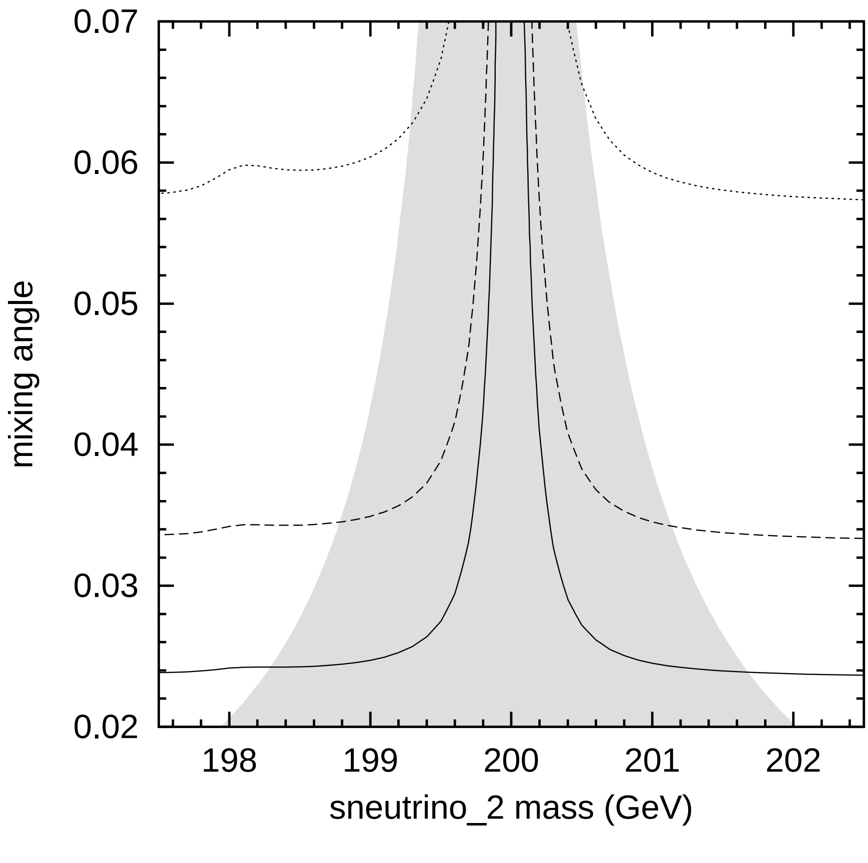

Figure 2: Contours of the branching ratio $\mathrm{BR}(\omega_2^- \to e^-\mu^+\omega_1^-)$ for the parameter set (a). The solid line: BR=5.0×10^{-5}, the dashed line: BR=1.0×10^{-4}, the dotted line: BR=3.0×10^{-4}. The region consistent with the radiative μ decay is shaded light.

branching ratios 5.0×10^{-5}, 1.0×10^{-4}, and 3.0×10^{-4}. Unshaded regions are not allowed by the constraint from the radiative decay $\mu \to e\gamma$. The other radiative charged lepton decays

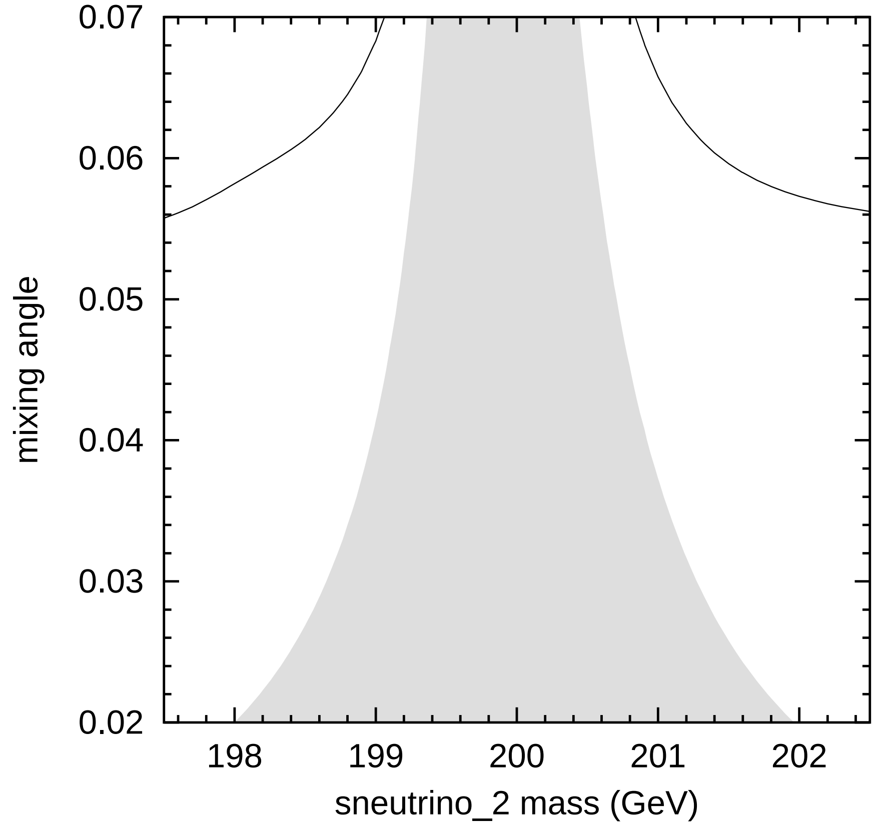

Figure 3: A contour of the branching ratio BR($\omega_2^- \to e^-\mu^+\omega_1^-$) for the parameter set (b). The solid line: BR=5.0×10^{-5}. The region consistent with the radiative μ decay is shaded light.

only impose less tight constraints. The branching ratio increases, as the mass difference between $\tilde{\nu}_1$ and $\tilde{\nu}_2$ or the mixing angle θ becomes large. Similar dependencies also hold for the radiative μ decay. Within the region allowed by the radiative μ decay, not a small part leads to a branching ratio larger than 1.0×10^{-4}. The mass difference between $\tilde{\nu}_3$ and $\tilde{\nu}_1$ or $\tilde{\nu}_2$ does not affect much the branching ratio nor the allowed region. Dependence on the mixing matrix is primarily determined by the mixing angle θ_{12}. A different value for θ_{23} or θ_{13} does not alter much the resultant branching ratio, as long as these mixing angles are small. The results are almost insensitive to the value of the CP violating phase δ.

The branching ratio for the parameter sets (b), (c), and (d) is respectively shown in figures 3, 4, and 5, with the other parameter values being the same as figure 2. The solid, dashed, dot-dashed, and dotted lines represent the branching ratios 5.0×10^{-5}, 1.0×10^{-4}, 2.0×10^{-4}, and 3.0×10^{-4}, respectively. Comparing these figures to each other, we can see the dependencies of the branching ratio on the parameters $\tilde{m}_2$, m_H, and $\tan\beta$. Although the region consistent with the radiative μ decay is not much different from each other for a fixed value of $\tan\beta$, the branching ratio manifestly depends on the relative magnitudes of $\tilde{m}_2$ and m_H. For a smaller value of $\tilde{m}_2/m_H$, the Higgsino component of the heavier

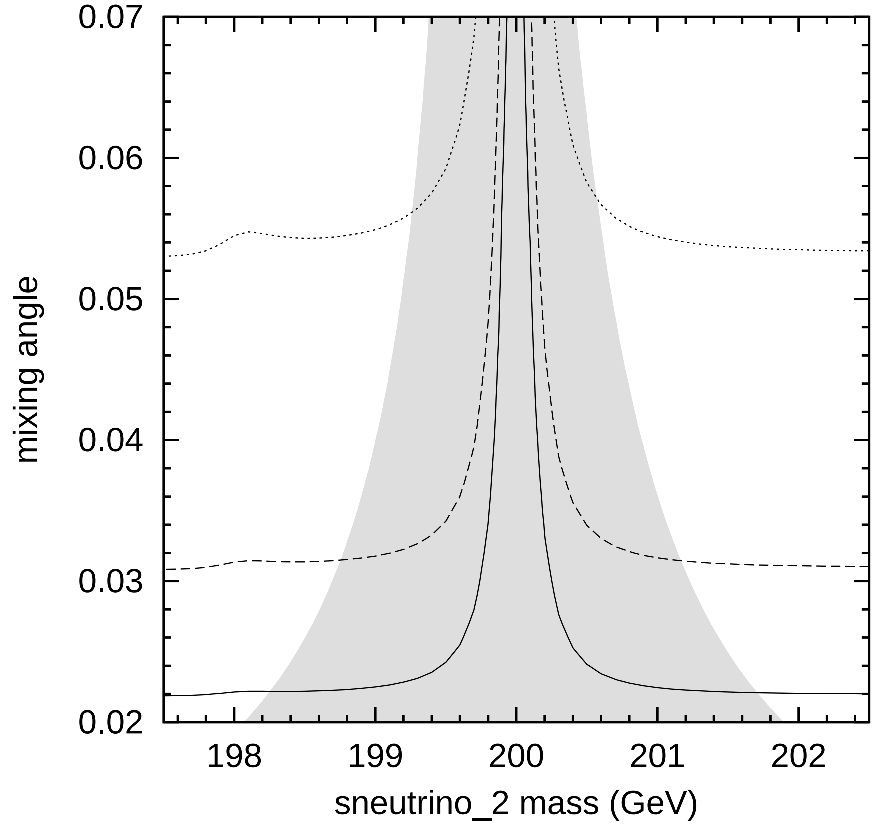

Figure 4: Contours of the branching ratio BR($\omega_2^- \to e^-\mu^+\omega_1^-$) for the parameter set (c). The solid line: BR=5.0×10^{-5}, the dashed line: BR=1.0×10^{-4}, the dotted line: BR=3.0×10^{-4}. The region consistent with the radiative μ decay is shaded light.

chargino is larger. Then, the width of the heavier chargino decay into a sneutrino and a charged lepton decreases, leading to a smaller branching ratio for the generation-changing decay. For a larger value of $\tan\beta$, the width of the radiative μ decay is enhanced, since the coupling constants for the right-handed charged leptons in eq. (2.5) increase. Consequently, the allowed parameter region becomes small. On the other hand, the branching ratio of $\omega_2^- \to e^-\mu^+\omega_1^-$ does not vary much with the value of $\tan\beta$.

We next discuss the cross section of the heavier chargino production. In e^+e^- collision experiments, the heavier chargino is produced as a pair of ω_1 and ω_2, or a pair of ω_2^+ and ω_2^-, provided that the collider energy is above the threshold. In hadron collision experiments, the squark is produced first while it decays into a quark and a heavier chargino at a large branching ratio. In any of these cases, the heavier chargino is expected to be produced abundantly. For definiteness, we evaluate the cross section of the process $e^+e^- \to \omega_1^+\omega_2^-$, which can occur at lower collider energies. This production is induced by the diagrams shown in figure 6, exchanging the Z boson and the sneutrinos. The cross section is obtained from the formula for the chargino pair production [9] by converting a pair of the same

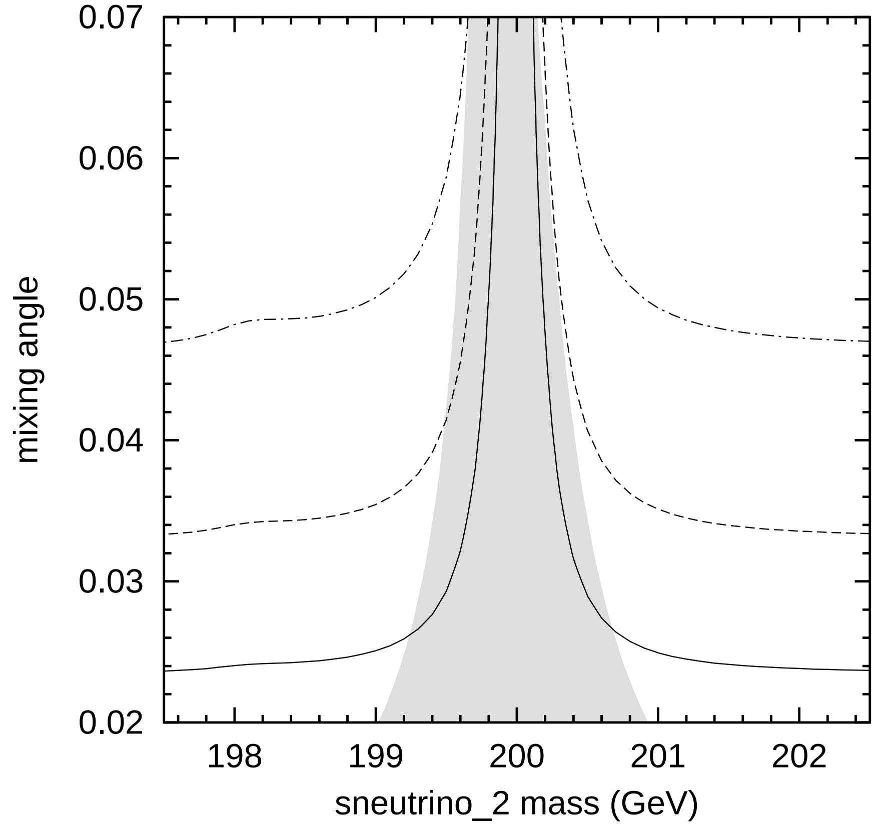

Figure 5: Contours of the branching ratio $\mathrm{BR}(\omega_2^- \to e^-\mu^+\omega_1^-)$ for the parameter set (d). The solid line: BR=5.0×10^{-5}, the dashed line: BR=1.0×10^{-4}, the dot-dashed line: BR=2.0×10^{-4}. The region consistent with the radiative μ decay is shaded light.

$\sqrt{s}$	(a)	(b)	(c)	(d)
500	109	18	102	112
600	108	20	97	109
700	93	18	81	94

Table 2: The cross section of $e^+e^- \to \omega_1^+\omega_2^-$ at $\sqrt{s}$ of different energies (GeV) for the parameter values (a)–(d), corresponding respectively to figures 2–5. The unit of cross section is fb.

chargino to a pair of ω_1 and ω_2. The result is written in appendix B, which is consistent with the formula in the literature [10].

In figure 7, contours of the cross section are shown in the $\tilde{m}_2$-$|m_H|$ plane for $\tan\beta = 5$, where the value of m_H is negative. All sneutrino masses are taken equal to 200 GeV and the generation mixing matrix V_C is assumed to be a unit matrix. The total energy in the center-of-mass frame is set at $\sqrt{s} = 500\,\mathrm{GeV}$. The solid, dashed, and dotted lines respectively represent the cross sections 10, 50, and 100 fb. In the left-lower unshaded region, the mass of the lighter chargino is less than 100 GeV, which is ruled out by LEP

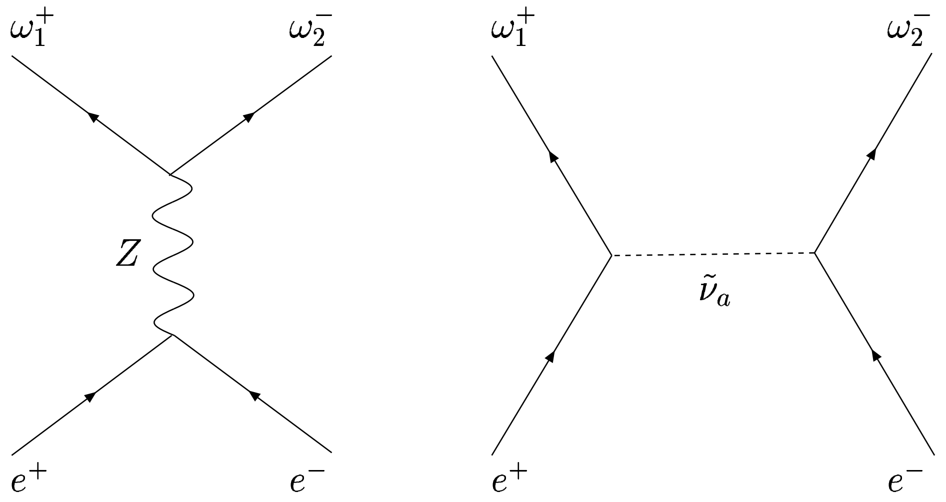

Figure 6: The Feynman diagrams for the pair creation of a lighter and a heavier charginos in e^+e^- annihilation.

experiments. In the right-upper unshaded region, the sum of the masses for the heavier and lighter charginos exceeds 500 GeV, so that the pair production is not allowed kinematically. In a sizable region of the parameter space, the cross section becomes of order of 100 fb. In table 2, the cross sections for the parameter values of figures 2– 5 are given at the total energies 500, 600, and 700 GeV.

5. Discussions

We have calculated the branching ratio of $\omega_2^- \to e^-\mu^+\omega_1^-$ and the cross section of $e^+e^- \to \omega_1^+ w_2^-$. It should be noted that the heavier chargino also has a decay mode $\omega_2^- \to \mu^- e^+\omega_1^-$ with almost the same branching ratio. Furthermore, there exist charge conjugate decays which have the same branching ratios. The cross section of $e^+e^- \to \omega_1^- w_2^+$ is equal to that of $e^+e^- \to \omega_1^+ w_2^-$. Since the lighter chargino decays dominantly into two quarks and the lightest neutralino, the final state of these successive production and decay processes mostly consists of a pair of e and μ and four jets with missing energy-momentum. For the integrated luminosity $100\,\text{fb}^{-1}$ of e^+e^- collisions, a few events or more are expected in sizable regions of the model parameter space. Although the event number is not large, the signature is distinctive. The generation mixing of the sneutrinos could be explored in the production and decay of the heavier chargino.

There are several processes which eventually lead to the same topology as the discussed generation-changing process. Suppose that a pair of sleptons are produced in e^+e^- collisions. Possible decay modes of the sneutrinos or the charged sleptons contain $\tilde{\nu}_a \to l_\alpha\omega_1$ or $\tilde{l}_a \to l_\alpha\chi_2$, respectively. The second lightest neutralino χ_2 dominantly decays into two

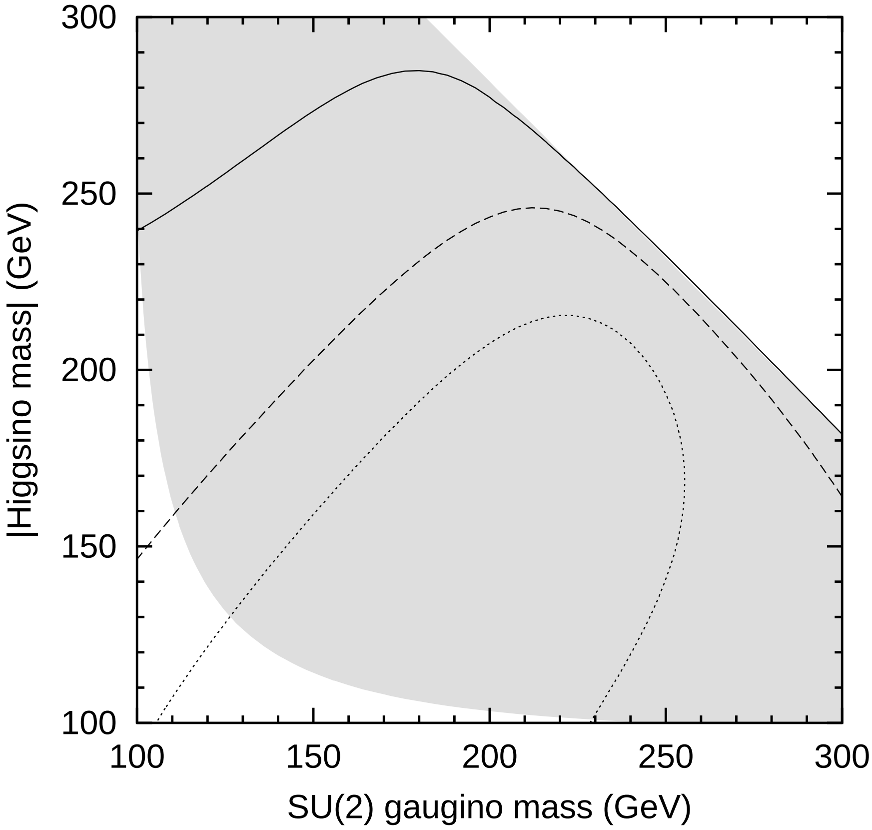

Figure 7: Contours of the cross section $\sigma(e^+e^- \to \omega_1^+ w_2^-)$ for $\tan\beta = 5$ at $\sqrt{s} = 500\,\mathrm{GeV}$. The sign of the Higgsino mass is negative. The solid line: $\sigma = 10\,\mathrm{fb}$, the dashed line: $\sigma = 50\,\mathrm{fb}$, the dotted line: $\sigma = 100\,\mathrm{fb}$. Outside the light shaded region, the lighter chargino mass is smaller than $100\,\mathrm{GeV}$, or the production of a pair of different charginos is not allowed kinematically.

quarks and the lightest neutralino, giving the same final topology as the lighter chargino. Generation-changing interactions of the sleptons could thus yield the final state of e, μ, and four jets with missing energy-momentum. If the energy of e^+e^- collisions is sufficiently higher than the primarily produced particle masses, the slepton decays give one charged lepton in each hemisphere, whereas two charged leptons are contained in one hemisphere for the heavier chargino decay. These processes could be distinguished from each other by the angular distributions of the final charged leptons. On the other hand, if the collision energy is not so high, the primarily produced particles are approximately at rest, so that their decays allow the charged leptons to go in any direction. Then, the distinction between the above processes becomes difficult. We could only know that the generation-changing processes are generated by the slepton interactions.

Serious experimental backgrounds receive contribution from generation-conserving interactions through the production of τ^+ and τ^- and their subsequent leptonic decays. For instance, after e^+e^- collisions the following reactions may occur: $\omega_1^+\omega_2^- \to \tau^+\tau^-\omega_1^+\omega_1^-$,

$\tilde{\nu}_\tau^* \tilde{\nu}_\tau \to \tau^+\tau^-\omega_1^+\omega_1^-$, and $\tilde{l}_\tau^* \tilde{l}_\tau \to \tau^+\tau^-\chi_2\chi_2$ by the supersymmetric model interactions and $ZW^+W^- \to \tau^+\tau^- W^+W^-$ by the standard model interactions. Their final states could contain e, μ, and four jets with missing energy-momentum. However, in these processes e and μ are produced by the three-body decays of τ. In the generation-changing processes, on the other hand, e and μ are produced by the two-body decays. Assuming the collision energy is not so high and thus ω_2 is nonrelativistic, the energies of e and μ are roughly monochromatic. The magnitudes and the distributions of the charged lepton energies are very different from the generation-conserving processes. In particular, if the masses of the charginos and the sneutrinos are known, the energies of e and μ can be specified. Appropriate energy cuts would enable reduction of the backgrounds.

Acknowledgments

M.O. would like to thank A. Sugamoto and G.C. Cho for encouragement. The work of N.O. is supported in part by the Grant-in-Aid for Scientific Research on Priority Areas (No. 16028204) from the Ministry of Education, Science and Culture, Japan.

A. Radiative decay

The width for the radiative charged lepton decays $\mu \to e\gamma$, $\tau \to e\gamma$, and $\tau \to \mu\gamma$ is given by

$$\Gamma(l_\beta \to l_\alpha \gamma) = \frac{\alpha_{EM}}{2} m_{l_\beta} \Big(|F_2|^2 + |G_2|^2 \Big) \left(1 - \frac{m_{l_\alpha}}{m_{l_\beta}} \right)^2 \left(1 - \frac{m_{l_\alpha}^2}{m_{l_\beta}^2} \right), \tag{A.1}$$

where F_2 and G_2 represent the dipole form factors,

$$\begin{aligned} F_2 = \; & \frac{g^2}{32\pi^2} \sum_{a,i} \frac{m_{l_\alpha} + m_{l_\beta}}{M_{\tilde{\nu}_a}} (V_C)_{a\beta} (V_C^*)_{a\alpha} \Bigg[\left(|C_{R1i}|^2 + \frac{|C_{L2i}|^2 m_{l_\alpha} m_{l_\beta}}{2\cos^2\beta M_W^2} \right) \frac{m_{l_\alpha} + m_{l_\beta}}{M_{\tilde{\nu}_a}} I_1 \left(\frac{m_{\omega_i}^2}{M_{\tilde{\nu}_a}^2} \right) \\ & + \left(\frac{C_{R1i}^* C_{L2i} m_{l_\alpha}}{\sqrt{2}\cos\beta M_W} + \frac{C_{R1i} C_{L2i}^* m_{l_\beta}}{\sqrt{2}\cos\beta M_W} \right) \frac{m_{\omega_i}}{M_{\tilde{\nu}_a}} I_2 \left(\frac{m_{\omega_i}^2}{M_{\tilde{\nu}_a}^2} \right) \Bigg] \end{aligned} \tag{A.2}$$

$$\begin{aligned} G_2 = \; & \frac{g^2}{32\pi^2} \sum_{a,i} \frac{m_{l_\alpha} + m_{l_\beta}}{M_{\tilde{\nu}_a}} (V_C)_{a\beta} (V_C^*)_{a\alpha} \Bigg[\left(|C_{R1i}|^2 - \frac{|C_{L2i}|^2 m_{l_\alpha} m_{l_\beta}}{2\cos^2\beta M_W^2} \right) \frac{m_{l_\beta} - m_{l_\alpha}}{M_{\tilde{\nu}_a}} I_1 \left(\frac{m_{\omega_i}^2}{M_{\tilde{\nu}_a}^2} \right) \\ & - \left(\frac{C_{R1i}^* C_{L2i} m_{l_\alpha}}{\sqrt{2}\cos\beta M_W} - \frac{C_{R1i} C_{L2i}^* m_{l_\beta}}{\sqrt{2}\cos\beta M_W} \right) \frac{m_{\omega_i}}{M_{\tilde{\nu}_a}} I_2 \left(\frac{m_{\omega_i}^2}{M_{\tilde{\nu}_a}^2} \right) \Bigg]. \end{aligned} \tag{A.3}$$

The functions I_1 and I_2 are defined as

$$I_1(r) = \frac{1}{12(1-r)^4} (2 + 3r - 6r^2 + r^3 + 6r\log r), \tag{A.4}$$

$$I_2(r) = \frac{1}{2(1-r)^3} (-3 + 4r - r^2 - 2\log r). \tag{A.5}$$

B. Chargino production

The production cross section for a pair of light and heavy charginos in e^+e^- collisions is, at the total energy $\sqrt{s}$ in the center-of-mass frame, given by

$$\sigma(e^+e^- \to \omega_1^+\omega_2^-) = \frac{1}{4\pi s^2}\int_{t_-}^{t_+} dt$$
$$\Bigg[\frac{(g^2+g'^2)^2}{4(s-M_Z^2)^2}\Big\{\left(|A_L|^2|F_R|^2+|A_R|^2|F_L|^2\right)\left(t-m_{\omega_1}^2\right)\left(t-m_{\omega_2}^2\right)$$
$$+\left(|A_L|^2|F_L|^2+|A_R|^2|F_R|^2\right)\left(t+s-m_{\omega_1}^2\right)\left(t+s-m_{\omega_2}^2\right)$$
$$+2\left(|A_L|^2+|A_R|^2\right)\mathrm{Re}[F_LF_R^*]m_{\omega_1}m_{\omega_2}s\Big\}$$
$$+\frac{g^4}{16}\left(\sum_a\frac{|(V_C)_{a1}|^2}{t-M_{\tilde{\nu}_a}^2}\right)^2|C_{R11}|^2|C_{R12}|^2\left(t-m_{\omega_1}^2\right)\left(t-m_{\omega_2}^2\right)$$
$$-\frac{(g^2+g'^2)g^2}{4(s-M_Z^2)}\sum_a\frac{|(V_C)_{a1}|^2}{t-M_{\tilde{\nu}_a}^2}A_L$$
$$\left\{\mathrm{Re}\left[F_R^*C_{R11}^*C_{R12}\right]\left(t-m_{\omega_1}^2\right)\left(t-m_{\omega_2}^2\right)+\mathrm{Re}\left[F_L^*C_{R11}^*C_{R12}\right]m_{\omega_1}m_{\omega_2}s\right\}\Bigg], \qquad \text{(B.1)}$$
$$A_L = -\frac{1}{2}+\sin^2\theta_W, \quad A_R = \sin^2\theta_W,$$

where the coefficients F_L and F_R are defined in eq. (2.14). The range of the integration is expressed by $t_\pm$ as

$$t_\pm = \frac{1}{2}\left[m_{\omega_1}^2+m_{\omega_2}^2-s\pm\sqrt{\lambda(s,m_{\omega_1}^2,m_{\omega_2}^2)}\right]. \qquad \text{(B.2)}$$

The mass of the electron has been neglected.

References

[1] For a review, see, e.g., G.L. Fogli, E. Lisi, A. Marrone, A. Palazzo and A.M. Rotunno, *Neutrino mass and mixing parameters: a short review*, hep-ph/0506307.

[2] For a recent review, see, e.g., A. Masiero and O. Vives, *Flavour and CP violation in supersymmetry*, *New J. Phys.* **4** (2002) 4.

[3] N. Arkani-Hamed, H.-C. Cheng, J.L. Feng and L.J. Hall, *Probing lepton flavor violation at future colliders*, *Phys. Rev. Lett.* **77** (1996) 1937 [hep-ph/9603431]; *CP-violation from slepton oscillations at the LHC and NLC*, *Nucl. Phys.* **B 505** (1997) 3 [hep-ph/9704205];
M. Hirouchi and M. Tanaka, *Lepton flavor violation at linear collider experiments in supersymmetric grand unified theories*, *Phys. Rev.* **D 58** (1998) 032004 [hep-ph/9712532];
J. Hisano, M.M. Nojiri, Y. Shimizu and M. Tanaka, *Lepton flavor violation in the left-handed slepton production at future lepton colliders*, *Phys. Rev.* **D 60** (1999) 055008 [hep-ph/9808410];
D. Nomura, *Probing left-handed slepton flavor mixing at future lepton colliders*, *Phys. Rev.* **D 64** (2001) 075001 [hep-ph/0004256];

JHEP08(2006)054

M. Guchait, J. Kalinowski and P. Roy, *Supersymmetric lepton flavor violation in a linear collider: the role of charginos*, *Eur. Phys. J.* **C 21** (2001) 163 [hep-ph/0103161];
M. Cannoni, S. Kolb and O. Panella, *Lepton flavour violation in $e^{+-}e^- \to L^{+-}e^-(L = \mu, \tau)$ induced by R-conserving supersymmetry*, *Phys. Rev.* **D 68** (2003) 096002 [hep-ph/0306170];
F. Deppisch, H. Päs, A. Redelbach, R. Rückl and Y. Shimizu, *The SUSY seesaw model and lepton-flavor violation at a future electron positron linear collider*, *Phys. Rev.* **D 69** (2004) 054014 [hep-ph/0310053].

[4] W. Porod and W. Majerotto, *Large lepton flavor violating signals in supersymmetric particle decays at future e^+e^- colliders*, *Phys. Rev.* **D 66** (2002) 015003 [hep-ph/0201284].

[5] N. Oshimo, *Generation-changing interaction of sneutrinos in e^+e^- collisions*, *Eur. Phys. J.* **C 39** (2005) 383 [hep-ph/0409018].

[6] N. Oshimo, *Radiative B meson decay in supersymmetric models*, *Nucl. Phys.* **B 404** (1993) 20.

[7] X.-J. Bi and Y.-B. Dai, *Lepton flavor violation and its constraints on the neutrino mass models*, *Phys. Rev.* **D 66** (2002) 076006 [hep-ph/0112077].

[8] Particle Data Group collaboration, S. Eidelman et al., *Review of particle physics*, *Phys. Lett.* **B 592** (2004) 1.

[9] T. Fukai, Y. Kizukuri, N. Oshimo, Y. Otake and N. Sugiyama, *Study of wino pair production in e^+e^- annihilation*, *Prog. Theor. Phys.* **78** (1987) 395.

[10] S.Y. Choi, A. Djouadi, H.S. Song and P.M. Zerwas, *Determining SUSY parameters in chargino pair-production in e^+e^- collisions*, *Eur. Phys. J.* **C 8** (1999) 669 [hep-ph/9812236].