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Neutralino dark matter in the minimal supersymmetric standard model with natural light Higgs sector

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We study the neutralino relic density in the minimal supersymmetric standard model with natural light Higgs sector in which all Higgs masses, the supersymmetry (SUSY) breaking parameters, and the Higgsino mass parameter μ are of order the weak scale. To realize this situation we adopt nonuniversal Higgs masses at the grand unified scale. We show that in some parameter space in which the SUSY breaking parameters are comparatively small, not only the constraint from the observed relic density of dark matter but also the LEP Higgs bound and the constraint from the $b \to s\gamma$ process are satisfied. In most of the parameter space, the neutralino relic density becomes smaller than the observed relic density in contrast with the results in the constrained minimal SUSY standard model (CMSSM). The reason is that the neutralino coannihilation processes to Higgs bosons open even if the gaugino mass is small and the cross sections become large due to the small dimensionful parameters. Especially the small μ parameter and the light CP-odd Higgs, which are difficult to be realized in the CMSSM, are essential for the result.

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I. INTRODUCTION

The minimal supersymmetric (SUSY) standard model (MSSM) is one of the hopeful extensions of the standard model (SM). It is attractive not only in the point of the weak scale stability, but also in the fact that SUSY models with R parity have the lightest supersymmetric particle (LSP) as a good candidate for dark matter. Since the thermal relic density of the LSP can be calculated once we fix the parameters in the MSSM, it is interesting to examine parameter space, which is consistent with the observed value

$$\Omega_{\rm DM}h^2 = \Omega_m h^2 - \Omega_b h^2 \tag{1}$$

$$= (0.1277^{+0.0080}_{-0.0079}) - (0.022\,29 \pm 0.000\,73), \tag{2}$$

where $\Omega_{\rm DM}$, Ω_m, and Ω_b are the energy densities of dark matter (DM), matter, and baryon of the Universe [1]. Here, h is the normalized Hubble parameter such as the present Hubble constant is given by $H_0 = 100h\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$. Many studies have been done about the neutralino relic density in the constrained MSSM (CMSSM) [2], in which all dimensionful parameters can be presented by only five parameters, the unified gaugino mass $m_{1/2}$, the unified scalar mass m_0, the universal couplings for three scalar vertex A, the parameter for Higgs mixing B, and the Higgsino mass μ. Unfortunately, the allowed region for the parameters in the CMSSM are quite limited because in most of the parameter region consistent with experiments, the calculated thermal relic density of the neutralino become too large to satisfy the observed value. Moreover, in the CMSSM, the LEP constraint to the standard model Higgs mass, $m_h > 114.4$ GeV (95% C.L.) [3], requires comparatively large SUSY breaking parameters in order to make the lightest MSSM Higgs heavier via loop corrections than the upper bound for the SM Higgs mass $m_h > 114.4$ GeV. Such large SUSY breaking parameters destabilize the weak scale. This problem is called the little hierarchy problem.

Recently, it has been pointed out that in the nonuniversal Higgs mass model, the LEP constraints can be avoided due to the smaller ZZh coupling than in the SM [4–7]. Here, h is the lightest CP-even Higgs. Therefore, the large SUSY breaking parameters are not needed. This avoids the little hierarchy problem. To obtain the small ZZh coupling, generically, the light Higgs sector is required, in which not only the usual CP-even Higgs but also the other Higgs bosons have the weak scale masses. Contributions of the light charged Higgs to the $b \to s\gamma$ process would be too large to be consistent with the experimental value, if the chargino contribution has not compensated the charged Higgs contribution. This cancellation due to the supersymmetry works well [6,8–10] because all the mass scales in the Feynman diagrams contributing the $b \to s\gamma$ process are of order the weak scale in the models with the natural SUSY breaking parameters and the light Higgs sector. In such models all the dimensionful parameters are of order the weak scale. The charged Higgs mass $m_{H^\pm}$ and the Higgsino mass μ are fixed at the weak scale. The sfermion mass m_0, the gaugino mass $m_{1/2}$, and the scalar three point coupling A_0 are fixed at the grand unified theory (GUT) scale. We call such a scenario the natural light Higgs scenario.

In this paper, we calculate the thermal relic density of the lightest neutralino in the natural light Higgs scenario.

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The result is totally different from the result in the CMSSM. The thermal relic density in this scenario tends to be smaller than the observed dark matter energy density. This is mainly because the neutralino coannihilation modes to Higgs bosons such as $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to hA$ and $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to HA$ open due to the light Higgs sector and because the cross sections become large due to the small dimensionful parameters, especially small μ. Here $\tilde{\chi}_1^0$, A, and H are the lightest neutralino, the CP-odd Higgs, and the heaviest CP-even Higgs, respectively. The larger total annihilation cross section of the neutralino leads to the smaller thermal relic density. If μ is large, the cross sections of neutralino coannihilation processes to Higgs bosons decrease because of the small Higgsino components of the lightest neutralino. Thus the energy density of the neutralino becomes larger than that with small μ.

There are two essential points. One of them is that the light Higgs bosons make it possible to open the neutralino coannihilation processes to Higgs bosons. And the other is that the small μ parameter makes the cross sections large. In the CMSSM, it is difficult to satisfy both of them. Roughly speaking, to obtain the light Higgs sector, both mass parameters $m_1^2 = m_{H_d}^2 + |\mu|^2$ and $m_2^2 = m_{H_u}^2 + |\mu|^2$ in the Higgs potential

$$V = m_1^2|H_d|^2 + m_2^2|H_u|^2 + (m_3^2 H_d H_u + \text{H.c.}) + \frac{g'^2 + g^2}{8}(|H_d|^2 - |H_u|^2)^2 \tag{3}$$

must be around the weak scale, which is difficult to be satisfied in the CMSSM because $m_1^2 - m_2^2$ becomes much larger than the weak scale. Here, H_u and H_d are up-type Higgs and down-type Higgs, respectively. Actually, in the CMSSM, the difference $m_1^2 - m_2^2$ at the weak scale becomes roughly $3m_{1/2}^2$, where $m_{1/2}$ is taken roughly larger than 300 GeV to satisfy the LEP constraint to the SM Higgs mass bound.

For the reasons stated above, the neutralino relic density in the natural light Higgs scenario tends to be smaller than the observed energy density. And, in this scenario, there are parameter regions where the neutralino relic density agrees with the observation.

In Sec. II, we show the numerical calculation of the neutralino thermal relic density in the natural light Higgs scenario. After a discussion about the allowed region, we conclude in Sec. III.

II. NEUTRALINO RELIC DENSITY IN NATURAL LIGHT HIGGS SCENARIO

In this section, we calculate the neutralino thermal relic density numerically in the MSSM with the light Higgs sector and natural SUSY breaking parameters. There are two additional dimensionful parameters, $m_{H_u}^2$ and $m_{H_d}^2$ in the nonuniversal Higgs mass model. Then we have seven parameters. One of the seven parameters is fixed by the Z boson mass, and thus we have six parameters. In this paper, three of them, the universal sfermion mass m_0, the gaugino mass $m_{1/2}$, and the universal coupling for the three scalar interaction A_0 are fixed at the GUT scale, and the other parameters, μ parameter, the ratio of two Higgs vacuum expectation values $\tan\beta$, and the CP-odd Higgs mass m_A are fixed at the weak scale.

In this paper, we adopt the small ZZh coupling scenario [4–7] to satisfy the LEP constraints to the SM Higgs mass.[1] We fix some of the parameters, A_0, μ, $\tan\beta$, and m_A to reduce the number of parameters. m_A and $\tan\beta$ are important to realize small ZZh coupling, because CP-even Higgs mass matrix is roughly given by

$$\begin{pmatrix} m_A^2 & -(m_A^2 + m_Z^2)\sin\beta\cos\beta \\ -(m_A^2 + m_Z^2)\sin\beta\cos\beta & m_Z^2 + \delta m_{H_u}^2 \end{pmatrix} \tag{4}$$

when $\tan\beta \gg 1$. Here, $\delta m_{H_u}^2$ is the loop correction to $m_{H_u}^2$, which can be large due to the large top Yukawa coupling. When $m_A^2 < m_Z^2 + \delta m_{H_u}^2$, the main component of the lightest Higgs h becomes H_d which has only very small ZZH_d coupling. Moreover, when $m_Z^2 + \delta m_{H_u}^2 - m_A^2 \gg (m_A^2 + m_Z^2)\sin\beta\cos\beta$, h includes only a small component of H_u. On the other hand, if the off diagonal element is large (i.e., $\tan\beta$ is small) and/or the difference of the diagonal element is small (i.e., m_A is large or the loop correction is small), the H_u component in h becomes large, which results in large ZZh coupling. Therefore, as discussed in [6], $7 < \tan\beta$ and $90\ \text{GeV} < m_A < 110\ \text{GeV}$ are required (if CP-even Higgs mass is smaller than 90 GeV, the $Z \to Ah$ process gives a severe constraint by LEP experiments). In this paper, we take rather large $\tan\beta$ and small m_A as $\tan\beta = 15$ and $m_A = 96$ GeV, which satisfy that the ZZh coupling is smaller than a half of the SM ZZh coupling in the parameter region discussed in this paper.[2] We examine two cases for A_0, $A_0 = 0$, and 250 GeV. For the μ parameter, we have a strong reason to take it as the weak scale in the scenario with the small ZZh coupling. Since both mass parameters $m_1^2 = m_{H_d}^2 + |\mu|^2$ and $m_2^2 = m_{H_u}^2 + |\mu|^2$ in the Higgs potential must be around the weak scale to obtain the small ZZh coupling, not only the tuning for m_1^2 but also that for m_2^2 are required if the μ parameter is much larger than the weak scale. Therefore, we take $\mu =$

[1]If we adopt the nonuniversal sfermion masses, then the naturalness requires that only the masses of the stops must be around the weak scale and the other sfermion masses can be taken much larger than the weak scale. E_6 GUT with horizontal symmetry naturally obtains such nonuniversal sfermion masses, and our discussion in this paper can be applied to the nonuniversal sfermion mass model [11].

[2]We checked by FEYNHIGGS 2.6.4 [12] that the ZZh coupling is smaller than half of the SM coupling in the parameter region we took in this paper.

275, 300, 325, 350 GeV, and for comparison, we examine the case $\mu = 600$ GeV, which is not so natural.[3]

To obtain the low-energy parameters (sfermion masses, A term and gaugino masses) from the GUT scale parameters, we use the one-loop renormalization group equations (RGEs) from the GUT scale down to the electroweak scale. In the calculation, we choose the GUT scale Higgs masses in order to realize $m_A = 96$ GeV, $\tan\beta = 15$, $\mu = 275$, 300, 325, 350 GeV and $m_Z = 91.18$ GeV at the electroweak scale. Concretely speaking, we choose the GUT scale parameters by calculating the RGEs iteratively to realize the parameters we fixed at the low energy. Then we calculate the neutralino relic density by using the MICROMEGAS 1.3.7 [13,14] package by inputting the parameters at the electroweak scale. Here we took the on shell top mass $M_t = 172.6$ GeV [15].

We display in Figs. 1(a)–1(d) the relic density of the lightest neutralino in the natural light Higgs scenario. In the figures, the light gray area is the cosmologically preferred region where the neutralino relic density is consistent with Eq. (2). The regions with larger and smaller relic density are painted black and white, respectively. The horizontal-striped region is excluded because the LSP becomes stau, which is a charged particle. The dark gray areas are allowed regions for $b \to s\gamma$ constraint. Since the observed branching ratio for the process, $\mathrm{Br}(b \to s\gamma)_{\mathrm{exp}} = (355 \pm 26) \times 10^{-6}$ [16], is now in agreement with the SM estimations, $\mathrm{Br}(b \to s\gamma)_{\mathrm{SM}} = (315 \pm 23) \times 10^{-6}$ [17], $\mathrm{Br}(b \to s\gamma)_{\mathrm{SM}} = (357 \pm 49) \times 10^{-6}$ [18], and $\mathrm{Br}(b \to s\gamma)_{\mathrm{SM}} = (298 \pm 26) \times 10^{-6}$ [19], we seek the region where the MSSM contributions for the process are moderate. Here we assume the minimal flavor violation (MFV) and the primary contributions coming from the SM, charged Higgs and chargino are taken into account using input parameters and RG method described in the previous paragraph. For simplicity, we require the effective Wilson coefficient C_7 at b quark mass scale to be within 20 % difference from the SM prediction in the leading order approximation for the process. That is to say, the coefficients evaluated at the electroweak scale from one-loop diagrams are translated into that of the b quark scale ($\mu_b = 4.7$ GeV) values using 8×8 evolution matrix calculated at the two-loop level [9,20]. The dashed line denotes the heavy Higgs mass bound, $m_H = 114.4$ GeV. In the model with small ZZh coupling, the ZZH coupling becomes almost the same as the SM value, and therefore, the LEP constraints to the SM Higgs mass can be roughly applied to the heaviest Higgs mass in the MSSM. In all parameter regions in these figures, the lightest CP-even Higgs mass is larger than 90 GeV. If $\tan\beta$ is fairly large, the constraint from the $B_s \to \mu^+\mu^-$ process must be taken into account [21–23]. However, the constraint can be negligible in the parameter region we took in our calculation, when $\tan\beta \simeq 15$.

There are two reasons for the small relic density. For roughly $m_{1/2} \lesssim 200$ GeV, the cross section of processes $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to A \to b\bar{b}$ and $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to Z \to b\bar{b}$ becomes so large that the neutralino relic density is smaller than the observed relic density of dark matter. The neutralino is roughly half as heavy as the CP-odd Higgs and the Z boson, so the sum of the masses of two neutralinos is nearly on the pole of the CP-odd Higgs and the Z boson in this region. The cross section of this process decreases as the gaugino mass grows up, because the sum of the two neutralino's masses becomes away from the poles. In the CMSSM, this left preferred areas are mostly excluded by the LEP bound. On the contrary, all preferred regions are allowed by the Higgs mass bound in the models with the small ZZh coupling. There is another area in which the neutralino relic density becomes smaller than the observed value when the gaugino mass becomes larger. This is because the modes of $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to$ two bosons such as $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to hA$, $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to HA$, and $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to W^\pm H^\mp$ modes open as well as $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to Zh$. It is essential that in the natural light Higgs scenario, all Higgs bosons are light. In the CMSSM, the relic density of the region corresponding to this region is larger than the cosmologically preferred range [24]. We can plot similar graphs even in the models with small ZZh coupling in the case of large the μ parameter as we show in Figs. 2(a) and 2(b) in which $\mu = 600$ GeV. This is because the sum of the cross sections of the processes $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to$ two bosons becomes too small to obtain sufficiently small relic density of the neutralino, because the Higgsino components of the lightest neutralino become smaller. In the CMSSM, in addition to the difficulty in realizing small μ, the modes $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to$ two bosons except for $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to Zh$ does not open in the small $m_{1/2}$ region because of the heavier Higgs sector. In the black region, the main mode is $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to bb$. We comment on the m_0 dependence of the relic density. When the sfermion mass becomes smaller, $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to$ two leptons process becomes larger because the cross section of the process via slepton t-channel exchange increases. Therefore, the smaller m_0 leads to the larger annihilation cross section and the smaller energy density of the lightest neutralino in the region.

The graph of the relic density depends on the μ parameter strongly as we commented. The distance between the two allowed band regions becomes wider in $\mu = 300$ GeV than in $\mu = 275$ GeV. When μ is larger, the left preferred band moves to the left because the lightest neutralino becomes heavier. The right preferred band moves to the right, because the coannihilation cross sections to two bosons becomes smaller for the larger μ parameter. In this scenario, the relic density of the neutralino does not depend on the gaugino mass so much when the gaugino mass is larger than 300 GeV in the parameter region we

[3]We calculated for $\mu = 250$ GeV and found that the neutralino relic density is smaller than the observed value in all natural parameter space.

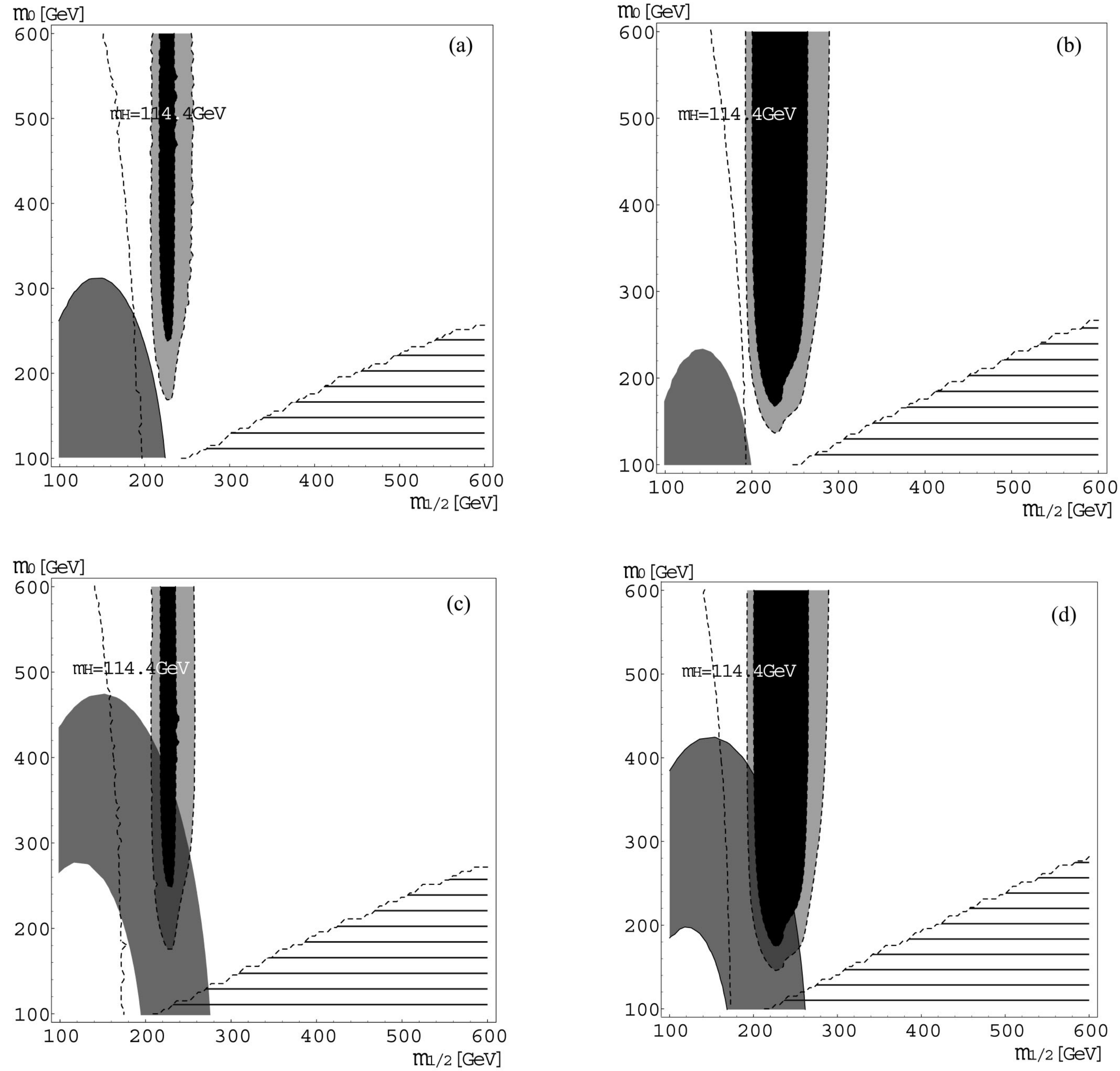

FIG. 1. The $(m_{1/2}, m_0)$ planes for $A_0 = 0$ GeV (upper), $A_0 = 250$ GeV (lower), $\mu = 275$ GeV (left), $\mu = 300$ GeV (right) with $\tan\beta = 15$ and $m_A = 96$ GeV. Each light gray area is the region where the relic density is consistent with the current observation. The relic density is larger (smaller) than that of the light gray area in each black (white) region. In the area with horizontal stripes, stau is the LSP. Each dark gray area is the region where $\mathrm{Br}(b \to s\gamma)$ is consistent with the experiment in the sense described in the text. Dashed lines are the contour on which the mass of the heaviest CP-even Higgs is 114.4 GeV.

scanned. Usually when the gaugino mass increases, the total cross section decreases. However, in our scenario, the Higgsino components of the neutralino increase, and thus the two effects can almost compensate each other. In Figs. 3(a) and 3(b) we can explicitly see the mild change of the relic density as the fairly broad preferred region when $\mu = 325$ and 350 GeV.

The relic density does not change so much if we enlarge A_0. On the other hand, the cross section of the $b \to s\gamma$ process depends on A_0 as in Figs. 1(a)–1(d). There are reasonable regions which are consistent with the observed relic density of dark matter and experimental constraints when $A_0 = 250$ GeV. When $A_0 = 0$ GeV, there is no or an absolutely thin preferred region. However, we do not take

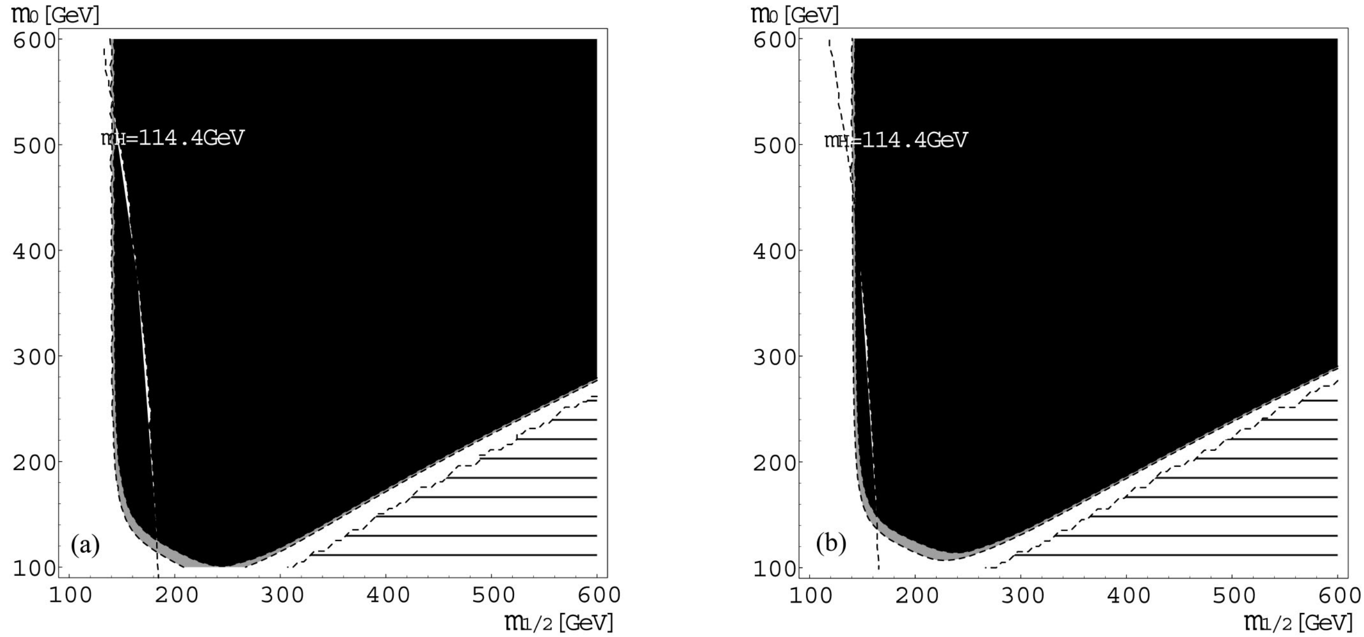

FIG. 2. The $(m_{1/2}, m_0)$ planes for $A_0 = 0$ GeV (left) and $A_0 = 250$ GeV (right) with $\mu = 600$ GeV, $\tan\beta = 15$, and $m_A = 96$ GeV. The usage of each color and line is the same as the previous figures. In these figures, the constraints from $b \to s\gamma$ are not presented.

this allowed region for the $b \to s\gamma$ constraint seriously. This is because the allowed region can be changed if there are other contributions to $b \to s\gamma$ as a sizable gluino contribution. Moreover, the experimental value of the $\mathrm{Br}(b \to s\gamma)$ is larger than the SM prediction. In order to increase the $\mathrm{Br}(b \to s\gamma)$, a larger SUSY breaking scale is required because the chargino contribution decreases the branching ratio. This requirement makes the allowed region move to the upper right.

III. CONCLUSIONS

We have studied the thermal relic density of the neutralino in the MSSM with the light Higgs sector and reasonable SUSY breaking parameters. Actually, we took all the dimensionful parameters as order of the weak scale.

The neutralino relic density with the light Higgs bosons is totally different from the well-known result in the CMSSM. In the natural light Higgs scenario, the neutralinos to two boson processes, such as $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to hA$ and

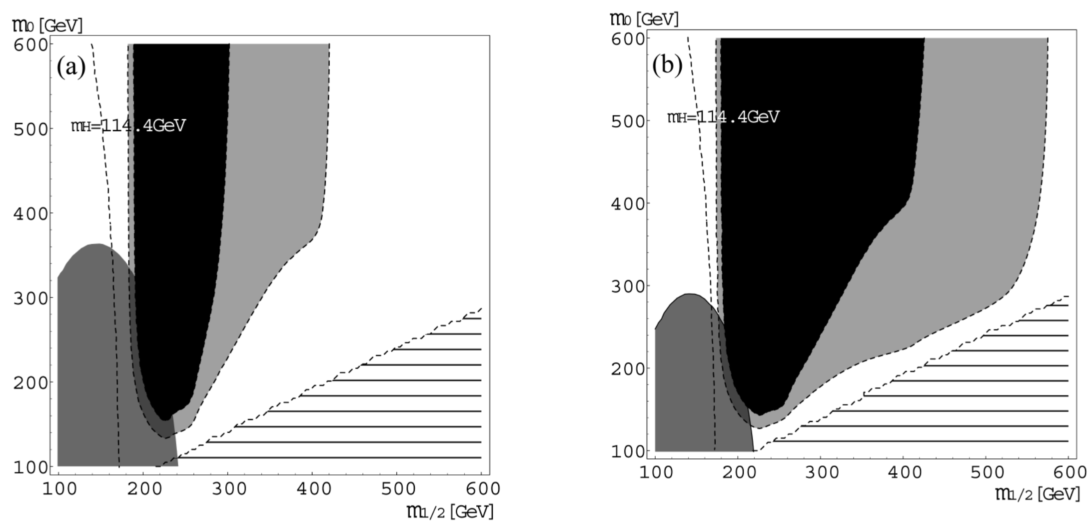

FIG. 3. The $(m_{1/2}, m_0)$ planes for $\mu = 325$ GeV (left) and $\mu = 350$ GeV (right) with $A_0 = 250$ GeV, $\tan\beta = 15$, and $m_A = 96$ GeV. The usage of each color and line is the same as the previous figures.

$\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow HA$ open even when the gaugino mass is small. Furthermore, they dominate the total cross section because the μ parameter is so small that the Higgsino components of the lightest neutralino become comparatively large. For those reasons, the relic density becomes smaller than the observed value. In contrast, it is mostly larger than the observed value in the CMSSM because all Higgs bosons except for the SM-like Higgs are heavy. The region with small relic density cannot be excluded because it is not inconsistent if there is other dark matter sources. Furthermore, there are cosmologically preferred regions in this scenario, which are not excluded by the experiments. Thus, the MSSM with the natural light Higgs sector is a good model not only for naturalness but also for cosmology.

The cosmologically preferred regions which we studied so far can be tested by future direct searches for the weakly interacting massive particles (WIMP) because the small μ parameter makes the spin-independent interaction between Higgs and the lightest neutralinos large [25,26], unless recent direct searches for the WIMP such as CDMSII [27] and XENON10 [28] have excluded the regions. In the region where the gaugino mass is roughly larger than 300 GeV, even if the relic density is smaller than the observed relic density of dark matter, it is not so small. (It is larger than 20% of the observed value in Figs. 1(a)–1(d), 2(a), 2(b), 3(a), and 3(b).) Therefore, even if the main component for dark matter around the galaxies has only super weak interaction and cannot be found in the direct searches of the WIMP, the searches can find the signal for the neutralino which is a subdominant component, though the concrete prediction becomes difficult. We think it is an interesting future subject to study the direct detection of the WIMP in our scenario.

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