Phenomenological Constraints on SUSY $SU(5)$ GUTs with Non-universal Gaugino Masses

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(September 9, 1999)

We study phenomenological aspects of supersymmetric $SU(5)$ grand unified theories with non-universal gaugino masses. For large $\tan\beta$, we investigate constraints from the requirement of successful electroweak symmetry breaking, the positivity of stau mass squared and the $b \to s\gamma$ decay rate. In the allowed region, the nature of the lightest supersymmetric particle is determined. Examples of mass spectra are given. We also calculate loop corrections to the bottom mass due to superpartners.

11.30.Pb, 12.10.Dm

I. INTRODUCTION

Supersymmetric gauge field theories are among the most promising models for physics beyond the standard model. The low-energy supersymmetry (SUSY) solves the so-called hierarchy problem, which basically follows from the tremendous scale differences in realistic models including gravity.

After SUSY breaking, SUSY models, e.g. the minimal supersymmetric standard model (MSSM) have over hundred free parameters in general. Most of these new parameters in the MSSM are in fact related to the SUSY breaking, i.e. gaugino masses $M_a$, soft scalar masses $m_i$, SUSY breaking trilinear couplings $A_{ijk}$ and SUSY breaking bilinear couplings. They are expected to be of the order of 1 TeV.

To probe the SUSY breaking mechanisms is very important in order to produce solid information on physics beyond the standard model. Two types of SUSY breaking mechanisms, gravity-mediated SUSY breaking and gauge-mediated SUSY breaking, have been actively studied in recent years. The signatures of gravity mediated and gauge mediated SUSY breaking are quite different. A specific SUSY breaking mechanism usually reduces the number of a priori free parameters from about one hundred to only a few by introducing solid relations among the SUSY breaking parameters. This makes the phenomenology of the MSSM more accessible for study.

For phenomenology of SUSY models, various aspects have been studied in several regions of the parameter space. Most phenomenological analyses have been done under the assumption that the soft SUSY breaking parameters are universal, i.e. $M_a = M_{1/2}$ for $a = 1, 2, 3$, $m_i = m_0$ for any scalar and $A_{ijk} = A$ at a certain energy scale, e.g. the Planck scale or the grand unified theory (GUT) scale. From the phenomenological viewpoint, the universality assumption is useful to simplify analysis. Actually, the universal parameters can be derived from a certain type of underlying theories, e.g. minimal supergravity.

However, the universality assumption may remove some interesting degrees of freedom. Indeed, there exist interesting classes of models in which non-universal soft SUSY breaking terms can be derived. For example, string-inspired supergravity can lead to non-universality for SUSY breaking parameters at the Planck scale [1, 2]. Also, gauge-mediated SUSY breaking models, in general, lead to non-universality [3].

Recently phenomenological implications of non-universal SUSY breaking parameters have been investigated. For example, in Ref. [4] phenomenological implications have been studied for non-universal gaugino masses derived from string models. GUTs without a singlet also lead to non-universal gaugino masses [5, 6]. In Ref. [7] phenomenological aspects in the small $\tan\beta$ scenario have been discussed, e.g. mass spectra and some decay modes. Some phenomenological constraints reduce the allowed region of the universal SUSY breaking parameters a lot. For example, in the large $\tan\beta$ scenario, it is hard to fulfill the constraints due to the requirement of successful electroweak breaking, SUSY corrections to the bottom mass [8, 9] and the $b \to s\gamma$ decay rate [10, 11]. These constraints can be relaxed in non-universal cases.

In this paper, we study phenomenological aspects of SUSY $SU(5)$ GUTs where the gaugino masses come from a condensation of $F$-component with a representation $24$, $75$ or $200$. Each of them leads to a proper pattern of non-universal gaugino masses. We mostly concentrate on the large $\tan\beta$ scenario. We take into account the full one-loop effective potential of the MSSM, in order to calculate the physical spectrum of the MSSM, given the initial conditions at the GUT scale. In particular, we investigate constraints from the requirement of successful electroweak...
symmetry breaking, the positivity of stau mass squared and the $b \to s\gamma$ decay rate. We take SUSY corrections to the bottom quark mass carefully into account. We then find the allowed parameter space for each model and describe the particle spectrum.

This paper is organized as follows. In section 2 SUSY SU(5) GUTs with non-universal gaugino masses are reviewed. In section 3 we study their phenomenological aspects, i.e. successful radiative breaking of the electroweak symmetry, the LSP mass, the stau mass, SUSY corrections to the bottom mass and the $b \to s\gamma$ decay. We also give comments on small $\tan\beta$ cases. Section 4 is devoted to conclusions.

II. SUSY SU(5) GUTS WITH NON-UNIVERSAL GAUGINO MASSES

We discuss the non-universality of soft SUSY breaking gaugino masses in SUSY SU(5) GUT and the constraints on parameters at the GUT scale $M_X$ in our analysis. The gauge kinetic function is given by

$$
\mathcal{L}_{g.k.} = \sum_{\alpha,\beta} \int d^2 \theta f_{\alpha\beta}(\Phi^I) W^\alpha W^\beta + H.c.
$$

$$
= -\frac{1}{4} \sum_{\alpha,\beta} \text{Re} f_{\alpha\beta}(\phi^I) F^\alpha_{\mu\nu} F^\beta_{\mu\nu} + \sum_{\alpha,\beta,\alpha',\beta'} \sum_I F^I_{\alpha'\beta'} \frac{\partial f_{\alpha\beta}(\phi^I)}{\partial \phi^I_{\alpha'\beta'}} \lambda^\alpha \chi^\beta + H.c. + \cdots
$$

(1)

where $\alpha, \beta$ are indices related to gauge generators, $\Phi^I$'s are chiral superfields and $\lambda$ is the SU(5) gaugino field. The scalar and $F$-components of $\Phi^I$ are denoted by $\phi^I$ and $F^I$, respectively. The $\Phi^I$'s are classified into two categories. One is a set of SU(5) singlet supermultiplets $\Phi^S$ and the other one is a set of non-singlet ones $\Phi^N$. The gauge kinetic function $f_{\alpha\beta}(\Phi^I)$ is, in general, given by

$$
f_{\alpha\beta}(\Phi^I) = f_0(\Phi^S) \delta_{\alpha\beta} + \sum_N \xi_N(\Phi^S) \frac{f_{\alpha\beta}^N}{M} + O\left(\frac{\Phi^N}{M}\right)^2
$$

(2)

where $f_0$ and $\xi_N$ are functions of gauge singlets $\Phi^S$ and $M$ is the reduced Planck mass defined by $M \equiv M_{Pl}/\sqrt{8\pi}$. Since the gauge multiplets are in adjoint representation, one finds the possible representations of $\Phi^N$ with non-vanishing $\xi_N$ by decomposing the symmetric product $24 \times 24$ as

$$
(24 \times 24)_s = 1 + 24 + 75 + 200.
$$

(3)

Thus, the representations of $\Phi^N$ allowed as a linear term of $\Phi^N$ in $f_{\alpha\beta}(\Phi^I)$ are $24$, $75$ and $200$.

Here we make two basic assumptions. The first one is that SUSY is broken by non-zero VEVs of $F$-components $F^I$, i.e., $\langle F^I \rangle = O(m_{3/2})$ where $m_{3/2}$ is the gravitino mass. The second one is that the SU(5) gauge symmetry is broken down to the standard model gauge symmetry $G_{SM} = SU(3) \times SU(2) \times U(1)$ by non-zero VEVs of non-singlet scalar fields $\phi^N$ at the GUT scale $M_X$.

After the breakdown of SU(5), the gauge couplings $g_a$'s of $G_{SM}$, are, in general, non-universal. We take a gauge coupling unification scenario within the framework of the MSSM, that is,

$$
\alpha_1(M_X) = \alpha_2(M_X) = \alpha_3(M_X) \equiv \alpha \approx 1/25
$$

(5)

where $\alpha \equiv g_a^2/4\pi$ and $M_X = 2.0 \times 10^{16}$GeV. The relation (5) leads to $\langle \text{Re} f_0 \rangle \approx 2$. We neglect the contribution of non-universality to the gauge couplings. Such corrections of order $O(\langle \phi^N \rangle / M) = O(M_X / M) = O(1/100)$ have little effects on phenomenological aspects which we will discuss in the next section, although such corrections would be important for precision study on the gauge coupling unification.

2) Gaugino masses

Thus, the representations of $\Phi^N$ allowed as a linear term of $\Phi^N$ in $f_{\alpha\beta}(\Phi^I)$ are $24$, $75$ and $200$. As we see from the formula $g_{a}^{-2}(M_X) \delta_{ab} = \langle \text{Re} f_{ab} \rangle$. The index $a(=3, 2, 1)$ represents $(SU(3), SU(2), U(1))$ generators as a whole. The gaugino field acquires soft SUSY breaking mass after SUSY breaking. The mass formula is given by

$$
M_a(M_X) \delta_{ab} = \sum_I \frac{\langle F^I_{ab} \rangle}{2} \frac{\partial f_{ab} / \partial \phi^I}{\langle \text{Re} f_{ab} \rangle}.
$$

(4)

Thus the $M_a$'s are also, in general, non-universal at the scale $M_X$.

Next we will consider the constraints on the physical parameters used at the scale $M_X$ for the analysis in this paper.

1) Gauge couplings

We take a gauge coupling unification scenario within the framework of the MSSM, that is,

$$
\alpha_1(M_X) = \alpha_2(M_X) = \alpha_3(M_X) \equiv \alpha \approx 1/25
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(5)

where $\alpha \equiv g_a^2/4\pi$ and $M_X = 2.0 \times 10^{16}$GeV. The relation (5) leads to $\langle \text{Re} f_0 \rangle \sim 2$. We neglect the contribution of non-universality to the gauge couplings. Such corrections of order $O(\langle \phi^N \rangle / M) = O(M_X / M) = O(1/100)$ have little effects on phenomenological aspects which we will discuss in the next section, although such corrections would be important for precision study on the gauge coupling unification.

2) Gaugino masses
We assume that dominant component of gaugino masses comes from one of non-singlet $F$-components. The VEV of the $F$-component of a singlet field whose scalar component $\phi^S$ has a VEV of $O(M)$ in $f_{\alpha}B$ is supposed to be small enough $(F^S) \ll O(m_{3/2}M)$ such as dilaton multiplet in moduli-dominant SUSY breaking in string models. In this case, ratios of gaugino masses at $M_X$ are determined by group theoretical factors and shown in table I. The patterns of gaugino masses which stem from $F$-term condensation of 24, 75 and 200 are different from each other. The table also shows corresponding ratios at the weak scale $M_Z$ based on MSSM. In the table, gaugino masses are shown in the normalization $M_3(M_X) = 1$. Note that the signs of $M_a$ are also fixed by group theory up to an overall phase as shown in Table I. There is no direct experimental constraint on these signs. For example, these signs affect radiative corrections of $A$-terms and thus off-diagonal elements of sfermion matrices, that is, radiative corrections of $M_a$ to $A_t$ are constructive in the universal case, while in the model 24 radiative corrections between $M_3$ and the others interfere with each other leading to 30% reduction. In the other cases, the radiative corrections are larger by 20 $\sim$ 30% than the universal case.

3) Scalar masses
For simplicity, we assume universal soft SUSY breaking scalar masses $m_0^{GUT}$ at $M_X$ in our analysis in order to clarify phenomenological implications of non-universal gaugino masses. The magnitude of $m_0^{GUT}$ is supposed not to be too large compared with that of $m_a$’s in order not to overclose the universe with a huge amount of relic abundance of the lightest neutralino $\tilde{\chi}^0_1$.

The non-universal gaugino masses $M_a$ and scalar masses $m_k$ may have sizable SUSY threshold corrections for running of gauge couplings [13]. These threshold effects and non-universal contributions of $O((\phi^N)/M)$ in $g_{\alpha}^{-2}$ will be discussed elsewhere.

III. PHENOMENOLOGICAL CONSTRAINTS AND MASS SPECTRA

In this section, we study several phenomenological aspects of SUSY SU(5) GUTs with non-universal gaugino masses. The patterns of the gaugino masses in the models are different from each other as shown in table I. That leads to different phenomenology in these models. For example, in the model 24 we have a large gap between $M_1(M_Z)$ and $M_3(M_Z)$, i.e. $M_1(M_Z)/M_3(M_Z) \approx 0.1$. In the model 75 gaugino masses are almost degenerate at the weak scale. In the model 200, $M_2(M_Z)$ is smallest. Some phenomenological aspects have been previously studied in the case with low $\tan \beta$ [3]. We will study the case of a large value of $\tan \beta$, e.g. $\tan \beta \sim 40$.

We take the trilinear scalar couplings, the so-called $A$-terms, to vanish at the GUT-scale. Similarly, the case with non-vanishing $A$-terms can be studied, but the conclusions remain qualitatively unchanged. Also we ignore the supersymmetric $CP$-violating phase of the bilinear scalar coupling of the two Higgs fields, the so-called $B$-term. Assuming vanishing $A$-terms and a real $B$-term, we have no SUSY-CP problem. Ignoring the complex phases has no significant effect on the results of this work, although they would naturally be very relevant to the problem of CP-violation. We could fix magnitudes of the supersymmetric Higgs mixing mass $\mu$ and $B$ by assuming some generation mechanism for the $\mu$-term. However, we do not take such a procedure here. We will instead fix these magnitudes by use of the minimization conditions of the Higgs potential as shall be shown.

Given the quantum numbers of $F^N$ irreducible representation, one can characterize the models as a function of four parameters: $\tan \beta$, the gluino mass $M_3^{GUT}$ at the GUT scale, the universal mass of the scalar fields $m_0^{GUT}$ at the GUT scale and the sign of the $\mu$-term sign($\mu$).

We will check the compatibility of the model with the experimental branching ratio $b \rightarrow s\gamma$. Since this branching ratio increases with $\tan \beta$, we will study the four models at the region of large $\tan \beta$, taking $\tan \beta = 40$ as a representative value and scanning over the gaugino mass and the scalar mass squared term. We require that the gauge coupling constants unify at the scale $2.0 \times 10^{16}$GeV.

Successful electroweak symmetry breaking is an important constraint. The one-loop effective potential written in terms of the VEVs, $v_u = \langle H_u^0 \rangle$ and $v_d = \langle H_d^0 \rangle$, is

$$V(Q) = V_0(Q) + \Delta V(Q),$$

where

$$V_0(Q) = (m_{H_u}^2 + \mu^2) v_u^2 + (m_{H_d}^2 + \mu^2) v_d^2 - 2Bv_u v_d + \frac{1}{8} (g^2 + g'^2) (v_u^2 - v_d^2)^2,$$

$$\Delta V(Q) = \frac{1}{64\pi^2} \sum_{k=\text{all the MSSM fields}} (-1)^{2S_k} n_k M_k^4 \left[ -\frac{3}{2} + \ln \frac{M_k^2}{Q^2} \right],$$

$3$
where $S_k$ and $n_k$ are respectively the spin and the number of degrees of freedom. Here $m_{H_u}$ and $m_{H_d}$ denote soft SUSY breaking Higgs masses.

We use the minimization conditions of the full one-loop effective potential,

$$\frac{\partial V}{\partial v_u} = \frac{\partial V}{\partial v_d} = 0,$$

so that we can write $\mu^2 = \mu_0^2 + \delta \mu^2$ and $B = B_0 + \delta B$ in terms of other parameters, that is, the soft scalar masses, the gaugino masses and $\tan \beta$. Here $\mu_0^2$ and $B_0$ denote the values determined only by use of the tree-level potential, and $\delta \mu^2$ and $\delta B$ denote the corrections due to the full one-loop potential, which are obtained

$$\delta \mu^2 = \frac{1}{2} \left( \frac{v_d \partial \Delta V}{\partial v_d} - \frac{v_u \partial \Delta V}{\partial v_u} \right),$$

$$\delta B = \frac{1}{2} \left( \frac{v_u \partial \Delta V}{\partial v_u} - \frac{v_d \partial \Delta V}{\partial v_d} \right).$$

Numerically, the most significant one-loop contribution to $\delta B$ and $\delta \mu^2$ comes from the $(s)top$ and $(s)bottom$ loops [16].

Successful electroweak symmetry breaking requires $\mu^2 > 0$. Furthermore, we require the mass squared eigenvalues for all scalar fields to be non-negative. In particular, in the large $\tan \beta$ scenario the stau mass squared becomes easily negative due to large negative radiative corrections from the Yukawa coupling against positive radiative corrections from the gaugino masses.

These constraints are shown in Fig.1. In the model 1 with the universal gaugino mass, requirement of proper electroweak symmetry breaking excludes the region with very small ($\sim 100$ GeV) scalar mass and gaugino masses. In the model 24 the region where radiative symmetry breaking fails is considerably larger than in the model 1 because of negative $m_\tau^2$ for small $m_0^{GUT}$. In the model 24 $M_2(M_Z)$ and $M_1(M_Z)$ are quite small compared with $M_3(M_Z)$. Such small values of $M_2(M_Z)$ and $M_1(M_Z)$ are not enough to push up $m_\tau^2$ against large negative radiative correction due to the Yukawa coupling. It is interesting to note that in the model 75 large gaugino masses drive the Higgs boson mass-squared $m_{H_u,d}^2$ to very large positive values at the SUSY scale. This aspect combined with the contribution from the effective potential correction makes $\mu^2$ small and negative at large gaugino masses. As a result, in the model 75 there are no consistent solutions having large gluino mass $M_G^{GUT} \gtrsim 800$ GeV. Furthermore, around the border to the region with $\mu^2 < 0$, i.e. $M_3^{GUT} \sim 800$ GeV, the magnitude of $|\mu|$ is very small, and the lightest neutralino and the lighter chargino are almost higgsinos. Thus, the region around the border $M_3^{GUT} \sim 800$ GeV is excluded by the experimental lower bound of the chargino mass, $m_{\chi^\pm} \gtrsim 90$ GeV. The region with $M_3^{GUT} < 700$ GeV leads to large $|\mu|$ enough to predict $m_{\chi^0} > O(100)$ GeV. In the model 200 radiative symmetry breaking works for all the scanned values.

From the experimental point of view, a crucial issue is the nature of the LSP, since it is a decisive factor in determining signals of the models in detectors. One candidate for the LSP is the lightest neutralino $\chi^0$. In the large $\tan \beta$ scenario, the lightest stau is another possibility [1]. Figs. 1 show what is the LSP for the four models. They also show the excluded region by the current experimental limit $m_{\tilde{\tau}} \geq 72$ GeV [3]. The limit on the stau mass excludes the models 1 and 24 having small scalar masses. The models 75 and 200, on the other hand, always have relatively heavy stau, independent of the SUSY parameters, and in the latter two models the neutralino is always the LSP. For the models 1 and 24, the content of the LSP is similar and narrow regions lead to the stau LSP.

In our models the present experimental lower bound of the Higgs mass does not provide a strong constraint, because in the large $\tan \beta$ scenario the Higgs mass is heavy.

We also consider the constraint due to the $b \to s \gamma$ decay. The prediction of the $b \to s \gamma$ decay branching ratio [12] should be within the current experimental bounds [21]

$$1.0 < 10^4 \times BR_{\text{EXP}}(b \to s \gamma) < 4.2.$$  

Combined with the theoretical uncertainty in the SM prediction ($10^4 \times BR_{\text{SM}}(b \to s \gamma) = 3.5 \pm 0.3$ ) the branching ratio must be be between 0.3 and 1.4 times the SM prediction.

As expected, the constraint is very strong for negative nu-term sign($\mu$) = −1 [4], because the supersymmetric contributions interfere constructively to the amplitude, causing the branching ratio to exceed the experimental bound.

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1In Ref. [17] cosmological implications of the stau LSP have been discussed.
2We follow the conventional definition of the sign of $\mu$ [21].
Figs. 1 show excluded regions due to $BR(b \to s\gamma)$ for the four models with $\mu = -1$. We have taken into account squark mixing effects. These excluded regions are similar for the four models. The regions with small gluino masses $M_{GUT}^3 \lesssim 700$ GeV are ruled out due to too large $b \to s\gamma$ branching ratio in the four models unless $m_0^{GUT} \gtrsim 1$ TeV. In addition, the model 75 has an excluded region with $M_{GUT}^3 \gtrsim 800$ GeV due to the unsuccessful electroweak symmetry breaking. Thus, in the model 75 with $\mu = -1$ only a narrow region for $M_{GUT}^3$ is allowed for $m_0^{GUT} \lesssim 1$ TeV. In the case with positive $\mu$-term sign($\mu$) = $+1$ the constraints are much weaker, only some models with small gluino and soft scalar masses are ruled out due to the charged Higgs contribution.

The superpartner-loop corrections to the bottom-quark Yukawa coupling become numerically sizable for large $\tan \beta$. These corrections are significant for precise prediction of the bottom mass. Thus, we also show how these SUSY-corrections to the bottom mass depend on our models with non-universal gaugino masses. The threshold effect can be expressed as 

$$\lambda_b^{SM}(m_{SUSY}) = \lambda_b^{SM}(m_{SUSY})/((1 + \delta_b) \cos \beta),$$

where $\lambda_b^{SM,MSSM}$ are the bottom quark Yukawa couplings in the standard model and MSSM, respectively. The dominant part of the corrections is given by

$$\delta_b = \mu \tan \beta \left[ \frac{2\alpha_3}{3\pi} M_3 I(m_b^2, m_{b2}^2, M_3^2) + \frac{\lambda_t}{16\pi^2} A_t \lambda_t I(m_t^2, m_{t2}^2, \mu^2) \right],$$

where $\lambda_t$ is the top Yukawa coupling and

$$I(x, y, z) = -\frac{xy \ln x/y + yz \ln y/z + zx \ln z/x}{(x - y)(y - z)(z - x)}.$$ 

The sign of $\delta_b$ is the same as the one of $\mu$. Figs. 2 show for the four models the regions with $0\% < |\delta_b| < 10\%$, $10\% < |\delta_b| < 20\%$ and $20\% < |\delta_b| < 50\%$. Most of the allowed regions in the models 1 and 24 lead to $10\% < |\delta_b| < 20\%$ for $\tan \beta = 40$, while most of the allowed region in the model 75 leads to $0\% < |\delta_b| < 10\%$. In the model 200, small $m_0^{GUT}$ leads to $10\% < |\delta_b| < 20\%$, while large $m_0^{GUT}$ leads to $0\% < |\delta_b| < 10\%$.

The large correction to the bottom mass affects the $b - \tau$ Yukawa coupling unification, which is one of interesting aspects in GUTs. We assume the $b - \tau$ Yukawa coupling unification at the GUT scale and use the experimental value $m_\tau = 1.777$ GeV. Without the SUSY correction $\delta_b$ we would have $m_b(M_Z) = 3.3$ GeV for $\tan \beta = 40$. The present experimental value of the bottom mass contains large uncertainties: Ref. [22], for instance, gives

$$m_b(M_Z) = 2.67 \pm 0.50 \text{ GeV},$$

while the analysis of the $\Upsilon$ system [23] and the lattice result [24] give $m_b(m_b) = 4.13 \pm 0.06 \text{ GeV}$ and $4.15 \pm 0.20 \text{ GeV}$, respectively, which translate into

$$m_b(M_Z) = 2.8 \pm 0.2 \text{ GeV}.$$ 

Thus, the negative SUSY corrections, that is $\mu < 0$, with $10\% < |\delta_b| < 20\%$ are favored for $\tan \beta = 40$. Hence most of the region in the model 75 leads to too small $|\delta_b|$ to fit the experimental value for $\tan \beta = 40$. The SUSY correction $\delta_b$ is proportional to $\tan \beta$. Therefore, in the case with large $\tan \beta$, e.g. $\tan \beta = 50$ and 55, some parameter regions in the model 75 as well as the model 200 become more favorable. Because the prediction $m_b(M_Z) = 3.3$ GeV without the SUSY correction $\delta_b$ is similar for $\tan \beta = 40$, 50 and 55.

Finally we show sparticle spectra in the regions allowed by the electroweak breaking conditions and the constraint due to $BR(b \to s\gamma)$ for $\tan \beta = 40$ and $\mu = -1$. The whole particle spectrum is fixed by gluino mass $M_{GUT}^3$, the soft scalar mass $m_0^{GUT}$ and $\tan \beta$. The sign of the $\mu$-term $\mu$ has numerically insignificant effect to the mass spectrum. In the case of negative $\mu$-term the experimental upper bound to the $b \to s\gamma$ decay branching ratio severely restricts the parameter space. As an example, we show mass spectra of the four models for $(M_{GUT}^3, m_0^{GUT})[\text{GeV}] = (800, 400)$ and $(100, 1500)$ in table II. These parameters correspond to almost smallest mass parameters allowed by theoretical and experimental considerations common in the four models. Most of the non-SM degrees of freedom have masses around 1 TeV. Note that the model 75 with $M_{GUT}^3 = 800$ GeV and $m_0^{GUT} = 400$ GeV predicts very small $|\mu|$

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See also ref. [22].
and the lightest chargino mass, which is actually excluded by the experimental lower bound. On the other hand, the model 24 for small \( M_{3}^{GUT} \) predicts a very small mass of the lightest neutralino.

In the models 75 and 200 the lightest neutralino \( \chi_{0}^{0} \) and the lightest chargino \( \chi_{1}^{\pm} \) are almost degenerate. This would potentially create a very difficult experimental setup unless \( \tan \beta = 5 \) and 25. The charginos would be extremely difficult to detect, at least near the kinematical production threshold: as the charginos decay practically all of the reaction energy is deposited into the invisible LSP neutralinos. If the charginos decay very close to the interaction point, the photon background would quite effectively hide the signal. The chargino would be easy to detect only if it is sufficiently stable, having a decay length of at least millimeters.

In the models 1 and 24, the LSP is almost the bino. On the other hand, the wino-like LSP or the higgsino-like LSP can be realised in the models 75 and 200. In particular, the model 75 has the region around \( M_{3}^{GUT} \sim 800 \) GeV where the higgsino is very light. These different patterns of mass spectra also have cosmological implications, which will be discussed elsewhere.

We have assumed universal soft scalar mass at the GUT scale in order to concentrate on phenomenological implications of the non-universal gaugino masses, but we give some comments on non-universal soft scalar masses. Certain types of non-universality can relax the given constraints. For example, the non-universality between the stau mass and the others is important for the constraint \( m_{\tilde{\tau}}^{2} > 0 \) and obviously a large value of the stau mass at the GUT can remove the excluded region. For the electroweak symmetry breaking, the non-universality between the Higgs masses \( m_{Hd} \) and \( m_{Hd} \) is interesting and a large difference of \( m_{Hd}^{2} - m_{Hd}^{2} \) enlarges the parameter region for the successful electroweak symmetry breaking.

We give a comment for the small \( \tan \beta \) scenario. For small \( \tan \beta \), the stau (mass)\(^2\) has no sizable and negative radiative corrections. Thus, the constraints \( m_{\tilde{\tau}}^{2} > 0 \) and \( m_{\tilde{\tau}} \geq 72 \) GeV are no longer serious. In addition most cases lead to the neutralino LSP. Furthermore, the SUSY contributions to \( BR(b \to s\gamma) \) is roughly proportional to \( \tan \beta \). Hence, the constraint due to \( BR(b \to s\gamma) \) is also relaxed for small \( \tan \beta \).

**IV. CONCLUSIONS**

We have studied the large \( \tan \beta \) scenario of the SUSY model in which the gaugino masses are not universal at the GUT scale. We find that the gluino mass at the electroweak scale is restricted to multi-TeV values due to experimental limits on the \( b \to s\gamma \) decay for \( \mu < 0 \). In the model 75 the allowed region is narrow for \( M_{3}^{GUT} \). We find that in two of the models 1 and 24 we have neutralino LEP and stau NLSP, while in the models 75 and 200 the lightest neutralino and the lighter chargino are almost mass degenerate. This would provide for quite different kind of the first signature for the MSSM as is usually assumed within the minimal supergravity scenario. We have also calculated the SUSY correction to the bottom mass \( \delta_{b} \). The model 75, as well as the model 200 with large \( m_{0}^{GUT} \), leads to smaller \( \delta_{b} \) than the others.

We have possibilities that gaugino fields acquire a different pattern of non-universal masses. For example, there is the case that some linear combination of \( F \)-components of 1, 24, 75 and 200 contributes to gaugino masses. It is pointed out that there exists a model-independent contribution to gaugino masses from the conformal anomaly. Furthermore, soft scalar masses and \( A \)-parameters at the GUT scale can, in general, be non-universal. We leave these types of extension to future work.

**Note added:**

After completion of this paper, Ref. 29 appears, where several signals of the \( SU(5) \) GUTs with non-universal gaugino masses have been discussed for \( \tan \beta = 5 \) and 25.

**ACKNOWLEDGMENTS**

The authors would like to thank K. Österberg for useful correspondence. This work was partially supported by the Academy of Finland under Project no. 44129. Y.K. acknowledges support by the Japanese Grant-in-Aid for Scientific Research (110740111) from the Ministry of Education, Science and Culture.

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[1] A. Brignole, L.E. Ibáñez and C. Muñoz, Nucl. Phys. **B422** (1994) 125; A. Brignole, L.E. Ibáñez, C. Muñoz and C. Scheich, Z. Phys. **C74** (1997) 157.
TABLE I. Relative masses of gauginos for different representations of the $F$-term at the GUT scale and the corresponding relations at the weak scale. The singlet representation $1$ of the $F$-term corresponds to the minimal supergravity model.

| $F_2$ | $M_1^{GUT}$ | $M_2^{GUT}$ | $M_3^{GUT}$ | $M_1^{m_Z}$ | $M_2^{m_Z}$ | $M_3^{m_Z}$ |
|-------|-------------|-------------|-------------|-------------|-------------|-------------|
| 1     | 1           | 1           | 1           | 0.4         | 0.8         | 2.9         |
| 24    | –0.5        | –1.5        | 1           | –0.2        | –1.2        | 2.9         |
| 75    | –5          | 3           | 1           | –2.1        | 2.5         | 2.9         |
| 200   | 10          | 2           | 1           | 4.1         | 1.6         | 2.9         |
TABLE II. Mass spectra in the four models (1, 24, 75, 200) for $\tan \beta = 40$. All the masses are shown in GeV and evaluated at the scale $m_{GUT}$.

| Model | $\tan \beta$ | $\mu$ | $m_{H^\pm}$ | $m_{\tilde{\chi}^\pm}$ | $m_{\tilde{\chi}^0_{1,2}}$ | $m_{\tilde{\chi}^0_{1,2,3,4}}$ | $m_{\tilde{\tau}_{1,2}}$ | $m_{\tilde{\tau}_{1,2}}$ |
|-------|--------------|-------|--------------|----------------|-----------------|------------------|----------------|----------------|
| 1     | 40           | 0.982 | 472          | 660/993        | 342/660/985/993 | 506/690          | 407/676        |                  |
| (800, 400) | 1.5         | 1963  | 685/658      | 1749/1819      | 1375/1573       | 1740/1821        | 1468/1561      |                  |
| 24    | 40           | 0.791 | 581          | 778/1018       | 170/778/794/1018| 430/906          | 220/872        |                  |
| (800, 400) | 1.4         | 1963  | 903/865      | 1740/1916      | 1394/1681       | 1738/1917        | 1517/1674      |                  |
| 75    | 40           | 0.8   | 1521         | 8/2006         | 7/9/1717/2006   | 1592/1836        | 1387/1751      |                  |
| (800, 400) | 1.2         | 1963  | 1834/1749    | 2018/2387      | 1287/2072       | 1812/2388        | 1668/2061      |                  |
| 200   | 40           | 0.784 | 1218         | 780/1342       | 778/785/1342/3433| 1923/3107        | 1721/2861      |                  |
| (800, 400) | 1.2         | 1963  | 1921/1720    | 2108/2690      | 1480/2053       | 2018/2109        | 1480/1642      |                  |
| 1     | 40           | 0.464 | 1017         | 82/477         | 44/82/471/473   | 1501/1502        | 1260/1388      |                  |
| (100, 1500) | 1.3         | 222   | 1500/1385    | 1511/1512      | 830/1065        | 1511/1514        | 1053/1247      |                  |
| 24    | 40           | 0.457 | 1013         | 122/472        | 21/122/464/469  | 1500/1503        | 1250/1390      |                  |
| (100, 1500) | 1.3         | 222   | 1501/1387    | 1511/1513      | 830/1066        | 1511/1515        | 1055/1245      |                  |
| 75    | 40           | 0.444 | 1027         | 243/463        | 219/243/453/460 | 1512/1516        | 1271/1402      |                  |
| (100, 1500) | 1.3         | 222   | 1514/1399    | 1516/1523      | 828/1077        | 1513/1525        | 1066/1247      |                  |
| 200   | 40           | 0.456 | 1032         | 164/471        | 164/423/462/488 | 1518/1548        | 1308/1405      |                  |
| (100, 1500) | 1.3         | 222   | 1516/1399    | 1517/1532      | 850/1066        | 1517/1519        | 1055/1252      |                  |
FIG. 1. Scan over the gluino mass term $M_{3}^{GUT}$ and the universal scalar mass term $m_{0}^{GUT}$ for all four models (1, 24, 75, 200; $\tan \beta = 40$).
FIG. 2. The bottom mass correction $|\delta_b|$ for all four models (1, 24, 75, 200: $\tan\beta = 40$)