The loop effects on the chargino decays $\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 ff'$ in the MSSM

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Abstract

The lighter chargino three body decays $\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 ff'$ via the $W^\pm$ boson and the charged Higgs boson $H^\pm$ are studied in the R-parity conserved Minimal Supersymmetric Standard Model (MSSM). We treat $\tilde{\chi}_1^\pm$ decays as production and decay of $W^\pm$ and $H^\pm$: i.e., $\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 W^\pm (H^\pm) \rightarrow \tilde{\chi}_1^0 ff'$. Both higgsino-like and wino-like $\tilde{\chi}_1^\pm$ decays are well investigated. These decays are calculated at 1-loop level and the loop corrections are found to be less than three percent. The signal of the charged Higgs $H^\pm$ production from $\tilde{\chi}_1^\pm$ decays are discussed. It will offer important information about the chargino and neutralino sector, as well as the charged Higgs sector in the MSSM.

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I. INTRODUCTION

The Minimal Supersymmetric Standard Model (MSSM)\cite{1,2} is one of the most popular extension of the Standard Model (SM). Supersymmetry (SUSY) connects fermions with bosons, which introduces scalar partners to all SM fermions as well as fermionic partners to all SM bosons. In comparison with SM, two Higgs doublets are required in the MSSM. After the electroweak symmetry is broken, it leads to five physical Higgs bosons: three neutral Higgs bosons and two charged Higgs bosons. Furthermore, superpartners for Higgs bosons and gauge bosons (the so-called higgsinos and gauginos, respectively) will mix into charginos and neutralinos, too. In the R-parity conserved MSSM, the lightest supersymmetric particle (LSP), which in many scenarios is the lightest neutralino $\tilde{\chi}_1^0$, appears at the end of the decay chain of each supersymmetric particle. The LSP escapes the detector, giving the characteristic SUSY signature of missing energy. Moreover, the stable neutral LSP interacts only weakly with ordinary matter, it can therefore make a good cold dark matter candidate.

Heavier supersymmetric particles can be produced at the Large Hadron Collider (LHC)\cite{3}, weakly interaction particles can also be produced at the future $e^+e^-$ collider if kinematically allowed. Moreover, precision determination of the properties of supersymmetric particles is expected at future $e^+e^-$ collider\cite{4}. Heavier supersymmetric particles produced at LHC and the future $e^+e^-$ collider will decay into lighter charginos or neutralinos. Of particular interest are decay chains leading to the next-to-lightest neutralino $\tilde{\chi}_2^0$ and/or the lighter chargino $\tilde{\chi}_1^\pm$. The next-to-lightest neutralino $\tilde{\chi}_2^0$ in turn can always decay into the LSP and two SM fermions, which was well studied at 1-loop level \cite{5,6}. Neutralino decays in the complex MSSM was also studied in ref.\cite{7}. Signal of chargino is difficult to be extracted from large $tt$ and $W^+W^-$ backgrounds at the LHC, while chargino pair production would be easily seen at the future $e^+e^-$ collider due to much more constrained kinematics \cite{3}. Depending on the lighter chargino, the lightest neutralino, sfermion as well as charged Higgs boson masses, the possible decays of the lighter chargino $\tilde{\chi}_1^\pm$ are three-body decays $\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 f f'$, cascade two-body decays $\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 W^\pm (H^\pm) \rightarrow \tilde{\chi}_1^0 f f'$ and $\tilde{\chi}_1^\pm \rightarrow \tilde{f} f' \rightarrow \tilde{\chi}_1^0 f f'$, where $f$ and $f'$ are SM fermions. Tree- and one-loop-level chargino decays in different theory of framework are investigated in refs.\cite{9,11}. In ref.\cite{12}, two body decays of chargino to $W$ boson, charged Higgs bosons, as well sleptons in the complex MSSM are investigated at one-loop level.

In this paper we concentrate our attention on chargino $\tilde{\chi}_1^\pm$ decays into $ff'$ via $W$ and charged Higgs boson $H^\pm$ in the real MSSM with heavy sfermions masses. Suppose the decay mode $\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 W^\pm$ is open while others are closed, the branching ratios of decays into $\chi_1^0 f f'$ are same as $W$ decays to $ff'$ in the SM. Here we choose SUSY parameters so that two body decay modes $\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 W^\pm \rightarrow \tilde{\chi}_1^0 f f'$ and $\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 H^\pm \rightarrow \tilde{\chi}_1^0 f f'$ are open, while others are closed kinematically. The exit of charged Higgs in $\tilde{\chi}_1^\pm$ decays makes its branching ratios of decays to $l\nu_l$ ($l = e, \mu, \tau$) and hadrons final states are different from that of $W$ decays. This is one of the important signal of the charged Higgs production at the collider, and will offer essential information about the Higgs sector in the MSSM.

This paper is organized as following. In Sec. II the MSSM and the renormalization of those sectors which are relevant for $\tilde{\chi}_1^\pm$ decays are summarized. Calculating techniques are briefly discussed in Sec. III. The parameter choices, numerical results, some discussions and conclusions are also presented in this section.
II. THE MSSM AND RENORMALIZATION

In this section we first review the chargino and neutralino sector, as well as Higgs sector in the R-parity conserved MSSM. Their renormalization which is required for the precision calculation is discussed too.

A. Chargino and neutralino sector

Charginos and neutralinos are mixture of charged and neutral gauginos and higgsinos, respectively. In the gaugino and higgsino eigenbasis, the mass terms of the charginos and neutralinos can be written as

\begin{equation}
- \mathcal{L}_{\chi^c-\text{mass}} = \psi_R^T X \psi_L + h.c., \\
- \mathcal{L}_{\chi^0-\text{mass}} = \frac{1}{2} \psi^0 Y \psi^0 + h.c.
\end{equation}

Here \( \psi_L, \psi_R \) and \( \psi^0 \) are two-components Weyl spinors, their expressions are shown as following,

\begin{equation}
\psi_L = (\tilde{W}^+, \tilde{\nu}_2^+)^T, \quad \psi_R = (\tilde{W}^-, \tilde{\nu}_1^-)^T, \quad \psi^0 = \left( \tilde{B}^0, \tilde{W}^3, \tilde{h}_1^0, \tilde{h}_2^0 \right)^T.
\end{equation}

The mass matrices for charginos and neutralinos are

\begin{equation}
X = \begin{pmatrix}
M_2 & \sqrt{2} M_W s_\beta \\
\sqrt{2} M_W c_\beta & \mu
\end{pmatrix},
\end{equation}

\begin{equation}
Y = \begin{pmatrix}
M_1 & M_Z s_W c_\beta & M_Z s_W s_\beta \\
0 & -M_Z s_W c_\beta & -M_Z s_W s_\beta \\
-M_Z s_W c_\beta & M_Z c_W c_\beta & M_Z c_W s_\beta \\
M_Z s_W s_\beta & -M_Z c_W s_\beta & -\mu & 0
\end{pmatrix}.
\end{equation}

Here \( M_1 \) is the SUSY breaking \( U(1)_Y \) gaugino (bino) mass, \( M_2 \) is the SUSY breaking \( SU(2) \) gaugino (wino) mass, \( \mu \) is the supersymmetric higgsino mass, and tan \( \beta \) is the ratio of vacuum expectation values of the two neutral Higgs fields of the MSSM. Abbreviations \( s_W, s_\beta, c_W \) and \( c_\beta \) stand for sin \( \theta_W \), sin \( \beta \), cos \( \theta_W \) and cos \( \beta \), respectively, where \( \theta_W \) is the weak mixing angle.

Mass matrices \( X \) and \( Y \) can be diagonalized by transforming the original wino and higgsino fields with the help of unitary matrices,

\begin{equation}
\chi_L = V \psi_L, \quad \chi_R = U \psi_R, \quad M_{\chi^+} = UXV^T = \text{diag} \left( m_{\tilde{\chi}_1^+}, m_{\tilde{\chi}_2^+} \right),
\end{equation}

\begin{equation}
\chi^0 = N \psi^0, \quad M_{\chi^0} = N^* Y N^\dagger = \text{diag} \left( m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_2^0}, m_{\tilde{\chi}_3^0}, m_{\tilde{\chi}_4^0} \right).
\end{equation}

Here \( U, V \) are unitary \( 2 \times 2 \) matrices which determined by the third part of eq.(5), \( N \) is a unitary \( 4 \times 4 \) matrix which determined by the second part of eq.(6), \( \chi_{L/R}, \chi^0 \) are chargino and neutralino mass eigenstates, respectively. The four-component spinors for chargino and neutralino are defined by

\begin{equation}
\tilde{\chi}_i^+ = \begin{pmatrix}
\chi_{L_i} \\
\chi_{R_i}
\end{pmatrix}, \quad \tilde{\chi}_i^0 = \begin{pmatrix}
\chi_{L_i}^0 \\
\chi_{R_i}^0
\end{pmatrix},
\end{equation}

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where neutralinos are Majorana fermions. There are two charginos and four neutralinos in the MSSM. They are labeled in ascending order,

\[ 0 < m_{\tilde{\chi}_1^+} \leq m_{\tilde{\chi}_2^+}, \quad 0 \leq m_{\tilde{\chi}_1^0} \leq m_{\tilde{\chi}_2^0} \leq m_{\tilde{\chi}_3^0} \leq m_{\tilde{\chi}_4^0}. \]  

(8)

In the R-parity conserved MSSM, the lightest neutralino \( \tilde{\chi}_1^0 \) can be a good cold dark matter candidate.

Concerning the renormalization of chargino and neutralino sector at one-loop level, different approaches were developed \([5, 13–19]\). Here we assume all the parameters are real and employ the on-shell renormalization following refs. \([5, 13, 17]\). Mass matrices and fields of charginos and neutralinos are renormalized as following

\[ X \rightarrow X + \delta X, \quad Y \rightarrow Y + \delta Y, \]

\[ \omega_{L, R} \tilde{\chi}_i \rightarrow \left( \delta_{ij} + \frac{1}{2} (\delta Z^L)_{ij} \right) \omega_{L, R} \tilde{\chi}_j, \]

\[ \omega_{L, R} \tilde{\chi}_i \rightarrow \left( \delta_{ij} + \frac{1}{2} (\delta Z^R)_{ij}^* \right) \omega_{L, R} \tilde{\chi}_j, \]

(10)

where each element of \( \delta X \) and \( \delta Y \) is the counterterm for the corresponding entry in \( X \) and \( Y \) mass matrices, respectively. In eq. (10), \( \omega_{L, R} = (1 \mp \gamma_5)/2 \) are chiral operators and this equation holds for both charginos, with \( \tilde{\chi}_i \equiv \tilde{\chi}_i^+, i \in \{1, 2\} \), and neutralinos, with \( \tilde{\chi}_i \equiv \tilde{\chi}_i^0, i \in \{1, 2, 3, 4\} \). Note that the right- and left-handed field renormalization constant for neutralinos are same, i.e. \( \delta Z^L = \delta Z^R = \delta Z^0 \), since they are Majorana fermions.

Altogether mass counterterms \( \delta X \) and \( \delta Y \) contain seven different counterterms: \( \delta M_W, \delta M_Z, \delta \theta_W, \delta \tan \beta, \delta M_1, \delta M_2 \) and \( \delta \mu \). The first three of these already appear in the SM and their renormalization have been discussed in ref. \([20]\), we will not repeat it here. Parameter \( \tan \beta \) will be renormalized in Higgs sector in the next subsection. In the on-shell renormalization scheme for the charginos/neutralinos \([13, 17]\), the counterterms \( \delta M_1, \delta M_2 \) and \( \delta \mu \) are determined by requiring that three pole-masses of six charginos and neutralinos are the same as at tree-level. Ref. \([17]\) has studied all instabilities and singularities of different type of choices for inputs. It concludes that one should choose the masses of a bino-like, a wino-like and a higgsino-like state as inputs in order to avoid large corrections to the masses of the other eigenstates. In this paper, We keep masses of \( \tilde{\chi}_1^0, \tilde{\chi}_1^+ \) and \( \tilde{\chi}_2^0 \) unchanged at tree- and one-loop-level, as in ref. \([13]\). In our numerical set-up, see Sec. III the lightest neutralino is always bino-like. This makes our choices reasonable. Considering the on-shell field renormalization of charginos and neutralinos, the diagonal entries of the field renormalization constants are fixed by the condition that the corresponding renormalized propagator has unit residue. Furthermore, the renormalized one-particle irreducible two-point functions should be diagonal for on-shell external particles, which fixes the off-diagonal entries of the field renormalization constants.

### B. Charged Higgs sector

The mass term for the charged Higgs at tree level can be expressed as

\[ \mathcal{L}_{H_{\pm}^{\text{mass}}} = (H^+, G^+) \begin{pmatrix} m_{H_{\pm}^2}^2 & m_{H_{\pm}G^0}^2 \\ m_{H_{\pm}G^0}^2 & m_{G^0}^2 \end{pmatrix} \begin{pmatrix} H^- \\ G^- \end{pmatrix}. \]

(11)
The mass matrix elements are as following,

\[
\begin{align*}
m^2_{H^\pm} &= m^2_{A^0} + M_W^2, \\
m^2_{H^+G^-} &= m^2_{H^-G^+} = -(m^2_{A^0} + m^2_W) \tan(\beta - \beta_c) \\
&\quad - \frac{e}{2m_Z s_W c_W} (T_{h^0} \sin(\alpha - \beta_c) + T_{h^0} \cos(\alpha - \beta_c)) / \cos(\beta - \beta_c), \\
m^2_{G^\pm} &= -(m^2_{A^0} + m^2_W) \tan(\beta - \beta_c) \\
&\quad - \frac{e}{2m_Z s_W c_W} T_{h^0} \cos(\alpha + \beta - 2\beta_c) / \cos^2(\beta - \beta_c) \\
&\quad + \frac{e}{2m_Z s_W c_W} T_{h^0} \sin(\alpha + \beta - 2\beta_c) / \cos^2(\beta - \beta_c). \tag{12}
\end{align*}
\]

Here \(m_{A^0}\) is the mass for the neutral CP-odd Higgs boson \(A^0\), \(\alpha\) is the mixing angle of two neutral CP-even Higgs bosons, \(\beta_c\) is the mixing angle of two charged Higgs bosons. \(T_{h^0}\) and \(T_{H^0}\), denote tadpoles of the physical neutral Higgs fields \(h^0\) and \(H^0\), are zero at tree-level. The mass matrix in eq.(11) should be diagonal at tree level. This leads to the following conclusions,

\[
\beta_c = \beta, \quad \tan 2\alpha = \tan 2\beta \frac{m^2_{A^0} + m^2_Z}{m^2_{A^0} - m^2_Z}, \quad -\frac{\pi}{2} < \alpha < \frac{\pi}{2}. \tag{13}
\]

Concerning renormalization of the Higgs sector, we follow the approach in Ref.[21]. Introduce renomalization constants for the mass matrix and fields of the charged Higgs sector as following,

\[
\begin{align*}
m^2_{H^\pm} &\rightarrow m^2_{H^\pm} + \delta m^2_{H^\pm}, \tag{14} \\
m^2_{H^-G^+} &\rightarrow m^2_{H^-G^+} + \delta m^2_{H^-G^+}, \tag{15} \\
m^2_{G^\pm} &\rightarrow m^2_{G^\pm} + \delta m^2_{G^\pm}, \tag{16} \\
\begin{pmatrix} H^- \\ G^- \end{pmatrix} &\rightarrow \begin{pmatrix} 1 + \frac{1}{2} \delta Z \\ \delta Z \end{pmatrix} \begin{pmatrix} H^- \\ G^- \end{pmatrix}. \tag{17}
\end{align*}
\]

Here the filed renormalization constant \(\delta Z\) is a \(2 \times 2\) matrix, which is fixed by using \(\overline{DR}\) scheme, which means that the counterterms only contain UV-divergent parts. The mass counterterms \(\delta m^2_{H^\pm}, \delta m^2_{H^-G^+}\) and \(\delta m^2_{G^\pm}\) contain counterterms \(\delta T_{h^0}, \delta T_{H^0}, \delta m^2_{A^0}\), and \(\delta \tan \beta\). The counterterm \(\delta m^2_{A^0}\) is determined by renormalizing the neutral CP-odd Higgs boson \(A^0\) via the on-shell renormalization scheme. Counterterms for the tadpoles \(T_{h^0}\) and \(T_{H^0}\) are fixed by requiring the renormalized tadpoles are equal to zero at one-loop level. Same as the field renormalization constants of the charged Higgs, \(\delta \tan \beta\) is determined in the \(\overline{DR}\) scheme[22],

\[
\frac{\delta \tan \beta^{\overline{DR}}}{\tan \beta} = \frac{1}{2m_Z s_c \beta} \left[ \text{Im} \Sigma_{A^0 Z}(m^2_{A^0}) \right]_{\text{div}}. \tag{18}
\]

Here the subscript ”div” means that only the UV-divergent parts are considered. This scheme has the advantage of providing the gauge invariant and process independent counterterms.
III. CALCULATIONS AND NUMERICAL RESULTS

In this work SUSY parameters are chosen to make the cascade two-body decays of lighter chargino $\tilde{\chi}_1^\pm$ via $W^\pm$ and charged Higgs boson $H^\pm$ possible. No other two-body decay mode is open. The decays $\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 f \bar{f}'$ can be approximately treated as production and decays of the $W^\pm$ and charged Higgs boson $H^\pm$, where $Br(W^\pm \to f \bar{f}')$ and $Br(H^\pm \to f \bar{f}')$ are branching ratios of $W^\pm$ and $H^\pm$ boson decay to two SM fermions, respectively. Since the branching ratios of $W$ boson decays have been measured precisely, we here will not repeat the theoretical calculation, but take the measured values from Particle Data Group \[23\]. For the relevant charged Higgs decays in the MSSM, they are calculated at one-loop level by using the program FEYNHIGGS\[24\]. Suppose the couplings of charged Higgs with fermions are well known, one can determine the branching ratios of $\tilde{\chi}_1^- \to \tilde{\chi}_1^0 W^- (H^-)$ from the measured branching ratios $Br \left( \tilde{\chi}_1^- \to \tilde{\chi}_1^0 \tau^- \bar{\nu}_\tau \right)$ by

$$Br \left( \tilde{\chi}_1^- \to \tilde{\chi}_1^0 \tau^- \bar{\nu}_\tau \right) = x Br \left( W^- \to \tau^- \bar{\nu}_\tau \right) + (1 - x) Br \left( H^- \to \tau^- \bar{\nu}_\tau \right),$$

where $x$ and $1 - x$ are the branching ratios of $\tilde{\chi}_1^-$ decays to $W^-$ and $H^-$, respectively.

Decays $\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 W^\pm$ and $\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 H^\pm$ are calculated at one-loop level with the help of the packages FEYNARTS\[25\], FORMCALC and LOOPTOOLS\[26\], respectively. The virtual contributions of these processes only contain vertex type corrections, which are ultraviolet(UV) divergent. These corrections become UV-finite after adding the contributions of the counterterms that originate from the renormalization of the MSSM, as discussed in Sec. II. Virtual diagrams with photon attached to two external particles will give infrared (IR) divergences, which are regularized by a photon mass. When the photon energy $E_\gamma$ is very small, the real photon bremsstrahlung will also give IR-divergent contribution which is sufficient to cancel the IR divergences from the virtual corrections. Contribution of the real photon bremsstrahlung is split into two parts: the “soft photon bremsstrahlung”($E_\gamma \leq \Delta E$) and the “hard photon bremsstrahlung”($E_\gamma > \Delta E$) contribution, here the cutoff parameter $\Delta E$ should be small compared to the relevant physical energy scale. The contribution of the soft photon bremsstrahlung can be described as a convolution of the differential tree-level decay width with a universal factor. Explicit expressions can be found in Refs. \[20\, 27\]. Since external charged particles in processes $\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 W^\pm/H^\pm$ are quite heavy, contribution of the hard photon bremsstrahlung contains no collinear divergences and can be calculated numerically using Monte Carlo integration. The dependence on the largely arbitrary parameter $\Delta E$ cancels after summing soft and hard contributions, provided it is sufficiently small.

Considering the constraint on SUSY parameters from recent experiments \[28\], the soft SUSY-breaking parameters in the diagonal entries of the sfermion mass matrices are chosen to be the same

$$M_{SUSY} = 1.5 TeV,$$
while the trilinear couplings of the third generation and other relevant input parameters are chosen as

\[ A_t = A_b = A_r = 2.5 \text{TeV}, \quad M_1 = 150 \text{GeV}, \quad M_{H^\pm} = 160 \text{GeV}, \quad M_g = 1 \text{TeV}. \quad (23) \]

As discussed in Sec. II, pole masses of the lightest neutralino and two charginos are chosen to be input parameters in our on-shell renormalization approach. Parameters \( M_2 \) and \( \mu \) therefore can be expressed as a function of pole masses of two charginos, see Ref.[13]. For given pole masses of two charginos, there are two type of choices for parameters \( M_2 \) and \( \mu \): \( M_2 > \mu \) and \( M_2 < \mu \), which make the lighter chargino \( \tilde{\chi}_1^\pm \) is more higgsino-like and gaugino-like, respectively. Though small \( \mu \) is preferred in Natural SUSY [29], here we focus on more general cases. In our calculation, parameters \( M_2 \) and \( \mu \) are chosen as in Table I, where \( \tan \beta = 20 \).

\begin{table}
\centering
\begin{tabular}{|c|c|c|c|c|}
\hline
 & \( M_2 > \mu \) & \( M_2 < \mu \) \\
\hline
\hline
Set-I & 600 & 550 \text{–} 800 \\
Set-II & 320 & 550 \text{–} 800 \\
Set-III & 320 & 550 \text{–} 800 \\
Set-IV & 320 & 550 \text{–} 800 \\
\hline
\end{tabular}
\caption{Different choices for parameters \( M_2 \) and \( \mu \) for \( \tan \beta = 20 \): Set-I to Set-IV.}
\end{table}

Note that all SUSY parameters as given in Eqs.(22-23) and in Table I are real numbers. It ensures CP is conserved in our consideration, ie. the decay rate of \( \tilde{\chi}_1^- \) is exactly same as its conjugate state \( \tilde{\chi}_1^+ \). In this paper only \( \tilde{\chi}_1^- \) decay is investigated, the conclusion can be applied to \( \tilde{\chi}_1^+ \) decay. By using the fixed input parameters as given in Eqs.(22-23) and different choices for \( M_2 \) and \( \mu \) as listed in Table I, we calculate the decay widths and branching ratios for all considered decays, and show the theoretical predictions in Figs.1-3.

In Fig.1 the decay widths and branching ratios of the lighter chargino decays to the lightest neutralino and \( W^-/H^- \) boson at the tree and one-loop level are presented for the case of \( M_2 > \mu \), i.e. \( \tilde{\chi}_1^- \) is higgsino-like. In Fig.1(a)-1(b), we show the \( \mu \)-dependence of the decay widths and branching ratios of \( \tilde{\chi}_1^- \to \tilde{\chi}_1^0 W^-/(H^-) \) decays. In Fig.1(c)-1(d), we show the \( M_2 \)-dependence of the decay widths and branching ratios of the same decay modes. From the curves in these figures one can see the following points:

- For the parameter choice Set-I, the mass of \( \tilde{\chi}_1^- \) increases with \( \mu \) which makes decay width of \( \tilde{\chi}_1^- \to \tilde{\chi}_1^0 W^-/H^- \) and total decay width of \( \tilde{\chi}_1^- \) increase kinematically, see Fig.1(a)-1(b). Couplings of \( \tilde{\chi}_1^- \tilde{\chi}_1^0 W^+ \) (higgsino-higgsino, wino-wino interaction) and \( \tilde{\chi}_1^- \tilde{\chi}_1^0 H^+ \) (wino-higgsino, higgsino-wino, higgsino-bino interaction) vary with \( \mu \), too. The competition of kinematics and couplings makes the branching ratio \( Br(\tilde{\chi}_1^- \to \tilde{\chi}_1^0 H^-) \) increases while \( Br(\tilde{\chi}_1^- \to \tilde{\chi}_1^0 W^-) \) decreases when \( \mu \) becomes large, as illustrated by the curves in Fig.1(a) and 1(b).

- For the parameter choice Set-II, \( M_2 \) is much bigger than \( \mu \). Increasing \( M_2 \) will not change the higgsino and gaugino part of the lighter chargino \( \tilde{\chi}_1^- \) too much and hence the couplings of \( \tilde{\chi}_1^- \tilde{\chi}_1^0 W^+/(H^+) \) are nearly invariant. On the other hand, the mass of \( \tilde{\chi}_1^- \) depends mainly on the parameter \( \mu \) in case of \( M_2 > \mu \), varying parameter \( M_2 \) make

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little difference on the kinematics. This makes the decay width and branching ratios of \( \tilde{\chi}_1^- \) change a little bit with varying parameter \( M_2 \) once the decay channel \( \tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 H^- \) is open, see Fig.1(c) and 1(d).

In Fig.2 the decay widths and branching ratios of the \( \tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 W^-(H^-) \) decays at the tree and one-loop level are illustrated for the case of \( M_2 < \mu \), i.e. \( \tilde{\chi}_1^- \) is wino-like.

- In Fig.2(a)-2(b), the theoretical predictions are obtained by using the parameter choice Set-III: \( M_2 = 320 GeV, \mu = 550 GeV \sim 800 GeV \). The effects of 2-body kinematics on the decay width is quite small. Couplings of \( \tilde{\chi}_1^- \tilde{\chi}_1^0 W^+(H^+) \) decrease with increasing parameter \( \mu \), but the descent speed for coupling \( \tilde{\chi}_1^- \tilde{\chi}_1^0 W^+ \) is much faster than that of couplings \( \tilde{\chi}_1^- \tilde{\chi}_1^0 H^+ \). The branching ratio of \( \tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 W^- \) (\( \tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 H^- \) ) become consequently smaller (larger) when the scale \( \mu \) increases, as shown by the curves in Fig.2(a) and 2(b).

- In Fig.2(c)-2(d), we show the theoretical predictions obtained by using the parameter choice Set-IV: \( M_2 = 320 \sim 550 GeV, \mu = 600 GeV \). The competition of the kinematics and couplings makes the decay widths of two decay modes increase with increasing \( M_2 \),

![Graphs showing theoretical predictions for decay widths and branching ratios of \( \tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 W^-(H^-) \) decays.](8)

**FIG. 1.** The decay widths and branching ratios of \( \tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 W^-(H^-) \) decays for the case of \( M_2 > \mu \). The curves in (a)-(b)/(c)-(d) are obtained by using the Set-I (Set-II) input parameters as defined in Table I.
and the branching ratio $Br(\tilde{\chi}_1^- \to \tilde{\chi}_1^0 H^-)$ is larger than $Br(\tilde{\chi}_1^- \to \tilde{\chi}_1^0 W^-)$ in almost all the parameter space.

From Figs.1 and 2 one can see that the loop effects on the decay widths are very small: less than 3% in magnitude. Furthermore, comparing Fig.1(a)-1(b) with Fig.2(c)-2(d) (Fig.1(c)-1(d) with Fig.2(a)-2(b)), one concludes that exchanging values for parameter $M_2$ and $\mu$ will change the decay width of charginos and its branching ratios, though their masses are fixed. The branching ratio $Br(\tilde{\chi}_1^- \to \tilde{\chi}_1^0 H^\pm)$ is smaller than $Br(\tilde{\chi}_1^- \to \tilde{\chi}_1^0 W^-)$ for $M_2 > \mu$, while $Br(\tilde{\chi}_1^- \to \tilde{\chi}_1^0 H^\pm)$ can be comparable with or even larger than $Br(\tilde{\chi}_1^- \to \tilde{\chi}_1^0 W^-)$ for $M_2 < \mu$, for our choice of parameters in Table I.

Parameter $\tan \beta$ is one of the most important parameters in the SUSY models. The $\tan \beta$-dependence of branching ratios of the lighter chargino $\tilde{\chi}_1^-$ decay modes is investigated here, as illustrated in Fig.3, where the branching ratios of $\tilde{\chi}_1^- \to \tilde{\chi}_1^0 W^-(H^-)$ and $\tilde{\chi}_1^- \to \tilde{\chi}_1^0 f \bar{f}$ at one-loop level are shown with $7 \leq \tan \beta \leq 50$. We choose charged Higgs mass to be light so that $m_{H^-} < m_t + m_b$, therefore the main decay mode of the charged Higgs is $\tau^- \bar{\nu}_\tau$, not $\bar{t}b$.

For the case of $(M_2, \mu) = (600, 320)$ GeV, $\tilde{\chi}_1^-$ is higgsino-like, as illustrated by Fig.3(a) and 3(b), we find the following points:
FIG. 3. The tan β-dependence of the branching ratios $\text{Br}(\tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 W^-)$, $\text{Br}(\tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 H^-)$, $\text{Br}(\tilde{\chi}_1^- \rightarrow \chi_1^0 f \bar{f'})$ with $f = e^-, \tau^-$ and hadrons, by assuming $(M_2, \mu) = (600, 320)$ GeV (the upper two figures (a) and (b)), or $(M_2, \mu) = (320, 600)$ GeV (the lower figures (c) and (d)).

- The branching ratios of $\tilde{\chi}_1^-$ decays to $W^-$ and $H^-$ have a rather weak dependence on tan β, and

$$\text{Br}(\tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 W^-) > \text{Br}(\tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 H^-),$$

in the whole region of tan β = [7, 50].

- For the considered three body decays, there is the hierarchy

$$\text{Br}(\tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 \text{hadrons}) > \text{Br}(\tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 \tau^- \bar{\nu}_\tau) > \text{Br}(\tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 l^- \bar{\nu}_l),$$

where $l = (e, \mu)$.

For the case of $(M_2, \mu) = (320, 600)$ GeV, as illustrated by Fig.3(c) and 3(d), we find a rather different picture from the case for $(M_2, \mu) = (600, 320)$ GeV: For the region of large tan β, say tan β > 15, we find

$$\text{Br}(\tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 W^-) \gtrsim \text{Br}(\tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 H^-),$$

$$\text{Br}(\tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 \text{hadrons}) \lesssim \text{Br}(\tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 \tau^- \bar{\nu}_\tau) \gg \text{Br}(\tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 l^- \bar{\nu}_l),$$
with \( l = (e, \mu) \). From Eqs.\((24, 27)\) one can see that the pattern of the branching ratios of the considered decays for two sets of input parameters \((M_2, \mu)\) are rather different, which can be tested in the future experiments. Once people find branching ratios of \( \tilde{\chi}_1^- \) decay modes are different from \( W \) decays, one can believe that the charged Higgs most possibly exist.

In Table II we list the theoretical predictions for the branching ratios of the three body decays \( \tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 f f' \) for the four sets of input parameters \((M_2, \mu)\), and for \( \tan \beta = 20 \). Set-A: \((M_2, \mu) = (600, 430) \text{ GeV}\); Set-B: \((M_2, \mu) = (650, 320) \text{ GeV}\); Set-C: \((M_2, \mu) = (320, 650) \text{ GeV}\); and Set-D: \((M_2, \mu) = (430, 600) \text{ GeV}\).

TABLE II. Theoretical predictions for the branching ratios of the lighter chargino three body decays \( \tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 f f' \) for the given values of \((M_2, \mu)\), and for \( \tan \beta = 20 \).

| Tree | 1-Loop |
|------|--------|
| \( \tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 f f' \) | \( \tilde{\chi}_1^0 \rightarrow \tilde{\chi}_1^0 f f' \) |
| Set-A | 0.0647 0.0661 0.4622 0.4070 0.0637 0.0640 0.4670 0.4063 |
| Set-B | 0.0875 0.0882 0.2895 0.5347 0.0875 0.0867 0.2738 0.5532 |
| Set-C | 0.0557 0.0574 0.5298 0.3570 0.0531 0.0540 0.5529 0.3409 |
| Set-D | 0.0381 0.0403 0.6632 0.2583 0.0359 0.0377 0.6916 0.2353 |

In the framework of R-parity conserved MSSM, we study the higgsino and wino-like lighter chargino decays to LSP and two SM fermions at one loop level. The relevant SUSY parameters are chosen to make two body decay modes \( \tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 W^- \) and \( \tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 H^- \) are kinematically open while others are closed. In this work the lightest neutralino is supposed to be bino-like, and the charged Higgs boson mass is supposed to be lighter than \( m_t + m_b \). From our studies we find that (a) the loop effects on the branching ratios are small, less than 3\% in magnitude; (b) the pattern of the decay rates of the considered decays on the choice of \((M_2, \mu)\) are specific and could be tested by future experiments, which could also be help for searching for the signal of the charged Higgs boson.

For the light charged Higgs boson with mass lighter than the top quark mass, it’s dominant decay mode is \( H^- \rightarrow \tau^- \nu_\tau \) with branching ratio \( \sim 100\% \). The main background of charged Higgs production is \( W \) boson, which mainly decays to hadronic final states. Once branching ratio of \( \tilde{\chi}_1^- \) decays to \( \tau^- \nu_\tau \) final state is found to be larger than that of \( W \) boson decays, it indicates that the charged Higgs boson may exist. Suppose coupling of charged Higgs boson with \( \tau^- \nu_\tau \) is well measured in other processes, branching ratios of \( \tilde{\chi}_1^- \) decays to \( H^- \) and \( W^- \), and hence the relation between SUSY parameters can be well determined from the branching ratio of \( \tilde{\chi}_1^- \) decaying to \( \tilde{\chi}_1^0 \tau^- \nu_\tau \) final state.

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