Constraints on Supergravity in the Light Gluino Scenario*

MARCO AURELIO DÍAZ

Department of Physics and Astronomy
Vanderbilt University, Nashville, TN 37235

Abstract

Minimal $N = 1$ supergravity with a radiatively broken electroweak symmetry group is studied in the light gluino scenario. Constraints from the $b \to s\gamma$ decay and from the masses of the light CP-even neutral Higgs $m_h$, the lightest chargino $m_{\chi^\pm_1}$, and the second lightest neutralino $m_{\chi^0_2}$ are analyzed. We find that a gluino with a mass of a few GeV is incompatible with this kind of models.

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It is well known that in the Standard Model (SM) the three gauge couplings $g_s$, $g$, and $g'$, corresponding to the gauge groups $SU(3) \times SU(2) \times U(1)$, do not converge to a single value when we run these couplings up to scales near the Planck scale. Although it is not a proof of supersymmetry, it is interesting that within the minimal supersymmetric extension of the Standard Model (MSSM) this gauge coupling unification can be achieved\[1\].

In supersymmetry, fermionic and bosonic degrees of freedom are related by a symmetry. If the symmetry is unbroken, every known fermion (boson) has a bosonic (fermionic) supersymmetric partner degenerate in mass. Differences in mass appear between partners as soon as supersymmetry is broken. This is achieved through soft-supersymmetry terms which do not introduce quadratic divergences to the unrenormalized theory\[2\].

The supersymmetric partner of the gluon is the gluino, and discussions about the existence of a light gluino have been in the literature for some time\[3\]. Motivated by the discrepancy between the value of the strong coupling constant $\alpha_s$, determined by low energy deep inelastic lepton-nucleon scattering: $\alpha_s(m_Z) = 0.112 \pm 0.004$, and the one determined by high energy $e^+e^-$ LEP experiments: $\alpha_s = 0.124 \pm 0.005$, there has been a renewed interest in the possibility of a light gluino\[4-6\].

Experimentally, gluinos lighter than 5 GeV are not ruled out\[7\], nevertheless, this window might be overestimated and according to H.E. Haber the light gluino is\[8\]:

$$2.6 \lesssim m_{\tilde{g}} \lesssim 3 \text{ GeV}$$ \hspace{1cm} (1)

where the lower limit comes from the non-observation of a pseudoscalar $\tilde{g}\tilde{g}$ bound state in quarkonium decays, and the upper limit follows from an analysis of CERN $p\bar{p}$ Collider data\[9\].

One of the most successful supersymmetric models is minimal $N = 1$ supergravity, in which the electroweak symmetry breaking can be achieved radia-
tively \[^{[10]}\] through the evolution of the Higgs mass parameters from the unification scale to the weak scale. In this model, the three gaugino masses $M_s$, $M$, and $M'$ are different at the weak scale but equal to a common gaugino mass $M_{1/2}$ at the grand unification scale $M_X$. The difference at the weak scale is due to the fact that the evolution of the three masses is controlled by different renormalization group equations (RGE). The approximated solution of these RGE is:

$$
M_s \approx M_{1/2} \left[ 1 + \frac{3g_s^2}{8\pi^2} \ln \frac{M_X}{m_Z} \right], \quad m_{\tilde{g}} = |M_s|
$$

$$
M \approx M_{1/2} \left[ 1 - \frac{g^2}{8\pi^2} \ln \frac{M_X}{m_Z} \right]
$$

$$
M' \approx M_{1/2} \left[ 1 - \frac{11g'_2}{8\pi^2} \ln \frac{M_X}{m_Z} \right]
$$

where we are neglecting the supersymmetric threshold effects. Taking $M_X = 10^{16}$ GeV, we find that $M \approx 0.30 m_{\tilde{g}}$ and $M' \approx 0.16 m_{\tilde{g}}$.

Similarly, the scalar masses are also degenerate at the unification scale, and equal to $m_0$. The RGE make both the Higgs mass parameters $m_1$ and $m_2$, and the squark and slepton mass parameters, evolve differently. A third independent parameter at the unification scale is the mass parameter $B$. This mass defines the value of the unified trilinear mass parameter $A$ at $M_X$ by $A = B + m_0$, a relation valid in models with canonical kinetic terms. Moreover, it also defines the third Higgs mass parameter $m^2_{1/2} = -B\mu$, valid at every scale, where $\mu$ is the supersymmetric Higgs mass parameter. The set of independent parameters we choose to work with, given by $M_{1/2}$, $m_0$, and $B$ at the unification scale, is completed by the value of the top quark Yukawa coupling $h_t = g m_t / (\sqrt{2} m_W s_\beta)$ at the weak scale. Here the angle $\beta$ is defined through $\tan \beta = v_2 / v_1$, where $v_1$ and $v_2$ are the vacuum expectation values of the two Higgs doublets. We define the top Yukawa coupling in a on-shell scheme.

Knowing the parameters of the Higgs potential at the weak scale $m^2_1$, $m^2_2$, and $B$, we can calculate the more familiar parameters $m_t$, $m_A$, and $\mu$, for a given
value of the top quark Yukawa coupling $h_t$, through the following formulas valid at tree level

\[
\begin{align*}
    m_{1H}^2 &\equiv m_1^2 + \mu^2 = -\frac{1}{2}m_Z^2c_{2\beta} + \frac{1}{2}m_A^2(1 - c_{2\beta}), \\
    m_{2H}^2 &\equiv m_2^2 + \mu^2 = \frac{1}{2}m_Z^2c_{2\beta} + \frac{1}{2}m_A^2(1 + c_{2\beta}), \\
    m_{12}^2 &\equiv -B\mu = \frac{1}{2}m_A^2s_{2\beta},
\end{align*}
\]  

(3)

where $s_{2\beta}$ and $c_{2\beta}$ are sine and cosine functions of the angle $2\beta$, and it is understood that all the parameters are evaluated at the weak scale. We alert the reader that for a given set of values $M_{1/2}$, $m_0$, $B$, and $h_t$ there may exist more than one solution for the parameters at the weak scale $m_t$, $t_\beta$, $m_A$, and $\mu$. According to ref. [6], and we will confirm this, the relevant region of parameter space in the light gluino scenario is characterized by low values of the top quark mass and values of $\tan \beta$ close to unity. Considering the low values of the top quark mass relevant for our calculations, radiative corrections to the chargino and neutralino masses (recently calculated in ref. [11]) will have a minor effect.

The region $\tan \beta$ close to unity has been singled out by the grand unification condition $m_b = m_\tau$ at $M_X^{[12]}$, and was analyzed in detail in ref. [13]. Here we do not impose the Yukawa unification, but we stress the fact that if $\tan \beta = 1$, the lightest CP-even neutral Higgs is massless at tree level. Nevertheless, the supersymmetric Coleman-Weinberg mechanism\cite{14} generates a mass $m_h$ different from zero via radiative corrections. The fact that $m_t$ is also small will result in a radiatively generated $m_h$ close to the experimental lower limit $m_h \gtrsim 56$ GeV, valid for $m_A > 100$ GeV\cite{15}. Therefore, experimental lower limits on $m_h$ impose important restrictions on the light gluino window.

It has been pointed out that the branching ratio $B(b \rightarrow s\gamma)$ has a strong dependence on the supersymmetric parameters\cite{16,17}. The theoretical branching ratio must remain within the experimental bounds $0.65 \times 10^{-4} < B(b \rightarrow s\gamma) < 5.4 \times 10^{-4}$. We calculate this ratio, including loops involving $W^\pm/U$-quarks, $H^\pm/U$-quarks, $\chi^\pm/U$-squarks, and $\tilde{g}/D$-squarks, neglecting only the contribution from the neutralinos, which were reported to be small\cite{16}. We also include QCD corrections
to the branching ratio \(^{[18]}\) and one loop electroweak corrections to both the charged Higgs mass \(^{[19]}\) and the charged Higgs-fermion-fermion vertex \(^{[20]}\).

Another important source of constraints comes from the chargino/neutralino sector. For \(\tan \beta \gtrsim 4\), a neutralino with mass lower than 27 GeV is excluded, but the lower bound decreases when \(\tan \beta\) decreases, and no bound is obtained if \(\tan \beta < 1.6\) \(^{[21]}\). The lower bound for the heavier neutralinos (collectively denoted by \(\chi'\)) is \(m_{\chi'} > 45\) GeV for \(\tan \beta \gtrsim 3\), and this bound also decreases with \(\tan \beta\) and eventually disappears \(^{[22]}\). On the other hand, if the lightest neutralino has a mass \(\lesssim 40\) GeV (as we will see, in the light gluino scenario, the lightest neutralino has a mass of the order of 1 GeV), the lower bound for the lightest chargino mass is 47 GeV \(^{[22]}\). For notational convenience, this latest experimental bound will be denoted by \(\bar{m}_{\chi^\pm_i} \equiv 47\) GeV.

In the following, we study the chargino/neutralino sector in more detail by analysing the mass matrices. The chargino mass matrix is given by \(^{[23]}\)

\[
M_C = \begin{bmatrix}
M & \sqrt{2}m_W c_\beta \\
\sqrt{2}m_W s_\beta & \mu
\end{bmatrix}.
\]

(4)

The chargino masses are the square roots of the eigenvalues of the matrix \(M_C M_C^\dagger\), and we denote them by \(m_{\chi^\pm_i}, i = 1, 2\) with \(m_{\chi^+_1} < m_{\chi^+_2}\):

\[
m_{\chi^\pm_{1,2}}^2 = \frac{1}{2} (M^2 + \mu^2) + m_W^2 \pm \frac{1}{2} \sqrt{(M^2 - \mu^2)^2 + 4m_W^4 c^2_\beta + 4m_W^2 (M^2 + \mu^2 + 2\mu M s_\beta)}
\]

(5)

In the light gluino case we have \(M \ll m_W\), and the chargino masses can be approximated by

\[
m_{\chi^\pm_{1,2}}^2 = \frac{1}{2} \mu^2 + m_W^2 \pm \frac{1}{2} \sqrt{R} \pm \frac{2m_W^2 \mu M s_\beta}{\sqrt{R}} + O(M_{1/2}^2)
\]

(6)

where \(R = \mu^4 + 4m_W^2 \mu^2 + 4m_W^4 c^2_\beta\). Since the lightest chargino mass is bounded
from below: \( m_{\chi^\pm_i} > \bar{m}_{\chi^\pm_i} \), where \( \bar{m}_{\chi^\pm_i} \approx 47 \) GeV, we get the following constraint:

\[
m_4^W c_{2\beta}^2 + \mu^2 \bar{m}_{\chi^\pm_i}^2 < \left( m_4^W - \bar{m}_{\chi^\pm_i}^2 \right)^2 - \frac{4m_4^W \mu M_{2\beta} \left( \frac{1}{2} \mu^2 + m_4^W - \bar{m}_{\chi^\pm_i}^2 \right)}{\sqrt{\mu^2 + 4m_4^W \mu^2 + 4m_4^W c_{2\beta}^2}} + O(M_{1/2}^2)
\]

(7)

and this limits the values of \( \mu \) and \( \tan \beta \):

\[
\mu^2 < \bar{m}_{\chi^\pm_i}^2 \left( \frac{m_4^W}{\bar{m}_{\chi^\pm_i}^2} - 1 \right) - \frac{4m_4^W \mu_0 M_{1/2} \left( \frac{1}{2} \mu_0^2 + m_4^W - \bar{m}_{\chi^\pm_i}^2 \right)}{\bar{m}_{\chi^\pm_i}^2 \mu_0 \sqrt{\mu_0^2 + 4m_4^W}} + O(M_{1/2}^2)
\]

\[ \implies |\mu| \approx (90 \pm 0.87 m_{\tilde{g}}) \text{ GeV}, \quad \pm = \text{sign}(\mu M) \]

(8)

\[ |c_{2\beta}| < 1 - \frac{\bar{m}_{\chi^\pm_i}^2}{m_4^W} + O(M_{1/2}^2) \implies 0.46 < t_\beta < 2.2 \]

where \( \mu_0^2 = \bar{m}_{\chi^\pm_i}^2 \left( m_4^W / \bar{m}_{\chi^\pm_i}^2 - 1 \right)^2 \approx 90 \) GeV is the zeroth order solution (\( M = 0 \)), and \( \mp 0.87 m_{\tilde{g}} \) correspond to the first order correction. The type of constraints given in eq. (8) were already found in ref. [6] at zeroth order, but as we will see, the neutralino sector will restrict the parameter space even more.

The neutralino mass matrix is given by:

\[
M_N = \begin{bmatrix}
M' & 0 & -m_Z s_W c_\beta & m_Z s_W s_\beta \\
0 & M & m_Z c_W c_\beta & -m_Z c_W s_\beta \\
-m_Z s_W c_\beta & m_Z c_W c_\beta & 0 & -\mu \\
m_Z s_W s_\beta & -m_Z c_W s_\beta & -\mu & 0
\end{bmatrix}
\]

(9)

and in the zero gluino mass limit (\( M = M' = 0 \)) one eigenvalue is zero. Calculating the first order correction, we get for the lightest neutralino mass:

\[
m_{\chi^0_i} = M_4^W + M_4^W c_{2\beta}^2 + O(M_{1/2}^2) \approx 0.19 m_{\tilde{g}}
\]

(10)

and using eq. (1) and the relations between \( M, M' \), and \( m_{\tilde{g}} \) given below eq. (2).
we get

\[ 0.49 \lesssim m_{\chi^0_1} \lesssim 0.57 \text{ GeV}. \]  

(11)

This light neutralino (the lightest supersymmetric particle, or LSP) is, up to terms of \( \mathcal{O}(M^2_{1/2}/m^2_Z) \), almost a pure photino, and there is no bound on its mass from LEP collider data. Nevertheless, in the case of a stable LSP (R-parity conserving models), ref. [6] pointed out some cosmological implications that make this scenario less attractive. On the other hand, the possibility of having a small amount of R-parity violation is not ruled out, in which case the LSP would not be stable \[5\].

The other three neutralino masses are, in first approximation, solutions of the cubic equation

\[ m^3_{\chi^0} - (\mu^2 + m^2_Z)m_{\chi^0} - s_{2\beta}\mu m^2_Z = 0 \]  

(12)

According to eq. (8), the value of \( \tan \beta \) will be close to unity, i.e., \( s_{2\beta} \approx 1 \). If we expand around this value we get for the other neutralino masses:

\[
\begin{align*}
    m_{\chi^0_2} &= -\mu - \mu \frac{m^2_Z(1 - s_{2\beta})}{2\mu^2 - m^2_Z} + \mathcal{O}(1 - s_{2\beta})^2 + \mathcal{O}(M^2_{1/2}) \\
    m_{\chi^0_{3,4}} &= \frac{1}{2} \mu \pm \frac{1}{2} \sqrt{\mu^2 + 4m^2_Z} + \frac{m^2_Z(\mu + m_\pm)(M^2_{\text{W}} + M^{'2}_{\text{W}})}{3\mu m^2_Z + 2(\mu^2 + m^2_Z)m_\pm} \\
    &\quad - \frac{\mu m^2_Z m_\pm (1 - s_{2\beta})}{3\mu m^2_Z + 2(\mu^2 + m^2_Z)m_\pm} + \mathcal{O}(1 - s_{2\beta})^2 + \mathcal{O}(M^2_{1/2})
\end{align*}
\]

(13)

where \( m_\pm \equiv \frac{1}{2} \mu \pm \frac{1}{2} \sqrt{\mu^2 + 4m^2_Z} \). It is understood that if an eigenvalue of the neutralino mass matrix is negative, a simple rotation of the fields will give us a positive mass. The approximation in eq. (13) breaks down when \( \mu^2 \approx \frac{1}{2} m^2_Z \) except for \( t_\beta = 1 \). The second lightest neutralino is a higgsino with a mass close to the absolute value of \( \mu \), and experimental bounds on its mass will impose important restrictions on the model.

Now we turn to the exact numerical calculation of the chargino and neutralino masses. In Fig. 1 we plot contours of constant masses in the \( \mu - t_\beta \) plane. The
curve \( m_{\chi^\pm} = 47 \text{ GeV} \) corresponds to the constraint expressed in eq. (7). We also plot contours defined by \( m_{\chi^0} = 5 - 45 \text{ GeV} \), and the \( \tan \beta \) dependent experimental bound on \( m_{\chi^0} \) is represented by the solid line that joins the crosses. In this way, the “allowed” region (including chargino/neutralino searches only) corresponds to the region below the two solid lines. For \( \mu < 0 \) the allowed region is almost an exact reflection. The approximate bounds for \( \mu \) we got in eq. (8) are confirmed numerically: \( \mu < 87.4 \text{ GeV} \) for \( m_{\tilde{g}} = 3 \text{ GeV} \). Nevertheless, the bounds on \( \tan \beta \) come only from the experimental result \( m_{\chi^\pm} > 47 \text{ GeV} \), and we must include also the experimental results on \( m_{\chi^0} \). From Fig. 1 we see that this bound restricts the model to \( \tan \beta \lesssim 1.82 \), with the equality valid for \( \mu = 49.4 \text{ GeV} \). Since for \( \tan \beta \lesssim 1 \) there is no solution for the radiatively broken electroweak symmetry group, the allowed values of \( \tan \beta \) in the light gluino scenario and with \( \mu > 0 \) are

\[
1 \lesssim \tan \beta \lesssim 1.82 . \tag{14}
\]

If \( \mu < 0 \), the upper bound is \( \tan \beta \lesssim 1.85 \) with the equality valid for \( \mu = -51.8 \text{ GeV} \). We go on to analyze the viability of the “allowed” region in Fig. 1. We will find that the region allowed by the \( \chi^\pm \) and \( \chi^0 \) analysis is in fact disallowed by the experimental bound on \( m_h \) and \( m_t \).

In ref. [25] the RGE are solved for the special case in which only the top quark Yukawa coupling is different from zero. In the case of a light gluino (\( M_{1/2} \approx 0 \)), the value of \( \mu \) at the weak scale can be approximated by\(^{[25]}\)

\[
\frac{1}{2} m_Z^2 + \mu^2 = -m_0^2 + \frac{z - 1}{z(1 - t_{\beta}^2)} \left[ \frac{3m_0^2}{2} + \frac{A^2}{2z} \right], \tag{15}
\]

with

\[
z^{-1} = 1 - (1 + t_{\beta}^2) \left( \frac{m_t}{193 \text{GeV}} \right)^2. \tag{16}
\]

As it was reported in ref. [6], there is a fine-tuning situation in which we can have \( m_0 \gg |\mu| \) (producing larger radiative corrections to \( m_h \)) and it is obtained when
the coefficient of $m_0^2$ in eq. (15) is zero. Ref. [6] concluded that constraints on $m_h$ can be satisfied in a small window around $\tan \beta = 1.88 - 1.89$ (they did not consider the constraint on the second lightest neutralino). We will see that if the relation $A = B + m_0$ holds we do not find this type of solution ($m_0 \gg |\mu|$) as opposed to the case in which $A = 0$[26]. However, the later is obtained for a value of the top quark mass below the value of the experimental lower bound $m_t \geq 131$ GeV[27].

We survey the parameter space $m_0$, $B$, $M_{1/2}$, and $h_t$, looking for the maximum value of $\tan \beta$ allowed by collider negative searches in the chargino/neutralino sector, using the SUSY-GUT model described earlier. We consider models in which the relation $A = B + m_0$ holds. We expect maximum $\tan \beta$ to maximize $m_h$. For example, for the value $h_t = 0.87$ and $M_{1/2} = 1$ GeV (essentially fixed by the light gluino mass hypothesis) we find that $m_0 = 132.9$ and $B = -225.5$ GeV (at the unification scale) gives us $\tan \beta = 1.82$ and $\mu = 49.4$ GeV, i.e., the critical point with maximum $\tan \beta$ in the upper corner of the allowed region in Fig. 1. The values of other important parameters at the weak scale are $m_{\chi^\pm_1} \approx 47.1$, $m_{\chi^0_2} \approx 36.8$, $m_t = 131.1$, $m_A = 152.1$, and $m_\tilde{g} = 2.75$ GeV. We find a value for $B(b \rightarrow s\gamma) = 5.35 \times 10^{-4}$ consistent with the CLEO bounds. However, the lightest CP-even neutral Higgs fails to meet the experimental requirement: we get $m_h = 47.7$ GeV, inconsistent with LEP data.

In Fig. 2 we take the critical value $B = -225.5$ GeV and vary $m_0$ from 61 to 151 GeV [solid curve (a)] and we also take $B = -200$ GeV and vary $m_0$ from 51 to 133 GeV [solid curve (b)]. The two dashed lines correspond to the experimental constraint on the lightest chargino and the second lightest neutralino. The “allowed” region lies below both dashed curves. Curve (a) intersect the “allowed” region in almost a point (the critical point), as opposed to curve (b) which pass through the “allowed” region below the critical point. We see that low values of $m_0$ produce a too light neutralino and, on the other hand, larger values of $m_0$ produce a too light chargino. In Fig. 3 we can see the evolution of the masses $m_h$, $m_{\chi^\pm_1}$, and $m_{\chi^0_2}$ in both cases. Experimental bounds on $m_h$ and $m_{\chi^\pm_1}$ are repre-
sented by horizontal dotted lines, and the dotted line joining the crosses represent the experimental bound on the neutralino. In Fig. 3(a) we see that the bounds on chargino and neutralino masses are satisfied only at the critical point but the lightest CP-even Higgs mass is in conflict with its experimental bound in the hole range. In Fig. 3(b) the bounds on the chargino and neutralino masses are satisfied in a wider region around the critical point, however, the Higgs mass is even lighter than the previous case.

From the two fixed parameters, $h_t$ and $M_{1/2}$, the one that could affect the mass of the CP-even neutral Higgs is the first one; for a fixed value of $\tan \beta$, a larger value of the top quark Yukawa coupling will give us a larger $m_t$, and this will increase $m_h$. However, $h_t$ also enters the RGE for the Higgs mass parameters, and in order to get the correct electroweak symmetry breaking, a smaller value of $m_0$ is necessary. This implies smaller squark masses, which in turn reduce $m_h$ through radiative corrections. As an example with a larger $h_t$, we have found that for $h_t = 0.97$ and $M_{1/2} = 1$ GeV, the critical point is obtained at $m_0 = 103.8$ and $B = -132.5$ GeV. As expected, the value of the top quark mass is larger ($m_t = 146.2$ GeV), but we get smaller values for the squark masses. The net effect is that now $m_h$ is even smaller, 43.5 GeV, also in conflict with the experimental lower bound. (We caution the reader that at the small values of $m_t$ and $m_0$ used here, the contributions to $m_h$ coming from the Higgs/Gauge-boson/neutralino/chargino are also important\cite{14}; we include these in our analysis.)

We go back to $h_t = 0.87$ to analyze the case $\mu < 0$. In this case the critical point, given by $\tan \beta = 1.85$ and $\mu = -51.8$ GeV, is obtained for $m_0 = 71.1$ and $B = 111$ GeV. However the light CP-even Higgs is lighter than before: $m_h = 40.4$ GeV, incompatible with LEP data.

Our conclusion is that N=1 Supergravity with a radiatively broken electroweak symmetry group is incompatible with a light gluino with a mass of a few GeV. This is valid in models where the relation $A = B + m_0$ holds as well as in models where $A$ and $B$ are independent parameters\cite{26}.
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FIGURE CAPTIONS

1) Contours of constant value of the lightest chargino and the second lightest neutralino masses, for a gluino mass $m_{\tilde{g}} = 3$ GeV. The contour corresponding to the chargino mass is defined by the experimental lower bound $m_{\chi^\pm_1} = 47$. For $\chi^0_2$ we plot contour of constant mass from 5 to 45 GeV (dashed lines). The solid line that joins the crosses represent the $\tan\beta$ dependent bound on $m_{\chi^0_2}$. The “allowed” region lies below the two solid lines. We are considering in this graph experimental restrictions from the chargino/neutralino searches only.

2) For a fixed value of $M_{1/2} = 1$ GeV and $h_t = 0.87$ we vary $m_0$: (a) $B = -225.5$ GeV and $m_0 = 61 - 151$ GeV; (b) $B = -200$ GeV and $m_0 = 51 - 133$ GeV (solid lines). From chargino/neutralino searches only, the experimentally allowed region lies below the two dashed lines. In case (a) the curve passes through the critical point defined by $\tan\beta = 1.82$ and $\mu = 49.4$ GeV. In case (b), with a smaller value of the magnitude of $B$, the curve passes below the critical point.

3) Masses of the lightest chargino (upper dashed line), the second lightest neutralino (lower dashed line) and the lightest CP-even Higgs (solid line) as a function of $\mu$ for the two cases in the previous figure: (a) $B = -225.5$ GeV and (b) $B = -200$ GeV. The two horizontal dotted lines correspond to the experimental bounds $m_h > 56$ GeV and $m_{\chi^\pm_1} > 47$ GeV. The dotted line joining the crosses represents the experimental bound on the second lightest neutralino.
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