Gauge coupling unification due to non-universal soft supersymmetry breaking

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Gauge coupling unification due to non-universal soft supersymmetry breaking

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Abstract

Gauge coupling unification is studied in the MSSM with non-universal soft supersymmetry breaking terms. If gaugino masses are sufficiently smaller than scalar soft masses and the scalar soft masses have also certain types of non-universality, the gauge coupling unification scale can be larger than 3×10^{16} GeV even within the MSSM contents. String unification may not need a large threshold correction or a large modulus value. We also discuss the relation to the string model building.

Superstring theory is the presently known unique theory which unifies all interactions including the gravity. Various features of the superstring unification are studied by now. The unification of the gauge coupling constants is one of the expected features. Its unification is different from the usual grand unification scenario and does not need a unification group like $SU(5)$ or $SO(10)$. The gauge coupling unification $k_3 g_3^2 = k_2 g_2^2 = k_1 g_1^2$ takes place due to the fact that all gauge interactions are induced from the affine Kac-Moody algebras on the world sheet [1]. Its unification scale is estimated as $M_{\rm str} \simeq 0.5 \times g_{\rm str} \times 10^{18}$ GeV [2]. Recent study based on the precise measurements at LEP shows that the gauge coupling constants of $SU(3) \times SU(2) \times U(1)$ correctly meet at $M_X \simeq 3 \times 10^{16}$ GeV in the minimal supersymmetric standard model (MSSM) [3]. The explanation of this discrepancy between $M_{\rm str}$ and M_X is an important issue for building up superstring inspired models.

Some stringy explanations for the discrepancy are proposed by now. One of such possibilities is based on the existence of additional massless fields which become massive at an intermediate scale [4]. In general there are extra massless colored modes beyond the MSSM spectrum in the superstring models. However, the inclusion of these fields usually causes various phenomenological problems like proton decay. Moreover there are too many degrees of freedom to make some predictions. Thus as the first trial it seems more promising to find another explanation which works within the MSSM spectrum at least for the unification of $SU(3)$ and $SU(2)$ factor groups. In superstring there are infinite number of massive modes around $M_{\rm pl}$. These modes may bring the large threshold correction to the gauge coupling constants at $M_{\rm str}$ [5]. If this is the case, the gauge coupling constants split at $M_{\rm str}$ and appear to coincide at M_X. This possibility has been studied using the MSSM spectrum at the low energy reginon [6–10]. The models are stringently

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constrained to realize this scenario. Every field of the MSSM must have a nontrivial modular weight and also an overall modulus is required to have a large vacuum expectation value. For example, the Z_N ($Z_N \times Z_M$) orbifold models require $\mathrm{Re}\,T \equiv T_R \geq 7$ (3) to obtain the large threshold corrections consistent with the measured values of the coupling at M_Z.

As is well-known, the superstring theory generally has the stringy symmetry called the target space modular invariance [11]. If we impose this invariance on the model, the potential minimum will be around the selfdual point $T_R \sim \sqrt{2}$. In this case we cannot expect the large threshold correction. From this viewpoint, it is very interesting to study the possibility of pulling up the unification scale M_X to near $M_{\rm str}$ without the large threshold correction in the MSSM spectrum. In this letter we investigate this point noting non-universal soft supersymmetry breaking masses.

First of all we briefly review the string threshold correction [5] and the soft supersymmetry breaking masses [7,12,13]. In the following we concentrate ourselves on the case with an overall modulus. The generalization will be done in a straightforward way. As mentioned above, it is expected that superstring theory is invariant under the following target space modular transformation [14]:

$$T \to \frac{aT - ib}{icT + d}; \quad ad - bc = 1, \quad a,b,c,d \in \mathbf{Z} \qquad (1)$$

$$C_i \to (icT + d)^{n_i} C_i, \qquad (2)$$

where T is an overall modulus and C_i is a matter field. A modular weight n_i is an integer. Imposing the target space modular invariance, the threshold correction to the gauge coupling constants is calculated in certain types of orbifold models. Due to such an effect the gauge coupling constants at $M_{\rm str}$ are effectively shifted as [5]

$$\frac{1}{g_a^2} = \frac{k_a}{g_{\rm str}^2} - \frac{1}{16\pi^2}(b'_a - k_a\delta_{\rm GS}) \log[(T+T^*)|\eta(T)|^4], \qquad (3)$$

where k_a is the Kac-Moody level of the gauge group G_a and $\delta_{\rm GS}$ is a gauge group independent constant. It cancels a part of the duality anomaly in the same way as the Green-Schwarz mechanism of the $U(1)$ gauge [15]. The Dedekind function η is expressed as

$$\eta(T) = e^{-\pi T/12} \prod_{n=1}^{\infty} (1 - e^{-2\pi n T}). \qquad (4)$$

A duality anomaly coefficient b'_a is related to a coefficient b_a of a one-loop β-function in the MSSM as

$$b'_a = b_a + 2 \sum_i T_a(C_i)(1 + n_i). \qquad (5)$$

Here $T_a(C_i)$ is a second order index of the field C_i for G_a. The gauge coupling unification has been examined based on these formulae and the universal soft supersymmetry breaking terms within the MSSM framework. It is also suggested that the unification at $M_{\rm str}$ is possible if each superfield in the MSSM has a certain modular weight and the value of T_R is rather large. However, in the duality invariant theory the minimum of the potential is realized around the selfdual point $T_R \sim \sqrt{2}$. Actually, in the gaugino condensation scenario the selfdual point appears as the potential minimum [16] [5]. If this is the case, there seems to be a contradiction.

As is known from the study of the soft supersymmetry breaking terms, the fields with different modular weights have a non-universal soft masses. In the orbifold models with zero cosmological constant the scalar masses m_i and gaugino masses M_a at $M_{\rm str}$ are represented as [7,12]

$$m_i^2 = m_{3/2}^2 \left(1 + n_i \cos^2\theta\right) \qquad (6)$$

$$M_a = \sqrt{3} m_{3/2} \left(\frac{k_a \mathrm{Re} S}{\mathrm{Re} f_a} \sin\theta + \left(\frac{(b'_a - k_a\delta_{\rm GS}(T+T^*)\hat{G}_2(T+T^*)}{32\pi^3\sqrt{3}\mathrm{Re} f_a} \right) \cos\theta \right) \qquad (7)$$

where S is a dilaton field and $m_{3/2}$ is a gravitino mass. f_a is a gauge kinetic function of G_a. The nonholomorphic Eisenstein function $\hat{G}_2$ is defined as

$$\hat{G}_2(T+T^*) = -4\pi (\partial\eta(T)/\partial T)(\eta(T))^{-1} - 2\pi/(T+T^*).$$

A goldstino angle θ expresses the feature of the supersymmetry breaking. This fact suggests that we should

[5] Recently it is suggested that large T_R can be possible if we consider the loop correction in the gaugino condensation mechanism [17].

carefully treat the threshold correction due to the non-universal soft masses at the low energy region in the renormalization group study, especially if we consider the models with nontrivial modular weights.

At the low energy region the soft supersymmetry breaking masses are determined by the following supersymmetric one-loop renormalization group equations [6]

$$\frac{dm_i^2}{dt} = \frac{1}{8\pi^2}\Big(-4\sum_a C_a(i) M_a^2 g_a^2 + (\text{Yukawa terms})\Big), \tag{8}$$

$$\frac{dM_a}{dt} = \frac{b_a}{8\pi^2} g_a^2 M_a, \tag{9}$$

where $C_a(i)$ is the quadratic Casimirs for each scalar labelled by i. If we neglect Yukawa coupling contributions [7], these equations can be easily solved analytically and the results are

$$m_i^2(Q) = m_i^2(M_{\rm str}) + \sum_a \frac{2C_a(i)}{b_a}\left(1 - \frac{1}{(1+b_a\frac{g^2(M_{\rm str})}{8\pi^2}\ln\frac{M_{\rm str}}{Q})^2}\right) M_a^2(M_{\rm str}), \tag{10}$$

$$M_a(Q) = \frac{M_a(M_{\rm str})}{g^2(M_{\rm str})}\left(\frac{g^2(M_{\rm str})}{1+b_a\frac{g^2(M_{\rm str})}{8\pi^2}\ln\frac{M_{\rm str}}{Q}}\right). \tag{11}$$

If these masses widely split, their threshold corrections can affect the evolution of the gauge coupling constants and then the unification scale. Hereafter noting this point, we study the relation between the unification scale and the soft breaking masses. In the following study we consider the unification of $SU(3)$ and $SU(2)$ alone because the Kac-Moody level of $U(1)$ is a free parameter in the superstring theory [18].

[6] If some superpartners decouple at M_S, the one loop β-function coefficient b_a in the Eq. (9) happens to be modified below M_S. It is also different from $\tilde{b}_a$ in Eq. (12). This is because one-loop corrections to the gaugino mass include graphs which have both of the fermions and their superpartners simultaneously in internal lines. In the following analysis we take account of this point.

[7] Except for the contribution of top Yukawa coupling, this approximation will be completely justified. We will return to this point later.

We now classify the models by the mass patterns of the gauginos, squarks and sleptons at the low energy region. To simplify the analysis, we divide the fields of the MSSM into two groups named as A and B. Group A is a set of superpartners which decouple from the renormalization group equations at $M_S(\geqslant M_Z)$. The remaining superpartners belong to Group B and contribute to them down to M_Z. This procedure will be sufficient to see the qualitative feature of the gauge coupling unification. As we only consider the unification scale of $SU(3)$ and $SU(2)$, the relevant superpartners in the MSSM are squark doublets Q, squark singlets U, D, slepton doublets L [8], Higgsino H_1, H_2 and gauginos λ_3, λ_2. The typical cases presented here are the following:

Case I (ordinary MSSM):
$A = \{Q, U, D, L, H_1, H_2, \lambda_3, \lambda_2\}$,
Case II: $A = \{Q, U, D, L, H_1, H_2\}$, $B = \{\lambda_3, \lambda_2\}$,
Case III: $A = \{Q, L, H_1, H_2\}$, $B = \{U, D, \lambda_3, \lambda_2\}$,
Case IV: $A = \{L, H_1, H_2\}$, $B = \{Q, U, D, \lambda_3, \lambda_2\}$,
Case V: $A = \{Q, U, D, H_1, H_2\}$, $B = \{L, \lambda_3, \lambda_2\}$,
Case VI: $A = \{U, D, H_1, H_2\}$, $B = \{Q, L, \lambda_3, \lambda_2\}$,
where the generation indices are abbreviated. For the Higgs scalars we confine ourselves to the situation in each case that one Higgs doublet decouples at M_S.

Here we should note some points on the non-universality of soft scalar masses. At first to justify the above classification the gaugino masses should not be large so as not to erase the difference in the soft scalar masses. Otherwise, as seen from the renormalization group equations of the scalar masses, the contribution to the scalar mass from gauginos becomes dominant and erases the non-universality at the low energy region. Secondly the non-universal soft squark masses are dangerous for the flavor changing neutral currents. To avoid it we need to choose the non-universality which induces no dangerous mass difference between the generations. Finally M_S cannot be so large from the naturalness argument. It should be at most a few TeV.

Now we study the unification scale M_X of $SU(3)$ and $SU(2)$ gauge couplings beginning from the low energy region. They are related by the renormalization group equation as

[8] Later we shall discuss the $U(1)$ gauge coupling where the slepton singlets will be treated in the similar way.

$$\alpha_a^{-1}(M_X) = \alpha_a^{-1}(M_S) - \frac{b_a}{2\pi}\ln\frac{M_X}{M_S},$$
$$\alpha_a^{-1}(M_Z) = \alpha_a^{-1}(M_S) - \frac{\bar{b}_a}{2\pi}\ln\frac{M_Z}{M_S}. \qquad (12)$$

Using these formulae, we found that the unification scale M_X is expressed as a function of M_S,

$$M_X = M_S\left(\frac{M_Z}{M_S}\right)^{(\bar{b}_3-\bar{b}_2)/(b_3-b_2)} \times \exp\left(\frac{2\pi}{b_3-b_2}\left(\alpha_3^{-1}(M_Z) - \alpha_2^{-1}(M_Z)\right)\right). \qquad (13)$$

Our models are completely equivalent to the MSSM from M_X to M_S so that $b_3 = -3$ and $b_2 = 1$. In the region below M_S $\bar{b}_a$ is different in each case. The values of $(\bar{b}_3, \bar{b}_2)$ are the following: $(-7, -19/6)$ in *Case I*, $(-5, -11/6)$ in *Case II*, $(-4, -11/6)$ in *Case III*, $(-3, -1/3)$ in *Case IV*, $(-5, -4/3)$ in *Case V*, $(-4, 1/6)$ in *Case VI*. As easily seen from Eq. (13), the smaller value of $(\bar{b}_3 - \bar{b}_2)/(b_3 - b_2)$ is preferable for our scenario. The unification scale M_X can be estimated for the various values of M_S if we use

$$M_Z = 91.173\ \text{GeV}, \quad \alpha^{-1}(M_Z) = 127.9,$$
$$\sin^2\theta_W(M_Z) = 0.2328, \quad \alpha_3(M_Z) = 0.118, \qquad (14)$$

as the input data [19]. Fig. 1 shows the change of the unification scale M_X against the decoupling scale M_S of the superpartners in Group A for each case. It is remarkable that M_X becomes larger accompanied with the increase of M_S in *Case II* $\sim$ *V*. This feature is very different from *Case I* in which $M_X \sim 3\times10^{16}$ GeV is almost stable against M_S. It should be also noted that the unification scale M_X moves upward if the squark doublet decouples at M_S. The non-universal soft masses tend to give a higher unification scale than the case of the universal soft masses. If this qualitative tendency is the case, M_X can reach $M_{\rm str}$ even if the threshold correction is not so large. From the quantitative point of view we should note that there is an ambiguity of order $10^{0.3}$ GeV also in the present estimation of M_X as usual.

Using Eqs. (3) and (14), the necessary threshold correction is estimated as

$$\sqrt{T+T^*}|\eta(T)|^2 = \left(\frac{M_{\rm str}}{M_X}\right)^{(b_3-b_2)/(b'_3-b'_2)}, \qquad (15)$$

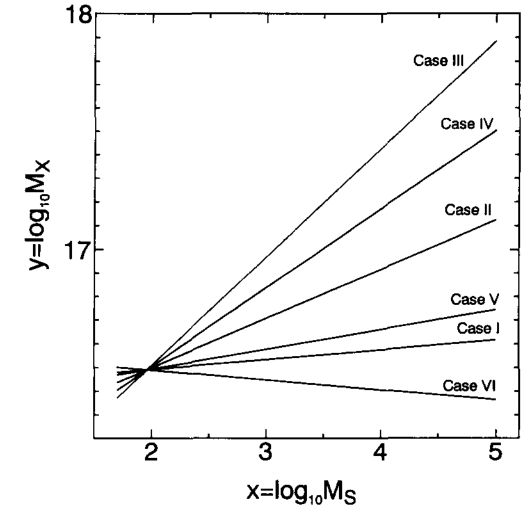

Fig. 1. Unification scale M_X of the gauge couplings of $SU(3)$ and $SU(2)$ corresponding to the decoupling scale M_S of some superpartners of MSSM. Both scales are defined as $M_X = 10^y$ GeV and $M_S = 10^x$ GeV. The explanation of each case is given in the text.

where we take the Kac-Moody level as $k_3 = k_2 = 1$. As an example, let us adopt *Case III* and estimate the threshold correction required to realize the unification at $M_{\rm str}$. In Ref. [10] it is shown that the MSSM derived from the Z_N orbifold models can have $b'_3 - b'_2 = 3$ or 4 and for Z_6-II the maximum value of $b'_3 - b'_2$ is equal to 6. Putting $M_S = 1$ TeV and 3 TeV, we have $M_X = 10^{17.0}$ GeV and $10^{17.2}$ GeV, respectively (see Fig. 1). In the case where $M_X = 10^{17.0}$ GeV and $b'_3 - b'_2 = 3, 4$ and 6, we obtain $T_R = 5.5, 4.5$ and 3.5, respectively, using (16) and $M_{\rm str} = 3.7\times10^{17}$ GeV. These values of T_R are fairly smaller than the ones estimated in the universal soft breaking case where the unification scale is $M_X = 10^{16.5}$ GeV. For example, in the case of $M_X = 10^{16.5}$ GeV the difference $b'_3 - b'_2 = 3$ leads to $T_R = 9$. Further in the case where $M_X = 10^{17.2}$ GeV and $b'_3 - b'_2 = 3$ and 4, we can have $T_R = 4$ and 3.5. The $Z_N \times Z_M$ orbifold models can have larger values of $b'_3 - b'_2$ than the Z_N orbifold models [9] and then derive the smaller values of T_R, e.g. $T_R < 2$ in the case of $M_X = 10^{17}$ GeV.

Next we shall consider in what type of superstring models the favorable soft breaking masses presented in the previous part are realized. From the recent study of the soft supersymmetry breaking terms, we know their general features at M_X [12]. On the other hand,

Table 1
The change of the soft breaking mass from the low energy region ($M = M_S$ or M_Z) to M_X and the ratio of the unification coupling α_X and $U(1)$ coupling $\alpha_1 \equiv g_1^2/4\pi$ at M_X

	$M_S = 1$ TeV						$M_S = \sqrt{10}$ TeV					
	Case I	*Case II*	*Case III*	*Case IV*	*Case V*	*Case VI*	*Case I*	*Case II*	*Case III*	*Case IV*	*Case V*	*Case VI*
$\Delta m_Q^2/M_U^2$	5.48	4.98	5.31	7.24	4.86	6.79	3.69	4.31	4.68	7.35	4.17	6.84
$\Delta m_U^2/M_U^2$	5.10	4.60	6.74	6.81	4.47	4.64	3.32	3.96	6.97	6.92	3.80	3.98
$\Delta m_L^2/M_U^2$	0.48	0.47	0.50	0.50	0.55	0.50	0.46	0.45	0.49	0.49	0.52	0.48
M_3/M_U	2.34	3.56	3.25	2.93	3.51	3.18	2.16	3.90	3.43	2.95	3.82	3.31
M_2/M_U	0.84	0.91	0.90	0.85	0.89	0.83	0.85	0.95	0.94	0.86	0.92	0.84
M_1/M_U	0.43	0.42	0.40	0.40	0.42	0.43	0.44	0.43	0.40	0.40	0.43	0.44
α_X/α_1	1.57	1.57	1.52	1.57	1.60	1.65	1.55	1.55	1.48	1.55	1.60	1.67

For an example we take $M_S = 1$ TeV and $M_S = \sqrt{10}$ TeV. Δm_i^2 is defined as $\Delta m_i^2 = m_i^2(M) - m_i^2(M_X)$ and $M_a = M_a(M_Z)$. The listed values are normalized by the gaugino mass M_U at $M_{\rm str}$. In the MSSM with $M = 100$ GeV, $\Delta m_Q^2/M_U^2 = 6.87$, $\Delta m_U^2/M_U^2 = 6.45$, $\Delta m_L^2/M_U^2 = 0.53$, $M_3/M_U = 2.86$, $M_2/M_U = 0.82$, $M_1/M_U = 0.40$ and $\alpha_X/\alpha_1 = 1.61$.

we can transmute the soft masses at the low energy region into the ones at M_X using Eqs. (10) and (11) in our present cases. Comparing them we can know what kinds of minimal superstring standard models do not need the large threshold correction for the string unification. We show the change of the soft masses from the low energy region to M_X against the gaugino mass M_U at M_X for each case in Table 1. As mentioned in the previous part the large gaugino mass will dilute the non-universality in the soft scalar masses by the renormalization group effect. This imposes a certain condition on the upper bound of gaugino mass to make our scheme work. We can find from Table 1 that the dilution effects of the non-universality will be escapable if $m_i^2(M_X)/M_U > 0.1$ is satisfied.

It is very interesting to know in what type of supersymmetry breaking this situation is generally realized. As discussed in Ref. [12] such soft terms can be caused in the moduli dominated supersymmetry breaking (large $\cos^2\theta$). However, our scenario needs various modular weights $n_i \leq -2$ for the non-universality in *Case III* $\sim$ *VI*. The goldstino angle $\cos^2\theta$ cannot be so large to guarantee $m_i^2(M_X) > 0$ because of its modular weight dependence as seen from Eq. (6). In such cases generally the dilaton contribution to the soft breaking masses is dominated and then $m_i^2/M_U < 1$ for the suitable values of $\cos\theta$ and T_R at M_X. The original non-universality in the soft scalar masses may be diluted away. A more careful study for these cases will be necessary. The most promising case where $m_i(M_X)/M_U > 1$ is *Case II*. Such soft masses can be easily realized in the orbifold model in which the modular weights of all massless modes are $n_i = -1$ and also the gaugino condensation model as suggested in Ref. [20]. In such models it is sufficient for our scenario to take $M_S = 1 \sim 4$ TeV.

Some comments are in order. Firstly we have introduced the soft scalar masses which are degenerate between the different generations in the same type flavors. The non-universality presented here will not yield the dangerous FCNC. Secondly we neglected the Yukawa couplings in the renormalization group equations to estimate the scalar masses. Except for the case of the top sector this treatment will be justified. The top Yukawa reduces the stop mass at the low energy region. The stop mass at M_X must be large enough to keep the degeneracy between the same flavor at M_Z. Anyway its effect will not affect our results crucially. Thirdly we do not refer to the unification of $U(1)$. However, its occurence can be expected by choosing a suitable value of the Kac-Moody level k_1 as suggested in Ref. [18,9,10]. The level k_1 can be estimated from the last row in the Table 1.

In summary, we investigated the gauge coupling unification in MSSM with the non-universal soft supersymmetry breaking masses. We found that in such cases the unification scale could be pulled up toward the string unification scale without the large threshold correction. This seems to be favorable to the superstring unification in the duality invariant string models. The physics of the non-universal soft supersymmetry breaking will deserve further investigation for the string unification.

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