Closing the Light Gluino Window in a Class of Supergravity Models

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We study the light gluino scenario giving special attention to constraints from the masses of the light CP-even neutral Higgs boson m_h, the lightest chargino $m_{\chi_1^\pm}$, and the second lightest neutralino $m_{\chi_2^0}$, and from the $b \to s\gamma$ decay. We find that minimal $N = 1$ supergravity, with a radiatively broken electroweak symmetry group and universality of scalar and gaugino masses at the unification scale, is incompatible with the existence of a light gluino.

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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 group SU(3) × SU(2) × 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 breaking terms which do not introduce quadratic divergences to the unrenormalized theory [2], like the trilinear and bilinear mass parameters A and B.

The supersymmetric partner of the gluon is the gluino, and discussions about the existence of a light gluino have been in the literature for a long time [3]. Recently, motivated by the discrepancy between the value of the strong coupling constant determined by low energy deep inelastic lepton-nucleon scattering and the one determined by high energy e^+e^- experiments at the CERN collider LEP, there has been a renewed interest in this possibility [4–6].

An analysis of Υ decays in the CUSB detector excluded gluinos with a mass $0.6 < m_{\tilde g} < 2.2$ GeV [7]. Combining this and other results, the UA1 Collaboration found that the gluino mass is allowed in the region $2.6 < m_{\tilde g} \lesssim 6$ GeV and $m_{\tilde g} < 0.6$ GeV [8]. These bounds are controversial and, according to Ref. [9], the upper bound is $m_{\tilde g} \lesssim 3$ GeV. Even more recently Ref. [10] pointed out that results from quarkonium decays cannot rule out gluino masses below about 2 GeV [$m(\eta_{\tilde g}) \lesssim 3$ GeV, where $\eta_{\tilde g}$ is a pseudoscalar $\tilde g \tilde g$ bound state].

In supersymmetric grand unified theories (SUSY-GUT) [11], 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 approximate solution of these RGE is:

$$\begin{aligned} M_s &\approx M_{1/2}[1 + (3g_s^2/8\pi^2)\ln(M_X/m_Z)], \qquad m_{\tilde g} = |M_s|, \\ M &\approx M_{1/2}[1 - (g^2/8\pi^2)\ln(M_X/m_Z)], \qquad (1) \\ M' &\approx M_{1/2}[1 - (11g'^2/8\pi^2)\ln(M_X/m_Z)], \end{aligned}$$

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 $M' \approx 0.16 m_{\tilde g}$ at the weak scale.

Similarly, the scalar masses are also degenerate at the unification scale and equal to m_0. The RGE make both the Higgs boson 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 bilinear mass B. This mass defines the value of the unified trilinear mass A at M_X by $A = B + m_0$, a relation valid in models with canonical kinetic terms. 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 $h_t = gm_t/(\sqrt{2}m_W s_\beta)$ at the weak scale. Here the angle β 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.

Knowing the parameters of the Higgs potential at the weak scale m_1^2, m_2^2, and B, we can calculate the more familiar parameters m_t, t_β, m_A, and μ, for a given value of h_t, through the following formulas:

$$\begin{aligned} m_{1H}^2 &\equiv m_1^2 + \mu^2 = -\tfrac{1}{2}m_Z^2 c_{2\beta} + \tfrac{1}{2}m_A^2(1 - c_{2\beta}), \\ m_{2H}^2 &\equiv m_2^2 + \mu^2 = \tfrac{1}{2}m_Z^2 c_{2\beta} + \tfrac{1}{2}m_A^2(1 + c_{2\beta}), \qquad (2) \\ m_{12}^2 &= -B\mu = \tfrac{1}{2}m_A^2 s_{2\beta}, \end{aligned}$$

where $s_{2\beta}$ and $c_{2\beta}$ are sine and cosine functions of the angle 2β, m_A is the mass of the CP-odd Higgs boson, and it is understood that all the parameters are evaluated at the weak scale. The parameter μ is called the supersymmetric Higgs mass parameter and is the coefficient of the term H_1H_2 in the superpotential, where H_1 and H_2 are the two Higgs superdoublets. According to Ref. [6], and we 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

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quark mass relevant for our calculations, radiative corrections to the chargino and neutralino masses (recently calculated in Ref. [12]) 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 [13] and was analyzed in detail in Ref. [14]. Here we do not impose this condition, but we stress the fact that if $\tan\beta = 1$, the lightest CP-even neutral Higgs boson is massless at tree level. Nevertheless, the supersymmetric Coleman-Weinberg mechanism [15] 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 [16]. Therefore, experimental lower limits on m_h impose important restrictions on the light gluino window.

It has been pointed out that the branching ratio $B(b \to s\gamma)$ has a strong dependence on the supersymmetric parameters [17,18]. The theoretical branching ratio must remain within the experimental bounds $0.65 \times 10^{-4} < B(b \to s\gamma) < 5.4 \times 10^{-4}$. 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 [17]. We also include QCD corrections to the branching ratio [19] and one loop electroweak corrections to both the charged Higgs boson mass [20] and the charged-Higgs-boson–fermion–fermion vertex [21].

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 $\tan\beta < 1.6$ [22]. The lower bound for the heavier neutralinos (collectively denoted by χ') is $m_{\chi'} > 45$ GeV for $\tan\beta > 3$, and this bound also decreases with $\tan\beta$ and eventually disappears [23]. On the other hand, if the lightest neutralino has a mass $\lesssim 40$ GeV (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 [23]. This latest experimental bound will be denoted by $\bar{m}_{\chi_1^\pm} \equiv 47$ GeV.

In the following, we study the chargino-neutralino sector in more detail by analyzing the mass matrices. The chargino mass matrix [24] has eigenvalues denoted by $m_{\chi_i^\pm}$, $i = 1, 2$, and $m_{\chi_1^\pm} < m_{\chi_2^\pm}$. In the light gluino case we have $M \ll m_W$, and the chargino masses can be approximated by

$$m^2_{\chi^\pm_{1,2}} = \tfrac{1}{2}\mu^2 + m_W^2 \pm \tfrac{1}{2}\sqrt{R} \pm \frac{2m_W^2 \mu M s_{2\beta}}{\sqrt{R}} + O(M_{1/2}), \tag{3}$$

where $R = \mu^4 + 4m_W^2\mu^2 + 4m_W^4 c_{2\beta}^2$. Since the lightest chargino mass is bounded from below, we get the following constraint:

$$m_W^4 c_{2\beta}^2 + \mu^2 \bar{m}^2_{\chi_1^\pm} < \left(m_W^2 - \bar{m}^2_{\chi_1^\pm}\right)^2 - 4m_W^2 \mu M s_{2\beta}\left(\tfrac{1}{2}\mu^2 + m_W^2 - \bar{m}^2_{\chi_1^\pm}\right) \Big/ \sqrt{R}, \tag{4}$$

plus terms of $O(M_{1/2}^2)$. This limits the values of μ and $\tan\beta$:

$$\mu^2 < \bar{m}^2_{\chi_1^\pm}\left(\frac{m_W^2}{\bar{m}^2_{\chi_1^\pm}} - 1\right)^2 - \frac{4m_W^2 \mu_0 M\left(\frac{1}{2}\mu_0^2 + m_W^2 - \bar{m}^2_{\chi_1^\pm}\right)}{\bar{m}^2_{\chi_1^\pm}|\mu_0|\sqrt{\mu_0^2 + 4m_W^2}} + O(M_{1/2}^2) \Longrightarrow |\mu| \lesssim 90 \mp 0.87 m_{\tilde{g}} \text{ GeV}, \quad \pm = \text{sgn}(\mu M),$$
$$|c_{2\beta}| < 1 - \frac{\bar{m}^2_{\chi_1^\pm}}{m_W^2} + O(M_{1/2}^2) \Longrightarrow 0.46 < t_\beta < 2.2, \tag{5}$$

where $\mu_0^2 = \bar{m}^2_{\chi_1^\pm}(m_W^2/\bar{m}^2_{\chi_1^\pm} - 1)^2 \approx (90 \text{ GeV})^2$ is the zero-order solution ($M = 0$), and $\mp 0.87 m_{\tilde{g}}$ correspond to the first-order correction. The constraints in Eq. (5) were already found in Ref. [6] at zero order, but, the neutralino sector will restrict the parameter space even more.

The neutralino mass matrix [25] in the zero gluino mass limit ($M = M' = 0$) has one eigenvalue equal to zero. Calculating the first-order correction, we find for the lightest neutralino mass $m_{\chi_1^0} \approx M s_W^2 + M' c_W^2 \approx 0.19 m_{\tilde{g}}$ where we used the relations between M, M', and $m_{\tilde{g}}$ given below in Eq. (1). Considering that $m_{\tilde{g}}$ is less than a few GeV, we get $m_{\chi_1^0} \lesssim 1$ GeV. This light neutralino (the lightest supersymmetric particle, or LSP) is, up to terms of $O(M_{1/2}^2/m_Z^2)$, 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 second lightest neutralino mass, in the approximation in which $\tan\beta$ is close to unity, i.e., $s_{2\beta} \approx 1$, is given by

$$m_{\chi_2^0} = -\mu - \mu\frac{m_Z^2(1 - s_{2\beta})}{2\mu^2 - m_Z^2}, \tag{6}$$

where we neglect terms of $O((1 - s_{2\beta})^2)$ and $O(M_{1/2}^2)$. 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. (6) breaks down when $\mu^2 \approx \frac{1}{2}m_Z^2$ except for $t_\beta = 1$.

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 μ-t_β plane. The curve $m_{\chi_1^\pm} = 47$ GeV corre^ponds to the constraint expressed in Eq. (4). We also plot contours defined by $m_{\chi_2^0} = 5$–45 GeV, and these curves show that $m_{\chi_2^0} \approx |\mu|$ when $\tan\beta \approx 1$, in agreement with Eq. (6). The $\tan\beta$ dependent

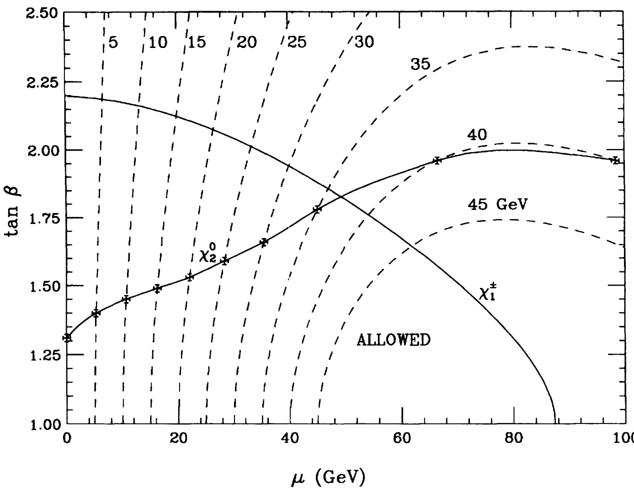

FIG. 1. Contours of constant value of the lightest chargino and the second lightest neutralino masses, for a gluino mass $m_{\tilde{g}} = 3$ GeV. The contour corresponding to the chargino mass is defined by the experimental lower bound $m_{\chi_1^\pm} = 47$. For χ_2^0 we plot contour of constant mass from 5 to 45 GeV (dashed lines). The solid line that joins the crosses represents the $\tan\beta$ dependent bound on $m_{\chi_2^0}$. The "allowed" region lies below the two solid lines. We are considering in this graph experimental restrictions from the chargino-neutralino searches only.

experimental bound on $m_{\chi_2^0}$ 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 μ we got in Eq. (5) are confirmed numerically: $\mu < 87.4$ GeV for $m_{\tilde{g}} = 3$ GeV. Nevertheless, the bounds on $\tan\beta$ come only from the experimental result $m_{\chi_2^\pm} > 47$ GeV, and we must include also the experimental results on $m_{\chi_2^0}$. From Fig. 1 we see that this bound restricts the model to $\tan\beta \lesssim 1.82$, with the equality valid for $\mu = 49.4$ 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 $1 \lesssim \tan\beta \lesssim 1.82$, and if $\mu < 0$, the upper bound is $\tan\beta \lesssim 1.85$ with the equality valid for $\mu = -51.8$ 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 χ^0 analysis is in fact disallowed by the experimental bound on m_h and m_t.

In Ref. [26] 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 μ at the weak scale can be approximated by [26]

$$\frac{1}{2}m_Z^2 + \mu^2 = -m_0^2 + \frac{z-1}{z(1-t_\beta^{-2})}\left[\frac{3m_0^2}{2} + \frac{A^2}{2z}\right], \quad (7)$$

with $z^{-1} = 1 - (1 + t_\beta^{-2})(m_t/193\ \text{GeV})^2$. 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. (7) is zero. Reference [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 $A = 0$. However, the latter 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 first 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) give 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 $m_{\chi_1^\pm} \approx 47.1$, $m_{\chi_2^0} \approx 36.8$, $m_t = 131.1$, $m_A = 152.1$, and $m_{\tilde{g}} = 2.75$ GeV. We find a value for $B(b \to s\gamma) = 5.35 \times 10^{-4}$ consistent with the CLEO bounds. However, the lightest CP-even neutral Higgs boson fails to meet the experimental requirement: We get $m_h = 47.7$ GeV, inconsistent with LEP data since it is required that $m_h > 56$ GeV for $m_A > 100$ GeV [16]. It is known that relative to the SM coupling, the ZZh coupling in the MSSM is suppressed by $\sin(\beta - \alpha)$, where α is the mixing angle in the CP-even neutral Higgs boson sector, nevertheless, this angle approaches the asymptotic value $\beta - \pi/2$ when m_A increases, i.e., the lightest Higgs boson h behaves like the SM Higgs boson, and the experimental lower bound on its mass will approach the SM bound.

From the two fixed parameters, h_t and $M_{1/2}$, the one that could affect the mass of the CP-even neutral Higgs boson 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 and $m_A = 119.3$ GeV. 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 [15]; 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 boson is lighter than before: $m_h = 40.4$ GeV, incompatible with LEP data since this time $m_A = 83.4$ GeV and the LEP bound decreases to $m_h > 55$ GeV [16].

If A and B are independent there is one extra degree of freedom that may help to satisfy the experimental constraints. According to Eq. (7) the fine tuning $m_0 \gg |\mu|$ is obtained for $A = 0$. Adopting that value and considering $\mu > 0$, for $h_t = 0.87$ and $M_{1/2} = 1$ GeV we obtain the critical point for $m_0 = 151.6$ and $B = -256.8$ GeV, which implies $m_{\chi_1^\pm} = 47.1$, $m_{\chi_2^0} = 36.8$, $m_t = 131.1$, $m_A = 173.4$, and $m_{\tilde{g}} = 2.75$ GeV. However, we get $B(b \to s\gamma) = 7.15 \times 10^{-4}$ and $m_h = 48.8$ GeV, both inconsistent with experimental bounds.

In order to illustrate the fine-tuning we consider $h_t = 0.77$ and $M_{1/2} = 1$ GeV. The critical point is obtained for $m_0 = 930$ and $B = -9576$ GeV. The masses of $\chi_1^\pm$, χ_2^0, and $\tilde{g}$ are the same as before, and we also get $m_A = 1059$, $m_h = 64.8$ GeV consistent with LEP bound, and $B(b \to s\gamma) = 4.14 \times 10^{-4}$ consistent with the CLEO bound, but this time it is the top quark mass that does not meet the experimental bound: We get $m_t = 116.0$ GeV, incompatible with the D0 lower bound of 131 GeV.

If $\mu < 0$, no big changes are found. For $h_t = 0.87$ the critical point, defined now by $\tan\beta = 1.85$ and $\mu = -51.8$ GeV, is obtained for $m_0 = 159.4$ and $B = 268$ GeV. In this case $m_A = 182.2$ GeV and, as before, the two quantities inconsistent with experimental results are $B(b \to s\gamma) = 8.42 \times 10^{-4}$ and $m_h = 50.5$ GeV.

Our conclusion is that $N = 1$ supergravity, with a radiatively broken electroweak symmetry group and universality of scalar and gaugino masses at the unification scale, 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.

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