

# Higgs boson Mass in GMSB with Messenger-Matter mixing

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## Abstract

A Higgs-like particle of order 125 GeV has been observed by both ATLAS and CMS experiments. In simple version of minimal GMSB models, this Higgs mass causes sparticle masses in the several to multi-TeV range in the simple version of minimal GMSB models. We consider the effects of messenger–matter mixing on the lightest CP–even Higgs boson mass in gauge–mediated supersymmetry breaking models. We find with such mixings a 125 GeV Higgs boson can be naturally obtained even with a sub–TeV SUSY spectrum, and when the gravitino has a cosmologically preferred sub–keV mass. In addition, when these models are embedded into a grand unification framework with a  $U(1)$  flavor symmetry they explain the fermion mass hierarchy and generate naturally large neutrino mixing angles accompanied with small quark mixing angles. While SUSY mediated flavor changing processes are sufficiently suppressed in such an embedding, it can resolve the apparent discrepancy in the CP asymmetry parameters  $\sin 2\beta$  and  $\epsilon_K$ , and it predicts an observable  $\mu \rightarrow e\gamma$  decay rate.

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## 1. Introduction

The Higgs boson field is introduced in the Standard Model (SM) in order to explain why the electroweak force carriers (W and Z boson) and fermions have mass. As a consequence of electroweak symmetry breaking, a massive Higgs particle is predicted by SM. A gauge hierarchy problem arises when SM is assumed to be an unbroken symmetry upto the Planck or grand unification scale. As a result the physical Higgs mass receives huge quantum loop corrections. This can be avoided by assuming a new physics at TeV scale. Supersymmetry (SUSY) is one of most promising candidates of new physics beyond the SM. The minimal supersymmetric extension of the SM (MSSM) provides us with not only a solution to the gauge hierarchy problem but also with various interesting features such as a candidate for the dark matter of our universe, an upper bound for the lightest Higgs boson mass of order 130 GeV so MSSM can be tested experimentally, a mechanism for electroweak symmetry breaking by driving the soft breaking mass-squared of the up-Higgs boson ( $m_{H_u}^2$ ) to negative values at low energy scale, and the success-

ful SM gauge couplings unification. This unification does not occur exactly in the SM. However, in the case of MSSM, the unification occurs with impressive precision at  $M_{GUT} \approx 2 \times 10^{16}$  GeV. This strongly suggests that MSSM might be remnant of a supersymmetric grand unification theory. Therefore, gauge-mediated supersymmetry breaking models (GMSB) presented in this paper are embedded in a unified  $SU(5)$  framework. On the other hand, MSSM has shortcomings such as it contains an intractably large number of parameters (around 124 parameters) for meaningful phenomenological analysis and suffers from SUSY flavor problem. Adopting GMSB as a mechanism underlying SUSY breaking not only reduces the free parameter space of MSSM to only 5 fundamental parameters but also solves the SUSY flavor problem as we will discuss later.

Recently, the ATLAS [1] and CMS [2] experiments have reported the discovery of a Higgs-like particle with mass around 125 GeV. The observations are supported by recent analysis of the Tevatron experiments [3]. These experimental results fortunately do not exclude

MSSM since the upper limit, 130 GeV, on the lightest mass Higgs boson is not violated. A Higgs boson with mass 125 GeV has great impact on the phenomenology of supersymmetric models because the lightest Higgs boson is related to soft supersymmetry breaking (SSB) terms, mainly quadratic stop masses and trilinear SSB A-terms. Realizing CP-even Higgs of order 125 GeV in the MSSM requires either very heavy stop masses, above 10 TeV, or a large trilinear SSB A-terms with stop quark mass still around a TeV [4]. In simple versions of GMSB scenarios [5] the trilinear SSB A-terms are relatively small at the messenger scale and they are not sufficiently generated at low energy scale through renormalization group equation (RGE) running. Therefore, the 125 GeV Higgs boson is only obtained in GMSB models by making most of the sparticles very heavy and difficult to access at LHC [6, 7]. However, the 125 GeV Higgs boson mass can be obtained naturally in minimal GMSB models, with all SUSY particles below 1.5 TeV, if the messengers of SUSY breaking are allowed to mix with the SM fields [8]. The SUSY flavor violation that arises from messenger-matter mixing is suppressed in agreement with experiment as discussed later.

## 2. SUSY flavor problem

In the MSSM with arbitrary SSB terms, there are new sources of flavor changing neutral current (FCNC). Thus supersymmetric contributions to FCNC processes can, in principle, exceed the SM predictions by orders of magnitude. Experiments tell us that such FCNC processes are strongly suppressed. The difficulty to explain this suppression is known as the SUSY flavor problem. The flavor structure of the soft SUSY-breaking sector with large off-diagonal entries would induce large FCNCs in both quark and lepton sectors. For example, the  $\mu \rightarrow e\gamma$  process, which is prohibited in SM, is induced by the supersymmetric particles as illustrated in the Fig.1. This process is highly suppressed as reported by the recent experimental upper bound of  $Br(\mu \rightarrow e\gamma) \leq 2.4 \times 10^{-12}$  [9]. Large mixing of smuon and selectron clearly violates this bound.

One approach to overcome SUSY flavor problem is to assume that the SSB parameters have a universal form at SUSY-breaking scale. This universality condition is naturally satisfied in the GMSB where the soft terms are generated at the messenger scale, below the GUT scale, from radiative corrections. A small amount of flavor mixing is generated due to the renormalization-group evolution from the messenger scale down to the electroweak scale.

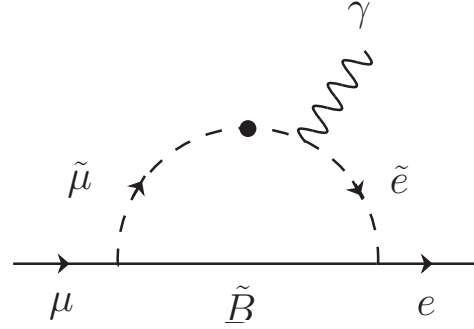


Figure 1: This diagram contributes to  $\mu \rightarrow e\gamma$  process in supersymmetric models. The off-diagonal element of smuon and selectron is indicated by dot.

## 3. Features of minimal GMSB

In GMSB theories, messenger fields communicate the SUSY breaking from the hidden sector to the visible sector. In addition to the observable sector, at least one gauge singlet superfield ( $Z$ ) is needed in order to give mass to the messenger fields and break SUSY by giving vacuum expectation values (VEVs) to its scalar-component ( $\langle Z \rangle$ ) and to its auxiliary F-component ( $\langle F_Z \rangle$ ) respectively. This field couples with a set of messenger fields  $\Phi_i$  and  $\bar{\Phi}_i$  which transform vectorially under SM gauge symmetry:

$$W = \lambda_i Z \Phi_i \bar{\Phi}_i \quad (1)$$

The SUSY breaking factor (i.e.  $\langle F_Z \rangle$ ) that appears in the mass splitting between the fermionic and scalar components of the messenger field is communicated to the MSSM particles through radiative corrections. The gauginos and the scalars of MSSM get their masses at the messenger scale  $M_{\text{mess}}$  from one-loop and two-loop Feynman diagrams respectively as follows:

$$M_{\lambda_r} = N_{\text{mess}} \frac{\alpha_r}{4\pi} \Lambda, \quad (2)$$

$$\tilde{m}^2 = 2 \sum_{r=1}^3 N_{\text{mess}} C_r^{\tilde{f}} \frac{\alpha_r^2}{(4\pi)^2} \Lambda^2, \quad (3)$$

where we have assumed  $\langle F_Z \rangle \ll \langle Z \rangle$ . Here  $N_{\text{mess}}$  is called the messenger index. For example,  $N_{\text{mess}} = 1$  ( $N_{\text{mess}} = 3$ ) for messenger fields belong to  $5 + \bar{5}$  ( $10 + \bar{10}$ ) of  $SU(5)$ .  $\Lambda = \frac{\langle F_Z \rangle}{\langle Z \rangle}$  is the effective SUSY breaking scale,  $C_r^{\tilde{f}}$  are the quadratic Casimir invariants for the scalar fields, and  $\alpha_r$  are the gauge coupling constants at the scale  $M_{\text{mess}}$ . In order to preserve the successful gauge coupling unification of MSSM, the messenger

$\lambda'_0$	$m_h$ GeV	$\Lambda$ $10^5$ GeV	$M_{mess}$ $10^{13}$ GeV	$\tilde{m}_{t_1}$ GeV	$\tilde{m}_{t_2}$ GeV
0	114	2	1.78	1249	1695
0.8	116	2	10	1212	1583
1.2	119	2	10	384	2613

Table 1: The lightest Higgs boson mass  $m_h$  in the  $5 + \bar{5}$  model as functions of the GMSB input parameters,  $\Lambda$ ,  $\lambda'_0$  and  $M_{mess}$  for  $\tan\beta = 10$ . Here we have fixed  $f_0 = 0.25$ .

fields should reside in complete  $SU(5)$  multiplets such as  $5 + \bar{5}$  and  $10 + \bar{10}$ . In addition, the A-terms in GMSB models vanish at the messenger scale as long as the MSSM fields and the messenger fields do not mix. Introducing messenger-matter mixing generates not only a non-zero A-terms but also additional contributions to universal masses in Eq.3.

Two interesting features of GMSB follow from Eqs.2 and 3. Firstly, the scalar masses are only functions of gauge quantum number so scalar masses with the same gauge quantum number are degenerate. As a result, the SUSY flavor problem is solved. Secondly, GMSB is highly predictive because SUSY spectrum is completely specified by only five parameters

$$M_{mess}, \Lambda, N_{mess}, \tan\beta, \text{sign}(\mu). \quad (4)$$

Here  $\tan\beta$  is the ratio of the VEVs of the two MSSM Higgs doublets. The magnitude of  $\mu$  is determined by the radiative electroweak condition that arises from minimizing the Higgs potential.

The gravitino is the lightest supersymmetric particle in the minimal GMSB. Its mass is given by

$$m_{\tilde{G}} = \frac{M_{mess}\Lambda}{\sqrt{3}M_P}, \quad (5)$$

where  $M_P = 2.4 \times 10^{18}$  GeV is the reduced Planck mass. The cosmological preference requires  $m_{\tilde{G}} \leq 1$  KeV so the gravitinos do not overclose the universe [10]. This constraint requires  $M_{mess} \leq 10^8$  GeV for  $\Lambda \approx 3 \times 10^4$  GeV.

#### 4. Higgs boson mass bound in minimal GMSB models without messenger-matter mixing

The leading 1- and 2- loop contributions to the CP-even Higgs boson mass in the MSSM are given by [11]

$$m_h^2 = M_z^2 \cos^2 2\beta \left( 1 - \frac{3}{8\pi^2} \frac{m_t^2}{v^2} t \right) + \frac{3}{4\pi^2} \frac{m_t^4}{v^2} \left[ \frac{1}{2} \chi_t + t + \frac{1}{16\pi^2} \left( \frac{3}{2} \frac{m_t^2}{v^2} - 32\pi\alpha_3 \right) (\chi_t t + t^2) \right], \quad (6)$$

where  $v^2 = v_d^2 + v_u^2$ ,

$$t = \log\left(\frac{M_s^2}{M_t^2}\right), \chi_t = \frac{2\tilde{A}_t^2}{M_s^2} \left( 1 - \frac{\tilde{A}_t^2}{12M_s^2} \right). \quad (7)$$

Here  $\tilde{A}_t = A_t - \mu \cot\beta$ , where  $A_t$  denotes the stop left and stop right soft mixing parameter and  $M_s$  is defined in terms of the stop mass eigenvalues as  $M_s^2 = \tilde{m}_{t_1}\tilde{m}_{t_2}$ . Eq.6 is accurate to about 3 GeV, when compared with computational packages such as SuSpect [12] which do not make certain simplification assumption made in obtaining Eq.6.

Note that the lightest Higgs mass depends mainly on the stop quark mass and on  $\chi_t$ . The upper bound of the Higgs mass in an arbitrary MSSM model (i.e  $m_h = 130$  GeV) corresponds to the maximal mixing condition,  $\tilde{A}_t = \sqrt{6}M_s$ . This condition is not realized in the minimal GMSB model because  $A_t/\tilde{t}_R \leq 1$  is always the case, no matter how large the values of  $M_{mess}$  and  $\Lambda$  [6]. As shown in Ref. [6], with  $A_t/\tilde{t}_R \leq 1$ , the 125 GeV Higgs boson can only be obtained in minimal GMSB models if the right-hand stops mass is above 6 TeV for messenger fields belonging to  $5 + \bar{5}$  of  $SU(5)$  and becomes larger than 5 TeV for the case of five copies of  $5 + \bar{5}$ . As a result, most of the sparticles are heavy and difficult to see at the LHC. However, the maximal mixing condition can be realized naturally along with a light supersymmetric spectrum if we allow the messenger fields to mix with MSSM fields in minimal GMSB model.

#### 5. Higgs boson mass bound in minimal GMSB models with messenger-matter mixing

In order to preserve perturbative gauge coupling unification, we shall consider two models with minimal choices:  $5 + \bar{5}$  and  $10 + \bar{10}$  model where the messenger fields belong to  $5 + \bar{5}$  of  $SU(5)$  and  $10 + \bar{10}$  of  $SU(5)$  model respectively. In these models, messenger fields can mix with MSSM superfields [8].

##### 5.1. $5 + \bar{5}$ Model

The messenger fields belonging to  $5 + \bar{5}$  of  $SU(5)$  decompose to down-quark singlets  $d_m^c$  and  $\bar{d}_m^c$ , and to lepton doublets  $L_m$  and  $\bar{L}_m$ . The superpotential at the messenger scale due to messenger-matter couplings is

$$W_5 = f_d \bar{d}_m^c d_m^c Z + \lambda'_b Q_3 d_m^c H_d + f_e \bar{L}_m L_m Z + \lambda'_c L_m e_3^c H_d. \quad (8)$$

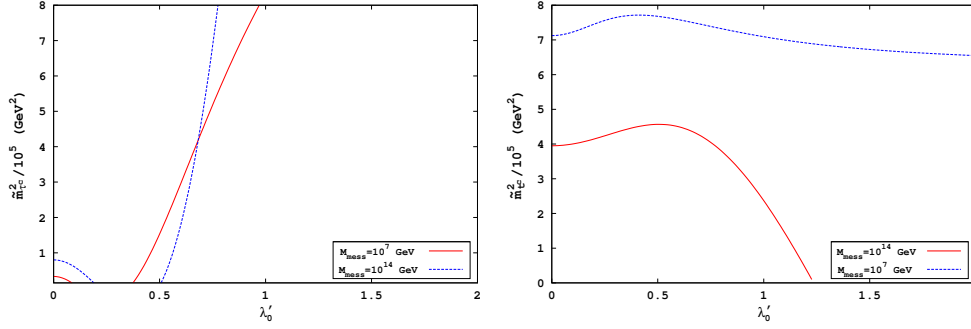


Figure 2:  $\tilde{m}_{\tau^c}^2$  versus  $\lambda'_0$  at the scale  $M_{\text{mess}}$  for two different messenger scales  $M_{\text{mess}} = (10^7, 10^{14})$  GeV, in the  $5 + \bar{5}$  model (left panel). The right panel shows  $\tilde{m}_{\tau^c}^2$  versus  $\lambda'_0$  at low energy scale for the same two messenger scales in this model. Here  $f_0 = 0.25$  has been used.

Here we have assumed the messenger fields couple only with the third generation of MSSM. The superpotential  $W_5$  is obtained by assuming  $U(1)$  flavor symmetry of the Froggatt-Nielsen mechanism. In the  $SU(5)$  basis, Eq.8 arises from  $W = f_0 5_m \bar{5}_m Z + \lambda'_0 10_3 \bar{5}_m \bar{5}_H$  at the GUT scale. The exotic Yukawa couplings  $\lambda'_b$  and  $\lambda'_{\tau^c}$  ( $f_d$  and  $f_e$ ) originate from one unified coupling  $\lambda'_0(f_0)$  at the GUT scale.

The messenger-matter couplings induce two-loop contributions to the quadratic soft terms and one-loop contributions to the  $A$ -terms. In addition to the universal masses given by Eqs.2 and 3, the new contributions to quadratic soft terms ( $\delta\tilde{m}_{Q_3}^2$  and  $\delta\tilde{m}_{e_3^c}^2$ ) and  $A_t$  term due to the messenger-matter couplings at the messenger scale are given as follows:

$$\delta\tilde{m}_{Q_3}^2 = \frac{\alpha'_b \Lambda^2}{8\pi^2} \left( 3\alpha'_b + \frac{1}{2}\alpha'_{\tau^c} - \frac{8}{3}\alpha_3 - \frac{3}{2}\alpha_2 - \frac{7}{30}\alpha_1 \right), \quad (9)$$

$$\delta\tilde{m}_{e_3^c}^2 = \frac{2\alpha'_{\tau^c} \Lambda^2}{8\pi^2} \left( 2\alpha'_{\tau^c} + \frac{3}{2}\alpha'_b - \frac{3}{2}\alpha_2 - \frac{9}{10}\alpha_1 \right), \quad (10)$$

$$\delta A_t = -\frac{1}{4\pi} \alpha'_b \Lambda, \quad (11)$$

where  $\alpha'_b = \frac{\lambda'^2_b}{4\pi}$ , and  $\alpha'_{\tau^c} = \frac{\lambda'^2_{\tau^c}}{4\pi}$ . New contributions to  $\delta\tilde{m}_{H_d}^2$ ,  $\delta A_b$  and  $\delta A_{\tau^c}$  can be found in Ref. [8].

Below the scale  $M_{\text{mess}}$ , the theory is just MSSM. Therefore, we have solved the one-loop RGEs of MSSM at the supersymmetry breaking scale with the boundary conditions at the scale  $M_{\text{mess}}$  given by Eqs.2 and 3 plus the new contributions due to messenger matter mixing.

Since  $\lambda'_b$  and  $\lambda'_{\tau^c}$  originate from one unified coupling  $\lambda'_0$ , the scalar mass spectra is determined by  $\lambda'_0$ , the messenger scale  $M_{\text{mess}}$ , and the effective SUSY breaking scale  $\Lambda$ . The requirements of positive values for both  $m_{\tilde{t}_R}^2$  and  $m_{\tilde{\tau}_R}^2$  impose constraint on the values of  $\lambda'_0$  as shown in Fig 2. The interval  $0.2 < \lambda'_0 < 0.5$  ( $0.1 < \lambda'_0 < 0.4$ ) is excluded, corresponding to  $M_{\text{mess}} = 10^{14}$  GeV ( $M_{\text{mess}} = 10^7$  GeV) since that lead to negative  $m_{\tilde{\tau}_R}^2$  at the messenger scale as shown in the left graph of Fig 2. In order to avoid a negative value of  $m_{\tilde{t}_R}^2$  at low energy scale, the region of  $\lambda'_0 > 1.3$  for  $M_{\text{mess}} = 10^{14}$  GeV is forbidden as shown in the right graph of Fig 2.

All the soft terms at the messenger scale are fully determined by three parameters:  $\lambda'_0$ ,  $\Lambda$  and  $M_{\text{mess}}$ . Consequently, the lightest Higgs mass is also determined by these three parameters. As we discussed previously, the maximal mixing condition  $-\tilde{A}_t = \sqrt{6}M_s$  gives the upper bound on the lightest Higgs mass of MSSM. It is not possible to realize this maximal condition in GMSB without messenger-matter mixing because  $A_t$  vanishes at the scale  $M_{\text{mess}}$  and the induced value at low energy scale through RGEs is not sufficient. On the other hand, allowing messenger matter couplings generates  $A_t$  as shown in Eq.11. This leads to an enhancement of the Higgs mass. By allowing these parameters to be in the respective ranges  $4 \times 10^4 \text{ GeV} < \Lambda < 2 \times 10^5 \text{ GeV}$ ,  $10^7 \text{ GeV} < M_{\text{mess}} < 10^{14} \text{ GeV}$  and  $0 < \lambda'_0 < 2$ , we report the numerical values of these parameters that give rise to the highest  $m_h$  value in Table 1. In this Table, we exclude values of  $\lambda'_0$  that give negative values for  $\tilde{m}_{\tilde{\tau}_R}^2$  and  $\tilde{m}_{\tilde{t}_R}^2$ . 2 GeV should be added to the reported values of  $m_h$  in Table 1 since Suspect gives  $m_h$  values systematically higher by 2 GeV than the one calculated by using Eq (8). The lightest Higgs mass around 116 GeV is obtained in the  $5 + \bar{5}$  model without messenger-matter mixing and an enhancement of around 5 GeV is

obtained in the presence of messenger-matter mixing as shown in Table 1. The maximal mixing is not realized in this model because the large values of  $\lambda_0$  lead to negative values of  $m_{\tilde{t}^c}^2$  at low energy scale. In addition, the induced  $A_t$  in  $5 + \bar{5}$  model is not as large as the induced  $A_t$  in the case of the  $10 + \bar{10}$  model. For example, if the exotic Yukawa couplings are taken to be of order one, the induced  $A_t$  in the  $10 + \bar{10}$  model is nine times order of magnitude of the  $A_t$  in the  $5 + \bar{5}$  model as shown from Eqs.11 and 16. Therefore, the maximal mixing is naturally realized when the messenger fields belong to  $10 + \bar{10}$  in the presence of messenger-matter mixing.

### 5.2. $10 + \bar{10}$ Model

In this subsection we have messenger fields belonging to  $10 + \bar{10}$  of  $SU(5)$ . This decomposes in terms of MSSM multiplets as:

$$10 + \bar{10} = (Q + \bar{Q}) + (u^c + \bar{u}^c) + (e^c + \bar{e}^c). \quad (12)$$

We have assumed the messenger fields only couple with the third generation of MSSM fields. In this case the MSSM superpotential has the additional contribution

$$\begin{aligned} W_{10} = & \lambda'_{t^c} Q_3 u_m^c H_u + \lambda'_t Q_m u_3^c H_u + \lambda'_m Q_m u_m^c H_u \\ & + f_{e^c} \bar{e}_m^c e_m^c Z + f_{u^c} \bar{u}_m^c u_m^c Z + f_Q \bar{Q}_m Q_m Z. \end{aligned} \quad (13)$$

The above superpotential is valid at the messenger and arises, in terms of  $SU(5)$  basis, from the superpotential,  $W = \lambda'_0 10_3 10_m 5_H + \lambda'_{m0} 10_m 10_m 5_H + f_0 10_m 10_m Z$  at the GUT scale. Although the coupling  $Q_m d^c H_d$  is allowed by gauge symmetry, we have not included it in the above superpotential because it is suppressed by the small expansion parameter  $\epsilon$ . We have assumed that the Yukawa couplings  $\lambda'_{t^c}$  and  $\lambda'_t$  are equal to one unified coupling  $\lambda'_0$  at the GUT scale.

The three Yukawa couplings  $f_{e^c}$ ,  $f_Q$  and  $f_{u^c}$  are equal to  $f_0$  at the GUT scale as well. In other words, the six Yukawa couplings appearing in the superpotential  $W_{10}$  are reduced to three ( $\lambda'_0$ ,  $f_0$  and  $\lambda'_{m0}$ ) at the GUT scale. These six Yukawa couplings are obtained from the unified ones by solving the RGEs given in Ref.[8]

The exotic Yukawa couplings  $\lambda'_{t^c}$ ,  $\lambda'_t$  and  $\lambda'_m$  generate 2-loop (1-loop) scalar masses ( $A$ -terms) at the scale  $M_{\text{mess}}$ . So, the universal scalar masses given by Eqs.2 and 3, substituting  $N_{\text{mess}} = 3$ , have additional contributions at the scale  $M_{\text{mess}}$  given by

$$\begin{aligned} \delta \tilde{m}_{Q_3}^2 = & \frac{\Lambda^2}{8\pi^2} \left( \alpha'_{t^c} (3\alpha'_{t^c} + \frac{3}{2}\alpha'_t + \frac{5}{2}\alpha'_m - \frac{8}{3}\alpha_3 \right. \\ & \left. - \frac{3}{2}\alpha_2 - \frac{13}{30}\alpha_1) - \alpha_t (\frac{5}{2}\alpha'_t + \frac{3}{2}\alpha'_m) \right), \end{aligned}$$

$\lambda'_0$	$m_h$ GeV	$\Lambda$ $10^5$ GeV	$M_{\text{mess}}$ GeV	$\tilde{m}_{t_1}$ GeV	$\tilde{m}_{t_2}$ GeV	$A_t/M_s$
0	117	1.6	$3 \times 10^{13}$	2656	3284	-0.86
0.4	118	1.36	$10^8$	1795	2396	-1.27
0.8	122	0.912	$10^{13}$	1553	2143	-1.95
1.1	123	0.784	$2 \times 10^{11}$	735	1429	-2.0
2	123	0.784	$10^8$	743	1426	-2.26

Table 2: The lightest Higgs boson mass  $m_h$ , along with the stop masses, and the stop mixing parameter  $A_t/m_s$  for different values of the GMSB input parameters  $\Lambda$ ,  $\lambda'_0$  and  $M_{\text{mess}}$  in the  $10 + \bar{10}$  model. Here we have fixed  $\lambda'_{m0} = 0$ ,  $f_0 = 0.25$ , and set  $\tan\beta = 10$ .

$$\begin{aligned} \delta \tilde{m}_{u_3^c}^2 = & \frac{2\Lambda^2}{8\pi^2} \left( \alpha'_t (3\alpha'_t + \frac{3}{2}\alpha'_{t^c} + 2\alpha'_m - \frac{8}{3}\alpha_3 \right. \\ & \left. - \frac{3}{2}\alpha_2 - \frac{13}{30}\alpha_1) - \alpha_t (2\alpha'_{t^c} + \frac{3}{2}\alpha'_m) \right), \end{aligned} \quad (14)$$

$$\delta A_t = - \left( \frac{5\alpha'_t + 4\alpha'_{t^c} + 3\alpha'_m}{4\pi} \right) \Lambda, \quad (16)$$

where  $\alpha'_{t^c} = \frac{\lambda'^2_{t^c}}{4\pi}$ ,  $\alpha'_t = \frac{\lambda'^2_t}{4\pi}$ , and  $\alpha'_m = \frac{\lambda'^2_m}{4\pi}$ . New contributions to  $\delta \tilde{m}_{H_u}^2$  and  $\delta A_b$  can be found in Ref. [8]. The advantage of the  $10 + \bar{10}$  model over the  $5 + \bar{5}$  model is that  $A_t$  is generated sufficiently at the scale  $M_{\text{mess}}$ . Consequently, we are able to obtain the maximal mixing condition (i.e.  $\frac{A_t}{M_s} = \sqrt{6}$ ). So the lightest Higgs boson can be raised naturally to about 125 GeV even with all SUSY particles below 1.5 TeV. Such model would be compatible with the recent Higgs observations.

In order to find the Higgs mass and the other scalar mass spectra, we solved the MSSM RGEs numerically from the messenger scale to the low scale. The scalar mass spectra depend on the four parameters  $\Lambda$ ,  $M_{\text{mess}}$ ,  $\lambda'_0$  and  $\lambda'_{m0}$ . We report the values of three of these parameters  $\Lambda$ ,  $M_{\text{mess}}$ , and  $\lambda'_0$  for  $\lambda'_{m0} = 0$  that lead to the highest  $m_h$  in Table 2.  $m_h = 125$  GeV can be obtained (once 2 GeV is added to the numbers quoted in these tables), with all SUSY particles below 1.5 TeV. On the other hand, in the case of  $\lambda'_0 = 0$  (i.e without messenger-matter mixing), the Higgs mass limit 119 GeV is obtained and requires one of the stop masses above 3 TeV as shown in Table 2.

Fig. 3 shows the Higgs mass as a function of  $\Lambda$  for two values of the unified Yukawa coupling  $\lambda'_0 = (0, 1.2)$ , where  $\lambda'_0 = 0$  corresponds to minimal GMSB without messenger-matter mixing. We see that the Higgs mass is raised by 10 GeV in the case of  $\lambda'_0 = 1.2$  compared

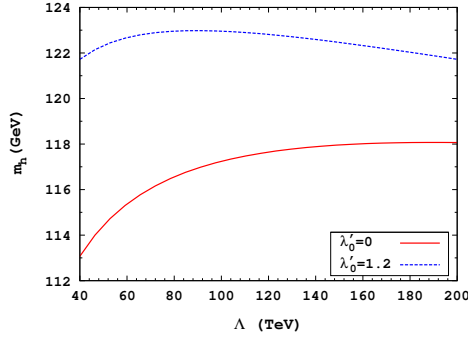


Figure 3: The graph is a plot of  $m_h$  versus  $\Lambda$  for  $\lambda'_0 = 0$  and  $\lambda'_0 = 1.2$

to the case of  $\lambda'_0 = 0$  for low values of  $\Lambda = 4 \times 10^4$  GeV. This increase is about 6 GeV for larger  $\Lambda$ . Note that smaller values of  $\Lambda$  leads to lighter SUSY particles, with the stop mass around 500 – 600 GeV, which might be accessible to early run of LHC.

Table 3 shows three different spectra, two corresponding to the  $10 + \overline{10}$  model, and one for the  $5 + \overline{5}$  model of the previous subsection. In this Table, the masses quoted in the third column shows a Higgs boson mass around 125 GeV, along with all SUSY particle below 1 TeV, even for low messenger scale  $M_{mess} \leq 3 \times 10^8$  GeV, preferred by cosmology.

## 6. $U(1)$ flavor symmetry and Froggatt-Nielsen mechanism

One advantage of assuming  $U(1)$  flavor symmetry in the models discussed in the previous sections is to explain the hierarchy in the fermion masses and mixings. This can be done by employing the Froggatt-Nielsen mechanism [13]. In this approach, there is a flavon field  $S$ , which is a scalar, usually a SM singlet field, which acquires a VEV and breaks the  $U(1)$  symmetry. This symmetry breaking is communicated to the fermions at different orders in a small parameter  $\epsilon = \langle S \rangle / M^*$ . Here  $M^*$  is the high energy scale (of order the Planck scale) at which  $U(1)$  flavor symmetry is broken. This  $U(1)$  flavor symmetry also leads, when embedded in the  $SU(5)$  framework, to lopsided structure that explains simultaneously the largeness of the neutrino mixing angles and smallness of quark mixing angles [14]. As shown in [8], a good fit to all mixing angles in the quark and lepton sector is obtained with the choice of  $\epsilon \approx 0.22$ .

The three families of quarks and leptons belong to  $\overline{5}_i + 10_i$  under  $SU(5)$ , with  $i = 1 - 3$ . Here  $10_i \subset \{Q_i, u_i^c, e_i^c\}$  and  $\overline{5}_i \subset \{d_i^c, L_i\}$ . The Higgs doublets ( $H_u, H_d$ ) of

Particle		$10 + \overline{10}$	$10 + \overline{10}$	$5 + \overline{5}$
Inputs	$M_{mess}$	$10^8$	$4 \times 10^5$	$10^8$
	$N_{mess}$	3	3	1
	$\Lambda(10^5 \text{ GeV})$	0.45	0.3	1.5
	$\tan\beta$	10	6.1	15.6
	$f_0$	0.25	0.25	0.25
Higgs:	$\lambda_0$	1.3	1.2	1.2
	$m_h$	122	118	114.5
	$m_H^0$	858	592	1690
	$m_A$	858	591	1690
Gluino:	$m_{H^\pm}$	862	597	1689
	$\tilde{m}_g$	980	667	1041
Neutralinos:	$\tilde{m}_{\chi_1}$	186	124	208
	$\tilde{m}_{\chi_2}$	346	225	408
	$\tilde{m}_{\chi_3}$	800	557	781
	$\tilde{m}_{\chi_4}$	807	569	790
Charginos:	$\chi_1^+$	347	227	409
	$\chi_2^+$	807	569	790
Squarks:	$\tilde{m}_{u_L, cL}$	972	657	1480
	$\tilde{m}_{u_R, cR}$	929	632	1377
	$\tilde{m}_{d_L, sL}$	971	657	1480
	$\tilde{m}_{d_R, sR}$	922	630	1365
	$\tilde{m}_{b_L}$	800	555	1315
	$\tilde{m}_{b_R}$	919	629	1294
	$\tilde{m}_{t_L}$	853	621	1315
	$\tilde{m}_{t_R}$	412	270	1123
Sleptons:	$\tilde{m}_{e_L, \mu L}$	323	200	596
	$\tilde{m}_{\nu_{eL}, \nu_{\mu L}}$	323	200	596
	$\tilde{m}_{e_R, \mu R}$	152	92	290
	$\tilde{m}_{\tau_L}$	322	197	539
	$\tilde{m}_{\tau_R}$	151	92	1543

Table 3: The SUSY spectrum corresponding to  $10 + \overline{10}$  model and  $5 + \overline{5}$  model for three choices of input parameters. All masses are in GeV. The values of  $\tan\beta$  in the last two columns are derived from the condition that  $B = 0$  at  $M_{mess} = 2 \text{ GeV}$  should be added to  $m_h$  quoted here to be consistent with results obtained from SuSpect.

MSSM are contained in  $5_H$  and  $\overline{5}_H$  of  $SU(5)$ . The  $U(1)$  charge assignment of the flavon field  $S$ , MSSM fields and messenger fields belonging to  $5_m + \overline{5}_m$  and  $10_m + \overline{10}_m$  (in the notation of  $SU(5)$ ) are given in Table 4. Employing  $U(1)$  flavor symmetry along with  $SU(5)$  theory produces the superpotentials  $W_5$  and  $W_{10}$  given in Eqs.8 and 13 respectively.

## 7. Flavor violation induced by messenger-matter mixing

The minimal GMSB without messenger matter mixing leads to the universal scalar masses given by Eqs.2 and 3. This universality is violated by messenger-matter mixing as seen from Eqs. 9-11 and Eqs.14-16. The SUSY flavor violation induced by messenger-matter mixing is investigated by calculating the mass insertion parameters of various FCNC processes in powers of the

Particle	$10_1$	$10_2$	$10_3$	$\bar{5}_1$	$\bar{5}_2, \bar{5}_3$	$5_H, \bar{5}_H$	$S$	$5_m$	$\bar{5}_m$	$10_m$	$\bar{10}_m$	$Z$
$U(1)$	4	2	0	$p+1$	$p$	0	-1	$-\alpha$	0	0	$-\alpha$	$\alpha$

Table 4: The  $U(1)$  charges of the MSSM fields, the messenger fields, and the singlets  $Z$  and  $S$  in the  $5 + \bar{5}$  messenger model in the  $SU(5)$  notation.  $p$  here is an integer which can take values  $p = (0, 1, 2)$  corresponding to (large, medium, small)  $\tan\beta$ .

small parameters  $\epsilon \approx 0.2$ . As shown in Ref. [8], the  $5 + \bar{5}$  model is only safe from flavor violation as long as  $p \geq 2$  especially when the unification of Yukawa couplings  $\lambda'_{\tau_c}$  and  $\lambda'_{b_c}$  at the GUT scale is not valid in  $SU(5)$  theory. On the other hand, all FCNC processes are suppressed in agreement with experimental bounds as long as  $p \geq 1$  in the case of  $10 + \bar{10}$  model. Besides, the unification of the exotic Yukawa couplings condition at the GUT scale is satisfied. Setting  $p = 1$  makes the  $\mu \rightarrow e\gamma$  decay and CP violation in  $K^0$  system close to experimental limits.  $\mu \rightarrow e\gamma$  decay is predicted to occur with an increased experimental sensitivity and the new contribution to CP violation in K system might resolve the apparent discrepancy in the CP asymmetry parameters  $\sin 2\beta$  and  $\epsilon_K$  [15].

## 8. Summary

125 GeV Higgs boson sets restriction on the SUSY spectrum to be in the several to multi-TeV range in minimal GMSB models. This restriction is due to the vanishing  $A_t$  at messenger scale that occurs in the simple versions of minimal GMSB model. On the other hand, introducing messenger-matter couplings in minimal GMSB models induces a non-vanishing  $A_t$  term and additional contributions to some quadratic soft terms. A 125 GeV Higgs boson is naturally obtained when the messenger fields belonging to  $10 + \bar{10}$  of  $SU(5)$  are allowed to mix with MSSM fields. In this kind of model, with a 125 GeV Higgs boson, a relatively light SUSY spectrum is realized even for  $M_{mess} < 10^8$  GeV, which is preferred by cosmology. The FCNC processes induced by messenger-matter mixing are suppressed in agreement with experiment.

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