Anomalies and decoupling of charginos and neutralinos in the MSSM

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(Received 3 February 1997)

We study the contribution of charginos and neutralinos of the minimal SUSY extension of the standard model (MSSM) to the one-loop vertices ZAA, ZZA, ZZZ, and examine the related cancellation of anomalies. It is found that when the SUSY parameter μ satisfies $|\mu| \gg M, M', m_W$, the couplings of charginos and neutralinos with the gauge bosons become purely vectorial, and then their contribution to the amplitudes for ZAA, ZZA, and ZZZ vanishes, which implies that this sector of the MSSM does not generate a Wess-Zumino term. We evaluate also the contribution of charginos and neutralinos to the ρ parameter, and find that $\rho = 0$ in the large-μ limit. [S0556-2821(97)04913-8]

PACS number(s): 12.60.Jv, 11.30.Pb, 14.80.Ly

The minimal supersymmetric (SUSY) standard model (MSSM) [1,2] has become one the most preferred extensions of the standard model (SM). The success of the MSSM is not only due to its ability to imitate the SM agreement with most high-energy data, but also because it gives a plausible explanation of the new results that seem to be in conflict with the SM (e.g., the large $Z \to b\bar{b}$ width [3], the $ee\gamma\gamma$ event observed at Fermilab [4]). Moreover, the model predicts new signatures associated with the superpartners that are expected to appear in the future colliders [the CERN Large Hadron-Collider, the Next Linear Collider] or even in the present ones (Fermilab, the CERN e^+e^- collider LEP). However, if the superpartners are not light, it will become relevant to search for any indirect physical effect that could be left by them, and to verify by explicit calculations their expected decoupling.

Since gauge-invariant masses are allowed in vectorlike theories, the effects of heavy fermion decouple from the corresponding low-energy effective Lagrangian [5]. However, in chiral theories heavy particles do not decouple in general. For instance, if the Higgs mechanism of spontaneous symmetry breaking (SSB) is used to generate masses, the associated vacuum expectation value (VEV) (v) is fixed by the scale of the interactions, then in order to generate a heavy fermion mass ($m \gg v$), a large Yukawa coupling is required, which induces strong effects that prevent the decoupling of the fermion. Chiral fermions may also pose another problem, namely, the appearance of anomalies in gauge currents. An interesting problem arises when the anomaly cancellation occurs between fermions with very different masses [6,7]. In this case, integrating out the heavy fermion leaves an anomalous effective theory, which is the signal of its nondecoupling [8].

In the MSSM there are two sources of anomalies: the ones due to quarks and leptons, and the ones due to the fermionic partners of the Higgs bosons, the Higgsinos, which cancel separately to make the model anomaly-free. In fact, the Higgsinos are not mass eigenstates, they mix with the superpartners of the gauge bosons (gauginos), and the resulting charged and neutral eigenstates are known as chargino and neutralino, respectively. Gauginos do not contribute to the anomaly because their couplings to the gauge bosons are vectorial.

In this Brief Report we are interested in studying the effects of heavy charginos and neutralinos, and to understand the role that the anomalies can play for their decoupling. In particular, we evaluate the contribution of charginos and neutralinos to the vertex ZAA, ZZA, ZZZ, and to the ρ parameter, focusing in the limit when the SUSY parameter μ satisfies $|\mu| \gg M, M', m_W$, where M, M' denote the gaugino soft-breaking masses, and the W-boson mass m_W is used to characterize the electroweak scale.[1]

Although the MSSM is anomaly-free, it is relevant to understand the conditions under which charginos and neutralinos participate in the cancellation of anomalies, since this can play an important role for their decoupling. For instance, if it were possible for a heavy Higgsino to contribute to the anomaly, the cancellation of anomalies would take place between different scales, which could prevent its decoupling.

In order to identify the origin of anomalies we shall work with four-component spinors for the gaugino and Higgsino fields, however, the analysis of the large-μ limit and the calculations of interest will be performed in the mass-eigenstate basis, namely, in terms of charginos and neutralinos. We shall review first the Lagrangian of the model, focusing mainly on the interaction of the gauge bosons ($A_\mu, W_\mu^\pm, Z_\mu$), with the charged ($\widetilde{H}$) and neutral ($\widetilde{H}_1, \widetilde{H}_2$) Higgsinos, and with the W-ino ($\widetilde{W}$), photino ($\widetilde{A}$), and Z-ino ($\widetilde{Z}$) fields.

The Lagrangian for the mass and mixing terms of gauginos and Higgsinos in the MSSM is given by

$$\mathcal{L} = M_{\widetilde{W}} \bar{\widetilde{W}} \widetilde{W} + \frac{M_{\widetilde{A}}}{2} \bar{\widetilde{A}} \widetilde{A} + \frac{M_{\widetilde{Z}}}{2} \bar{\widetilde{Z}} \widetilde{Z} + \mu \bar{\widetilde{H}} \widetilde{H} + \frac{M_{\widetilde{Z}} - M_{\widetilde{A}}}{2} \times \tan 2\theta_W \bar{\widetilde{A}} \widetilde{Z} - \frac{\mu}{2} [\bar{\widetilde{H}}_1 \widetilde{H}_2 + \bar{\widetilde{H}}_2 \widetilde{H}_1] - \frac{g}{\sqrt{2}} [\bar{\widetilde{Z}} P_R \widetilde{H}_1 H_1^1 - \bar{\widetilde{H}}_2 P_R \widetilde{Z} H_2^2 + \text{H.c.}] - g[\bar{\widetilde{W}} P_R \widetilde{H} H_1^1 + \bar{\widetilde{H}} P_R \widetilde{W} H_2^2 + \text{H.c.}], \tag{1}$$

[1]The case when a complete supermultiplet is integrated out was discussed in [9]; however, in this Brief Report we are interested in the limit when only the superpartners are heavy.

which includes the interaction of gauginos and Higgsinos with the neutral components of the scalar Higgs boson doublets (H_1^1, H_2^2). The Z-ino and photino masses can be expressed, in terms of the soft-breaking masses M and M', as follows: $M_{\tilde{Z}} = M\cos^2\theta_W + M'\sin^2\theta_W$, $M_{\tilde{A}} = M\sin^2\theta_W + M'\cos^2\theta_W$.

After SSB the Higgs scalars acquire (VEV's) ($\langle H_1^1\rangle = v_1$ and $\langle H_2^2\rangle = v_2$), and the trilinear terms in Eq. (1) generate a mixing among the gauginos and Higgsinos. The resulting mass-mixing matrices need to be diagonalized; the mass eigenstates and the diagonalizing matrices depend in general on the parameters M, M', μ, and $\tan\beta(=v_2/v_1)$. The diagonalizing matrices (U,V) for the charged case can be found in [10], whereas the (4×4) matrix corresponding to the neutral case (Z) is evaluated numerically. The charginos and neutralinos are denoted by $\tilde{\chi}_i^+$ $(i=1,2)$ and $\tilde{\chi}_j^0$ $(j=1\text{–}4)$, respectively.

The interaction of gauginos and Higgsinos with the gauge bosons of the model are described by the Lagrangian:

$$\begin{aligned}\mathcal{L} = {}& e[\bar{\tilde{W}}\gamma_\mu\tilde{W} + \bar{\tilde{H}}\gamma_\mu\tilde{H}]A^\mu - e[\bar{\tilde{A}}\gamma^\mu\tilde{W}W_\mu^+ + \bar{\tilde{W}}\gamma^\mu\tilde{A}W_\mu^-]\\ &- g\cos\theta_W[\bar{\tilde{Z}}\gamma^\mu\tilde{W}W_\mu^- + \bar{\tilde{W}}\gamma^\mu\tilde{Z}W_\mu^+ - \bar{\tilde{W}}\gamma_\mu\tilde{W}Z^\mu]\\ &+ \frac{g}{2\cos\theta_W}[\cos2\theta_W\bar{\tilde{H}}\gamma_\mu\tilde{H} - \tfrac{1}{2}(\bar{\tilde{H}}_1\gamma_\mu\gamma_5\tilde{H}_1\\ &- \bar{\tilde{H}}_2\gamma_\mu\gamma_5\tilde{H}_2)]Z^\mu. \end{aligned} \tag{2}$$

We can discuss now the origin of anomalies in the Higgsino sector. Before SSB the charged Higssino couplings to the neutral gauge bosons are of vector-type, and at this stage it does not contribute to the gauge anomaly. However, after SSB the mixing treats in a different way the left- and right-handed components of the charged Higgsinos and W-inos, which induces an axial-vector part for their couplings, then each chargino contributes to the anomaly, but with opposite signs for the MSSM to remain anomaly-free. However, the coupling becomes again vectorlike for $\tan\beta=1$ $(v_1=v_2)$. On the other hand, the neutral Higgsinos contribute to the anomaly, because their couplings have an axial-vector part even before SSB. However, these axial-vector couplings also vanish in the large μ limit.

The complete Feynman rules for the interaction of the charginos and neutralinos are summarized in [1,10,11]. For the purpose of evaluating the three-point vertex functions $Z_\mu A_\nu A_\rho, Z_\mu Z_\nu A_\rho$, and $Z_\mu Z_\nu Z_\rho$, we only need to specify the vertices

$$\chi_i^+\chi_i^- A^\mu: -ie\gamma^\mu, \tag{3}$$

$$\chi_i^+\chi_j^0 W^{-\mu}: +ig\gamma^\mu(O_{ij}^L P_L + O_{ij}^R P_R), \tag{4}$$

$$\chi_i^+\chi_j^- Z^\mu: -i\frac{g}{\cos\theta_W}\gamma^\mu(O'_{ij}LP_L + O'_{ij}RP_R), \tag{5}$$

$$\chi_i^0\chi_j^0 Z^\mu: -i\frac{g}{\cos\theta_W}\gamma^\mu(O''_{ij}LP_L + O''_{ij}RP_R), \tag{6}$$

where $P_{R,L} = (1\pm\gamma_5)/2$, and

$$O_{ij}^L = Z_{i2}V_{j1}^* - (1/\sqrt{2})\,Z_{i4}V_{j2}^*, \tag{7}$$

$$O_{ij}^R = Z_{i2}^*U_{j1} + (1/\sqrt{2})\,Z_{i3}^*U_{j2}, \tag{8}$$

$$O'^L_{ij} = -V_{i1}V_{j1}^* - \tfrac{1}{2}V_{i2}V_{j2}^* + \delta_{ij}\sin^2\theta_W, \tag{9}$$

$$O'^R_{ij} = -U_{j1}V_{i1}^* - \tfrac{1}{2}U_{j2}U_{i2}^* + \delta_{ij}\sin^2\theta_W, \tag{10}$$

$$O''^L_{ij} = \tfrac{1}{2}(Z_{i4}Z_{j4}^* - Z_{i3}Z_{j3}^*), \tag{11}$$

$$O''^R_{ij} = -\tfrac{1}{2}(Z_{i4}Z_{j4}^* - Z_{i3}Z_{j3}^*). \tag{12}$$

We can evaluate now the SUSY contribution to the one-loop vertex $Z_\mu A_\nu A_\rho$. Using the CP properties of the vector (V) and axial-vector (A) currents, it can be shown that the three-point functions VVV and VAA vanish in general. These CP properties can be used also to show that sfermions, Goldstone, Higgs, and gauge bosons do not contribute to the vertex $Z_\mu A_\nu A_\rho$. Thus, the amplitude can only arise from the triangle graphs with charged fermions inside the loop. The contribution from each chargino $(\tilde{\chi}_i^+)$ to the amplitude for the vertex $Z_\mu(q)A_\nu(k_1)A_\rho(k_2)$ can be obtained from the results of [12], and it is written as

$$\begin{aligned}T_i^{\mu\nu\rho} = {}& \frac{4\alpha g a'_{ii}Q_i^2}{\pi\cos\theta_W}\{\varepsilon^{\mu\nu\rho\alpha}[k_{1\alpha}(f_1k_2^2 - f_3k_1\cdot k_2)\\ &- k_{2\alpha}(f_2k_1^2 - f_3k_1\cdot k_2)] + \varepsilon^{\alpha\mu\beta\nu}k_{1\alpha}k_{2\beta}[f_2k_1^\rho + f_3k_2^\rho]\\ &+ \varepsilon^{\alpha\mu\beta\rho}k_{1\alpha}k_{2\beta}[f_1k_2^\nu + f_3k_1^\nu]\},\end{aligned} \tag{13}$$

where the axial-vector coupling is given by $a'_{ij} = O'^R_{ij} - O'^L_{ij}$, and the functions f_i are defined by

$$f_1 = \int_0^1 dx_1\int_0^{1-x_1}dx_2\frac{x_1(x_1-1)}{D}, \tag{14}$$

$$f_2 = \int_0^1 dx_1\int_0^{1-x_1}dx_2\frac{x_2(x_2-1)}{D}, \tag{15}$$

$$f_3 = \int_0^1 dx_1\int_0^{1-x_1}dx_2\frac{x_1x_2}{D}, \tag{16}$$

with $D = M_{\chi_i^+}^2 + x_2(x_2-1)k_1^2 + x_1(x_1-1)k_2^2 - 2k_1\cdot k_2x_1x_2$. Then, the condition for the nonconservation of the axial-vector current is written as

$$\begin{aligned}q_\mu T^{\mu\nu\rho} &= \sum_i \frac{4\alpha g a_{ii}Q_i^2}{\pi\cos\theta_W}\varepsilon^{\mu\nu\rho\alpha}k_{1\alpha}k_{2\mu}\\ &\quad\times(f_1k_2^2 + f_2k_1^2 - 2f_3k_1\cdot k_2)\\ &= \sum_i \frac{4\alpha g a_{ii}Q_i^2}{\pi\cos\theta_W}\varepsilon^{\mu\nu\rho\alpha}k_{1\alpha}k_{2\mu}\left[\frac{1}{2} - M_{\chi_i^+}^2f_0\right],\end{aligned} \tag{17}$$

where

$$f_0 = \int_0^1 dx_1\int_0^{1-x_1}dx_2\frac{1}{D}. \tag{18}$$

When both charginos are taken into account the mass-independent term (i.e., the anomaly) should cancel ($\Sigma_i q_\mu T_i^{\mu\nu\rho}=0$), as we have verified by the direct substitution of the elements of U,V in Eq. (17), namely, $\Sigma_i Q_i^2 a'_{ii}=0$.

In order to study the limit when the mass parameters are very large ($\gg m_W$), one can use the results of [13], which presents an analytical expression for the diagonalizing matrices U,V,Z, under the assumption that the couplings are CP invariant, and with the mass parameters satisfying the conditions, $|M\pm\mu|,|M'\pm\mu|\gg m_W$, and $|M\mu|\gg m_W^2\sin 2\beta$. Then, the matrices U,V are given by

$$U=\begin{pmatrix} 1 & \sqrt{2}m_W\dfrac{Mc_\beta+\mu s_\beta}{M^2-\mu^2} \\ -\sqrt{2}m_W\dfrac{Mc_\beta+\mu s_\beta}{M^2-\mu^2} & 1 \end{pmatrix}, \tag{19}$$

$$V=\begin{pmatrix} 1 & \sqrt{2}m_W\dfrac{Ms_\beta+\mu c_\beta}{M^2-\mu^2} \\ -\sqrt{2}m_W\dfrac{Ms_\beta+\mu c_\beta}{M^2-\mu^2} & \mathrm{sgn}(\mu) \end{pmatrix}, \tag{20}$$

whereas the neutralino Z matrix takes the form

$$Z=\begin{pmatrix} A & B \\ C & D \end{pmatrix}, \tag{21}$$

with

$$A=\begin{pmatrix} 1 & -\dfrac{m_Z^2 s_{2W}(M'+\mu s_{2\beta})}{2(M'-M)(M'^2-\mu^2)} \\ -\dfrac{m_Z^2 s_{2W}(M+\mu s_{2\beta})}{2(M'-M)(M'^2-\mu^2)} & 1 \end{pmatrix}, \tag{22}$$

$$B=\begin{pmatrix} \dfrac{-m_Z s_W(M'c_\beta+\mu s_\beta)}{M'^2-\mu^2} & \dfrac{m_Z s_W(M'c_\beta+\mu s_\beta)}{M'^2-\mu^2} \\ \dfrac{m_Z c_W(Mc_\beta+\mu s_\beta)}{M^2-\mu^2} & \dfrac{-m_Z c_W(Ms_\beta+\mu c_\beta)}{M^2-\mu^2} \end{pmatrix}, \tag{23}$$

$$C=\begin{pmatrix} \dfrac{-m_Z s_W(s_\beta-c_\beta)}{\sqrt{2}(M'+\mu)} & \dfrac{m_Z c_W(s_\beta-c_\beta)}{\sqrt{2}(M+\mu)} \\ \dfrac{m_Z s_W(s_\beta+c_\beta)}{\sqrt{2}(M'-\mu)} & -\dfrac{m_Z c_W(s_\beta+c_\beta)}{\sqrt{2}(M-\mu)} \end{pmatrix}, \tag{24}$$

$$D=\begin{pmatrix} 1/\sqrt{2} & 1/\sqrt{2} \\ 1/\sqrt{2} & -1/\sqrt{2} \end{pmatrix}, \tag{25}$$

and where $s_W=\sin\theta_W$, $s_{2W}=\sin 2\theta_W$, $s_\beta=\sin\beta$, $c_\beta=\cos\beta$, $s_{2\beta}=\sin 2\beta$.

Our results will be presented assuming also that $|\mu|\gg M,M',m_W$, and keeping only the leading terms in $1/\mu$, in which case the mass eigenstates are given by $M_{\chi_2^+}=\mu$, $M_{\chi_1^+}=M$, $M_{\chi_1^0}=M'$, $M_{\chi_2^0}=M$, $M_{\chi_3^0}=\mu$, $M_{\chi_4^0}=\mu$. The chargino-mixing matrices take the values $U=V=1$, whereas the expression for Z also reduces considerably. In this limit one obtains $(M_{\chi_i^+}^2/D)\to 1$, and consequently $(M_{\chi_i^+}^2 f_0)\to 1/2$, which appears as if an anomalous term would remain. However, a careful analysis of the couplings shows that in this limit the lightest chargino becomes a pure gaugino ($\widetilde{\chi}_1^+=\widetilde{W}$), which does not have axial-vector couplings, i.e., $a'_{11}=0$, and the heavy chargino becomes a pure Higgsino, which also has $a'_{22}=0$, thus $T^{\mu\nu\rho}=0$, and charginos decouple from this function.

Similarly, we can evaluate the contribution of charginos to the vertex $Z(q_1)Z(q_2)A(k)$, which we denote by $R^{\mu\nu\rho}$. In this case the condition for the conservation of the axial-vector current is written as

$$q_\mu R^{\mu\nu\rho}=-\sum_i \frac{4\alpha g a'_{ii}v'_{ii}Q_i^2}{\pi\cos^2\theta_W}\varepsilon^{\mu\nu\rho\alpha}q_{2\alpha}k_\mu, \tag{26}$$

which must be zero because of the anomaly cancellation. The vector coupling is given by $v'_{ij}=O'^R_{ij}+O'^L_{ij}$. Moreover, the vertex $R^{\mu\nu\rho}$ itself also vanishes in the large-μ limit, because the chargino couplings a'_{ij} vanish.

The amplitude for the one-loop vertex $Z(q_1)Z(q_2)Z(q_3)$ ($=S^{\mu\nu\rho}$), receives contributions from charginos and neutralinos, and the conservation of the currents takes the form

$$q_\mu S^{\mu\nu\rho}=-\sum_i \frac{g^3}{2\pi^2\cos^3\theta_W}\left(v''^2_{ii}+\frac{1}{3}a''^2_{ii}\right)\times a''_{ii}\varepsilon^{\mu\nu\rho\alpha}q_{2\alpha}q_{3\mu}, \tag{27}$$

which also vanishes because of the anomaly cancellation. Charginos do not contribute to the vertex $S^{\mu\nu\rho}$ itself, because their axial-vector couplings vanish in the limit $\mu\gg M,M',m_W$, and the three-point function with vector couplings (VVV) only vanish. Moreover, since the axial-vector couplings of the neutralinos vanish in the large-μ limit, its contribution to $S^{\mu\nu\rho}$ itself vanishes too. Thus, integrating out the charginos and neutralinos does not leave a mass-independent Wess-Zumino term in the low-energy effective Lagrangian.

Another process that illustrates this decoupling result is the (one-loop) Higgs amplitude $hA_\mu A_\nu$. For the light Higgs scalar (h^0) of the MSSM, the contribution of charginos to the amplitude is proportional to the function [11]:

$$I(m_h,m_{\chi_i^+})=\frac{4m_W m_{\chi_i^+}A_{ii}}{\sin\beta}\int_0^1 dx\int_0^{1-x}dy\frac{1-4xy}{m_{\chi_i^+}^2-xym_h^2}, \tag{28}$$

where A_{ij} is a dimensionless coefficient that depends on the elements of the matrices U,V. The amplitude behaves like $m_W/M_{\chi_i^+}$, and it vanishes in the large-μ limit. On the other hand, the contribution of the top quark to the amplitude becomes a constant in the limit of a large top quark mass.[2]

Finally, we evaluate the contributions of heavy charginos and neutralinos to Veltman's ρ parameter. Complete calculations of radiative corrections for the MSSM have been performed in the literature [16]; however, the results for the chargino or neutralino sector are presented only in numerical form, which does not help to clarify the subtleties associated with the heavy-mass limits.

The definitions of the ρ parameter in terms of the self-energies of the gauge bosons (Π_{ZZ},Π_{WW}) is [17]

$$\rho=\Pi_{ZZ}(0)/m_Z^2-\Pi_{WW}(0)/m_W^2, \tag{29}$$

where $\Pi(0)$'s are obtained from the expansions $\Pi_{ij}(q^2)=\Pi_{ij}(0)+\Pi'_{ij}(0)q^2$.

The total contribution of chargino and neutralino to the self-energies, keeping only the leading terms in the limit $|\mu|\gg M,M',m_W$, is

$$\Pi_{WW}(0)=(g^2/8\pi^2)[\mu^2+A_0(\mu)], \tag{30}$$

$$\Pi_{ZZ}(0)=(g^2/8\pi^2c_W^2)[\mu^2+A_0(\mu)], \tag{31}$$

where $A_0(\mu)=-\mu^2+2\mu^2\ln(\mu/\mu_0)$, and μ_0 is the mass scale that arises in the $\overline{\rm MS}$ scheme with dimensional regularization.

Thus, it follows Eqs. (30) and (31) that $\rho=0$. This result can be understood if we recall that ρ is associated with the breaking of isospin, and the large-μ limit does not induce a mass splitting among the charginos and neutralinos that interact with the gauge bosons, i.e., $M_{\chi^0_{3,4}}=M_{\chi^+_2}$; thus ρ must vanish in this limit.

In conclusion, we have studied the effects that remain after taking the large μ limit in the MSSM. It is found that despite the fact that charginos and neutralinos contribute to the anomaly, they do not induce a Wess-Zumino terms in the effective Lagrangian, unlike other cases studied in the literature [18]. This result can be explained by the form of the soft-SUSY-breaking mass terms, which do not allow a large mass splitting among the Higgsinos; moreover, the large-μ limit in the gaugino-Higgsino sector of the MSSM is obtained by rendering large a dimensional parameter, associated with gauge-invariant mass terms, which does not produce strong interaction effects. A large mass splitting among Higgsinos could be obtained if it were possible to include a mass term for each Higgsino in the Lagrangian, however, this type of term is not soft [1]. Moreover, we also found that the effects of charginos and neutralinos to the ρ parameter vanish in the large-μ limit. Thus, they decouple in all quantities studied in this Brief Report.

We have also reviewed the pattern of anomaly cancellation due to Higgsinos in the minimal SUSY extension of the standard model (MSSM), and found that they have different characteristics as compared with the ones due to quarks and leptons. For instance, when $\tan\beta=1$ it happens that the charged Higgsinos do not contribute to the anomaly, whereas the neutralinos do not contribute to the anomaly when μ is large. This result suggests an alternative mechanism to obtain anomaly-free theories. In the usual approach, it is assumed that the chirality of the fermions is fixed, then the representations are adjusted in order to cancel the anomalies. However, in extended SUSY models, new particles are predicted, whose chiralities are not known yet, and if their fixing depends on some unknown parameters, then it may be possible that those new parameters have values that make the theory anomaly-free.

Valuable discussions with G. Kane, M. J. Herrero, J. J. Toscano, M. Hernandez, and correspondence with E. D'Hoker are acknowledged. This work was supported by CONACYT and SNI (México).

[2] In order to derive systematically the full effective Lagrangian that remains after the charginos or neutralinos are integrated out, one could use the method of Ref. [14], as it was done in [15] for the integration of the top quark in the SM; however, the specific cases discussed in this Brief Report allow us to understand the limit of heavy charginos and neutralinos.

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