PHYSICS LETTERS B

A practical GMSB model for explaining the muon (g − 2) with gauge coupling unification

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A R T I C L E   I N F O

A B S T R A C T

We present a gauge mediated supersymmetry breaking model having weak SU(2) triplet, color SU(3) octet and SU(5) 5-plet messengers, that can simultaneously explain the muon $(g − 2)$ data within 1σ and the observed Higgs boson mass of 125 GeV. Gauge coupling unification is nontrivially maintained. Most of the parameter space satisfying both is accessible to the 14 TeV LHC. The lighter of the two staus weighs around (100–200) GeV, which can be a potential target of the ILC.

1. Introduction

Following the latest combination of mass and signal strengths of the Higgs boson by the ATLAS and CMS Collaborations of the Large Hadron Collider (LHC) [1,2], the particle spectrum of the standard model (SM) is complete and it reigns supreme as an effective theory for weak scale physics. However, in spite of its astonishing success, the anomalous magnetic moment of the muon, namely $a_\mu \equiv (g − 2)/2$, remains an enigma. When compared to the SM estimate [3], the latest experimental result [4] stands as

$$\Delta a_\mu \equiv (a_\mu)_{\text{exp}} − (a_\mu)_{\text{SM}} = (26.1 \pm 8.1) \times 10^{-10}. \quad (1)$$

The deviation is above 3σ level (see also [5]), and it can be resolved if we invoke new physics at a scale $m_{\text{NP}} = \mathcal{O}(100)$ GeV, which follows from $(\Delta a_\mu)_{\text{NP}} \sim (g^2/16\pi^2)(m_\mu^2/m_{\text{NP}}^2) = 20.7 \times 10^{-10}(120 \text{ GeV}/m_{\text{NP}})^2(g/0.65)^2$, where g is a coupling relevant to the new physics. In the minimal supersymmetric standard model (MSSM), a resolution of this deviation requires light superparticles, namely the smuons and chargino/neutralinos of $\mathcal{O}(100)$ GeV, which propagate in the loop. With $\tan\beta \equiv \langle H_u \rangle/\langle H_d \rangle \sim 10$, the size of Δa_μ can be as large as $\mathcal{O}(10^{-9})$ [6]. On the other hand, the observed Higgs boson mass, $m_h \sim 125$ GeV, demands rather large radiative corrections, which are enhanced by heavy stops weighing $\mathcal{O}(10)$ TeV or substantial left–right mixing [7]. Gauge mediated supersymmetry breaking (GMSB) models [8] start with an advantage in this context that at the supersymmetry breaking scale itself the squarks/gluino are heavier than sleptons/gauginos, i.e. the splitting is in the right direction. However, in minimal conventional GMSB,

which employs a **5** and a **5̄** of SU(5)$_{\text{GUT}}$ as messengers, the heavy stop pulls up the slepton and weak gaugino soft masses to several hundred GeV to a TeV which are too high to explain the muon $(g − 2)$.

In a previous paper [9] (see also [10]), we proposed a GMSB model that naturally yielded light uncolored and heavy colored superpartners. To accomplish this, we employed weak SU(2) triplet and color SU(3) octet messenger multiplets instead of using the conventional SU(5) 5-plets. Even with these incomplete SU(5) multiplets, gauge couplings still unify, though at the string scale $M_{\text{str}} \sim 10^{17}$ GeV which is somewhat higher than the grand unification theory (GUT) scale $M_G \sim 10^{16}$ GeV. In addition to satisfying the 125 GeV Higgs boson mass, we could explain the muon $(g − 2)$ at 2σ level, with the agreement getting better upon the addition of SU(5) 5-plet messengers. In the most favorable region the stau would be the next to lightest supersymmetric particle (NLSP) being lighter than the bino. For satisfying the cosmological and accelerators constraints, mild R-parity violation (RPV) had to be invoked which facilitated prompt stau decay.

Recently, radiative corrections to the Higgs mass have been computed at 3-loop level [11] (see also [12]), and it has been observed that $m_h \sim 125$ GeV is consistent with stop mass as light as 3–5 TeV even for minimal left–right scalar mixing [13]. We show in the present Letter that this reduction of the stop mass allows us to present an improved scenario which is more comfortable with experimental data. Through the discussion that follows, we show that a GMSB model with weak SU(2) triplet, color SU(3) octet and SU(5) 5-plet messengers not only satisfies $m_h \sim 125$ GeV, but also can explain the muon $(g − 2)$ at 1σ level. Gauge coupling unification is indeed nontrivially maintained. No less importantly, we can satisfy the (cosmological) gravitino problem and the LHC

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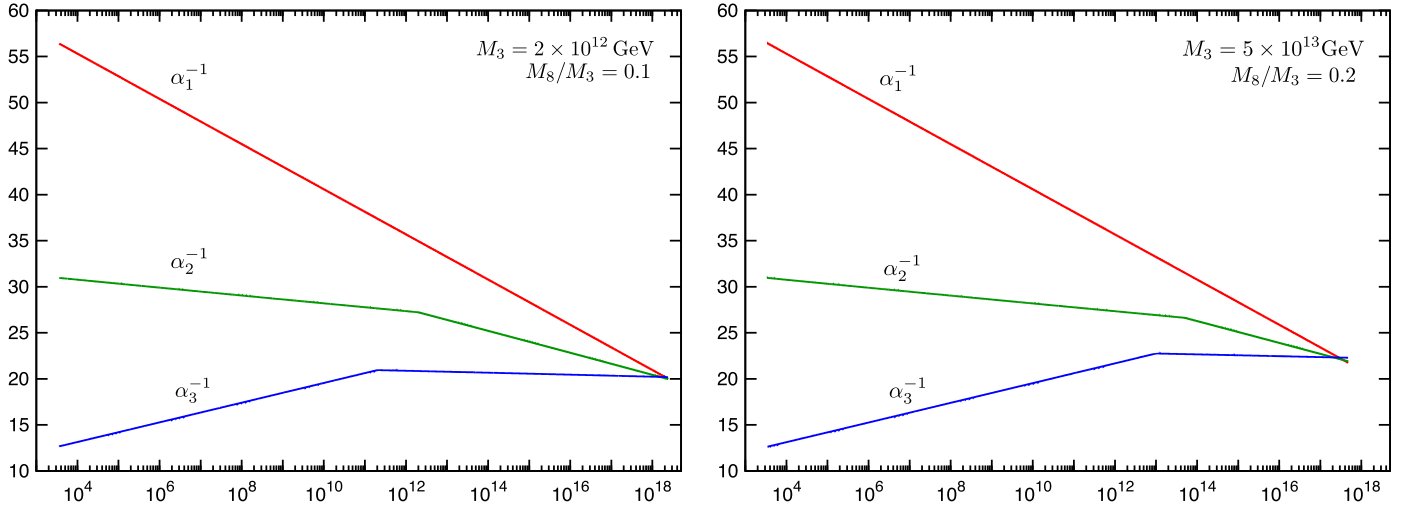
Fig. 1. Two-loop evolution of the gauge couplings with Σ_3 and Σ_8 as a function of the renormalization scale (GeV). We take $\alpha_s(M_Z) = 0.1184$ and the supersymmetry breaking scale $m_{SUSY} \sim m_{stop} \simeq 3.6$ TeV.

constraints without any need of introducing RPV operators (for an alternative approach, where sparticles of 1st/2nd generation are light and of the 3rd generation are heavy, see [14]).

2. A practical GMSB model

We employ three types of messenger fields: Φ_5 ($\Phi_{\bar{5}}$) transforming as **5** ($\bar{\mathbf{5}}$) of SU(5)$_{\mathrm{GUT}}$, weak SU(2) triplet $\Sigma_3(\mathbf{1}, \mathbf{3}, \mathbf{Y} = \mathbf{0})$, and color SU(3) octet $\Sigma_8(\mathbf{8}, \mathbf{1}, \mathbf{Y} = \mathbf{0})$. The superpotential can be written as

$$W = \left(M_5 + \lambda_5 F \theta^2\right)\Phi_5 \Phi_{\bar{5}} + \left(M_8 + \lambda_8 F \theta^2\right)\mathrm{Tr}\left(\Sigma_8^2\right) + \left(M_3 + \lambda_3 F \theta^2\right)\mathrm{Tr}\left(\Sigma_3^2\right), \tag{2}$$

where F characterizes the supersymmetry breaking scale. The leading contributions to the gaugino and sfermion masses arising from the messenger loops are given by

$$m_{\tilde{B}} \simeq \frac{\alpha_1}{4\pi}\Lambda_5, \qquad m_{\tilde{W}} \simeq \frac{\alpha_2}{4\pi}(2\Lambda_3 + \Lambda_5),$$

$$m_{\tilde{g}} \simeq \frac{\alpha_3}{4\pi}(3\Lambda_8 + \Lambda_5);$$

$$m_{\tilde{Q}}^2 \simeq \frac{1}{8\pi^2}\left[\frac{4}{3}\alpha_3^2\left(3\Lambda_8^2 + \Lambda_5^2\right) + \frac{3}{4}\alpha_2^2\left(2\Lambda_3^2 + \Lambda_5^2\right) + \frac{1}{60}\alpha_1^2\Lambda_5^2\right],$$

$$m_{\tilde{U}}^2 \simeq \frac{1}{8\pi^2}\left[\frac{4}{3}\alpha_3^2\left(3\Lambda_8^2 + \Lambda_5^2\right) + \frac{4}{15}\alpha_1^2\Lambda_5^2\right],$$

$$m_{\tilde{D}}^2 \simeq \frac{1}{8\pi^2}\left[\frac{4}{3}\alpha_3^2\left(3\Lambda_8^2 + \Lambda_5^2\right) + \frac{1}{15}\alpha_1^2\Lambda_5^2\right],$$

$$m_{\tilde{L}}^2 = m_{H_u}^2 = m_{H_d}^2 \simeq \frac{1}{8\pi^2}\left[\frac{3}{4}\alpha_2^2\left(2\Lambda_3^2 + \Lambda_5^2\right) + \frac{3}{20}\alpha_1^2\Lambda_5^2\right],$$

$$m_{\tilde{E}}^2 \simeq \frac{1}{8\pi^2}\left[\frac{3}{5}\alpha_1^2\Lambda_5^2\right]; \tag{3}$$

where

$$\alpha_i \equiv \frac{g_i^2}{4\pi}, \qquad \Lambda_8 \equiv \frac{\lambda_8 F}{M_8}, \qquad \Lambda_3 \equiv \frac{\lambda_3 F}{M_3}, \qquad \Lambda_5 \equiv \frac{\lambda_5 F}{M_5}. \tag{4}$$

Gauge coupling unification Even with incomplete GUT multiplets, i.e. with Σ_3 and Σ_8 only as messengers, gauge couplings do unify with $M_{\mathrm{mess}} \equiv M_8 \sim M_3$ [15]. Solving the coupling evolution equations explicitly, as done in our previous paper [9], it follows that lower the messenger scale M_{mess} below the GUT scale M_G,
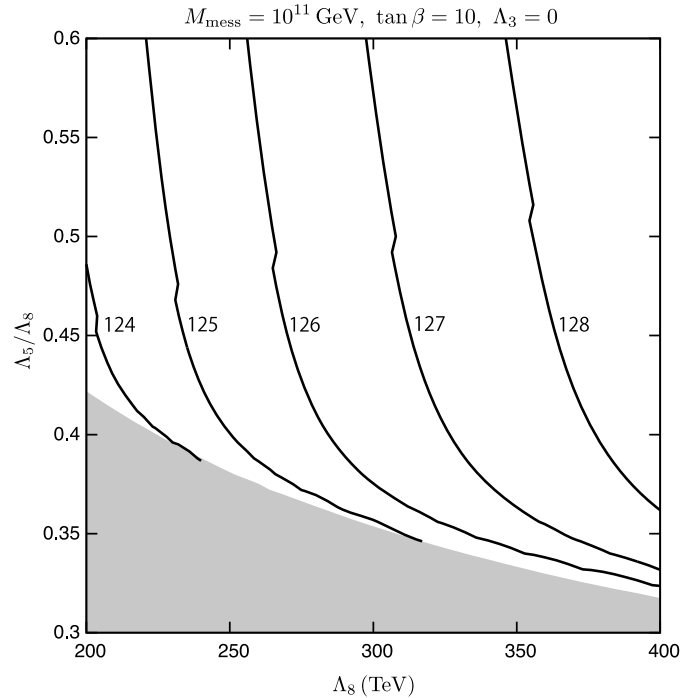
Fig. 2. Contours of the Higgs boson mass including $\mathcal{O}(y_t \alpha_s^2)$ corrections. Here, $m_t = 173.2$ GeV and $\alpha_s(M_Z) = 0.1184$. In the gray region, the stau mass is below the LEP2 limit of 90 GeV.

higher the actual unification scale M_{str} above M_G. Pushing M_{str} closer to the Planck scale $M_{\mathrm{Pl}} \simeq 2.4 \times 10^{18}$ GeV sets a lower limit $M_8 \gtrsim 10^{11}$ GeV. The presence of the 5-plets does not change the evolution slopes, so the above discussion holds in the present scenario. In Fig. 1, we exhibit the evolutions of the gauge couplings with M_8 and M_3 around $(10^{11}$–$10^{13})$ GeV scale. The calculation has been performed using the renormalization group equations (RGE) at 2-loop level [16]. The gauge couplings are unified at $M_{\mathrm{str}} \sim 10^{18}$ GeV. This allows us to take M_8 closer to its lower limit. Since F/M_8 sets the squark mass, and F/M_{Pl} determines the gravitino mass, a lower value of M_8 implies a lighter gravitino, which helps us solve the cosmological problem (see later).

The Higgs boson mass The observed $m_h \sim 125$ GeV sets the scale of the stop mass, which in turn fixes Λ_8. In Fig. 2, we show the
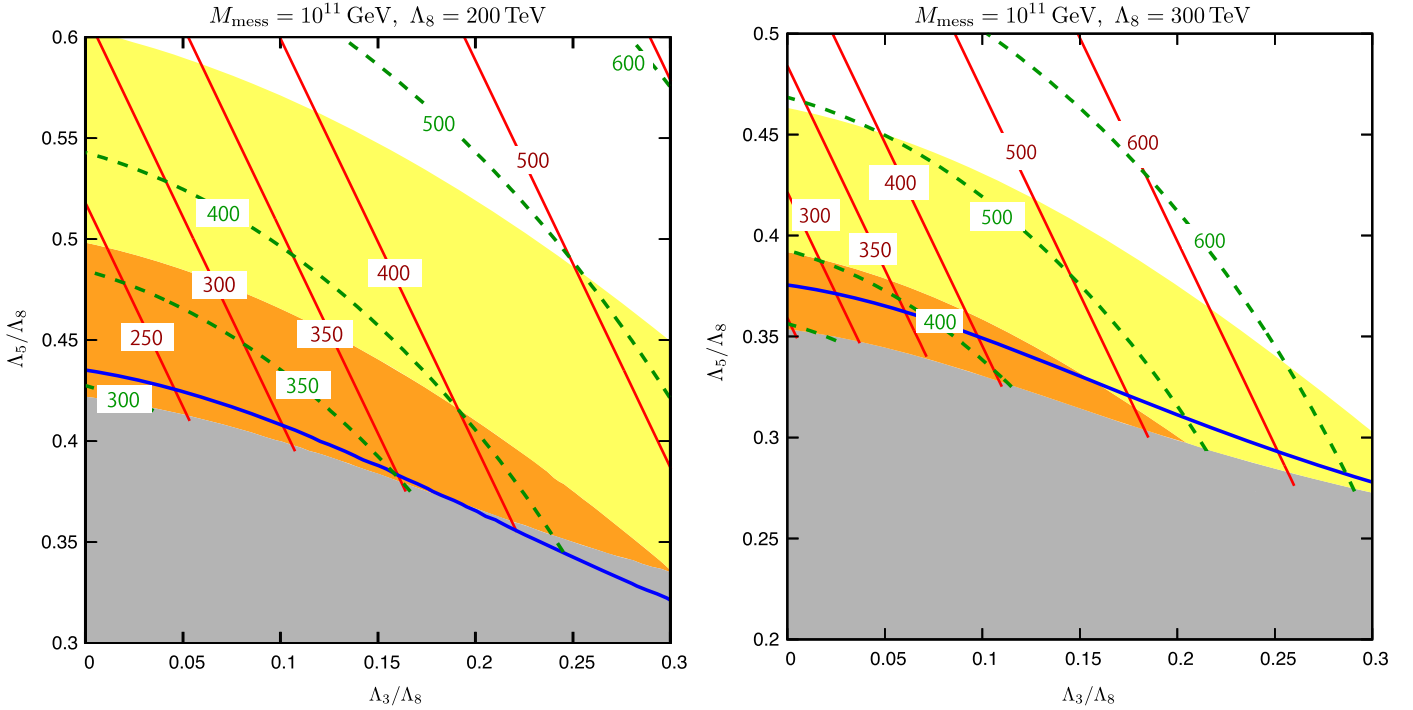
Fig. 3. In the orange (yellow) region, the muon $g - 2$ is explained at $1(2)\sigma$ level. The neutralino (stau) is NLSP above (below) the blue solid lines. In the gray region, the stau mass is smaller than 90 GeV. The contours of the chargino mass (red solid lines) and the soft mass of the left-handed sleptons (green dashed lines) are shown in units of GeV. (For interpretation of the references to color, the reader is referred to the web version of this article.)

contours of the Higgs boson mass in the $\Lambda_8 - (\Lambda_5/\Lambda_8)$ plane. The Higgs boson mass has been evaluated using H3m-v1.2 package [11], which includes $\mathcal{O}(y_t\alpha_s^2)$ corrections, where y_t is the top quark Yukawa coupling. We take note of the fact that $m_h \sim 125$ GeV can be explained with $\Lambda_8 \simeq$ 200–300 TeV. The corresponding stop masses are in the (3.6–5.1) TeV range.

Muon $g - 2$ A rough estimate of the Higgsino mixing parameter is

$$\mu^2 \sim \left(-m_{H_u}^2\right) \sim \frac{3}{4\pi^2} y_t^2 \left(m_{stop}^2\right) \frac{M_{mess}}{m_{stop}}, \tag{5}$$

where $m_{stop} \equiv (m_{\tilde{Q}_3} m_{\tilde{U}_3})^{1/2}$ is the (geometric) average stop mass scale. For illustration, we have neglected the soft mass of H_u generated at the messenger scale, and considered only the radiative mass generation. Putting $m_{stop} = 3$ TeV and $M_{mess} = 10^{11}$ GeV, one obtains $\mu \sim 2.7$ TeV. The value of μ is still too large to make the chargino induced contributions to $(g-2)$ numerically relevant. This contribution is dominated by the bino-slepton loop, which is given by

$$(\Delta a_\mu)_{SUSY} \simeq \frac{3}{5} \frac{g_1^2}{8\pi^2} \frac{m_\mu^2 \mu \tan\beta}{M_1^3} F_b\left(\frac{m_{\tilde{L}}^2}{M_1^2}, \frac{m_{\tilde{E}}^2}{M_1^2}\right), \tag{6}$$

where m_μ is the muon mass. The contribution is proportional to the left–right smuon mixing term which contains the $(\mu \tan\beta)$ factor. The loop function F_b is defined and explicitly displayed in Ref. [17] (for a rough guide, $F_b(1, 1) = 1/6$). In order to explain the muon $g - 2$, the bino has to be necessarily light as $\mathcal{O}(100)$ GeV, and the smuon not much heavier.

In Fig. 3 we display to what extent we can explain the muon $(g - 2)$. We take $M_{mess} = M_8 = M_3$ for simplicity. The supersymmetric mass spectrum as well as the RGE running of various parameters has been performed using SuSpect [18]. The supersymmetric contributions to the muon $g-2$ have been evaluated by

FeynHiggs2.9.5 [19]. To include the threshold corrections to slepton masses from the Higgsino and heavy Higgs boson [20,21], we have modified the SuSpect package appropriately. The contours of different chargino masses have been shown by red solid lines. In the orange (yellow) region, the muon $g - 2$ is explained at 1σ (2σ) level, at the same time keeping consistency with $m_h \sim 125$ GeV. In the region above the blue solid line, the neutralino (dominantly the bino, since μ is large) is the NLSP, while in the region below the line, the stau is the NLSP. When the stau is the NLSP, even though it eventually decays to gravitino, it is stable inside the detector. In this case, the stau mass of less than 340 GeV is excluded by the LHC data [22]. But we need the stau to weigh in the (100–250) GeV ballpark so that the smuon acquires an appropriate mass to explain the muon $g - 2$ at $(1-2)\sigma$ level. Hence, viable regions are only above the blue solid line, where the lightest neutralino (dominantly, the bino) is the NLSP. Because of the Λ_5 induced contributions in Eq. (3), the bino mass is generated in a way which is completely uncorrelated to the gravitino mass generation. The gravitino mass is estimated as

$$m_{3/2} \simeq 0.01 \text{ GeV} \left(\frac{\Lambda_8}{200 \text{ TeV}}\right)\left(\frac{(\Lambda_3/\Lambda_8)}{0.2}\right)$$
$$\times \left(\frac{M_8}{10^{11} \text{ GeV}}\right)\left(\frac{(M_3/M_8)}{10}\right). \tag{7}$$

With this gravitino mass of $\mathcal{O}(10^{-2})$ GeV, the life-time of the neutralino is (1–10) second, giving a constraint on the primordial neutralino abundance. However, this abundance is very small, as a result of which the successful prediction of the big bang nucleosynthesis (BBN) is maintained [23], thus avoiding the gravitino problem.

In Table 1, we have presented two sets of reference points, displaying the mass spectra and the prediction for $(g - 2)$, that pass all constraints. In this context, two types of constraints deserve special mention:

Table 1
Mass spectra and $(\Delta a_\mu)_{SUSY}$ for two reference points.

Λ_3/Λ_8	0.17	Λ_3/Λ_8	0.11
Λ_5/Λ_8	0.41	Λ_5/Λ_8	0.35
Λ_8	200 TeV	Λ_8	300 TeV
M_{mess}	10^{11} GeV	M_{mess}	10^{11} GeV
$\tan\beta$	10	$\tan\beta$	10
μ	2.4 TeV	μ	3.5 TeV
m_{stop}	3.6 TeV	m_{stop}	5.1 TeV
δa_μ	20.3×10^{-10}	δa_μ	18.6×10^{-10}
m_{gluino}	4.4 TeV	m_{gluino}	6.3 TeV
m_{squark}	4.1 TeV	m_{squark}	5.8 TeV
$m_{\tilde{e}_L}(m_{\tilde{\mu}_L})$	379 GeV	$m_{\tilde{e}_L}(m_{\tilde{\mu}_L})$	425 GeV
$m_{\tilde{e}_R}(m_{\tilde{\mu}_R})$	181 GeV	$m_{\tilde{e}_R}(m_{\tilde{\mu}_R})$	218 GeV
$m_{\tilde{\tau}_1}$	123 GeV	$m_{\tilde{\tau}_1}$	133 GeV
$m_{\chi_1^0}$	100 GeV	$m_{\chi_1^0}$	128 GeV
$m_{\chi_1^\pm}/m_{\chi_2^0}$	375 GeV	$m_{\chi_1^\pm}/m_{\chi_2^0}$	411 GeV

(i) When the left–right stau mixing term proportional to $(m_\tau \mu \tan\beta)$ is large, the charge breaking global minimum can appear. The life-time of the electroweak vacuum restricts the size of the $\mu \tan\beta$, which depends of course on the stau soft mass parameters [24,25]. However, this constraint is not very decisive in our case. In fact, the LEP bound on the stau mass is stronger in the relevant region of the parameter space [26].

(ii) LHC constraints on electroweak gauginos/sleptons also restrict the relevant parameter space. Searches for three leptons plus missing energy put a constraint on the wino mass [27]. In the region consistent with the muon $g-2$ at 1σ level, the left handed sleptons are some what heavier than the wino. In this case, the final state leptons are the taus rather electrons/muons, giving the constraint $m_{\chi_1^\pm} \simeq m_{\chi_2^0} \gtrsim (300\text{–}350)$ GeV [27,28]. Note that in some regions of the parameter space, the wino and the left-handed sleptons are nearly degenerate in mass. These regions are difficult to be constrained. Besides, separate (but, not so tight) constraints exist on the left-handed sleptons, namely, $m_{\tilde{\ell}_L} \gtrsim 300$ GeV [29]. The restrictions on the right-handed sleptons are, however, much less stringent.

3. Conclusions

Reconciling the observed Higgs boson mass and the measurement of the muon $(g-2)$ poses a big challenge to supersymmetric model building. In this Letter we have presented a realistic GMSB model that can address both these issues satisfying all other constraints. From the model-building perspective, the situation has considerably improved since we constructed the scenario of Ref. [9]. We summarize below the salient features behind this improvement. The recent 3-loop radiative corrections to the Higgs boson mass imply that the stop squark is perhaps not as heavy as order $\mathcal{O}(10)$ TeV. A stop mass of mere (3–5) TeV can explain the observed 125 GeV mass of the Higgs boson even for small stop mixing. A lighter stop means a relatively smaller value of μ (but still $\sim$3 TeV). This has two implications. First, the lightest neutralino weighing $\sim$100 GeV is bino dominated because μ is still quite large ($\sim$3 TeV). Second, the left–right mixing in the slepton sector, which is proportional to $\mu \tan\beta$, is relatively smaller because the value of μ has come down from 6 TeV to 3 TeV thanks to the smaller stop masses. Since a smaller left–right mixing implies a smaller splitting between the two slepton mass eigenvalues of the same flavor, for a wide region of the interesting parameter space the lightest neutralino can remain lighter than stau. Note that we could have generated light uncolored and heavy colored superpartners just with Σ_3 and Σ_8, still nontrivially satisfying gauge coupling unification. The key area where we really improved with respect to Ref. [9], thanks to the presently known three-loop corrections to the Higgs boson mass and our assumption of a somewhat *late* unification, is that we can now take bino light enough to explain the muon $(g-2)$ within 1σ, satisfying at the same time the BBN constraint and LHC data *without* introducing RPV operators. The interesting region of parameter space can be probed at the 14 TeV LHC, and precision measurements of the lighter stau can be performed at the future International Linear Collider (ILC).

Acknowledgements

References

[1] ATLAS Collaboration, ATLAS-CONF-2013-014.
[2] S. Chatrchyan, et al., CMS Collaboration, J. High Energy Phys. 1306 (2013) 081, arXiv:1303.4571 [hep-ex].
[3] K. Hagiwara, R. Liao, A.D. Martin, D. Nomura, T. Teubner, J. Phys. G 38 (2011) 085003, arXiv:1105.3149 [hep-ph].
[4] G.W. Bennett, et al., Muon G-2 Collaboration, Phys. Rev. D 73 (2006) 072003, arXiv:hep-ex/0602035.
[5] M. Davier, A. Hoecker, B. Malaescu, Z. Zhang, Eur. Phys. J. C 71 (2011) 1515, arXiv:1010.4180 [hep-ph];
M. Davier, A. Hoecker, B. Malaescu, Z. Zhang, Eur. Phys. J. C 72 (2012) 1874 (Erratum).
[6] J.L. Lopez, D.V. Nanopoulos, X. Wang, Phys. Rev. D 49 (1994) 366, arXiv:hep-ph/9308336;
U. Chattopadhyay, P. Nath, Phys. Rev. D 53 (1996) 1648, arXiv:hep-ph/9507386;
T. Moroi, Phys. Rev. D 53 (1996) 6565, arXiv:hep-ph/9512396;
T. Moroi, Phys. Rev. D 56 (1997) 4424 (Erratum).
[7] Y. Okada, M. Yamaguchi, T. Yanagida, Prog. Theor. Phys. 85 (1991) 1;
J.R. Ellis, G. Ridolfi, F. Zwirner, Phys. Lett. B 257 (1991) 83;
H.E. Haber, R. Hempfling, Phys. Rev. Lett. 66 (1991) 1815;
J.R. Ellis, G. Ridolfi, F. Zwirner, Phys. Lett. B 262 (1991) 477.
[8] M. Dine, A.E. Nelson, Phys. Rev. D 48 (1993) 1277, arXiv:hep-ph/9303230;
M. Dine, A.E. Nelson, Y. Shirman, Phys. Rev. D 51 (1995) 1362, arXiv:hep-ph/9408384;
M. Dine, A.E. Nelson, Y. Nir, Y. Shirman, Phys. Rev. D 53 (1996) 2658, arXiv:hep-ph/9507378.
[9] G. Bhattacharyya, B. Bhattacherjee, T.T. Yanagida, N. Yokozaki, Phys. Lett. B 725 (2013) 339, arXiv:1304.2508 [hep-ph].
[10] M. Ibe, S. Matsumoto, T.T. Yanagida, N. Yokozaki, J. High Energy Phys. 1303 (2013) 078, arXiv:1210.3122 [hep-ph].
[11] R.V. Harlander, P. Kant, L. Mihaila, M. Steinhauser, Phys. Rev. Lett. 100 (2008) 191602, arXiv:0803.0672 [hep-ph];
R.V. Harlander, P. Kant, L. Mihaila, M. Steinhauser, Phys. Rev. Lett. 101 (2008) 039901 (Erratum);
P. Kant, R.V. Harlander, L. Mihaila, M. Steinhauser, J. High Energy Phys. 1008 (2010) 104, arXiv:1005.5709 [hep-ph].
[12] S.P. Martin, Phys. Rev. D 75 (2007) 055005, arXiv:hep-ph/0701051.
[13] J.L. Feng, P. Kant, S. Profumo, D. Sanford, Phys. Rev. Lett. 111 (2013) 131802, arXiv:1306.2318 [hep-ph].
[14] M. Ibe, T.T. Yanagida, N. Yokozaki, J. High Energy Phys. 1308 (2013) 067, arXiv:1303.6995 [hep-ph].
[15] C. Bachas, C. Fabre, T. Yanagida, Phys. Lett. B 370 (1996) 49, arXiv:hep-th/9510094;
M. Bastero-Gil, B. Brahmachari, Phys. Lett. B 403 (1997) 51, arXiv:hep-ph/9610374.
[16] S.P. Martin, M.T. Vaughn, Phys. Rev. D 50 (1994) 2282, arXiv:hep-ph/9311340;
S.P. Martin, M.T. Vaughn, Phys. Rev. D 78 (2008) 039903 (Erratum).
[17] G.-C. Cho, K. Hagiwara, Y. Matsumoto, D. Nomura, J. High Energy Phys. 1111 (2011) 068, arXiv:1104.1769 [hep-ph].
[18] A. Djouadi, J.-L. Kneur, G. Moultaka, Comput. Phys. Commun. 176 (2007) 426, arXiv:hep-ph/0211331.
[19] S. Heinemeyer, W. Hollik, G. Weiglein, Comput. Phys. Commun. 124 (2000) 76, arXiv:hep-ph/9812320;
S. Heinemeyer, W. Hollik, G. Weiglein, Eur. Phys. J. C 9 (1999) 343, arXiv:hep-ph/9812472;
G. Degrassi, S. Heinemeyer, W. Hollik, P. Slavich, G. Weiglein, Eur. Phys. J. C 28 (2003) 133, arXiv:hep-ph/0212020;
M. Frank, T. Hahn, S. Heinemeyer, W. Hollik, H. Rzehak, G. Weiglein, J. High Energy Phys. 0702 (2007) 047, arXiv:hep-ph/0611326.

[20] D.M. Pierce, J.A. Bagger, K.T. Matchev, R.-j. Zhang, Nucl. Phys. B 491 (1997) 3, arXiv:hep-ph/9606211.

[21] A.D. Box, X. Tata, Phys. Rev. D 79 (2009) 035004, arXiv:0810.5765 [hep-ph]; A.D. Box, X. Tata, Phys. Rev. D 82 (2010) 119905 (Erratum).

[22] S. Chatrchyan, et al., CMS Collaboration, arXiv:1305.0491 [hep-ex].

[23] M. Kawasaki, K. Kohri, T. Moroi, A. Yotsuyanagi, Phys. Rev. D 78 (2008) 065011, arXiv:0804.3745 [hep-ph].

[24] R. Rattazzi, U. Sarid, Nucl. Phys. B 501 (1997) 297, arXiv:hep-ph/9612464.

[25] J. Hisano, S. Sugiyama, Phys. Lett. B 696 (2011) 92, arXiv:1011.0260 [hep-ph]; J. Hisano, S. Sugiyama, Phys. Lett. B 719 (2013) 472 (Erratum).

[26] J. Beringer, et al., Particle Data Group, Phys. Rev. D 86 (2012) 010001.

[27] CMS Collaboration, CMS-PAS-SUS-13-006.

[28] ATLAS Collaboration, ATLAS-CONF-2013-028.

[29] ATLAS Collaboration, ATLAS-CONF-2013-049.