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Date: 2016-12-28T00:00:00+00:00

Abstract

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Full Text

Preamble

Prepared for submission to JHEP

Reconciling the muon g-2 anomaly with LHC data in SUGRA with generalized gravity mediation

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Abstract: From generalized gravity mediation we construct a SUGRA scenario in which the gluino is much heavier than the electroweak gauginos at the GUT scale. We find that such a non-universal gaugino scenario with a very heavy gluino at the GUT scale can be naturally obtained with proper high-dimensional operators in the framework of SU(5) GUT. Then, due to the effects of the heavy gluino, at the weak scale all colored sparticles are heavy while the uncolored sparticles are light, which can explain the Brookhaven muon g-2 measurement while satisfying the collider constraints (both the 125 GeV Higgs mass and the direct search limits of sparticles) and dark matter requirements. We also find that, in order to explain the muon g-2 measurement, the neutralino dark matter must be lighter than 200 GeV in our scenario, which can be mostly covered by the future Xenon1T experiment.

Contents

1 Introduction

If the particle discovered by the ATLAS and CMS collaborations of the LHC [?, ?] is indeed the long-sought Standard Model (SM) Higgs boson, then the hierarchy problem related to fundamental scalars may readily indicate new physics beyond the SM. Another hint of new physics arises from the precise measurement of the muon anomalous magnetic moment by the Brookhaven experiment [?, ?], which gives a larger value than the SM prediction, with a discrepancy of about 3 [?].

Among new physics theories, low-energy supersymmetry (SUSY), which was initially proposed to solve the gauge hierarchy problem, remains one of the most appealing extensions. The observed 125 GeV Higgs boson at the LHC falls miraculously within the narrow 115–135 GeV "window" predicted by the Minimal Supersymmetric Standard Model (MSSM). Furthermore, within the framework of low-energy SUSY, the three gauge couplings can naturally be unified [?], cosmic cold dark matter can be naturally explained, the vacuum instability problem can be solved, and the muon g-2 discrepancy can also be accounted for.

However, low-energy SUSY also encounters difficulties in the LHC era. The heavy top squarks needed for a 125 GeV Higgs boson, the null search results for sparticles, and the perfect agreement of $B_s^0 \to \mu^+\mu^-$ with the SM prediction all imply SUSY at a rather high scale. In fact, LHC data has already pushed the gluino and squarks of the first two generations to the TeV scale [?, ?], i.e., $m_{\tilde{g}} > 1.5$ TeV for $m_{\tilde{q}} \sim m_{\tilde{g}}$ and $m_{\tilde{g}} \gtrsim 1$ TeV for $m_{\tilde{q}} \gg m_{\tilde{g}}$, while for top squarks the bounds from LHC searches are model-dependent, e.g., above 600 GeV in natural SUSY [?]. On the other hand, if the muon g-2 anomaly is to be solved within SUSY, the relevant electroweak sparticles (smuons, neutralinos, and charginos) need to be around $\mathcal{O}(100)$ GeV for a $\tan\beta$ value of order $\mathcal{O}(10)$. Thus, it seems that low-energy SUSY should be realized in a more involved way [?].

If SUSY is required to account for the muon g-2 anomaly without contradicting recent LHC results, a split spectrum for sparticles is favored, with one scale (relatively high) governing the colored sparticle masses and another scale (relatively low) governing the uncolored sparticle masses [?]. This can be realized in a supergravity (SUGRA) grand unified model called gluino-SUGRA [?], which has non-universal gaugino masses [?], with the gluino being much heavier than the electroweak gauginos at the GUT scale [?].

In this note we attempt to build such a gluino-SUGRA model from generalized gravity mediation of SUSY breaking [?]. Our results show that this scenario can be naturally obtained with proper high-dimensional operators in the framework of SU(5) GUT. Then, due to the effects of the heavy gluino, at the weak scale all colored sparticles are heavy while the uncolored sparticles are light, which can explain the Brookhaven muon g-2 measurement while satisfying the collider constraints and dark matter requirements. We also find that, in order to explain the muon g-2 measurement, the neutralino dark matter must be below 200 GeV in this scenario, which can be mostly covered by the future Xenon1T experiment.

This paper is organized as follows. In Sec. 2, we construct a gluino-SUGRA model in the framework of SU(5) GUT from generalized gravity mediation. In Sec. 3, we examine the phenomenological constraints on our scenario, which come from muon g-2, LHC data, and the dark matter relic density and direct detection limits. Sec. 4 contains our conclusions.

2 SUGRA with Heavy Gluino Constructed from Generalized Gravity Mediation

To mediate SUSY breaking effects from the hidden sector to the visible sector, many mechanisms have been proposed, for example, gravity mediation [?], gauge mediation [?], and anomaly mediation [?]. Among these mechanisms, gravity mediation is a very predictive scenario. In this scenario, the SM-like Higgs boson mass lies close to the upper limit of 130 GeV predicted in grand unified SUGRA models [?].

In the popular gravity mediation scenario, the Kähler potential is assumed to be minimal. When certain high-representation chiral fields of the GUT group are involved in the non-renormalizable Kähler potential, the kinetic terms of superfields can have alternative contributions after GUT symmetry breaking. New non-renormalizable terms in the superpotential involving high-representation fields can also be important. In general, both gauge singlet and non-singlet fields can acquire non-vanishing F-term VEVs to break supersymmetry. We focus on the SU(5) grand unified SUGRA model in our analysis.

A general form of the kinetic terms for vector supermultiplets is

$$\int d^2\theta \left(\frac{1}{4g^2} + a_1 \frac{\Phi}{M_*} + b_1 \frac{S}{M_*} \right) W^a W^a + \text{h.c.},$$

with Φ denoting a GUT group non-singlet chiral supermultiplet and S a GUT group singlet which can acquire a VEV of order (or below) M_*.

From the symmetric product of SU(5) adjoint

$$(24 \otimes 24)_{\text{symmetric}} = 1 \oplus 24 \oplus 75 \oplus 200,$$

we see that the non-renormalizable terms can be constructed with 24, 75, and 200 representation chiral supermultiplets of SU(5). For simplicity, we assume that only the 75 representation chiral field appears in the gauge kinetic terms and in the Kähler potential of the form

$$K = \phi^\dagger \phi + \sum_a c_a S \phi_a^\dagger \phi_a + c' \frac{(\Phi_{75} \otimes \Phi_{75})_{ab}}{M_*^2} \phi_a^\dagger \phi_b,$$

with r denoting some representation from the product expansion of $75 \otimes 75$. We assume that the superfield Φ_{75} acquires both the lowest component and F-term VEVs. After the GUT singlet S field and the 75 field acquire the lowest component VEVs

$$\langle \Phi_{75} \rangle_{ab} = v_{75} U_{ab},$$

with the universal group factor U_{ab} given in terms of a 10×10 matrix as

$$U_{ab} = (1, 1, 1, -1, -1, -1, -1, -1, -1, 3),$$

the wave-function normalization factor for the gauge kinetic term will have the form

$$Z_i = 1 + a_1 \frac{\langle S \rangle}{M_*} + b_1 \frac{\langle \Phi \rangle_i}{M_*} \equiv \alpha + \beta_i,$$

with the ratios of the non-universal parts given by

$$\beta_1 : \beta_2 : \beta_3 = -5 : 3 : 1.$$

The F-term VEV of Φ_{75} given by $(F_\Phi)_{ab} = F_\Phi \cdot U_{ab}$ will lead to a non-canonical gaugino mass ratio

$$M_1 : M_2 : M_3 = -b_1 \frac{F_\Phi}{M_*} : 3b_1 \frac{F_\Phi}{M_*} : 5b_1 \frac{F_\Phi}{M_*},$$

which, after re-scaling the normalization factor, gives a physical non-universal gaugino mass ratio

$$M_1 : M_2 : M_3 = -\frac{5}{\alpha - 5} : \frac{3}{\alpha + 3} : \frac{1}{\alpha + 1}.$$

For the choice of coefficient $Z_3 \equiv \alpha + \beta_3 \approx \mathcal{O}(0.1) \approx 0$, we can fix the value of α and thus the values of Z_1, Z_2 correspondingly. The ratio for Z_i is given approximately by

$$Z_1 : Z_2 : Z_3 \approx -6 : 2 : Z_3,$$

so we can obtain

$$M_1 : M_2 : M_3 = \frac{5}{6} : \frac{3}{2} : \frac{1}{Z_3}.$$

We see that at the GUT scale the gluino can be much heavier than the bino and wino. On the other hand, the gluino will in general not be too much heavier than the other two if no fine-tuning in the normalization factor is introduced.

From group theory we know

$$75 \otimes 75 \supset 1 \oplus 24 \oplus 75 \oplus 200,$$

so a universal sfermion mass can be generated from the Kähler potential by F-term VEVs of Φ_{75}:

$$\tilde{m}^2_{\tilde{10}_i, \tilde{5}_i, \tilde{H}_{u,d}} = c' \frac{|F_{75}|^2}{M_*^2}.$$

Note that there are many possible contractions of group factors in the Kähler potential, and we adopt here the simplest case with $(\Phi_{75} \otimes \Phi_{75})_{ab} \propto \delta_{ab}$. On the other hand, it can be seen from formula (2.3) that the kinetic terms for matter fields will also receive additional contributions from GUT breaking effects by the lowest component VEVs of Φ_{75}. Therefore, the universal sfermion masses should be rescaled with respect to the kinetic factor to obtain the physical soft masses:

$$\tilde{m}^2_{\text{physical}} = \frac{c' |F_{75}|^2 / M_*^2}{Z_\phi},$$

with the possible kinetic factor Z_ϕ as

$$Z_\phi = 1 + c_1 \langle S \rangle + c' \frac{\langle \Phi_{75} \rangle^2}{M_*^2} \approx 1 + c_1 \langle S \rangle \equiv Z_U.$$

Thus, the universal sfermion mass can be set as a free parameter in our scenario. The universal sfermion masses, which control the masses for sleptons, should not be heavy in order to explain the g-2 anomaly. The squarks, on the other hand, will receive large corrections from gluino loops. Therefore, the typical universal sfermion mass scale should not be too much larger than that of the lightest gaugino.

The trilinear term can be generated from non-renormalizable operators in the superpotential involving the Φ_{75} superfield:

$$W \supset \frac{\Phi_{75}}{M_*}\sum_{i,j=1}^{3}\left(y_{ij}10_i \otimes 10_j \otimes 5_{H_u} + y'_{ij}10_i \otimes \bar{5}_j \otimes \bar{5}_{H_d}\right),$$

with i, j denoting the family index. Relevant calculations can be found in our previous works [?]. Similar calculations give the resulting trilinear terms after rescaling the kinetic factor Z_U for sfermions and Higgs chiral fields $5_{H_u}, \bar{5}_{H_d}$:

$$A_u\tilde{Q}_i\tilde{U}_jH_u - y_U\tilde{Q}_i\tilde{U}_jH_u - y_D\tilde{L}_i\tilde{E}_jH_d - y_D\tilde{Q}_i\tilde{D}_jH_d,$$

with appropriate suppression factors. Note that our previous calculations [?] indicate that the up-type squark trilinear terms vanish if we only introduce the F-term VEV for Φ_{75}.

The SUSY-preserving μ term, which will be determined by electroweak symmetry breaking conditions, is generated by fine-tuning with the lowest component VEV of Φ_{24}:

$$W \supset (M + \langle\Phi_{24}\rangle)5_{H_u}\bar{5}_{H_d}.$$

Because one cannot construct gauge-invariant combinations involving only 5, $\bar{5}$, and 75, the $B\mu$ term can be generated from

$$(M + \langle\Phi_{24}\rangle)\frac{\Phi_{24}\Phi_{75}}{M_*^2}5_{H_u}\bar{5}_{H_d},$$

which gives

$$B\mu = (M + \langle\Phi_{24}\rangle)\frac{\langle\Phi_{24}\rangle\langle\Phi_{75}\rangle}{M_*^2}.$$

Thus, we see that the $B_0 \equiv B\mu/\mu$ term at the GUT scale is suppressed by a GUT/Planck factor relative to A_0 and can be set to zero at the GUT scale.

We can introduce only the 24 or 200 representation field as the GUT non-singlet field Φ in the generalized gauge kinetic terms, and then the GUT-scale non-universal gaugino input will change accordingly:

The scenario with only 24 representation Higgs:

The lowest component VEV for the 24 representation field has the form

$$\langle \Phi_{24} \rangle_{ab} = v_{24} U_{ab},$$

with the universal group factor U_{ab} given in terms of a 5×5 matrix by

$$U_{ab} = \text{diag}\left(1, 1, 1, -\frac{3}{2}, -\frac{3}{2}\right).$$

Similar to the case of 75 representation Higgs, the ratios of the non-universal parts within the wave-function normalization factor of gauge kinetic terms will be given by

$$\beta_1 : \beta_2 : \beta_3 = 1 : 3 : -2.$$

This leads to GUT-scale non-universal gaugino input:

$$M_1 : M_2 : M_3 = \frac{1}{\alpha + 1} : \frac{3}{\alpha + 3} : \frac{-2}{\alpha - 2} \sim \mathcal{O}(10).$$

The scenario with only 200 representation Higgs:

The lowest component VEV for the 200 representation field has the form

$$\langle \Phi_{200} \rangle_{ab} = v_{200} U_{ab},$$

with the universal group factor U_{ab} given in terms of a 15×15 matrix by appropriate normalization. The ratios of the non-universal parts within the wave-function normalization factor of gauge kinetic terms are given by

$$\beta_1 : \beta_2 : \beta_3 = 10 : 2 : 1.$$

This leads to a GUT-scale non-universal gaugino input:

$$M_1 : M_2 : M_3 = \frac{10}{\alpha + 10} : \frac{2}{\alpha + 2} : \frac{1}{\alpha + 1} \sim \mathcal{O}(10).$$

Thus, we see that such a non-universal gaugino scenario with a very heavy gluino at the GUT scale can be naturally obtained with proper high-dimensional operators in the framework of SU(5) GUT.

3 Phenomenological Constraints

We now scan the parameter space of our gluino-SUGRA scenario. The GUT-scale inputs are given by:

- The gaugino mass scale $M_{1/2}$ with non-universal gaugino mass ratio $M_1 : M_2 : M_3 = \frac{5}{6} : \frac{3}{2} : \frac{1}{Z_3}$ (with $k \equiv 1/Z_3 \sim \mathcal{O}(10)$) for the case with the 75 representation Higgs. Here we define $M_{1/2}$ as $M_1 = (5/6)M_{1/2}$, and in our numerical calculations we vary $1/Z_3$ from 10 to 50. At the weak scale, the gaugino mass ratio is estimated to be $M_1 : M_2 : M_3 \approx 1 : 2 : 6k$.
- The universal sfermion mass M_S.
- The trilinear term $A_{b,\tau}$ (at the same order as M_S) while $A_t = 0$.
- The B_0 parameter is set to zero at the GUT scale.
- The parameter $\tan\beta$ (in our scan we vary it in the range $1 < \tan\beta < 50$). Choices of $\tan\beta$ that do not trigger successful radiative EWSB are not kept in our numerical scan.

The μ parameter is determined by the electroweak symmetry breaking conditions.

We use the code DarkSUSY [?] to scan over the parameter space and the code SuSpect2 [?] to obtain the low-energy spectrum by RGE running from the GUT scale (at this energy scale $g_1 = g_2$) to the weak scale. The central values of g_1, g_2, and g_3 at the weak scale are used as inputs. Other inputs, for example, the top Yukawa coupling h_t, are extracted from the Standard Model taking into account threshold corrections (the relevant details can be found in the appendix of [?, ?]).

In our scan we consider the following constraints (the relevant details can be found in our previous work [?]):

1. The relic density of the neutralino dark matter given by Planck $\Omega_{\rm DM} = 0.1199 \pm 0.0027$ [?] (in combination with WMAP data [?]).
2. The LEP lower bounds on neutralinos and charginos ($m_{\chi^\pm} > 103$ GeV) as well as the bounds from invisible Z decay $\Gamma(Z \to \chi^0\chi^0) < 1.71$ MeV, which is consistent with the 2σ precision EW measurement result $\Gamma_{\text{non-SM}} < 2.0$ MeV.
3. The precision electroweak observables S, T, U [?] must be compatible with LEP/SLD data at the 2σ level [?].
4. The LHC constraints on the SM-like Higgs boson mass 123 GeV $< M_h <$ 127 GeV [?, ?].

In our scan, we also require that the surviving points satisfy successful electroweak symmetry breaking requirements; otherwise, they are not kept. Under these constraints, we show the SUSY contributions to the muon g-2 and the spin-independent dark matter-nucleon scattering rates compared with dark matter direct detection limits from Xenon100 [?] and LUX [?]:

- For the spin-independent dark matter-nucleon scattering rate, we calculate it with the parameters [?]: $f_{T_u}^{(p)} = 0.032$, $f_{T_d}^{(p)} = 0.041$, $f_{T_s}^{(p)} = 0.020$, $f_{T_u}^{(n)} = 0.017$, $f_{T_d}^{(n)} = 0.023$, $f_{T_s}^{(n)} = 0.020$. The value of f_{T_G} is taken from lattice simulation results [?]. All known contributions, including QCD corrections, are taken into account in our calculation of the scattering rate.
- For the SUSY contributions to the muon g-2, we know they are dominated by chargino-sneutrino and neutralino-smuon loops. At leading order in $m_W/m_{\rm SUSY}$ and $\tan\beta$ ($m_{\rm SUSY}$ denotes the SUSY-breaking masses), the SUSY loop contributions are [?, ?]:

$$\Delta a_\mu(\tilde{W}, \tilde{H}, \tilde{\nu}_\mu) \simeq 15 \times 10^{-9} \left(\frac{100\ \text{GeV}}{m_{\rm SUSY}}\right)^2 \tan\beta,$$

$$\Delta a_\mu(\tilde{W}, \tilde{H}, \tilde{\mu}_L) \simeq -2.5 \times 10^{-9} \left(\frac{100\ \text{GeV}}{m_{\rm SUSY}}\right)^2 \tan\beta,$$

$$\Delta a_\mu(\tilde{B}, \tilde{H}, \tilde{\mu}_L) \simeq 0.76 \times 10^{-9} \left(\frac{100\ \text{GeV}}{m_{\rm SUSY}}\right)^2 \tan\beta \left(\frac{\mu M_2}{m_{\rm SUSY}^2}\right),$$

$$\Delta a_\mu(\tilde{B}, \tilde{H}, \tilde{\mu}_R) \simeq -1.5 \times 10^{-9} \left(\frac{100\ \text{GeV}}{m_{\rm SUSY}}\right)^2 \tan\beta \left(\frac{\mu M_1}{m_{\rm SUSY}^2}\right),$$

$$\Delta a_\mu(\tilde{\mu}_L, \tilde{\mu}_R, \tilde{B}) \simeq 1.5 \times 10^{-9} \left(\frac{100\ \text{GeV}}{m_{\rm SUSY}}\right)^2 \tan\beta \left(\frac{\mu M_1}{m_{\rm SUSY}^2}\right).$$

The SUSY contributions to the muon g-2 are enhanced for small soft masses and large $\tan\beta$. Since the experimental value is larger than the SM prediction, a positive $\mu M_{1,2}$ is favored in most of the parameter space. See also the results from the numerical code [?].

The numerical results from our scan are shown in Fig. 1, Fig. 2, Fig. 3, and Table 1 . All points in the figures satisfy constraints (1-4), where the green circles (red squares) can (cannot) explain the muon g-2 deviation $\Delta a_\mu = (255 \pm 80) \times 10^{-11}$ at the 1σ level. As shown in these figures, some samples in our gluino-SUGRA scenario can satisfy the LHC constraints and explain the Brookhaven g-2 experiment. For these samples, we have the following observations:

(i) From the upper left panel of Fig. 1, we see that the g-2 explanation constrains $M_{1/2}$ (defined as $M_1 = (5/6)M_{1/2}$ at the GUT scale) below 600 GeV. The upper right panel shows that the g-2 explanation also requires a light value for the universal sfermion mass M_S at the GUT scale (so that at the electroweak scale we have light sleptons and electroweakinos while squarks are heavy due to RGE running). These results can be easily understood from Eqs. (3.3–3.7).

(ii) Due to a rather heavy gluino, when squark masses run down to the electroweak scale, they become sufficiently heavy (although M_S is light at the GUT scale) as required by a 125 GeV SM-like Higgs boson and the LHC bounds. We see from the lower left panel of Fig. 1 that the squarks at the electroweak scale are heavier than 4 TeV in our scenario.

(iii) From the lower right panel of Fig. 1, we see that the g-2 explanation requires low masses for the lightest chargino and the lightest neutralino. The lightest neutralino dark matter lies in the mass range of 80 to 200 GeV.

(iv) From Fig. 3, we see that for $k = 10$ ($k \geq 30$), most (all) samples required to explain the g-2 at the 1σ level can be covered by the future Xenon1T experiment. This means that in case of null results from the Xenon1T experiment, our scenario with $k \geq 30$ will be excluded.

(v) The low-energy particle spectrum for some typical benchmark points is shown in Table 1 . We see that the sleptons are typically light while the squarks are heavy due to the much heavier gluino.

Figure 1 [Figure 1: see original paper]. Scatter plots of samples satisfying constraints (1–4) for $k \equiv 1/Z_3 = 10$. Green circles (red squares) can (cannot) explain the muon g-2 at the 1σ level. The upper panels show input parameters at the GUT scale, while the lower panels show output parameters at the electroweak (EW) scale, with M_{UQ} denoting the up-squark soft mass, $M_{\chi^\pm}$ the lightest chargino mass, and M_{χ^0} the lightest neutralino mass.

Figure 2 [Figure 2: see original paper]. Same as Fig. 1, but showing the muon g-2 versus $M_{1/2}$ for different values of $k \equiv 1/Z_3$. The region between the two horizontal dashed lines corresponds to the Brookhaven measured g-2 at the 1σ level.

Table 1. Masses (in GeV) of some sparticles at the weak scale for different values of $k \equiv 1/Z_3$. All points satisfy g-2 constraints and other electroweak constraints.

k	$M_{1/2}$	$m_{\tilde{d}_1}$	⋯

Figure 3 [Figure 3: see original paper]. Same as Fig. 2, but showing μ versus $M_{1/2}$ in the upper panel and the spin-independent dark matter-nucleon scat-

tering rate versus the lightest neutralino dark matter mass in the lower panel. The curves in the lower panel show the dark matter direct detection limits from Xenon100 [?] and LUX [?].

4 Conclusion

From generalized gravity mediation we constructed a SUGRA scenario in which the gluino is much heavier than the electroweak gauginos at the GUT scale. We chose the framework of SU(5) GUT and found that such a non-universal gaugino scenario with a very heavy gluino at the GUT scale can be naturally obtained with proper high-dimensional operators. Due to the contributions of the heavy gluino, at the weak scale the squarks are sufficiently heavy as required by a 125 GeV SM-like Higgs boson, while the uncolored sparticles can be light enough to explain the Brookhaven muon g-2 measurement. Since the g-2 explanation requires neutralino dark matter below 200 GeV in our scenario, the parameter space can be mostly covered by the future Xenon1T experiment.

Acknowledgement

This work was supported by the Natural Science Foundation of China under grant numbers 11105124, 11105125, 11275245, 10821504, 11135003, 11375001, 11172008, by the Ri-Xin Foundation of BJUT, and by the Talents Foundation of the Education Department of Beijing.

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