Radiative Corrections to Chargino Production in Electron-Positron Collisions with Polarised Beams

Marco A. Díaz\textsuperscript{1}, Stephen F. King\textsuperscript{2} and Douglas A. Ross\textsuperscript{2}

\textsuperscript{1}Departamento de Física, Universidad Católica de Chile, Av. Vicuña Mackenna 4860, Santiago, Chile
\textsuperscript{2}Department of Physics and Astronomy, University of Southampton, Southampton, SO17 1BJ, U.K.

Abstract

We study radiative corrections to chargino production at linear colliders with polarised electron beams. We calculate the one-loop corrected cross-sections for polarised electron beams due to three families of quarks and squarks, working in the $\overline{MS}$ scheme, extending our previous calculation of the unpolarised cross-section with one-loop corrections due to the third family of quarks and squarks. In some cases we find rather large corrections to the tree-level cross-sections. For example for the case of right-handed polarised electrons and large $\tan\beta$ the corrections can be of order 30\%, allowing sensitivity to the squark mass parameters.
Charginos are important in Supersymmetry (SUSY) for several reasons. To begin with they will possibly be the next-to-lightest SUSY particles (after the lightest neutralino) and so be amongst the first supersymmetric particles to be discovered. Secondly, being colour singlets, they provide a clean laboratory for studying and extracting the fundamental parameters of SUSY. Thirdly they are naturally produced in a polarised state, and their polarisation is imprinted onto the angular distribution of their decay products, enabling important information about the nature of the underlying SUSY theory to be extracted from experiment.

Since LEP has failed to find evidence for any SUSY particles [1], one must await the construction of the next generation of electron-positron machines, which will be linear colliders, to perform high precision studies of chargino physics. Although charginos may be discovered earlier at hadron colliders, it is only at such linear colliders, with the added advantage of polarised beams, that the parameters of SUSY can begin to be extracted with any precision [2]. In the context of such high energy, high precision colliders, the polarisation properties of the produced charginos can be studied via the angular distribution of the decay products as has been recently discussed by several groups [3].

Such studies involve helicity amplitudes for both chargino production and decay which undergo quantum interference due to the short lifetime of the charginos. Thus far both the production and decay helicity amplitudes have only been studied to lowest order, although the spin averaged cross-section for chargino production in $e^+e^-$ collisions has been calculated at one-loop, including third family quark and squark loop corrections [4, 5], and the radiative corrections to the chargino self-energy has been calculated including all one-loop radiative corrections [6].

In this letter, then, we present the first study of the radiative corrections to chargino production in electron-positron collisions, including contributions from three generations of squark and quark loops, for the case of polarised electron beams. Our main purpose here is to study such corrections numerically, and show that the effects may be rather large in some cases. Although the radiative corrections in the cross-sections are of order 1-10% in general, for the cross-section for right-handed electrons we observe strong cancellations in the tree-level result due to interference terms with negative signs, and in this case the radiative corrections may be of order 30% for large $\tan \beta$.

We consider pair production of charginos with momenta $k_1$ and $k_2$ in electron-
positron scattering with incoming momenta $p_1$ and $p_2$:

$$e^+(p_2) + e^-(p_1) \rightarrow \tilde{\chi}^+(k_2) + \tilde{\chi}^-(k_1)$$

(1)

where we take $\tilde{\chi}^+$ to be the particle and $\tilde{\chi}^-$ to be the antiparticle, with the Feynman rules as given in Haber and Kane \[7\]. Henceforth we drop the subscripts $b$ and $a$, but understand that the two charginos have masses $m_b$ and $m_a$ respectively and in general $m_b \neq m_a$.

In \[8\] it was shown that at the tree-level one can (after appropriate Fierz transformation) write the scattering amplitudes as

$$-ie^2 s \left[ \bar{v}(e^+) \gamma^\mu \frac{(1 - \gamma^5)}{2} u(e^-) \right] \left( Q_{LL}^{(0)} \left[ \bar{u}(\tilde{\chi}^+) \gamma_\mu \frac{(1 - \gamma^5)}{2} v(\tilde{\chi}^-) \right] + Q_{LR}^{(0)} \left[ \bar{u}(\tilde{\chi}^+) \gamma_\mu \frac{(1 + \gamma^5)}{2} v(\tilde{\chi}^-) \right] \right)$$

(2)

for left-polarized incident electrons, with a similar result for right-polarized incident electrons with the electron projection operator $\frac{(1 - \gamma^5)}{2}$ replaced by $\frac{(1 + \gamma^5)}{2}$ and $Q_{L/\beta}^{(0)}$ replaced by $Q_{R/3}^{(0)}$, where the superscript zero indicates tree-level. Note that since we take the positive chargino to be the particle, the index $\beta = L, R$ is related to that in \[8\] by $L \leftrightarrow R$.

At one-loop order we find a more general structure. Nevertheless the amplitudes may be written as

$$-ie^2 s \left[ \bar{v}(e^+) \gamma^\mu \frac{(1 - \gamma^5)}{2} u(e^-) \right] \sum_{i=1}^{5} Q_{Li}^{(1)} \left[ \bar{u}(\tilde{\chi}^+) \Gamma^i v(\tilde{\chi}^-) \right],$$

(3)

for left-polarized incident electrons, with a similar result for right-polarized incident electrons with the electron projection operator $\frac{(1 - \gamma^5)}{2}$ replaced by $\frac{(1 + \gamma^5)}{2}$, and $Q_{Li}^{(1)}$ replaced by $Q_{Ri}^{(1)}$ where the superscript unity indicates one-loop, and where

$$\Gamma^1 = \frac{(1 + \gamma^5)}{2}$$

(4)

$$\Gamma^2 = \frac{(1 - \gamma^5)}{2}$$

(5)

$$\Gamma^3 = \gamma^\nu \frac{(1 + \gamma^5)}{2}$$

(6)

$$\Gamma^4 = \gamma^\nu \frac{(1 - \gamma^5)}{2}$$

(7)

$$\Gamma^5 = \sigma^{\nu\rho} = 2 \left[ \gamma^\nu, \gamma^\rho \right]$$

(8)
Figure 1: One–loop renormalized $M_Z$, $M_\gamma$ and $M_{\tilde{\nu}_e}$ amplitudes in the approximation where three families of quarks and squarks are considered inside the loops.
Note that the coefficients $Q_{Li}^{(1)}$ and $Q_{L2}^{(1)}$ are vectors, $Q_{Li}^{(1)}$ and $Q_{L4}^{(1)}$ are two-rank tensors, and $Q_{L5}^{(1)}$ is a three-rank tensor, and similarly for $Q_{Ri}^{(1)}$.

In the presence of one-loop corrections, due to the three families of quarks and squarks, the amplitude for $e^+e^- \rightarrow \tilde{\chi}_a^+ \tilde{\chi}_a^-$ may be expressed as the sum of three amplitudes $M_Z$, $M_\gamma$, $M_{\tilde{\nu}}$ as shown in Fig. 1. The shaded bubbles in that figure are one–loop renormalized total vertex functions defined as $iG_{Z\chi\chi}^{ab}$, $iG_{\gamma\chi\chi}^{ab}$, $iG_{\tilde{\nu}\chi\chi}^{\pm b}$, and $iG_{\tilde{\nu}\chi\chi}^{-a}$. In the total vertex functions we include the tree level vertex, the one–particle irreducible vertex diagrams plus the vertex counterterm, and the one–particle reducible vertex diagrams plus their counterterms. Although the detailed expressions for the total vertex functions is quite complicated, by exploiting the possible Lorentz structures of the diagrams it is possible to express them in terms of just a few form factors which are generalisations of those presented for the case of the third quark and squark family in [4], where explicit expressions may be found. These form factors may in turn be related to the quantities $Q_{Li}^{(1)}$ defined in Eq. (3), and similarly for $Q_{Ri}^{(1)}$, as we shall show in detail in a forthcoming publication [9].

One of the main purposes of this letter is to examine the numerical effect of these corrections, and show that in some cases they may be rather large. For definiteness at the $\overline{MS}$ scale $Q = M_Z$ we take the $SU(2)_L$ gaugino mass $M_2$ to be 165 GeV, the $\mu$ parameter to be 400 GeV and the remaining trilinear $A$ and (degenerate) squark soft mass parameters $A = M_Q = M_U = M_D$ to be 500 GeV initially. We also assume a sneutrino mass of 500 GeV. Note that the lighter chargino (1) will be mainly wino, with a mass $\approx M_2$, and the heavier chargino (2) will be mainly higgsino with a mass $\approx \mu$ in this example.

Assuming these parameters with $\tan \beta = 5$, Figure 2 shows the cross-section for the production of the lightest chargino pair for beams of left-handed polarized electrons as a function of the centre of mass energy. The effect of radiative corrections is to reduce the cross-section by a few per cent, with a noticeable shift in the lightest chargino mass threshold due to the more steeply rising threshold.

Figure 3 displays the cross-section for the production of both lightest and unequal mass chargino pairs for beams of right-handed polarized electrons as a function of the centre of mass energy, for the same parameters as before with $\tan \beta = 5$. The unequal mass cross-section $\sigma^{12}$ refers to $b = 1, a = 2$, which is equal to the cross-
Figure 2: Lowest order (L.O.) and higher order (H.O.) cross-section for lightest chargino pair production for left-polarized electrons with \( \tan \beta = 5 \) and the other parameters as given in the text.

Figure 3: Lowest order (L.O.) and higher order (H.O.) cross-sections for lightest and unequal mass chargino pair production for right-polarized electrons with \( \tan \beta = 5 \) and the other parameters as given in the text.
Figure 4: Lowest order (L.O.) and higher order (H.O.) cross-sections for lightest and unequal mass chargino pair production for right-polarized electrons with \( \tan \beta = 50 \) and the other parameters as given in the text.

section for \( b = 2, a = 1 \) assuming CP to be conserved, although the two cross-sections are not added together in the figures. Note that the cross-section for the lightest chargino pairs with right-handed electrons in Figure 3 are about 500 times smaller than with left-handed electrons in Figure 2, nevertheless with an integrated luminosity of \( 10^6 \, pb^{-1} \) it will be easily measurable. The radiative corrections involving right-handed incident electrons in Figure 3 are larger than for left-handed incident electrons in Figure 2, and may now be as large as about 10%. Note the shift in the second chargino mass threshold.

Increasing \( \tan \beta \) to 50 makes very little difference to the tree-level and one-loop corrected cross-section for left-handed electrons, as compared to the results for \( \tan \beta = 5 \) in Figure 2. However for right-handed electrons, increasing \( \tan \beta \) to 50 leads to the much larger radiative corrections shown in Figure 4 as compared to Figure 3. In view of the large radiative corrections in this case, we proceed to study these regions in a little more detail.

\(^2\) The reason for the smallness of the cross-section for lightest chargino production with right-handed electrons is due to a destructive interference between the photon and \( Z \) diagrams, compared to a constructive interference with left-handed electrons. This is due to the approximately axial couplings of electrons to the \( Z \). The absence of the sneutrino exchange diagram for right-handed incident electrons then guarantees a small cross-section in this case. For the production of unequal mass charginos and right-handed electrons the photon exchange diagram is not present (at least at tree-level) and the cancellation does not occur, leading to the larger cross-section than the equal mass case in Figure 3.
Figure 5: Detailed blow-up of cross-sections for right-polarized electrons for the lightest chargino pair with $\tan \beta = 50$. The H.O. cross-sections are for degenerate squark soft mass parameters of 0.5 TeV and 1 TeV.

Figure 6: Detailed blow-up of the cross-sections for right-polarized electrons for the unequal mass chargino pair with $\tan \beta = 50$. The H.O. cross-sections are for degenerate squark soft mass parameters of 0.5 TeV and 1 TeV.
In Figure 5 we magnify a region of the cross-section for lightest chargino pair production for right-handed electrons above the threshold region in Figure 4. As already remarked, the effect of radiative corrections is quite large. The corrections depend on the (degenerate) squark mass as shown in Figure 5, where squark masses of 500 GeV (1 TeV) leads to negative corrections of about 25% (35%).

In Figure 6 we magnify a region of the cross-section for unequal mass chargino production for right-handed electrons, this time concentrating on the threshold region of Figure 4 where the corrections appear to be largest. The shift in the second chargino mass is clearly apparent, and is about 20 GeV (30 GeV) for squark masses of 500 GeV (1 TeV). The peak cross-section is reduced by about 20% (30%) for squark masses of 500 GeV (1 TeV). The sensitivity of the higher order corrections to the squark soft mass parameters for the case of right-handed incident electrons, shown in Figures 5 and 6, means that for the case of large tan $\beta$ at least, information about the soft squark masses may be inferred from sufficiently accurate measurements of the chargino production cross-sections.

In summary we have seen that for the case of right-handed polarised electron beams the effects of radiative corrections due to loops of quarks and squarks may give significant corrections to the lowest order result, particularly for large values of tan $\beta$. These results highlight the importance of being able to measure cross-sections with polarised electron beams at future linear colliders. Such large radiative corrections must be taken into account if the underlying SUSY parameters are to be accurately extracted from the experimentally measured chargino cross-sections. The corrections will involve the squark masses which may therefore be probed via radiative corrections. The effect of radiative corrections on the production of polarised charginos will be considered in a future publication [9].

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