How to Save the Minimal Supersymmetric SU(5) Model?

J.L. Chkareuli, and I.G. Gogoladze
Institute of Physics, Georgian Academy of Sciences
380077 Tbilisi, Georgia

Abstract

We show that all the present difficulties of the minimal supersymmetric $SU(5)$ model including the large $\alpha_s(M_Z)$ prediction (with no marginally high SUSY soft-breaking scale), the proton decay mode $p \to \bar{\nu} K^+$ at a rate largely excluded by experiment, a considerable mismatch with string scale unification and uncontrollable gravitational smearing can be successfully overcome with a new renormalizable reflection-invariant superpotential with two adjoint scalars, one of which is interpreted as a massive string mode essentially decoupled from the lower-energy particle spectra. This superpotential is proved to fix a mass ratio of the basic adjoint scalar moduli $(8_c, 1)$ and $(1, 3_w)$, $M_3 = 4M_8$ (just as in non-SUSY $SU(5)$ model), while its gauge-type reflection symmetry essentially protect the model from gravitational smearing. The significant heavy threshold effect related with the generic mass splitting of adjoint moduli is shown to alter properly the running of gauge couplings, thus giving a natural solution to the realistic string-scale grand unification. The further symmetry condition of the (top-bottom) Yukawa and gauge coupling superunification at a string scale leads immediately to a series of the very distinctive predictions (of α_s in general, while top and bottom quark masses in absence of any large supersymmetric threshold corrections):

$$\alpha_s(M_Z) = 0.119 \pm 0.001 \ , \quad m_t = 180 \pm 1 \ , \frac{m_b}{m_\tau}(M_Z) = 1.79 \pm 0.01$$

in a surprising agreement with experiment.

Some euphoria caused by the first indication [1] of unification of gauge couplings extrapolated from their low-energy values under assumption of the simplest particle content corresponding to the Minimal Supersymmetric Standard Model (MSSM) seems to be over. In recent years new through tests of the Standard Model have been performed [2]. They show clearly that new states beyond those of MSSM should be included into play not to be in conflict with the present precision measurement data, if one contemplated the gauge coupling unification with not unacceptably high SUSY soft-breaking scale ($M_{SUSY}\rangle\rangle M_Z$) [3].

On the other hand, the scale M_U at which the couplings would meet lies one order of magnitude below than the typical string scale $M_{STR} \simeq 5 \cdot 10^{17}$ GeV [4]. This mismatch, while often considered as a drawback of string phenomenology, may be interpreted as the most clear string motivation for a possible grand-unified symmetry beyond MSSM [5] In this scenario [4], the standard gauge couplings would still unify at M_U to form the single coupling g_U, but then it would run up to the string scale M_{STR} and unify with any other gauge ("hidden") and gravitational couplings.

Now, speaking about the possible string-inspired GUT candidates, the minimal supersymmetric $SU(5)$ model [6] should be considered at the first place, although it could be stringy realized at higher affine levels $k \geq 2$ only, or in the so-called "diagonal construction" within a k-fold product of the $SU(5)$'s at a level $k = 1$ [4]. The $SU(5)$ model with just the light MSSM spectra contributing to the evaluation of the gauge couplings can initiate the additional logarithmic threshold corrections due to the super-heavy states $\Sigma_8(8_c, 1) + \Sigma_3(1, 3_W)$ and $H_c(3_c, 1) + \bar{H}_c(\bar{3}_c, 1)$, which are left as the non-Goldstone remnants of the starting Higgs multiplets $\Sigma(24)$ and $H(5) + \bar{H}(\bar{5})$ when $SU(5)$ breaks to $SU(3)_C \otimes SU(2)_W \otimes U(1)_Y$ and then to $SU(3)_C \otimes U(1)_{EM}$, respectively. At the same time the model has an additional severe restriction following from proton decay due to the color-triplet $H_c(\bar{H}_c)$ exchange [7]. While at the moment its mass M_c can favorably be arranged inside of the narrow interval $2.0 \div 2.4 \cdot 10^{16}$ GeV (from the negative search for the proton decay and the detailed renormalization group (RG) analysis for the gauge couplings, respectively) [8], the model is apparently nearing to be ruled out [9] by a combination of the improved lower limits on the proton decay mode $p \to \bar{\nu} K^+$ from SuperKamiokande and on the superparticle masses at LEP2, expected in the short run.

In this Letter we argue that the above-mentioned adjoint remnants Σ_8

and Σ_3 could play a larger part in superhigh-scale physics, than it was yet taken, thus giving somewhat missing details to the unification picture in the minimal supersymmetric $SU(5)$ model. It is well known [4, 10] that they appear in many string models as continuous moduli which is why they can remain relatively light ($M_\Sigma << M_U$) and, as a result they push the unification scale M_U up to M_{STR}, inclusive [8, 10]. At the same time, while a prediction for α_s was found independent (at one-loop order) of M_U [11] and M_Σ [8, 12], that is turned out to depend crucially on the mass-splitting between Σ_8 and Σ_3, as it is demonstrated clearly below. While in the standard one-adjoint superpotential [6] such a splitting is generically absent at a GUT scale, with a new renormalizable superpotential proposed, which contains also the second adjoint Ω (interpreted as a massive string mode), the large generic mass-splitting appeared between Σ_8 and Σ_3 is found fairly ample for gauge coupling unification to be completely adapted with the present values of $\alpha_s(M_Z)$, weak mixing angle Θ_W and top-quark pole mass ($\overline{MS}$ values) [2]

$$\alpha_s(M_Z) = 0.119 \pm 0.004, \quad sin^2_W = 0.2313 \pm 0.0003, \\ m_t = 175.6 \pm 5.5 \ , \tag{1}$$

even though the SUSY soft-breaking scale M_{SUSY} ranges closely to M_Z and the color triplet mass M_c is taken at the GUT scale M_U. Both of cases of the low and high values of $tan\beta$ (the ratio of the vacuum expectation values (VEVs) of the up-type and down-type Higgs doublets involved) therewith look in the model to be physically interesting.

We start recalling that, to one-loop order, gauge coupling unification is given by the three RG equations relating the values of the gauge couplings at the Z-peak $\alpha_i(M_Z)$ $(i = 1, 2, 3)$, and the common gauge coupling α_U [1]:

$$\alpha_i^{-1} = \alpha_U^{-1} + \sum_p \frac{b_i^p}{2\pi} ln \frac{M_U}{M_P} \tag{2}$$

where b_i^p are the three b-factors corresponding to the $SU(5)$ subgroups $U(1)$, $SU(2)$ and $SU(3)$, respectively, for the particle lebeled by p. The sum extends over all the contributing particles in the model, and M_p is the mass threshold at which each decouples. All of the SM particles and also the second Higgs doublet of MSSM are already presented at the starting scale M_Z. Next is assumed to be supersymmetrice threshold associated with the decoupling of the supersymmetric particles at some single effective (lumped) scale M_{SUSY}

[3]; we propose thereafter the relatively low values of M_{SUSY}, $M_{SUSY} \sim M_Z$, to keep sparticle masses typically in a few hundred GeV region. The superheavy states, such as the adjoint fragments Σ_8 and Σ_3 at the masses M_8 and M_3, respectively, and the color-triplets H_c and $\bar{H}_c$ at a mass M_c are also included in the evaluation equations (2). As to the superheavy gauge bosons and their superpartners (X-states), they do not contribute to the Eq.(2), for they are assumed to lie on the GUT scale M_U ($M_X = M_U$), above which all particles fill complete $SU(5)$ multiplets.

Now, by taking the special combination of Eqs.(2) we are led to the simple relation between gauge couplings and the logarithms of the neighboring threshold mass ratios

$$\begin{aligned} 12\alpha_2^{-1} - 7\alpha_3^{-1} - 5\alpha_1^{-1} \; &= \\ \frac{3}{2\pi}(-2ln\frac{M_X}{M_c} + ln\frac{M_c}{M_3} - 7ln\frac{M_3}{M_8} - \frac{19}{6}ln\frac{M_{SUSY}}{M_Z}) \end{aligned} \qquad (3)$$

which can be viewed as the basis for giving the qualitative constraints to the $\alpha_s(M_Z)$ depending on the present (very precise) measurement of $sin^2\Theta_W$ (1) and superheavy mass splitting, when one goes beyond the MSSM limit ($M_X = M_c = M_3 = M_8$). One can see from Eq.(3) that α_s increases with $\frac{M_c}{M_3}$ and decreases with $\frac{M_X}{M_c}$, $\frac{M_{SUSY}}{M_Z}$ and, especially, with $\frac{M_3}{M_8}$ (the largest coefficient before logarithm). On the other hand, with an "alive" color triplet H_c ($M_c < M_X$) one can raise the GUT scale M_X by lowering the masses of the Σ remnants (say, M_3 with M_8 then calculated) without affecting α_s, as theory predicts (to one-loop order) the entire mass combination $M_X^2 M_3$ in addition to M_c and common gauge coupling α_U (that can be more clearly viewed from the other running coupling combinations $5\alpha_1^{-1} - 3\alpha_2^{-1} - 2\alpha_3^{-1}$ and $3\alpha_2^{-1} - 2\alpha_3^{-1} - \alpha_1^{-1}$ extracted from Eq.(1) respectively [8, 11, 12]. When the color triplet is taken at a GUT scale ($M_c = M_X$), both of masses M_X and M_3 and α_U [13] are then predicted. And finally, when all thresholds are taken to be degenerate ($M_c = M_3 = M_X$), besides the M_X and α_U, the strong coupling $\alpha_S(M_Z)$ depending on the generic mass ratio M_3/M_8 can also be predicted – somewhat naive, while truly predictive, ansatz of grand unification leading in the standard case ($M_3/M_8 = 1$ at a GUT scale M_X) [6] to the unacceptably high values of $\alpha_S(M_Z)$ for the physically most interesting SUSY soft-breaking scale area [3].

However, a somewhat different (more string-motivated) version of the minimal supersymmetric $SU(5)$ model, we are coming to, with a generically large mass splitting between Σ_3 and Σ_8 suggests wholly different unification picture. That follows essentially from a general renormalizable two-adjoint superpotential of Σ and Ω satisfying also the reflection symmetry ($\Sigma \to -\Sigma$, $\Omega \to \Omega$) [14]

$$W = \frac{1}{2}m\Sigma^2 + \frac{1}{2}M_P\Omega^2 + \frac{1}{2}h\Sigma^2\Omega + \frac{1}{3}\lambda\Omega^3 + W' \tag{4}$$

where the second adjoint Ω can be considered as a state originated from the massive string mode with the (conventianally reduced) Planck mass $M_P = (8\pi G_N)^{-1/2} \simeq 2.4 \cdot 10^{18}$ GeV, while the basic adjoint is left (relatively) light when one goes from the string scale to lower energies, $m\langle\langle M_P$ [15]. The superpotential includes also the ordinary Higgs-doublet containing fundamental chiral supermultiplets H and $\bar{H}$ presented in W', which will be discussed just below. It is particularly remarkable that there are no any generically massless non-trivial string modes, appart from those corresponding to the standard supersymmetric $SU(5)$ GUT [6].

One can find now from the vanishing F-terms of the adjoints Σ and Ω that their basic supersymmetric vacuum configurations, besides the trivial (symmetry-unbroken) case and the case, when the superheavy adjoint Ω alone developes the vacuum expectation value (VEV), include also the desired case when both of them develop the paralel VEVs which break $SU(5)$ down to $SU(3) \otimes SU(2) \otimes U(1)$

$$\begin{gathered}\Sigma = diag(1,\ 1,\ 1,\ \ -3/2,\ \ -3/2)\sigma\ , \\ \sigma = \frac{\sqrt{8mM_P}}{h}(1 - \frac{m}{M_P}\frac{\lambda}{h})^{1/2} \simeq \frac{\sqrt{8mM_P}}{h}\end{gathered} \tag{5}$$

$$\Omega = diag(1,\ 1,\ 1,\ \ -3/2,\ \ -3/2)\omega\ ,\quad \omega = \frac{2m}{h} \tag{6}$$

with the hierarchical large VEV ratio $r = (2M_P/m)^{1/2}$ inversed to their masses. After symmetry breaking the non-Goldstone remnants of Σ (Σ_3 and Σ_8) survive, while being a little mixed ($\sim r^{-1}$) with Ω_3 and Ω_8, respectively. Remarkably enough, to the obviously good approximation ($\frac{h}{\lambda}\rangle\rangle\frac{m}{M_P}$ for any reasonable values of the couplings h and λ), already used in Eq.(5), the diagonalized mass ratio of the Σ_3 and Σ_8 is definitely fixed (at GUT scale) as

$$M_3 = 10m \ , \quad M_8 = \frac{5}{2}m \ , \quad \frac{M_3}{M_8} = 4 \tag{7}$$

in contrast to $M_3/M_8 = 1$ in the standard one-adjoint superpotential [6]. Another distinctive feature of the superpotential considered (which can easily be viewed from Eqs.(5) and (7)) is the quite moderate values of the adjoint coupling h even in the case of the pushed string-scale unification: $h \sim 0.1$ instead of somewhat fine-tuned adjoint coupling value $\sim 10^{-5}$ in the ordinary one-adjoint case [8, 12].

Let us turn now to the electroweak symmetry breaking in the model induced by the fundamental Higgs supermultiplets H and $\bar{H}$ in W' Eq.(4). It is apparent that they must necessarily interact with the basic adjoint Σ, since another (superheavy) adjoint Ω develop too small VEV (6) to give a reasonable order of mass to the color triplets H_c and $\bar{H}_c$ after a fine-tuning (to make the accompanied doublets light) occurs. That is the $\bar{H}H$ pair, along with Σ, has to change sign ($\bar{H}H \to -\bar{H}H$) under reflection symmetry, owing to which their mass term can not be included in the superpotential. Instead, the singlet superfield S ("the 25th component" of the Σ with $S \to -S$ defined) should be introduced to make a fine-tuning required. That part W' of the reflection-invariant superpotential Eq.(4) takes a general form

$$W' = \bar{H}(\lambda_1 \Sigma + \lambda_2 S)H + \frac{1}{2}m' S^2 + \lambda' S \Sigma \Omega \tag{8}$$

As it can routinely be established from a total superpotential W (4,8), there always appears possibility in a new supersymmetric vacuum configuration ($H = \bar{H} = 0$)

$$S = -\frac{\lambda\prime}{m'} Tr(\Sigma\Omega) \simeq -15 q\sigma \quad (q \equiv \frac{\lambda'}{h} / \frac{m'}{m}) \tag{9}$$

(see σ in Eq.(5)) to pick a right order of the coupling-and-mass ratio q so that, from the one hand, not to disturb noticeably the adjoint vacuum solutions (5,6) and masses M_3 and M_8 (7) and, from the other hand, to attain (after a fine-tuning $10q = \lambda_1/\lambda_2$) the desired order of the color-triplet mass M_c in the vicinity of the unification scale M_X, $M_c = \frac{2}{5}\frac{\lambda_1}{g_U} M_X$ ($M_X = \frac{5}{\sqrt{2}} g_U \sigma$, g_U is the unified coupling constant).

So, with the observations made we are ready now to carry out the standard two-loop analysis (with conversion from $\overline{MS}$ scheme to $\overline{DR}$ one included) [1, 16] for gauge (α_1, α_2, α_3) and Yukawa (α_t, α_b and α_τ in a self-evident notation for top- and bottom-quarks and tau-lepton) coupling evolution depending on, apart from the single-scale (M_{SUSY}) supersymmetric threshold corrections mentioned above, the heavy Σ threshold only. This varies, in turn, from the GUT scale M_X ($M_3 = M_X$, $M_8 = \frac{1}{4}M_X$) down to some intermediate value $O(10^{14})$ GeV pushing thereafter the M_X up to the string scale M_{STR}. The mass splitting between weak triplet Σ_3 and color octet Σ_8 in themselves noticeably decreases, while M_3 and M_8 run from M_X down to the lower energies, as it results from their own two-loop RG evolution, which is also included in the analysis. On the other hand, the color triplets $H_c(\bar{H}_c)$ are always taken at M_X, for the strings seem to say nothing why any states, other than the adjoint moduli Σ_3 and Σ_8, could left relatively light.

As to the Yukawa coupling evolution, we consider the two possible cases of low and large values of $tan\beta$ leading to the proper bottom-tau Yukawa unification [6, 17] with their mass ratio $R = m_b/m_\tau$ within the experimental region $R_{exp}(M_Z) = 1.60 \pm 0.25$ [2, 17] required. The first case corresponds to the large enough value of α_t at a unification scale M_X, $\alpha_t \rangle 0.1$ (while $\alpha_b(M_X)$ is significantly smaller), evolving rapidly towards its infrared fixed point. From the observable values of the t and b quark and τ lepton masses (m_t, m_b and m_τ) the proper values of $tan\beta$ are then predicted. The second case, while generally admitted over the whole area for the starting values for α_t and α_b at M_X, is favorably advanced to the physically well-motivated (with or without the underlying SO(10) gauge symmetry of no concern) top-bottom unification case [17] with the relatively low, though still providing the fixed-point solution, α_t and α_b values at M_X, $\alpha_t(M_X) = \alpha_b(M_X) = 0.02 \div 0.1$, required. Here, not only $tan\beta$, but also m_t could distinctively be predicted (from m_b and m_τ), if there were a more detailed information about superparticle mass spectrum, since the large supersymmetric loop contributions to the bottom mass are generally expected which make uncertain the top mass prediction as well [17]. Remarkably enough, the top-bottom unification is turned out to work well when the SUSY parameter sector is arranged in such a way (low values of μ and $m_{1/2}$ and large values of m_0 [18] to make the above radiative corrections to be negligible.

Our results, as appeared after numerical integration of all the RG equations listed above, are largely summarized in Figs. 1a and 1b. One can see from them that the $\alpha_s(M_Z)$ values predicted with a high accuracy (within of a percent), following essentially from the used (very precise) values of $sin^2\theta_W$ (1), under Yukawa coupling appropriately fixed at M_X (wherever in the above intervals), are in a good agreement with the World average value (1) for the unification mass M_X ranging closely to M_{STR}.

The values of $\alpha_s(M_Z)$ on the very left of Fig.1a correspond to the case when $M_3 = M_X$ (thresholds are degenerate). This value, $\alpha_S(M_Z) = 0.116 \pm 0.001$ (for the $\alpha_t(M_X) = 0.3$ taken) , can be considered as a naive threshold-neglecting prediction of the present model in the contrast to the analogous value $\alpha_S(M_Z) = 0.125 \pm 0.001$ in the standard $SU(5)$ under the same conditions.

In Fig.1b the predicted values of the top quark pole mass are also exposed. It is readily seen that the experimentally favorable intervals for m_t and α_S (1) correspond in much to the same area of M_X in the vicinity of M_{STR}. Interestingly, the unification mass region allowed is automatically turned out to largely be safe for proton decay through the Higgs color-triplet exchange [7, 8, 9].

And lastly, the most interesting thing which seems to occur in the case of the high-scale top-bottom unification considered. The low starting values of α_t and α_b at M_X, as well as the closeness of the unification mass M_X to the string scale, allow one to make a next step towards the most symmetrical case which can be realized in the present string-motivated $SU(5)$ - Yukawa and gauge coupling superunification at a string scale:

$$\begin{aligned} \alpha_t(M_X) = \alpha_b(M_X) = \alpha_\tau(M_X) = \alpha_U \ , \\ M_X = M_{STR} \end{aligned} \tag{10}$$

This conjecture certainly could concern the third-family Yukawa couplings solely, since those ones could naturally arise from the basic string-inspired interactions, whereas masses and mixing of the other families seemed to be caused by some more complex and model-dependent dynamics showing itself at lower energies. Due to a crucial reduction of a number of the fundamental parameters the gauge-Yukawa coupling unification leads immediately (in absence of any large supersymmetric threshold corrections mentioned) to a series of the very distinctive predictions

$$\alpha_S(M_Z) = 0.119 \pm 0.001 \ , \quad m_t = 180 \pm 1 \ ,$$

$$\frac{m_b}{m_\tau} = 1.79 \pm 0.01 \ , \quad tan\beta = 52 \pm 0.2 \tag{11}$$

in a surprising agreement with experiment [2]. In Fig.2 the superunification of gauge and Yukawa couplings is demonstrated.

The two concluding remarks concern the other salient features of the superpotential W (4).

The first one is that a generic adjoint mass ratio (7), while underlying the self-consistent string-scale minimal supersymmetric $SU(5)$ model presented, remains in a general $SU(N)$ theory broken to $SU(5)$ by the set of the $N-5$ additional fundamental supermultiplets $\phi^{(k)}$ and $\bar{\phi}^{(k)}$ ($k = 1, \ldots, N-5$), which interact with the adjoint Σ via the general invariant couplings of type $\bar{\phi}\Sigma\phi$ (other terms are forbidden by the above reflection symmetry[3] $\bar{\phi}\phi \to -\bar{\phi}\phi$, $\Sigma \to -\Sigma$) included in the superpotential W (4). This is to say that one can equally well start from the $SU(N)$ GUT and drive at the same unification picture.

The second one refers to the possible corrections to the superpotential W arising from the high-dimension operators [19] induced at the Planck scale. Fortunately, due to the same basic reflection symmetry[3] of the model, such operators, if appeared for scalars Σ and S developing the principal VEVs, should have dimension six and higher, $\delta L = \frac{c}{M_P^2}\, Tr(GG\Sigma^2) + \ldots$ (G is the gauge field-strengh matrix of the $SU(5)$, c=$O(1)$), whose influence on the present model predictions seems to be negligible in contrast to the standard $SU(5)$ where they can be largely smeared out [19].

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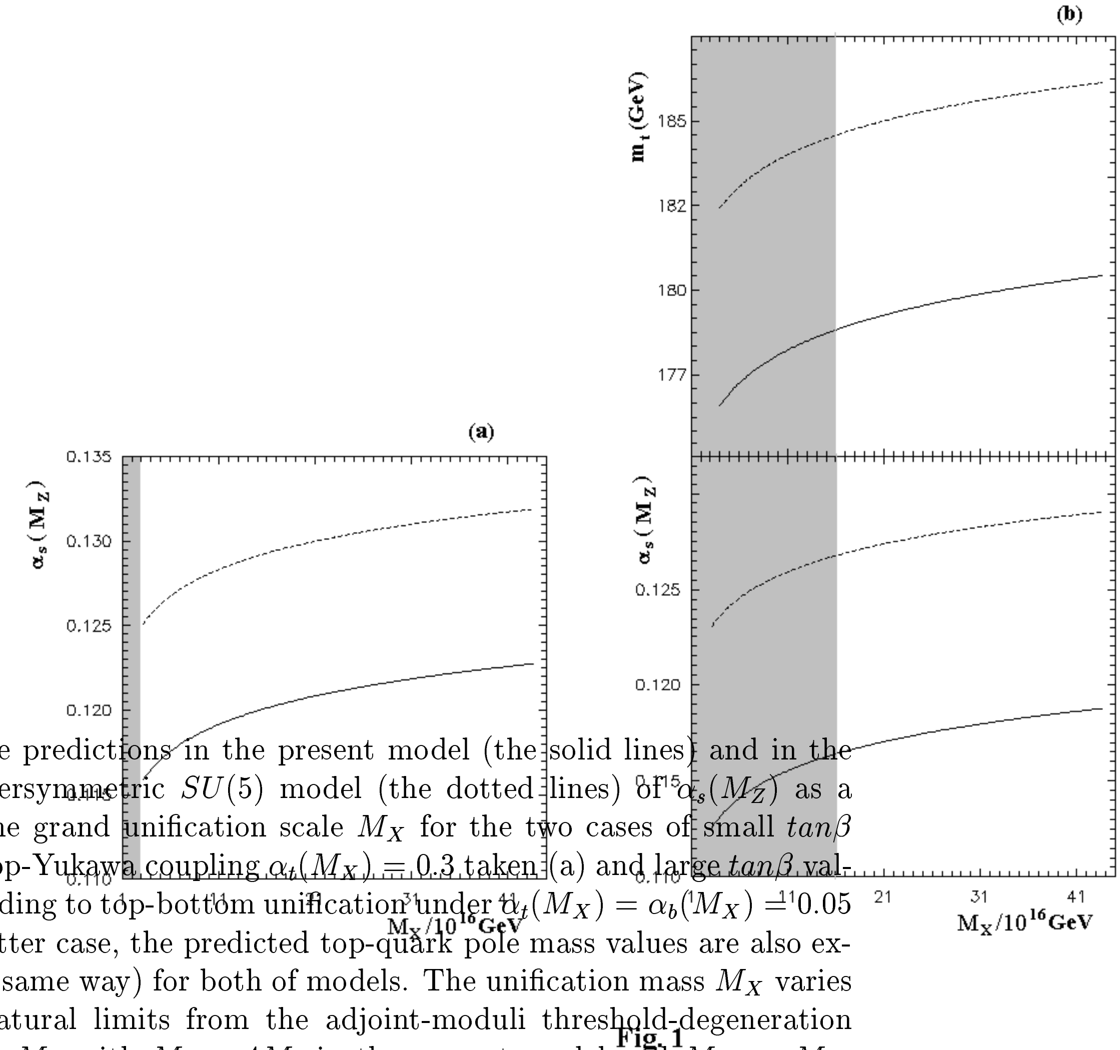

Figure 1: The predictions in the present model (the solid lines) and in the standard supersymmetric $SU(5)$ model (the dotted lines) of $\alpha_s(M_Z)$ as a function of the grand unification scale M_X for the two cases of small $tan\beta$ values with top-Yukawa coupling $\alpha_t(M_X) = 0.3$ taken (a) and large $tan\beta$ values corresponding to top-bottom unification under $\alpha_t(M_X) = \alpha_b(M_X) = 0.05$ (b). In the latter case, the predicted top-quark pole mass values are also exposed (in the same way) for both of models. The unification mass M_X varies within the natural limits from the adjoint-moduli threshold-degeneration point ($M_X = M_\Sigma$ with $M_3 = 4M_8$ in the present model and $M_{\Sigma_3} = M_{\Sigma_8}$ in the standard $SU(5)$) to the string scale ($M_X = M_{STR}$), while the color-triplet mass is assumed to be at unification scale in all cases ($M_c = M_X$). The all-shaded areas on the left of the figures (a) and (b) are generally disallowed by the present bound on nucleon stability.

Figure 2: The superunification of gauge (α_1, α_2, α_3) and Yukawa (top, bottom, tau) couplings at the string scale (the solid and dotted lines, respectively).

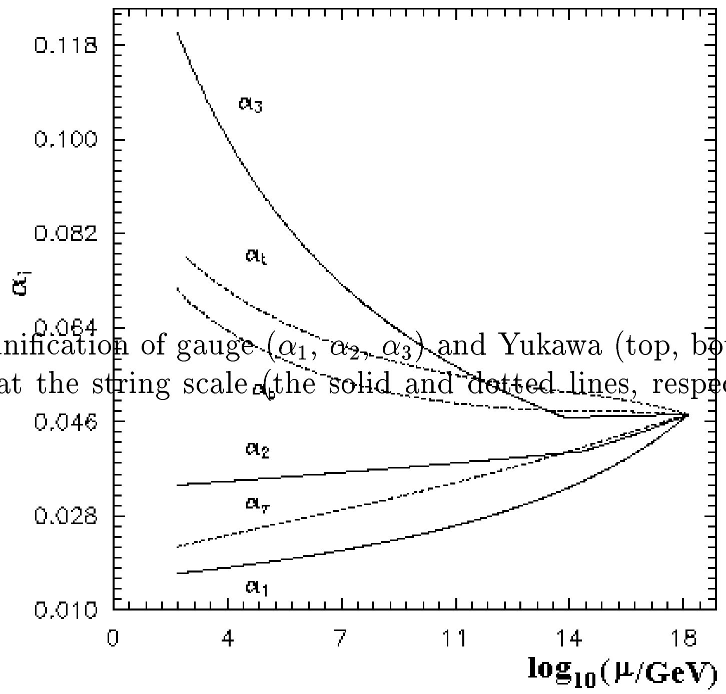

Fig. 2