Neutralinos from Chargino Decays
in the Complex MSSM

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We review the evaluation of two-body decay modes of charginos in the Minimal Supersymmetric Standard Model with complex parameters (cMSSM). Assuming heavy scalar quarks we take into account all decay channels involving charginos, neutralinos, (scalar) leptons, Higgs bosons and SM gauge bosons. The evaluation of the decay widths is based on a full one-loop calculation including hard and soft QED radiation. Here we focus on the decays involving the Lightest Supersymmetric Particle (LSP), i.e. the lightest neutralino, or a heavier neutralino and a W boson. The higher-order corrections of the chargino decay widths can easily reach a level of $\pm 10\%$, translating into corrections of similar size in the respective branching ratios. These corrections are important for the correct interpretation of LSP and heavier neutralino production at the LHC and at a future linear e^+e^- collider.

1 Introduction

The search for physics effects beyond the Standard Model (SM), both at present and future colliders, constitutes one of the priorities of current high energy physics, where the Minimal Supersymmetric Standard Model (MSSM) [1] is one of the leading candidates. A related important task is investigating the production and measurement of the properties of Cold Dark Matter (CDM). The MSSM offers a natural candidate of CDM, the Lightest Supersymmetric Particle (LSP), i.e. the lightest neutralino, $\tilde{\chi}_1^0$ [2]. Having a stable LSP also ensures that any produced supersymmetric particle will lead to cascades with neutralinos in the final state, motivating experimental and phenomenological analyses of these decay chains. While discoveries of supresymmetric particles will possibly be made by the LHC, a precise determination of their properties is expected at the ILC [3–5] (or any other future e^+e^- collider such as CLIC).

Charginos, $\tilde{\chi}_i^\pm$, $(i = 1, 2)$, and neutralinos, $\tilde{\chi}_j^0$, $(j = 1, 2, 3, 4)$, are, respectively, the charged and neutral supersymmetric partners of the Higgs and gauge bosons. Therefore masses and couplings of charginos and neutralinos depend on common parameters, and an analysis of chargino decays provides direct and indirect information on the neutralino sector.

In order to yield a sufficient accuracy, one-loop corrections to the various chargino decay modes have to be considered. A precise calculation of the branching ratio (BR) at the one-loop level requires the calculation of all decay modes at this level of precision. Here we review the results for the evaluation of these decay modes (and BRs) obtained in the MSSM with complex parameters (cMSSM) [6] (original results for the tree-level decays were presented in [7]). We show results for

$$\Gamma(\tilde{\chi}_2^\pm \to \tilde{\chi}_j^0 W^\pm), \quad j = 1, 2, 3 . \tag{1}$$

The total decay width is defined as the sum of all the partial two-body decay widths, *all* evaluated at the one-loop level. Detailed references to existing calculations of these decay widths, branching ratios, as well as about the extraction of complex phases can be found in Ref. [6]. Our results will be implemented into the Fortran code `FeynHiggs` [8–11].

2 Renormalization of the cMSSM

All the relevant two-body decay channels have been evaluated at the one-loop level, including hard QED radiation. This requires the simultaneous renormalization of several sectors of the cMSSM: the gauge and Higgs sector, the chargino/neutralino sector, and the lepton and slepton sector. The on-shell renormalization conditions for the chargino/neutralino sector are fixed requiring that the masses of the two charginos and of the lightest neutralino are not renormalized. An analysis of various renormalization schemes for the chargino/neutralino sector was recently published in Ref. [12]. Further details about our notation and about the renormalization of the cMSSM can be found in Refs. [6, 13, 14].

In order to highlight the important role of the absorptive contributions in the presence of complex couplings, we also evaluated for comparison the decay widths neglecting the imaginary parts of self-energy type corrections to external (on-shell) particles. These imaginary contributions, in product with an imaginary part of a complex coupling (such as M_1 in our case), can give an additional real contribution to the decay width. This contribution is odd under charge conjugation and leads to a difference in the decay widths for the chargino and its antiparticle. The resulting CP-asymmetry, however, is one-loop suppressed (and will not be analyzed here).

The diagrams and corresponding amplitudes have been obtained with `FeynArts` [15]. The model file, including the MSSM counter terms, is based largely on Ref. [16] and is discussed in more detail in Ref. [13]. The further evaluation has been performed with `FormCalc` (and `LoopTools`) [17]. As regularization scheme for the UV-divergences we have used constrained differential renormalization [18], which has been shown to be equivalent to dimensional reduction [19] at the one-loop level [17]. Thus the employed regularization preserves SUSY [20,21]. All UV-divergences cancel in the final result. (Also the IR-divergences cancel in the one-loop result as required.)

3 Numerical results

The numerical examples shown below have been evaluated using the parameters given in Tab. 1. We assume that the scalar quarks are heavy such that they do not contribute to the total decay widths of the charginos. We invert the expressions of the chargino masses in order to express the parameters μ and M_2 (which are chosen real) as a function of $m_{\tilde{\chi}_1^\pm}$ and $m_{\tilde{\chi}_2^\pm}$. This leaves two choices for the hierarchy of μ and M_2:

$$\mathcal{S}_> : \mu > M_2 \quad (\tilde{\chi}_2^\pm \text{ more higgsino-like}) , \tag{2}$$

$$\mathcal{S}_< : \mu < M_2 \quad (\tilde{\chi}_2^\pm \text{ more gaugino-like}) . \tag{3}$$

The absolute value of M_1 is fixed via the GUT relation (with $|M_2| \equiv M_2$),

$$|M_1| = \frac{5}{3} \tan^2 \theta_{\mathrm{w}} M_2 \approx \frac{1}{2} M_2 . \tag{4}$$

Scen.	$\tan\beta$	$M_{H^\pm}$	$m_{\tilde\chi_2^\pm}$	$m_{\tilde\chi_1^\pm}$	$M_{\tilde l_L}$	$M_{\tilde l_R}$	A_l
$\mathcal{S}$	20	160	600	350	300	310	400

Table 1: MSSM parameters for the initial numerical investigation; all masses are in GeV.

leaving φ_{M_1} as a free parameter.

The values of $m_{\tilde\chi_{1,2}^\pm}$ allow copious production of the charginos in SUSY cascades at the LHC. Furthermore, the production of $\tilde\chi_1^\pm\tilde\chi_2^\mp$ or $\tilde\chi_1^+\tilde\chi_1^-$ at the ILC(1000), i.e. the ILC with $\sqrt{s}=1000$ GeV, via $e^+e^- \to \tilde\chi_1^\pm\tilde\chi_{1,2}^\mp$ will be possible, with all the subsequent decay modes to a neutralino and a W boson being open. The clean environment of the ILC would permit a detailed study of the chargino decays [4,5]. For the values in Tab. 1 and unpolarized beams we find, for $\mathcal{S}_>$ ($\mathcal{S}_<$), $\sigma(e^+e^- \to \tilde\chi_1^\pm\tilde\chi_2^\mp) \approx 4\,(12)$ fb, and $\sigma(e^+e^- \to \tilde\chi_1^+\tilde\chi_1^-) \approx 55\,(80)$ fb. Choosing appropriate polarized beams these cross sections can be enhanced by a factor of approximately 2 to 3. An integrated luminosity of $\sim 1\,\mathrm{ab}^{-1}$ would yield about $4-12\times 10^3$ $\tilde\chi_1^\pm\tilde\chi_2^\mp$ events and about $55-80\times 10^3$ $\tilde\chi_1^+\tilde\chi_1^-$ events, with appropriate enhancements in the case of polarized beams.

The ILC environment would result in an accuracy of the relative branching ratio close to the statistical uncertainty: assuming an integrated luminosity of $1\,\mathrm{ab}^{-1}$ a BR of 10% could be determined to $\sim 2\%$ for the $m_{\tilde\chi_i^\pm}$ values of Tab. 1.

The results shown here consist of "tree", which denotes the tree-level value and of "full", which is the decay width including *all* one-loop corrections. Also shown in Fig. 1, is the result leaving out the contributions from absorptive parts of the one-loop self-energy corrections as discussed in the previous section, labeled as "full R". Not shown here are the BRs and their relative corrections, since they are more parameter dependent.

In Figure 1 we show $\Gamma(\tilde\chi_2^- \to \tilde\chi_1^0 W^-)$ (top), $\Gamma(\tilde\chi_2^- \to \tilde\chi_2^0 W^-)$ (middle), and $\Gamma(\tilde\chi_2^- \to \tilde\chi_3^0 W^-)$ (bottom row) as a function of of φ_{M_1}, for the parameters of Tab. 1. The left (right) columns display the (relative one-loop correction to the) decay width.

We observe a strong dependence on φ_{M_1} in scenario $\mathcal{S}_<$, in which the three lightest neutralinos are highly mixed states. The effect of the absorptive contributions, both from the imaginary parts of the self energies (see as the difference between the "full" and "full R" curves), as well as from the imaginary parts of the vertex corrections, turn out to be of a few percent. On the contrary, in scenario $\mathcal{S}_>$, where only $\tilde\chi_2^- \to \tilde\chi_{1,2}^0 W^-$ is kinematically allowed, the mixing of the neutralinos is small, and consequently the dependence on φ_{M_1} turns out to be much smaller. The size of the one-loop corrections, reach $\mathcal{O}(10\%)$ for $\mathcal{S}_<$ and show an important dependence on φ_{M_1}. For $\mathcal{S}_>$ the corrections are of the order of a few percent with a negligible φ_{M_1} dependence.

Figure 2 shows $\Gamma(\tilde\chi_2^- \to \tilde\chi_1^0 W^-)$ (top) and $\Gamma(\tilde\chi_2^- \to \tilde\chi_{2,3}^0 W^-)$ (bottom row) as a function of $m_{\tilde\chi_2^\pm}$, keeping all other parameters as in Tab. 1. As in the previous figure, the left (right) column shows (the relative size of the corrections of) the decay widths. The vertical lines indicate where $m_{\tilde\chi_1^\pm} + m_{\tilde\chi_2^\pm} = 1000$ GeV, i.e. the maximum reach of the ILC(1000). Coincidentally, around this value of $m_{\tilde\chi_2^\pm}$ we observe a level crossing of the second and third neutralino in $\mathcal{S}_<$, which points out at the large neutralino mixing for these paramters.

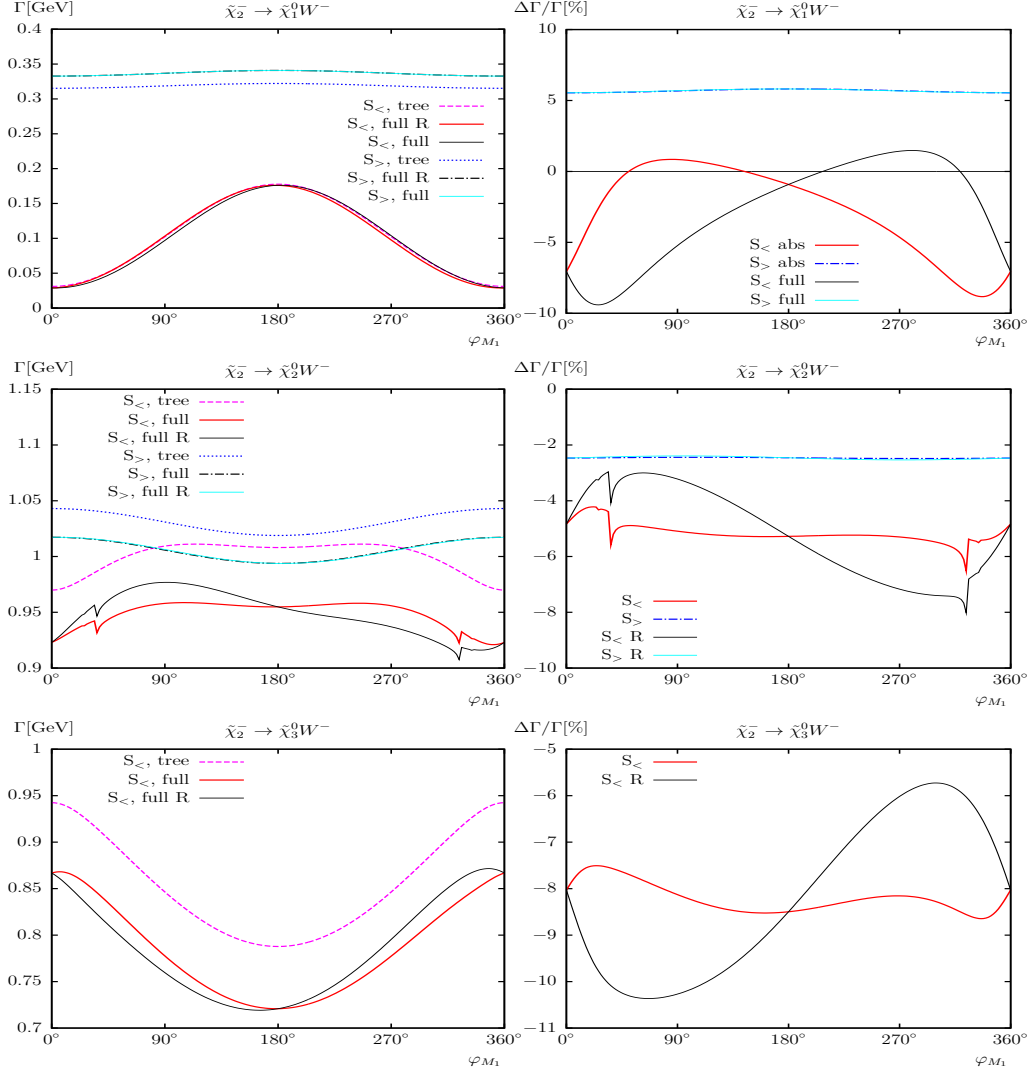The decay widths show a strong dependence on $m_{\tilde\chi_2^\pm}$ which is mainly due to the changing

Γ[GeV] $\tilde{\chi}_2^- \to \tilde{\chi}_1^0 W^-$ **ΔΓ/Γ[%]** $\tilde{\chi}_2^- \to \tilde{\chi}_1^0 W^-$

- $S_<$, tree
- $S_<$, full R
- $S_<$, full
- $S_>$, tree
- $S_>$, full R
- $S_>$, full

- $S_<$ abs
- $S_>$ abs
- $S_<$ full
- $S_>$ full

Γ[GeV] $\tilde{\chi}_2^- \to \tilde{\chi}_2^0 W^-$ **ΔΓ/Γ[%]** $\tilde{\chi}_2^- \to \tilde{\chi}_2^0 W^-$

- $S_<$, tree
- $S_<$, full
- $S_<$, full R
- $S_>$, tree
- $S_>$, full
- $S_>$, full R

- $S_<$
- $S_>$
- $S_<$ R
- $S_>$ R

Γ[GeV] $\tilde{\chi}_2^- \to \tilde{\chi}_3^0 W^-$ **ΔΓ/Γ[%]** $\tilde{\chi}_2^- \to \tilde{\chi}_3^0 W^-$

- $S_<$, tree
- $S_<$, full
- $S_<$, full R

- $S_<$
- $S_<$ R

φ_{M_1}

Figure 1: $\Gamma(\tilde{\chi}_2^- \to \tilde{\chi}_j^0 W^-)$, $j = 1, 2, 3$. Tree-level ("tree") and full one-loop ("full") corrected decay widths are shown with the parameters chosen according to $\mathcal{S}$ (see Tab. 1), with ϕ_{M_1} varied. Also shown are the full one-loop corrected decay widths omitting the absorptive contributions ("full R"). The left (right) plots show (the relative size of the corrections of) the decay width.

chargino-neutralino couplings, as well as the change in the phase space. For $\mathcal{S}_<$ the decay width into the lightest neutralino almost vanishes at one point, resulting in large relative corrections. The relative one-loop corrections are mostly of $\mathcal{O}(10\%)$. The dips in the one-loop corrections are due to thresholds in the vertex corrections. It should be noted that
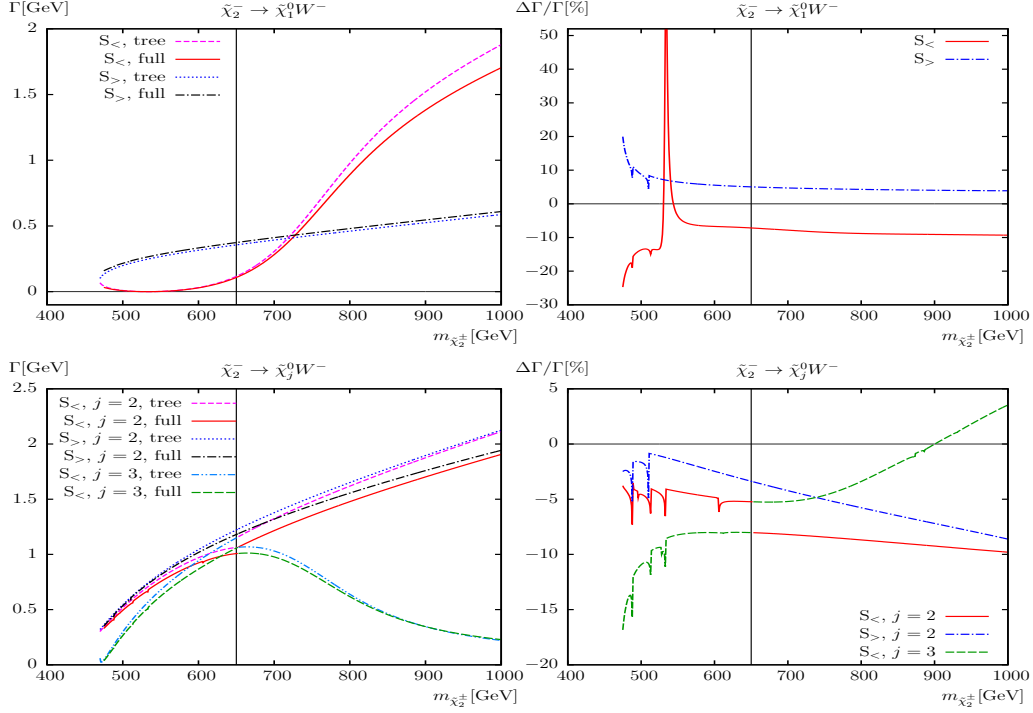
Figure 2: $\Gamma(\tilde{\chi}_2^- \to \tilde{\chi}_j^0 W^-)$, $j = 1, 2, 3$. Tree-level ("tree") and full one-loop ("full") corrected decay widths are shown with the parameters chosen according to $\mathcal{S}$ (see Tab. 1), with $m_{\tilde{\chi}_2^\pm}$ varied. The left (right) plots show the decay width (the relative size of the corrections).

a calculation very close to threshold requires the inclusion of additional (non-relativistic) contributions, which is far beyond the scope of this analysis.

The decay width into $\tilde{\chi}_2^0$ reaches ~ 2 GeV at $m_{\tilde{\chi}_2^\pm} = 1$ TeV, while for the decay into $\tilde{\chi}_3^0$ it reaches ~ 1 GeV in the region of maximal neutralino mixing. The relative one-loop corrections are of $\mathcal{O}(5 - 10\%)$.

Summarizing, we reviewed the evaluation of two-body decay modes of charginos in the cMSSM, and show numerical results for the decay of the heavier chargino into neutralinos. The relative size of the one-loop corrections is found to be significant and should be taken into account in a reliable determination of the chargino/neutralino sector parameters. This also applies in particular to the effects of the imaginary parts of the self-energies of the external particles.

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