Effective Lagrangian for $\bar{q}q' \chi^+_j$, $\bar{q}q' \chi^0_j$ interactions and Fermionic Decays of the Squarks with CP Phases

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Abstract

The one loop corrected effective Lagrangian for the quark-squark-chargino and quark-squark-neutralino interactions is computed. The effective Lagrangian takes into account the loop corrections arising from the exchange of the gluinos, charginos, neutralinos, W, Z, the charged Higgs, and the neutral Higgs. We further analyze the squark decays into charginos and neutralinos and discuss the effect of the loop corrections on them. The analysis takes into account CP phases in the soft parameters. It is found that the loop corrections to the stop decay widths into chargino and neutralinos can be as much as thirty percent or even larger. Further, the stop decay widths show a strong dependence on the CP phases. These results are of relevance in the precision predictions of squark decays in the context of specific models of soft breaking in supergravity and string based models.

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1 Introduction

The $\tilde{q}\tilde{q}'\chi_j^+$ and $\tilde{q}\tilde{q}_i\chi_0^j$ interactions are of great interest since they enter in the decay of squarks. We expect that such decays will be observed at the collider experiments. Specifically one expects under the usual naturalness criteria that most of the sparticles should become visible at the Large Hadron Collider (LHC) with the possibility that some of the sparticles may also become visible at RUN II of the Tevatron. Measurements of sparticle masses and of their decay branching ratios will be a primary focus of attention after the discovery of such particles, while a more precise measurement will come eventually at the next linear collider (NLC). With the above in mind it is of great importance to refine the theoretical computations of the decay branching ratios beyond the tree level predictions. In this paper we extend the previous analyzes of squark decays into charginos and neutralinos[1, 2, 3] by taking into account the loop corrections with CP phases. For this purpose it is found advantageous to compute the one loop corrected effective Lagrangian for the $\tilde{q}\tilde{q}'\chi_j^+$ and $\tilde{q}\tilde{q}_i\chi_0^j$ couplings. In the analysis we also include the effect of CP phases. It is now well known that large CP phases can be made compatible[4, 5, 6, 7] with the experimental constraints on the electric dipole moments of the electron[8], of the neutron[9], and of the $Hg^{199}$ atom[10]. Further, if the phases are large they could affect a whole host of low energy phenomena. These include the effect on the higgs masses, couplings and decays[11, 12, 13, 14, 15, 16, 17, 18], dark matter[19, 20], and a variety of other phenomena[21]. The outline of the rest of the paper is as follows: In Sec.2 we compute the effective Lagrangian for the $\tilde{t}\tilde{b}\chi_j^+$ and $\tilde{b}\tilde{t}\chi_j^C$ interactions. In Sec.3 a similar analysis is done for the $\tilde{q}\tilde{q}_i\chi_j^0$ interaction. In Sec.4 we give an analysis of the decay widths of the squarks into charginos and neutralinos using the effective Lagrangian. In Sec.5 we give a numerical analysis of the size of the loop effects on the decay widths. We also study in this section the effect of CP phases on the decay widths. Conclusions are given in Sec.6.
2 Effective Lagrangian for $\bar{q}\tilde{q}_i\chi_j^\pm$ Interaction

In this section we study the effect of loop corrections on $\bar{t}\tilde{b}_i\chi_j^+$ and on $\bar{b}_i\tilde{t}_j\chi_c^-$ interactions.

We begin with the tree level Lagrangian density

$$L = g\bar{t}(R_{bij}P_R + L_{bij}P_L)\tilde{\chi}_j^+\tilde{b}_i + g\bar{b}(R_{ti}P_R + L_{ti}P_L)\tilde{\chi}_j^c\tilde{t}_i + H.c. \quad (1)$$

where

$$R_{bij} = -(U_{j1}D_{b1i} - K_bU_{j2}D_{b2i})$$
$$L_{bij} = K_tV_{j2}^*D_{bli}$$
$$R_{ti} = -(V_{j1}D_{t1i} - K_tV_{j2}D_{t2i})$$
$$L_{ti} = K_bU_{j2}^*D_{t1i} \quad (2)$$

and where

$$K_{t(b)} = \frac{m_{t(b)}}{\sqrt{2}m_W \sin \beta (\cos \beta)} \quad (3)$$

and the matrices $U, V$ and $D_{b(t)}$ are the diagonalizing matrices of the chargino and squark mass matrices so that

$$U^*M_\chi V^{-1} = \text{diag}(m_{\chi_1^+}, m_{\chi_2^+})$$
$$D_{\tilde{q}}^\dagger M_{\tilde{q}}^2 D_{\tilde{q}} = \text{diag}(m_{\tilde{q}_1}^2, m_{\tilde{q}_2}^2) \quad (4)$$

where $m_{\chi_i^+}$ ($i=1,2$) are the eigen values of the chargino mass matrix and $m_{\tilde{q}_i}^2$ ($i=1,2$) are the eigen values of the squark mass matrix. The loop corrections produce shift in the couplings of Eq. (2) as follows

$$L_{\text{eff}} = g\bar{t}(\Delta R_{bij}P_R + (L_{bij} + \Delta L_{bij})P_L)\tilde{\chi}_j^+\tilde{b}_i + g\bar{b}(\Delta R_{ti}P_R + (L_{ti} + \Delta L_{ti})P_L)\tilde{\chi}_j^c\tilde{t}_i + H.c. \quad (5)$$

where $\Delta R_{bij}, \Delta L_{bij}, \Delta R_{ti},$ and $\Delta L_{ti}$ are the corrections that arise from the diagrams in Figs.(1-4). As is conventional we will use the zero external momentum approximation in the analysis of these corrections (see, e.g., Ref.[22]).
2.1 $\Delta R_{bij}$ and $\Delta L_{bij}$ analysis

Contributions to $\Delta R_{bij}$ and $\Delta L_{bij}$ arise from the nine loop diagrams of Fig.(1). We discuss now in detail the contribution of each of these diagrams, figs. (1a-1i). We begin with the loop diagram of Fig.(1a) which contributes the following to $\Delta R_{bij}$ and $\Delta L_{bij}$

$$\Delta R_{bij}^{(1)} = \frac{2\alpha_s}{3\pi} \sum_{k=1}^{2} K_b U_{j2} D_{t1k}^* D_{b1l} e^{i\xi_3} D_{t1k} m_b m_{\tilde{g}} f(m_b^2, m_{\tilde{g}}^2, m_{t_k}^2)$$

$$\Delta L_{bij}^{(1)} = -\frac{2\alpha_s}{3\pi} \sum_{k=1}^{2} (V_{j1}^* D_{t1k}^* - K_l V_{j2}^* D_{t2k}^*) D_{t2k} D_{b2l} e^{-i\xi_3} m_b m_{\tilde{g}} f(m_b^2, m_{\tilde{g}}^2, m_{t_k}^2)$$

where

$$f(x, y, z) = \frac{1}{(x-y)(x-z)(z-y)} \left( zxlnx - xlynx + yzlynz \right)$$

Next for the loop Fig.(1b) we find

$$\Delta R_{bij}^{(2)} = \sum_{k=1}^{2} \sum_{l=1}^{4} 2K_b U_{j2} D_{t1k}^* (\beta_{dl} D_{bli} + \alpha_{ul}^* D_{b2l})$$

$$\times (\beta_{ul} D_{t1k} + \alpha_{ul}^* D_{t2k}) \frac{m_b m_{\chi^0}}{16\pi^2} f(m_b^2, m_{\chi^0_i}^2, m_{t_k}^2)$$

$$\Delta L_{bij}^{(2)} = -\sum_{k=1}^{2} \sum_{l=1}^{4} 2(V_{j1}^* D_{t1k}^* - K_l V_{j2}^* D_{t2k}^*) (\alpha_{ul} D_{b1l} - \gamma_{ul} D_{b2l})$$

$$\times (\alpha_{ul} D_{t1k} - \gamma_{ul} D_{t2k}) \frac{m_b m_{\chi^0}}{16\pi^2} f(m_b^2, m_{\chi^0_i}^2, m_{t_k}^2)$$

$$\alpha_{b(t)k} = \frac{g m_{b(t)} X_{b(t)k} \sin \beta}{2m_W}$$

$$\beta_{b(t)k} = e Q_{b(t)} X_{1k}^* + \frac{g}{\cos \theta_W} X_{2k}^* (T_{3b(t)} - Q_{b(t)} \sin^2 \theta_W)$$

$$\gamma_{b(t)k} = e Q_{b(t)} X_{1k}^* - \frac{g Q_{b(t)} \sin^2 \theta_W}{\cos \theta_W} X_{2k}^*$$

where $X'$'s are given by

$$X'_{1k} = X_{1k} \cos \theta_W + X_{2k} \sin \theta_W$$

$$X'_{2k} = -X_{1k} \sin \theta_W + X_{2k} \cos \theta_W$$

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and where $X$ is the matrix that diagonalizes the neutralino mass matrix so that

$$X^T M_{\chi^0} X = \text{diag}(m_{\chi^0_1}, m_{\chi^0_2}, m_{\chi^0_3}, m_{\chi^0_4})$$

(13)

Fig. (1c) contributes the following

$$\Delta R_{b_{ij}}^{(3)} = \frac{1}{\sqrt{2}} \sum_{k=1}^{2} \sum_{l=1}^{3} (U_{j1} D_{b_{1k}} - k_b U_{j2} D_{b_{2k}})$$

$$+ H_{k_l} (Y_{l1} - i Y_{l3} \sin \beta)(C_{ti}^S + i C_{ti}^P) \frac{m_t}{16 \pi^2} f(m_t^2, m_{b_k}^2, m_{H_i}^2)$$

(14)

where $Y$ is the diagonalizing matrix of the Higgs mass matrix

$$YM_{\text{Higgs}} Y^T = \text{diag}(m_{H_1}^2, m_{H_2}^2, m_{H_3}^2)$$

(15)

and

$$G_{ij} = \frac{gm_Z}{\sqrt{2} \cos \theta_W} \left[ \left( -\frac{1}{2} + \frac{1}{3} \sin^2 \theta_W \right) D_{b_{1i}}^* D_{b_{1j}} - \frac{1}{3} \sin^2 \theta_W D_{b_{2i}}^* D_{b_{2j}} \right] \sin \beta$$

$$+ \frac{g m_b}{\sqrt{2} m_W \cos \beta} \mu D_{b_{1i}} D_{b_{1j}}$$

(16)

$$H_{ij} = -\frac{g m_Z}{\sqrt{2} \cos \theta_W} \left[ \left( -\frac{1}{2} + \frac{1}{3} \sin^2 \theta_W \right) D_{b_{1i}}^* D_{b_{1j}} - \frac{1}{3} \sin^2 \theta_W D_{b_{2i}}^* D_{b_{2j}} \right] \cos \beta$$

$$- \frac{g m_b^2}{\sqrt{2} m_W \cos \beta} [D_{b_{1i}}^* D_{b_{1j}} + D_{b_{2i}}^* D_{b_{2j}}] - \frac{g m_b m_0 A_b}{\sqrt{2} m_W \cos \beta} D_{b_{2i}}^* D_{b_{1j}}$$

(17)

and

$$C_{ti}^S = \tilde{C}_{ti}^S \cos \chi_t - \tilde{C}_{ti}^P \sin \chi_t$$

$$C_{ti}^P = \tilde{C}_{ti}^S \sin \chi_t + \tilde{C}_{ti}^P \cos \chi_t$$

$$\sqrt{2} \tilde{C}_{ti}^S = \text{Re}(h_t + \delta h_t) Y_{l2} + [-\text{Im}(h_t + \delta h_t) \cos \beta$$

$$+ \text{Im}(\Delta h_t) \sin \beta] Y_{l3} + \text{Re}(\Delta h_t) Y_{l1}$$

$$\sqrt{2} \tilde{C}_{ti}^P = -\text{Im}(h_t + \delta h_t) Y_{l2} + [-\text{Re}(h_t + \delta h_t) \cos \beta$$

$$+ \text{Re}(\Delta h_t) \sin \beta] Y_{l3} - \text{Im}(\Delta h_t) Y_{l1}$$

(18)

with

$$\tan \chi_t = \frac{\text{Im}(\frac{\delta h_t}{h_t} + \frac{\Delta h_t}{h_t} \cot \beta)}{1 + \text{Re}(\frac{\delta h_t}{h_t} + \frac{\Delta h_t}{h_t} \cot \beta)}$$

(19)
and

$$h_t = \frac{g m_t}{\sqrt{2} m_W \sin \beta}$$  \hspace{1cm} (20)$$

The corrections $\Delta h_t$ and $\delta h_t$ are defined in Appendix A.

$$\Delta L_{bi}^{(3)} = -\frac{1}{\sqrt{2}} \sum_{k=1}^{2} \sum_{l=1}^{3} K_l V_{jl}^2 D_{bik}(G_{kl}(Y_{l2} + i Y_{l3} \cos \beta) + G_{ik}^*(Y_{l2} - i Y_{l3} \cos \beta)
+ H_{ki}(Y_{l1} + i Y_{l3} \sin \beta) + H_{ik}^*(Y_{l1} - i Y_{l3} \sin \beta])(C_{il}^s - i C_{il}^p) \frac{m_t}{16 \pi^2} f(m_t^2, m_{b_k}^2, m_{H_1}^2)$$  \hspace{1cm} (21)$$

Fig.(1d) gives the following contributions

$$\Delta R_{bi}^{(4)} = \sqrt{2} \sum_{i=1}^{4} (\beta_{bi} D_{bi1} + \alpha_{bi}^* D_{bi2})(B_{bi}^{S*} - B_{bi}^{P*}) \xi'_{ij} \sin \beta \frac{m_b m_{X_{j1}^0}}{16 \pi^2} f(m_b^2, m_{X_{j1}^0}^2, m_{H_1}^2)$$  \hspace{1cm} (22)$$

where

$$B_{bi}^S = -\frac{1}{2} (h_b + \overline{h_b}) e^{-i \theta_{bi}} \sin \beta + \frac{1}{2} \Delta h_b e^{-i \theta_{bi}} \cos \beta$$

$$-\frac{1}{2} (h_t + \overline{h_t}) e^{i \theta_{bi}} \cos \beta + \frac{1}{2} \Delta h_t e^{i \theta_{bi}} \sin \beta$$

$$B_{bi}^P = -\frac{1}{2} (h_b + \overline{h_b}) e^{i \theta_{bi}} \cos \beta + \frac{1}{2} \Delta h_b e^{i \theta_{bi}} \sin \beta$$

$$+ \frac{1}{2} (h_t + \overline{h_t}) e^{-i \theta_{bi}} \sin \beta - \frac{1}{2} \Delta h_t e^{-i \theta_{bi}} \cos \beta$$  \hspace{1cm} (23)$$

where $\theta_{bi} = (\chi_b + \chi_t)/2$ and where $\chi_b$ is defined by the following

$$\tan \chi_b = \frac{\text{Im}(\chi_b + \Delta h_b \tan \beta)}{1 + \text{Re}(\chi_b + \Delta h_b \tan \beta)}$$  \hspace{1cm} (24)$$

and

$$h_b = \frac{g m_b}{\sqrt{2} m_W \cos \beta}$$  \hspace{1cm} (25)$$

where the corrections $\Delta h_f$, $\delta h_f$, $\overline{\Delta h}_f$ and $\overline{\delta h}_f$ are defined in Appendix A.

$$\Delta L_{bi}^{(4)} = \sqrt{2} \sum_{i=1}^{4} (\alpha_{bi} D_{bi1} - \gamma_{bi} D_{bi2})(B_{bi}^{S*} + B_{bi}^{P*}) \xi_{ij} \cos \beta \frac{m_b m_{X_{j1}^0}}{16 \pi^2} f(m_b^2, m_{X_{j1}^0}^2, m_{H_1}^2)$$  \hspace{1cm} (26)$$

where

$$\xi'_{ji} = -g X_{3j}^* U_{i1} + \frac{g}{\sqrt{2}} X_{3j}^* U_{i2} + \frac{1}{\sqrt{2}} g \tan \theta_{W} U_{i1}$$

$$-g X_{3j}^* U_{i1} - \frac{g}{\sqrt{2}} X_{3j}^* U_{i2} + \frac{1}{\sqrt{2}} g \tan \theta_{W} U_{i2}$$  \hspace{1cm} (27)$$
Next we discuss the contributions from Fig.(1e). Here on using the properties of the projection operators, i.e., \( \gamma^\mu P_R = P_L \gamma^\mu \), \( P_L P_R = 0 \), and the property of Dirac \( \gamma^\mu \) that \( g_{\mu\nu} \gamma^\mu \gamma^\nu = 4 \), we get

\[ \Delta R_{bij}^{(5)} = 0 \]  
(28)

and

\[ \Delta L_{bij}^{(5)} = -4g \sum_{l=1}^{4} R_{ij}'(\alpha_{bl} D_{bl1} - \gamma_{bl} D_{bl2}) \frac{m_b m_{\chi_l^0}}{16\pi^2} f(m_b^2, m_{\chi_l^0}^2, m_W^2) \]  
(29)

where

\[ R_{ij}' = \frac{1}{\sqrt{2}} X_{3i} U_{j3} + X_{2i} U_{j1} \]  
(30)

Contributions from Fig.(1f) are as follows

\[ \Delta R_{bij}^{(6)} = -g \sum_{l=1}^{3} \sum_{k=1}^{3} [Q_{jl}(Y_{k1} + iY_{k3} \sin \beta) + S_{jl}(Y_{k2} + iY_{k3} \cos \beta)] 
(C_{ik}^S + iC_{ik}^P)[U_{i1} D_{b1i} - K_b U_{i2} D_{b2i}] \frac{m_t m_{\chi_l^-}}{16\pi^2} f(m_t^2, m_{\chi_l^-}^2, m_{H_k}^2) \]  
(31)

and

\[ \Delta L_{bij}^{(6)} = g \sum_{l=1}^{3} \sum_{k=1}^{3} [Q_{jl}^*(Y_{k1} - iY_{k3} \sin \beta) + S_{jl}^*(Y_{k2} - iY_{k3} \cos \beta)] 
(C_{ik}^S - iC_{ik}^P)[K_t V_{i2}^* D_{b1i}] \frac{m_t m_{\chi_l^-}}{16\pi^2} f(m_t^2, m_{\chi_l^-}^2, m_{H_k}^2) \]  
(32)

where

\[ Q_{ij} = \frac{1}{\sqrt{2}} U_{i2} V_{j1} \]

\[ S_{ij} = \frac{1}{\sqrt{2}} U_{i1} V_{j2} \]  
(33)

Fig.(1g) contributes as follows

\[ \Delta R_{bij}^{(7)} = \frac{4g^2}{\cos^2 \theta_W} \sum_{l=1}^{2} L_{ij}' \left( \frac{2}{3} \sin^2 \theta_W \right) (U_{i1} D_{b1l} - K_b U_{i2} D_{b2l}) \frac{m_t m_{\chi_l^-}}{16\pi^2} f(m_t^2, m_{\chi_l^-}^2, m_Z^2) \]  
(34)
Finally, the contribution from Fig. (1i) is as follows

\[ \Delta L^{(7)}_{bij} = \frac{4g^2}{\cos^2 \theta_W} \sum_{l=1}^{2} R_{ij}'' \left( \frac{1}{2} - \frac{2}{3} \sin^2 \theta_W \right) K_l V_{i2}^* D_{bl1} \frac{m_t m_W}{16\pi^2} f(m_t^2, m_W^2, m_Z^2) \]  

where

\[ L''_{ij} = -V_{il} V_{j2}^* - \frac{1}{2} V_{il} V_{j2}^* + \delta_{ij} \sin^2 \theta_W \]

\[ R''_{ij} = -U_{il} U_{j2} - \frac{1}{2} U_{il} U_{j2} + \delta_{ij} \sin^2 \theta_W \]

The contribution of Fig. (1h) is as follows

\[ \Delta R^{(8)}_{bij} = -\frac{\sqrt{2}}{g} \sum_{l=1}^{2} \sum_{k=1}^{4} \xi_{lj} \sin \beta (\beta_{lk} D_{l1l} + \alpha_{lk}^* D_{l2l}) \]

\[ (\eta_{ij} \cos \beta + \eta_{ij}' \sin \beta) \frac{m_t^2}{16\pi^2} f(m_t^2, m^2_{H^-, m^2_i}) \]

and

\[ \Delta L^{(8)}_{bij} = -\frac{\sqrt{2}}{g} \sum_{l=1}^{2} \sum_{k=1}^{4} \xi_{kj} \cos \beta (\alpha_{lk} D_{l1l} - \gamma_{lk} D_{l2l}) \]

\[ (\eta_{ij} \cos \beta + \eta_{ij}' \sin \beta) \frac{m_t^2}{16\pi^2} f(m_t^2, m^2_{H^-, m^2_i}) \]

where

\[ \eta_{ij} = \frac{g m_t}{\sqrt{2} m_W \sin \beta} m_0 A_t D_{bli} D_{l2j}^* + \frac{g m_b}{\sqrt{2} m_W \cos \beta} \mu D_{bli} D_{l2j}^* \]

\[ + \frac{g m_t m_b}{\sqrt{2} m_W \sin \beta} D_{bli} D_{l2j}^* + \frac{g m_t^2}{\sqrt{2} m_W \sin \beta} D_{bli} D_{l2j}^* - \frac{g}{\sqrt{2}} m_W \sin \beta D_{bli} D_{l2j}^* \]

and

\[ \eta_{ji}' = \frac{g m_b}{\sqrt{2} m_W \cos \beta} m_0 A_t D_{bli} D_{l2j}^* + \frac{g m_t}{\sqrt{2} m_W \sin \beta} \mu D_{bli} D_{l2j}^* \]

\[ + \frac{g m_b}{\sqrt{2} m_W \cos \beta} D_{bli} D_{l2j}^* + \frac{g m_t^2}{\sqrt{2} m_W \cos \beta} D_{bli} D_{l2j}^* - \frac{g}{\sqrt{2}} m_W \cos \beta D_{bli} D_{l2j}^* \]

Finally, the contribution from Fig. (1i) is as follows

\[ \Delta R^{(9)}_{bij} = \frac{g}{\sqrt{2}} \sum_{l=1}^{3} \sum_{s=1}^{2} \sum_{k=1}^{2} \{ Q_{js} (Y_{i1} + i Y_{i3} \cos \beta) + S_{js} (Y_{i2} + i Y_{i3} \sin \beta) \} \]

\[ (U_{s1} D_{b1k} - K_{s1} U_{s2} D_{b2k}) (G_{k1} (Y_{i2} + i Y_{i3} \cos \beta) + G^*_{k1} (Y_{i2} - i Y_{i3} \cos \beta) + H_{k1} (Y_{i1} + i Y_{i3} \sin \beta) \]

\[ + H^*_{k1} (Y_{i1} - i Y_{i3} \sin \beta)) \frac{m_X^2}{16\pi^2} f(m_{bi}^2, m_{H^+}^2, m_{X^+}^2) \] 

(41)
\[ \Delta L^{(9)}_{bij} = -\frac{g}{\sqrt{2}} \sum_{l=1}^{3} \sum_{s=1}^{2} \sum_{k=1}^{2} \{ Q^*_s (Y_{l1} - iY_{l3} \sin \beta) + S^*_s (Y_{l2} - iY_{l3} \cos \beta) \} \\
= (K_l V^*_{s2} D_{b1k}) [G_{ki} (Y_{l1} + iY_{l3} \cos \beta) + H_{ki} (Y_{l1} + iY_{l3} \sin \beta) + H^*_ik (Y_{l1} - Y_{l3} \sin \beta)] \frac{m_{\chi_0}^2}{16\pi^2} f \left( m_{b_k}^2, m_{H}, m_{\chi}^2 \right) \] 

(42)

Summing the contribution from the nine loop diagrams of Fig. (1a-1i) we find that \( \Delta R_{bij} \) and \( \Delta L_{bij} \) that appear in Eq. (5) are then given by

\[ \Delta R_{bij} = \sum_{n=1}^{9} \Delta R^{(n)}_{bij} \] 

(43)

\[ \Delta L_{bij} = \sum_{n=1}^{9} \Delta L^{(n)}_{bij} \] 

(44)

We note that the loop diagram of Fig. (1c) with the interchange \( Z \leftrightarrow H^0_1 \) vanishes in the zero external momentum approximation because the vertex is proportional to the external momentum. Similarly, the loop diagram of Fig. (1h) with the interchange \( W^- \leftrightarrow H^- \) vanishes and the loop diagram of Fig. (1i) with the interchange \( Z \leftrightarrow H^0_1 \) vanishes in the zero external momentum approximation.

### 2.2 Analysis of corrections \( \Delta R_{tij} \) and \( \Delta L_{tij} \)

The corrections \( \Delta R_{tij} \) and \( \Delta L_{tij} \) arise from the nine diagrams of Fig. (2), i.e., the loops (a)-(i) of Fig. (2). We label the contribution from the nine diagrams by superscripts 1-9. Thus, for example, the contributions of Fig. (2a) are \( \Delta R^{(1)}_{tij} \) and \( \Delta L^{(1)}_{tij} \) etc. We now list the contributions of the nine loops of Fig. (2). We have

\[ \Delta R^{(1)}_{tij} = \frac{2\alpha_s}{3\pi} \sum_{k=1}^{2} K_l V_{j2}^* D^*_{b1k} D_{t1i} e^{i\xi_3} D_{b1k} m_t m_g f (m_t^2, m_g^2, m_{b_k}^2) \] 

(45)

\[ \Delta L^{(1)}_{tij} = -\frac{2\alpha_s}{3\pi} \sum_{k=1}^{2} (U_{j1}^* D^*_{b1k} - K_b U_{j2}^* D^*_{b2k}) D_{t1i} D_{b2k} e^{-i\xi_3} m_t m_g f (m_t^2, m_g^2, m_{b_k}^2) \] 

(46)

\[ \Delta R^{(2)}_{tij} = \sum_{k=1}^{2} \sum_{i=1}^{4} 2K_l V_{j2}^* D_{b1k} (\beta_{t1i} D_{t1i} + \alpha_{t1i}^* D_{t1i}) \frac{m_t m_{\chi_0}^2}{16\pi^2} f (m_t^2, m_{\chi_0}^2, m_{t_k}^2) \] 

(47)
\[ \Delta L_{ij}^{(2)} = - \sum_{k=1}^{2} \sum_{l=1}^{4} 2(U_{j1}^* D_{blk} - K_b U_{j2}^* D_{b2k}^*) (\alpha_{ti} D_{l1i} - \gamma_{ti} D_{l2i}) (\alpha_{bk} D_{b1k} - \gamma_{bl} D_{b2k}) \frac{m_b m_{\chi_0}^i}{16 \pi^2} f(m_b^2, m_{\chi_0^i}^2, m_{H_1}^2) \] 

\[ \Delta R_{ij}^{(3)} = \frac{1}{\sqrt{2}} \sum_{k=1}^{2} \sum_{l=1}^{3} (V_{j1} D_{l1k} - K_l V_{j2} D_{l2k}) (E_{ki}(Y_{l2} + iY_{l3} \cos \beta) + E_{ik}^*(Y_{l2} - iY_{l3} \cos \beta) + F_{ki}(Y_{l1} + iY_{l3} \sin \beta) + F_{ik}^*(Y_{l1} - iY_{l3} \sin \beta)) (C_{bl}^S + iC_{bl}^P) \frac{m_b}{16 \pi^2} f(m_t^2, m_{t_1}^2, m_{H_1}^2) \] 

where

\[ E_{ij} = \frac{g m_Z}{\sqrt{2} \cos \theta_W} \left( \frac{1}{2} - 3 \sin^2 \theta_W \right) D_{l1i}^* D_{l1j} + \frac{2}{3} \sin^2 \theta_W W_{l2i}^* W_{l2j} \sin \beta \] 

\[ F_{ij} = -\frac{g m_Z}{\sqrt{2} \cos \theta_W} \left( \frac{1}{2} - 3 \sin^2 \theta_W \right) D_{l1i}^* D_{l1j} + \frac{2}{3} \sin^2 \theta_W W_{l2i}^* W_{l2j} \cos \beta \] 

and

\[ C_{bl}^S = \tilde{C}_{bl}^S \cos \chi_b - \tilde{C}_{bl}^P \sin \chi_b \] 

\[ C_{bl}^P = \tilde{C}_{bl}^S \sin \chi_b + \tilde{C}_{bl}^P \cos \chi_b \] 

\[ \sqrt{2} \tilde{C}_{bl}^S = \text{Re}(h_b + \delta h_b) Y_{l1} + [-\text{Im}(h_b + \delta h_b) \sin \beta \] 

\[ + \text{Im}(\Delta h_b) \cos \beta] Y_{l3} + \text{Re}(\Delta h_b) Y_{l2} \] 

\[ \sqrt{2} \tilde{C}_{bl}^P = -\text{Im}(h_b + \delta h_b) Y_{l1} + [-\text{Re}(h_b + \delta h_b) \sin \beta \] 

\[ + \text{Re}(\Delta h_b) \cos \beta] Y_{l3} - \text{Im}(\Delta h_b) Y_{l2} \] 

\[ \Delta L_{ij}^{(3)} = -\frac{1}{\sqrt{2}} \sum_{k=1}^{2} \sum_{l=1}^{3} K_b U_{j1}^* D_{l1k} [E_{ki}(Y_{l2} + iY_{l3} \cos \beta) + E_{ik}^*(Y_{l2} - iY_{l3} \cos \beta) \] 

\[ + F_{ki}(Y_{l1} + iY_{l3} \sin \beta) + F_{ik}^*(Y_{l1} - iY_{l3} \sin \beta)] (C_{bl}^S - iC_{bl}^P) \frac{m_b}{16 \pi^2} f(m_t^2, m_{t_1}^2, m_{H_1}^2) \] 

\[ \Delta R_{ij}^{(4)} = \frac{\sqrt{3}}{g} \sum_{l=1}^{4} (\alpha_{ti} D_{l1i} + \alpha_{ti}^* D_{l2i}) (B_{bl}^S + \tilde{B}_{bl}^P) \xi_{ij}^* \cos \beta \frac{m_t m_{\chi_0}^i}{16 \pi^2} f(m_t^2, m_{\chi_0^i}^2, m_{H_1}^2) \]
$$\Delta L_{ij}^{(4)} = \sqrt{\frac{7}{g}} \sum_{l=1}^{4} (\alpha_D \delta_{lij} - \gamma_D \delta_{lj}) (B_{bl}^S - B_{bl}^P) \xi_{ij}^{*} \sin \beta \frac{m_t m_{\chi_i}^0}{16\pi^2} f(m_t^2, m_{\chi_i}^2, m_{H^-}^2)$$

$$\Delta R_{ij}^{(5)} = 0$$

and

$$\Delta L_{ij}^{(5)} = -4g \sum_{l=1}^{4} R_{ij}^{*} (\alpha_D \delta_{lij} - \gamma_D \delta_{lj}) \frac{m_t m_{\chi_i}^0}{16\pi^2} f(m_t^2, m_{\chi_i}^2, m_{H^-}^2)$$

$$\Delta R_{ij}^{(6)} = -g \sum_{l=1}^{3} \sum_{k=1}^{3} [Q_{lj}^*(Y_{k1} + iY_{k3} \sin \beta) + S_{lj}^*(Y_{k2} + iY_{k3} \cos \beta)] (C_{bk}^S + iC_{bk}^P) [V_{l1} D_{lij} - K_{l1} V_{l2} D_{l2i}] \frac{m_b m_{\chi_i}^0}{16\pi^2} f(m_b^2, m_{\chi_i}^2, m_{H_k}^2)$$

and

$$\Delta L_{ij}^{(6)} = g \sum_{l=1}^{3} \sum_{k=1}^{3} [Q_{lj}^*(Y_{k1} - iY_{k3} \sin \beta) + S_{lj}^*(Y_{k2} - iY_{k3} \cos \beta)] (C_{bk}^S - iC_{bk}^P) (K_{l1} U_{l2}^* D_{lij}) \frac{m_b m_{\chi_i}^0}{16\pi^2} f(m_b^2, m_{\chi_i}^2, m_{H_k}^2)$$

$$\Delta R_{ij}^{(7)} = -\frac{4g^2}{\cos^2 \theta_W} \sum_{l=1}^{2} L_{jl}^{*} \left( \frac{1}{3} \sin^2 \theta_W \right) \left( V_{l1} D_{lij} - K_{l1} V_{l2} D_{l2i} \right) \frac{m_b m_{\chi_i}^0}{16\pi^2} f(m_b^2, m_{\chi_i}^2, m_Z^2)$$

$$\Delta L_{ij}^{(7)} = -\frac{4g^2}{\cos^2 \theta_W} \sum_{l=1}^{2} L_{jl}^{*} \left( \frac{1}{2} - \frac{1}{3} \sin^2 \theta_W \right) K_{l1} U_{l2}^* D_{lij} \frac{m_t m_{\chi_i}^0}{16\pi^2} f(m_b^2, m_{\chi_i}^2, m_Z^2)$$

where

$$\Delta R_{ij}^{(8)} = -\sqrt{\frac{2}{g}} \sum_{l=1}^{2} \sum_{k=1}^{4} \xi_{jk}^* \cos \beta \left( \beta_{bk} D_{bl} + \alpha_{bk} D_{b2l} \right) \frac{m_t m_{\chi_k}^0}{16\pi^2} f(m_t^2, m_{\chi_k}^2, m_{H^-}^2, m_{ij}^2)$$

$$\Delta L_{ij}^{(8)} = -\sqrt{\frac{2}{g}} \sum_{l=1}^{2} \sum_{k=1}^{4} \xi_{jk}^* \sin \beta \left( \alpha_{bk} D_{b1l} - \gamma_{bk} D_{b2l} \right) \frac{m_t m_{\chi_k}^0}{16\pi^2} f(m_t^2, m_{\chi_k}^2, m_{H^-}^2, m_{ij}^2)$$
\[ \Delta R_{tij}^{(9)} = \frac{g}{\sqrt{2}} \sum_{l=1}^{3} \sum_{s=1}^{2} \sum_{k=1}^{2} \{ Q_{sj}(Y_{l1} + iY_{l3} \sin \beta) + S_{sj}(Y_{l2} + iY_{l3} \cos \beta) \} \]

\[ (V_{s1}D_{tik} - K_{t}V_{s2}D_{t2k})[E_{ki}(Y_{l2} + iY_{l3} \cos \beta) + E_{ik}^{*}(Y_{l2} - iY_{l3} \cos \beta) + F_{ki}(Y_{l1} + iY_{l3} \sin \beta) \]

\[ + F_{ik}^{*}(Y_{l1} - iY_{l3} \sin \beta)] \frac{m_{\chi_{-}^{0}}}{16\pi^{2}} f(m_{k}^{2}, m_{H}^{2}, m_{\chi_{-}^{0}}^{2}) \] (64)

\[ \Delta L_{bij}^{(9)} = -\frac{g}{\sqrt{2}} \sum_{l=1}^{3} \sum_{s=1}^{2} \sum_{k=1}^{2} \{ Q_{sj}^{*}(Y_{l1} - iY_{l3} \sin \beta) + S_{sj}^{*}(Y_{l2} - iY_{l3} \cos \beta) \} \]

\[ (K_{b}U_{s2}^{*}D_{t1k})[E_{ki}(Y_{l2} + iY_{l3} \cos \beta) + E_{ik}^{*}(Y_{l2} - iY_{l3} \cos \beta) + F_{ki}(Y_{l1} + iY_{l3} \sin \beta) \]

\[ + F_{ik}^{*}(Y_{l1} - iY_{l3} \sin \beta)] \frac{m_{\chi_{-}^{0}}}{16\pi^{2}} f(m_{k}^{2}, m_{H}^{2}, m_{\chi_{-}^{0}}^{2}) \] (65)

\[ \Delta R_{tij} = \sum_{n=1}^{9} \Delta R_{tij}^{(n)} \] (66)

\[ \Delta L_{tij} = \sum_{n=1}^{9} \Delta L_{tij}^{(n)} \] (67)

The loops corresponding to Fig.(2c) and Fig.(2i) where \( Z \leftrightarrow H_{t}^{0} \) vanishes for the same reason as discussed earlier in Sec.(2.1). Similarly, the loop corresponding to Fig.(2h) with \( W^{+} \leftrightarrow H^{+} \) vanishes for the same reason.

### 3 The effective Lagrangian for \( \bar{q}q\chi_{j}^{0} \) interaction

We turn now to an analysis of the loop corrections to the squark-quark-neutralino interaction. We begin with the tree level \( \bar{q}q\chi_{j}^{0} \) interaction which is given by

\[ \mathcal{L} = g\bar{b}[K_{bij}P_{R} + M_{bij}P_{L}]\chi_{j}^{0}\bar{b}_{i} \]

\[ + g\bar{t}[K_{tij}P_{R} + M_{tij}P_{L}]\chi_{j}^{0}\bar{t}_{i} + H.c. \] (68)

where

\[ K_{bij} = -\sqrt{2}[\beta_{bij}D_{b1i} + \alpha_{bij}^{*}D_{b2i}] \]

\[ K_{tij} = -\sqrt{2}[\beta_{tij}D_{t1i} + \alpha_{tij}^{*}D_{t2i}] \]

\[ M_{bij} = -\sqrt{2}[\alpha_{bij}D_{b1i} - \gamma_{bij}D_{b2i}] \]

\[ M_{tij} = -\sqrt{2}[\alpha_{tij}D_{t1i} - \gamma_{tij}D_{t2i}] \] (69)
The loop corrections produce a shift in the couplings of Eq.(69) as follows
\[ \mathcal{L}_{\text{eff}} = g \bar{b}[(K_{bij} + \Delta K_{bij}) P_R + (M_{bij} + \Delta M_{bij}) P_L] \chi_j^0 \bar{b} + g \bar{t}[(K_{tij} + \Delta K_{tij}) P_R + (M_{tij} + \Delta M_{tij}) P_L] \chi_j^0 \bar{t} + H.c. \]  
(70)

Thus in this part of the analysis we will calculate the quantities \( \Delta K_{bij} \), \( \Delta K_{tij} \), \( \Delta M_{bij} \), and \( \Delta M_{tij} \) from the one loop corrections arising from Figs.(3) and (4) using as in the previous analysis the zero external momentum approximation.

### 3.1 Analysis of loop corrections to \( \bar{b}b_i \chi_j^0 \) interaction

Loop corrections to \( \bar{b}b_i \chi_j^0 \) interaction, i.e., \( \Delta K_{bij} \) and \( \Delta M_{bij} \), arise from the nine diagrams of Fig.(3). We give now the individual contribution of these nine loops. The contribution from Fig.(3a) is
\[ \Delta K_{bij}^{(1)} = -\frac{2\sqrt{2}\alpha_s}{3\pi g} \sum_{k=1}^{2} e^{i\xi_3} D_{b_{1i}} D_{b_{1k}} (\alpha_{bij} D_{b_{1k}}^* - \gamma_{bij} D_{b_{2k}}^*) m_b m_3 f(m_b^2, m_3^2, m_{b_k}^2) \]  
(71)
\[ \Delta M_{bij}^{(1)} = -\frac{2\sqrt{2}\alpha_s}{3\pi g} \sum_{k=1}^{2} e^{-i\xi_3} D_{b_{2i}} D_{b_{2k}} (\beta_{bij} D_{b_{1k}}^* + \alpha_{bij} D_{b_{2k}}^*) m_b m_3 f(m_b^2, m_3^2, m_{b_k}^2) \]  
(72)

Fig.(3b) contribute as follows
\[ \Delta K_{bij}^{(2)} = -\frac{2\sqrt{2}}{g} \sum_{l=1}^{2} \sum_{k=1}^{2} (\beta_{bl} D_{b_{1i}} + \alpha_{bl} D_{b_{2i}}) (\alpha_{bl} D_{b_{1k}}^* + \beta_{bl} D_{b_{2k}}^*) (\alpha_{bij} D_{b_{1k}}^* - \gamma_{bij} D_{b_{2k}}^*) \]  
\[ \frac{m_b m_{\chi_l} f(m_b^2, m_{\chi_l}^2, m_{b_k}^2)}{16\pi^2} \]  
(73)
\[ \Delta M_{bij}^{(2)} = -\frac{2\sqrt{2}}{g} \sum_{l=1}^{2} \sum_{k=1}^{2} (\alpha_{bl} D_{b_{1i}} - \gamma_{bl} D_{b_{2i}}) (\gamma_{bl} D_{b_{1k}}^* + \alpha_{bl} D_{b_{2k}}^*) (\beta_{bij} D_{b_{1k}}^* + \alpha_{bij} D_{b_{2k}}^*) \]  
\[ \frac{m_b m_{\chi_l} f(m_b^2, m_{\chi_l}^2, m_{b_k}^2)}{16\pi^2} \]  
(74)

Fig.(3c) makes the following contribution
\[ \Delta K_{bij}^{(3)} = \frac{1}{g} \sum_{l=1}^{3} \sum_{k=1}^{3} [G_{k l} (Y_{l2} + i Y_{l3} \cos \beta) + G_{k l}^* (Y_{l2} - i Y_{l3} \cos \beta)] \]  
\[ + H_{k l} (Y_{l1} + i Y_{l3} \sin \beta) + H_{k l}^* (Y_{l1} - i Y_{l3} \sin \beta)] (C_{l1}^S + i C_{l1}^P) [\beta_{bj} D_{b_{1k}} + \alpha_{bj} D_{b_{2k}}] \]  
\[ \frac{m_b}{16\pi^2} f(m_b^2, m_{H_{l1}}^2, m_{b_k}^2) \]  
(75)
\[
\Delta M^{(3)}_{bij} = \frac{1}{g} \sum_{l=1}^{3} \sum_{k=1}^{2} [G_{ki}(Y_{l2} + iY_{l3}\cos \beta) + G_{ik}^*(Y_{l2} - iY_{l3}\cos \beta) + H_{ki}(Y_{l1} + iY_{l3}\sin \beta) + H_{ik}^*(Y_{l1} - iY_{l3}\sin \beta)](C_{bl}^S - iC_{bl}^P)[\alpha_{lj}D_{b1l} - \gamma_{lj}D_{b2l}]
\]
\[
\frac{m_b}{16\pi^2} f(m_b^2, m_{H1}^2, m_{H2}^2)
\]

Fig.(3d) contributes as follows
\[
\Delta K^{(4)}_{bij} = -\sum_{l=1}^{4} \sum_{k=1}^{3} [Q'_{lj}(Y_{k1} + iY_{k3}\sin \beta) - S'_{lj}(Y_{k2} + iY_{k3}\cos \beta)](C_{bk}^S + iC_{bk}^P)(\beta_{bl}D_{b1l} + \alpha_{bl}^*D_{b2l})\frac{m_b m_{\chi_l^0}}{16\pi^2} f(m_b^2, m_{\chi_l}^2, m_{Hk}^2)
\]

\[
\Delta M^{(4)}_{bij} = -\sum_{l=1}^{4} \sum_{k=1}^{3} [Q''_{lj}(Y_{k1} - iY_{k3}\sin \beta) - S''_{lj}(Y_{k2} - iY_{k3}\cos \beta)](C_{bk}^S - iC_{bk}^P)(\alpha_{bl}D_{b1l} - \gamma_{bl}D_{b2l})\frac{m_b m_{\chi_l^0}}{16\pi^2} f(m_b^2, m_{\chi_l}^2, m_{Hk}^2)
\]

where
\[
Q'_{lj} = \frac{1}{\sqrt{2}} [X_{3k}(X_{2j}^* - \tan \theta_W X_{1ij}^*)]
\]
\[
S'_{lj} = \frac{1}{\sqrt{2}} [X_{1i}(X_{2j}^* - \tan \theta_W X_{1ij}^*)]
\]

Fig.(3e) contributes as follows
\[
\Delta K^{(5)}_{bij} = -\frac{4\sqrt{2}g}{\cos^2 \theta_W} \sum_{l=1}^{4} L''_{lj}(\frac{1}{3} \sin^2 \theta_W)(\beta_{bl}D_{b1l} + \alpha_{bl}^*D_{b2l})\frac{m_b m_{\chi_l^0}}{16\pi^2} f(m_b^2, m_{\chi_l}^2, m_{Hk}^2)
\]

\[
\Delta M^{(5)}_{bij} = \frac{4\sqrt{2}g}{\cos^2 \theta_W} \sum_{l=1}^{4} R''_{lj}(\frac{1}{2} - \frac{1}{3} \sin^2 \theta_W)(\alpha_{bl}D_{b1l} - \gamma_{bl}D_{b2l})\frac{m_b m_{\chi_l^0}}{16\pi^2} f(m_b^2, m_{\chi_l}^2, m_{Hk}^2)
\]

\[
L''_{ij} = \frac{1}{2} X_{3i}^* X_{3j} + \frac{1}{2} X_{4i}^* X_{4j}
\]
\[
R''_{ij} = -L''_{ij}
\]

The contribution of Fig.(3f) is
\[
\Delta K^{(6)}_{bij} = \sum_{l=1}^{2} (B_{bl}^S + B_{bl}^P)(U_{l1}D_{b1l} - K_{bl}U_{l2}D_{b2l})\xi_{jl}^0 \cos \beta
\]
\[
\frac{m_i m_{\chi_j^-}}{16\pi^2} f(m_i^2, m_{\chi_j^-}^2, m_{H^-}^2)
\]
\[
\Delta M_{bij}^{(6)} = -\sum_{l=1}^{2} (B_{bl}^{S} - B_{bl}^{P})(K_{l1}V_{l2}^{*}D_{bl})\xi_{j1}^{'\ast} \sin \beta \sin \left(\frac{m_{l}m_{\chi_{l}^{\ast}}}{16\pi^{2}}f(m_{l}^{2}, m_{\chi_{l}^{\ast}}^{2}, m_{H}^{2})\right)
\]

Fig.(3g) contributes as follows

\[
\Delta K_{bij}^{(7)} = 0
\]

\[
\Delta M_{bij}^{(7)} = \frac{4g^{2}}{\sqrt{2}} \sum_{l=1}^{2} R_{ij}^{l}K_{l1}V_{l2}^{*}D_{bl}m_{l}m_{\chi_{l}^{\ast}} \frac{m_{l}m_{\chi_{l}^{\ast}}}{16\pi^{2}}f(m_{l}^{2}, m_{\chi_{l}^{\ast}}^{2}, m_{W}^{2})
\]

The contribution from Fig.(3h) is

\[
\Delta K_{bij}^{(8)} = -\sum_{k=1}^{2} \sum_{l=1}^{2} \xi_{jl}^{'\ast} \sin \beta (V_{kl}D_{l1l} - K_{l1}V_{l2}^{*}D_{l2l})(\eta_{kl} \cos \beta + \eta_{kl}^{'\ast} \sin \beta) \sin \left(\frac{m_{l}m_{\chi_{l}^{\ast}}}{16\pi^{2}}f(m_{l}^{2}, m_{\chi_{l}^{\ast}}^{2}, m_{H}^{2})\right)
\]

\[
\Delta M_{bij}^{(8)} = \sum_{k=1}^{2} \sum_{l=1}^{2} \xi_{jl}^{'\ast} \cos \beta (K_{k}U_{k2}^{*}D_{l1l})(\eta_{kl} \cos \beta + \eta_{kl}^{'\ast} \sin \beta) \sin \left(\frac{m_{l}m_{\chi_{l}^{\ast}}}{16\pi^{2}}f(m_{l}^{2}, m_{\chi_{l}^{\ast}}^{2}, m_{H}^{2})\right)
\]

Finally Fig.(3i) gives

\[
\Delta K_{bij}^{(9)} = \sum_{s=1}^{4} \sum_{k=1}^{2} \sum_{l=1}^{3} [G_{kl}(Y_{l2} + iY_{l3} \cos \beta) + G_{kl}^{*}(Y_{l2} - iY_{l3} \cos \beta) + H_{kl}(Y_{l1} + iY_{l3} \sin \beta) + H_{kl}^{*}(Y_{l1} - iY_{l3} \sin \beta)]
\]

\[
\times [Q_{s}^{l}(Y_{l1} + iY_{l3} \sin \beta) - S_{s}^{l}(Y_{l1} + iY_{l3} \sin \beta)] \sin \left(\frac{m_{l}m_{\chi_{l}^{\ast}}}{16\pi^{2}}f(m_{l}^{2}, m_{\chi_{l}^{\ast}}^{2}, m_{H}^{2})\right)
\]

\[
\Delta M_{bij}^{(9)} = \sum_{s=1}^{4} \sum_{k=1}^{2} \sum_{l=1}^{3} [G_{kl}(Y_{l2} + iY_{l3} \cos \beta) + G_{kl}^{*}(Y_{l2} - iY_{l3} \cos \beta) + H_{kl}(Y_{l1} + iY_{l3} \sin \beta) + H_{kl}^{*}(Y_{l1} - iY_{l3} \sin \beta)]
\]

\[
\times [Q_{s}^{l}(Y_{l1} + iY_{l3} \sin \beta) - S_{s}^{l}(Y_{l1} + iY_{l3} \sin \beta)] \sin \left(\frac{m_{l}m_{\chi_{l}^{\ast}}}{16\pi^{2}}f(m_{l}^{2}, m_{\chi_{l}^{\ast}}^{2}, m_{H}^{2})\right)
\]
The sum of the contribution of the nine diagrams of Fig. (3) gives \( \Delta K_{bij} \) and \( \Delta M_{bij} \)

\[
\Delta K_{bij} = \sum_{n=1}^{9} \Delta K_{bij}^{(n)}
\]

\[
\Delta M_{bij} = \sum_{n=1}^{9} \Delta M_{bij}^{(n)}
\]  \((91)\)

We note that the diagram corresponding to Fig. (3c) and Fig. (3i) with \( Z \leftrightarrow H_t^0 \), and the diagram corresponding to Fig. (3h) with \( W^- \leftrightarrow H^- \) vanish in the zero external momentum approximation.

### 3.2 Loop corrections to \( \bar{t}t_1 \chi^0_j \) interaction

Loop corrections to \( \bar{t}t_1 \chi^0_j \) interaction, i.e., \( \Delta K_{tij} \) and \( \Delta M_{tij} \), arise from the nine loops of Fig. (4). We now give the explicit computation of each loop. Fig. (4a) gives

\[
\Delta K_{tij}^{(1)} = -\frac{2\sqrt{2} \alpha_s}{3\pi g} \sum_{k=1}^{2} e^{i\xi_3} D_{1t1i} D_{1t1k}(\alpha_{tj} D_{t1k}^* - \gamma_{tj} D_{t2k}^*) m_t m_g f(m_t^2, m_g^2, m_{t_k}^2)
\]  \((92)\)

\[
\Delta M_{tij}^{(1)} = -\frac{2\sqrt{2} \alpha_s}{3\pi g} \sum_{k=1}^{2} e^{-i\xi_3} D_{1t2i} D_{1t2k}(\beta_{tj} D_{t1k}^* + \alpha_{tj} D_{t2k}^*) m_t m_g f(m_t^2, m_g^2, m_{t_k}^2)
\]  \((93)\)

Fig. (4b) gives

\[
\Delta K_{tij}^{(2)} = -\frac{2\sqrt{2}}{g} \sum_{l=1}^{4} \sum_{k=1}^{2} (\beta_{tl} D_{t1i} + \alpha_{tl} D_{t2i})(\beta_{tl} D_{t1k} + \alpha_{tl} D_{t2k})(\alpha_{tj} D_{t1k}^* - \gamma_{tj} D_{t2k})
\]

\[
\times \frac{m_t m_{\chi_1^0}^2}{16\pi^2} f(m_t^2, m_{\chi_1^0}^2, m_{t_k}^2)
\]  \((94)\)

\[
\Delta M_{tij}^{(2)} = -\frac{2\sqrt{2}}{g} \sum_{l=1}^{4} \sum_{k=1}^{2} (\alpha_{tl} D_{t1i} - \gamma_{tl} D_{t2i})(\alpha_{tl} D_{t1k} + \gamma_{tl} D_{t2k})(\beta_{tj} D_{t1k}^* + \alpha_{tj} D_{t2k})
\]

\[
\times \frac{m_t m_{\chi_1^0}^2}{16\pi^2} f(m_t^2, m_{\chi_1^0}^2, m_{t_k}^2)
\]  \((95)\)

Fig. (4c) makes the following contribution

\[
\Delta K_{tij}^{(3)} = \frac{1}{g} \sum_{l=1}^{3} \sum_{k=1}^{2} [E_{kl}(Y_{t2} + iY_{t3} \cos \beta) + E_{ik}^*(Y_{t2} - iY_{t3} \cos \beta)
\]

\[
+ F_{ki}(Y_{t1} + iY_{t3} \sin \beta) + F_{ik}^*(Y_{t1} - iY_{t3} \sin \beta)](C_{t1}^{(8)} + iC_{t1}^{(9)})][\beta_{tj} D_{t1k} + \alpha_{tj} D_{t2k}]
\]

\[
\times \frac{m_t}{16\pi^2} f(m_t^2, m_{H_1}, m_{t_k}^2)
\]  \((96)\)
\[ \Delta M_{tij}^{(3)} = \frac{1}{g} \sum_{l=1}^{g} \sum_{k=1}^{k} \left[ E_{kl}(Y_{i2} + iY_{i3} \cos \beta) + E_{ik}^*(Y_{i2} - iY_{i3} \cos \beta) + F_{ki}(Y_{i1} + iY_{i3} \sin \beta) + F_{ik}^*(Y_{i1} - iY_{i3} \sin \beta) \right] \frac{m_t}{16\pi^2} f(m_t^2, m_{H^+}^2, m_{\chi^0_i}^2) \]  

(97)

Fig. (4d) gives
\[ \Delta K_{tij}^{(4)} = -\sum_{l=1}^{4} \sum_{k=1}^{3} L_{jl}(Y_{i1} + iY_{i3} \sin \beta - S_{jl}^*(Y_{i1} + iY_{i3} \sin \beta)) \frac{m_t m_{\chi^0_i}}{16\pi^2} f(m_t^2, m_{\chi^0_i}^2, m_{H^+}^2) \]  

(98)

Fig. (4e) gives
\[ \Delta M_{tij}^{(4)} = -\sum_{l=1}^{4} \sum_{k=1}^{3} L_{jl} \left[ (C_{tk}^P + iC_{tk}^S) (\beta_{ti} D_{t1i} + \alpha_{ti} D_{t2i}) \right] \frac{m_t m_{\chi^0_i}}{16\pi^2} f(m_t^2, m_{\chi^0_i}^2, m_{H^+}^2) \]  

(99)

Fig. (4f) gives
\[ \Delta K_{tij}^{(5)} = \sum_{l=1}^{4} L_{jl}^\prime \left[ (B_{bl}^S - B_{bl}^P) (V_{i1} D_{t1i} - K_{tl} V_{i2} D_{t2i}) \right] \frac{m_t m_{\chi^0_i}}{16\pi^2} f(m_t^2, m_{\chi^0_i}^2, m_{H^+}^2) \]  

(100)

Fig. (4g) gives
\[ \Delta M_{tij}^{(6)} = \sum_{l=1}^{2} (B_{bl}^S + B_{bl}^P) (K_{bl} U_{i2}^* D_{t1i}) \frac{m_t m_{\chi^0_i}}{16\pi^2} f(m_t^2, m_{\chi^0_i}^2, m_{H^+}^2) \]  

(101)

Fig. (4f) gives
\[ \Delta K_{tij}^{(6)} = \sum_{l=1}^{2} (B_{bl}^S - B_{bl}^P) (V_{i1} D_{t1i} - K_{tl} V_{i2} D_{t2i}) \xi_{jl} \sin \beta \frac{m_t m_{\chi^0_i}}{16\pi^2} f(m_t^2, m_{\chi^0_i}^2, m_{H^+}^2) \]  

(102)

Fig. (4g) gives
\[ \Delta M_{tij}^{(7)} = 0 \]  

(103)

Fig. (4g) gives
\[ \Delta K_{tij}^{(7)} = 0 \]  

(104)
\[
\Delta M_{ij}^{(7)} = \frac{4g^2}{\sqrt{2}} \sum_{l=1}^{2} R_{ji} U_{l2}^* D_{li} \frac{m_b m_{\chi_i^l}}{16\pi^2} f(m_b^2, m_{\chi_i^l}^2, m_W^2) \] (105)

Fig. (4h) makes the following contribution

\[
\Delta K_{ij}^{(8)} = -\sum_{k=1}^{2} \sum_{l=1}^{2} \xi_{jk} \cos \beta (U_{kl} D_{bi} - K_{jl} U_{k2} D_{bi2})(\eta_i^l \sin \beta + \eta_i^r \cos \beta) \]
\[
\frac{m_{\chi_i^l}}{16\pi^2} f(m_b^2, m_{\chi_i^l}^2, m_{H^+}^2) \] (106)

\[
\Delta M_{ij}^{(8)} = \sum_{k=1}^{2} \sum_{l=1}^{2} \xi_{jk}^* \sin \beta (K_{li} V_{k2}^* D_{bi2})(\eta_i^l \sin \beta + \eta_i^r \cos \beta) \]
\[
\frac{m_{\chi_i^l}}{16\pi^2} f(m_b^2, m_{\chi_i^l}^2, m_{H^+}^2) \] (107)

Finally Fig. (4i) gives

\[
\Delta K_{ij}^{(9)} = \sum_{s=1}^{4} \sum_{k=1}^{2} \sum_{l=1}^{3} [E_{ki}(Y_{l2} + iY_{l3} \cos \beta) + E_{ik}^*(Y_{l2} - iY_{l3} \cos \beta) + F_{ki}(Y_{l1} + iY_{l3} \sin \beta) \]
\[+ F_{ik}^*(Y_{l1} - iY_{l3} \sin \beta)](Q_s^t Y_{l1} + iY_{l3} \sin \beta) - S_{s}^t(Y_{l2} + iY_{l3} \cos \beta)] \]
\[
\frac{m_{\chi_i^l}}{16\pi^2} f(m_b^2, m_{\chi_i^l}^2, m_{H^+}^2) \] (108)

\[
\Delta M_{ij}^{(9)} = \sum_{s=1}^{4} \sum_{k=1}^{2} \sum_{l=1}^{3} [E_{ki}(Y_{l2} + iY_{l3} \cos \beta) + E_{ik}^*(Y_{l2} - iY_{l3} \cos \beta) + F_{ki}(Y_{l1} + iY_{l3} \sin \beta) \]
\[+ F_{ik}^*(Y_{l1} - iY_{l3} \sin \beta)](\alpha_{ts} D_{l1k} - \gamma_{ts} D_{l2k})(Q_s^t Y_{l1} - iY_{l3} \sin \beta) - S_{s}^t(Y_{l2} - iY_{l3} \cos \beta)] \]
\[
\frac{m_{\chi_i^l}}{16\pi^2} f(m_b^2, m_{\chi_i^l}^2, m_{H^+}^2) \] (109)

The sum of contributions above give \( \Delta K_{bij} \) and \( \Delta M_{bij} \) so that

\[
\Delta K_{ij} = \sum_{n=1}^{9} \Delta K_{ij}^{(n)}
\]
\[
\Delta M_{ij} = \sum_{n=1}^{9} \Delta M_{ij}^{(n)} \] (110)

As in the previous analysis, the contribution from Fig. (4c) with the interchange \( Z \leftrightarrow H_i^0 \) vanishes in the zero external momentum approximation since the vertex is proportional to the external momentum. Similarly, the contribution from Fig. (4h) with the interchange...
$W^- \leftrightarrow H^-$ vanishes and Fig.(4i) with the interchange $Z \leftrightarrow H_i^0$ vanishes in the zero external momentum approximation for the same reason. We also note that loops where one of the internal lines is a gluon line also vanishes in the zero external momentum approximation since the squark-gluon interaction gives a vertex of $-ig_s(p+p')^\mu$ which is of course dependent on the momenta.

### 4 Loop corrected squark decays into charginos and neutralinos

Eqs.(5) and (70) give the loop corrected effective Lagrangian for $\bar{q}_i \tilde{q}_j^\pm$ and $\bar{q}_i \tilde{q}_j^0$ interactions. Next we use this loop corrected Lagrangian to compute the decay widths of the third generation squarks into charginos and neutralinos. Specifically we will analyze the following decays

\[
\begin{align*}
\tilde{b}_i &\rightarrow t + \chi_j^- \\
\tilde{t}_i &\rightarrow b + \chi_j^+ \\
\tilde{b}_i &\rightarrow b + \chi_j^0 \\
\tilde{t}_i &\rightarrow t + \chi_j^0 
\end{align*}
\]

To make the analysis more compact we begin by writing both Eqs.(5) and (70) in the following form

\[
\mathcal{L} = \bar{f}(B_{ij}^S + B_{ij}^P \gamma_5) f_j \tilde{q}_i + H.c.
\]

where $f$ takes on the values ($t, b$) and $f_j$ stands for $\chi_j^\pm, \chi_j^0$ while $\tilde{q}_i$ can be $\tilde{b}_i, \tilde{t}_i$. The decay width $\Gamma(\tilde{q}_i \rightarrow f_j f)$ is given by

\[
\Gamma(\tilde{q}_i \rightarrow f_j f) = \frac{1}{4\pi m_i^2} [(m_j^2 + m_j^2 - m_i^2)^2 - 4m_j^2m_i^2]^{1/2} \times \left\{ \frac{1}{2} (|B_{ij}^S|^2 + |B_{ij}^P|^2)(m_i^2 - m_j^2 - m_f^2) - \frac{1}{2} (|B_{ij}^S|^2 - |B_{ij}^P|^2)2m_j m_f \right\}
\]

The co-efficients $B_{ij}^S$ and $B_{ij}^P$ contain the loop corrections and depend on the CP phases. Thus, for example, the process $\tilde{b}_i \rightarrow \chi_j^- + t$ gives the co-efficients

\[
B_{ij}^S = \frac{g}{2} [R_{bij} + L_{bij} + \Delta R_{bij} + \Delta L_{bij}]
\]
\[ B_{ij}^{P} = \frac{q}{2} [R_{bij} - L_{bij} + \Delta R_{bij} - \Delta L_{bij}] \]  

(114)

where \( R_{bij}, L_{bij}, \Delta L_{bij} \) and \( \Delta R_{bij} \) are defined by Eqs.(2), (43) (44).

5 Numerical Analysis and Size of Effects

In this section we discuss in a quantitative fashion the size of loop effects on the decay widths of the squarks into chargino and neutralinos. The analysis of Secs.(2-4) is quite general and valid for the minimal supersymmetric standard model (MSSM). For the sake of numerical analysis we will limit the parameter space by working within the framework of the SUGRA models[23]. Specifically within the framework of the extended mSUGRA model including CP phases, we take as our parameter space at the grand unification scale to be the following: the universal scalar mass \( m_0 \), the universal gaugino mass \( m_{1/2} \), the universal trilinear coupling \( |A_0| \), the ratio of the Higgs vacuum expectation values \( \tan \beta = \frac{< H_2 >}{< H_1 >} \) where \( H_2 \) gives mass to the up quarks and \( H_1 \) gives mass to the down quarks and the leptons. In addition, we take for CP phases the following: the phase \( \theta_\mu \) of the Higgs mixing parameter \( \mu \) so that \( \mu = |\mu| e^{i\theta_\mu} \), the phase \( \alpha_{A_0} \) of the trilinear coupling where \( A_0 = |A_0| e^{i\alpha_{A_0}} \), and the phases \( \xi_i \) (i=1,2,3) of the \( SU(3)_C, SU(2)_L \) and \( U(1)_Y \) gauginos, so that \( \tilde{m}_i = |\tilde{m}_i| e^{i\xi_i} \) (i=1,2,3) where \( m_i \) (i=1,2,3) are the \( SU(3)_C, SU(2)_L \) and \( U(1)_Y \) gaugino masses. We note that not all the phases are independent and only certain combinations of them appear in the analysis[5]. In the numerical analysis we compute the loop corrections and also analyze their dependence on the phases.

In Fig.5(a) we give a plot of the decay width of the heavy stop (\( \tilde{t}_1 \)) into light and heavy chargino, \( \chi_1^\pm \) and \( \chi_2^\pm \), i.e., a plot of \( \Gamma(\tilde{t}_1 \rightarrow b\chi_{1,2}^\pm) \) as a function of \( \alpha_{A_0} \). The plots are given with the analysis done at the tree level and at the level of the effective Lagrangian including loop corrections. The analysis shows that the loop effects can produce a correction of as much as 25% to the tree level values. Further, the analysis of Fig.5(a) shows that the dependence on \( \alpha_{A_0} \) is quite significant and both the tree and the loop corrections are affected by it. From Fig.5(a) one finds that the variation with \( \alpha_{A_0} \) in the range \( (0, \pi) \) can be as much as 40-50%. In Fig.5(b) a similar plot is given for the decay width \( \Gamma(\tilde{t}_1 \rightarrow t\chi_{3,4}^0) \) as a function of \( \alpha_{A_0} \). Here one finds that the loop corrections can be as much as 20% and further that the variations with \( \alpha_{A_0} \) can be as much as 25-30%. The effect of \( \alpha_{A_0} \) on the
decay width arises from two sources: (1) $\alpha_{A_0}$ enters the off diagonal elements of the squark mass\textsuperscript{2} matrix. So it affects the squark masses that enter in the decay width. In fact, the modification of the squark masses due to $\alpha_{A_0}$ can be large enough that a decay channel may close or open as $\alpha_{A_0}$ is varied. This phenomenon will be illustrated explicitly later. This type of effect appears both at the tree and at the loop level. (2) The matrix $D_q$ that diagonalizes the squark matrix is sensitive to variations of $\alpha_{A_0}$ and this variation again affects both the tree and the loop level analysis. Thus at the tree level the couplings $R_{qij}$, $L_{qij}$, $K_{qij}$ and $M_{qij}$ depend on $\alpha_{A_0}$ and similarly at the loop level the couplings $\Delta R_{qij}$, $\Delta L_{qij}$, $\Delta K_{qij}$ and $\Delta M_{qij}$ also depend on $\alpha_{A_0}$. An important phenomena related to the dependence on $\alpha_{A_0}$ is that the effects are strongly dependent on the quark mass. This is so because phases enter in the squark mass\textsuperscript{2} matrix via the off diagonal terms in a prominent way and these off diagonal terms are proportional to the quark mass. Because of this, the sensitivity of the stop decay widths to $\alpha_{A_0}$ is far greater than the sensitivity of the sbottom decay width. The loop corrections are bigger in the case of the stop decay than for the sbottom case due to the relative difference of their Yukawa couplings. For this reason in our numerical analysis we will focus mostly on the effects of phases on stop decays.

Fig. 6(a) is a repeat of Fig. 5(a) with a plot of the light stop ($\tilde{t}_2$) decay width into charginos, i.e., $\Gamma(\tilde{t}_2 \rightarrow b\chi_{1,2}^0)$ as a function of $\alpha_{A_0}$. Here one finds that while the loop corrections are comparable to the case of Fig. 5(a), the variations of the decay width is more strongly dependent on $\alpha_{A_0}$ in this part of the parameter space. Fig. 6(b) gives an analysis similar to that of Fig. 5(b) where plots are given for the decay width $\Gamma(\tilde{t}_2 \rightarrow t\chi_{3,4}^0)$ as a function of $\alpha_{A_0}$. Here one finds that the loop corrections can be as much as 30%. Further, one finds that the variations with $\alpha_{A_0}$ are now much stronger than in the case of Fig. 5(b). Thus the effect of $\alpha_{A_0}$ is large enough that for values of $\alpha_{A_0} \geq 1.3$ (radian) the decays into $\chi_3^0, \chi_4^0$ are closed. The reason for this is purely kinematical, in that the mass of $\tilde{t}_2$ is strongly dependent on $\alpha_{A_0}$ and varies strongly with $\alpha_{A_0}$ and falls below the kinematical limit to allow for the decay into $\chi_3^0, \chi_4^0$ for values of $\alpha_{A_0} \geq 1.3$. In Fig. 7(a) a plot is given of the decay width $\Gamma(\tilde{t}_1 \rightarrow b\chi^+, t\chi^0)$ (where we summed over the final states of charginos and neutralinos) both at the tree level and at the loop level as a function of $\alpha_{A_0}$.

The analysis of Fig. 7(b) is similar to that of Fig. 7(a) except that one is looking at
the decay width of $\tilde{t}_2$. The discontinuities in Fig.7(b) are kinematical and arise from the
closing of some of the neutralino final states. The analysis of Fig.8(a) is similar to that
of Fig.7(a) while the analysis of Fig.8(b) is similar to that of Fig.7(b) except that the
plots are made as a function of $\theta_\mu$. It is interesting to observe that the dependence of
the stop widths on $\theta_\mu$ in Fig.8(b) appears to be relatively weaker. This arises because we
are summing over the chargino and neutralino final states. Thus, for example, the decay
width $\Gamma(\tilde{t}_1 \rightarrow b\chi^+_1)$ increases with $\theta_\mu$ for the parameters of Fig.8(a) while $\Gamma(\tilde{t}_1 \rightarrow b\chi^+_2)$
decreases. This results in the sum $\Gamma(\tilde{t}_1 \rightarrow b\chi^+_1, b\chi^+_2)$ having only a weak dependence on
$\theta_\mu$. An analysis similar to that of Figs.7(a)-7(b) but as a function of $\xi_3$ is carried out
in Figs.9(a)-9(b). One important new feature of the decay widths here is that the $\xi_3$ dependence of the widths at the tree level is absent while the loop corrected widths show
a dependence on $\xi_3$. Here one finds that the loop corrections are typically of size 10-15%
while the overall variation with $\xi_3$ can be as large as 20%. Typically, the loop correction
to the sbottom decays are small and the dependence on phases is also relatively small.
This is exhibited in Fig.10 where the decay width $\Gamma(\tilde{b}_1 \rightarrow t\chi^-_1)$ is plotted. Here one finds
that the loop effects are essentially negligible while the variations of the decay width with
$A_{0}$ is also essentially negligible. The reasons for this weak dependence on the phase and
the smallness of loop corrections have already been explained on an analytical basis at
the end of the second paragraph of this section. Here we see that the reasoning presented
there is borne out by the numerical analysis. Thus the largest loop corrections as well as
the largest variations with phases arise only for the decay of the stops.

The experimental upper limits of the electric dipole moments are[8, 9, 10]: $|d_e| < 4.3 \times 10^{-27}$cm, $|d_n| < 6.5 \times 10^{-26}$cm and $|d_{Hg}| < 9.0 \times 10^{-28}$ecm. The last constraint for Hg$^{199}$
could be transformed into a constraint on a specific combination of the chromoelectric
dipole moments of u, d and s quarks[6], $C_{Hg} = |d^C_q - d^C_u - 0.012d^C_s| < 3.0 \times 10^{-28}$cm.
These constraints are satisfied by the cancellation mechanism in the numerical analysis
presented above as follows: In figure 5, 6 and 7 the constraints are satisfied for the inputs
tan $\beta = 40$, $m_0 = 300$ GeV, $m_{1/2} = 300$ GeV, $\xi_1 = 0.5$ (radian), $\xi_2 = 0.66$ (radian),
$\xi_3 = 0.63$ (radian), $\theta_\mu = 2.5$ (radian), $\alpha_{A_0} = 1.0$ (radian) and $|A_0| = 1$. At this point
we have $|d_e| = 1.88 \times 10^{-27}$cm, $|d_n| = 1.79 \times 10^{-27}$cm and $C_{Hg} = 8.99 \times 10^{-27}$cm. In
figures 8, 9 and 10 they are satisfied for the inputs tan $\beta = 45$, $m_0 = 400$ GeV, $m_{1/2} = 400$
GeV, $\xi_1 = 0.6$ (radian), $\xi_2 = 0.65$ (radian), $\xi_3 = 0.65$ (radian), $\theta_\mu = 2.5$ (radian), $\alpha_{A_0} = 2.0$
(radian) and $|A_0| = 1$. At this point we have $|d_e| = 3.94 \times 10^{-27}$ ecm, $|d_n| = 9.21 \times 10^{-27}$ ecm and $C_{Hg} = 3.86 \times 10^{-27}$ cm.

6 Conclusion

In this paper we have analyzed supersymmetric one loop corrections to the squark-quark-chargino and to the squark-quark-neutralino couplings. The analysis involves the exchange of the gluino, chargino, neutralino, W, Z, charged Higgs and neutral Higgs. With the above analysis the one loop effective Lagrangian for these interactions was derived. The full CP dependence arising from the soft CP parameters was taken into account in the analysis. The effective Lagrangian was then used to obtain the decay of the squarks into charginos and neutralinos at the one loop order. A detailed numerical analysis within extended SUGRA model was then carried out to study the size of the loop effects and also to study the effect of CP phases on the decay widths of the squarks into charginos and neutralinos. The analysis exhibits that the loop corrections to the decay widths of the stops can be very substantial, i.e., as much as 30% or more. Further, the phase dependence of the decay width is found to be very strong producing a variation of as much as 40-50% or more. The phases enter in the decay widths in two ways; in modifying the stop-bottom-chargino, and the stop-top-neutralino couplings and in modifying the stop, chargino and neutralino masses. In some cases the effect of phases is large enough to open or close a decay channel. However, a similar analysis for the decay of the sbottoms shows the effect of loops as well as the effect of CP phases to be much smaller. The one loop effective Lagrangian derived in this paper would be useful in the analysis of squark decays at colliders and in connecting experimental data with the underlying theoretical schemes such as supergravity and string based models.

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Appendix A

For completeness we give below the loop corrections to the Yukawa couplings $\Delta h_b$, $\delta h_b$ etc that appear in Sec.2. A derivation of these results can be found in Ref.[13] and Ref.[15].
\[-\Delta h_b = -\frac{2}{\sqrt{2}} \sum_{i=1}^{2} \sum_{j=1}^{2} \sum_{k=1}^{2} \frac{2\alpha s}{3\pi} e^{-i\xi_3} m_g G_{ij}^* D_{b1i} D_{b2j} f(m_{g}^{2}, m_{b_i}^{2}, m_{b_j}^{2}) \]

\[-\sum_{i=1}^{2} \sum_{j=1}^{2} \sum_{k=1}^{2} g^{2} E_{ij} \{V_{k1}^* D_{t1i}^{*} - K_{t1} V_{k2}^* D_{t2i}^{*}\} (K_{b1} U_{k2}^* D_{t1j}) \frac{m_{\chi_k^+} m_{\chi_i^+}}{16\pi^2} f(m_{\chi_k^+}^{2}, m_{\chi_i^+}^{2}, m_{\chi_j^+}^{2}) \]

\[-\sum_{i=1}^{2} \sum_{j=1}^{2} \sum_{k=1}^{2} \sum_{l=1}^{4} 2G_{ij} \{\beta_{bk} D_{b1j} - \gamma_{bk} D_{b2j}\} \{\beta_{bk} D_{b1j}^* + \alpha_{bk} D_{b2j}^*\} \frac{m_{\chi_k^0} m_{\chi_i^0}}{16\pi^2} f(m_{\chi_k^0}^{2}, m_{\chi_i^0}^{2}, m_{\chi_j^0}^{2}) \]

\[C_{ij} = -\frac{g}{\sin \beta} \frac{m_{\chi_i^+}}{2M_W} \delta_{ij} - Q_{ij}^* \cos \beta - R_{ij}^* \]  

\[\Gamma_{ij} = -\frac{g}{2\sin \beta} \frac{m_{\chi_i^0}}{2M_W} \delta_{ij} - Q_{ij}^* \cos \beta - R_{ij}^{''*} \]  

\[R_{ij} = \frac{1}{2M_W} [\bar{m}_2 U_{i1} V_{j1} + \mu^* U_{i2} V_{j2}] \]

\[g Q_{ij}'' = \frac{1}{2} [X_{3i}^* (g X_{2j}^* - g' X_{1j}^* ) + (i \leftrightarrow j)] \]

\[R_{ij}'' = \frac{1}{2M_W} [\bar{m}_1 X_{1i}^* X_{1j}^* + \bar{m}_2 X_{2i}^* X_{2j}^* - \mu^* (X_{3i}^* X_{4j}^* + X_{4i}^* X_{3j}^*)] \]  

\[-\delta h_t = -\frac{2}{\sqrt{2}} \sum_{i=1}^{2} \sum_{j=1}^{2} \sum_{k=1}^{2} \frac{2\alpha s}{3\pi} e^{-i\xi_3} m_g F_{ij}^* D_{t1i} D_{t2j} f(m_{g}^{2}, m_{t_i}^{2}, m_{t_j}^{2}) \]

\[-\sum_{i=1}^{2} \sum_{j=1}^{2} \sum_{k=1}^{2} \sum_{l=1}^{4} g^{2} F_{ij} \{V_{k1}^* D_{t1i}^{*} - K_{t1} V_{k2}^* D_{t2i}^{*}\} (K_{b1} U_{k2}^* D_{t1j}) \frac{m_{\chi_k^+} m_{\chi_i^+}}{16\pi^2} f(m_{\chi_k^+}^{2}, m_{\chi_i^+}^{2}, m_{\chi_j^+}^{2}) \]

\[+\sum_{i=1}^{2} \sum_{j=1}^{2} \sum_{k=1}^{2} \sum_{l=1}^{4} 2H_{ij} \{\beta_{bk} D_{b1j} - \gamma_{bk} D_{b2j}\} \{\beta_{bk} D_{b1j}^* + \alpha_{bk} D_{b2j}^*\} \frac{m_{\chi_k^0} m_{\chi_i^0}}{16\pi^2} f(m_{\chi_k^0}^{2}, m_{\chi_i^0}^{2}, m_{\chi_j^0}^{2}) \]

\[-\Delta h_t = -\frac{2}{\sqrt{2}} \sum_{i=1}^{2} \sum_{j=1}^{2} \sum_{k=1}^{2} \frac{2\alpha s}{3\pi} e^{-i\xi_3} m_g F_{ij}^* D_{t1i} D_{t2j} f(m_{g}^{2}, m_{t_i}^{2}, m_{t_j}^{2}) \]
\[ -\sum_{i=1}^{2} \sum_{j=1}^{2} \sum_{k=1}^{2} g^2 H^*_i \{ U_{1i}^* D_{b1i}^* - K_b U_{k2}^* D_{b2i}^* \} (K_i V_{k2}^* D_{b1j}) \frac{m_{x_k}}{16\pi^2} f(m^2_{x_k}, m^2_{b_i}, m^2_{b_j}) \]

\[ -\sum_{i=1}^{2} \sum_{j=1}^{2} \sum_{k=1}^{2} g^2 K^*_i \{ U_{1i}^* D_{b1k}^* - K_b U_{k2}^* D_{b2k}^* \} (K_i V_{k2}^* D_{b1j}) \frac{m_{x_k}^+ m_{x_j}^+}{16\pi^2} f(m^2_{x_k}, m^2_{x_i}, m^2_{x_j}) \]

\[ +\sum_{i=1}^{2} \sum_{j=1}^{2} \sum_{k=1}^{2} \frac{2 F^*_i}{(\alpha_{tk} D_{t1j} - \gamma_{tk} D_{t2j}) \{ \beta^*_i D_{t1k}^* + \alpha_{tk} D_{t2k}^* \}} \frac{m_{x_k}^0}{16\pi^2} f(m^2_{x_k}, m^2_{x_i}, m^2_{x_j}) \]

\[ +\sum_{i=1}^{2} \sum_{j=1}^{2} \sum_{k=1}^{2} \frac{2 \Delta^*_i}{(\alpha_{tj} D_{t1k} - \gamma_{tj} D_{t2k}) \{ \beta^*_i D_{t1k}^* + \alpha_{ti} D_{t2k}^* \}} \frac{m_{x_k}^0 m_{x_j}^0}{16\pi^2} f(m^2_{x_k}, m^2_{x_i}, m^2_{x_j}) \] (120)

where

\[ K_{ij} = -\sqrt{2} g Q_{ij} \] (121)

\[ \Delta_{ij} = -\frac{g}{\sqrt{2}} Q''_{ij} \] (122)

\[ -\delta h_t = -\sum_{i=1}^{2} \sum_{j=1}^{2} \frac{2 \alpha^*}{3\pi} e^{-i\xi_3} m_g E_{j1} D_{t11}^* D_{t12j} f(m^2_{g}, m^2_{t_i}, m^2_{t_j}) \]

\[ -\sum_{i=1}^{2} \sum_{j=1}^{2} \sum_{k=1}^{2} g^2 g_{ji} \{ U_{1i}^* D_{b1i}^* - K_b U_{k2}^* D_{b2i}^* \} (K_i V_{k2}^* D_{b1j}) \frac{m_{x_k}^+}{16\pi^2} f(m^2_{x_k}, m^2_{b_i}, m^2_{b_j}) \]

\[ +\sum_{i=1}^{2} \sum_{j=1}^{2} \sum_{k=1}^{2} \frac{4 E_{ji}}{(\alpha_{tk} D_{t1j} - \gamma_{tk} D_{t2j}) \{ \beta^*_i D_{t1k}^* + \alpha_{tk} D_{t2k}^* \}} \frac{m_{x_k}^0}{16\pi^2} f(m^2_{x_k}, m^2_{t_i}, m^2_{t_j}) \] (123)

\[ -\Delta h_b = -\sum_{i=1}^{2} \sum_{j=1}^{2} \frac{2 \alpha^*}{3\pi} e^{-i\xi_3} D_{b2j}^* D_{t11}^* \eta_{ji}^* m_g f(m^2_{g}, m^2_{t_i}, m^2_{b_j}) \]

\[ +\sum_{i=1}^{2} \sum_{j=1}^{2} \sum_{k=1}^{2} \frac{4 \eta_{ji}^* (\alpha_{bk} D_{b1j} - \gamma_{bk} D_{b2j}) (\beta^*_i D_{t11}^* + \alpha_{tk} D_{t2i}^*)}{16\pi^2} \]

\[ \frac{m_{x_k}^0}{16\pi^2} f(m^2_{x_k}, m^2_{t_i}, m^2_{b_j}) + \sum_{i=1}^{2} \sum_{j=1}^{2} \sum_{k=1}^{2} \sqrt{2} g \xi_{ki} \frac{m_{x_k}^+ m_{x_i}^+}{16\pi^2} [-K_b U_{t2} D_{t1j} (\beta^*_i D_{t11}^* + \alpha_{tk} D_{t2j}) \]

\[ f(m^2_{t_j}, m^2_{x_j}, m^2_{x_k}) + (\alpha_{bk} D_{b1j} - \gamma_{bk} D_{b2j}) (U_{1i}^* D_{b1j}^* - K_b U_{k2}^* D_{b2j}) f(m^2_{b_j}, m^2_{x_i}, m^2_{x_k})] \] (124)

\[ -\delta h_b = -\sum_{i=1}^{2} \sum_{j=1}^{2} \frac{2 \alpha^*}{3\pi} e^{-i\xi_3} D_{b2j}^* D_{t11}^* \eta_{ji}^* m_g f(m^2_{g}, m^2_{t_i}, m^2_{b_j}) \]

\[ -\sum_{i=1}^{2} \sum_{j=1}^{2} \sum_{k=1}^{2} \frac{2 \eta_{ji}^* (\alpha_{bk} D_{b1j} - \gamma_{bk} D_{b2j}) (\beta^*_i D_{t11}^* + \alpha_{tk} D_{t2i}^*)}{16\pi^2} \]

\[ \frac{m_{x_k}^0}{16\pi^2} f(m^2_{x_k}, m^2_{t_i}, m^2_{b_j}) \] (125)
\[-\Delta h_t = - \sum_{i=1}^{2} \sum_{j=1}^{2} \left( \frac{2\alpha_s}{3\pi} e^{-\xi_3} D_{b_{ii}}^* D_{t_{ij}} \eta_{ij} m^g f(m^2_g, m^2_{b_i}, m^2_{t_j}) \right) \]

\[+ \sum_{i=1}^{2} \sum_{j=1}^{2} \sum_{k=1}^{4} 2\eta_{ij} (\alpha_{tk} D_{t_{ij}} - \gamma_{tk} D_{t_{2j}})(\beta_{bk} D_{b_{ii}}^* + \alpha_{bk} D_{b_{2i}}^*) \frac{m_{\chi_k}}{16\pi^2} f(m^2_{\chi_k}, m^2_{b_i}, m^2_{t_j}) \]

\[+ \sum_{i=1}^{2} \sum_{j=1}^{2} \sum_{k=1}^{4} \sqrt{2} g^{\xi_3} \frac{m_{\chi_k}}{16\pi^2} \left[ - K_i V_{t_{ij}}^* D_{b_{1j}} (\beta_{bk} D_{b_{1j}}^* + \alpha_{bk} D_{b_{2j}}^*) \right] f(m^2_{b_j}, m^2_{\chi_i}, m^2_{\chi_k}) \]

\[+ \sum_{i=1}^{2} \sum_{j=1}^{2} \sum_{k=1}^{4} 2\eta_{ij} (\alpha_{tk} D_{t_{ij}} - \gamma_{tk} D_{t_{2j}})(\beta_{bk} D_{b_{ii}}^* + \alpha_{bk} D_{b_{2i}}^*) \frac{m_{\chi_k}}{16\pi^2} f(m^2_{\chi_k}, m^2_{b_i}, m^2_{t_j}) \] (126)

\[-\delta h_t = \sum_{i=1}^{2} \sum_{j=1}^{2} \left( \frac{2\alpha_s}{3\pi} e^{-\xi_3} D_{b_{ii}}^* D_{t_{ij}} \eta_{ij} m^g f(m^2_g, m^2_{b_i}, m^2_{t_j}) \right) \]

\[+ \sum_{i=1}^{2} \sum_{j=1}^{2} \sum_{k=1}^{4} 2\eta_{ij} (\alpha_{tk} D_{t_{ij}} - \gamma_{tk} D_{t_{2j}})(\beta_{bk} D_{b_{ii}}^* + \alpha_{bk} D_{b_{2i}}^*) \frac{m_{\chi_k}}{16\pi^2} f(m^2_{\chi_k}, m^2_{b_i}, m^2_{t_j}) \] (127)

References


Figure 1: List of one loop graphs that contribute to the $\bar{b}_i t\chi^-_j$ couplings arising from the exchange of the gluino, charginos, neutralinos, W, Z, charged Higgs and neutral Higgs.

Figure 2: List of one loop graphs that contribute to the $\bar{t}_i b\chi^+_j$ couplings arising from the exchange of the gluino, charginos, neutralinos, W, Z, charged Higgs and neutral Higgs.
Figure 3: List of one loop graphs that contribute to the $\bar{b}b\chi^+_j$ couplings arising from the exchange of the gluino, charginos, neutralinos, W, Z, charged Higgs and neutral Higgs.

Figure 4: List of one loop graphs that contribute to the $\bar{t}t\chi^+_j$ couplings arising from the exchange of the gluino, charginos, neutralinos, W, Z, charged Higgs and neutral Higgs.
(a) Plot of the decay width $\Gamma(\tilde{t}_1 \rightarrow b\chi^+_1,2)$ as a function of $\alpha_{A_0}$. The solid lines correspond to analysis at the tree level while the long-dashed lines include loop corrections. The inputs for the thin lines is $\tan \beta = 40$, $m_0 = 300$ GeV, $m_{1/2} = 300$ GeV, $\xi_1 = 0.5$ (radian), $\xi_2 = .66$ (radian), $\xi_3 = .63$ (radian), $\theta_{\mu} = 2.5$ (radian), and $|A_0| = 1$. The thick lines are for $\chi^+_2$ decay and the thin lines are for $\chi^+_1$ decay.

(b) Plot of the decay width $\Gamma(\tilde{t}_1 \rightarrow t\chi^0_{3,4})$ as a function of $\alpha_{A_0}$. The solid lines correspond to analysis at the tree level while the long-dashed lines include loop corrections. The inputs for the thin lines is $\tan \beta = 40$, $m_0 = 300$ GeV, $m_{1/2} = 300$ GeV, $\xi_1 = 0.5$ (radian), $\xi_2 = .66$ (radian), $\xi_3 = .63$ (radian), $\theta_{\mu} = 2.5$ (radian), and $|A_0| = 1$. The thick lines are for $\chi^0_4$ decay and the thin lines are for $\chi^0_3$ decay.

Figure 5:
(a) Plot of the decay width $\Gamma(t \rightarrow b\chi_{1,2}^\pm)$ as a function of $\alpha_{A_0}$. The solid lines correspond to analysis at the tree level while the long-dashed lines include loop corrections. The inputs for the thin lines is $\tan \beta = 40$, $m_0 = 300$ GeV, $m_{1/2} = 300$ GeV, $\xi_1 = 0.5$ (radian), $\xi_2 = 0.66$ (radian), $\xi_3 = 0.63$ (radian), $\theta_\mu = 2.5$ (radian), and $|A_0| = 1$. The thick lines are for $\chi_2^\pm$ decay and the thin lines are for $\chi_1^\pm$ decay.

(b) Plot of the decay width $\Gamma(t \rightarrow t\chi_{3,4}^0)$ as a function of $\alpha_{A_0}$. The solid lines correspond to analysis at the tree level while the long-dashed lines include loop corrections. The inputs for the thin lines is $\tan \beta = 40$, $m_0 = 300$ GeV, $m_{1/2} = 300$ GeV, $\xi_1 = 0.5$ (radian), $\xi_2 = 0.66$ (radian), $\xi_3 = 0.63$ (radian), $\theta_\mu = 2.5$ (radian), and $|A_0| = 1$. The thick lines are for $\chi_4^0$ decay and the thin lines are for $\chi_3^0$ decay.

Figure 6:
(a) Plot of the decay width $\Gamma(\tilde{t}_1 \to b\chi^+, t\chi^0)$ as a function of $\alpha A_0$. The solid lines correspond to analysis at the tree level while the long-dashed lines include loop corrections. The inputs for the thin lines is $\tan \beta = 40, m_0 = 300 \text{ GeV}, m_{1/2} = 300 \text{ GeV}, \xi_1 = 0.5 \text{ (radian)}, \xi_2 = 0.66 \text{ (radian)}, \xi_3 = 0.63 \text{ (radian)}, \theta_\mu = 2.5 \text{ (radian)},$ and $|A_0| = 1$. The thick lines are for the sum over the neutralino final states and the thin lines are for the sum over the chargino final states.

(b) Plot of the decay width $\Gamma(\tilde{t}_2 \to b\chi^+, t\chi^0)$ as a function of $\alpha A_0$. The solid lines correspond to analysis at the tree level while the long-dashed lines include loop corrections. The inputs for the thin lines is $\tan \beta = 40, m_0 = 300 \text{ GeV}, m_{1/2} = 300 \text{ GeV}, \xi_1 = 0.5 \text{ (radian)}, \xi_2 = 0.66 \text{ (radian)}, \xi_3 = 0.63 \text{ (radian)}, \theta_\mu = 2.5 \text{ (radian)},$ and $|A_0| = 1$. The thick lines are for the sum over the neutralino final states and the thin lines are for the sum over the chargino final states.
(a) Plot of the decay width $\Gamma(\tilde{t}_1 \rightarrow b\chi^+ , t\chi^0)$ as a function of $\theta_\mu$. The solid lines correspond to analysis at the tree level while the long-dashed lines include loop corrections. The inputs for the thin lines is $\tan\beta = 45$, $m_0 = 400$ GeV, $m_{1/2} = 400$ GeV, $\xi_1 = 0.6$ (radian), $\xi_2 = .65$ (radian), $\xi_3 = .65$ (radian), $\alpha_{A_0} = 2$ (radian), and $|A_0| = 1$. The thick lines are for the sum over the neutralino final states and the thin lines are for the sum over the chargino final states.

(b) Plot of the decay width $\Gamma(\tilde{t}_2 \rightarrow b\chi^+ , t\chi^0)$ as a function of $\theta_\mu$. The solid lines correspond to analysis at the tree level while the long-dashed lines include loop corrections. The inputs for the thin lines is $\tan\beta = 45$, $m_0 = 400$ GeV, $m_{1/2} = 400$ GeV, $\xi_1 = 0.6$ (radian), $\xi_2 = .65$ (radian), $\xi_3 = .65$ (radian), $\alpha_{A_0} = 2$ (radian), and $|A_0| = 1$. The thick lines are for the sum over the neutralino final states and the thin lines are for the sum over the chargino final states.

Figure 8:
(a) Plot of the decay width $\Gamma(\tilde{t}_1 \rightarrow b\chi^+, t\chi^0)$ as a function of $\xi_3$. The solid lines correspond to analysis at the tree level while the long-dashed lines include loop corrections. The inputs for the thin lines is $\tan \beta = 45$, $m_0 = 400$ GeV, $m_{1/2} = 400$ GeV, $\xi_1 = 0.6$ (radian), $\xi_2 = 0.65$ (radian), $\theta_\mu = 2.5$ (radian), $\alpha_{A_0} = 2$ (radian), and $|A_0| = 1$. The thick lines are for the sum over the neutralino final states and the thin lines are for the sum over the chargino final states.

(b) Plot of the decay width $\Gamma(\tilde{t}_2 \rightarrow b\chi^+, t\chi^0)$ as a function of $\xi_3$. The solid lines correspond to analysis at the tree level while the long-dashed lines include loop corrections. The inputs for the thin lines is $\tan \beta = 45$, $m_0 = 400$ GeV, $m_{1/2} = 400$ GeV, $\xi_1 = 0.6$ (radian), $\xi_2 = 0.65$ (radian), $\theta_\mu = 2.5$ (radian), $\alpha_{A_0} = 2$ (radian), and $|A_0| = 1$. The thick lines are for the sum over the neutralino final states and the thin lines are for the sum over the chargino final states.

Figure 9:

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Figure 10: Plot of the decay width $\Gamma(\tilde{b}_1 \to t\chi^-)$ as a function of $\alpha A_0$. The solid lines correspond to analysis at the tree level while the long-dashed lines include loop corrections. The inputs for the thin lines is $\tan\beta = 45$, $m_0 = 400$ GeV, $m_{1/2} = 400$ GeV, $\xi_1 = 0.6$ (radian), $\xi_2 = .65$ (radian), $\xi_3 = .65$ (radian), $\theta_\mu = 2.5$ (radian), and $|A_0| = 1$. The input for the thick lines is the same as for the thin lines except that $\xi_2 = .5$ (radian).