Higgs mass and $b \to s\gamma$ constraints on SUSY models with no-scale boundary condition

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Abstract

No-scale structure of the Kähler potential is obtained in many types of supersymmetric models. In this paper, phenomenological aspects of these models are investigated with special attention to the current Higgs mass bound at LEP and $b \to s\gamma$ result at the CLEO. When the boundary condition is given at the GUT scale and gaugino masses are universal at this scale, very narrow parameter region is allowed only for positive Higgsino mass region if R-parity is conserved. The negative Higgsino mass case is entirely excluded. On the other hand, relatively large parameter region is allowed when the boundary condition is given above the GUT scale, and Tevatron can discover SUSY signals for the positive Higgsino mass case. The no-scale models with Wino, Higgsino or sneutrino LSP are also considered. We show that the Higgs mass constraint is important for the Higgsino LSP case, which requires the LSP mass to be larger than about 245 GeV.
I. INTRODUCTION

Supersymmetry (SUSY) is one of the most attractive extensions of the standard model. This symmetry solves the naturalness problem and predicts gauge coupling unification at the GUT scale $M_{\text{GUT}} \simeq 2 \times 10^{16}\text{GeV}$. It also predicts the existence of superpartner of the standard model (SM) particles. From the naturalness argument, their masses should be below TeV range, hence these particles will be discovered at Tevatron or Large Hadron Collider (LHC).

Mechanisms of SUSY breaking and its mediation to the minimal supersymmetric standard model (MSSM) sector are one of the most important problems in the SUSY phenomenology. In many models, this dynamics is related to high energy physics far above the electroweak (EW) scale, e.g., GUT scale or Planck scale. Once the mechanism is specified, mass spectrum and flavor structure of SUSY particle at the EW scale can be determined by a small number of parameters. Hence it may be possible to confirm or exclude the mechanism by direct search or flavor-changing-neutral-current (FCNC) experiments in near future.

If SUSY breaking is mediated by gravity, the structure of SUSY breaking masses of scalars are determined by Kähler potential. In the present paper, we focus on the no-scale type Kähler potential, in which the hidden sector and the observable sector are separated as follows:

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

where $z$ and $\phi$ are hidden sector fields and observable sector fields, respectively. This type of Kähler potential is originally investigated in Ref. [1] with $f_{\text{hid}}(z, z^*) = z + z^*$ and $f_{\text{obs}}(\phi, \phi^*) = \sum_i \phi_i \phi_i^*$. Characteristic features of the Kähler potential eq. (1) is that all scalar masses and trilinear scalar couplings (A-terms) vanish as the cosmological constant vanishes [2]. The only source of SUSY breaking is gaugino masses. Hence this scenario is highly predictive, various phenomenological consequences are obtained with a few parameters. The separation in eq. (1) implies that couplings of the hidden sector and the observable sector is flavor blind, and contributions of SUSY particles to FCNC are suppressed. Therefore this Kähler potential is also interesting from the viewpoint of the SUSY flavor problem.

The no-scale structure of the Kähler potential is obtained in various models. It has been shown that in some classes of string theory, for example weakly coupled $E_8 \times E_8$ heterotic string theory, Kähler potential becomes the no-scale type [3,4]. If the hidden sector and the observable sector are separated in the superspace density in the supergravity Lagrangian, the Kähler potential is indeed given as in eq. (1). In the two cases, the gaugino masses can be induced if the hidden sector fields couple to the gauge multiplets via the gauge kinetic function. Recently it has been pointed out that the form eq. (1) is realized naturally in a five-dimensional setting with two branes, namely, sequestered sector scenario [5]. In this scenario, the hidden sector fields live on one brane and the visible sector fields live on the other. It has been shown that the form of the Kähler potential of the effective theory obtained by dimensional reduction is indeed eq. (1) [6]. If
the SM gauge fields dwell in the bulk, gaugino mediate the SUSY breaking on the hidden sector brane to the visible sector brane and the no-scale boundary condition is given at the compactification scale of the fifth dimension (gaugino mediation [7,8]).

In the no-scale scenario, degrees of freedom of SUSY particle mass spectrum is limited because only non-zero soft SUSY breaking masses are gaugino masses and Higgs mixing mass B at the energy scale where the boundary condition is given. Hence phenomenological aspects of this scenario have been investigated in the literature, mainly focusing on the mass spectrum. Direct search bounds and the cosmological constraint (i.e., a charged particle can not be the LSP if the R-parity is conserved) were considered and allowed region in the parameter space was identified. For the boundary condition, the following three cases were considered. First, universal gaugino masses are given at the GUT scale. In this case, the cosmological constraint is severe and only the region $200\text{GeV} \lesssim M_{1/2} \lesssim 250\text{GeV}$ and $\tan \beta \lesssim 8$ is allowed since stau tends to be light [2,11]. The second case is that universal gaugino masses are given above the GUT scale. And the third case is that non-universal gaugino masses are given at the GUT scale. In this case Wino, Higgsino or sneutrino can be the LSP. In the latter two cases, it is shown that the cosmological constraint is not severer than the first case.

In the present paper, current limits from the lightest Higgs mass $m_h$ and the branching ratio for $b \to s\gamma$ are also used to constrain the no-scale scenario. Combining these constraints, we will show that almost all the parameter region is excluded when universal gaugino masses are given at the GUT scale. However, when the boundary condition is given above the GUT scale, relatively large parameter region is allowed. We also consider the case that the non-universal gaugino masses are given at the GUT scale. We will show that these constraints are important when the Higgsino-like neutralino is the LSP.

This paper is organized as follows. In section II, we review some phenomenological aspects of SUSY models with no-scale boundary condition, especially indications of the direct search bounds and the cosmological bound. In section III, we further constrain these models from the Higgs mass bound and BR$(b \to s\gamma)$ result. Indications of these bounds for the Tevatron are also discussed. Our conclusions are given in section IV.

II. MODELS WITH NO-SCALE BOUNDARY CONDITION

In this section, we briefly review phenomenological aspects of SUSY models with no-scale boundary condition, mainly indications of the cosmological bound and direct search limit at LEP 2. We consider the following three cases.

- Universal gaugino masses are given at the GUT scale. Hereafter we call this case the minimal scenario.

- Universal gaugino masses are given above the GUT scale $M_* > M_{GUT}$. Throughout this paper, we take the minimal SU(5) to be the theory above the GUT scale as a typical example.

- Non-universal gaugino masses are given at the GUT scale.
Once one of the above boundary conditions is given, mass spectrum of SUSY particles at the EW scale and their contributions to FCNC can be calculated. In this paper we solve the one-loop level RGEs to obtain the soft SUSY breaking mass parameters at the EW scale. The Higgsino mass parameter $\mu$ is determined by potential minimum condition at the one-loop level.

First, we discuss the minimal scenario. In this case, the following boundary condition is given at the GUT scale,

$$m_0^2 = 0, \quad A_0 = 0, \quad M_1(M_{GUT}) = M_2(M_{GUT}) = M_3(M_{GUT}) = M_{1/2},$$

(2)

where $m_0$ is the common scalar mass and $A_0$ is universal trilinear scalar coupling. With this boundary condition, Bino and right-handed sleptons are lighter than other SUSY particles. Their masses are approximately,

$$M_2 \approx 0.18 M_{1/2}^2, \quad m_{\tilde{e}_R} \approx 0.15 M_{1/2}^2 - 0.23 m_Z^2 \cos 2\beta.$$  

(3)

From eq.(3) we see that the charged right-handed slepton is the LSP if the D-term $0.23 m_Z^2 \cos 2\beta$ is negligible, i.e., $M_{1/2} \gtrsim 250\text{GeV}$. Hence this parameter region is excluded by the cosmological consideration. On the other hand, LEP 2 experiments yields the upper bound on the cross section for smuon pair production, $\sigma(e^+e^- \to \tilde{\mu}_R^+\tilde{\mu}_R^-) < 0.05\text{pb}$ for $m_{\tilde{\mu}_R} \lesssim 98\text{GeV}$ and $m_{\tilde{\chi}_1^0} \lesssim 0.98 m_{\tilde{\mu}_R} - 4.1\text{GeV}$ [12], so the parameter region $M_{1/2} \lesssim 200\text{GeV}$ is excluded. In Fig. 1 and 2, allowed region of the parameter space are shown in the $M_{1/2} - \tan \beta$ plane. The regions above the dash-dotted line and the left side of the dash-dot-dotted line are excluded by cosmological bound and LEP 2 bound on smuon pair production, respectively. Therefore the minimal scenario is constrained severely.

Next we see the case that the universal gaugino masses are given above the GUT scale. In the minimal SU(5) case, the right-handed slepton belongs to 10-plet, so the large group factor makes slepton masses heavier. For example, when $M_* = 10^{17}\text{GeV}$ the Bino mass and the right-handed slepton mass at the weak scale are approximately given,

$$M_1^2 \approx 0.18 M_{1/2}^2, \quad m_{\tilde{e}_R} \approx 0.30 M_{1/2}^2 - 0.23 m_Z^2 \cos 2\beta.$$  

(4)

Hence the cosmological constraint is not severe because the stau mass is large enough and neutralino is the LSP in the large parameter region [9,10,8]. In the Fig. 3 and 4, the same figures as in the Fig. 1 and 2 are shown. Unlike in the minimal case, the stau search bound at LEP [12] is also plotted because mass difference between $\tilde{\chi}_1^0$ and $\tilde{\tau}$ is larger than in the minimal case and it can be stronger than the smuon search. From these figures we see that the $\tilde{\tau}$ LSP is avoided unless $\tan \beta$ is larger than about 20.

The charged stau LSP can also be avoided if gaugino masses at the GUT scale are non-universal [11], i.e., the following boundary condition is given,

$$m_0^2 = 0, \quad A_0 = 0, \quad M_1(M_{GUT}) = M_{1,0}, \quad M_2(M_{GUT}) = M_{2,0}, \quad M_3(M_{GUT}) = M_{3,0}.$$  

(5)
This boundary condition can be given naturally within the GUT framework \cite{13,14}. In this case, not only Bino-like neutralino, but also Wino-like, Higgsino-like neutralino or sneutrino can be the LSP. For \( M_{1,0}/M_{2,0} \gtrsim 2 \) and \( M_{3,0}/M_{2,0} \gtrsim 1 \), the LSP is wino-like neutralino. For example, when \( M_{1,0}/M_{2,0} = 4 \) and \( M_{3,0}/M_{2,0} = 2 \), then Wino mass and charged slepton mass are (notice that in this case the left-handed sleptons are lighter than right-handed sleptons);

\[
M_2^2 \simeq 0.69 M_{2,0}^2, \quad m_{\tilde{\nu}_L}^2 \simeq 1.06 M_{2,0}^2 - 0.27 m_Z^2 \cos 2\beta. \quad (6)
\]

The Higgsino is the LSP if \( M_{3,0}/M_{2,0} \lesssim 0.5 \). For example, when \( M_{1,0}/M_{2,0} = 2 \) and \( M_{3,0}/M_{2,0} = 0.5 \), then the Higgsino mass and the right-handed slepton mass are

\[
m_H^2 \simeq \mu^2 \simeq 0.416 M_{2,0}^2 - 0.5m_Z^2, \quad m_{\tilde{\nu}_R}^2 \simeq 0.60 M_{2,0}^2 - 0.23m_Z^2 \cos 2\beta. \quad (7)
\]

In the two cases given above, neutral wino or Higgsino is the LSP. In fact from Fig.5 - 9 we find that neural particle is the LSP in large parameter region, thus it is cosmologically viable.

**III. HIGGS MASS AND \( b \to s\gamma \) CONSTRAINT ON NO-SCALE SCENARIO**

In the previous section we take into account only LEP 2 bound and the cosmological constraint. We find that the minimal scenario is severely constrained, but the other two scenarios are not. In this section we also include the current Higgs mass bound and \( b \to s\gamma \) constraint. As we will see, combining the above four constraint, not only the minimal case but also the other two scenarios can be constrained more severely. We also discuss the possibility whether this scenario can be seen at the Tevatron Run 2 or not.

Before we show the numerical results, some remarks on our calculation of the Higgs mass and \( \text{BR}(b \to s\gamma) \) are in order.

It is well known that radiative correction is important when the lightest Higgs mass is evaluated \cite{15}. In the present paper, the lightest Higgs mass is evaluated by means of the one-loop level effective potential \cite{16}. This potential is evaluated at the renormalization point of the geometrical mean of the two stop mass eigenvalues \( \sqrt{m_{\tilde{t}_1}m_{\tilde{t}_2}} \). We compared our result with a two-loop result by using \textit{FeynHiggs} \cite{17}, and checked that the difference between these two results is smaller than 5 GeV as long as \( \tan \beta \) is bigger than 5. When \( \tan \beta \) is close to 2, the difference can be 7 GeV. However, as we will see later, Higgs mass bound plays an important role around \( \tan \beta \simeq 10 \). And the two-loop effects always make the Higgs mass lighter than that obtained at the one-loop level. So our conclusion is conservative and is not significantly changed by the two-loop effect. We exclude the parameter region where the lightest Higgs mass is lighter than the current 95\% C.L. limit from LEP 2 experiments, \( m_h > 113.5\text{GeV} \) \cite{18}.

In the present paper, \( \text{BR}(b \to s\gamma) \) is calculated including leading order (LO) QCD corrections \cite{19}, and compare it to the current CLEO measurement. In the MSSM, chargino contribution can be comparable to the SM and charged Higgs contributions. They interfere constructively (destructively) each other when \( \mu < 0 \) (\( \mu > 0 \)). The difference between
the LO and the next-to-leading order (NLO) result can be sizable only when cancellation among different contributions at the LO is spoiled by the NLO contributions. As we will see, however, the $b \to s\gamma$ constraint is severe when the interference is constructive. In the case of destructive interference where the deviation from the NLO result may be large, this constraint is not so important. Hence we expect that our conclusion is not changed significantly by the inclusion of the NLO corrections. For the experimental value, we use 95\% C.L. limit from CLEO, $2.0 \times 10^{-4} < \text{BR}(b \to s\gamma) < 4.5 \times 10^{-4}$ [20].

A. Minimal scenario

First we show the numerical results for the minimal case. The case for $\mu > 0$ is shown in Fig.1. In this case, for small $\tan \beta$ region, the stop mass is not so large that radiative correction factor $\log(m_{\tilde{t}_1}/m^{2}_{\tilde{t}_2})$ which raises the Higgs mass is small. (For example, $m_{\tilde{t}_1} = 361$ GeV and $m_{\tilde{t}_2} = 567$ GeV for $M_{1/2} = 200$ GeV and $\tan \beta = 3$). Hence the Higgs mass limit constrains this scenario severely. In Fig.1, the Higgs mass bound and BR($b \to s\gamma$) constraints in the $M_{1/2} - \tan \beta$ plane are shown. The regions below the solid line and above the dashed line are excluded by the Higgs mass and BR($b \to s\gamma$) bound, respectively. The indication of $m_h = 115$GeV reported by LEP 2 [18] is also shown in this figure. From the figure we find that the Higgs mass bound almost excludes the region where the stau LSP is avoided. Note that, as we discussed earlier, the bound we put on the Higgs mass may be conservative, because the two loop correction may further reduce the Higgs mass.

The same figure but for $\mu < 0$ is shown in Fig.2. Now BR($b \to s\gamma$) also constrains parameter region strongly since chargino contribution to $b \to s\gamma$ interferes with SM and charged Higgs ones constructively. The region above the dashed line is excluded by BR($b \to s\gamma$) constraint. We find that only one of the two constraints is enough to exclude all the region where cosmological bound and the smuon mass bound are avoided. Hence if R-parity is conserved, i.e., the cosmological bound is relevant, this scenario with $\mu < 0$ is excluded.

B. $M_* > M_{\text{GUT}}$ case

Next we show the numerical results in the case that the cutoff scale is larger than the GUT scale. As a typical example, we choose the minimal SU(5) as the theory above the GUT scale. In Fig.3 and 4, results are shown for positive and negative $\mu$, respectively. In both figures, we take $M_* = 10^{17}$ GeV. For $\mu > 0$ case, large parameter region is allowed and SUSY scale $M_{1/2}$ can be as small as about 180 GeV, which indicates the LSP mass $\tilde{\chi}^0_1 \simeq 80$ GeV. For $\mu < 0$, as in the minimal case, BR($b \to s\gamma$) constraint is severer, and $M_{1/2}$ must be larger than around 280 GeV. We also considered other values of the boundary scale $M_*$ from $5 \times 10^{16}$GeV to $10^{18}$GeV, and checked that the behavior of the contour plot does not change so much.
According to Ref. [22], Tevatron Run 2 experiment can explore up to $M_{1/2} \simeq 230$ GeV for integrated luminosity $2\text{fb}^{-1}$. Hence if $180\text{GeV} \lesssim M_{1/2} \lesssim 230\text{GeV}$ and $\mu > 0$, SUSY particles can be discovered at the experiment. In this range, trilepton from chargino-neutralino associated production $qq' \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^\pm$, $\tilde{\chi}_2^0 \rightarrow \tilde{\ell}_R^0 \ell$, $\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 \ell \nu$ is one of clean signals for SUSY search. Notice that now two body decay $\tilde{\chi}_2^0 \rightarrow \tilde{\ell}_R^0 \ell$ opens. So same flavor, opposite sign dilepton from $\tilde{\chi}_2^0$ decay may be useful. The two body decay allows us to observe the peak edge of invariant mass of two leptons at the $M_{\ell\ell_{\text{max}}}$. It is expressed in terms of the neutralino masses and the slepton mass as,

$$M_{\ell\ell_{\text{max}}} = m_{\tilde{\chi}_2^0} \sqrt{1 - \frac{m_{\tilde{\ell}_R^0}^2}{m_{\tilde{\chi}_2^0}^2}} \sqrt{1 - \frac{m_{\tilde{\chi}_1^0}^2}{m_{\tilde{\ell}_R^0}^2}},$$  \hspace{1cm} (8)

In Table I, the dependence of $M_{\ell\ell_{\text{max}}}$ on $M_*$ is shown. Here we fix $m_{\tilde{\chi}_1^0} = 100\text{GeV}$. Notice that as $M_*$ changes, the right-handed mass changes sizably while the neutralino masses do not. Hence we can obtain the mass relation among them and also cutoff scale $M_*$, which corresponds to the compactification scale in the sequestered sector scenario, by measuring $M_{\ell\ell_{\text{max}}}$. On the other hand, since only $M_{1/2} \gtrsim 280$ GeV is allowed for $\mu < 0$, the Tevatron Run 2 can not survey this scenario, and we have to wait LHC experiment.

C. Case of non-universal gaugino masses

Next, we turn to the case that gaugino masses are non-universal at the GUT scale. We explore the following three cases, Wino-like neutralino LSP, Higgsino-like neutralino LSP and the tau sneutrino LSP. We will see that in the Wino-like neutralino LSP and tau sneutrino LSP cases, constraint is not so severe even if we combine Higgs mass bound and BR($b \rightarrow s\gamma$) data, but in the Higgsino-like LSP case where stops are as light as sleptons and charginos, the predicted Higgs mass tends to be small, and thus the Higgs mass bound becomes important.

First, we discuss the Wino-LSP case. The results for $M_{1,0}/M_{2,0} = 4$, $M_{3,0}/M_{2,0} = 2$ are shown in Fig. 1 and Fig. 2, for $\mu > 0$ and $\mu < 0$, respectively. In this case, we obtain a relatively large Higgs mass since $M_{3,0}$ is large and so are the masses of stops. Hence, for $\mu > 0$, $M_{2,0}$ can be as small as 100 GeV at $\tan \beta \simeq 10$, where the mass of the LSP $\tilde{\chi}_1^0$ is about 90 GeV. For $\mu < 0$, though BR($b \rightarrow s\gamma$) constraint is slightly severer than in the $\mu > 0$ case, $M_{2,0} \simeq 160\text{GeV}$ is allowed, which corresponds to $m_{\tilde{\chi}_1^0} \simeq 142\text{GeV}$. Hence the Wino-LSP with mass around 100 GeV is allowed. Examples of the mass spectrum in this case are listed as point A ($\mu > 0$) and point B ($\mu < 0$) in Table II. At the both points, $M_{1/2}$ is chosen to be near the smallest value such that all constraints are avoided.

In general, however, masses of $\tilde{\chi}_1^0$ and $\tilde{\chi}_1^\pm$ are highly degenerate when Wino is the LSP. In fact, from Table II we see that the mass difference is less than 1 GeV. Therefore a lepton from $\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 \ell \nu$ is very soft and trilepton signal search is not useful because acceptance cut usually requires the smallest transverse momentum of the three leptons $p_T(\ell_3)$ to be larger than 5 GeV [22]. Recently collider phenomenology in such cases are studied in Ref. [23]. It is shown that certain range of $m_{\tilde{\chi}_1^\pm}$ and $m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0}$, SUSY signals
which are different from those in the minimal case can be detected. The high degeneracy requires to include radiative corrections to calculate $m_{\tilde{\chi}_1^±} - m_{\tilde{\chi}_1^0}$ [24], which is beyond of this work. It deserves detail study to estimate the mass difference in the scenario.

Since the constraint for the sneutrino LSP case in the $M_{2,0} - \tan \beta$ plane is similar to those in the Wino-LSP case, we show the result for $\mu > 0$ only in Fig. 7. In the figure, we take $M_{1,0}/M_{2,0} = 2.5$ and $M_{1,0}/M_{2,0} = 1.5$. Notice that the decomposition of the LSP depends on $\tan \beta$ and the sneutrino is the LSP for $\tan \beta \gtrsim 5$. An example of the mass spectrum is listed as the Point C in Table I. In this case, trilepton signal comes from $qq' \to \tilde{\chi}_2^0 \tilde{\nu}_1, \tilde{\chi}_1^\pm \to \nu_\tau \ell, \tilde{\chi}_2^0 \to \ell \ell \nu_\tau \bar{\nu}_\tau$. Since $m_{\tilde{\chi}_1^\pm} - m_{\tilde{\nu}_\tau} = 6$ GeV, $p_T$ of a lepton from $\tilde{\chi}_1^\pm$ decay is small and this signal may be hard to be detected. We may need unusual trigger to explore this scenario.

Next, we turn to the Higgsino LSP case. Higgsino LSP scenario is realized when $M_{3,0}$ is smaller than half of $M_{2,0}$, which indicates that colored particles are lighter than in the universal gaugino mass case. Hence the one-loop correction to the Higgs potential which enhances the Higgs mass is small and the Higgs mass constraint is important. The same figures as Fig. 1 and 2 are shown in Fig. 8 ($\mu > 0$) and Fig. 9 ($\mu < 0$) for $M_{1,0}/M_{2,0} = 2$ and $M_{3,0}/M_{2,0} = 0.5$. In order to satisfy the Higgs mass bound, $M_{2,0}$ must be larger than around 300 GeV. Combining the bound with $\text{BR}(b \to s\gamma)$, constraint becomes severer, especially for $\mu < 0$ case where $M_{2,0} \gtrsim 520$ GeV is required. Example of mass spectrum in this scenario is listed as Point D and E in Table I. Again we choose almost the smallest value of $M_{2,0}$ where all constraints are avoided. We see that the LSP mass must be at least $m_{\tilde{\chi}_1^0} \simeq 245$ GeV for $\mu > 0$ and $m_{\tilde{\chi}_1^0} \simeq 370$ GeV for $\mu < 0$. Hence this scenario can not be explored at the Tevatron Run 2.

IV. CONCLUSIONS

The no-scale type boundary conditions are obtained in various types of SUSY models. This scenario is attractive because it is highly predictive and can be a solution to the SUSY flavor problem. In this paper we investigated the indication of the current Higgs mass and $b \to s\gamma$ constraint on SUSY models with the boundary condition.

First we considered the minimal case where the universal gaugino mass are given at the GUT scale. This scenario has been already constrained by direct search at LEP and the cosmological bound severely, under the assumption of the exact R-parity. We showed that the Higgs mass bound and $b \to s\gamma$ constraint are also taken into account, then almost all the parameter region is excluded, leaving very narrow allowed region for $\mu > 0$.

Next we considered the case that the boundary condition is given above the GUT scale. Since the cosmological constraint is not severe, wide region of the parameter space is allowed. In the $\mu > 0$ case, Tevatron have a chance to observe SUSY signatures like trilepton events. The scale $M_s$ may be explored by measuring the peak edge of invariant mass of two leptons at the $M_{\ell\ell}^{\text{max}}$. However for the $\mu < 0$ case, since $M_{1/2} \gtrsim 280$ GeV is required, we have to wait LHC.
Finally we considered the case where non-universal gaugino masses are given at the GUT scale. We see that the Higgs mass bound is strong in the Higgsino LSP case because stop masses are as light as sleptons and charginos. The mass of the Higgsino-like neutralino must be larger than about 245 GeV and 370 GeV for $\mu > 0$ and $\mu < 0$, respectively. In the Wino LSP and sneutrino LSP case, the mass of the LSP can be as small as 150 GeV. However, the mass difference between the LSP and parent particles produced at the collider is much smaller than in the minimal case, unusual acceptance cut may be required.

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| $M_s$         | $m_{\tilde{\chi}_0}$ | $m_{\tilde{\ell}}$ | $M_{\ell\ell}$ max |
|--------------|-----------------------|---------------------|-------------------|
| $10^{17}$GeV | 185 GeV               | 138 GeV             | 85 GeV            |
| $2 \times 10^{17}$GeV | 185 GeV               | 149 GeV             | 81 GeV            |
| $4 \times 10^{17}$GeV | 186 GeV               | 160 GeV             | 74 GeV            |
| $10^{18}$GeV | 186 GeV               | 172 GeV             | 58 GeV            |
| $2.4 \times 10^{18}$GeV | 186 GeV               | 182 GeV             | 32 GeV            |

**TABLE I.** The dependence of $M_{\ell\ell}$ max on $M_s$. We fix $m_{\tilde{\chi}_1} = 100$GeV.

|          | Point A | Point B | Point C | Point D | Point E |
|----------|---------|---------|---------|---------|---------|
| $M_{1,0}$| 480     | 680     | 375     | 800     | 1160    |
| $M_{2,0}$| 120     | 170     | 150     | 400     | 580     |
| $M_{3,0}$| 240     | 340     | 225     | 200     | 290     |
| $\tan \beta$ | 10 | 6       | 10      | 7       | 6       |
| $\text{sgn}(\mu)$ | + | −     | +       | +       | −       |
| $m_{\tilde{\chi}_1}^0$ | 91 | 142    | 112     | 225     | 371     |
| $m_{\tilde{\chi}_1}^2$ | 199 | 290    | 156     | 277     | 402     |
| $m_{\tilde{\chi}_2}^2$ | 366 | 520    | 343     | 338     | 491     |
| $m_{\tilde{\chi}_3}^2$ | 380 | 521    | 359     | 386     | 516     |
| $m_{\tilde{\chi}_1}^+$ | 91 | 142    | 113     | 235     | 380     |
| $m_{\tilde{\chi}_2}^+$ | 379 | 524    | 358     | 377     | 507     |
| $m_{\tilde{\ell}}^L$ | 132 | 181    | 134     | 318     | 456     |
| $m_{\tilde{\ell}}^R$ | 190 | 266    | 151     | 312     | 449     |
| $m_{\tilde{\tau}}^L$ | 124 | 179    | 117     | 307     | 447     |
| $m_{\tilde{\tau}}^R$ | 194 | 266    | 164     | 321     | 457     |
| $m_\nu$ | 105 | 163    | 107     | 307     | 449     |
| $m_{\tilde{u}}^L$ | 561 | 781    | 524     | 536     | 766     |
| $m_{\tilde{u}}^R$ | 553 | 770    | 524     | 504     | 718     |
| $m_{\tilde{d}}^L$ | 559 | 774    | 530     | 542     | 771     |
| $m_{\tilde{d}}^R$ | 552 | 768    | 520     | 473     | 672     |
| $m_{\tilde{t}}^1$ | 423 | 623    | 392     | 337     | 515     |
| $m_{\tilde{t}}^2$ | 592 | 767    | 564     | 555     | 735     |
| $m_{h_1}$ | 509 | 711    | 483     | 467     | 669     |
| $m_{h_2}$ | 553 | 766    | 519     | 489     | 690     |
| $m_{h}$ | 116 | 116    | 116     | 115     | 117     |

**TABLE II.** Examples of mass spectrum for five representative points. All dimensionful parameters are given in the GeV unit.
FIG. 1. Constraint in the $M_{1/2} - \tan \beta$ plane for the minimal case with $\mu > 0$. In the region above the dash-dotted line, the stau is the LSP. The left side of the dash-dot-dotted line is excluded by the upper bound on smuon pair production cross section at LEP. The current Higgs mass bound excludes the region below the solid line. In the region above the dashed line, $\text{BR}(b \to s\gamma)$ is smaller than the lower limit obtained by the CLEO. The shaded region is allowed. The $m_h = 115\text{GeV}$ curve is also shown as the dotted line. ‘NoEWSB’ means that radiative breaking does not occur.

FIG. 2. The same as Fig.1 but $\mu < 0$. The region above the dashed line is excluded since $\text{BR}(b \to s\gamma)$ is larger than the upper limit obtained by the CLEO. The other lines are the same as in Fig.1. Notice that all region is excluded.
FIG. 3. Constraint in the $M_{1/2} - \tan \beta$ plane for universal gaugino masses, $M_* = 10^{17}\text{GeV}$ and $\mu > 0$. The left sides of the dash-dot-dotted and dash-dot-dot-dotted line are excluded by the upper bound on the smuon and stau pair production cross section, respectively. The other lines are the same as in Fig. 4.

FIG. 4. The same as Fig. 3 but for $\mu < 0$.

FIG. 5. Constraint in the $M_{2,0} - \tan \beta$ plane for the Wino LSP case, $M_{1,0}/M_{2,0} = 4$, $M_{3,0}/M_{2,0} = 2$, $M_* = M_{\text{GUT}}$ and $\mu > 0$. 
FIG. 6. The same as Fig. 5 but for $\mu < 0$.

FIG. 7. Constraint in the $M_{2,0} - \tan \beta$ plane for $M_{1,0}/M_{2,0} = 2.5, \ M_{3,0}/M_{2,0} = 1.5, \ M_* = M_{\text{GUT}}$ and $\mu > 0$. The regions above and below the thick dashed line, the sneutrino and the Wino are the LSP, respectively.

FIG. 8. Constraint in the $M_{2,0} - \tan \beta$ plane for the Higgsino LSP case, $M_{1,0}/M_{2,0} = 2, \ M_{3,0}/M_{2,0} = 0.5, \ M_* = M_{\text{GUT}}$ and $\mu > 0$. In the region between the two dashed line, BR($b \to s\gamma$) is smaller than the lower limit of the CLEO result.
FIG. 9. The same as Fig. 8 but for $\mu < 0$. Notice that the region below the dash-dotted line is excluded by the cosmological argument unlike in the other figures.