No-scale scenario with nonuniversal gaugino masses

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Phenomenological issues of the no-scale structure of the Kähler potential are reexamined, which arises in various approaches to supersymmetry breaking. When no-scale boundary conditions are given at the grand unified scale and universal gaugino masses are postulated, a *B*-ino mass is quite degenerate with right-handed slepton masses and the requirement that the lightest superparticle (LSP) be neutral supplemented with slepton searches at CERN LEP200 severely constrains the allowed mass regions of superparticles. The situation drastically changes if one moderately relaxes the assumption of the universal gaugino masses. After reviewing some interesting scenarios where nonuniversal gaugino masses arise, we show that the nonuniversality diminishes the otherwise severe constraint on the superparticle masses and leads to a variety of superparticle mass spectra: in particular the LSP can be a *W*-ino-like neutralino, a Higgsino-like neutralino, or even a sneutrino, and also left-handed sleptons can be lighter than right-handed ones.

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I. INTRODUCTION

One of the most important phenomenological issues in supersymmetric (SUSY) standard models (SSMs) is to identify the mechanisms of supersymmetry breaking in the hidden sector and its mediation to the SSM sector (observable sector). Soft supersymmetry breaking masses which arise in effective theories after integrating over the hidden sector are in fact constrained by various requirements. For instance, they should lie in the range of 10^2–10^3 GeV to solve the naturalness problem in the Higgs sector which is responsible for electroweak symmetry breaking and satisfy the mass bounds given by collider experiments. They should also satisfy flavor-changing neutral-current (FCNC) constraints as well. Furthermore, if the lightest superparticle (LSP) is stable, which is often the case, cosmological arguments require it be electrically neutral and $SU(3)_c$ singlet.

The structure of the soft scalar masses is characterized by the Kähler potential. In this paper, we shall focus on a special class of the Kähler structure in which the hidden sector and the observable sector are separated from each other in the Kähler potential K as follows:

$$e^{-K/3}=f_{hid}(z,z^*)+f_{obs}(\phi,\phi^*), \tag{1}$$

where z and ϕ symbolically represent fields in the hidden and observable sectors, respectively. The first example which exhibits this form of the Kähler potential is a so-called *no-scale* model [1], and thus we call it the *no-scale* structure. The characteristics of the Kähler potential in no-scale form are that the soft SUSY breaking scalar masses vanish (as the vacuum energy vanishes) and gaugino masses are a dominant source of SUSY breaking mass. Of course, this mass pattern is given at the energy scale where the soft masses are given, and the renormalization group effects due to the nonvanishing gaugino masses raise the masses of the scalar superparticles at the weak scale.

The no-scale structure of the Kähler potential is obtained in many types of models. As we will see in the next section, such models include the (tree-level) Kähler potential of simple Calabi-Yau compactification of heterotic string theories [2] both in the weak- and strong-coupling regimes, the splitting ansatz of the hidden and observable sectors in the superspace density in a supergravity formalism [3], and the geometrical splitting of the two sectors in a brane scenario [4,5].

In this paper we reexamine some phenomenological issues of the models with the no-scale boundary conditions. This class of models has closely been investigated in the literature. Particular attention was paid to the *minimal* case where the boundary conditions are given at the grand unified theory (GUT) scale of 2×10^{16} GeV and the gaugino masses are assumed to be universal at this energy scale. In this case the mass spectrum of superparticles is very constrained, and the *B*-ino mass is almost degenerated with those of the right-handed sleptons. In fact it was shown that the neutralino can be the LSP only when its mass is less than about 120 GeV [3,6,7]: otherwise the stau would be the LSP which is charged, and thus not allowed if it is stable. We will revise this result, emphasizing that the present experimental bounds already exclude the large $\tan\beta$ case, leaving only $\tan\beta \lesssim 8$.

One of the main points in this paper is that slight modifications of the minimal scenario will drastically change the mass spectrum of the superparticles. In particular, we shall devote ourselves to the case where the gaugino masses are nonuniversal at the GUT scale. We will first review several cases in which the nonuniversality of the gaugino masses results. Then we will discuss its phenomenological implications. Most remarkably relaxing the universality condition within a factor of 2 or so will result in a variety of mass spectra. In particular the LSP can be not only the *B*-ino-dominant neutralino, but also a *W*-ino or Higgsino-dominant neutralino, or an admixture of the gaugino and the Higgsino, or even a sneutrino. Furthermore, the severe upper bound on

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the masses of the superparticles no longer exists. Thus we expect the superparticle phenomenology in this case to be much richer than the minimal case.

The paper is organized as follows. In the subsequent section, we review some examples which possess the no-scale Kähler potential. In Sec. III, we reexamine the case where the no-scale boundary conditions are given at the GUT scale and gaugino masses are universal at the scale, and show that the superparticle mass spectrum is very restrictive and tight constraints already exclude much of the parameter space. In Sec. IV, we argue that the very constrained mass spectrum can be relaxed in several ways, and then we focus on one of them, namely, the case with nonuniversal gaugino masses. After recalling some mechanisms to realize the nonuniversality of the gaugino masses, we consider its phenomenological implications. The final section is devoted to the conclusions.

II. NO-SCALE BOUNDARY CONDITIONS

In this section, we would like to review some models which have the no-scale Kähler potential. The first model is the no-scale model [1] with the Kähler potential

$$K = -3\ln(T + T^* - \phi^*\phi) \tag{2}$$

and the superpotential

$$W = W(\phi), \tag{3}$$

where T is a hidden sector field responsible for the SUSY breaking and ϕ is a generic matter field. Here and in the following, we use a unit that the reduced Planck scale $M_{pl} = 2.4\times 10^{18}$ GeV set to unity. With the above Kähler potential and superpotential, one can compute the scalar potential in supergravity and find that

$$V = \frac{1}{3(T + T^* - \phi^*\phi)^2}\left|\frac{\partial W}{\partial \phi}\right|^2 \tag{4}$$

and no supersymmetry breaking masses arise in the scalar sector. Furthermore, the gravitino mass is not fixed, which can be arbitrarily heavy or light at this level. Thus the no-scale model is named after this property. A nontrivial dependence of the gauge kinetic functions on the field T yields nonvanishing gaugino masses in this case.

The no-scale structure appears when one considers a Calabi-Yau compactification of weakly coupled $E_8\times E_8$ heterotic string theory. If one focuses on the overall modulus field whose scalar component represents the overall size of the compactified space, then one finds [2]

$$K = -\ln(S + S^*) - 3\ln(T + T^* - \phi^*\phi), \tag{5}$$

where S is the dilaton field and T is the overall modulus field. The superpotential in this case generally depends on these fields S and T. Now if T dominates the SUSY breaking, then one finds that the soft SUSY breaking scalar mass as well as a trilinear scalar coupling (A term) vanishes as the vacuum energy, i.e., the vacuum expectation value of the scalar potential, vanishes. Note that the T dominant SUSY breaking occurs when the gaugino condensation triggers the SUSY breaking.

The same structure was also obtained for the heterotic M theory [8] which corresponds to the strong-coupling regime of the heterotic string theory, but this time the fields S and T have physically different meanings. In both the weak-coupling and strong-coupling cases, one has to keep in mind that quantum corrections may alter the form of the Kähler potential (5).

Severe FCNC constraints on the superparticle masses may suggest that the hidden sector and the observable sector are in some way separated from each other in the Kähler potential. An assumption often taken along this line of reasoning is the separation of the two sectors in the Kähler potential itself; namely, the Kähler potential is a sum of the contributions from the two sectors. This ansatz will generate the superparticle mass spectrum of the well-known minimal supergravity model and nonzero scalar masses arise. It may be, however, more natural to consider the same separation in the superspace density in the supergravity Lagrangian [3], before making Weyl transformations to obtain the Einstein-Hilbert action for the gravity part. This spirit indeed leads the form of the Kähler potential in Eq. (1). In this case and in the string cases, the gaugino masses become nonzero, provided that the hidden sector couples to the gauge multiplets via the gauge kinetic functions.

Recently it has been pointed out that the form (1) is naturally realized in a five-dimensional setting with two separated three-branes [4,5]. Consider the five-dimensional supergravity on $R^4\times S^1/Z_2$. The geometry has two four-dimensional boundaries, i.e., three-branes. Suppose that the hidden sector is on one of the three-branes and the observable sector is on the other. Now a dimensional reduction of the theory yields, in four dimensions, the following form of the Kähler potential:

$$K = -3\ln[T + T^* + f_{hid}(z,z^*) + f_{obs}(\phi,\phi^*)], \tag{6}$$

where this time the real part of T stands for the length of the compactified fifth dimension.

In the brane separation scenario, the two sectors are really split geometrically, and thus not only the scalar masses, but also the gaugino masses vanish. Therefore one needs to seek another mechanism to mediate the SUSY breaking occurring in the hidden sector. One way is to invoke the superconformal anomaly to obtain loop-suppressed soft masses [4,9]. This anomaly mediation is very appealing, albeit its minimal version has negative masses squared for sleptons. Many attempts to build realistic models have been made [10], and the superparticle masses obtained are in general different from those from the no-scale boundary conditions. In Ref. [11], a new U(1) gauge interaction is assumed to play the role of a mediator of the SUSY breaking. The resulting mass pattern is similar to that of gauge-mediated SUSY breaking. On the other hand, if the SM gauge sector exists in the bulk, then the gauginos can play the role of the SUSY breaking messenger [12] and the resulting mass spectrum of the superparticles exhibits the no-scale structure with nonvanishing gaugino masses, which is given at the scale of (the inverse of) the length of the fifth dimension.

III. MINIMAL SCENARIO

In this section, we would like to discuss the phenomenological consequences of the minimal no-scale scenario which has been mainly studied in the literature. The soft SUSY breaking masses in the minimal case are parametrized by vanishing scalar masses $m_0=0$, vanishing trilinear scalar couplings $A=0$, nonzero Higgs mixing masses B, and nonzero universal gaugino masses $M_{1/2}$.

Note that these values are given at the GUT scale $M_{GUT} \simeq 2\times 10^{16}$ GeV. In addition to these soft masses, we assume a nonzero supersymmetric Higgsino mass μ. These masses at the weak scale are obtained by solving renormalization group equations. Given $M_{1/2}$, requiring the correct electroweak symmetry breaking relates B and μ to the Z boson mass m_Z and the ratio of the two Higgs vacuum expectation values $\tan\beta$ as in the usual manner.

At first we roughly estimate the mass spectrum of superparticles when the Yukawa effects and the left-right mixing effects are neglected. The B-ino, W-ino, and gluino masses at the weak scale are given by one parameter $M_{1/2}$ (in the following we set the renormalization point to be 500 GeV):

$$M_1^2 \simeq 0.18 M_{1/2}^2, \quad M_2^2 \simeq 0.69 M_{1/2}^2, \quad M_3^2 \simeq 7.0 M_{1/2}^2. \tag{7}$$

The soft SUSY breaking masses of scalars in the first two generations are also determined by one parameter $M_{1/2}$:

$$\tilde{m}_{u_L}^2 \simeq 5.8 M_{1/2}^2 + 0.35 m_Z^2 \cos 2\beta, \tag{8}$$

$$\tilde{m}_{d_L}^2 \simeq 5.8 M_{1/2}^2 - 0.42 m_Z^2 \cos 2\beta, \tag{9}$$

$$\tilde{m}_{u_R}^2 \simeq 5.4 M_{1/2}^2 + 0.15 m_Z^2 \cos 2\beta, \tag{10}$$

$$\tilde{m}_{d_R}^2 \simeq 5.4 M_{1/2}^2 - 0.077 m_Z^2 \cos 2\beta, \tag{11}$$

$$\tilde{m}_{l_L}^2 \simeq 0.51 M_{1/2}^2 - 0.27 m_Z^2 \cos 2\beta, \tag{12}$$

$$\tilde{m}_{l_R}^2 \simeq 0.15 M_{1/2}^2 - 0.23 m_Z^2 \cos 2\beta, \tag{13}$$

$$\tilde{m}_{\nu}^2 \simeq 0.51 M_{1/2}^2 + 0.5 m_Z^2 \cos 2\beta. \tag{14}$$

The terms proportional to $m_Z^2 \cos 2\beta$ are $\mathrm{U}(1)_Y$ D-term contributions. From these equations, we find that the B-ino and right-handed slepton are light. When $M_{1/2} \gtrsim 2.8 m_Z \sim 260$ GeV, the $\mathrm{U}(1)_Y$ D-term contribution becomes small, and then the charged right-handed slepton becomes the LSP, and this scenario contradicts cosmological observations.

In Fig. 1, we show the numerical result. The region above the solid line is excluded cosmologically since the charged stau is the LSP. For $\tan\beta \lesssim 10$ where the left-right mixing effect is negligible, the region $M_{1/2} \gtrsim 260$ GeV is excluded as we estimate above. For $\tan\beta \gtrsim 10$, since the left-right mixing effect makes the stau mass lighter, the constraint becomes stronger. In Fig. 1, we also show the value of the right-handed smuon mass. From the cosmological constraint, we find that the right-handed smuon must be lighter than about 120 GeV.

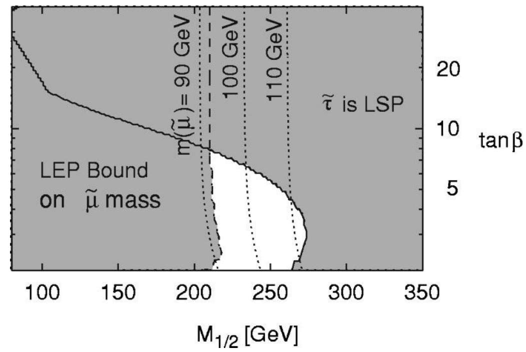

FIG. 1. Allowed region of the minimal no-scale scenario. The horizontal axis is the universal gaugino mass at the GUT scale $M_{1/2}$ and the vertical axis is $\tan\beta$. In the region above the solid line $\tilde{\tau}$ is the LSP and it should be cosmologically excluded. The left side of the dashed line is excluded by smuon searches by the LEP experiments at $\sqrt{s}=202$ GeV. We also show the contour of right-handed smuon mass.

On the other hand, the CERN e^+e^- collider LEP experiments at $\sqrt{s}=202$ GeV provide a rather strong lower bound on slepton masses [13]. For the smuon, except near the threshold, the cross section for smuon pair production, $\sigma(e^+e^- \to \tilde{\mu}_R^+ \tilde{\mu}_R^-)$, must be smaller than 0.05 pb to survive the smuon searches at LEP. Here we impose that $\sigma(e^+e^- \to \tilde{\mu}_R^+ \tilde{\mu}_R^-) \leqslant 0.05$ pb for $m_{\tilde{\mu}_R} \leqslant 98$ GeV and $m_{\tilde{\chi}_1^0} \leqslant 0.98 m_{\tilde{\mu}_R} - 4.1$ GeV. This constraint excludes the left side of the dashed line in Fig. 1. Combining these two constraints, we conclude that the no-scale scenario with universal gaugino masses is allowed only for $\tan\beta \lesssim 8$ and 210 GeV$\lesssim M_{1/2} \lesssim 270$ GeV.

IV. CASE OF NONUNIVERSAL GAUGINO MASSES

In this section, we consider modifications of the minimal boundary conditions discussed in the previous section, and argue that slight modifications will drastically change the phenomenological consequences.

The reason for the very constrained superparticle mass spectrum in the minimal case is the degeneracy of the B-ino mass and that of the right-handed sleptons. The degeneracy is resolved if one considers renormalization group effects above the GUT scale [14–16]. The point is that the right-handed slepton multiplets belong to 10-plets in the minimal choice of the matter representations in the SU(5) GUT, and the large group factor in the gauge loop contributions yields large positive corrections to the slepton masses. We should note, however, that in some realistic models, to attempt to explain the masses of quarks, leptons, and neutrinos, matter multiplets in different generations are often taken to be in different representations of the GUT groups [17], and then the renormalization group effects would violate the mass degeneracy among the different generations, which might cause unacceptably large FCNCs.

Second, the stau can be the lightest superparticle in the SSM sector if it is not stable. This is indeed the case when R parity is violated or there exists another superparticle such as a gravitino out of the SSM sector which is lighter than the stau [18].

Another possibility is to relax the universality of the gaugino masses. In the rest of this section, we will discuss this case in detail. In the next subsection, we shall review various possibilities to realize nonuniversal gaugino masses. In particular we will emphasize that the nonuniversality of the gaugino masses does not conflict with the universality of the gauge couplings. Then we will look into phenomenological implications of the nonuniversality.

A. Examples of nonuniversal gaugino masses

Once the gaugino masses are given universal at some high energy scale where the gauge groups are unified, it is shown that the gaugino mass relation $M_1:M_2:M_3 \simeq 1:2:6$ holds at low energy, irrespective of the breaking patterns of the GUT group [19,14]. Here we review some mechanisms in which the gaugino masses are nonuniversal from the beginning.

In string models with simple Calabi-Yau compactification, the gauge kinetic functions for the standard model gauge multiplets can be written as [20]

$$f_i = S + \epsilon_i T, \tag{15}$$

where $i=1,2,3$ represent the three standard model gauge groups and ϵ_i are some coefficients of one-loop order determined by the details of the compactification. If ϵ_i depends on a gauge group and the modulus field T is dominantly responsible for the SUSY breaking, we will have the nonuniversal gaugino masses

$$M_1:M_2:M_3 = \epsilon_1:\epsilon_2:\epsilon_3. \tag{16}$$

Here we would like to emphasize that large threshold corrections are necessary for the string unification scenario in the weak-coupling regime where the string scale is more than one order of magnitude larger than the naive GUT scale, and thus the appearance of the nonuniversal ϵ_i terms seems to be requisite. Note again that the Kähler potential may receive quantum corrections at the same order and the no-scale structure may be distorted.

The nonuniversality of the gaugino masses can be achieved in the conventional GUT approaches. Suppose that the gauge kinetic functions are written in the following form [21]:

$$f = c + \Sigma Z, \tag{17}$$

where c is a universal constant, Σ is a field which breaks the GUT group to the SM group, and Z is assumed to break SUSY. The first term respects the GUT symmetry and is thus universal for all SM gauge groups, while the second term is a symmetry breaking part which depends on each SM group. As for the gauge couplings, the first term gives a dominant contribution and hence the gauge couplings are unified up to small nonuniversal effects from the second term. On the other hand, the gaugino masses are assumed to come from the second term in Eq. (17). They are proportional to the vacuum expectation value of Σ and are thus nonuniversal. The form of Eq. (17) can also be obtained through GUT threshold corrections to the gauge kinetic functions [22].

Nonuniversal gaugino masses can also be realized in scenarios of product GUTs [23] where the gauge group has the structure of $G_{GUT} \times G_H$ and the standard model gauge groups are obtained as diagonal subgroups of the two product groups. The idea of the product GUTs provides an elegant solution to the triplet-doublet splitting problem in the Higgs sector based on the missing doublet mechanism. Gauge coupling unification is achieved if the gauge couplings of the G_H group are sufficiently large, while contributions to the gaugino masses from the G_H sector are generally sizable and destroy their universality [24].

The flipped SU(5) is another example where the nonuniversality of the gaugino masses naturally arises [25]. The gauge group is $SU(5) \times U(1)$ and thus even if the SU(5) part gives a universal contribution, the gaugino mass from U(1) in general gives a different mass, violating the universality of the $U(1)_Y$ gaugino mass with the other two.

In summary, the nonuniversality of the gaugino masses is not a peculiar phenomenon even in the light of gauge coupling unification. Motivated by this observation, we will discuss its phenomenological consequences.

B. Phenomenological implications

In this subsection we discuss some phenomenological implications of nonuniversal gaugino masses. At the cutoff scale, all scalar masses are vanishing as in the minimal case, while the B-ino, W-inos, and gluinos possess nonzero masses $M_{1,0}$, $M_{2,0}$, and $M_{3,0}$, respectively, and now they are no longer degenerate in general. The soft SUSY breaking mass parameters at the weak scale are obtained by solving the renormalization group equations (RGEs). In this paper we use the one-loop level RGEs. With the soft SUSY breaking masses, we evaluate the physical masses using the tree-level potential. We also obtain the value of μ from the electroweak symmetry breaking condition with the tree-level Higgs potential.

Before showing the numerical results, we discuss the mass spectrum of superparticles when the Yukawa effects to the RG evolutions and left-right mixings are neglected. The relations of the gaugino masses at the GUT scale M_{GUT} and the electroweak scale M_{EW} are

$$M_1^2 \simeq 0.18 M_{1,0}^2, \quad M_2^2 \simeq 0.69 M_{2,0}^2, \quad M_3^2 \simeq 7.0 M_{3,0}^2. \tag{18}$$

Neglecting the effects of the Yukawa interaction, the masses squared of sfermions at the weak scale are evaluated to be

$$\tilde{m}_{u_L}^2 \simeq 5.4 M_{3,0}^2 + 0.47 M_{2,0}^2 + 4.2 \times 10^{-3} M_{1,0}^2 + 0.35 m_Z^2 \cos 2\beta, \tag{19}$$

$$\tilde{m}_{d_L}^2 \simeq 5.4M_{3,0}^2 + 0.47M_{2,0}^2 + 4.2\times 10^{-3} M_{1,0}^2 - 0.42 m_Z^2 \cos 2\beta, \quad (20)$$

$$\tilde{m}_{u_R}^2 \simeq 5.4M_{3,0}^2 + 0.066M_{1,0}^2 + 0.15 m_Z^2 \cos 2\beta, \quad (21)$$

$$\tilde{m}_{d_R}^2 \simeq 5.4M_{3,0}^2 + 0.017M_{1,0}^2 - 0.077 m_Z^2 \cos 2\beta, \quad (22)$$

$$\tilde{m}_{l_L}^2 \simeq 0.47M_{2,0}^2 + 0.037M_{1,0}^2 - 0.27 m_Z^2 \cos 2\beta. \quad (23)$$

$$\tilde{m}_{l_R}^2 \simeq 0.15M_{1,0}^2 - 0.23 m_Z^2 \cos 2\beta, \quad (24)$$

$$\tilde{m}_{\nu}^2 \simeq 0.47M_{2,0}^2 + 0.037M_{1,0}^2 + 0.5 m_Z^2 \cos 2\beta. \quad (25)$$

From the above equations, we find that if $M_{1,0} \gtrsim 2.0 M_{2,0}$, $\tilde{m}_{l_R}^2$ is heavier than M_1^2, M_2^2, $\tilde{m}_{\ell_L}^2$, and $\tilde{m}_\nu^2$. Notice that the mass of the charged left-handed slepton is heavier than the mass of the neutral sneutrino because $\cos 2\beta \leqslant 0$ for $\tan\beta \geqslant 1$. On the other hand, for $M_{1,0}/M_{2,0} \gtrsim 2.5$, the *W*-ino mass tends to be lighter than the sneutrino mass. Hence we expect that the sneutrino can be the LSP when $2 \lesssim M_{1,0}/M_{2,0} \lesssim 2.5$, and the *W*-ino-like neutralino can be the LSP when $M_{1,0}/M_{2,0} \gtrsim 2.5$.

Next, we consider how μ affects the mass spectrum of the superparticles. The value μ is determined by minimizing the Higgs potential. At the tree level, μ is calculated in terms of the soft SUSY breaking masses of the Higgs bosons and $\tan\beta$,

$$\mu^2 = \frac{\tilde{m}_{H_d}^2 - \tilde{m}_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} - \frac{1}{2} m_Z^2. \quad (26)$$

In order to obtain the value of $\tilde{m}_{H_d}^2$ and $\tilde{m}_{H_u}^2$, we have to include the Yukawa interaction. For the moment we consider the low $\tan\beta$ region; i.e., we take only the top Yukawa coupling into account and neglect the bottom and tau Yukawa couplings for simplicity. In this case $\tilde{m}_{H_d}^2 = \tilde{m}_{l_L}^2$ and we can obtain an analytic solution for the RGE of $\tilde{m}_{H_u}^2$. For $\tan\beta = 10$, μ is, approximately,

$$\mu^2 = 2.1M_{3,0}^2 - 0.22M_{2,0}^2 - 0.0064M_{1,0}^2 + 0.0063M_{1,0}M_{2,0} + 0.19M_{2,0}M_{3,0} + 0.029M_{3,0}M_{1,0} - \frac{1}{2} m_Z^2. \quad (27)$$

From this equation, we find that the size of μ is strongly correlated with the size of the gluino mass $M_{3,0}$ and $|\mu|$ becomes large as $M_{3,0}$ increases. Hence when $M_{3,0}$ is large enough, left-right mixing in the slepton masses is important, which makes one of the staus, $\tilde{\tau}_1$, lighter than the sneutrino. On the other hand, if $M_{3,0}$ is small enough, $|\mu|$ becomes smaller than the mass of the *B*-ino, *W*-ino, slepton, and sneutrinos, and then a Higgsino-like neutralino can be the LSP. Actually, for $\tan\beta = 10$, from Eq. (27) we find that $|\mu|$ is smaller than M_2 if $M_{3,0}/M_{2,0} \lesssim 0.5$ is satisfied.

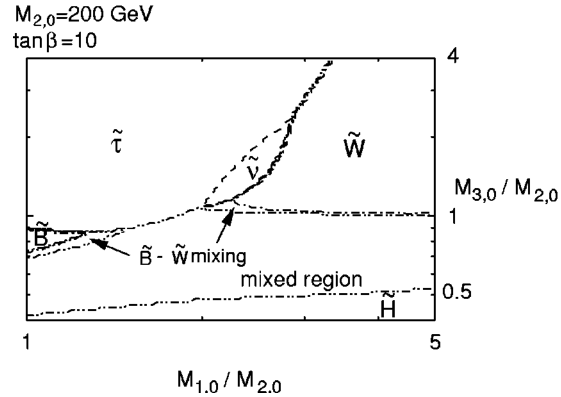

FIG. 2. The composition of the LSP in the $M_{1,0}/M_{2,0}$-$M_{3,0}/M_{2,0}$ plane, for $M_{2,0} = 200$ GeV and $\tan\beta = 10$. The classification of the neutralino LSP is given in the text.

In the nonuniversal case, not only the mass spectrum but also the mixing properties of the neutralinos are very different from those in the minimal case. To see this we classify the lightest neutralino χ_1^0 into five cases as follows. $\tilde{\chi}_1^0$ is a linear combination of the *B*-ino, *W*-ino, and Higgsinos and is written as

$$\tilde{\chi}_1^0 = (O_N)_{1B}\tilde{B} + (O_N)_{1W}\tilde{W} + (O_N)_{1H_d}\tilde{H}_d + (O_N)_{1H_u}\tilde{H}_u, \quad (28)$$

where O_N is orthogonal matrix diagonalizing the neutralino mass matrix. When $|(O_N)_{1B}|^2 > 0.8$, $|(O_N)_{1W}|^2 > 0.8$, or $|(O_N)_{1H_d}|^2 + |(O_N)_{1H_u}|^2 > 0.8$, we call these parameter regions the ''*B*-ino region,'' ''*W*-ino region,'' or ''Higgsino region,'' respectively. When $|(O_N)_{1B}|^2 < 0.8$, $|(O_N)_{1W}|^2 < 0.8$, and $|(O_N)_{1B}|^2 + |(O_N)_{1W}|^2 > 0.8$, we call the region the ''*B*-ino–*W*-ino mixed region.'' The other parameter region is called the ''mixed region.''

In Fig. 2 we show the composition of the LSP when we relax the gaugino mass universality. Here we take $M_{2,0} = 200$ GeV, $\tan\beta = 10$, and $\mathrm{sgn}(\mu) = +1$. Recall that for the universal gaugino masses at the GUT scale, the LSP is the lighter stau and this parameter set is excluded. Once we relax universality, however, we see that the situation drastically changes, and the composition of the LSP behaves as we have discussed with the approximate expressions (18)–(25). The lightest neutralino can be the LSP in a large parameter region, and furthermore unlike the universal case, it can be *W*-ino-like, Higgsino-like, or an admixture of them as well as *B*-ino-like. When $M_{1,0}/M_{2,0} \gtrsim 2.5$ and $M_{3,0}/M_{2,0} \gtrsim 1$ the *W*-ino is the LSP. And as the ratio $M_{3,0}/M_{2,0}$ decreases, $|\mu|$ becomes comparable to M_1 and M_2 and the lightest neutralino is an admixture of the *B*-ino, *W*-ino, and Higgsinos. Further, $M_{3,0}/M_{2,0}$ becomes smaller than about 0.5; the dominant component of the lightest neutralino is a Higgsino. Also we find in the region $2 \lesssim M_{1,0}/M_{2,0} \lesssim 2.5$ that the tau sneutrino is indeed the LSP. And we find that when $M_{3,0}/M_{2,0}$ is larger than 2, i.e., when $|\mu|$ is large and so is

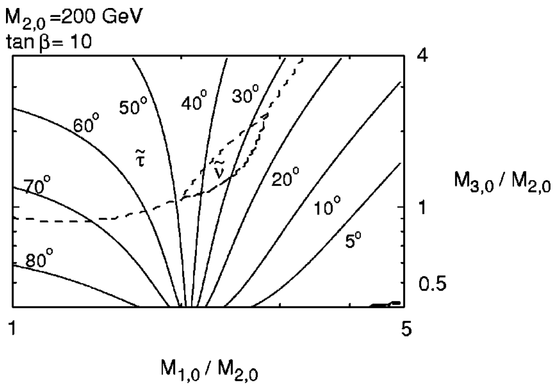

FIG. 3. Mixing angle θ_τ in the $M_{1,0}/M_{2,0}$-$M_{3,0}/M_{2,0}$ plane for $M_{2,0}=200$ GeV and $\tan\beta=10$. We also show the region where the stau and tau sneutrinos are the LSP. The definition of the mixing angle is given in the text.

the left-handed and right-handed stau mixing, the sneutrino cannot be the LSP, and the stau is the LSP even when $M_{1,0}/M_{2,0}$ is bigger than 2.5–3.

In the nonuniversal case sfermions, as well as neutralinos and charginos, show a variety of mass spectra. From Eqs. (23) and (24), we find that when $M_{1,0}/M_{2,0}\gtrsim 2$ left-handed sfermions are smaller than right-handed sfermions in contrast to the universal case. For the stau, the mixing angle of $\tilde{\tau}_L$ and $\tilde{\tau}_R$ also depends on this ratio. In Fig. 3 we show the behavior of this mixing angle θ_τ in the $M_{1,0}/M_{2,0}$-$M_{3,0}/M_{2,0}$ plane, where θ_τ is defined such that the lighter stau $\tilde{\tau}_1$ is written as $\tilde{\tau}_1=\cos\theta_\tau\tilde{\tau}_L+\sin\theta_\tau\tilde{\tau}_R$. Around $M_{1,0}/M_{2,0}\simeq 2$, the mass of the right-handed stau is as heavy as that of the left-handed stau, and they mix maximally ($\theta_\tau=40-50$) as expected. Also the masses of squarks strongly depend on M_3, and thus the mass relations between squarks and sleptons drastically change. As we shall see later, some of the squarks can be lighter than the sleptons.

In Fig. 4 we show the same graph as Fig. 2 except for $\tan\beta=35$. In this case the Yukawa interaction and the left-right mixing make the stau mass lighter. In fact, although the *W*-ino-like, Higgsino-like, and mixed neutralino is the LSP in the large parameter region, the sneutrino cannot be the

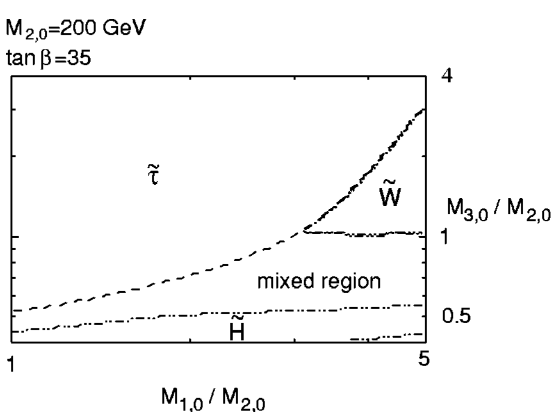

FIG. 4. The same as Fig. 2, but for $M_{2,0}=200$ GeV and $\tan\beta=35$.

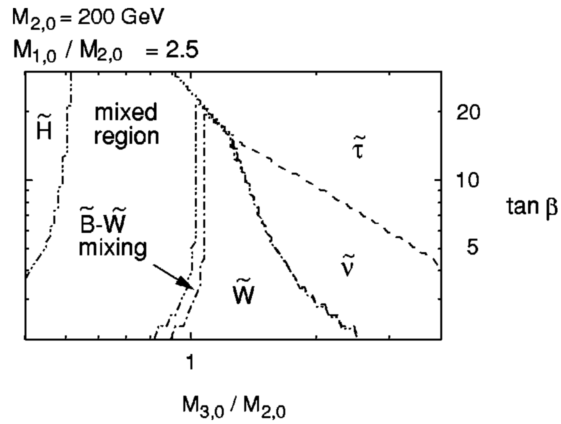

FIG. 5. The composition of the LSP in the $M_{3,0}/M_{2,0}$-$\tan\beta$ plane, for $M_{2,0}=200$ GeV and $M_{1,0}/M_{2,0}=2.5$.

LSP. To see the relation among the stau mass, the tau sneutrino mass, and $\tan\beta$, we plot in Fig. 5 the composition of the LSP in the $M_{3,0}/M_{2,0}$-$\tan\beta$ plane, fixing $M_{3,0}/M_{2,0}=2.5$. This figure shows that the tau sneutrino can be the LSP when $\tan\beta\lesssim 15$ where the left-right mixing is not so sizable. We have checked that these features are insensitive to the signs of μ and gaugino masses.

We shall next investigate the mass spectrum of superparticles in detail, by choosing some representative parameter sets, and discuss the phenomenology for each parameter set. The points we choose are listed in Table I. In Table II we show the contamination of $\tilde{\chi}_1^0$ for each point. At points A and E, the LSP is the *W*-ino-like neutralino. At points B, C, and E the LSP is the Higgsino-like neutralino. And at point D the tau sneutrino is the LSP. In Table III we list the mass spectrum of superparticles.

The *W*-ino-like neutralino is the LSP when $M_{1,0}/M_{2,0}\gtrsim 2$ and $M_{3,0}/M_{2,0}\gtrsim 1$. In the *W*-ino-like neutralino LSP case, the lighter chargino and the lightest neutralino are highly degenerate generally. This character and the resulting phenomenology have been studied in [25–30]. On top of this our scenario also predicts that the right-handed sfermions are heavier than the left-handed ones because of the inequality $M_{1,0}/M_{2,0}\gtrsim 2$, and colored superparticles are heavier than other superparticles because of the inequality $M_{3,0}/M_{2,0}\gtrsim 1$ (see the list for points A and E in Table III). The former may be an interesting feature. The anomaly-mediated SUSY breaking (AMSB) scenario also predicts the *W*-ino-like LSP. However, in the minimal AMSB model where universal mass is added to all scalars to avoid negative slepton masses squared, the left-handed and right-handed sleptons in the first

TABLE I. Gaugino masses at the GUT scale for each point. All dimensionful parameters are given in the GeV unit.

	Point A	Point B	Point C	Point D	Point E	Point F
$M_{1,0}$	800	1000	400	500	800	600
$M_{2,0}$	200	250	200	200	200	200
$M_{3,0}$	400	125	100	300	300	100
$\tan\beta$	10	10	10	10	35	35

TABLE II. Components of the lightest neutralino $\tilde{\chi}_1^0$ which is a linear combination of the B-ino, W-ino and Higgsinos, $\tilde{\chi}_1^0 = (O_N)_{1B}\tilde{B} + (O_N)_{1W}\tilde{W} + (O_N)_{1H_d}\tilde{H}_d + (O_N)_{1H_u}\tilde{H}_u$.

	Point A	Point B	Point C	Point D	Point E	Point F
$(O_N)_{1B}$	-0.017	0.0835	0.241	0.092	-0.022	0.126
$(O_N)_{1W}$	0.987	-0.478	-0.457	-0.967	0.973	-0.445
$(O_N)_{1H_d}$	-0.149	0.689	0.710	0.219	-0.213	0.729
$(O_N)_{1H_u}$	0.054	-0.539	-0.479	-0.096	0.084	-0.504

two generations tend to be degenerate [29]. Thus we can distinguish two scenarios with the W-ino LSP, the no-scale scenario with nonuniversal gaugino masses, and the minimal AMSB, by measuring these slepton masses.

The Higgsino-like neutralino is the LSP when $M_{3,0}/M_{2,0} \lesssim 0.5$ regardless of $M_{1,0}/M_{2,0}$. In the Higgsino-like neutralino LSP case, the mass deference between the Higgsino-like neutralino LSP and the lighter chargino is generally small. The resulting phenomenology has been studied in [31–33]. Furthermore, in our case, the sleptons are as heavy as the squarks due to the inequality $M_{3,0}/M_{2,0} \lesssim 0.5$. Especially the lighter top squark and bottom squark can be lighter than some of the sleptons. Actually, at points B, C, and F, the lighter top squark is comparable to the slepton masses, and all superparticle masses are below 400–450 GeV.

In the nonuniversal scenario, the tau sneutrino can also be the LSP when $2 \lesssim M_{1,0}/M_{2,0} \lesssim 2.5$, $1 \lesssim M_{3,0}/M_{2,0} \lesssim 5$, and $\tan\beta \lesssim 15$. From the first inequality, we find that the mass difference between left-handed and right-handed squarks in the first two generations is small, and the left-right mixing angle of the stau is big as shown in Fig. 3.

TABLE III. Mass spectrum for each point. All values are given in the GeV unit.

Particle	Point A	Point B	Point C	Point D	Point E	Point F
χ_1^0	160	106	70	156	159	72
χ_2^0	336	152	126	209	332	120
χ_3^0	594	248	169	444	438	202
χ_4^0	603	430	222	457	453	267
χ_1^+	160	113	81	157	159	81
χ_2^+	602	253	216	457	449	212
$\tilde{u}_L$	929	336	263	701	702	265
$\tilde{d}_L$	932	345	275	706	707	277
$\tilde{u}_R$	941	384	249	700	718	274
$\tilde{d}_R$	925	316	237	692	697	244
$\tilde{\nu}$	196	250	144	155	196	167
$\tilde{e}_L$	212	262	164	174	212	185
$\tilde{e}_R$	312	389	161	198	312	236
$\tilde{t}_1$	742	233	164	538	544	176
$\tilde{t}_2$	925	409	339	721	709	338
$\tilde{b}_1$	855	293	230	646	602	200
$\tilde{b}_2$	922	317	252	691	676	252
$\tilde{\nu}_\tau$	195	249	143	154	183	156
$\tilde{\tau}_1$	205	261	154	159	166	169
$\tilde{\tau}_2$	314	387	169	209	316	225
$\tilde{g}$	1053	329	263	790	790	263

V. CONCLUSIONS

In this paper, we have reexamined the no-scale scenario where the vanishing SUSY breaking scalar masses and trilinear scalar couplings are given at the GUT scale. When the gaugino masses are given as universal, the renormalization group analysis implies that the B-ino mass and the right-handed slepton masses are close to each other. This degeneracy leads to an upper bound of the LSP mass of around 120 GeV: above it the LSP would be the charged stau, which must be excluded cosmologically. Furthermore, the negative results of the slepton searches at LEP200 already excluded a large portion of parameter space including a large $\tan\beta$ region, leaving $\tan\beta \lesssim 8$.

We next considered various ways to avoid the aforementioned severe constraints. Among them, we concentrated on the case of the nonuniversal gaugino masses. In fact the nonuniversality of the gaugino masses is by no means a peculiar phenomenon; rather it is realized in various scenarios, including some approaches to grand unification. We investigated some phenomenological implications of the no-scale model with nonuniversal gaugino masses. We found that there is no longer a severe constraint on the superparticle masses and the mass spectrum of the superparticle has a much richer structure. In particular, the LSP can be the W-ino-like neutralino, the Higgsino-like neutralino, or even the sneutrino. We also found that unlike the conventional universal gaugino mass case, the left-handed slepton masses can be lighter than the right-handed slepton masses. We expect that resulting collider signatures with these features will be quite different from the usual scenario with universal gaugino masses. Further studies along this direction should be encouraged.

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