Phenomenological constraints on SUSY SU(5) GUTs with nonuniversal gaugino masses

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We study the phenomenological aspects of supersymmetric SU(5) grand unified theories with nonuniversal 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.

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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 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 theory, e.g., minimal supergravity.

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

Recently phenomenological implications of nonuniversal SUSY breaking parameters have been investigated. For example, in Refs. [4–6] phenomenological implications have been studied for nonuniversal gaugino masses derived from string models. GUTs without a singlet also lead to nonuniversal gaugino masses [7–9]. In Ref. [8] 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 [10,11] and the $b \to s\gamma$ decay rate [12,13]. These constraints can be relaxed in nonuniversal cases.

In this paper, we study phenomenological aspects of SUSY SU(5) GUTs where the gaugino masses come from a condensation of the F component with a representation **24**, **75**, or **200**. Each of them leads to a proper pattern of nonuniversal 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 Sec. II SUSY SU(5) GUTs with nonuniversal gaugino masses are reviewed. In Sec. III we study their phenomenological aspects, i.e., successful radiative breaking of the electroweak symmetry, the lightest supersymmetric particle (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 IV is devoted to conclusions.

II. SUSY SU(5) GUTS WITH NONUNIVERSAL GAUGINO MASSES

We discuss the nonuniversality 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

$$\mathcal{L}_{\rm GK}=\sum_{\alpha,\beta}\int d^2\theta f_{\alpha\beta}(\Phi^I)W^\alpha W^\beta+\text{H.c.}$$
$$=-\frac{1}{4}\sum_{\alpha,\beta}Ref_{\alpha\beta}(\phi^I)F^\alpha_{\mu\nu}F^{\beta\mu\nu}$$
$$+\sum_{\alpha,\beta,\alpha',\beta'}\sum_I F^I_{\alpha'\beta'}\frac{\partial f_{\alpha\beta}(\phi^I)}{\partial\phi^I_{\alpha'\beta'}}\lambda^\alpha\lambda^\beta+\text{H.c.}+\cdots, \tag{1}$$

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

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

where f_0 and ξ_N are functions of gauge singlets Φ^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 Φ^N with nonvanishing ξ_N by decomposing the symmetric product **24**×**24** as

$$(\mathbf{24}\times\mathbf{24})_s=\mathbf{1}+\mathbf{24}+\mathbf{75}+\mathbf{200}. \tag{3}$$

Thus, the representations of Φ^N allowed as a linear term of Φ^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 nonzero vacuum expectation values (VEVs) of F-components $F^{I'}$, i.e., $\langle F^{I'}\rangle=O(m_{3/2}M)$ 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 $G_{\rm SM}=\text{SU(3)}\times\text{SU(2)}\times\text{U(1)}$ by nonzero VEVs of nonsinglet scalar fields ϕ^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, nonuniversal at the scale M_X [14] as we see from the formula $g_a^{-2}(M_X)\delta_{ab}=\langle Ref_{ab}\rangle$. 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

$$M_a(M_X)\delta_{ab}=\sum_I \frac{\langle F^I_{a'b'}\rangle}{2}\frac{\langle\partial f_{ab}/\partial\phi^I_{a'b'}\rangle}{\langle Ref_{ab}\rangle}. \tag{4}$$

Thus the M_a's are also, in general, nonuniversal at the scale M_X [7].

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,

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_Φ	$M_1^{\rm GUT}$	$M_2^{\rm GUT}$	$M_3^{\rm GUT}$	$M_1^{m_Z}$	$M_2^{m_Z}$	$M_3^{m_Z}$
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

$$\alpha_1(M_X)=\alpha_2(M_X)=\alpha_3(M_X)\equiv\alpha_X\sim 1/25, \tag{5}$$

where $\alpha_a\equiv g_a^2/4\pi$ and $M_X=2.0\times10^{16}$ GeV. The relation (5) leads to $\langle Ref_0\rangle\sim2$. We neglect the contribution of nonuniversality 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 nonsinglet F components. The VEV of the F-component of a singlet field whose scalar component $\phi^{S'}$ has a VEV of $O(M)$ in $f_{\alpha\beta}$ is supposed to be small enough $\langle F^{S'}\rangle\ll O(m_{3/2}M)$ 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 20–30 % than the universal case.

(3) Scalar masses. For simplicity, we assume universal soft SUSY breaking scalar masses $m_0^{\rm GUT}$ at M_X in our analysis in order to clarify phenomenological implications of nonuniversal gaugino masses. The magnitude of $m_0^{\rm GUT}$ 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 [6].

The nonuniversal gaugino masses M_a and scalar masses m_k may have sizable SUSY threshold corrections for running of gauge couplings [15]. These threshold effects and nonuniversal contributions of $O(\langle\phi^N\rangle/M)$ in g_a^{-2} will be discussed elsewhere.

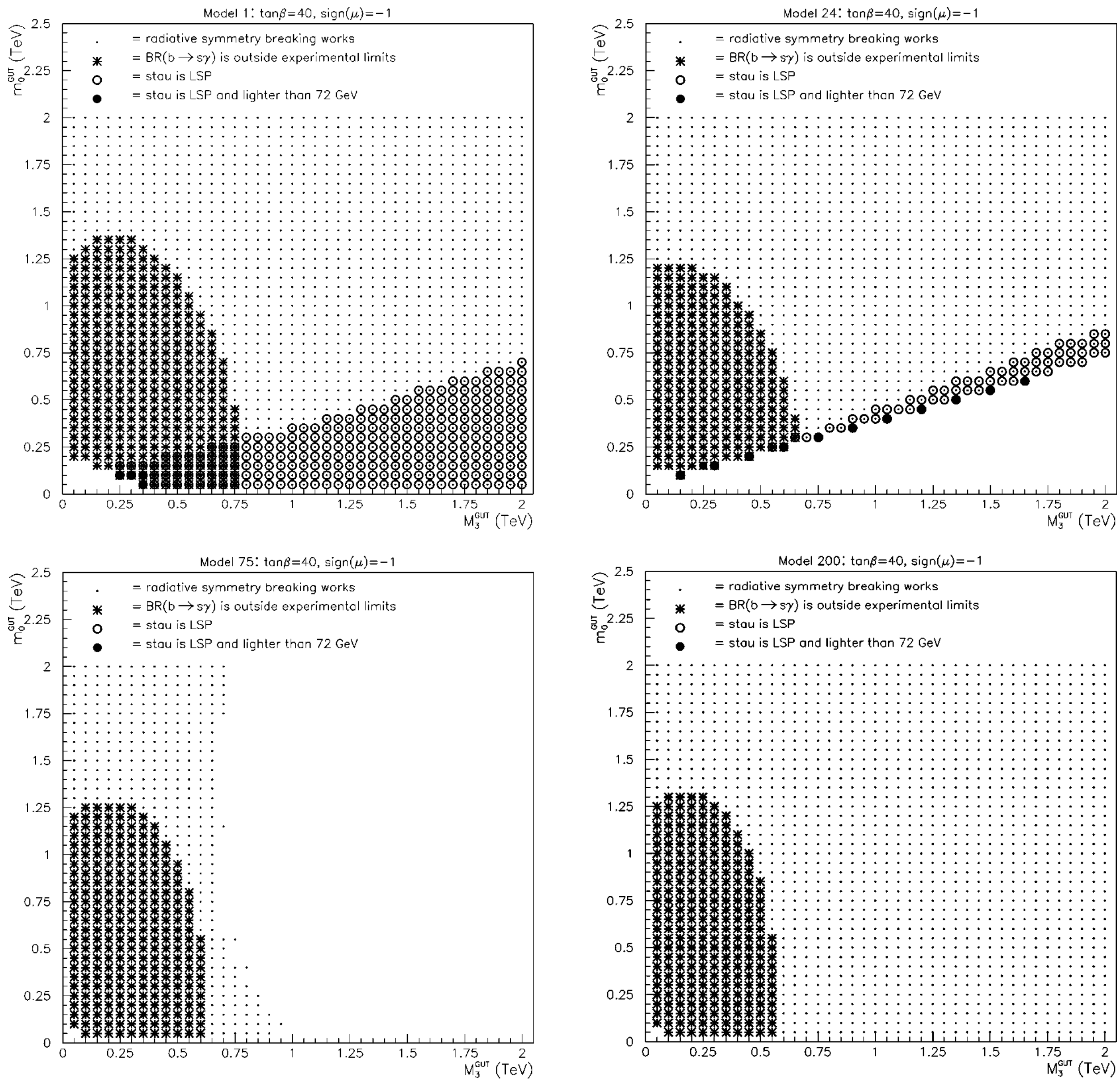

FIG. 1. Scan over the gluino mass term $M_3^{\rm GUT}$ and the universal scalar mass term $m_0^{\rm GUT}$ for all four models (**1**, **24**, **75**, **200**; $\tan\beta=40$).

III. PHENOMENOLOGICAL CONSTRAINTS AND MASS SPECTRA

In this section, we study several phenomenological aspects of SUSY SU(5) GUTs with nonuniversal 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 $\tan\beta$ [8]. 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 μ and B by assuming some generation mechanism for the μ 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 $M_3^{\rm GUT}$ at the GUT scale, the universal mass of the scalar fields $m_0^{\rm GUT}$ at the GUT scale, and the sign of the μ term sgn(μ). We will check the compatibility of the model with the experimental branching ratio $b\to s\gamma$. 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 2.0×10^{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

$$V(Q)=V_0(Q)+\Delta V(Q), \tag{6}$$

where

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

$$\Delta V(Q)=\frac{1}{64\pi^2}\sum_{k=\text{all the MSSM fields}}(-1)^{2S_k}n_kM_k^4 \times\left[-\frac{3}{2}+\ln\frac{M_k^2}{Q^2}\right], \tag{7}$$

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 boson masses.

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

$$\frac{\partial V}{\partial v_u}=\frac{\partial V}{\partial v_d}=0, \tag{8}$$

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 μ_0^2 and B_0 denote the values determined only by use of the tree-level potential, and $\delta\mu^2$ and δB denote the corrections due to the full one-loop potential, which are obtained

$$\delta\mu^2=\frac{1}{2}\,\frac{v_d\partial\Delta V/\partial v_d-v_u\partial\Delta V/\partial v_u}{v_u^2-v_d^2},$$

$$\delta B=\frac{1}{2}\,\frac{v_u\partial\Delta V/\partial v_d-v_d\partial\Delta V/\partial v_u}{v_u^2-v_d^2}. \tag{9}$$

Numerically, the most significant one-loop contribution to δB 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 model **1** with the universal gaugino mass, requirement of proper electroweak symmetry breaking excludes the region with very small (~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 $m_{\tilde\tau}^2$ for small $m_0^{\rm GUT}$. 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 $m_{\tilde\tau}^2$ 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 μ^2 small and negative at large gaugino masses. As a result, in the model **75** there are no consistent solutions having large gluino mass $M_3^{\rm GUT}\gtrsim800$ GeV. Furthermore, around the border to the region with $\mu^2<0$, i.e., $M_3^{\rm GUT}\sim800$ 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 $M_3^{\rm GUT}\sim800$ GeV is excluded by the experimental lower bound of the chargino mass, $m_{\chi^\pm}\gtrsim90$ GeV. The region with $M_3^{\rm GUT}<700$ GeV leads to large $|\mu|$ enough to predict $m_{\chi^\pm}>O(100)$ 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 determing signals of the models in detectors. One candidate for the LSP is the lightest neutralino χ^0. In the large $\tan\beta$ scenario, the lightest stau is another possibility.[1] Figure 1 shows what is the LSP for the four models. They also show the excluded region by the current experimental limit $m_{\tilde\tau_1}\geqslant72$ GeV [18]. 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 [19,20]

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

Combined with the theoretical uncertainty in the SM predic-

[1]In Ref. [17] cosmological implications of the stau LSP have been discussed.

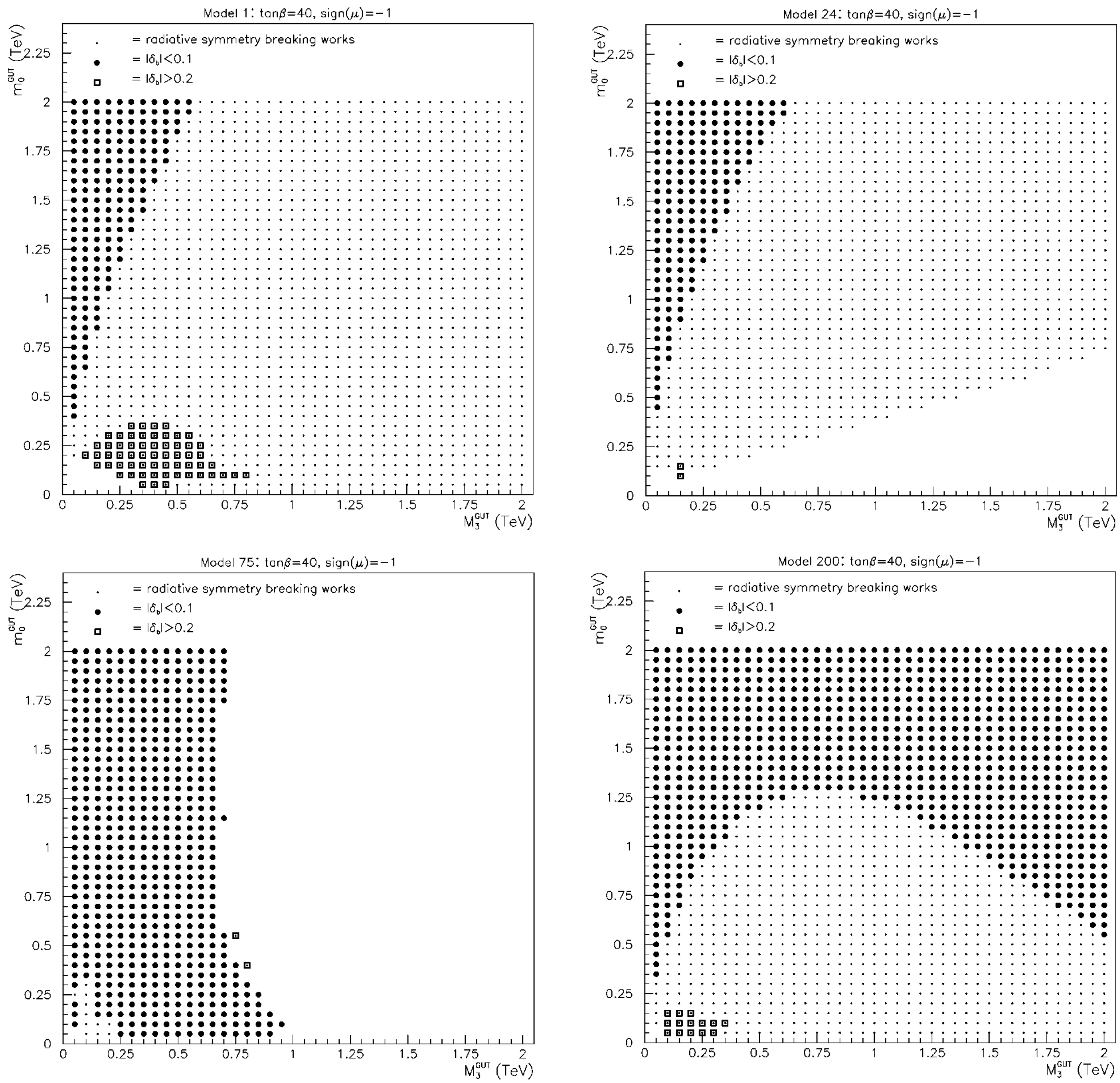

FIG. 2. The bottom mass correction $|\delta_b|$ for all four models (**1**, **24**, **75**, **200**; $\tan\beta = 40$)

tion $[10^4 \times \mathrm{BR}_{\mathrm{SM}}(b \to s\gamma) = 3.5 \pm 0.3]$ the branching ratio must be between 0.3 and 1.4 times the SM prediction.

As expected, the constraint is very strong for negative mu-term $\mathrm{sign}(\mu) = -1$,[2] because the supersymmetric contributions interfere constructively to the amplitude, causing the branching ratio to exceed the experimental bound. Figure 1 shows excluded regions due to $\mathrm{BR}(b \to s\gamma)$ for the four models with $\mathrm{sgn}(\mu) = -1$. We have taken into account squark mixing effects. These excluded regions are similar for the four models. The regions with small gluino masses $M_3^{\mathrm{GUT}} \lesssim 700$ GeV are ruled out due to too large $b \to s\gamma$ branching ratio in the four models unless $m_0^{\mathrm{GUT}} \gtrsim 1$ TeV. In addition, the model **75** has an excluded region with $M_3^{\mathrm{GUT}} \gtrsim 800$ GeV due to the unsuccessful electroweak symmetry breaking. Thus, in the model **75** with $\mathrm{sgn}(\mu) = -1$ only a narrow region for M_3^{GUT} is allowed for $m_0^{\mathrm{GUT}} \lesssim 1$ TeV. In the case with positive mu-term $\mathrm{sign}(\mu) = +1$ 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 nonuniversal gaugino masses. The threshold effect can be expressed as [10]

$$\lambda_b^{\mathrm{MSSM}}(m_{\mathrm{SUSY}}) = \lambda_b^{\mathrm{SM}}(m_{\mathrm{SUSY}}) / [(1 + \delta_b)\cos\beta], \quad (11)$$

[2]We follow the conventional definition of the sign of μ [21].

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 $m_0^{\rm GUT}$.

Model $(M_3^{\rm GUT}, m_0^{\rm GUT})$	$\tan\beta$ $\frac{\Gamma(b\to s\gamma)}{\Gamma_{SM}}$	μ M_3	$m_{H^\pm}$ $m_{\tilde{\nu}_e}/m_{\tilde{\nu}_\tau}$	$m_{\tilde{\chi}^\pm_{1,2}}$ $m_{\tilde{u}_{1,2}}$	$m_{\tilde{\chi}^0_{1,2,3,4}}$ $m_{\tilde{t}_{1,2}}$	$m_{\tilde{e}_{1,2}}$ $m_{\tilde{d}_{1,2}}$	$m_{\tilde{\tau}_{1,2}}$ $m_{\tilde{b}_{1,2}}$
1	40	−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	−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	−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	−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	−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	−457	1013	122/472	21/122/464/469	1500/1503	1259/1390
(100, 1500)	1.3	222	1501/1387	1511/1513	830/1066	1511/1515	1055/1245
75	40	−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	−456	1032	164/471	164/423/462/488	1518/1548	1308/1403
(100, 1500)	1.3	222	1516/1399	1517/1532	850/1066	1517/1519	1055/1252

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

$$\delta_b = \mu \tan\beta \left[\frac{2\alpha_3}{3\pi} M_3 I(m^2_{\tilde{b}_1}, m^2_{\tilde{b}_2}, M_3^2) + \frac{\lambda_t}{16\pi^2} A_t \lambda_t I(m^2_{\tilde{t}_1}, m^2_{\tilde{t}_2}, \mu^2) \right], \tag{12}$$

where λ_t is the top Yukawa coupling and

$$I(x,y,z) = -\frac{xy \ln x/y + yz \ln y/z + zx \ln z/x}{(x-y)(y-z)(z-x)}. \tag{13}$$

The sign of δ_b is the same as the one of μ. Figure 2 shows for the four models the regions with $0\% < |\delta_b| < 10\%$, $10\% < |\delta_b| < 20\%$, and $20\% < |\delta_b|$. 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 $m_0^{\rm GUT}$ leads to $10\% < |\delta_b| < 20\%$, while large $m_0^{\rm GUT}$ 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 δ_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. Reference [22], for instance, gives

$$m_b(M_Z) = 2.67 \pm 0.50 \ \text{GeV}, \tag{14}$$

while the analysis of the Υ system [23] and the lattice result [24] give $m_b(m_b) = 4.13 \pm 0.06$ GeV and 4.15 ± 0.20 GeV, respectively,[3] which translate into

$$m_b(M_Z) = 2.8 \pm 0.2 \ \text{GeV}. \tag{15}$$

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 δ_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 δ_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 $\text{sign}(\mu) = -1$. The whole particle spectrum is fixed by gluino mass $M_3^{\rm GUT}$, the soft scalar mass $m_0^{\rm GUT}$, and $\tan\beta$. The sign of the μ-term $\text{sign}(\mu)$ has numerically insignificant effect to the mass spectrum. In the case of negative μ-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 $(M_3^{\rm GUT}, m_0^{\rm GUT})$[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 $M_3^{\rm GUT}$

[3]See also Ref. [25].

$=800$ GeV and $m_0^{\rm GUT}=400$ GeV predicts very small $|\mu|$ and the lightest chargino mass, which is actually excluded by the experimental lower bound. On the other hand, the model **24** for small $M_3^{\rm GUT}$ predicts a very small mass of the lightest neutralino.

In the models **75** and **200** the lightest neutralino χ_1^0 and the lightest chargino $\chi_1^{\pm}$ are almost degenerate. This would potentially create a very difficult experimental setup [26,4,27]. 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 realized in the models **75** and **200**. In particular, the model **75** has the region around $M_3^{\rm GUT}\sim 800$ GeV where the Higgsino is very light. These different patterns of mass spectra also have cosmological implications, which will be discussed elsewhere [28].

We have assumed universal soft scalar mass at the GUT scale in order to concentrate on phenomenological implications of the nonuniversal gaugino masses, but we give some comments on nonuniversal soft scalar masses. Certain types of nonuniversalities can relax the given constraints. For example, the nonuniversality 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 nonuniversality between the Higgs boson masses m_{Hu} and m_{Hd} is interesting and a large difference of $m_{Hd}^2-m_{Hu}^2$ enlarges the parameter region for the succesful electroweak symmetry breaking.

We give a comment for the small $\tan\beta$ scenario. For small $\tan\beta$, the stau $(\text{mass})^2$ has no sizable and negative radiative corrections. Thus, the constraints $m_{\tilde\tau}^2>0$ and $m_{\tilde\tau_1}\geqslant 72$ GeV are no longer serious. In addition most cases lead to the neutralino LSP. Furthermore, the SUSY contributions to $\mathrm{BR}(b\to s\gamma)$ is roughly proportional to $\tan\beta$. Hence, the constraint due to $\mathrm{BR}(b\to s\gamma)$ 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 $M_3^{\rm GUT}$. We find that in two of the models **1** and **24** we have neutralino LSP 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 δ_b. The model **75**, as well as the model **200** with large $m_0^{\rm GUT}$, leads to smaller δ_b than the others.

We have possibilities that gaugino fields acquire a different pattern of nonuniversal 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 [9]. Furthermore, soft scalar masses and A parameters at the GUT scale can, in general, be nonuniversal. 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 nonuniversal gaugino masses have been discussed for $\tan\beta=5$ and 25.

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