

Topcolor-Assisted Supersymmetry Postprint

Authors: Chun Liu

Date: 2017-09-17T00:00:00+00:00

Abstract

It has been known that the supersymmetric flavor changing neutral current problem can be avoided if the squarks take the following mass pattern, namely the #12; 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 topcolor model with gauge mediated supersymmetry breaking.

Full Text

Abstract

It has been known that the supersymmetric flavor changing neutral current problem can be avoided if the squarks take the following mass pattern: 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 topcolor model with gauge mediated supersymmetry breaking.

PACS numbers: 12.60.Cn, 12.60.Jv

Introduction

Supersymmetry (SUSY) provides a solution to the gauge hierarchy problem if it breaks dynamically. However, the general supersymmetric extension of the Standard Model (SM) suffers from the flavor changing neutral current (FCNC) problem. 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 popular choice for the sfermion mass matrix is universality in the flavor space. Such a mass matrix can result from the gauge mediated SUSY breaking (GMSB) scenario. Here “gauge” means the SM gauge interactions.

Another inspiring choice is that the first two generation sfermions are very heavy around 10-100 TeV while the third generation sfermions are at the weak scale. This kind of model is often referred to as effective SUSY. It can be realized in the GMSB scenario, or in one where an anomalous U(1) mediates SUSY breaking. 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 effective SUSY: the first two generations with the same chirality are degenerate with masses around the weak scale, and the third generation is super heavy. The SUSY FCNC is also suppressed in this case. 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. In this paper an alternative origin of it will be discussed. We note that the above mass pattern can also be a result of a supersymmetric topcolor model with GMSB. Here “gauge” (G) means the gauge interactions of the topcolor model.

Topcolor models 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 topcolor 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 topcolor can be generalized into SUSY models naturally. In the scenario of GMSB, suppose the strong topcolor 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 topcolor models. Because the third generation quarks obtain dynamical masses, the Yukawa couplings are always small.

The whole physical picture is as follows. At the energy scale about 10 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 GeV. The topcolor 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. Besides 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 topcolor symmetry breaking are as heavy as 100 TeV, and the Higgs bosons for the EWSB at the weak scale.

By integrating out the heavy fields above 1 TeV or so, the effective theory is the ordinary (two-Higgs-doublets) topcolor 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 topcolor model in the next section, the supersymmetric extension of the topcolor model within the framework of the GMSB is described in Sec. III. Summary and discussions are presented in Sec. IV.

Topcolor Model Review

In this paper, we consider the topcolor model which, at the scale about (1-10) TeV, has interactions $SU(3) \times SU(3) \times U(1)Y \times U(1)Y \times SU(2)L$. The fermions are assigned $(SU(3), SU(3), U(1)Y, U(1)Y)$ quantum numbers as follows:

$$(t,b)L \quad (3,1, \frac{1}{2}, 0); (t,b)R \quad (3,1, (, -), 0); (,)L \quad (1,1, -1, 0); R \quad (1,1, -2, 0); (u,d)L, (c,s)L \quad (1,3, 0, \frac{1}{2}); (u,d)R, (c,s)R \quad (1,3, 0, (, -)); (e,l)L (l=e,) \quad (1,1, 0, -1); lR \quad (1,1, 0, -2)$$

The topcolor symmetry breaks spontaneously to $SU(3) \times SU(3) \rightarrow SU(3)_{QCD}$ and $U(1)Y \times U(1)Y \rightarrow U(1)Y$ through a scalar field $\Phi(3,3, -, -)$ which develops a vacuum expectation value (VEV). The $SU(3) \times U(1)Y$ 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 $SU(3)$ instanton effect. The lepton does not condensate.

Supersymmetric Extension with GMSB

In the supersymmetric extension, the gauge symmetries of the above topcolor model keep 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 topcolor symmetry needs one pair of the Higgs superfields Φ and $\bar{\Phi}$. And the EWSB requires another pair of the Higgs superfields H_u and H_d , like in the ordinary supersymmetric SM. Their quantum numbers under $SU(3) \times SU(3) \times U(1)Y \times U(1)Y \times SU(2)L$ are:

$$\Phi(3,3, -, -, 0); \bar{\Phi}(3,3, -, -, 0); H_u(1,1,0,1,2); H_d(1,1,0,-1,2)$$

The messenger sector is introduced as:

$$S, \bar{S}, T, \bar{T} = (1,1,1,0,2); \tilde{S}, \tilde{\bar{S}} = (3,1, -, 0,1); \tilde{T}, \tilde{\bar{T}} = (3,1, -, 0,1); S, \bar{S} = (1,1,0,1,2); \tilde{S}, \tilde{\bar{S}} = (1,1,0,-1,2); T, \bar{T} = (1,3,0, -, 1); \tilde{T}, \tilde{\bar{T}} = (1,3,0, -, 1)$$

Compared to Ref. [4], we have introduced an extra set of messengers so as to mediate the SUSY breaking to both $SU(3) \times U(1)Y$ and $SU(3) \times U(1)Y$. 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 topcolor symmetry breaking.

The superpotential is written as follows:

$$W = m(S_S + S_S) + m(T_T + T_T) + m S S + m T T + m'(S_S + S_S) + m'(T_T + T_T) + m' S S + m' T T + Y(S_S + T_T + S_S + T_T - \Phi^2) + X(H_u H_d - \Phi'^2) + Z[\text{Tr}(\Phi \Phi) - \Phi'^2]$$

where the Yukawa interactions are not written. It is required that $m = m' = 0$ so that the terms proportional to m and m' cannot be eliminated by a shift in Y . The model conserves the number of Si-type and Ti-type ($i=1,2$) fields. In addition, the superpotential has a discrete symmetry of $(S, T) \rightarrow (S, T)$. The way of introducing the singlet fields X, Y and Z more naturally was discussed in Ref. [11] where these kinds 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 and Φ' in the superpotential avoid such D-terms at the one-loop order.

The SUSY breaking is characterized by the term $\Phi^2 Y$ in Eq. (5). It is communicated to the observable sector through the gauge interactions by the messengers. The $SU(3) \times U(1)_Y \times SU(2)_L$ are weak enough to be described in perturbation theory. Their gauginos acquire masses at one-loop order:

$$M_{\{SU(3)\}} = (g^2/4) M_{\{T\}}; M_{\{U(1)_Y\}} = (g^2/4)(M_S + M_T); M_{\{\tilde{W}\}} = (g^2/4) M_S$$

where $g^2 = g^2/4$ with g, g' and g being the gauge coupling constants of $SU(3), U(1)_Y$ and $SU(2)_L$. For simplicity, we take $m = m'$ and $\Phi = \Phi'$,

O(1). In this case, M_S and M_T are approximately:

$$M_S = (\Phi^2)/m; M_T = (\Phi^2)/m$$

They are about 100 TeV by choosing, say $\Phi = 10$ GeV and $m = 10\Phi$. For $SU(3) \times U(1)_Y$, however, the gaugino masses cannot be calculated by perturbation methods because the interactions are too strong. Nevertheless they should be of order Φ^2/m , giving:

$$M_{\{SU(3)\}} = M_{\{U(1)_Y\}} = 100 \text{ TeV}$$

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

$$m_{\{\tilde{u}_L\}}^2 = m_{\{\tilde{c}_L\}}^2 = m_{\{\tilde{d}_L\}}^2 = m_{\{\tilde{s}_L\}}^2 = (g^2/4)^2(\Delta_S^2 + \Delta_T^2) m_{\{\tilde{u}_R\}}^2 = m_{\{\tilde{c}_R\}}^2 = (g^2/4)^2 \Delta_S^2 m_{\{\tilde{d}_R\}}^2 = m_{\{\tilde{s}_R\}}^2 = (g^2/4)^2 \Delta_T^2 m_{\{h_u\}}^2 = m_{\{h_d\}}^2 = (g^2/4)^2(\Delta_S^2 + \Delta_T^2)$$

where Q and \tilde{Q} stand for the superfields of $(u,d)_L$ and $(c,s)_L$ respectively, and (h_u, h_d) are the scalar components of (H_u, H_d) . Δ_S^2 and Δ_T^2 were calculated to be:

$$\Delta_S^2 = (1/4)(g')^2 \Phi; \Delta_T^2 = (1/4)(g')^2 \Phi$$

For the third generation squarks and the topcolor Higgses Φ and Φ' , the masses are around:

$$m_{\tilde{t}_R}^2 = m_{\tilde{b}_R}^2 = m_{\Phi}^2 = m_{\tilde{\Phi}}^2 = \Delta_S^2, \Delta_T^2 \quad (100 \text{ TeV})^2$$

We have seen that for the superstrong topcolor interactions, the relevant supersymmetric particles are super heavy ($\sim 100 \text{ TeV}$) so that they decouple at the topcolor scale. The topcolor physics does not change even after the supersymmetric extension. However, the topcolor Higgs fields seem to be too heavy.

Let us consider the breaking of the gauge symmetries. The $SU(3) \times SU(3) \times U(1)_Y \times U(1)_Y$ break into the diagonal subgroups $SU(3)_{\text{QCD}} \times U(1)_Y$ when the Higgs fields Φ and $\tilde{\Phi}$ get non-vanishing VEVs, $\langle \Phi \rangle = v$ and $\langle \tilde{\Phi} \rangle = \tilde{v}$. v and \tilde{v} are determined by the minimum of the following potential:

$$V_{\text{topc}} = \frac{1}{2} (3v - \tilde{v})^2 + \frac{1}{2} g^2 (v^2 - \tilde{v}^2)^2 + m_{\Phi}^2 v^2 + m_{\tilde{\Phi}}^2 \tilde{v}^2$$

where g is the coupling constant of $U(1)_Y$. It is easy to see that in the case $m_{\Phi}^2 = m_{\tilde{\Phi}}^2$, $v = \tilde{v} = (m_{\Phi}^2 - m_{\tilde{\Phi}}^2)^{1/2}$. To keep v and \tilde{v} around a few TeV, certain fine-tuning for the scale Φ is required in this model to cancel the $100 \text{ TeV } m_{\Phi}^2$, where the coupling g is $O(1)$. The value of Φ is more natural if the topcolor scale is higher, such as 10 TeV . However, it should be noted that raising the topcolor scale makes the effective topcolor theory more tuned.

At energies below the topcolor 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 topcolor interaction 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 the EWSB. There are also topcolor Higgsinos of Φ and $\tilde{\Phi}$ after the topcolor symmetry breaking. They typically have (1-10) TeV mass and are not expected to be important to 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 topcolor four-fermion interaction and the EWSB in this model is essentially the same as that without SUSY, which will not be discussed further.

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 super heavy. We have constructed a supersymmetric topcolor 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 therefore has the phenomenologies of both SUSY and topcolor. 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. The indirect evidences of this model in low energy processes,

such as in B decays, and the R_{cb} problem of it are more complicated because of the involvement of both SUSY and topcolor, and deserve 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 topcolor Higgs. These fields are closely related to the topcolor 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 the EWSB requires the third generation scalars to be lighter than 20 TeV. Note that the large mass 100 TeV is just a rough estimate due to our lack of nonperturbative calculation methods. 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 and the SUSY topcolor model of this paper are on an equal footing.

A comment should be made on the necessity of the supersymmetric topcolor. Although SUSY does not necessarily need the help from topcolor, 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. In this case, it is natural to expect that the physics which explains the fermion masses is also at some low energy. Topcolor provides such physics for the hierarchy between the third generation and the first two generations. On the other hand, SUSY may be helpful to understand the hierarchy between the first and the second generation 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.

Finally, it should be noted that the very heavy third generation squarks may pull up the light scalars. This pull-up occurs through two- or more-loop diagrams with the topcolor Higgs exchanges. The heavy topcolor Higgs suppress this quantum correction. The suppression, however, may be not enough to keep the results of Eq. (8) from significant changing numerically. The fine-tuning problem which was discussed above reappears here. In fact, the drawback of the SUSY and topcolor combination is that the SUSY breaking scale and the topcolor scale are irrelevant. It might be hopeful to think of certain dynamics to make relation between them. For example, it is possible that the topcolor 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 the supersymmetric topcolor is an interesting scenario which is worthy to be studied further.

The author would like to thank many Korean colleagues for various helpful

discussions.

References

- [1] J. Wess and B. Zumino, Nucl. Phys. B 70, 39 (1974); Y. Gol' f and E. Likhtman, JETP Lett. 13, 323 (1971); D. V. Volkov and V. Akulov, Phys. Lett. B 46, 109 (1973).
- [2] E. Witten, Nucl. Phys. B 188, 513 (1981).
- [3] For example, see F. Gabbiani, E. Gabrielli, A. Masiero and L. Silvestrini, Nucl. Phys. B 477, 321 (1996).
- [4] M. Dine and W. Fischler, Phys. Lett. B 110, 227 (1982); L. Alvarez-Gaume, M. Claudson and M. Wise, Nucl. Phys. B 207, 96 (1982); C. R. Nappi and B. A. Ovrut, Phys. Lett. B 113, 175 (1982).
- [5] M. Dine and A. E. Nelson, Phys. Rev. D 48, 1277 (1993); M. Dine, A. E. Nelson and Y. Shirman, Phys. Rev. D 51, 1362 (1995); M. Dine, A. E. Nelson, Y. Nir and Y. Shirman, Phys. Rev. D 53, 2658 (1996).
- [6] A. G. Cohen, D. B. Kaplan and A. E. Nelson, Phys. Lett. B 388, 588 (1996); S. Dimopoulos and G. F. Giudice, Phys. Lett. B 357, 573 (1995).
- [7] S. Ambrosanio and A. E. Nelson, Phys. Lett. B 411, 283 (1997).
- [8] G. Dvali and A. Pomarol, Phys. Rev. Lett. 77, 3728 (1996).
- [9] A. Pomarol and D. Tommasini, Nucl. Phys. B 466, 3 (1996); R. Barbieri, G. Dvali and L. J. Hall, Phys. Lett. B 377, 76 (1996).
- [10] C. T. Hill, Phys. Lett. B 266, 419 (1991); Phys. Lett. B 345, 483 (1995); For a review, see C. T. Hill, hep-ph/9702320.
- [11] C. Liu, hep-ph/9903395.
- [12] For reviews, see G. F. Giudice and R. Rattazzi, hep-ph/9801271; S. L. Dubovsky, D. S. Gorbunov and S. V. Troitsky, hep-ph/9905466.
- [13] G. Buchalla, G. Burdman, C. T. Hill and D. Kominis, Phys. Rev. D 53, 5185 (1996); K. Y. Lee, Phys. Rev. D 57, 598 (1998); Z. Xiao et al., Eur. Phys. J. C 10, 51 (1999); hep-ph/9903346.
- [14] G. Burdman and D. Kominis, Phys. Lett. B 403, 101 (1997); C. T. Hill and X. Zhang, Phys. Rev. D 51, 3563 (1995); W. Loinaz and T. Takeuchi, Phys. Rev. D 60, 015005 (1999).
- [15] S. Weinberg, Phys. Rev. D 19, 1277 (1978); L. Susskind, Phys. Rev. D 20, 2619 (1979).
- [16] M. Dine, W. Fischler and M. Srednicki, Nucl. Phys. B 189, 575 (1981); S. Dimopoulos and S. Raby, Nucl. Phys. B 192, 353 (1981).
- [17] K. Choi and H. D. Kim, hep-ph/9906363.

[18] C. Liu, Int. J. Mod. Phys. A 11, 4307 (1996); C. Liu and J. Song, Phys. Rev. D 60, 036002 (1999); J. E. Kim, B. Kyae and J. S. Lee, Phys. Lett. B 447, 110 (1999).

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv –Machine translation. Verify with original.