Radiative corrections to chargino production in electron-positron collisions with polarized beams

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We study radiative corrections to chargino production at linear colliders with polarized electron beams. We calculate the one-loop corrected cross sections for polarized electon beams due to three families of quarks and squarks, working in the $\overline{\mathrm{MS}}$ scheme, extending our previous calculation of the unpolarized 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 polarized electrons and large tan β the corrections can be of order 30%, allowing sensitivity to the squark mass parameters.

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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 color singlets, they provide a clean laboratory for studying and extracting the fundamental parameters of SUSY. Thirdly they are naturally produced in a polarized state, and their polarization 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 the CERN e^+e^- collider 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 polarized 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 polarization 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 Brief Report, 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 polarized 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 β.

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:

$$e^+(p_2)+e^-(p_1)\to\tilde{\chi}_b^+(k_2)+\tilde{\chi}_a^-(k_1) \tag{1}$$

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

$$\begin{aligned}&\frac{-ie^2}{s}\left[\overline{v}(e^+)\gamma^\mu\frac{(1-\gamma^5)}{2}u(e^-)\right]\\&\times\left(Q_{LL}^{(0)}\left[\overline{u}(\tilde{\chi}^+)\gamma_\mu\frac{(1-\gamma^5)}{2}v(\tilde{\chi}^-)\right]\right.\\&\left.+Q_{LR}^{(0)}\left[\overline{u}(\tilde{\chi}^+)\gamma_\mu\frac{(1+\gamma^5)}{2}v(\tilde{\chi}^-)\right]\right)\end{aligned} \tag{2}$$

for left-polarized incident electrons, with a similar result for right-polarized incident electrons with the electron projection operator $(1-\gamma^5)/2$ replaced by $(1+\gamma^5)/2$ and $Q_{L\beta}^{(0)}$ replaced by $Q_{R\beta}^{(0)}$, 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

$$\begin{aligned}&\frac{-ie^2}{s}\left[\overline{v}(e^+)\gamma^\mu\frac{(1-\gamma^5)}{2}u(e^-)\right]\\&\times\sum_{i=1\ldots5}Q_{Li}^{(1)}[\overline{u}(\tilde{\chi}^+)\Gamma^i v(\tilde{\chi}^-)],\end{aligned} \tag{3}$$

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

$$\Gamma^{1,2} = \frac{(1 \pm \gamma^5)}{2} \tag{4}$$

$$\Gamma^{3,4} = \gamma^{\nu} \frac{(1 \pm \gamma^5)}{2} \tag{5}$$

$$\Gamma^5 = \sigma^{\nu\rho} = \frac{i}{2}[\gamma^{\nu}, \gamma^{\rho}]. \tag{6}$$

Note that the coefficients $Q_{L1}^{(1)}$ and $Q_{L2}^{(1)}$ are vectors, $Q_{L3}^{(1)}$ 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 $e^+e^- \rightarrow \tilde{\chi}_b^+ \tilde{\chi}_a^-$ may be expressed as the sum of three amplitudes M_Z, M_{γ}, $M_{\tilde{\nu}}$. As explained in Ref. [4], we define one-loop renormalized total vertex functions as $i\mathcal{G}_{Z\chi\chi}^{ab}$, $i\mathcal{G}_{\gamma\chi\chi}^{ab}$, $i\mathcal{G}_{\tilde{\nu}_e e\chi}^{+b}$, and $i\mathcal{G}_{\tilde{\nu}_e e\chi}^{-a}$. 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 generalizations 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[1] [9]. We consider our approximation reasonable since by keeping quarks and squarks in the loops we gain a color factor $N_c=3$ and a flavor factor $N_f=3$ (summation over generations was not done in our previous work in [4]), in addition to having large Yukawa couplings in the third generation, especially at large values of $\tan\beta$. For this reason we think that the electroweak corrections we have neglected (including box diagrams) will not dominate and, therefore, that our conclusions will not change. Despite this, we recognize that a complete one-loop calculation is necessary [9].

One of the main purposes of this Brief Report is to examine the numerical effect of these corrections, and show that in some cases they may be rather large and with some dependence on the squark masses. For definiteness at the modified minimal subtraction scheme ($\overline{\text{MS}}$) scale $Q=M_Z$ we take the $SU(2)_L$ gaugino mass M_2 to be 165 GeV, the μ 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 W-ino, with a mass $\approx M_2$, and the heavier chargino (2) will be mainly Higgsino with a mass $\approx \mu$ in this example. Since we work in the $\overline{\text{MS}}$ scheme, the above parameters are running parameters taken directly from the output of the renormalization group equations (RGE's), which is an advantage when working in supergravity- (SUGRA-) type models. Of course, the chargino masses we use to calculate the cross sections at one-loop are the pole (physical) masses.

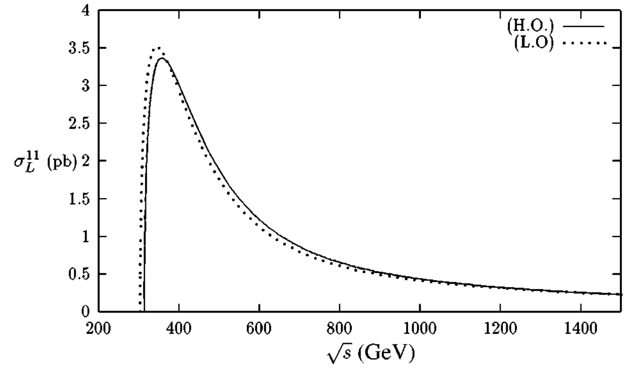

FIG. 1. Lowest order (LO) and higher order (HO) cross section for lightest chargino pair production for left-polarized electrons with $\tan\beta=5$ and the other parameters as given in the text.

Assuming these parameters with $\tan\beta=5$, Fig. 1 shows the cross section for the production of the lightest chargino pair for beams of left-handed polarized electrons as a function of the center of mass energy. The effect of radiative corrections is to reduce the cross section by a few percent, with a noticeable shift in the lightest chargino mass threshold due to the more steeply rising threshold. The difference between thresholds in this figure corresponds to twice the difference between the pole and running masses of the lightest chargino.

Figure 2 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 center

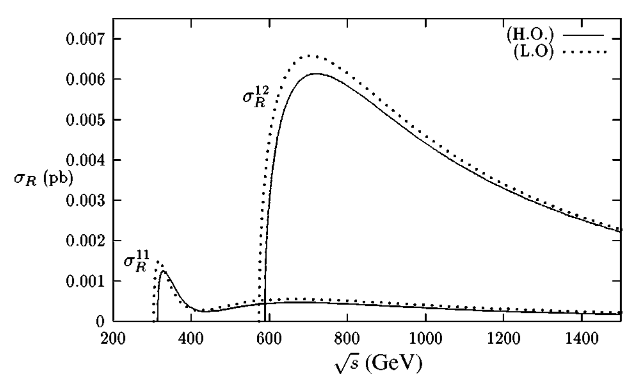

FIG. 2. Lowest order (LO) and higher order (HO) cross sections for lightest and unequal mass chargino pair production for right-polarized electrons with $\tan\beta=5$ and the other parameters as given in the text.

[1] The one-loop corrections due to quarks and squarks considered here do not involve the operator Γ^5.

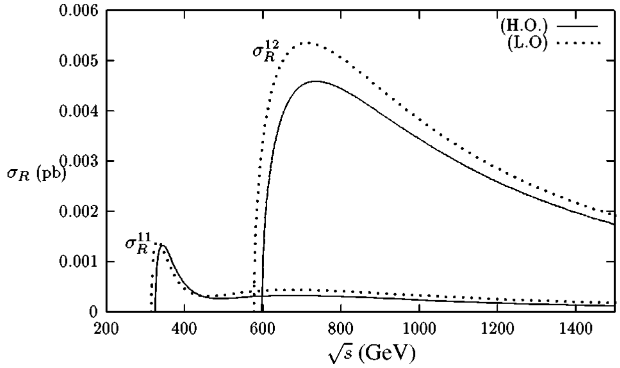

FIG. 3. Lowest order (LO) and higher order (H) cross sections for lightest and unequal mass chargino pair production for right-polarized electrons with $\tan\beta=50$ and the other parameters as given in the text.

of mass energy, for the same parameters as before with $\tan\beta=5$. The unequal mass cross-section σ^{12} refers to $b=1,a=2$, which is equal to the cross-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 Fig. 2 are about 500 times smaller than with left-handed electrons in Fig. 1, nevertheless with an integrated luminosity of 10^6 pb^{-1} it will be easily measurable.[2] The radiative corrections involving right-handed incident electrons in Fig. 2 are larger than for left-handed incident electrons in Fig. 1, 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 Fig. 1. However for right-handed electrons, increasing $\tan\beta$ to 50 leads to the much larger radiative corrections shown in Fig. 3 as compared to Fig. 2. In view of the large radiative corrections in this case, we proceed to study these regions in a little more detail.

In Fig. 4 we magnify a region of the cross section for lightest chargino pair production for right-handed electrons above the threshold region in Fig. 3. As already remarked, the effect of radiative corrections is quite large. The corrections depend on the (degenerate) squark mass as shown in Fig. 4, where squark masses of 500 GeV (1 TeV) leads to negative corrections of about 25% (35%).

In Fig. 5 we magnify a region of the cross section for

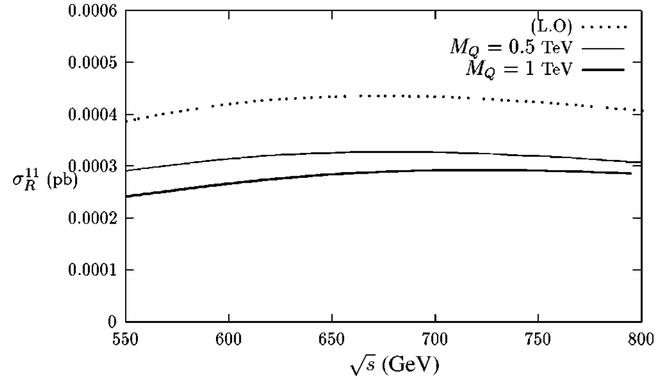

FIG. 4. Detailed blowup of cross sections for right-polarized electrons for the lightest chargino pair with $\tan\beta=50$. The HO cross sections are for degenerate squark soft mass parameters of 0.5 TeV and 1 TeV.

unequal mass chargino production for right-handed electrons, this time concentrating on the threshold region of Fig. 3 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 Figs. 4 and 5, 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.

Up to now we have chosen to compare the higher order corrections with a tree level cross section defined by fixing the SUSY parameters rather than the chargino masses, i.e., while the HO cross section involves the chargino pole masses, the LO cross section involves the chargino running masses, both pairs calculated with the same fixed values for the running parameters μ and M_2 at the scale m_Z. One may reasonably ask whether the higher order corrections described here are entirely due to the new threshold effects of the renormalized chargino masses. The way to answer that

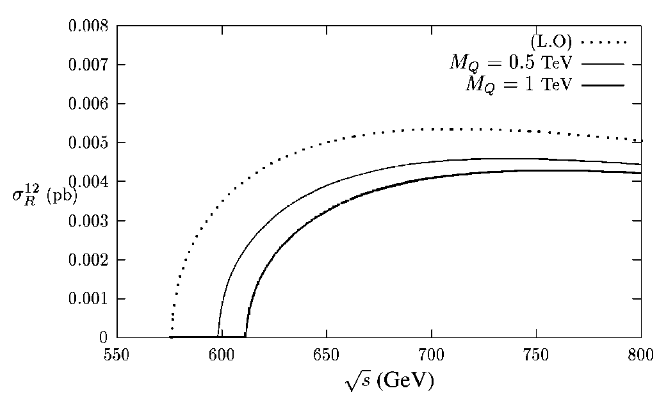

FIG. 5. Detailed blowup of the cross sections for right-polarized electrons for the unequal mass chargino pair with $\tan\beta=50$. The HO cross sections are for degenerate squark soft mass parameters of 0.5 TeV and 1 TeV.

[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 the tree level) and the cancellation does not occur, leading to the larger cross section than the equal mass case in Fig. 2.

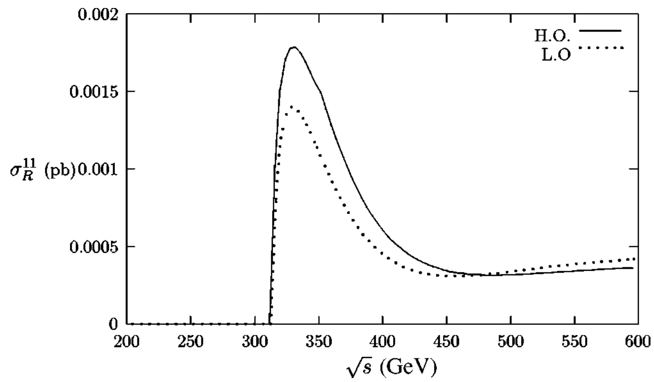

FIG. 6. LO and HO cross sections for tan $\beta = 50$ and degenerate squark soft mass parameters of 0.5 TeV, for the case where μ and M_2 are modified such that the chargino pole masses remain the same.

question is to compare the HO cross section involving the chargino pole masses calculated with the SUSY parameters $\mu(m_Z)$ and $M_2(m_Z)$ with a new LO cross section involving chargino running masses which have the same numerical value as the pole masses, but calculated with different SUSY parameters $\mu(m_Z)$ and $M_2(m_Z)$. In this way, all the corrections due to the renormalization of the chargino masses are hidden, and the difference between the LO and HO cross sections is due to genuine corrections to the cross section. In Fig. 6, where we take tan $\beta = 50$ and squark masses of 500 GeV, we show the comparison of the leading order and higher order corrections with these SUSY parameters so adjusted that the chargino masses remain unaltered. We see that in the region of the peak of the cross section for right handed polarized electrons we still get a substantial correction to the cross section which is of the order of 26% (and increasing to 34% for squark masses equal to 1 TeV). These corrections at the peak of the cross section are especially important because it is the center of mass energy likely to be used at a future Linear Collider to study these particles. In addition, since corrections become important rather close to the threshold, they may affect the chargino mass determination when the threshold method is used [10,11].

In summary we have seen that for the case of right-handed polarized 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 β. These results highlight the importance of being able to measure cross sections with polarized 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. An important part of the corrections are due to mass renormalization, but genuine corrections to the cross section can also be large, especially near the peak of the cross section. Since the radiative corrections to the chargino production cross section are sensitive to the squark masses, we have seen that information about the squark spectrum may be inferred from chargino production cross section. The effect of radiative corrections on the production of polarized charginos will be considered in a future publication [9].

Note added. After this Brief Report was submitted for publication there appeared [12] a complete one-loop calculation of the chargino production cross section and asymmetries, showing the importance of the corrections. The large radiative corrections to σ_R shown here were not observed in Ref. [12] because they only considered A_{LR} and since $\sigma_R \ll \sigma_L$ the effect was missed.

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