MSSM with $m_h = 125$ GeV in high-scale gauge mediation

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Abstract After the discovery of an SM-like Higgs with $m_h = 125$ 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 $\mathbb{5} + \mathbb{5}$ 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 $B_h$ nearly vanishes at the input scale, which can be constructed in a microscopic model.

1 Introduction

A SM-like Higgs boson with mass $m_h = 125$ 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 $m_h$ is needed, and this requires either a large stop mass, $\sim$ several TeV for $A_t = 0$, or $\sim$0.1 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 $A-m_H^2$ similar to $\mu-B_h$ 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 $m_H^2$. A large and positive $m_H^2$ 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 $H_d$ to the messengers can be forbidden. Together with a one-loop, negative, $(\Lambda/M^2)$-suppressed contribution to $m_H^2$, it can be driven to negative values at the electroweak (EW) scale EWSB 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 $M$ 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 $\Lambda/M \lesssim 1/\pi\sqrt{3}$ (or $M \gtrsim 10^3$ TeV) the one-loop, negative, $(\Lambda/M^2)$-suppressed contribution to $m_H^2$ 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,

\(^1\) 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.
(Λ/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 β is required in order to induce m_h = 125 GeV in the MSSM. In the large tan β 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 Λ = 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 μ ~ 800 GeV. Putting all these results together, we argue that the model of \( \mathbb{S} + 5 \) that fills out SU(5) is viable in GM with \( M \sim 10^8 - 10^{12} \) GeV if α_u \sim 0.02 -- 0.04. Finally, we conclude in Sect. 3.

2 The model

We follow the formalism of spurion superfields, \( X = M + \delta^2 F \), 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 \( \phi_i, \tilde{\phi}_i \) (with number of pairs \( N \)) fill out either \( \mathbf{10} + \mathbf{10} \) or \( \mathbb{S} + 5 \) of SU(5), which can ensure that grand unification still viable. The superpotential is chosen to be

\[
W = X \phi_i \tilde{\phi}_j + \lambda_{u_{ij}} H_u \cdot \phi_i \cdot \tilde{\phi}_j. \tag{2.1}
\]

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:

\[
m^2_{H_u} \mid M = \Lambda^2 \left[ 2N \left( \frac{\alpha_u}{4\pi} \right)^2 C_2(H_u) + 2N \left( \frac{\alpha_1}{4\pi} \right)^2 C_1(H_u) \right]
+ d_H (d_H + 3) \left( \frac{\alpha_u}{4\pi} \right)^2 - d_H C_r \frac{\alpha_u \alpha_{\tilde{H}_u}}{8\pi^2}, \tag{2.2}
\]

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 \( H_u \), \( \alpha_r \) are the SM gauge couplings (\( r = 1, 2, 3 \)), \( d_H \) the effective number of messengers coupled to the Higgs, and \( C_r = C'_{H_u} + C'_{\tilde{H}_u} + C'_{\tilde{\phi}} \), i, j, referring to the messengers. The same Yukawa coupling also induces deviations to \( A_I \), etc., from that of minimal GM^2, \( A_I = -d_H \frac{\alpha_u}{4\pi} \Lambda, \)

\[
\delta m^2_{\tilde{Q}_3} = -d_H \frac{\alpha_u \alpha_{\tilde{H}_u}}{16\pi^2} \Lambda^2, \tag{2.3}
\]

\[
\delta m^2_{\tilde{u}_3} = -d_H \frac{\alpha_u \alpha_{\tilde{H}_u}}{8\pi^2} \Lambda^2.
\]

In the following, we consider a type of \( \mathbb{S} + 5 \) model\(^3\), in which the \( SU(3) \times SU(2) \times U(1) \) representations of the messengers take the form

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

The superpotential (2.1) explicitly reads

\[W = X \phi_i \tilde{\phi}_j + \lambda_{u} H_u \cdot \phi_i \cdot \tilde{\phi}_j. \tag{2.5}\]

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 \( \lambda_u \). Also, we note that the one-loop, negative, (Λ/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 (Λ/M)^2-suppressed contribution guarantees that we obtain a negative \( m^2_{H_u} \) at the EW scale [28]. The authors of Ref. [27] focused on the possibility of driving \( m^2_{H_u} \) negative by the \( \alpha_3 \lambda_u \) 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 \( m^2_{H_u} \) 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 \( \Lambda \). 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 \( N, \Lambda \) 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 \( \lambda_u \). If \( \lambda_u \) is rather small, it will induce too small an \( A_I \) 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 \( \mathbf{10} + \mathbf{10} \) in detail, except that we will compare them with the \( \mathbb{S} + 5 \) model.
it will be impossible to drive $m_H^2$ negative at the EW scale. With an estimate on the range of $\lambda_u$ 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 $m_H^2$ 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 $\beta$ 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]

$$m_h^2 = m_\Sigma^2 \cos^2 2\beta + \frac{3m_t^4}{4\pi^2 v^2} \left\{ \log \left( \frac{M_S^2}{m_t^2} \right) + \frac{X_t^2}{M_4^2} \left( 1 - \frac{X_t^2}{12M_4^2} \right) + \frac{1}{16\pi^2} \left( \frac{3m_t^2}{2v^2} - 32\pi\alpha_3 \right) \right\}.$$  

(2.7)

where $X_t = A_t - \mu \cot \beta \simeq A_t$ in the large-tan $\beta$ limit, $M_4 = \sqrt{m_t^2 m_{H_u}^2}$ being the average stop mass, and $v = 174$ 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. For realistic EWSB, Fig. 2 shows that for $N = 2, 3 \mid A_t \mid \sim 1.0 - 1.5$ 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 $m_H^2$ at the input scale as functions of $\lambda_u$ with different $N$s for $\Lambda = 100$ TeV and $M = 10^8$ GeV. A negative $m_H^2$ 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 $m_H^2$ 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

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

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 $\alpha_{\lambda_u}$. 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 $\alpha_{\lambda_u}$ are explicitly shown in the plots. The dotted horizontal lines correspond to the range of 124–126 GeV.

Fig. 2 Plots of $m_H^2$ at the input scale as functions of $\lambda_u$ with different $N$s for $\Lambda = 100$ TeV and $M = 10^8$ GeV. Negative $m_H^2$ 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 $M$.}

EW scale. Figures 1 and 2 show the possible range for $\alpha_{\lambda_u}$ as

$$0.01 \lesssim \alpha_{\lambda_u} < 0.1.$$  

(2.8)

The corresponding range of $|A_t|$ is from several hundred GeV to $\sim 1$ TeV at the input scale. Similar plots can also be found for $\tilde{t}^0 + 10$. For realistic EWSB, Fig. 2 shows that a large RGE for $m_H^2$ 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 $\sim -1$ TeV at the EW scale. Recall the beta function $\beta_{A_t}$ below the messenger scale for $A_t$ [31],

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

Since the sign of \( \beta_A \) depends on the magnitude of \( |A_t| \) relative to \( M_3 \), or concretely the magnitude of \( \alpha_{\lambda u} \), 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 \( \alpha_{\lambda u} \) and \( M \) is obvious. In particular \( N = 1 \) is excluded (as shown from Fig. 3) regardless of the values of \( M \) and \( \alpha_{\lambda u} \); \( \alpha_{\lambda u} < 0.05 \) 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.

2.2 EWSB

In the previous section we address the parameter space which provides us with \( m_h = 125 \) 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:

\[ \mu^2 = \frac{m_H^2 - m_{H_u}^2}{\tan^2 \beta - 1} - \frac{m_Z^2}{2}, \] (2.10)

\[ \sin 2\beta = \frac{2B_\mu}{m_{H_u}^2 + 2m_{H_u}}. \]

which together with

\[ B_\mu < \frac{1}{2}(m_{H_d}^2 + m_{H_u}^2) + |\mu|^2 \] (2.11)

\[ B_\mu > (|\mu|^2 + m_{H_u}^2)(|\mu|^2 + m_{H_u}) \]

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

\[ \mu^2 = -m_{H_u}^2 - \frac{m_Z^2}{2}, \]

\[ B_\mu \ll \frac{1}{2}(m_{H_d}^2 + m_{H_u}^2) + |\mu|^2 = \frac{1}{2}(m_{H_d}^2 - m_{H_u}^2 - m_Z^2). \] (2.12)

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

In traditional MSSM without Yukawa coupling \( \lambda_u, m_{H_u}^2 \) is driven negative at the EW scale through the RGE. In our model, a similar phenomenon appears for small \( \alpha_{\lambda u} \). Otherwise, the input values significantly increase for \( m_{H_u}^2 \) and decrease for stop masses squared due to a large \( \alpha_{\lambda u} \), 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 \( \alpha_{\lambda u} \) is
Fig. 6 RGEs for $\text{Sign}(m_1^2) \sqrt{|m_2^2|}$ with $M = 10^8, 10^{12}$ GeV, and $\alpha_{\lambda} = 0.03$. The gray, blue, and green curves refer to $m_{H_u}^2$, $m_{H_d}^2$, and $B_\mu$, respectively.

not viable. Following Fig. 6 we obtain $\mu \sim 800$ GeV at EW scale. With this value of the $\mu$ term, we can estimate the REG for $B_\mu$ 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 $B_\mu$,

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

(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 $B_\mu$ 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 $B_\mu$ increases to $(500 \text{ GeV})^2$.

Finally, we use the traditional definition $c = \max(c_i)$ to measure fine tuning in the model, where $c_i = \partial \ln m^2_2/\partial \ln m^2_2$, $m^2_2$ 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 $\mu$ 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 $m_h = 125$ 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

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

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 $m_h = 125$ GeV and the lower bound on $A_t$ term $\sim 1$ 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 $M > 10^9$ GeV. Following these motivations, we find that a type of $\overline{5} + \overline{5}$ model [28] is viable in GM with $M \sim 10^8–10^{12}$ GeV and with a moderate value of the Higgs–messenger coupling $\alpha_{\lambda}$.

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, $m_h = 125$ GeV, and $M_3 > 1$ TeV.

This magnitude of the $\mu$ term can be either generated at one-loop level at the input scale, with $B_\mu$ 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 $\mu$ and $B_\mu$ 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 $\mu$ term by hand.

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