One-loop corrections to the chargino and neutralino mass matrices in the on-shell scheme

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We present a consistent procedure for the calculation of the one-loop corrections to the charginos and neutralinos by using their *on-shell* mass matrices. The on-shell gaugino mass parameters M and M' and the Higgsino mass parameter μ are defined by the elements of these on-shell mass matrices. The on-shell mass matrices are different by finite one-loop corrections from the tree-level ones given in terms of the on-shell input parameters. When the on-shell M and μ are determined by the chargino sector, the neutralino masses receive corrections up to 4%. This must be taken into account in precision measurements at future e^+e^- linear colliders.

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I. INTRODUCTION

For the comparison of the Standard Model predictions with the precision experiments at the CERN e^+e^- collider LEP, calculations at the tree-level were no longer sufficient, making the inclusion of radiative corrections necessary. They provided important information on the top quark mass, the Higgs boson mass, and the unification condition for the gauge couplings.

The future generation of colliders, the Fermilab Tevatron, CERN Large Hadron Collider (LHC), and an e^+e^- linear collider will explore an energy range where one expects the appearance of supersymmetric particles. It will be possible to measure cross sections, branching ratios, masses, etc. At an e^+e^- linear collider it will even be possible to perform precision experiments for the production and decay of supersymmetric (SUSY) particles [1]. This allows one to test the underlying SUSY model. For instance, for the mass determination of charginos and neutralinos an accuracy of $\Delta m_{\tilde{\chi}^{\pm,0}} = 0.1-1$ GeV might be reached by performing threshold scans [2]. The precision measurements of their couplings will also be possible [1,3–6]. Therefore, for a comparison with experiment, higher-order effects have to be included in the theoretical calculations.

For calculations of radiative corrections to the masses, production cross sections, decay rates, etc. of charginos and neutralinos, a proper renormalization of the chargino and neutralino mixing matrices is needed. One-loop corrections to the masses were given in [7,8] in the scale-dependent dimensional reduction ($\overline{\text{DR}}$) scheme. Chargino production at one loop was treated by several authors [9–11]. In [9], the $\overline{\text{DR}}$ scheme was used where the scale dependence was canceled by replacing the tree-level parameters by running ones. In [10], effective chargino mixing matrices were introduced, which are independent of the renormalization scale Q. A pure on-shell renormalization scheme was adopted for the full one-loop radiative corrections to chargino and neutralino production in e^+e^- annihilation [11] and squark decays into charginos and neutralinos [12]. In this paper, we study another type of the correction which has not been discussed so far.

We present a consistent procedure for the calculation of the one-loop corrections to the on-shell mass matrix of charginos, X, and that of neutralinos, Y. One has to distinguish three types of the mass matrix: the tree-level mass matrix $\tilde{X}$ ($\tilde{Y}$) given in terms of the on-shell parameters, the $\overline{\text{DR}}$ running tree-level matrix X^0 (Y^0), and the on-shell mass matrix X (Y) which generates physical (pole) masses and on-shell mixing matrices by diagonalization. The on-shell parameters in $\tilde{X}$ and $\tilde{Y}$ are given as follows: The SU(2) gaugino mass parameter M and the Higgsino mass parameter μ are defined by the elements of the chargino on-shell mass matrix X, the U(1) gaugino mass parameter M' by the neutralino mass matrix Y, and the other parameters ($m_W, m_Z, \sin^2\theta_W, \tan\beta$) are given by the gauge and Higgs boson sectors. We calculate the finite shifts $\Delta X = X - \tilde{X}$ and $\Delta Y = Y - \tilde{Y}$. Especially, the zero elements of the tree-level matrix $\tilde{Y}$ receive nonzero corrections by ΔY. In the numerical analysis, we calculate the contributions of the fermion and sfermion loops, which are usually most important. We also discuss the case where the on-shell M' is defined by the SUSY grand unified theory (GUT) relation $M' = \frac{5}{3}\tan^2\theta_W M$.

First we illustrate in Sec. II our renormalization procedure for the fermion field with n components. In Sec. III, we give the explicit one-loop corrections to the mass matrices of charginos and neutralinos. We work out the shifts in the matrix elements, with a discussion of the on-shell renormalization of M, μ, and M'. The case in which the on-shell M' is defined by M is also discussed. In Sec. IV, we present some numerical results of the corrections by fermion and sfermion loops, mainly the correction to the masses for fixed on-shell parameters. Conclusions are given in Sec. V.

II. ON-SHELL RENORMALIZATION OF FERMIONS

In this section, we show the on-shell renormalization of the fermion field ψ with n components (each component being a four-component Dirac spinor) and its mass matrix, following the formulas in [13,14].

The mass term of the fermion in the interaction basis is

$$V=\overline{\psi_R}M\psi_L+\overline{\psi_L}M^\dagger\psi_R. \tag{1}$$

M is an $n\times n$ mass matrix, which is real assuming CP conservation. With the rotations

$$f_R=U\psi_R, \tag{2}$$

$$f_L=V\psi_L, \tag{3}$$

the mass matrix can be diagonalized:

$$V=\overline{f}M_D f=\overline{f_L}M_D f_R+\overline{f_R}M_D f_L=\sum_{i=1}^{n} m_{f_i}\overline{f}_i f_i, \tag{4}$$

with the diagonal matrix $M_D=\mathrm{diag}(m_{f_1},m_{f_2},\ldots,m_{f_n})$. For Majorana fermions we allow negative m_{f_i} in order to keep $U=V$ real. M_D is related to M by

$$M_D=UMV^T. \tag{5}$$

We express the bare quantities (with superscript 0) by the renormalized ones:

$$f^0_{L,R}=(1+\tfrac{1}{2}\delta Z_{L,R})f_{L,R}, \tag{6}$$

$$\overline{f}^0_{L,R}=\overline{f}_{L,R}(1+\tfrac{1}{2}\delta Z^\dagger_{L,R}), \tag{7}$$

$$U^0=U+\delta U, \tag{8}$$

$$V^0=V+\delta V, \tag{9}$$

$$M^0=M+\delta M. \tag{10}$$

δZ, δU, δV, and δM are $(n\times n)$ matrices. Hence

$$\psi^0_R=[U^T(1+\tfrac{1}{2}\delta Z_R)+\delta U^T]f_R \tag{11}$$

and

$$\psi^0_L=[V^T(1+\tfrac{1}{2}\delta Z_L)+\delta V^T]f_L. \tag{12}$$

By demanding that the counterterms δU and δV cancel the antisymmetric parts of the wave-function corrections, we get the fixing conditions for δU and δV:

$$\delta U=\tfrac{1}{4}(\delta Z_R-\delta Z_R^T)U, \tag{13}$$

$$\delta V=\tfrac{1}{4}(\delta Z_L-\delta Z_L^T)V. \tag{14}$$

This is equivalent to redefining the wave-function shifts in a symmetric way,

$$f^0_{L,R}=[1+\tfrac{1}{4}(\delta Z_{L,R}+\delta Z^\dagger_{L,R})]f_{L,R}, \tag{15}$$

$$\overline{f}^0_{L,R}=\overline{f}_{L,R}[1+\tfrac{1}{4}(\delta Z^\dagger_{L,R}+\delta Z_{L,R})], \tag{16}$$

and setting $\delta U=\delta V=0$. The renormalization conditions Eqs. (13) and (14) have already been used in [13,11]. According to Eq. (5), the on-shell mass matrix M is composed of the on-shell mixing matrices (U,V) and the pole masses, $M_D=\mathrm{diag}(m_{f_i}(\mathrm{pole}))$.

We start from the most general form of the matrix element of the one-loop renormalized two-point function for mixing fermions,

$$i\hat{\Gamma}_{ij}(k^2)=i\{\delta_{ij}(\not{k}-m_{f_i})+\not{k}[P_L\hat{\Pi}^L_{ij}(k^2)+P_R\hat{\Pi}^R_{ij}(k^2)]+\hat{\Pi}^{S,L}_{ij}(k^2)P_L+\hat{\Pi}^{S,R}_{ij}(k^2)P_R\}. \tag{17}$$

$\hat{\Pi}^L$, $\hat{\Pi}^R$, $\hat{\Pi}^{S,L}$, and $\hat{\Pi}^{S,R}$ are the fermion self-energy matrices. The "hat" denotes the renormalized quantities. Then the mass shifts δm_{f_k} are given by

$$\delta m_{f_k}=\tfrac{1}{2}\mathrm{Re}\{m_{f_k}[\Pi^L_{kk}(m^2_{f_k})+\Pi^R_{kk}(m^2_{f_k})]+\Pi^{S,L}_{kk}(m^2_{f_k})+\Pi^{S,R}_{kk}(m^2_{f_k})\}, \tag{18}$$

and the off-diagonal wave-function renormalization constants of δZ_R and δZ_L read $(i\neq j)$

$$(\delta Z_R)_{ij}=\frac{2}{m^2_{f_i}-m^2_{f_j}}\mathrm{Re}[\Pi^R_{ij}(m^2_{f_j})m^2_{f_j}+\Pi^L_{ij}(m^2_{f_j})m_{f_i}m_{f_j}+\Pi^{S,R}_{ij}(m^2_{f_j})m_{f_i}+\Pi^{S,L}_{ij}(m^2_{f_j})m_{f_j}]. \tag{19}$$

$(\delta Z_L)_{ij}$ is obtained by replacing $L\leftrightarrow R$ in Eq. (19). The counterterm for the mass matrix element δM_{ij} can be written as

$$\delta M_{ij}=\tfrac{1}{2}\sum_{k,l}U_{ki}V_{lj}\,\mathrm{Re}[\Pi^L_{kl}(m^2_{f_k})m_{f_k}+\Pi^R_{kl}(m^2_{f_l})m_{f_l}+\Pi^{S,L}_{kl}(m^2_{f_k})+\Pi^{S,R}_{lk}(m^2_{f_l})]. \tag{20}$$

III. CHARGINO AND NEUTRALINO MASS MATRICES AT THE ONE-LOOP LEVEL

In the MSSM the chargino mass matrix is given by

$$X=\begin{pmatrix} M & \sqrt{2}m_W\sin\beta \\ \sqrt{2}m_W\cos\beta & \mu \end{pmatrix}. \tag{21}$$

It is diagonalized by the two real (2×2) matrices U and V:

$$UXV^T=M_D=\begin{pmatrix} m_{\tilde{\chi}^+_1} & 0 \\ 0 & m_{\tilde{\chi}^+_2} \end{pmatrix}, \tag{22}$$

with $m_{\tilde{\chi}^+_1}$ and $m_{\tilde{\chi}^+_2}$ the physical masses of the charginos (choosing $m_{\tilde{\chi}^+_1}<m_{\tilde{\chi}^+_2}$). The shifts for U and V are then given by Eqs. (13) and (14):

$$\delta U=\tfrac{1}{4}(\delta Z_R^{\tilde{\chi}^+}-\delta Z_R^{\tilde{\chi}^+T})U, \tag{23}$$

$$\delta V=\tfrac{1}{4}(\delta Z_L^{\tilde{\chi}^+}-\delta Z_L^{\tilde{\chi}^+T})V. \tag{24}$$

The shift in X follows from

$$\delta X=\delta(U^TM_DV)=\delta U^TM_DV+U^TM_D\delta V+U^T\delta M_DV. \tag{25}$$

Its matrix elements are

$$(\delta X)_{ij}=\sum_{k=1}^{2}\left[m_{\tilde{\chi}_k^+}(\delta U_{ki}V_{kj}+U_{ki}\delta V_{kj})+\delta m_{\tilde{\chi}_k^+}U_{ki}V_{kj}\right], \tag{26}$$

where the elements δU_{ki} and δV_{kj} are obtained from Eqs. (23) and (24) together with Eq. (19). $\delta m_{\tilde{\chi}_k^+}$ is given by Eq. (18). The explicit forms for the chargino self-energies are given in Eq. (A1).

Now we want to calculate the on-shell mass matrix X at the one-loop level. We first show the relation between three types of the mass matrix: X, $\tilde{X}$, and X^0. $\tilde{X}$ is the tree-level mass matrix, which has the form of Eq. (21) in terms of the on-shell parameters $(M,\mu,m_W,\tan\beta)$. $\tilde{X}$ is diagonalized by the matrices $\tilde{U}$ and $\tilde{V}$ to give the eigenvalues $\tilde{m}_i$. The bare mass matrix (or the $\overline{\rm DR}$ running tree-level matrix) X^0 is related to $\tilde{X}$ by

$$X^0=\tilde{X}+\delta_c X, \tag{27}$$

where δ_c means the variation of the (on-shell) parameters in $\tilde{X}$. The correction (25) represents the difference between X^0 and the on-shell X, with $X^0=X+\delta X$. This implies

$$X=\tilde{X}+\delta_c X-\delta X=\tilde{X}+\Delta X. \tag{28}$$

The one-loop corrected matrix X is the sum of the tree-level mass matrix $\tilde{X}$ with the on-shell quantities and the ultraviolet (UV) finite shifts ΔX.

To discuss the shifts ΔX, we need to fix the definition of the on-shell parameters in $\tilde{X}$. In this paper, we define the on-shell parameters M and μ by the elements of the on-shell mass matrix of charginos, by $M=X_{11}$ and $\mu=X_{22}$ respectively. This definition gives the counterterms

$$\delta M=(\delta X)_{11}, \tag{29}$$

$$\delta\mu=(\delta X)_{22}. \tag{30}$$

We comment later on the case in which M and μ are fixed by the neutralino mass matrix. In addition, we fix the on-shell m_W as the physical (pole) mass and $\tan\beta$ by the condition in the Higgs sector, as given in the Appendix. As a result, we have

$$\Delta X_{11}=0, \tag{31}$$

$$\Delta X_{12}=\left(\frac{\delta m_W}{m_W}+\cos^2\beta\,\frac{\delta\tan\beta}{\tan\beta}\right)X_{12}-\delta X_{12}, \tag{32}$$

$$\Delta X_{21}=\left(\frac{\delta m_W}{m_W}-\sin^2\beta\,\frac{\delta\tan\beta}{\tan\beta}\right)X_{21}-\delta X_{21}, \tag{33}$$

$$\Delta X_{22}=0, \tag{34}$$

with δX_{12} and δX_{21} given by Eq. (25) with the replacements $U\to\tilde{U}$, $V\to\tilde{V}$, and $m_{\tilde{\chi}_k}\to\tilde{m}_k$. The counterterm δm_W is given in Eq. (A9) together with Eq. (A11). $\delta\tan\beta$ is obtained from Eqs. (A15) and (A16). By diagonalizing the matrix X, one gets the one-loop pole masses of charginos, $m_{\tilde{\chi}_{1,2}^+}$, and their on-shell rotation matrices U and V, which enter in all chargino couplings.

If the chargino masses $m_{\tilde{\chi}_{1,2}^+}$ are known from experiment (e.g., from a threshold scan), one first calculates the tree-level parameters $\tilde{M}$, $\tilde{\mu}$, $\tilde{U}$, and $\tilde{V}$, using Eqs. (21) and (22) together with the experimental information of chargino couplings [5,6,15]. $\delta\tilde{U}$ and $\delta\tilde{V}$ are then obtained from Eqs. (23) and (24), depending on the sfermion parameters. This enables one to calculate ΔX_{12} and ΔX_{21} and the one-loop corrected mass matrix X. By requiring that X give the measured chargino masses $m_{\tilde{\chi}_{1,2}^+}$, one then gets the correct on-shell parameters M and μ. The error that one starts from $\tilde{M}$ and $\tilde{\mu}$ is of higher order. The dependence of this procedure on sfermion parameters will be discussed in Sec. IV.

Let us now turn to the neutralino sector. The mass matrix in the interaction basis has the form

$$Y=\begin{pmatrix} M' & 0 & -m_Z\sin\theta_W\cos\beta & m_Z\sin\theta_W\sin\beta \\ 0 & M & m_Z\cos\theta_W\cos\beta & -m_Z\cos\theta_W\sin\beta \\ -m_Z\sin\theta_W\cos\beta & m_Z\cos\theta_W\cos\beta & 0 & -\mu \\ m_Z\sin\theta_W\sin\beta & -m_Z\cos\theta_W\sin\beta & -\mu & 0 \end{pmatrix}. \tag{35}$$

Since we assume CP conservation, this matrix is real and symmetric. It is diagonalized by the real matrix Z:

$$ZYZ^T=M_D={\rm diag}(m_{\tilde{\chi}_1^0},m_{\tilde{\chi}_2^0},m_{\tilde{\chi}_3^0},m_{\tilde{\chi}_4^0}). \tag{36}$$

We allow negative values for the mass parameters $m_{\tilde{\chi}_i^0}$. The convention $|m_{\tilde{\chi}_1^0}|<|m_{\tilde{\chi}_2^0}|<|m_{\tilde{\chi}_3^0}|<|m_{\tilde{\chi}_4^0}|$ is used.

The shift for the rotation matrix Z is obtained from Eqs. (13) and (14) by the substitutions $U\to Z$ and $V\to Z$,

$$\delta Z=\tfrac{1}{4}(\delta Z_L^{\tilde{\chi}^0}-\delta Z_L^{\tilde{\chi}^0 T})Z, \tag{37}$$

$$\delta Z^T=\tfrac{1}{4}Z^T(\delta Z_R^{\tilde{\chi}^0 T}-\delta Z_R^{\tilde{\chi}^0}). \tag{38}$$

Note that $\delta Z_L^{\tilde{\chi}^0} = \delta Z_R^{\tilde{\chi}^0}$ due to the Majorana character of the neutralinos. The shift δY is given by $\delta Y = \delta(Z^T M_D Z)$, i.e., for the matrix elements

$$(\delta Y)_{ij} = \sum_{k=1}^{4} [\delta m_{\tilde{\chi}_k^0} Z_{ki} Z_{kj} + m_{\tilde{\chi}_k^0} \delta Z_{ki} Z_{kj} + m_{\tilde{\chi}_k^0} Z_{ki} \delta Z_{kj}]. \tag{39}$$

The wave-function correction terms $\delta Z^{\tilde{\chi}^0}$ are given by Eq. (19) and $\delta m_{\tilde{\chi}_k^0}$ by Eq. (18). The formulas for the neutralino self-energies are shown in Eqs. (A4) and (A5).

We again start with the tree-level mass matrix $Y^{\text{tree}} \equiv \tilde{Y}$, which has the form of Eq. (35) in terms of the on-shell parameters $(M, \mu, M', m_Z, \sin\theta_W, \tan\beta)$. First one calculates the tree-level masses $\tilde{m}_k$ and the rotation matrix $\tilde{Z}$ by diagonalizing $\tilde{Y}$. In analogy to the chargino case, the one-loop on-shell mass matrix Y is

$$Y = Y^0 - \delta Y = \tilde{Y} + \delta_c Y - \delta Y = \tilde{Y} + \Delta Y. \tag{40}$$

Here δ_c means the variation of the parameters in $\tilde{Y}$. Again ΔY is UV-finite.

We need to fix the on-shell input parameters in $\tilde{Y}$. The on-shell M and μ are already determined by the chargino sector. We define the on-shell parameter M' by the on-shell mass matrix of neutralinos as $Y_{11} = M'$. This condition gives

$$\delta M' = (\delta Y)_{11}. \tag{41}$$

We further fix the on-shell m_Z, $\sin^2\theta_W = 1 - m_W^2/m_Z^2$, and $\tan\beta$ in the same way as in the case of charginos.

The 10 independent entries of the real and symmetric matrix ΔY are

$$\Delta Y_{11} = 0, \tag{42}$$

$$\Delta Y_{12} = -\delta Y_{12}, \tag{43}$$

$$\Delta Y_{13} = \left(\frac{\delta m_Z}{m_Z} + \frac{\delta \sin\theta_W}{\sin\theta_W} - \sin^2\beta \frac{\delta\tan\beta}{\tan\beta} \right) Y_{13} - \delta Y_{13}, \tag{44}$$

$$\Delta Y_{14} = \left(\frac{\delta m_Z}{m_Z} + \frac{\delta \sin\theta_W}{\sin\theta_W} + \cos^2\beta \frac{\delta\tan\beta}{\tan\beta} \right) Y_{14} - \delta Y_{14}, \tag{45}$$

$$\Delta Y_{22} = \delta M - \delta Y_{22}, \tag{46}$$

$$\Delta Y_{23} = \left(\frac{\delta m_Z}{m_Z} - \tan^2\theta_W \frac{\delta \sin\theta_W}{\sin\theta_W} - \sin^2\beta \frac{\delta\tan\beta}{\tan\beta} \right) Y_{23} - \delta Y_{23}, \tag{47}$$

$$\Delta Y_{24} = \left(\frac{\delta m_Z}{m_Z} - \tan^2\theta_W \frac{\delta \sin\theta_W}{\sin\theta_W} + \cos^2\beta \frac{\delta\tan\beta}{\tan\beta} \right) Y_{24} - \delta Y_{24}, \tag{48}$$

$$\Delta Y_{33} = -\delta Y_{33}, \tag{49}$$

$$\Delta Y_{34} = -\delta\mu - \delta Y_{34}, \tag{50}$$

$$\Delta Y_{44} = -\delta Y_{44}, \tag{51}$$

with δY_{ij} given by Eq. (39) with $Z \to \tilde{Z}$, and $m_{\tilde{\chi}_k^0} \to \tilde{m}_{\tilde{\chi}_k^0}$. $\delta\sin\theta_W$ and δm_Z can be calculated from Eqs. (A9)–(A13). Notice that the elements $Y_{12} = Y_{21}$, Y_{33}, and Y_{44} are no longer zero. Recall that $\delta M = \delta X_{11}$ and $\delta\mu = \delta X_{22}$. The corrected neutralino masses and the corrected rotation matrix Z are obtained by diagonalizing the matrix Y, Eq. (40).

So far we have treated M' as an independent parameter to be determined in the neutralino sector. If we assume a relation between gaugino masses, we may define the on-shell M' as a function of other on-shell parameters instead of Y_{11}. The shift ΔY_{11} is then no longer zero. For example, when the SUSY SU(5) relation $M' = \frac{5}{3}\tan^2\theta_W M$ holds for the $\overline{\text{DR}}$ parameters, and the on-shell M' is defined by imposing the same relation on the on-shell parameters, one has

$$\Delta Y_{11} = \left(\frac{2}{\cos^2\theta_W} \frac{\delta\sin\theta_W}{\sin\theta_W} + \frac{\delta M}{M} \right) Y_{11} - \delta Y_{11}. \tag{52}$$

We note that Eq. (52) is also applicable in other models for gaugino masses, e.g., in the anomaly mediated SUSY breaking model [16,17] where $M' = 11\tan^2\theta_W M$.

Finally, we would like to remark that one could also first determine the on-shell values of M', M, μ from the neutralino sector, which means $\Delta Y_{11} = \Delta Y_{22} = \Delta Y_{34} = \Delta Y_{43} = 0$, see Eqs. (35) and (42)–(51). This would imply corrections ΔX_{11} and ΔX_{22} in the chargino system.

IV. NUMERICAL EXAMPLES

In this section, we will give some numerical examples for the on-shell one-loop corrected mass matrices and masses of the charginos and neutralinos. We take into account the contributions from all fermions and sfermions.

For simplicity, we will take in the following (if not specified otherwise) for the soft breaking sfermion mass parameters of the first and second generation $M_{\tilde{Q}_{1,2}} = M_{\tilde{U}_{1,2}} = M_{\tilde{D}_{1,2}} = M_{\tilde{L}_{1,2}} = M_{\tilde{E}_{1,2}}$, of the third generation $M_{\tilde{Q}_3} = \frac{10}{9} M_{\tilde{U}_3} = \frac{10}{11} M_{\tilde{D}_3} = M_{\tilde{L}_3} = M_{\tilde{E}_3} = M_{\tilde{Q}}$, and for the trilinear couplings $A_t = A_b = A_\tau = A$. We take $m_t = 175$ GeV, $m_b = 5$ GeV, $m_Z = 91.2$ GeV, $m_W = 80$ GeV, and $m_{A^0} = 500$ GeV. Thus the input parameter set is $\{\tan\beta, M_{\tilde{Q}_1}, M_{\tilde{Q}}, A, M, M', \mu\}$.

We always assume that the (on-shell) values of M and μ are obtained from the chargino sector as described in Sec. III. Then the chargino mass matrix only gets corrections in the off-diagonal elements of the matrix X. In general, the corrections to the chargino masses are small ($<1\%$). For instance, for $\tan\beta = 7$ and $\{M_{\tilde{Q}_1}, M_{\tilde{Q}}, A, M, \mu\} = \{300, 300, -500, 300, -400\}$ GeV one gets for $\Delta X_{12}/X_{12} \simeq 0.7/122$ and for $\Delta X_{21}/X_{21} \simeq -1.1/16$, $\Delta m_{\tilde{\chi}_1^+}/m_{\tilde{\chi}_1^+} = -0.24\%$ and $\Delta m_{\tilde{\chi}_2^+}/m_{\tilde{\chi}_2^+} = -0.14\%$. For the same parameters but $\tan\beta = 40$ one gets for $\Delta X_{12}/X_{12} \simeq 2.3/113$, $\Delta X_{21}/X_{21} \simeq -3.2/2.8$, $\Delta m_{\tilde{\chi}_1^+}/m_{\tilde{\chi}_1^+} = -0.76\%$, and $\Delta m_{\tilde{\chi}_2^+}/m_{\tilde{\chi}_2^+} = -0.46\%$.

As shown in Sec. III, the on-shell parameters M and μ for

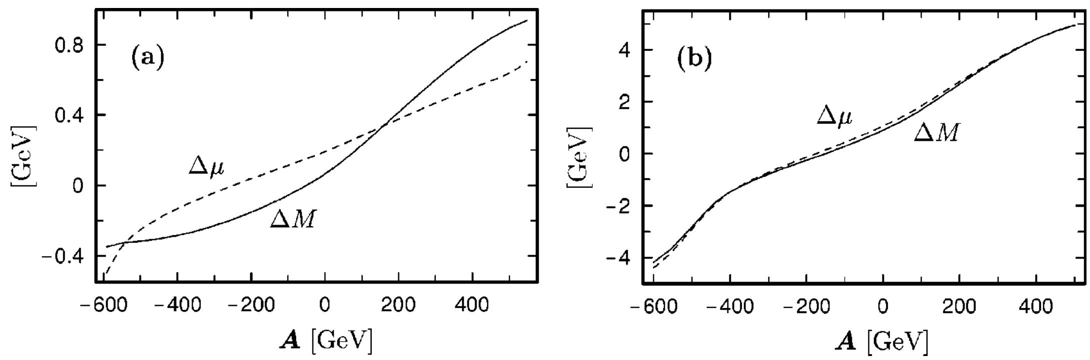

FIG. 1. $\Delta M = M - M^{\text{eff}}$ (full lines) and $\Delta\mu = \mu - \mu^{\text{eff}}$ (dashed lines) as functions of A with $\tan\beta = 7$, $M_{\tilde{Q}_1} = M_{\tilde{Q}} = 300$ GeV, and sgn(μ)$=-1$. In (a) $\{m_{\tilde{\chi}_1^+}, m_{\tilde{\chi}_2^+}\} = \{126.7, 322\}$ GeV giving $\{M^{\text{eff}}, \mu^{\text{eff}}\} = \{300, -130\}$ GeV for $M > |\mu|$. In (b) $\{m_{\tilde{\chi}_1^+}, m_{\tilde{\chi}_2^+}\} = \{200, 300\}$ GeV giving $\{M^{\text{eff}}, \mu^{\text{eff}}\} = \{227.7, -255.6\}$ GeV for $M < |\mu|$.

given values of the pole masses $m_{\tilde{\chi}_1^+}$ and $m_{\tilde{\chi}_2^+}$ depend on sfermion parameters. In Fig. 1, we show the values of M and μ as functions of A, for fixed $m_{\tilde{\chi}_{1,2}^+}$, $\tan\beta = 7$, and $M_{\tilde{Q}_1} = M_{\tilde{Q}} = 300$ GeV. For comparison we show the difference from the effective parameters used in [11], M^{eff} and μ^{eff}. These are obtained from the pole masses $m_{\tilde{\chi}_{1,2}^+}$ by tree-level sum rules and are therefore independent of sfermion parameters. We see that the dependence on the sfermion parameters becomes large for $M \sim |\mu|$, i.e., large gaugino-Higgsino mixing.

Let us now discuss the neutralino sector for the on-shell M and μ fixed by the chargino sector. We first treat the on-shell M' as an independent parameter. Then the one-loop corrections to the mass matrix (35) are calculated by Eqs. (42)–(51).

In Fig. 2(a), we show the relative correction $\delta m_{\tilde{\chi}_1^0}/m_{\tilde{\chi}_1^0}$ as a function of μ for $\tan\beta = 7$ and $\{M_{\tilde{Q}_1}, M_{\tilde{Q}}, A, M, M'\} = \{300, 300, -500, 300, 149.4\}$ GeV.

One can see that the corrections to $m_{\tilde{\chi}_1^0}$ and $m_{\tilde{\chi}_2^0}$ can go up to 2.2% for $|\mu| \sim 100$ GeV, where $\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0$ are Higgsino-like. Figure 2(b) shows the same as Fig. 2(a) for $\tan\beta = 40$ with the other parameters unchanged. The general behavior of the curves is very similar.

We also present numerical values of the mass matrix $\tilde{Y}$ and its correction ΔY calculated for the same set of parameters as in Fig. 2(a), with $\mu = 110$ GeV,

$$\tilde{Y} + \Delta Y = \begin{pmatrix} 149.4 & 0 & -6.2 & 43.3 \\ 0 & 300 & 11.3 & -79.2 \\ -6.2 & 11.3 & 0 & 110 \\ 43.3 & -79.2 & 110 & 0 \end{pmatrix} \text{GeV}$$
$$+ \begin{pmatrix} 0 & 0.3 & 0.0 & 0.9 \\ 0.3 & -0.1 & -0.1 & -0.2 \\ 0.0 & -0.1 & -0.0 & 0.2 \\ 0.9 & -0.2 & 0.2 & -4.3 \end{pmatrix} \text{GeV.}$$

Notice that also the zero elements of $\tilde{Y}$ get nonzero corrections. Especially, the most important contribution comes from the element ΔY_{44}, that is, from the $\tilde{H}_2^0$ to $\tilde{H}_2^0$ transition via a $t\tilde{t}$ loop. The effects of ΔY_{22}, ΔY_{33}, ΔY_{34}, and ΔY_{44} on the masses were discussed in the limiting cases, for $|\mu| \ll (M, M')$ in [18] and for $M \ll (|\mu|, M')$ in [19,17], respectively.

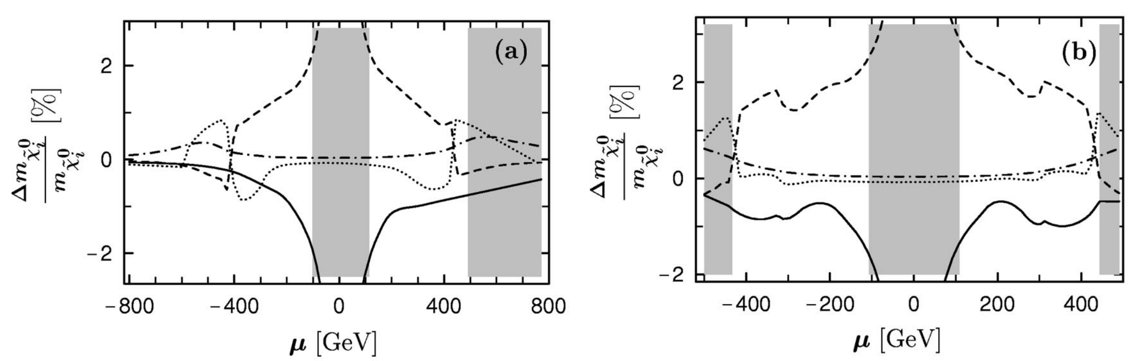

FIG. 2. Relative corrections to neutralino masses as a function of μ for $\tan\beta = 7$ (a) and $\tan\beta = 40$ (b) with $\{M_{\tilde{Q}_1}, M_{\tilde{Q}}, A, M, M'\} = \{300, 300, -500, 300, 149.4\}$ GeV. The full, dashed, dotted, and dash-dotted lines correspond to $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$, $\tilde{\chi}_3^0$, and $\tilde{\chi}_4^0$ mass corrections, respectively. The gray areas are excluded by the bounds $m_{\tilde{\chi}_1^+} \geq 100$ GeV, $m_{h^0} > 95$ GeV.

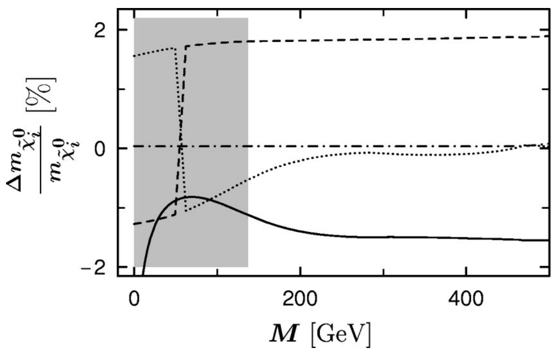

FIG. 3. Relative corrections to neutralino masses as a function of M for $\tan\beta=7$ and $\{M_{\tilde{Q}_1},M_{\tilde{Q}},A,\mu\}=\{300,300,-500,-130\}$ GeV. The full, dashed, dotted, and dash-dotted lines correspond to $\tilde{\chi}^0_1$, $\tilde{\chi}^0_2$, $\tilde{\chi}^0_3$, and $\tilde{\chi}^0_4$ mass corrections, respectively. The gray areas are excluded by the bound $m_{\tilde{\chi}^+_1}\geqslant 100$ GeV.

In Fig. 3, we show the M dependence with $M'=0.498M$ for $\mu=-130$ GeV and the other parameters as in Fig. 2(a). One sees that up to $M\simeq 200$ GeV, the M dependence of $\delta m_{\tilde{\chi}^0_1}/m_{\tilde{\chi}^0_1}$ is rather strong and becomes weak when $\tilde{\chi}^0_1$ becomes Higgsino-like. One also sees the various discontinuities in $\tilde{\chi}^0_2$ and $\tilde{\chi}^0_3$ due to "level crossings" (see, e.g., [20]).

Figure 4 exhibits the dependence on $M_{\tilde{Q}}$ for the same parameter set as in Fig. 2(a) with $\mu=-130$ GeV. The corrections to the masses become smaller with increasing $M_{\tilde{Q}}$. The dependence on $M_{\tilde{Q}_1}$ for fixed $M_{\tilde{Q}}$ is very small. The effects of the nondecoupling corrections [21,10] to the gaugino-Higgsino mixing elements of Y and X cannot be seen in Fig. 4.

In Fig. 5, we show the dependence on A_t, with $\mu=-130$ GeV, $A_b=A_\tau$ fixed to 500 GeV, and the other parameters as in Fig. 2(a). It is strong for the Higgsino-like states $\tilde{\chi}^0_1$ and $\tilde{\chi}^0_2$ being mainly due to the A_t dependence of ΔY_{44}. The sensitivity to the value of A_b and A_τ is very weak.

Finally, we discuss the interesting case in which M' and M are related by the SUSY SU(5) GUT relation $M'=\frac{5}{3}\tan^2\theta_W M$ in the $\overline{\rm DR}$ scheme. Then it is possible to define the on-shell M' by imposing this relation on the on-shell parameters. In this case, ΔY_{11} gets a contribution according to Eq. (52). This correction is relatively large. For instance, for the parameter set of Fig. 2(a) with $\mu=-130$ GeV one gets $\Delta Y_{11}/Y_{11}\simeq 5.7/149$. This corresponds to the SUSY threshold correction to the unification condition of the gaugino masses [7,22]. ΔY_{11} gives a large correction to the mass of a B-ino-like neutralino. This is clearly seen in Fig. 6. Figure 6(a) shows the correction to $m_{\tilde{\chi}^0_3}$ as a function of M for $\mu=-130$ GeV and the other parameters as in Fig. 2(a). The solid line shows the case in which the $\overline{\rm DR}$ parameters M and M' satisfy the SUSY GUT relation and the on-shell M' is defined by the same relation. For comparison, the dotted line shows the case in which the on-shell M' is defined by Y_{11} as an independent parameter (with $\Delta Y_{11}=0$), but its value coincides with the on-shell $\frac{5}{3}\tan^2\theta_W M$. $\tilde{\chi}^0_3$ is B-ino-like for $M>200$ GeV and $\delta m_{\tilde{\chi}^0_3}/m_{\tilde{\chi}^0_3}$ goes up to 4%. In Fig. 6(b), we show $\delta m_{\tilde{\chi}^0_1}/m_{\tilde{\chi}^0_1}$ for $\mu=-300$ GeV. Here $\tilde{\chi}^0_1$ is almost purely B-ino-like, hence it also gets a large correction.

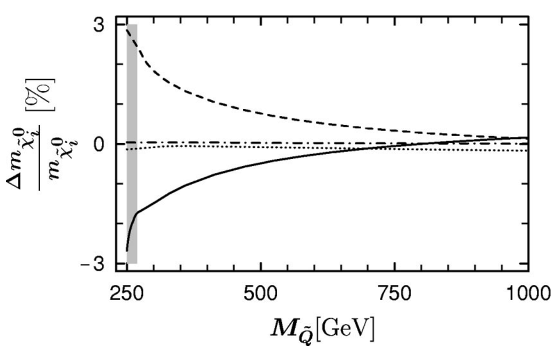

FIG. 4. Relative corrections to neutralino masses as a function of $M_{\tilde{Q}}$ for $\tan\beta=7$ and $\{M_{\tilde{Q}_1},A,M,M',\mu\}=\{300,-500,300,149.4,-130\}$ GeV. The full, dashed, dotted, and dash-dotted lines correspond to $\tilde{\chi}^0_1$, $\tilde{\chi}^0_2$, $\tilde{\chi}^0_3$, and $\tilde{\chi}^0_4$ mass corrections, respectively. The gray areas are excluded by the bound $m_{\tilde{t}_1}\geqslant 100$ GeV.

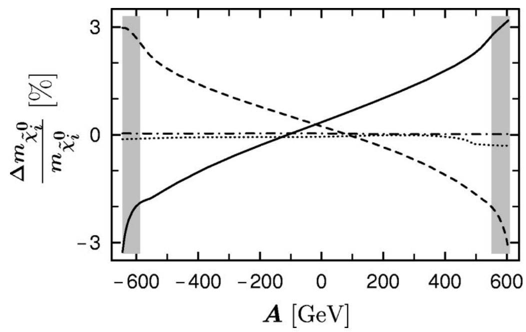

FIG. 5. Relative corrections to neutralino masses as a function of A for $\tan\beta=7$ and $\{M_{\tilde{Q}_1},M_{\tilde{Q}},M,M',\mu\}=\{300,300,300,149.4,-130\}$ GeV. The full, dashed, dotted, and dash-dotted lines correspond to $\tilde{\chi}^0_1$, $\tilde{\chi}^0_2$, $\tilde{\chi}^0_3$, and $\tilde{\chi}^0_4$ mass corrections, respectively. The gray areas are excluded by the bound $m_{\tilde{t}_1}\geqslant 100$ GeV.

V. CONCLUSIONS

We have presented a consistent method for the calculation of the one-loop corrections to the on-shell mass matrices of charginos and neutralinos, and hence their masses. The on-shell parameters M, μ, and M' are determined by the elements of the on-shell mass matrices. We have calculated the corrections to the tree-level mass matrices in terms of on-shell parameters. We have performed a detailed numerical analysis of the corrections due to fermion and sfermion loops, as a function of the SUSY parameters. When the parameters M and μ are determined by the chargino system, one gets corrections to the neutralino masses of up to 4%. We have also treated the case in which the on-shell M' is defined by M using the SUSY GUT relation. Therefore, these corrections have to be taken into account in precision experiments at future e^+e^- linear colliders.

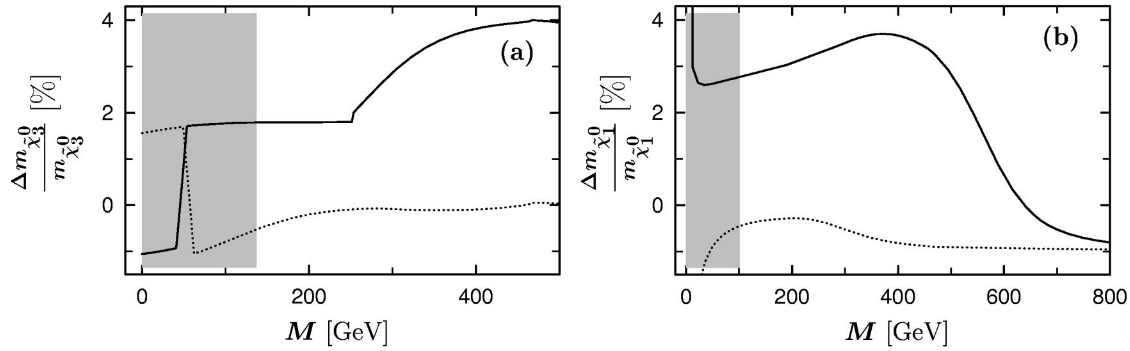

FIG. 6. Comparison of relative corrections to $m_{\chi^0_3}$ (a) and $m_{\chi^0_1}$ (b). The full line shows the case where the SUSY SU(5) GUT relation is assumed for the $\overline{\mathrm{DR}}$ parameters M and M', and the on-shell M' is determined from M by the same relation. The dotted line corresponds to the case where the on-shell M' is an independent parameter but satisfies the SUSY GUT relation. Other parameters are $\tan\beta=7$, $\{M_{\tilde Q_1}, M_{\tilde Q}, A\}=\{300,300,-500\}$ GeV, and $\mu=[-110\,(\mathrm{a}),-300\,(\mathrm{b})]$ GeV. The gray areas are excluded by the bound $m_{\tilde\chi^+_1}\geqslant 100$ GeV.

ACKNOWLEDGMENTS

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APPENDIX

In the following, we give the formulas for the various self-energies due to fermion and sfermion one-loop contributions and the formulas for the counterterms of m_Z, m_W, $\sin\theta_W$, and $\tan\beta$ used in this work.

Chargino self-energies

The chargino self-energies read

$$\Pi^L_{ij}(k^2)=-\frac{1}{(4\pi)^2}\sum_{\mathrm{gen}} N_C\sum_{a=1}^{2}\,[l^{\tilde u}_{ai}l^{\tilde u}_{aj}B_1(k^2,m_d^2,m^2_{\tilde u_a}) + k^{\tilde d}_{ai}k^{\tilde d}_{aj}B_1(k^2,m_u^2,m^2_{\tilde d_a})],$$

$$\Pi^R_{ij}(k^2)=-\frac{1}{(4\pi)^2}\sum_{\mathrm{gen}} N_C\sum_{a=1}^{2}\,[k^{\tilde u}_{ai}k^{\tilde u}_{aj}B_1(k^2,m_d^2,m^2_{\tilde u_a}) + l^{\tilde d}_{ai}l^{\tilde d}_{aj}B_1(k^2,m_u^2,m^2_{\tilde d_a})], \tag{A1}$$

$$\Pi^{S,L}_{ij}(k^2)=\frac{1}{(4\pi)^2}\sum_{\mathrm{gen}} N_C\sum_{a=1}^{2}\,[m_u l^{\tilde d}_{ai}k^{\tilde d}_{aj}B_0(k^2,m_u^2,m^2_{\tilde d_a}) + m_d k^{\tilde u}_{ai}l^{\tilde u}_{aj}B_0(k^2,m_d^2,m^2_{\tilde u_a})],$$

$$\Pi^{S,R}_{ij}(k^2)=\frac{1}{(4\pi)^2}\sum_{\mathrm{gen}} N_C\sum_{a=1}^{2}\,[m_u l^{\tilde d}_{aj}k^{\tilde d}_{ai}B_0(k^2,m_u^2,m^2_{\tilde d_a}) + m_d k^{\tilde u}_{aj}l^{\tilde u}_{ai}B_0(k^2,m_d^2,m^2_{\tilde u_a})].$$

Here and in the following, the index u (d) denotes an up (down) -type fermion and Σ_{gen} denotes the sum over all six fermion generations. $N_C=3$ (1) in the quark (lepton) case. The chargino-sfermion-fermion couplings are

$$l^{\tilde u}_{ak}=-gV_{k1}R^{\tilde u}_{a1}+h_uV_{k2}R^{\tilde u}_{a1}, \quad k^{\tilde u}_{ak}=h_dU_{k2}R^{\tilde u}_{a1},$$
$$l^{\tilde d}_{ak}=-gU_{k1}R^{\tilde d}_{a1}+h_dU_{k2}R^{\tilde d}_{a1}, \quad k^{\tilde d}_{ak}=h_uV_{k2}R^{\tilde d}_{a1}, \tag{A2}$$

where $U,V(R^{\tilde f})$ are the chargino (sfermion) mixing matrices and

$$h_u=\frac{gm_u}{\sqrt{2}m_W\sin\beta}, \quad h_d=\frac{gm_d}{\sqrt{2}m_W\cos\beta}. \tag{A3}$$

The two-point functions B_0 and B_1 [23] are given in the convention [24].

Neutralino self-energies

The neutralino self-energies read

$$\Pi^{\tilde\chi^0 L}_{ij}(k^2)=\Pi^{\tilde\chi^0 R}_{ij}(k^2) =\frac{-1}{(4\pi)^2}\sum_{\mathrm{gen}} N_C\sum_{f=u,d}\ \sum_{a=1}^{2}\,(a^{\tilde f}_{ai}a^{\tilde f}_{aj}+b^{\tilde f}_{ai}b^{\tilde f}_{aj}) \times B_1(k^2,m_f^2,m^2_{\tilde f_a}), \tag{A4}$$

$$\Pi^{\tilde\chi^0 S,L}_{ij}(k^2)=\Pi^{\tilde\chi^0 S,R}_{ij}(k^2) =\frac{1}{(4\pi)^2}\sum_{\mathrm{gen}} N_C\sum_{f=u,d}\ \sum_{a=1}^{2}\,(a^{\tilde f}_{ai}b^{\tilde f}_{aj}+a^{\tilde f}_{aj}b^{\tilde f}_{ai}) \times B_0(k^2,m_f^2,m^2_{\tilde f_a}). \tag{A5}$$

The neutralino-sfermion-fermion couplings are

$$a^{\tilde f}_{ak}=gf^f_{Lk}R^{\tilde f}_{a1}+h_fZ_{kx}R^{\tilde f}_{a2}, \quad b^{\tilde f}_{ak}=gf^f_{Rk}R^{\tilde f}_{a2}+h_fZ_{kx}R^{\tilde f}_{a1}, \tag{A6}$$

with $x=3$ for down-type and $x=4$ for up-type fermions. Z denotes the neutralino mixing matrix and the terms f^f_{Lk} and f^f_{Rk} are

$$f^f_{Lk}=\sqrt{2}[(e_f-I^{3L}_f)\tan\theta_W Z_{k1}+I^{3L}_f Z_{k2}], \tag{A7}$$

$$f^f_{Rk}=-\sqrt{2}e_f\tan\theta_W Z_{k1}. \tag{A8}$$

Gauge boson self-energies

The counterterms for m_W and m_Z are given by

$$\delta m_V^2=\mathrm{Re}\,\Pi^{VV}_T(m_V^2) \quad (V=W,Z). \tag{A9}$$

For the weak mixing angle we use the definition $\sin^2\theta_W=1-m_W^2/m_Z^2$. This gives [25]

$$\frac{\delta\sin\theta_W}{\sin\theta_W}=\frac{1}{2}\frac{\cos^2\theta_W}{\sin^2\theta_W}\left(\frac{\delta m_Z^2}{m_Z^2}-\frac{\delta m_W^2}{m_W^2}\right). \tag{A10}$$

The explicit forms for the self-energies are

$$\begin{aligned}\Pi^{WW}_T(k^2)=\frac{1}{(4\pi)^2}\frac{g^2}{2}\sum_{\text{gen}}N_C\Bigg[&(k^2-m_u^2-m_d^2)B_0(k^2,m_u^2,m_d^2)\\&+4B_{00}(k^2,m_u^2,m_d^2)-\sum_{f=u,d}A_0(m_f^2)\\&+\sum_{f=u,d}\sum_{a=1}^{2}(R^{\tilde f}_{a1})^2A_0(m^2_{\tilde f_a})\\&-4\sum_{a,b=1}^{2}(R^{\tilde u}_{a1})^2(R^{\tilde d}_{b1})^2B_{00}(k^2,m^2_{\tilde u_a},m^2_{\tilde d_b})\Bigg],\end{aligned} \tag{A11}$$

$$\begin{aligned}\Pi^{ZZ}_T(k^2)=&\frac{1}{(4\pi)^2}\left(\frac{g}{\cos\theta_W}\right)^2\\&\times\sum_{\text{gen}}N_C\sum_{f=u,d}\Bigg\{2\sum_{a=1}^{2}[(C^f_L)^2(R^{\tilde f}_{a1})^2\\&+(C^f_R)^2(R^{\tilde f}_{a2})^2]A_0(m^2_{\tilde f_a})-4\sum_{a,b=1}^{2}[C^f_L R^{\tilde f}_{a1}R^{\tilde f}_{b1}\\&+C^f_R R^{\tilde f}_{a2}R^{\tilde f}_{b2}]^2B_{00}(k^2,m^2_{\tilde f_a},m^2_{\tilde f_b})\\&-[(C^f_L)^2+(C^f_R)^2]2[A_0(m_f^2)-2B_{00}(k^2,m_f^2,m_f^2)]\\&+\{k^2[(C^f_L)^2+(C^f_R)^2]\\&-2m_f^2(C^f_L-C^f_R)^2\}B_0(k^2,m_f^2,m_f^2)\Bigg\},\end{aligned} \tag{A12}$$

with

$$C^f_L=I^{3L}_f-\sin^2\theta_W\,e_f,\quad C^f_R=-\sin^2\theta_W\,e_f. \tag{A13}$$

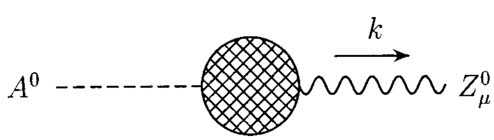
The functions A_0, B_0, B_{00} [23] are given in the convention of [24].

A^0-Z^0 self-energy

The mixing angle β is fixed by the condition [26]

$$\mathrm{Im}\,\hat\Pi_{A^0Z^0}(m_A^2)=0. \tag{A14}$$

The renormalized self-energy $\hat\Pi_{A^0Z^0}(k^2)$ is defined by the two-point function



$$=-i\,k^\mu\,\hat\Pi_{A^0Z^0}(k^2)\,\epsilon^*_\mu(k).$$

Thus we get the counterterm for $\tan\beta$:

$$\frac{\delta\tan\beta}{\tan\beta}=-\frac{1}{m_Z\sin2\beta}\mathrm{Im}\,\Pi_{A^0Z^0}(m_A^2). \tag{A15}$$

$\Pi_{A^0Z^0}$ denotes the unrenormalized self-energy

$$\begin{aligned}\Pi_{A^0Z^0}(k^2)=&\frac{i}{(4\pi)^2}m_Z\sin2\beta\sum_{\text{gen}}N_C\sum_{f=u,d}I^{3L}_f h_f^2\\&\times\left\{B_0(k^2,m_f^2,m_f^2)+\frac{\sin2\theta_{\tilde f}}{2m_f}\left[A_f+\mu\begin{pmatrix}\tan\beta\\ \cot\beta\end{pmatrix}\right](2B_1+B_0)(k^2,m^2_{\tilde f_1},m^2_{\tilde f_2})\right\}.\end{aligned} \tag{A16}$$

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