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MSSM with $m_{\rm h} = 125$ GeV in high-scale gauge mediation

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Abstract After the discovery of an SM-like Higgs with $m_{\rm h} = 125$ GeV, it is increasingly urgent to explore a solution to the hierarchy problem. In the context of MSSM from gauge-mediated SUSY breaking, the lower bound on the gluino mass suggests that the messenger scale M is probably large if the magnitude of $\Lambda \sim 100$ TeV. In this paper, we study the $\bar{\mathbf{5}} + \mathbf{5}$ model with $M \sim 10^8$–10^{12} GeV and $\Lambda \simeq 100$ TeV. For moderate Higgs–messenger coupling, a viable model will be shown with moderate fine tuning. In this model, $\mu \sim 800$ GeV, and B_μ nearly vanishes at the input scale, which can be constructed in a microscopic model.

1 Introduction

A SM-like Higgs boson with mass $m_{\rm h} = 125$ GeV [1,2] has been reported by the ATLAS and CMS collaborations at the Large Hadron Collider (LHC). Its implications in the context of the minimal supersymmetric standard model (MSSM) have been extensively explored, see, e.g, [3–15]. Specifically, a large loop-induced correction to $m_{\rm h}$ is needed, and this requires either a large stop mass, $\sim$ several TeV for $A_t = 0$, or $\sim$1 TeV for maximal mixing. Since it is not promising to examine the former case at the LHC, we focus on the latter case, in which there is a large or at least moderate value for the A_t term: $\sim$1 TeV.

In the scenario of gauge-mediated supersymmetry (SUSY) breaking [17–23] (for a recent review, see, e.g., [24]), the A term vanishes at one-loop level in models of minimal gauge mediation (GM). It is impossible to obtain a large A_t in virtue of the renormalization group equations (RGEs) for low-scale GM, except that it receives a non-vanishing input value at the messenger scale M. According to the one-loop calculation of A_t [25,26], it is required that we must add new Yukawa couplings between the Higgs sector and the messengers in the superpotential [27,28].

However, a little hierarchy of A–m^2_H similar to $\mu - B_\mu$ is usually induced after adding new Yukawa couplings between the Higgs sector and the messengers, i.e., a one-loop A term accompanied with a large, two-loop, positive m^2_H. A large and positive m^2_H spoils the electroweak symmetry breaking (EWSB). In order to evade this problem, the messengers should couple to X in the same way as in the minimal GM. In order to generate one-loop A_t, Yukawa couplings between (some of) the messengers and the doublet H_u are added to the superpotential. In terms of imposing an additional global symmetry, the coupling of the doublet $H_{\rm d}$ to the messengers can be forbidden. Together with a one-loop, negative, $(\Lambda/M)^2$-suppressed contribution to $m^2_{H_u}$, it can be driven to negative values at the electroweak (EW) scale EWSB even when $M \sim 10^2$ TeV. In other words, EWSB is still viable in low-scale GM.

The arguments that lead to a viable low-scale GM are obviously corrected if we consider the latest data as regards the gluino [29,30] at the LHC. Still we keep a low value of $\Lambda \equiv F/M \sim 100$ TeV, with M and $\sqrt{F}$ being the messenger scale and SUSY-breaking scale, respectively. It controls the whole magnitude of the soft mass parameters at the input scale $\sim$1 TeV.[1] The lower bound on the gluino mass $M_3 >$ 1 TeV suggests that M must be moderate or large (up to messenger number N). For $\Lambda/M \lesssim \frac{1}{4\pi}$ (or $M \gtrsim 10^3$ TeV) the one-loop, negative, $(\Lambda/M)^2$-suppressed contribution to $m^2_{H_u}$ is not significant. The EWSB seems impossible for this range of M.

In this paper, we continue to address GM with messenger scale $M > 10^3$ TeV. There are three main motivations for this study. First, for a large messenger scale it is easy to accommodate the lower bound on the gluino mass. Second, it is also possible to achieve an A term as required in terms of large RGE, thus providing a 125 GeV Higgs boson. Finally, we will find that instead of the negative, one-loop,

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[1] As noted in the previous discussions, a larger value of $\Lambda > 100$ TeV implies that the detection of a SUSY signal at the LHC is impossible.

$(\Lambda/M)^2$-suppressed contribution, the large RG corrections to $m^2_{H_u}$ due to the high messenger scale take over, thus providing EWSB. We will show that for a moderate value of the Higgs–messenger coupling there indeed exists a viable parameter space.

On the other hand, in contrast to SUSY models such as NMSSM, a large value of $\tan\beta$ is required in order to induce $m_h = 125$ GeV in the MSSM. In the large $\tan\beta$ limit the four conditions of EWSB reduce to two simple requirements: a one-loop magnitude of the μ term and vanishing B_μ (at least at two-loop level) at the input scale, which can be constructed in a microscopic model [32]. Alternatively, this type of μ–B_μ combination is a consequence of adding the μ term by hand, i.e., a μ term exists in the SUSY limit.

The paper is organized as follows. In Sect. 2, we explore the model in detail. First, we find the parameter space composed of N, M, and λ_u (with $\Lambda = 100$ TeV fixed) that gives rise to $m_h = 125$ GeV. Then we continue to discuss stringent constraints arising from EWSB, which finally sets the magnitude of $\mu \sim 800$ GeV. Putting all these results together, we argue that the model of $\bar{\mathbf{5}}+\mathbf{5}$ that fills out $SU(5)$ is viable in GM with $M \sim 10^8-10^{12}$ GeV if $\alpha_{\lambda_u} \sim 0.02-0.04$. Finally, we conclude in Sect. 3.

2 The model

We follow the formalism of spurion superfields, $X = M + \theta^2 F$, which stores the information of the SUSY-breaking hidden sector. The visible sector is the ordinary MSSM, which communicates with hidden X-sector via messenger sector. The messengers ϕ_i, $\tilde{\phi}_i$ (with number of pairs N) fill out either $\overline{\mathbf{10}}+\mathbf{10}$ or $\bar{\mathbf{5}}+\mathbf{5}$ of $SU(5)$, which can ensure that grand unification still viable. The superpotential is chosen to be

$$W = X\phi_i\tilde{\phi}_i + \lambda_{uij} H_u \cdot \phi_i \cdot \tilde{\phi}_j. \tag{2.1}$$

As noted in the introduction and argued in [28], this choice, which can be realized by global symmetry, reconciles the A–$m^2_{H_u}$ problem.

The total contributions to $m^2_{H_u}$ at input scale M are mainly composed of two parts:

$$m^2_{H_u}\,|_M = \Lambda^2\left[2N\left(\frac{\alpha_2}{4\pi}\right)^2 C_2(H_u) + 2N\left(\frac{\alpha_1}{4\pi}\right)^2 C_1(H_u) + d_H(d_H+3)\left(\frac{\alpha_{\lambda_u}}{4\pi}\right)^2 - d_H C_r \frac{\alpha_r\alpha_{\lambda_u}}{8\pi^2}\right], \tag{2.2}$$

with the first line in (2.2) arising from the minimal GM, and the second line in (2.2) arising from the Yukawa coupling in (2.1). Here $C_i(H_u)$ is the Casimir invariant for H_u, α_r are the SM gauge couplings ($r = 1, 2, 3$), d_H the effective number of messengers coupled to the Higgs, and $C_r = C^r_{H_u} + C^r_i + C^r_j$, i, j, referring to the messengers. The same Yukawa coupling also induces deviations to A_t, etc., from that of minimal GM[2],

$$\begin{aligned} A_t &= -d_H\frac{\alpha_{\lambda_u}}{4\pi}\Lambda, \\ \delta m^2_{Q_3} &= -d_H\frac{\alpha_t\alpha_{\lambda_u}}{16\pi^2}\Lambda^2, \\ \delta m^2_{u_3} &= -d_H\frac{\alpha_t\alpha_{\lambda_u}}{8\pi^2}\Lambda^2. \end{aligned} \tag{2.3}$$

In the following, we consider a type of $\bar{\mathbf{5}}+\mathbf{5}$ model[3], in which the $SU(3)\times SU(2)\times U(1)$ representations of the messengers take the form

$$(\phi_1, \phi_2, \phi_3) = ((\mathbf{1}, \mathbf{1}, 0), (\mathbf{1}, \mathbf{2}, 1/2), (\mathbf{3}, \mathbf{1}, -1/3)). \tag{2.4}$$

The superpotential (2.1) explicitly reads

$$W = X\phi_i\tilde{\phi}_i + \lambda_u H_u \cdot \phi_1 \cdot \tilde{\phi}_2. \tag{2.5}$$

For this model, the number of messenger pairs is $N = d_H$.

As shown in the last line of (2.2), the modifications to $m^2_{H_u}$ due to the Higgs–messenger coupling is controlled by d_H and the magnitude of the Yukawa coupling λ_u. Also, we note that the one-loop, negative, $(\Lambda/M)^2$-suppressed contribution is tiny in comparison with those in (2.2) for $\Lambda/M \ll 1/4\pi$.

For low-scale gauge mediation, the appearance of the one-loop negative $(\Lambda/M)^2$-suppressed contribution guarantees that we obtain a negative $m^2_{H_\mu}$ at the EW scale [28]. The authors of Ref. [27] focused on the possibility of driving $m^2_{H_u}$ negative by the $\alpha_3\alpha_{\lambda_u}$ term in (2.2). In our case, as we have emphasized in the previous section, we consider large RG running due to a high messenger scale. Therefore, the central point in our note is that the positive $m^2_{H_\mu}$ at the input scale is driven negative at the EW scale by a large RG correction.

The parameter space is described by the following four parameters:

$$(d_H, \lambda_u, \Lambda, M). \tag{2.6}$$

The first three determine the input values of the soft mass parameters at the messenger scale, while the last one controls the magnitudes of RG corrections when we run from M to the EW scale.

By setting $m_h = 125$ GeV, we can fix one parameter; let us choose Λ. Note that to obtain a natural EWSB it is suggested that $\Lambda \lesssim 100$ TeV, while to generate a large gaugino mass which exceeds 1 TeV a lower bound on $N\Lambda$ is set. Thus, with a specific N, Λ can be tightly constrained to be in a narrow range.

By imposing negative $m^2_{H_u}$ as favored by the EWSB, one can constrain the magnitude of λ_u. If λ_u is rather small, it will induce too small an A_t term. Conversely, if it is rather large,

[2] All other soft mass parameters, such as sfermion masses and gaugino masses, are nearly the same as in the minimal GM.

[3] In this paper we do not consider $\overline{\mathbf{10}}+\mathbf{10}$ in detail, except that we will compare them with the $\bar{\mathbf{5}}+\mathbf{5}$ model.

it will be impossible to drive $m_{H_u}^2$ negative at the EW scale. With an estimate on the range of λ_u at hand, the constraint on A_t at the messenger scale can be explicitly derived. In virtue of RGE for A_t, one builds the connection between the value of A_t required by $m_h = 125$ GeV at the EW scale and that required by negative $m_{H_u}^2$ at the scale M. This in turn determines the allowed range of M.

Putting all these observations together, we can examine the EWSB in the large-tan β limit in the parameter space of (2.6) favored by the above requirements.

2.1 Constraints from $m_h = 125$ GeV

The two-loop mass of the Higgs boson in the MSSM reads [7,16]

$$m_h^2 = m_Z^2 \cos^2 2\beta + \frac{3m_t^4}{4\pi^2 \upsilon^2}\left\{\log\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right) + \frac{1}{16\pi^2}\left(\frac{3}{2}\frac{m_t^2}{\upsilon^2} - 32\pi\alpha_3\right) \times \left[\frac{2X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right) + \log\left(\frac{M_S^2}{m_t^2}\right)\right]\log\left(\frac{M_S^2}{m_t^2}\right)\right\}, \quad (2.7)$$

where $X_t = A_t - \mu \cot\beta \simeq A_t$ in the large-tan β limit, $M_S = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$ being the average stop mass, and $\upsilon = 174$ GeV.

We show in Fig. 1 the plots of $m_h = 125 \pm 1$ GeV as a function of A_t with fixed $\Lambda = 10^2$ TeV for $M = 10^8$ GeV. The three colors represent different numbers of messenger pairs.[4] Figure 1 shows that for $N = 2, 3$ $|A_t| \sim 1.0-1.5$ TeV at the EW scale one is provided with 125 GeV. As M increases to $\sim 10^{12}$ GeV, there is no significant modification to the value of A_t, as required.

We show in Fig. 2 plots of $m_{H_u}^2$ at the input scale as functions of λ_u with different Ns for $\Lambda = 100$ TeV and $M = 10^8$ GeV. A negative $m_{H_u}^2$ can be obtained in the range $0.02 \lesssim \alpha_{\lambda_u} \lesssim 0.04$ for $N = 1$. On increasing N the allowed range will shrink. In particular, only the neighborhood of $\alpha_{\lambda_u} \simeq 0.02$ is possible for $N = 2$. Similar plots can be found for $M = 10^{12}$ GeV. Following Fig. 2 one observes that the region $\alpha_{\lambda_u} > 0.1$ induces $m_{H_u}^2$ to be positive and too large at the input scale to be driven negative at the EW scale. Actually, the positivity of the stop soft masses at the input scale require $\alpha_{\lambda_u} < 0.1$. On the other hand, the region $\lambda_u < 0.01$ provides an $|A_t|$ term too small at the input scale to accommodate the required value of $|A_t| \gtrsim 1$ TeV at the EW scale. Figures 1 and 2 show the possible range for α_{λ_u} as

$$0.01 \lesssim \alpha_{\lambda_u} < 0.1. \quad (2.8)$$

The corresponding range of $|A_t|$ is from several hundred GeV to ~ 1 TeV at the input scale. Similar plots can also be found for $\overline{\mathbf{10}} + \mathbf{10}$. For realistic EWSB, Fig. 2 shows that a large RGE for $m_{H_u}^2$ must be taken in most of the range of (2.8).

Now we consider the connection between the values of A_t at input and the EW scale in virtue of Fig. 1. Roughly we need a correct RGE, which ensures that A_t runs from a correct value at messenger scale to ~ -1 TeV at the EW scale. Recall the beta function β_{A_t} below the messenger scale for A_t [31],

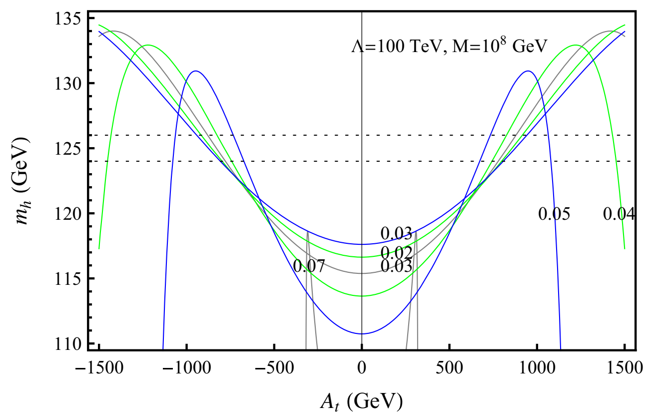

Fig. 1 Plots $m_h = 125 \pm 1$ GeV as functions of A_t for $\Lambda = 10^2$ TeV, $M = 10^8$ GeV and different values of N and α_{λ_u}. The value of A_t is shown at EW other than input scale. The *gray*, *green*, and *blue* colors represent $N = 1, N = 2$, and $N = 3$, respectively. For each case of N, the values of α_{λ_u}s are explicitly shown in the plots. The *dotted horizontal lines* correspond to the range of 124–126 GeV

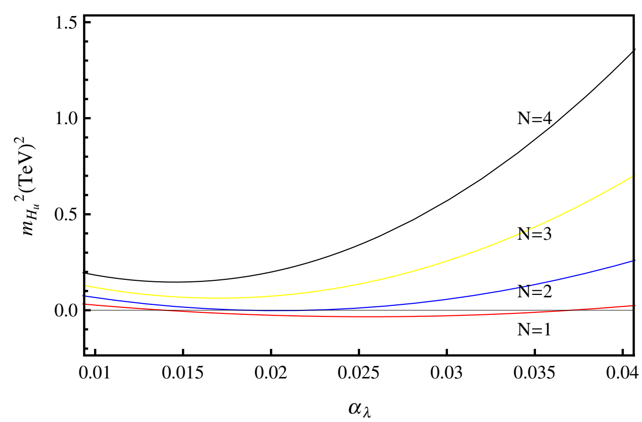

Fig. 2 Plots of $m_{H_u}^2$ at the input scale as functions of λ_u with different Ns for $\Lambda = 100$ TeV and $M = 10^8$ GeV. Negative $m_{H_u}^2$ can be obtained in the range $0.02 \lesssim \alpha_{\lambda_u} \lesssim 0.04$ for $N = 1$. On increasing N the allowed range will shrink. In particular, only the neighborhood of $\alpha_{\lambda_u} \simeq 0.02$ is possible for $N = 2$. Similar plots can be found for different choices of M

[4] One can examine that for $\Lambda = 10^2$ TeV, the parameter space $N \geqslant 1$ and $M \sim 10^8 - 10^{12}$ GeV can give rise to RGE large enough for M_3 such that at EW scale its value is larger than the mass bound $\sim$1 TeV [29,30] reported by the LHC experiments.

$$\beta_{A_t} = \frac{1}{4\pi}\left[18\alpha_t A_t - \frac{16}{3}\alpha_3(A_t - 2y_t M_3) - 3\alpha_2(A_t - 2y_t M_2) - \frac{13}{15}\alpha_1(A_t - 2y_t M_1)\right]. \quad (2.9)$$

Since the sign of β_{A_t} depends on the magnitude of $| A_t |$ relative to M_3, or concretely the magnitude of α_{λ_u} relative to α_3, it can be either positive or negative in the range of (2.8).

By using (2.9) we show the RGE for A_t in the cases $N = 1$ (Fig. 3), $N = 2$ (Fig. 4), and $N = 3$ (Fig. 5), from which the dependence on α_{λ_u} and M is obvious. In particular $N = 1$ is excluded (as shown from Fig. 3) regardless of the values of M and α_{λ_u}. $\alpha_{\lambda_u} < 0.05$ is excluded for the case of $N = 2$. In the case of $N = 3$, the parameter space allowed is possible for the whole range of $M \sim 10^8{-}10^{12}$ GeV and for $\alpha_{\lambda_u} \sim 0.03{-}0.05$. In summary, the parameter space for $\Lambda = 10^2$ TeV which can explain the 125 GeV Higgs boson is restricted to the region $N > 2$ and $\alpha_{\lambda_u} \sim 0.03{-}0.05$. In the next subsection, we will explore EWSB in this narrow region, determine the soft breaking masses at EW scale, and measure the fine tuning in this type of model.

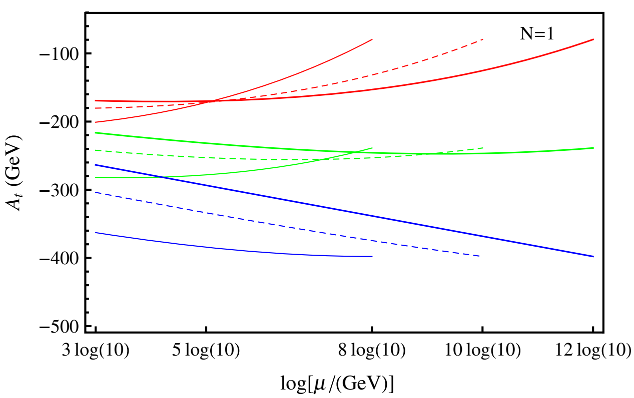

Fig. 3 RGEs for A_t as functions of α_{λ_u} and the input messenger scale M in the case of $N = 1$ and $\Lambda = 100$ TeV. The *red*, *green*, and *blue* colors correspond to $\alpha_{\lambda_u} = 0.01$, 0.03, and 0.05, respectively. The *solid*, *dashing*, and *thickness* refer to $M = 10^8$, 10^{10}, and 10^{12} (GeV), respectively

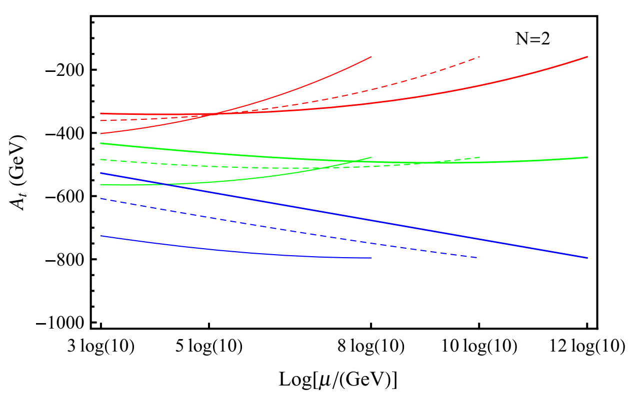

Fig. 4 Same as Fig. 3 for $N = 2$

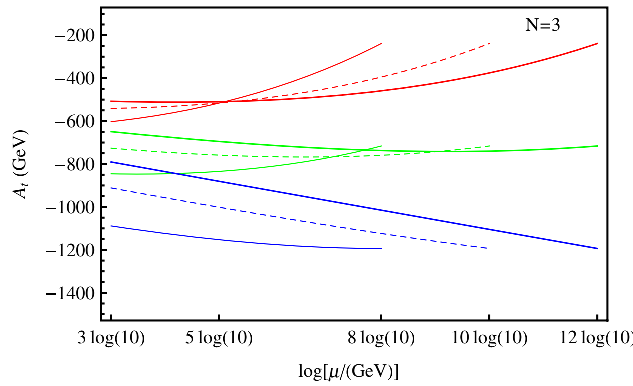

Fig. 5 Same as Fig. 3 for $N = 3$

2.2 EWSB

In the previous section we address the parameter space which provides us with $m_{\rm h} = 125$ GeV at the EW scale. In what follows, we continue to explore another question: whether this parameter space induces the EWSB simultaneously. We begin with the conditions of the EWSB involving soft parameters in the Higgs sector in the MSSM:

$$\mu^2 = \frac{m^2_{H_d} - m^2_{H_u}\tan^2\beta}{\tan^2\beta - 1} - \frac{m_Z^2}{2}$$
$$\sin 2\beta = \frac{2B_\mu}{m^2_{H_d} + m^2_{H_u} + 2\mu^2}, \quad (2.10)$$

which together with

$$B_\mu < \frac{1}{2}(m^2_{H_d} + m^2_{H_u}) + |\mu|^2$$
$$B_\mu^2 > (|\mu|^2 + m^2_{H_d})(|\mu|^2 + m^2_{H_u}) \quad (2.11)$$

guarantee a stable vacuum. In the large $\tan\beta$ limit together with negative $m^2_{H_u}$ and positive $m^2_{H_d}$, (2.10) and (2.11) reduce to

$$\mu^2 = -m^2_{H_u} - \frac{m_Z^2}{2},$$
$$B_\mu \ll \frac{1}{2}(m^2_{H_d} + m^2_{H_u}) + |\mu|^2 = \frac{1}{2}(m^2_{H_d} - m^2_{H_u} - m_Z^2). \quad (2.12)$$

The former constraint in (2.12) fixes the magnitude of μ at the input scale $\mu(M)$ through the RGE for μ, and the latter is the new constraint to be satisfied.

In traditional MSSM without Yukawa coupling λ_u, $m^2_{H_u}$ is driven negative at the EW scale through the RGE. In our model, a similar phenomenon appears for small α_{λ_u}. Otherwise, the input values significantly increase for $m^2_{H_u}$ and decrease for stop masses squared due to a large α_{λ_u}, which would spoil EWSB. In Fig. 6 we show RGEs for m_{H_u} and m_{H_d} for an input scale $M = 10^8$ GeV (10^{12} GeV) and $\alpha_{\lambda_u} = 0.03$ for the case $N = 3$. A larger value of α_{λ_u} is

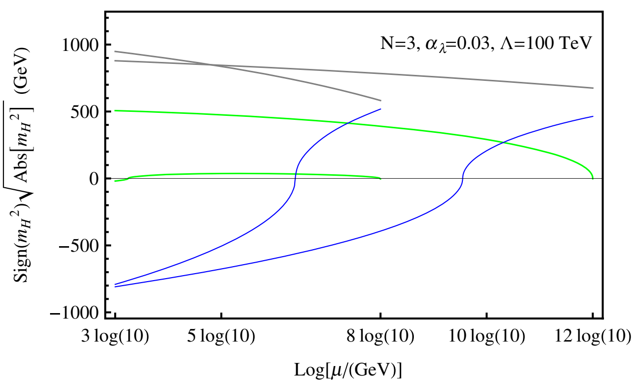

Fig. 6 RGEs for $\text{Sign}[m_i^2]\sqrt{|\ m_i^2\ |}$ with $M = 10^8, 10^{12}$ GeV, and $\alpha_{\lambda_u} = 0.03$. The *gray*, *blue*, and *green* curves refer to $m_{H_d}^2$, $m_{H_u}^2$, and B_μ, respectively

not viable. Following Fig. 6 we obtain $\mu \sim 800$ GeV at EW scale. With this value of the μ term, we can estimate the REG for B_μ as follows. In our model, $B_\mu \simeq 0$ (at two-loop level) at the input scale; therefore the second condition of (2.12) can be trivially satisfied in virtue of the REG for B_μ,

$$16\pi^2\beta_{B_\mu} \simeq B_\mu\left(3y_t^2 - 3g_2^2 - \frac{3}{5}g_1^2\right) +\mu\left(6y_tA_t + 6g_2^2M_2 + \frac{6g_1^2}{5}M_1\right). \quad (2.13)$$

For $M = 10^8(10^{12})$ GeV, substituting $\mu \sim 800$ GeV (from Fig. 6) into (2.13) and using the REGs for A_t (Fig. 5) and $M_{1,2}$, one obtains the RGE for B_μ term in each case[5], as shown by the green plots in Fig. 6. One finds that for small input scale $M = 10^8$ GeV, $B_\mu \sim (10\ \text{GeV})^2$. As we adjust the value of M to 10^{12} GeV, the RG correction to B_μ increases to $(500\ \text{GeV})^2$.

Finally, we use the traditional definition $c = \max\{c_i\}$ to measure fine tuning in the model, where $c_i = \partial \ln m_Z^2/\partial \ln m_i^2$, m_i^2 being the soft breaking mass squared. For the mass spectrum in Fig. 6, the main contribution to the large value of c arises from the stop masses, the gaugino masses, and the μ term. Typically we have $c \simeq 150$–200, which suggests that this type of model is moderately fine tuned.

3 Conclusions

The discovery of a SM-like Higgs boson with $m_{\text{h}} = 125$ GeV verifies the SM as a precise low-energy effective theory. It is increasingly urgent to find a solution to stabilize the mass of this scalar. The present status is that SUSY is still in the short list of frameworks which can provide such a solution with some fine tunings. This paper is devoted to an exploration of gauge-mediated SUSY with the latest results reported by the LHC experiments.

The constraint of $m_{\text{h}} = 125$ GeV and the lower bound on Λ need an A_t term ~1 TeV. However, since the A_t soft term at the input scale at one-loop level vanishes, it is impossible to obtain such a large value in low-scale GM except when we either introduce a direct Higgs–messenger coupling or consider a high messenger scale.

The situation is rather different in GM with a high messenger scale (with $\Lambda \sim 100$ TeV fixed). First, the negative $m_{H_u}^2$ required by EWSB must be realized due to the large RG correction instead of the one-loop, negative, $(\Lambda/M)^2$-suppressed contribution [28]. Second, the A_t term can still be obtained with a small or moderate Higgs–messenger coupling. Finally, the large lower bound on the gluino mass suggests that a large messenger scale is favored. Therefore, it is necessary to explore viable GM with $M > 10^7$ GeV. Following these motivations, we find that a type of $\bar{\mathbf{5}} + \mathbf{5}$ model [28] is viable in GM with $M \sim 10^8$–10^{12} GeV and with a moderate value of the Higgs–messenger coupling α_{λ_u}. In this model, $m_{H_u}^2$ is driven negative, although it has a positive input value, $\sim \mathcal{O}(1)\ \text{TeV}^2$. At the EW scale we obtain EWSB with the magnitude of $\mu \sim 800$ GeV, $m_{\text{h}} = 125$ GeV, and $M_3 > 1$ TeV.

This magnitude of the μ term can be either generated at one-loop level at the input scale, with B_μ vanishing at least at two-loop level, or it can be considered as an input scale in the SUSY limit. For the first case, we refer the reader to [32], where this type of μ and B_μ terms can indeed be realized in terms of adding SM singlets to the MSSM. The latter choice makes the model complete, although it seems ad hoc to add a μ term by hand.

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[5] It is crucial to note that the sign of B_μ must be positive, even if its absolute value is rather small in comparison with the magnitude of $(m_{H_d}^2 - m_{H_u}^2)$.

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