An extended gauge mediation for muon \((g − 2)\) explanation

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Abstract

It is increasingly becoming difficult, within a broad class of supersymmetric models, to satisfactorily explain the discrepancy between the measured \((g − 2)\) and its standard model prediction, and at the same time satisfy all the other constraints. In this paper we propose a new scheme of gauge mediation by introducing new soft supersymmetry breaking mass parameters for the messengers. Thus GMSB naturally provides an advantageous platform for addressing the representations of \(\bar{5}\) as in GMSB the gravitino constitutes the LSP. Third, minimal GMSB with a pair of messengers transforming in \(SU(5)\) are under control. Second, constraints from DM direct search experiments cease to apply on wino-higgsino mixing, \((\text{GMSB})\) models \([16–18]\) have got a distinct advantage for addressing all the issues. First, gauge interactions always keep strong for the chargino induced loop to have any numerical impact on \(a_\mu\). To avoid this problem, we may switch to the dominance of chargino-sneutrino loops, the necessary condition for which is a large wino-higgsino mixing. In this case, the lightest supersymmetric particle (LSP), which is a neutralino in the gravity mediated scenario, has a strong higgsino admixture, and such a DM candidate is strongly disfavored by the direct search experiments \([12–14]\). Also, if the chargino is heavier than sleptons, the LHC constraints on the chargino mass is too strong for the chargino induced loop to have any numerical impact on \(a_\mu\) \([15]\). Gauge mediated supersymmetry breaking \((\text{GMSB})\) models \([16][18]\) have got a distinct advantage for addressing all the issues. First, gauge interactions always keep FCNC under control. Second, constraints from DM direct search experiments cease to apply on wino-higgsino mixing, as in GMSB the gravitino constitutes the LSP. Third, minimal GMSB with a pair of messengers transforming in \(5\) and \(\bar{5}\) representations of \(SU(5)\) yields larger soft masses for sleptons than for the wino, with grand unified theory (GUT) breaking masses for the messengers. Thus GMSB naturally provides an advantageous platform for addressing the \(a_\mu\) crisis.

Now we face the next level of hurdles within the GMSB framework. LHC data tell us that a wino has to weigh above 1.1 TeV \([19]\) if it is heavier than sleptons. On the contrary, if sleptons are heavier than the wino, which is indeed the case in GMSB with a pair of \(5 + \bar{5}\) messengers (minimal GMSB), the wino mass limit weakens to much lower values. Now we recall that in a generic GMSB framework, to match a heavy stop in the range \(\sim 10\) TeV (necessary to reproduce the observed Higgs boson mass \(m_h \simeq 125\) GeV \([20][24]\)), the higgsino mass parameter \(\mu\) must be \((3 - 4)\) TeV for the correct realization of the weak scale \(M_Z \simeq 91\) GeV, even if the messenger scale is quite low. For \(\mu\) so large, the chargino is practically a wino, which in minimal GMSB constitutes the next-to-LSP (NLSP). The (weakened) limit on its mass is 460 GeV \([25]\), if gravitino is in the keV range, arising from non-observation of disappearing tracks at the LHC\(^2\).

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\(^1\) For a particularly light slepton and bino, bino-higgsino-slepton loop can be important. However, in this case, the stau tends to be much lighter than the selectron or smuon, and it becomes too light to escape collider constraints.
\(^2\) The above limit strengthens to around 600 GeV for superlight gravitino in the eV range \([19]\).
such a large \(\mu\)-parameter, the higgsino admixture to wino is negligible, and contributions from the bino-slepton induced loops dominate the SUSY contribution to \(a_\mu\). However, in this case, it is impossible to explain the \(a_\mu\) discrepancy at a satisfactory level since the sleptons are not enough light because of the wino mass limit of 460 GeV [26]. Also, we face the problem of charge breaking minimum in the stau-Higgs potential imposing tight constraints on the parameter space. The situation does not improve even in cases with \(10 + \overline{10}\) messengers or \(24\) messenger [26]. Also, the GMSB model with \(SU(3)\) octet and \(SU(2)\) triplet messengers [27][28] cannot avoid the current LHC constraints in the region where the \(a_\mu\) discrepancy is explained.

In this paper, our basic framework is minimal GMSB (with a pair of \(5 + \overline{5}\) messengers). However, to circumvent the above problems, we arrange for a smaller \(\mu\) through the introduction of a new soft SUSY breaking mass (3-4 TeV) of the Higgs bosons. This single parameter \((\delta m_H^2 = \delta m_{\tilde{H}}^2 = \delta m_{1/2}^2)\) brings in a clear advantage to \(a_\mu\) as shown in Ref. [26]. With a small \(\mu\), the wino-higgsino mixing becomes sizable, and chargino-sneutrino loops dominate the SUSY contribution to \(a_\mu\). Consequently, even with relatively heavier sleptons one can explain the \(a_\mu\) discrepancy. One more difficulty, as a consequence of the most updated LHC data, needs to be attended to, which is not considered in Ref. [26]. With just \(5 + \overline{5}\) messengers, \(B_{\mu}\) vanishes at the messenger scale. Then \(\tan \beta\) is predicted to be rather large (\(\sim 50\)) leading to rather small masses of the heavy neutral Higgs bosons (CP-even \(H\) and CP-odd \(A\)) disfavored by the latest LHC data [29]. To solve this last problem we introduce a soft \(B_{\mu}\) parameter (which couples the two Higgs doublets \(H_u\) and \(H_d\) in the scalar potential) of size \(\sim 10^5\) GeV\(^2\) at the messenger scale. We demonstrate that the dynamical origin of the new soft terms, \(\delta m_H^2\) and \(B_{\mu}\), can be traced to a simple extension of the minimal GMSB superpotential.

**Our model:** In our setup, we must keep provision for GUT breaking effects to create sizable mass splittings between colored and uncolored SUSY particles, without which it is impossible to simultaneously satisfy \(a_\mu\) and \(m_h \simeq 125\) GeV. Now we write the superpotential with \(5 + \overline{5}\) messenger multiplets as

\[
W = (M_L + k_L Z)\Psi_L \Psi_L + (M_L + k_D Z)\Psi_D \Psi_D,
\]

where \(\Psi_L\) and \(\Psi_D\) are the \(SU(2)\) doublet and \(SU(3)\) triplet messengers, respectively, and \(Z\) is a SUSY breaking superfield. It is assumed \(\langle Z \rangle \ll M_{L,D}\). The masses of the colored (uncolored) superpartners are essentially determined by \(\Lambda_D = k_D F_Z/M_D (\Lambda_L = k_L F_Z/M_L)\) as

\[
M_{\tilde{g}} \simeq \frac{g_1^2}{16\pi^2} \left( \frac{3}{5} \Lambda_L + \frac{2}{5} \Lambda_D \right), \quad M_{\tilde{\omega}} \simeq \frac{g_2^2}{16\pi^2} \Lambda_L, \quad M_{\tilde{\chi}} \simeq \frac{g_3^2}{16\pi^2} \Lambda_D,
\]

\[
\tilde{m}^2 \simeq \frac{2}{(16\pi^2)^2} \left[ C_2(r_3) g_3^4 \Lambda_D^2 + C_2(r_2) g_2^4 \Lambda_L^2 + \frac{3}{5} Q_Y^2 g_1^4 \Lambda_Y^2 \right],
\]

where \(M_{\tilde{g}}, M_{\tilde{\omega}}\) and \(M_{\tilde{\chi}}\) are the bino, wino and gluoino masses, respectively; \(\tilde{m}^2\) represents soft SUSY breaking mass-square of a squark, slepton or Higgs doublet; \(g_1, g_2\) and \(g_3\) are the gauge coupling constants of \(U(1)_Y, SU(2)_L\) and \(SU(3)_C; C_2(r_a)\) is the quadratic Casimir invariant of the representation \(r_a\); \(Q_Y\) stands for hypercharge; \(\Lambda_Y^2 = (3/5)\Lambda_D^2 + (2/5)\Lambda_L^2\). The equality \(\Lambda_L = \Lambda_D\) signifies GUT preserving condition, but it is only by taking \(\Lambda_D \gg \Lambda_L\) one can generate much larger masses for squarks and gluino than those for sleptons and wino [30]. Sleptons, which receive mass from \(\Lambda_L\) and \(\Lambda_D\), are naturally heavier than wino, which receives mass from \(\Lambda_L\) only. Satisfaction of \(m_h \simeq 125\) GeV requires the stop (squark) mass to be \(\sim 10\) TeV, and as a corollary, the electroweak symmetry breaking conditions dictate that the higgsino mass parameter \(\mu\) should also be large as \(\sim 3-4\) TeV. Consequently, the chargino induced loop contribution to \(a_\mu\) is suppressed. In such a situation, especially light sleptons, bino and wino are necessary to satisfy \(a_\mu\). However, as shown in Ref. [26], the required spectrum is excluded by the wino mass limit (\(\gtrsim 460\) GeV) at the LHC [25] and the vacuum stability constraint on the Higgs-stau potential [11].

As a remedy to the above problem, we must arrange for a small \(\mu\), which would enhance the chargino contribution to \(a_\mu\). This is achieved by the introduction of \(\delta m_H^2\) at the messenger scale. But this is not enough for escaping all the LHC constraints. If the soft parameter \(B_{\mu} = 0\) at the messenger scale, \(\tan \beta\) is predicted to be too large (\(\gtrsim 50\)). This in turn leads to rather small masses of the heavy neutral Higgs boson (\(\lesssim 1.5\) TeV) [26], which is excluded at the LHC from searches in the \(H/A \rightarrow \tau \tau\) channel [29]. Therefore, we introduce a non-vanishing \(B_{\mu}\) at the messenger scale, which enables us to choose smaller \(\tan \beta\) to evade the above constraint. Incidentally, the bino-higgsino-smuon loop contribution to \(a_\mu\) is numerically not significant in our scenario, since the bino is rather heavy due to the contribution from \(\Lambda_D(\gg \Lambda_L)\) – see Eq. (2).
Figure 1: The contours of $\Delta a_\mu$, $m_A$ (blue dashed) and $\mu$ (black solid), where $m_A$ and $\mu$ are shown in units of GeV. In the orange (yellow) regions, the muon $g - 2$ is explained at 1$\sigma$ (2$\sigma$) level. In the gray regions, $\mu < 110$ GeV or $m_A < 1500$ GeV. On the green dotted lines, $B_\mu = 0$ at the messenger scale $M_L = M_D$. In the left (right) panel, we take $\Lambda_D = 700$ TeV, $M_L = M_D = 1000$ TeV and $\delta m_H^2 = 8.96 \times 10^6$ GeV$^2$ ($\Lambda_D = 1000$ TeV, $M_L = M_D = 1200$ TeV and $\delta m_H^2 = 1.64 \times 10^7$ GeV$^2$). Here, $\alpha_s(m_Z) = 0.1185$ and $m_{t\text{(pole)}} = 173.34$ GeV.

**Parameters:** We deal with five parameters: ($\delta m_H^2, \tan\beta, \Lambda_L, \Lambda_D, M_L = M_D$). Here, $\delta m_H^2 = \delta m_{H_u}^2 = \delta m_{H_d}^2$, and we choose $\tan\beta$ to be a free parameter in lieu of a non-vanishing $B_\mu$. A toy scenario, as an existence proof for $B_\mu$, is presented later.

In Fig. 1 we show the contours of $\Delta a_\mu$, $m_A$ and $\mu$, on the $M_D$-tan $\beta$ plane, where $M_D$ ($\mu$) is the wino mass (higgsino mass) at the stop mass scale, $m_A$ is the CP-odd Higgs boson mass, and $\Delta a_\mu$ is the SUSY contribution to the muon $g - 2$. We have calculated $\Delta a_\mu$ and the mass of the SM-like Higgs boson using FeynHiggs 2.14.1. The SUSY mass spectra are evaluated using SOFTSUSY 3.7.4 with appropriate modifications. In the orange (yellow) regions, $a_\mu$ is explained at 1$\sigma$ (2$\sigma$) level. The higgsino mass parameter $\mu$ lies within the range of 200-400 GeV. In the viable regions for $a_\mu$ explanation, $B_\mu$ is $\mathcal{O}(10^5)$ GeV$^2$, $\Lambda_L/\Lambda_D = \mathcal{O}(0.1)$, and $m_h \approx 126$ GeV (127 GeV) in the left (right) panel. The required GUT breaking effect ($\Lambda_L \neq \Lambda_D$) is, notably, rather mild.

In Table 1 the mass spectra in sample points are shown. All the points are consistent with the muon $g - 2$ result at 1$\sigma$ level. The heavy Higgs boson masses calculated by FeynHiggs are sufficiently large on all the points. The mass spectra of the Heavy neutral Higgs bosons are large enough to avoid the LHC constraint ($m_A \gtrsim 1.5$ TeV for $\tan\beta \gtrsim 40$). The wino-like chargino and neutralino, $\chi^{\pm}_2$ and $\chi^0_3$, decay into $\chi^1_1$, $\chi^0_2$ and $\chi^\pm_1$ via emitting W/Z boson, and even when they are as light as $\sim 200$ GeV the LHC constraints are satisfied [19]. Note that we have focused on the cases where the messenger scale is as low as $\sim 10^6$ GeV. This is because for a large messenger scale, e.g. $\sim 10^{11}$ GeV, the stau becomes lighter eventually turning into NLSP due to radiative corrections in the region consistent with the muon $g - 2$. This light stau is excluded by the LHC searches [37,38].

It is also important to notice that we have only considered the cases where the NLSP is stable inside the LHC detector. This follows from the observation that the gravitino weighing less than $\sim 10$ keV is strongly constrained by the Lyman-α forest data [39]. For a heavier gravitino the NLSP decay length turns out to be longer than the detector size. To see this, we first estimate the gravitino mass as

$$m_{3/2} \simeq \frac{F_Z}{\sqrt{3}M_p} \approx 17 \text{ keV} \left( \frac{\Lambda_D}{700 \text{ TeV}} \right) \left( \frac{M_D}{1000 \text{ TeV}} \right) \left( \frac{k_D}{10^{-5}} \right)^{-1},$$

(3)

For a moderately large messenger scale, e.g. $10^9$ GeV, we still have a region consistent with the muon $g - 2$. However, the lightness of the stau renders this region to be extremely narrow.
Table 1: Mass spectra in sample points. We take $M_L = M_D$. Although the charginos and neutralinos are quite light, they satisfy the LHC constraints.\cite{19}

| Parameters                  | Point I | Point II | Point III |
|-----------------------------|---------|----------|-----------|
| $M_D$ (TeV)                 | 1000    | 1200     | 1200      |
| $\Lambda_D$ (TeV)          | 700     | 1000     | 1000      |
| $\Lambda_L/\Lambda_D$      | 0.18    | 0.14     | 0.09      |
| $\delta m^2_H$ (10^7 GeV^2) | 0.89    | 1.64     | 1.66      |
| $\tan \beta$               | 40      | 40       | 25        |

| Particles | Mass (GeV) | Mass (GeV) | Mass (GeV) |
|-----------|------------|------------|------------|
| $\tilde{g}$ | 5150     | 7510      | 7510      |
| $\tilde{q}$ | 6500     | 9080      | 9080      |
| $\tilde{l}$ | 6020     | 8430      | 8460      |
| $\tilde{\chi}_1^\pm$ | 266      | 243       | 178       |
| $\tilde{\chi}_2^\pm$ | 385      | 401       | 294       |
| $\tilde{\chi}_1^0$ | 261      | 238       | 174       |
| $\tilde{\chi}_2^0$ | 310      | 268       | 233       |
| $\tilde{\chi}_3^0$ | 380      | 399       | 290       |
| $\tilde{\chi}_4^0$ | 534      | 765       | 723       |
| $\tilde{e}_{L,R}$ | 556,796  | 689,1120  | 575,1110  |
| $\tilde{\tau}_{1,2}$ | 449,650  | 535,935   | 501,1030  |
| $H/A$ | 2180     | 2920      | 3690      |
| $h_{\text{SM-like}}$ | 125.9    | 127.5     | 127.8     |
| $\mu$ (GeV) | 296      | 254       | 218       |
| $B_{\mu}(M_D)$ (10^5 GeV^2) | 1.07     | 2.03      | 5.55      |
| $\Delta a_{\mu}(10^{-10})$ | 29.9     | 23.1      | 22.2      |

where $M_P \approx 2.4 \times 10^{18}$ GeV is the reduced Planck mass.\footnote{With the gravitino mass of $\mathcal{O}(10)$ keV, the decay length of the higgsino-like NLSP is given by

$$c\tau \approx 140 \text{ m} \times \left( \frac{\mu}{250 \text{ GeV}} \right)^{-5} \left( \frac{m_{3/2}}{20 \text{ keV}} \right)^2,$$

which is too large to be constrained at the LHC.\cite{41,42}. Therefore, the higgsino-like NLSP can be regarded effectively as a stable particle in the collider time scale. This argument also applies to the wino-like NLSP case as long as the gravitino mass is heavier than $\mathcal{O}(10)$ keV.}

An ultraviolet completion: Here we show an example model for generating the new soft parameters, namely, $\delta m^2_H$ and $B_{\mu}$, in the Higgs sector. The relevant superpotential is

$$W = \kappa Z X^2 + M_X X \bar{X} + \lambda X H_u H_d.$$

It generates, as in \cite{30},

$$\delta m^2_H \equiv \delta m^2_{H_u} = \delta m^2_{H_d},$$

where

$$\delta m^2_H \simeq \frac{|\lambda|^2 |\kappa|^2 |F_Z|^2}{32\pi^2 M_X^2},$$

which is required to be $\mathcal{O}(10^7)$ GeV^2. Note that $W$ has a $R$ symmetry which prevents the generation of the soft $B_{\mu}$ term and the trilinear $A$ parameter, as long as $\langle Z \rangle = 0$. However, it may be possible that the $\langle Z \rangle \neq 0$ due to unknown hidden sector dynamics, and the $R$ symmetry is spontaneously broken. Otherwise, one can introduce a term $M_X X^2/2$ in

\footnote{Although the gravitino lighter than 4.7 eV suffers no cosmological constraints,\cite{40} such a light gravitino requires $k_D$ to be much larger than $4\pi$ to compensate for the smallness of $F_Z$ for reproducing the allowed superpartner spectra.}
where $m_X$ may be considered to be small as this term is an explicit $R$-violating one. The induced $B_\mu$ and trilinear $A$-terms are given by

$$B_\mu/\mu, A_{u,d} \simeq \frac{|\lambda|^2 \kappa F_Z m_X}{32\pi^2 M_X m_X} \left[ 1 + O \left( \frac{m_X^2}{M_X^2} \right) \right].$$

(7)

On the other hand, if $\langle Z \rangle = 0$, one may add singlet superfields $S$ and $S^*$ to write a new superpotential

$$W' = \lambda_u \Psi_L H_u S + \lambda_d \Psi_L \bar{H}_d S + M_S S S^*.$$  

(8)

The superpotential $W'$ generates the $B_\mu$ term as

$$B_\mu \simeq \frac{\lambda_u \lambda_d}{16\pi^2} \Lambda_L R(x),$$

(9)

where $x = M_S/M_L$ and $R(x)$ is a loop function with $R(1) = 1/3$. Note that $W'$ also generates $m_{H_u}^2$ and $m_{H_d}^2$. But their magnitudes are too small, compared to what we get from Eq. (6) induced by the superpotential $W$, when we satisfy the phenomenological requirement $B_\mu = O(10^3)$ GeV$^2$ to be able to take $\tan \beta \sim 40$. Furthermore, the $W'$ induced $\mu$ and $A$-terms are negligible.

**Conclusion:** As the explanation of $a_\mu$ requires light sleptons and weak gauginos, gauge mediation provides an attractive framework by keeping FCNC under control, creating a slepton / weak gaugino mass hierarchy that is less constrained at the LHC, and separating the weak gaugino sector from the dark matter (gravitino) search. We have shown that a simple extension of minimal gauge mediation by introducing soft SUSY breaking parameters for the Higgs sector can achieve the non-trivial goal of explaining the $a_\mu$ discrepancy. We also demonstrated that the newly introduced parameters can be justified in an ultraviolet complete theory. We claim that our scenario stands out at least as the only GMSB model, to the best of our knowledge, that can explain $a_\mu$ and simultaneously satisfy all the other constraints. A low $\mu$ (few hundred GeV) that arises in our scenario also provides an impetus for a dedicated higgsino search at a future linear collider.

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