

Top-color-assisted supersymmetry

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It is known that the supersymmetric flavor changing neutral current problem can be avoided if the squarks take the following mass pattern: namely, the first two generations with the same chirality are degenerate with masses around the weak scale, while the third generation is very heavy. We realize this scenario through the supersymmetric extension of a top-color model with gauge-mediated supersymmetry breaking.

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I. INTRODUCTION

Supersymmetry (SUSY) [1] provides a solution to the gauge hierarchy problem if it breaks dynamically [2]. However, the general supersymmetric extension of the standard model (SM) suffers from the flavor changing neutral current (FCNC) problem [3]. The SUSY FCNC should be suppressed by certain specific mass patterns of the sleptons and squarks. The sfermion mass pattern depends on the underlying physics of SUSY breaking. For example, one of the popular choices for the sfermion mass matrix is universality in flavor space. Such a mass matrix can be resulted from the gauge-mediated SUSY breaking (GMSB) scenario [4,5]. Here gauge means the SM gauge interactions. Another inspiring choice is that the first two generation sfermions are very heavy around (10–100) TeV where the third generation sfermions are at the weak scale [6]. This kind of model is often referred to as effective SUSY. It can be realized in the GMSB scenario [7] or in that where an anomalous U(1) mediates SUSY breaking [8]. One point in this case is that the first two generations and the third generation are treated differently. For example, they may be in different representations of some new gauge interactions mediating SUSY breaking.

In this work, we consider a sfermion mass pattern which looks opposite to that of the effective SUSY. It is that the first two generations with the same chirality are degenerate with masses around the weak scale, and the third generation is superheavy. The SUSY FCNC is also suppressed in this case [3].¹ In fact, this pattern is not new. It could be understood by a U(2) symmetry between the first two generations in the supergravity scenario [9]. In this paper an alternative origin of it will be discussed. We note that the above mass pattern can be also a result of a supersymmetric top-color model with GMSB. Here gauge (G) means the gauge interactions of the top-color model.

Top-color models [10] were proposed for a dynamical understanding of the third generation quark masses. The basic idea is that the third generation (at least the top quark)

undergoes a superstrong interaction which results in a top quark condensation. The condensation gives the top quark a large mass, and the bottom quark mainly gets its mass due to the instanton effect of the top-color interactions. This top quark condensation contributes only a small part of the electroweak symmetry breaking (EWSB). The Higgs mechanism may be introduced for the EWSB. Therefore, the idea of top color can be generalized into SUSY models naturally. In the scenario of GMSB, supposing that the strong top-color gauge interaction involves the full third generation, and the first two generations participate in a weaker gauge interaction universally, the above-described sfermion mass pattern will be generated.

Note that the decoupling of the third generation scalars is a consistent choice in the supersymmetric top-color models. Because the third generation quarks obtain dynamical masses, the Yukawa couplings are always small.

The whole physical picture is like as follows. At the energy scale about 10^6 GeV, SUSY breaking occurs in a secluded sector. It is mediated to the observable sector through the gauge interactions. The scale of the messengers is around 10^7 GeV. The top-color scale is around (1–10) TeV. Below this scale, the gauge symmetries break into that of the SM. The resultant sparticle spectrum of the observable sector is the following. In addition to the squarks, the gauginos of the superstrong interaction are around 100 TeV. The gauginos of the weaker gauge interaction are at about the weak scale. The Higgs bosons for the top-color symmetry breaking are as heavy as 100 TeV and the Higgs bosons for EWSB at the weak scale. By integrating out the heavy fields above 1 TeV or so, the effective theory is the ordinary (two-Higgs-doublet) top-color model with the weak scale gauginos, Higgsinos, and the first two generation squarks with degeneracy.

This paper is organized as follows. After a brief review of the top-color model in the next section, the supersymmetric extension of the top-color model within the framework of the GMSB is described in Sec. III. A summary and discussion are presented in Sec. IV.

II. BRIEF REVIEW OF THE TOP-COLOR MODEL

In this paper, we consider the top-color model which, at the scale about (1–10) TeV, has interactions [10] $SU(3)_1 \times SU(3)_2 \times U(1)_{Y_1} \times U(1)_{Y_2} \times SU(2)_L$. The fermions are

¹There are other viable alternatives. For example, only the squarks satisfy this mass pattern, while the slepton mass matrices follow universality.

assigned $(SU(3)_1, SU(3)_2, U(1)_{Y_1}, U(1)_{Y_2})$ quantum numbers as follows:

$$\begin{aligned}
 (t, b)_L &\sim \left(3, 1, \frac{1}{3}, 0\right), & (t, b)_R &\sim \left(3, 1, \left(\frac{4}{3}, -\frac{2}{3}\right), 0\right), \\
 (\nu_\tau, \tau)_L &\sim (1, 1, -1, 0), & \tau_R &\sim (1, 1, -2, 0), \\
 (u, d)_L, (c, s)_L &\sim \left(1, 3, 0, \frac{1}{3}\right), \\
 (u, d)_R, (c, s)_R &\sim \left(1, 3, 0, \left(\frac{4}{3}, -\frac{2}{3}\right)\right), \\
 (\nu, l)_L (l=e, \mu) &\sim (1, 1, 0, -1), & l_R &\sim (1, 1, 0, -2).
 \end{aligned} \tag{1}$$

The top-color symmetry breaks spontaneously to $SU(3)_1 \times SU(3)_2 \rightarrow SU(3)_{\text{QCD}}$ and $U(1)_{Y_1} \times U(1)_{Y_2} \rightarrow U(1)_Y$ through a scalar field $\phi(3, \bar{3}, \frac{1}{3}, -\frac{1}{3})$ which develops a vacuum expectation value (VEV). The $SU(3)_1 \times U(1)_{Y_1}$ are assumed to be strong which make the formation of a top quark condensate but disallow the bottom quark condensate. The bottom quark mainly gets its mass due to the $SU(3)_1$ instanton effect. The τ lepton does not condensate.

III. SUPERSYMMETRIC TOP-COLOR MODEL

In the supersymmetric extension, the gauge symmetries of the above top-color model remain unchanged. The particle contents are given below. In addition to the superpartners of the particles described in the last section, some elementary Higgs superfields are introduced. The breaking of the top-color symmetry needs one pair of Higgs superfields Φ_1 and Φ_2 . And the EWSB requires another pair of Higgs superfields H_u and H_d , like in the ordinary supersymmetric SM. Their quantum numbers under the $SU(3)_1 \times SU(3)_2 \times U(1)_{Y_1} \times U(1)_{Y_2} \times SU(2)_L$ are

$$\begin{aligned}
 \Phi_1 &\left(3, \bar{3}, \frac{1}{3}, -\frac{1}{3}, 0\right), & \Phi_2 &\left(\bar{3}, 3, -\frac{1}{3}, \frac{1}{3}, 0\right), \\
 H_u &(1, 1, 0, 1, 2), & H_d &(1, 1, 0, -1, 2).
 \end{aligned} \tag{2}$$

The messenger sector is introduced as

$$\begin{aligned}
 S_1, S'_1 &= (1, 1, 1, 0, 2), & \bar{S}_1, \bar{S}'_1 &= (1, 1, -1, 0, 2), \\
 T_1, T'_1 &= \left(3, 1, -\frac{2}{3}, 0, 1\right), & \bar{T}_1, \bar{T}'_1 &= \left(\bar{3}, 1, \frac{2}{3}, 0, 1\right)
 \end{aligned} \tag{3}$$

and

$$\begin{aligned}
 S_2, S'_2 &= (1, 1, 0, 1, 2), & \bar{S}_2, \bar{S}'_2 &= (1, 1, 0, -1, 2), \\
 T_2, T'_2 &= \left(1, 3, 0, -\frac{2}{3}, 1\right), & \bar{T}_2, \bar{T}'_2 &= \left(1, \bar{3}, 0, \frac{2}{3}, 1\right).
 \end{aligned} \tag{4}$$

Compared to Ref. [4], we have introduced an extra set of messengers so as to mediate the SUSY breaking to both $SU(3)_1 \times U(1)_{Y_1}$ and $SU(3)_2 \times U(1)_{Y_2}$. Furthermore, there are three gauge-singlet superfields X, Y , and Z . Y is responsible for the SUSY breaking; X is related to the EWSB and Z to the top-color symmetry breaking.

The superpotential is written as follows:

$$\begin{aligned}
 \mathcal{W} = & m_1(\bar{S}'_1 S_1 + S'_1 \bar{S}_1) + m_2(\bar{T}'_1 T_1 + T'_1 \bar{T}_1) + m_3 S_1 \bar{S}_1 \\
 & + m_4 T_1 \bar{T}_1 + m'_1(\bar{S}'_2 S_2 + S'_2 \bar{S}_2) + m'_2(\bar{T}'_2 T_2 + T'_2 \bar{T}_2) \\
 & + m'_3 S_2 \bar{S}_2 + m'_4 T_2 \bar{T}_2 + Y(\lambda_1 S_1 \bar{S}_1 + \lambda_2 T_1 \bar{T}_1 \\
 & + \lambda'_1 S_2 \bar{S}_2 + \lambda'_2 T_2 \bar{T}_2 - \mu_2^2) + \lambda_3 X(H_u H_d - \mu_2^2) \\
 & + \lambda_4 Z[\text{Tr}(\Phi_1 \Phi_2) - \mu_3^2],
 \end{aligned} \tag{5}$$

where the Yukawa interactions are not written. It is required that $m_3^{(\prime)}/m_4^{(\prime)} \neq \lambda_1^{(\prime)}/\lambda_2^{(\prime)}$ so that the terms proportional to $m_3^{(\prime)}$ and $m_4^{(\prime)}$ cannot be eliminated by a shift in Y .

The model conserves the number of S_i -type and T_i -type ($i=1, 2$) fields. In addition, the superpotential has a discrete symmetry of $(\bar{S}_i^{(\prime)}, \bar{T}_i^{(\prime)}) \leftrightarrow (S_i^{(\prime)}, T_i^{(\prime)})$. The way of introducing the singlet fields X, Y , and Z more naturally was discussed in Ref. [11] where these kind of fields are taken to be composite. Moreover, the Fayet-Iliopoulos D terms for the $U(1)$ charges have been omitted. This is natural in the GMSB scenario. The above discrete symmetry and the exchange symmetry of Φ_1 and Φ_2 in the superpotential avoid such D terms at one-loop order.

The SUSY breaking is characterized by the term $\mu_1^2 Y$ in Eq. (5). It is communicated to the observable sector through the gauge interactions by the messengers. The $SU(3)_2 \times U(1)_{Y_2} \times SU(2)_L$ are weak enough to be described in perturbation theory. Their gauginos acquire masses at one-loop order [4, 12],

$$\begin{aligned}
 M_{\lambda_{SU(3)_2}} &= \frac{\alpha'_3}{4\pi} \mathcal{M}_T, \\
 M_{\lambda_{U(1)_{Y_2}}} &= \frac{\alpha'_1}{4\pi} \left(\mathcal{M}_S + \frac{2}{3} \mathcal{M}_T \right), \\
 M_{\tilde{W}} &= \frac{\alpha_2}{4\pi} \mathcal{M}_S,
 \end{aligned} \tag{6}$$

where $\alpha_i^{(\prime)} = g_i^{(\prime)2}/4\pi$ with g'_3, g'_1 , and g_2 being the gauge coupling constants of the $SU(3)_2 \times U(1)_{Y_2} \times SU(2)_L$. For simplicity, we take $m_1^2 \sim m_2^2 \sim m_1'^2 \sim m_2'^2 \gg \lambda_{1,2}^{(\prime)} \mu_1^2 \gg m_3^{(\prime)2} \sim m_4^{(\prime)2}$ and $\lambda_1 \sim \lambda_2 \sim \lambda'_1 \sim \lambda'_2 \sim \mathcal{O}(1)$. In this case, the \mathcal{M}_S and \mathcal{M}_T are approximately $\lambda_1 \mu_1^2/m_1$. They are about 100 TeV by choosing, say, $\mu_1 \sim 10^6$ GeV and $m_1 \sim 10\mu_1$. For the $SU(3)_1 \times U(1)_{Y_1}$, however, the gaugino masses cannot be calculated by the perturbation method, because the interac-

tions are too strong. Nevertheless, they should be at the order of $\lambda_1 \mu_1^2/m_1$ given the above parameter choice,

$$M_{\lambda_{\text{SU}(3)_1}} \sim M_{\lambda_{\text{U}(1)_{Y_1}}} \sim 100 \text{ TeV}. \quad (7)$$

Similarly, the first two generation scalar quarks and the electroweak Higgs particles obtain their masses at two-loop order,

$$\begin{aligned} m_{\tilde{Q}_1}^2 &= m_{\tilde{Q}_2}^2 \\ &\simeq \frac{4}{3} \left(\frac{\alpha'_3}{4\pi} \right)^2 \Lambda_T^2 + \frac{3}{4} \left(\frac{\alpha_2}{4\pi} \right)^2 \Lambda_S^2 + \frac{1}{4} \left(\frac{\alpha'_1}{4\pi} \right)^2 \left(\Lambda_S^2 + \frac{2}{3} \Lambda_T^2 \right), \\ m_{\tilde{c}_R}^2 &= m_{\tilde{u}_R}^2 \simeq \frac{4}{3} \left(\frac{\alpha'_3}{4\pi} \right)^2 \Lambda_T^2 + \frac{4}{9} \left(\frac{\alpha'_1}{4\pi} \right)^2 \left(\Lambda_S^2 + \frac{2}{3} \Lambda_T^2 \right), \\ m_{\tilde{s}_R}^2 &= m_{\tilde{d}_R}^2 \simeq \frac{4}{3} \left(\frac{\alpha'_3}{4\pi} \right)^2 \Lambda_T^2 + \frac{1}{9} \left(\frac{\alpha'_1}{4\pi} \right)^2 \left(\Lambda_S^2 + \frac{2}{3} \Lambda_T^2 \right), \\ m_{\tilde{h}_u}^2 &= m_{\tilde{h}_d}^2 \simeq \frac{3}{4} \left(\frac{\alpha_2}{4\pi} \right)^2 \Lambda_S^2 + \frac{1}{4} \left(\frac{\alpha'_1}{4\pi} \right)^2 \left(\Lambda_S^2 + \frac{2}{3} \Lambda_T^2 \right), \end{aligned} \quad (8)$$

where \tilde{Q}_1 and \tilde{Q}_2 stand for superfields of $(u, d)_L$ and $(c, s)_L$, respectively. And (h_u, h_d) are the scalar components of (H_u, H_d) . Λ_S^2 and Λ_T^2 were calculated to be [4]

$$\Lambda_S^2 = \frac{4\lambda_1'^2 \mu_1^4}{m_1'^2}, \quad \Lambda_T^2 = \frac{4\lambda_2'^2 \mu_1^4}{m_2'^2}. \quad (9)$$

For the third generation squarks and the top-color Higgs fields ϕ_1 and ϕ_2 , the masses are around Λ_S^2 or Λ_T^2 ,

$$m_{\tilde{Q}_3}^2 \sim m_{\tilde{t}_R}^2 \sim m_{\tilde{b}_R}^2 \sim m_{\phi_1}^2 = m_{\phi_2}^2 \sim \Lambda_S^2, \quad \Lambda_T^2 \sim (100 \text{ TeV})^2. \quad (10)$$

We have seen that for the superstrong top-color interactions, the relevant supersymmetric particles are superheavy, ~ 100 TeV, so that they decouple at the top-color scale. The top-color physics does not change even after the supersymmetric extension. However, the top-color Higgs fields seem to be too heavy.

Let us consider the breaking of the gauge symmetries. The $\text{SU}(3)_1 \times \text{SU}(3)_2 \times \text{U}(1)_{Y_1} \times \text{U}(1)_{Y_2}$ break into the diagonal subgroups $\text{SU}(3)_{\text{QCD}} \times \text{U}(1)_Y$ when the Higgs fields ϕ_1 and ϕ_2 get nonvanishing VEVs,

$$\langle \phi_1 \rangle = v_1 \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad \text{and} \quad \langle \phi_2 \rangle = v_2 \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}. \quad (11)$$

v_1 and v_2 are determined by the minimum of the following potential:

$$\begin{aligned} V_{\text{topc}} &= |\lambda_4(3v_1v_2 - \mu_3^2)|^2 + \frac{g_1^2 + g_1'^2}{2}(v_1^2 - v_2^2)^2 + m_{\phi_1}^2 v_1^2 \\ &\quad + m_{\phi_2}^2 v_2^2, \end{aligned} \quad (12)$$

where g_1 is the coupling constant of the $\text{U}(1)_{Y_1}$. It is easy to see that in the case of $\lambda_4 \mu_3^2 \geq m_{\phi_i}^2$,

$$v_1 = v_2 = \frac{1}{\sqrt{3}} \left(\mu_3^2 - \frac{m_{\phi_i}^2}{\lambda_4} \right)^{1/2}. \quad (13)$$

To keep v_1 and v_2 around a few TeV, a certain fine-tuning for the scale μ_3 is required in this model to cancel the 100 TeV m_{ϕ_i} , where the coupling λ_4 is $O(1)$. The value of μ_3 is more natural if the top-color scale is higher, such as 10 TeV. However, it should be noted that raising the top-color scale makes the effective top-color theory more tuned.

At the energy below the top-color scale, the model is described by an effective theory in which the gauge symmetry groups are that of the SM, and there are two Higgs doublets and three generation quarks with four-fermion top-color interactions for the third generation. In addition, there are weak scale gauginos of the SM, squarks of the first and second generations, and doublet Higgsinos which become massive after EWSB. There are also top-color Higgsinos of Φ_1 and Φ_2 after top-color symmetry breaking. They typically have (1–10) TeV mass and are not expected to be important to the low energy physics. Because of the degeneracy between the first two generation squarks and the decoupling of the third generation squarks, this model is free from the SUSY FCNC problem.

The physics of the top-color four-fermion interaction and EWSB in this model is essentially the same as that without SUSY, which will not be discussed further.

IV. SUMMARY AND DISCUSSION

It has been known that the SUSY FCNC problem can be avoided if the squarks take the mass pattern that the first two generations with the same chirality are degenerate and the third generation is superheavy. We have constructed a supersymmetric top-color model within GMSB to realize this mass pattern. The pattern is stable under the correction of the Yukawa interactions because they are weak and the third generation quarks obtain masses dynamically.

This model has, therefore, the phenomenologies of both SUSY and top color. It predicts weak scale SUSY particles, like the SM gauginos and Higgsinos. It also predicts top pions. These predictions can be tested directly in experiments in the near future. Indirect evidence of this model in low energy processes, such as in the B decays [13] and the R_b problem of it [14], is more complicated because of the involvement of both the SUSY and the top color, and deserves a separate study.

It should be addressed that this model has an inherent tuning problem. This required tuning follows from the very large masses (~ 100 TeV) of the third generation scalars and the top-color Higgs field. These fields are closely related to

the top-color and EWSB scales which are, however, lower than 100 TeV. We have explicitly mentioned the tuning below Eq. (13). Another aspect of this tuning is that the naturalness of EWSB requires the third generation scalars to be lighter than 20 TeV [6]. Note that the large mass of 100 TeV is just a rough estimate due to the fact that we are lacking a nonperturbative calculation method. On the other hand, if we adjust the SUSY breaking scale and the messenger scale to be somewhat lower than what we have chosen, this problem can be less severe.

We emphasize that it is the degeneracy of the first two generations, rather than the heaviness of the third generation, that plays the essential role in solving the SUSY FCNC problem. In this sense, the consideration of this paper is less nontrivial than the idea of effective SUSY. However, if we further consider the underlying theory, the models which realize effective SUSY [7,8] and the SUSY top-color model of this paper are on an equal footing.

A comment should be made on the necessity of the supersymmetric top color. Although SUSY does not necessarily need help from top color, their combination has certain advantages. As is well known, SUSY keeps the weak scale, but cannot explain it. The weak scale may have a dynamical origin [15,16,11,17]. In this case, it is natural to expect that the physics which explains the fermion masses is also at some low energy. Top color provides such physics for the hierarchy between the third generation and the first two generations. On the other hand, SUSY may be helpful to under-

stand the hierarchy between the first and second generations further. For instance, it is possible that the second generation quarks mainly get their masses from the electroweak Higgs VEVs and the first generation quarks purely from the sneutrino VEVs [18].

Finally, it should be noted that very heavy third generation squarks may pull up the light scalars. This pullup occurs through two- or more-loop diagrams with the top-color Higgs field exchanges. The heavy top-color Higgs field suppresses this quantum correction. The suppression, however, may not be enough to keep the results of Eq. (8) from significantly changing numerically. The fine-tuning problem which was discussed above reappears here. In fact, the drawback of the SUSY and top-color combination is that the SUSY breaking scale and the top-color scale are in principle unrelated. It might be hopeful to think of certain dynamics to make a relation between them. For example, it is possible that the top-color Higgs superfields are also the SUSY breaking messengers. This possibility will simplify the model and reduce the fine-tuning. It is reasonable to say that supersymmetric top color is an interesting scenario which is worthy of being studied further.

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