Invisible decays of low mass Higgs bosons in supersymmetric models

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The discovery of a 126 GeV Higgs-like scalar at the LHC along with the nonobservation of the supersymmetric particles has in turn led to constraining various supersymmetric models through the Higgs data. We here consider the case of both the minimal supersymmetric standard model (MSSM) as well its extension containing an additional chiral singlet superfield, the next-to-minimal or nonminimal supersymmetric standard model (NMSSM). A lot of work has been done in the context of the lightest scalar of these models being identified as the 126 GeV state discovered at the LHC. We here, however, concentrate on the case where we identify the second lightest Higgs boson as the 126 GeV state discovered at the CERN LHC and consider the invisible decays of the low mass Higgs bosons in both the MSSM and NMSSM. In the case of the MSSM we consider $H \approx 126$ GeV and $h \approx 98$ GeV, known as the nondecoupling regime, whereas in the case of the NMSSM $h_2 \approx 126$ GeV, with m_{h_1} and m_{a_1} varying depending on the parameter space. We find that, in the case of the MSSM with universal boundary conditions at the grand unified theory (GUT) scale, it is not possible to have light neutralinos leading to the decay channel $H \to \tilde{\chi}_1^0 \tilde{\chi}_1^0$. The invisible decay mode is allowed in the case of certain $SO(10)$ and E_6 grand unified models with large representations and nonuniversal gaugino masses at the GUT scale. In the case of the NMSSM, for the parameter space considered it is possible to have the invisible decay channel with universal gaugino masses at the GUT scale. We furthermore consider the most general case, with M_1 and M_2 as independent parameters for both the MSSM and NMSSM. We isolate the regions in parameter space in both cases where the second lightest Higgs boson has a mass of 126 GeV and then concentrate on the invisible decay of Higgs bosons to lighter neutralinos. The other nonstandard decay mode of the Higgs boson is also considered in detail. The invisible Higgs branching ratio being constrained by the LHC results, we find that, in this case with the second lightest Higgs boson being the 126 GeV state, more data from the LHC are required to constrain the neutralino parameter space, compared to the case when the lightest Higgs boson is the 126 GeV state.

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I. INTRODUCTION

A new era of particle physics has begun with the discovery of the neutral scalar by the ATLAS [1] and CMS [2] Collaborations. It is entirely likely that this state is the long sought after Higgs boson of the standard model (SM) and is being pursued as a main window for new physics searches. Though the recent results are already pointing towards a SM-like Higgs boson, the final conclusion can be drawn only through a detailed study of the properties of the new boson. These studies will indicate whether the decay widths of the particle are in accordance with the predictions of the SM or of its extensions. Popular among the latter are the minimal supersymmetric standard model (MSSM) and the next-to-minimal supersymmetric model (NMSSM). The Higgs sector in the MSSM consists of five physical Higgs bosons which includes two CP-even Higgs bosons (h, H), one CP-odd Higgs boson A, and a pair of charged Higgs bosons $(H^{\pm})$. In the case of the NMSSM, the μ parameter of the MSSM is replaced by $\lambda\langle S\rangle$, which is generated from a trilinear superpotential coupling $\lambda H_1 H_2 S$, when S obtains a vacuum expectation value $\langle S\rangle$. Here H_1 and H_2 are the two Higgs doublets, whereas S is the chiral singlet superfield. This term in turn leads to three CP-even Higgs bosons $h_{1,2,3}$, two CP-odd Higgs bosons $a_{1,2}$, and a pair of charged Higgs bosons $H^{\pm}$.

The MSSM as well as the NMSSM predicts the existence of a dark matter candidate, which in large parts of the parameter space is a neutralino. If the neutralino is sufficiently light, Higgs decay to neutralinos will be kinematically allowed. Such a light neutralino with the required relic density is still supported by the recent experimental results [3–6]. The presence of a light neutralino therefore has implications on the Higgs phenomenology, as it gives rise to the decay channel $h \to \tilde{\chi}_1^0 \tilde{\chi}_1^0$, i.e., the invisible branching ratio. With the latest experimental results, fits are being performed to check how much deviation is allowed by the recent data, in order to take into account new physics scenarios. The invisible Higgs decay width has been constrained by various groups by performing fits of the signal strengths in various search channels using the latest LHC Higgs data. The results of some of the most recent global fits are as follows.

(1) By considering the Higgs couplings to the quarks, leptons, and vector bosons to be free, $\mathrm{BR}(h \to \tilde{\chi}_1^0\tilde{\chi}_1^0) < 0.16$ (0.38) at 68% (95%) C.L. [7].
(2) With the assumption that the Higgs couplings to fermions and gauge bosons are SM-like and the only new physics is from the Higgs invisible decay width, $\mathrm{BR}(h \to \tilde{\chi}_1^0\tilde{\chi}_1^0) < 0.52$ at 68% C.L. [8].

A direct search for invisible decaying Higgs bosons produced in association with a Z boson has been carried out by the ATLAS and CMS Collaborations in the LHC. They have, in turn, placed limits on the branching fraction of the Higgs boson to invisible particles, with the branching fraction greater than 65% and 75% excluded at 95% C.L. by ATLAS [9,10] and CMS [11], respectively. The CMS Collaboration has also carried out a similar search for the invisible branching ratio of the Higgs boson produced in the vector boson fusion process and have placed an upper limit of 69% [12]. The invisible decay width of the Higgs boson has been investigated in the past, in the context of various scenarios, see for, e.g., [13–16].[1]

Direct searches for supersymmetry (SUSY) particles at the LHC so far have come up empty handed. Furthermore, several analyses based on simple versions of the MSSM and other models have ruled out significant regions of the parameter space. However, the parameter space under more general assumptions still remains largely unexplored. One possibility of exploring these regions is to ask under what conditions the 126 GeV state corresponds to the neutral Higgs particles in the spectrum of the model. Popular among these is the case where the lightest Higgs boson of the MSSM (h) and NMSSM (h_1) is identified with the state discovered at the LHC at 126 GeV and has been studied in great detail. In Ref. [17], the authors studied the decay of this lightest Higgs boson into neutralinos in these low energy supersymmetric models. The neutralino sectors of these models were then constrained, from the limits on the invisible decay width. The region of the parameter space where the lightest Higgs boson has a mass of around 126 GeV was isolated, and then the regions where this Higgs boson can decay into light neutralinos were studied in detail. It was found that it was not possible to have a massless neutralino in the MSSM in both the cases of universal and nonuniversal gaugino masses at the grand unified theory (GUT) scale, except for some higher representation of E_6. In the case of the NMSSM, although it was possible to have a massless neutralino with universal gaugino masses at the GUT scale, it was not possible to obtain $M_{h_1} = 126$ GeV and simultaneously have a massless neutralino or $M_{\tilde{\chi}_1^0} \leq M_{h_1}/2$. The results were therefore obtained by considering the soft gaugino masses M_1 and M_2 as two independent parameters, unconstrained by grand unification. In the case of the NMSSM, for certain regions of the parameter space there were additional nonstandard decay channels like $h_1 \to a_1 a_1, Z a_1$. The composition of the $\tilde{\chi}_1^0$ was important in determining the invisible branching ratio, with some regions of the parameter space allowing a large invisible branching ratio.

Note that there are no *a priori* reasons to believe hat the 126 GeV boson is the lightest Higgs boson. In the MSSM either h and H can be identified with the discovered 126 GeV boson, with either $h \approx 126$ GeV, $H \geq 800$ GeV or $H \approx 126$ GeV, $M_h < M_H$. Analogously, for the NMSSM there can be many choices: (a) $h_1 \approx 126$ GeV and $M_{h_{2,3}} > M_{h_1}$ (b) $h_2 \approx 126$ GeV and $M_{h_3} > M_{h_2}, M_{h_1} < M_{h_2}$. The mass of the CP-odd Higgs bosons varies in the range of 4 GeV to TeV (to be discussed later), whereas the charged Higgs bosons are very massive with masses of the order of 1 TeV. This scenario with $M_H \approx 126$ GeV is mainly in light of the observed LEP excess [18] in the $e^+e^- \to Zh \to Zb\bar{b}$ channel around $M_{b\bar{b}} \approx 100$ GeV, which indicates that there may be a lighter Higgs boson less than 100 GeV.

Here we take this possibility seriously and ask under what circumstances this is realized and to what extent the measured properties allow this scenario to survive. Crucial to this is the possibility that the uncertainty in the width is saturated by invisible decays, rendered possible when there are states lighter than 63 GeV in the spectrum. In this work, we first delineate regions of the parameter space, which give rise to two light Higgs bosons, and then study in detail the branching ratio of the 126 GeV Higgs boson to nonstandard SM particles. This second lightest 126 GeV Higgs boson can decay to a pair of lightest neutralinos as well as to a pair of lightest Higgs bosons in some regions of parameter space. We consider both cases here. Moreover, in the case of the NMSSM, the decay of h_2 to a pair of a_1 is also kinematically allowed in some regions. Considering the limit on the invisible branching ratio from the experiments and global fits, the neutralino sectors of these supersymmetric models are then constrained accordingly. In most studies, the parameter spaces of the models are constrained with the assumption of the universality of the gaugino masses at the GUT scale. Note that the gaugino masses need not be universal at the GUT scale. This happens when the SM gauge group is embedded in a grand unified gauge group. The phenomenology of the neutralinos at the weak scale is then affected via the renormalization group evolution of these gaugino mass parameters. At the weak scale, there will be a possibility of massless neutralinos [19] depending on the gaugino masses at the GUT scale. We find that, for the parameter space which allows a 126 GeV, the second lightest Higgs boson in the MSSM, analogous to the case where the 126 GeV state was identified with the lightest Higgs boson, it is not possible to have a massless neutralino with universal gaugino mass parameters M_1 and M_2. The result holds even for nonuniversal gaugino mass parameters except for a

[1]In our analysis, we will use the most stringent limit obtained on the invisible branching ratio to be less than 38% [7].

higher-dimensional representation of E_6. Nevertheless, the decay of Higgs bosons to lightest neutralinos ($M_{\tilde{\chi}_1^0} \leq M_H/2$) is allowed for some representations in the case of the MSSM with nonuniversal gaugino masses at the GUT scale. Analogously, in the case of the NMSSM, it is not possible to obtain $M_{h_2} = 126$ GeV and simultaneously have massless neutralinos, with universal gaugino masses at the GUT scale, but the decay of the Higgs boson (h_2) to the lightest neutralinos is allowed ($M_{\tilde{\chi}_1^0} \neq 0$ and $M_{\tilde{\chi}_1^0} \leq M_{h_2}/2$). This assumption of the GUT relation between M_1 and M_2 is biased to a particular scenario, so we do not consider the universality assumption on the gaugino mass parameters and rather treat M_1 and M_2 as two independent parameters.

In view of the considerations above, we have now considered the possibility of the second lightest neutral Higgs boson to be the 126 GeV state discovered by the LHC, in some versions of the MSSM and the NMSSM along with its invisible decays due to the presence of light neutralinos or other light states present in the spectrum. Thus, the outline of the paper is as follows. In Sec. II, we study the existence of a massless neutralino or a neutralino with mass less than half the mass of the 126 GeV Higgs boson in the context of the MSSM, with appropriate boundary conditions as dictated by grand unification based on $SU(5)$, $SO(10)$, and E_6 gauge groups. The relevant experimental constraints on the lightest Higgs ($m_h < m_H$, with $m_H \approx 126$ GeV) as well as other SUSY particles is considered. The decay of the lightest as well as the second lightest Higgs boson to neutralinos is considered in Sec. II A. The Higgs sector in the case of the NMSSM is investigated in detail in Sec. III. We first isolate the parameter space which supports h_2 in the appropriate mass window 123–127 GeV. Then the invisible decay of the second lightest Higgs boson along with the other nonstandard decay modes is considered in detail. The dominant decay mode of the lightest Higgs boson h_1 is also considered in this section. Finally, we summarize our results in Sec. IV.

II. HIGGS AND NEUTRALINO SECTOR IN THE MSSM

Let us begin by recalling that the Higgs sector in the MSSM has five physical mass eigenstates: two CP-even and one CP-odd neutral along with a pair of charged scalar bosons. The Higgs spectrum at tree level is completely determined by two independent parameters M_A and $\tan\beta$, where $\tan\beta$ is the ratio of the vacuum expectation value of the Higgs field and M_A is the mass of the pseudoscalar Higgs boson. In addition to this, the MSSM Higgs sector also depends on the top squark masses along with the top squark mixing parameter X_t, when the radiative corrections are taken into account. Here $X_t = A_t - \mu/\tan\beta$, with A_t as the trilinear Higgs–top squark coupling and μ is the Higgsino mass parameter. The Higgs sector of the MSSM, with a Higgs boson of mass $\approx$126 GeV and with SM-like cross sections and branching fractions, can be broadly divided into two distinct regimes depending on the magnitude of M_A.

(i) *The decoupling regime, where $M_A \gg M_Z$.*—In this case, the lightest CP-even boson h has a mass around 126 GeV, whereas all the others H, A, and $H^\pm$ are almost degenerate and have a mass equal to M_A.

(ii) *The nondecoupling regime, where $M_A \leq$ 130 GeV.*—The heavy CP-even state H is SM-like, whereas the other neutral bosons are almost degenerate in mass $M_h \equiv M_A$. The mass of h and A can vary from the Z boson mass to the heavy neutral state H, depending on the value of M_A and $\tan\beta$. The charged state $H^\pm$ will be slightly heavier but still light enough to be detected in the Large Hadron Collider. Moreover in this regime, with the mass of H being around 126 GeV, the mass of the other gauge bosons like h, A, and $H^\pm$ are bounded from above.

The LEP Collaborations have placed lower bounds on the masses of the neutral Higgs boson M_A and the lightest scalar h [20]. The lower bounds on M_h and M_A are usually obtained from the upper bound on the cross section $\sigma(e^+e^- \to Zh)$ and $\sigma(e^+e^- \to Ah)$. This in turn has led to values of M_h and M_A less than 92.9 and 93.4 GeV being excluded at 95% C.L. Along with it, values of $\tan\beta$ between 0.7 and 2 are also excluded. Recent searches of the extra Higgs boson at the LHC have put new bounds on $\tan\beta$ as a function of M_A [21–24]. CMS data [23] have excluded regions of $\tan\beta$ above 6 for M_A below 250 GeV in the $m_h^{\max}$ scenario.

The main focus in this present work will be on the nondecoupling regime, and, as a result, we would like to make some observations on the value of M_A and $\tan\beta$ chosen for our analysis. Since this regime is mainly characterized by the pseudoscalar mass being less than 150 GeV, we plot in Fig. 1 the MSSM Higgs boson mass as a function of M_A, for two different values of $\tan\beta$. The other SUSY parameter A_t, which affects the Higgs sector, is fixed by assuming maximal top squark mixing. It can be seen from the left-hand side of Fig. 1 that, in the case of $\tan\beta = 10$, for $M_A \leq 120$ GeV, M_H is around 126 GeV, whereas M_A and M_h are almost degenerate. The maximal value of M_A which allows for M_H around 126 GeV is 130 GeV. The right-hand side of Fig. 1 shows the masses of the Higgs bosons as a function of M_A for $\tan\beta = 40$. We see that for our choice of SUSY parameters, for M_A around 125 GeV, the three neutral Higgs bosons have comparable masses: $M_H \simeq M_h \simeq M_A$. This special case where the Higgs masses are close to each other is called the intense coupling scenario. The LHC phenomenology of this scenario has been studied in detail in the past [25–27]. It has been known that in this intense coupling scenario the neutral boson (h, H) couplings to the gauge bosons are suppressed with respect to the SM, since A does not couple to the gauge bosons. Furthermore, the neutral bosons in this

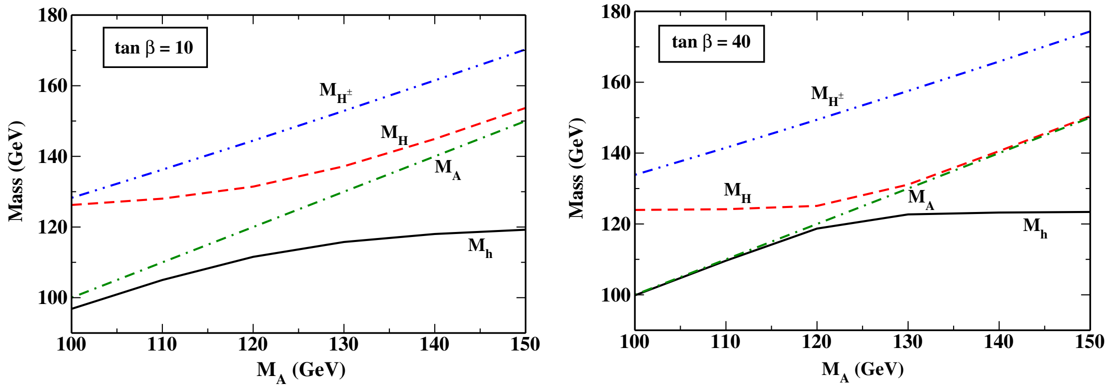

FIG. 1 (color online). The masses of MSSM Higgs bosons as a function of M_A for two distinct values of $\tan\beta$.

case will mainly decay to the down-type fermions, due to the enhancement of its coupling. The recent LHC results favoring a SM-like Higgs along with large values of $\tan\beta$ being disfavored by the CMS data, we have concentrated on the case with $M_A \approx 100$ GeV and small values of $\tan\beta$, in order to have the cross section times branching ratio of the Higgs boson to any SM particle in agreement with the recent LHC results. The value of $\tan\beta$ is tuned along with the parameter A_t, so that M_H is in the range $124 < M_H < 127$ GeV, and $M_h \simeq 97$ GeV.

In the past, various studies have shown that certain regions of the parameter space of the MSSM allow a Higgs boson with mass 126 GeV in both the decoupling and nondecoupling regimes, satisfying the LHC constraints. For most of the allowed parameter space, the Higgs decay to the lightest neutralinos is kinematically allowed, leading to invisible decay modes. It will therefore be very important to study the couplings of the newly discovered particle at high precision. As mentioned before, global fits have been performed on the couplings of the newly discovered particle, in order to place upper bounds on the invisible decay width. By taking into account these bounds, the parameter space of these new physics scenarios can be further constrained, since the regions giving a large invisible Higgs decay branching ratio will be in conflict with the experiments. This was earlier done in the context of the MSSM, in the decoupling scenario, where it was found that large regions in $\mu - M_1$ parameter space were disfavored [28] by the bounds on the invisible Higgs decay width, for different values of $\tan\beta$. In this work, we have investigated further to see whether the same result holds in the nondecoupling scenario, assuming H to be the 126 GeV boson.

Before proceeding further, we give a brief review of the neutralino sector in the MSSM. The physical mass eigenstates are obtained after the electroweak symmetry breaking, from the diagonalization of the neutralino mass matrix [29,30], with the neutralinos being an admixture of the fermionic partners of the two Higgs doublets H_1 and H_2 and the fermionic partners of the neutral gauge bosons:

$$M_{\mathrm{MSSM}} = \begin{pmatrix} M_1 & 0 & -M_Z \sin\theta_W \cos\beta & M_Z \sin\theta_W \sin\beta \\ 0 & M_2 & M_Z \cos\theta_W \cos\beta & -M_Z \cos\theta_W \sin\beta \\ -M_Z \sin\theta_W \cos\beta & M_Z \cos\theta_W \cos\beta & 0 & -\mu \\ M_Z \sin\theta_W \sin\beta & -M_Z \cos\theta_W \sin\beta & -\mu & 0 \end{pmatrix}, \tag{2.1}$$

where M_1 and M_2 are the $U(1)_Y$ and the $SU(2)_L$ soft supersymmetry breaking gaugino mass parameters, μ is the Higgs(ino) mass parameter, M_Z is the Z boson mass, θ_W is the weak mixing angle, and $\tan\beta = v_2/v_1$ is the ratio of the vacuum expectation values of the neutral components of the two Higgs doublet fields H_1 and H_2. Since we are concentrating on the Higgs invisible decay mode, the light neutralino eigenstate of the neutralino mass matrix (2.1) is favorable. Therefore, we consider the limiting case of the massless neutralino, which, at the tree level, arises when the determinant of the mass matrix (2.1) is zero. This in turn leads to the condition [19]

$$\mu[M_Z^2 \sin 2\beta (M_1 \cos^2\theta_W + M_2 \sin^2\theta_W) - M_1 M_2] = 0. \tag{2.2}$$

The chargino mass lower bounds from the LEP experiments [31] excludes the solution $\mu = 0$:

$$|\mu|, \qquad M_2 \geq 100 \text{ GeV}. \tag{2.3}$$

Therefore, the other possible solution to (2.2) is

$$M_1 = \frac{M_2 M_Z^2 \sin^2\theta_W \sin 2\beta}{\mu M_2 - M_Z^2 \cos^2\theta_W \sin 2\beta}. \tag{2.4}$$

In order to get a massless neutralino, for fixed values of μ, M_2, and $\tan\beta$, one can find a value of M_1 consistent with (2.4).

In the earlier work [17], it was found that it is not possible to have a massless neutralino with the gaugino parameters being both universal and nonuniversal at the GUT scale, except for some higher representation of E_6. The light neutralino with mass less than half the mass of the Higgs boson is still not ruled out by the current experiments. It is seen that, for the models with the ratio of $M_1/M_3 < 1/28$, the invisible decay of Higgs to the lightest neutralinos is allowed and holds true for both the coupling and the nondecoupling regimes of the MSSM. This is mainly by taking into account the constraint on the gluino mass $(M_{\tilde{g}} \approx M_3) > 1.3$ TeV from the LHC experiments and the other gaugino mass parameters being relatively fixed from the boundary conditions at the electroweak scale. As can be seen from Ref. [17], this condition on the ratio M_1/M_3 is satisfied by some of the higher-dimensional representation of $SO(10)$ and E_6.

A. Decay of Higgs boson to neutralinos in the MSSM

In this section, we mainly concentrate on constraining the Higgs parameter space in the case of the MSSM, from the Higgs invisible decay width. One of the main assumptions that go into limiting the parameter space of these models is the universality of the gaugino mass parameters at the GUT scale. The LEP constraint on the charginos has led to a lower bound on the lightest neutralino mass

$$M_{\tilde{\chi}_1^0} > 46 \text{ GeV} \tag{2.5}$$

at 95% C.L. in the context of the MSSM, assuming universal gaugino masses at the GUT scale [32]. The gaugino mass parameters need not be universal at the GUT scale; therefore, the phenomenology of the neutralinos in all these cases will be affected depending on the renormalization group evolution of the gaugino mass parameters. We do not consider any specific representations but instead consider a more generic case with M_1 and M_2 as independent parameters, in the nondecoupling scenario. With this consideration, the lightest neutralino so obtained will be binolike, because the chargino mass bounds from LEP have already set lower limits on M_2 and μ.

In the MSSM, the decay width of the CP-even neutral scalar bosons to a pair of lightest neutralinos can be written as [33]

$$\Gamma(h \to \tilde{\chi}_1^0\tilde{\chi}_1^0) = \frac{G_F M_W^2 M_h}{2\sqrt{2}\pi}(1 - 4M_{\tilde{\chi}_1^0}^2/M_h^2)^{3/2}[(Z_{12} - \tan\theta_W Z_{11})(Z_{13}\sin\alpha + Z_{14}\cos\alpha)]^2, \tag{2.6}$$

$$\Gamma(H \to \tilde{\chi}_1^0\tilde{\chi}_1^0) = \frac{G_F M_W^2 M_H}{2\sqrt{2}\pi}(1 - 4M_{\tilde{\chi}_1^0}^2/M_H^2)^{3/2}[(Z_{12} - \tan\theta_W Z_{11})(Z_{13}\cos\alpha - Z_{14}\sin\alpha)]^2, \tag{2.7}$$

where Z_{ij} are the elements of the matrix Z which diagonalize the neutralino mass matrix and α is the mixing angle in the CP-even Higgs sector. The above (2.6) and (2.7) show that the invisible branching ratio requires $\tilde{\chi}_1^0$ to be a mixed state, with both gaugino and Higgsino contributions. The invisible decay of the Higgs, though favored by a large Higgsino fraction neutralino, will be mainly constrained by the Z invisible decay width. The Z width to a pair of lightest neutralinos is given by [34]

$$\Gamma(Z \to \tilde{\chi}_1^0\tilde{\chi}_1^0) = \frac{G_F M_Z^3}{6\sqrt{2}\pi}(1 - 4M_{\tilde{\chi}_1^0}^2/M_Z^2)^{3/2}(Z_{13}^2 - Z_{14}^2). \tag{2.8}$$

The invisible decay width of Z to a pair of lightest neutralinos is restricted to

$$\Gamma(Z^0 \to \tilde{\chi}_1^0\tilde{\chi}_1^0) < 3 \text{ MeV} \tag{2.9}$$

at 95% C.L. by the LEP Collaborations [31].

The mass bound on the lightest chargino $M_{\tilde{\chi}^\pm} > 94$ GeV from the LEP experiments is taken into account [32]. The results are presented for a fixed value of $M_2 = 200$ GeV, with the parameters μ and M_1 being varied. The other SUSY parameters like the squarks and gluinos are fixed to masses around 1 TeV in accordance with the latest LHC results. The masses of the sleptons are taken to be greater than 500 GeV. Since we are considering the Higgs decay to the lightest neutralino pair, which are also one of the leading dark matter candidates, it will be necessary to check whether the kinematically allowed parameter region in the $\mu - M_1$ plane also gives the correct relic density as measured from WMAP [35,36], i.e., $0.0925 < \Omega h^2 < 0.1287$. In this work, the computation of the relic density has been performed with MICROMEGAs 3.2 [37], along with the production and decays of the SUSY particles being computed with CALCHEP [38].

Apart from the LHC constraints, the constraints from (g-2) of the muon and other flavor constraints such as $b \to s\gamma$ and $B_s \to \mu^+\mu^-$ are also taken into account, which are implemented within CALCHEP.

We show in Fig. 2 the branching ratio of both CP-even Higgs bosons [H (left) and h (right)] to the lightest neutralinos. The regions with large μ and M_1 values as expected give rise to massive neutralinos, with

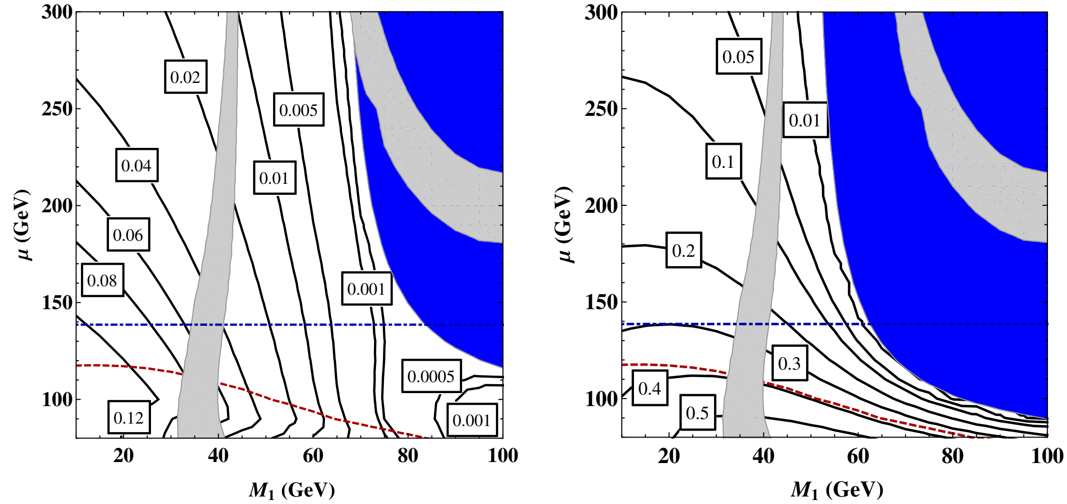

FIG. 2 (color online). The contours of the constant branching ratio of $(H \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0)$ (left) and $(h \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0)$ (right) for a fixed value of $\tan\beta = 6$ and $M_2 = 200$ GeV. The region shaded in blue is the region kinematically not allowed, whereas the gray shaded region (denoted by narrow bands) is the one with the relic density within the experimental limits.

$M_{\tilde{\chi}_0^1} > M_{H,h}/2$, and are therefore kinematically not allowed and are shaded in blue. The neutralino obtained by considering M_1 and M_2 as independent parameters is mostly binolike, as the LEP mass bound on chargino has already placed a lower bound on M_2 and μ. In the bino limit, the process which mainly contributes to the relic density is the one mediated by a t-channel sfermion. We have calculated the relic density for different slepton masses varying from 150 to 1000 GeV. There being no significant change in the allowed parameter space, we have presented the results for a sfermion mass of 500 GeV. It is seen that for most of the allowed parameter region of $\mu - M_1$, taking into account the LEP bound of the chargino mass (blue dot-dashed line) and the invisible decay width of the Z boson (red dashed line), the invisible branching ratio of the Higgs boson H is still too small to be probed at the LHC. The areas below the blue dot-dashed and red dashed lines are excluded from the LEP bound of the chargino and the invisible Z decay width, respectively. The parameter space cannot be constrained by the latest limits on the invisible decay width from the LHC fits. This is in contrast to the situation $M_h \approx 126$ GeV, where most of the $\mu - M_1$ parameter space was constrained from the bounds on the invisible branching ratio of the Higgs boson (h) [17,28]. Moreover, in the nondecoupling scenario, as can be seen from the right-hand side of Fig. 2, the $\mathrm{BR}(h \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0)$ is small compared to the decoupling case, due to an enhanced coupling to the b quarks. The enhancement is mainly due to the $\sin\alpha$ term, in the coupling of h to a pair of b quarks, which is sensitive to the parameter M_A.

The shape of the contours in the left plot of Fig. 2 can be understood from the fact that the $\mathrm{BR}(H \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0)$ decreases for increasing μ, due to the increase in neutralino mass. The dip in the contours for μ around 100 GeV is due to the fact that for a particular value of M_1, after μ decreases to a certain value, the other decay modes of Higgs bosons such as $h \rightarrow \tilde{\chi}_1^0\tilde{\chi}_2^0, \tilde{\chi}_1^0\tilde{\chi}_3^0, \tilde{\chi}_1^+\tilde{\chi}_1^-$ open up, leading to a decrease in the invisible BR. Most of the parameter space for $\mu < 140$ GeV is, however, excluded by the chargino mass bound of 110 GeV. The same argument holds for h, the right plot in Fig. 2. We finally list in Table I the branchings of h and H to different final states for our parameter choices of $M_A = 105$ GeV, $\tan\beta = 6$, $M_2 = 100$ GeV, $M_1 = 50$ GeV, and $\mu = 130$ GeV. The BR of decay to neutralinos changes with the change of μ and M_1 as discussed before.

The dependence of our result on the other input parameters is as follows. If the gaugino mass parameter M_2 is lowered, the mass bound of the chargino pushes up the blue dot-dashed line in Fig. 2 to large values of μ and vice versa. The coupling of the Higgs boson (h/H) with a neutralino decreases with the increase of $\tan\beta$ resulting in a smaller invisible branching ratio. Large values of $\tan\beta$ as discussed before are disfavored in the nondecoupling scenario, by the LHC experiments. Since there is an

TABLE I. Branching ratios of both h and H to various decay channels, with our parameter choices of $M_A = 105$ GeV, $\tan\beta = 6$, $M_2 = 200$ GeV, $M_1 = 50$ GeV, and $\mu = 130$ GeV.

Final states	H branchings $M_H = 125$ GeV	h branchings $M_h = 97$ GeV
$l, L(e, \mu, \tau)$	0.089	0.074
bb	0.841	0.735
cc	0.004	3.5×10^{-4}
GG	0.016	1.1×10^{-3}
AA	1.7×10^{-4}	3.3×10^{-5}
W^+W^-	0.024	6.5×10^{-5}
ZZ	2.9×10^{-3}	
$\tilde{\chi}_1^0\tilde{\chi}_1^0$	0.023	0.191

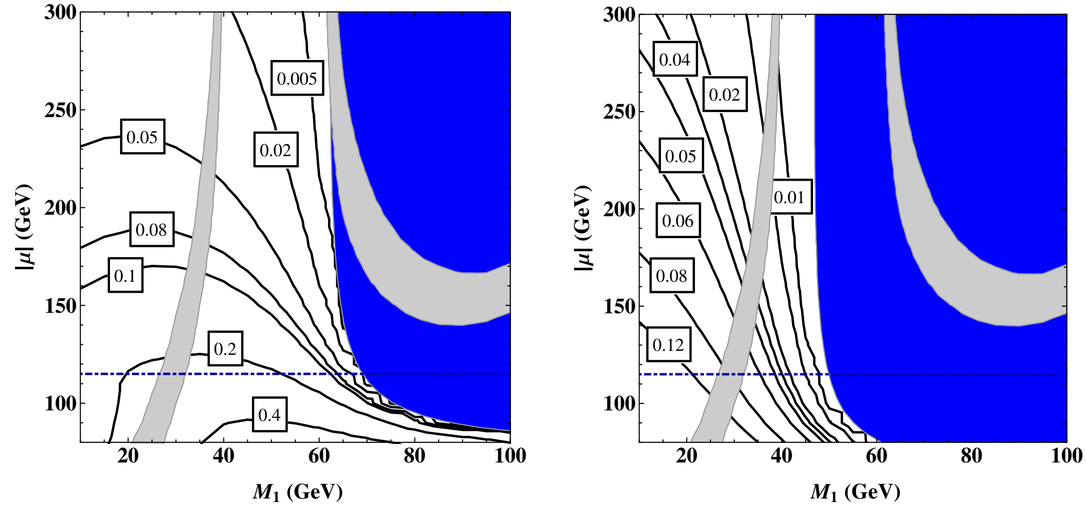

FIG. 3 (color online). The contours of the constant branching ratio of $(H \to \tilde{\chi}_1^0 \tilde{\chi}_1^0)$ (left) and $(h \to \tilde{\chi}_1^0 \tilde{\chi}_1^0)$ (right) for a fixed value of $\tan\beta = 6$ and $M_2 = 200$ GeV with $\mu < 0$. The region shaded in blue is the region kinematically not allowed, whereas the gray shaded region (denoted by narrow bands) is the one with relic density within the experimental limits.

enhancement in the branching ratio, if a smaller value of $\tan\beta$ is chosen, for the sake of completeness we also quote the results for $\tan\beta = 4$. It can be seen from the left-hand side of Fig. 2 that, for $\tan\beta = 6$, the largest possible branching ratio of H to a pair of neutralinos is 8%, if the LEP constraint on the chargino mass is considered. On the other hand, if the value of $\tan\beta$ is reduced to 4, the maximum possible BR satisfying the LEP constraint is 12%. In the case of h, the change is significant, as for $\tan\beta = 6$ the maximum possible BR was around 28% as can be seen from the right-hand side of Fig. 2. For $\tan\beta = 4$, this increases to about 40%.

We next show in Fig. 3 the contours of the invisible branching ratio (BR) of CP-even Higgs bosons H and h to the lightest neutralinos for μ less than 0. The values of the other parameters are the same as before with $M_2 = 200$ GeV and $\tan\beta = 6$. The chargino mass bound on μ decreases due to the increase in chargino mass. The branching ratio of Z to a pair of neutralinos decreases, with negative μ; therefore, the considered $\mu - M_1$ parameter space is not constrained by Eq. (2.9) in this case. The neutralino mass also increases with negative μ, resulting in larger regions of parameter space being kinematically not allowed. The invisible branching ratio of H increases for negative μ. This is mainly because, for $\mu > 0$, there is a cancellation between the terms $Z_{13}\cos\alpha$ and $Z_{14}\sin\alpha$ of (2.7), whereas these two terms add for $\mu < 0$ leading to enhanced neutralino Higgs coupling. This behavior is just the opposite for h as can be seen from the right plot in Fig. 3. Here for $\mu < 0$, there is a cancellation between the $Z_{13}\sin\alpha$ and $Z_{14}\cos\alpha$ terms of (2.6) leading to reduced coupling of Higgs bosons to the neutralinos. Overall, it can be seen from the above that in the nondecoupling regime it will not be possible to constrain the neutralino sector from the recent Higgs results, unlike the decoupling regime where it was possible to do so [28]. More data from the LHC are needed so as to constrain the neutralino parameter space from the Higgs result in this case.

III. DECAY OF THE HIGGS BOSON IN THE NMSSM

We now extend the considerations of the previous section to the NMSSM which has a richer Higgs and neutralino sector. To recapitulate, the NMSSM has an extra gauge singlet superfield S in addition to the two Higgs doublets H_1 and H_2, of the MSSM. The Higgs(ino) mass term $\mu H_1 H_2$ in the superpotential of the MSSM is replaced by the trilinear coupling $\lambda S H_1 H_2$, where λ is a dimensionless coupling [39–45]. There is also an additional trilinear self-coupling of the singlet S^3. The superpotential involving only the Higgs field then takes the form

$$W_{\rm NMSSM} = \lambda S H_1 H_2 - \frac{\kappa}{3} S^3. \tag{3.1}$$

Once the scalar potential of the singlet superfield acquires a vacuum expectation value s, the first term of the superpotential (3.1) then generates an effective μ term, where $\mu_{\rm eff} = \lambda s$. This $\mu_{\rm eff}$ term is naturally of the order of the electroweak scale, thereby providing a solution to the μ problem of the MSSM. The Higgs sector of the NMSSM at tree level is described by six parameters $\mu_{\rm eff}, \lambda, \kappa, \tan\beta, A_\lambda$, and A_κ, compared to the Higgs sector of the MSSM, which is defined by only two independent parameters ($\tan\beta$ and M_A). The physical Higgs spectrum consists of three CP-even states and two CP-odd states along with a pair of charged Higgs boson. The neutralino sector in the case of the NMSSM, due to the addition of the singlet, becomes a 5×5 matrix, which can be written in the bino, wino, Higgsino, and singlino basis [46–48]. It is described by six independent parameters $\mu_{\rm eff}, M_1, M_2, \tan\beta, \lambda$, and κ:

$$M_{\mathrm{NMSSM}} = \begin{pmatrix} M_1 & 0 & -M_Z \sin\theta_W \cos\beta & M_Z \sin\theta_W \sin\beta & 0 \\ 0 & M_2 & M_Z \cos\theta_W \cos\beta & -M_Z \cos\theta_W \sin\beta & 0 \\ -M_Z \sin\theta_W \cos\beta & M_Z \cos\theta_W \cos\beta & 0 & -\mu_{\mathrm{eff}} & -\lambda v_2 \\ M_Z \sin\theta_W \sin\beta & -M_Z \cos\theta_W \sin\beta & -\mu_{\mathrm{eff}} & 0 & -\lambda v_1 \\ 0 & 0 & -\lambda v_2 & -\lambda v_1 & 2\kappa x \end{pmatrix}. \tag{3.2}$$

For a massless neutralino the determinant of the mass matrix (3.2) should be zero, which leads to [19]

$$2\kappa x \mu_{\mathrm{eff}}(\Delta_0 \sin 2\beta - \mu_{\mathrm{eff}} M_1 M_2) + \lambda^2 v^2 [\Delta_0 - \mu_{\mathrm{eff}} M_1 M_2 \sin 2\beta] = 0, \tag{3.3}$$

where $\Delta_0 = M_Z^2(M_1 \cos^2\theta_W + M_2 \sin^2\theta_W)$. Equation (3.3) in turn leads to the following condition:

$$\kappa = \frac{\lambda}{2}\left(\frac{\lambda v}{\mu_{\mathrm{eff}}}\right)^2 \frac{\Delta_0 - \mu_{\mathrm{eff}} M_1 M_2 \sin 2\beta}{\mu_{\mathrm{eff}} M_1 M_2 - \Delta_0 \sin 2\beta}, \tag{3.4}$$

for a massless neutralino in the NMSSM.

Analogous to the MSSM, even in the case of the NMSSM it was earlier investigated whether the recent global fits from the Higgs data can constrain the parameter space of the neutralino sector [17], with the lightest Higgs boson (h_1) of the NMSSM being identified as the 126 GeV state observed at the LHC. There can also be another possibility where the second lightest CP-even Higgs boson (h_2) will lead to a SM-like Higgs boson in the mass range 124 GeV $\le M_{h_2} \le$ 127 GeV. The mass of the lightest CP-even Higgs boson h_1 and sometimes the lightest pseudoscalar Higgs boson a_1 will be less than M_{h_2}, and, in some regions of the parameter space, the decay of h_2 to a pair of h_1 or a_1 will be kinematically allowed. A lot of work has been done in the context of two light Higgs bosons within the NMSSM. Various scenarios have been proposed in this context and are examined or constrained in the light of the recent LHC results.

(a) One of them was proposed to explain the enhancement of the Higgs signal in some of the channels relative to the SM. The authors of Refs. [49–51] have identified a set of parameter space, in the context of the NMSSM where the two lightest CP-even Higgs bosons are found to be closely degenerate and lie in the mass window 123–128 GeV. We do not consider this possibility here.

(b) Another scenario that has been widely considered in the context of the NMSSM is where the heavier Higgs boson h_2 is considered as the SM-like Higgs boson in the mass range of [124, 127] GeV and the lighter Higgs boson h_1 is around 98 GeV in order to account for the LEP excess [52]. We will refer to this as the $98 + 126$ GeV Higgs scenario further in the text.

Since h_1 is in the mass range (96–100) GeV, in order to respect the LEP limit of $C_{\mathrm{eff}}^{2b} = [g_{ZZh}^2/g_{ZZh_{\mathrm{SM}}}^2]\mathrm{BR}(h \to b\bar{b})$, from the process $e^+e^- \to hZ \to b\bar{b}Z$, the mass of the lightest pseudoscalar a_1 is assumed to be less than $2M_b$. There have been additional constraints on the mass of a_1 from various other experiments. In a recent result from CMS, the experiment has excluded a pseudoscalar mass in the range 1 GeV $< M_{a_1} < 2M_\tau$, for a scalar Higgs boson in the mass range 86–150 GeV. Therefore, in order to study the $98 + 126$ GeV scenario, the light pseudoscalar should be either in the range $2M_\tau < M_{a_1} < 2M_b$ or heavier than M_{h_2}. Another way of evading the CMS bound in this two light Higgs scenario is to consider the mass of the lightest scalar (M_{h_1}) to be less than 86 GeV [53]. The LEP searches of a Higgs boson decaying into four τ leptons via an intermediate pseudoscalar [54] have placed a constraint on the combined production times branching ratio on the four τ's decay channel $[\sigma(e^+e^- \to Zh)/\sigma_{\mathrm{SM}}(e^+e^- \to Zh)) \times \mathrm{BR}(h \to a_1 a_1) \times \mathrm{BR}(a_1 \to \tau^+\tau^-)^2 < 1]$. All these searches have mainly considered the decay of Higgs bosons to pseudoscalar as the only nonstandard decay mode apart from the usual SM decay channels. Since in our analyses there are other nonstandard decay modes of the Higgs boson, like the Higgs boson decaying to a pair of lightest neutralinos, the constraint on the mass of the pseudoscalar will be lightened by the presence of these additional decay channels. We have considered the mass of the pseudoscalar such that the LEP limit from the process $e^+e^- \to hZ, h \to b\bar{b}$ is satisfied along with the process $e^+e^- \to hZ, h \to a_1 a_1, a_1 \to b\bar{b}$. In addition, we have also seen that the LEP constraint on the four τ's final state is also satisfied.

The Higgs sector of the NMSSM being described by six independent parameters, $\mu_{\mathrm{eff}}, \lambda, \kappa, \tan\beta, A_\lambda$, and A_κ, a

TABLE II. Ranges of the input parameters of the NMSSM of our scan.

Parameter	Lower range	Upper range
μ_{eff}	100	400
$\tan\beta$	5	40
λ	0.01	0.7
κ	0.01	0.6
A_λ	−500	1000
A_κ	−1000	100

scan is performed over 10^6 random points in the range of parameters listed in Table II. We have used NMSSMTools 4.1.0 [55,56] for our analysis. The scan includes all the recent experimental constraints from the Higgs, flavor, and precision electroweak measurements implemented within NMSSMTools. We have additionally demanded that the second lightest *CP*-even Higgs boson of the NMSSM (h_2) should lead to a SM-like Higgs boson in the mass range [124, 127] GeV. We have also restricted to values of κ and λ less than 0.7. This is due to the theoretical constraint that there should be no charge and color breaking global minima of the scalar potential and that a Landau pole does not develop below the GUT scale. Since the Higgs mass spectrum is independent of the gaugino mass parameters, we have considered universal boundary conditions at the GUT scale, with the $SU(3)_C$ gaugino mass parameter $M_3 = 1400$ GeV, from the gluino searches at the LHC. The remaining two soft SUSY breaking gaugino parameters have values $M_1 = 197$ GeV and $M_2 = 395$ GeV. In this work, we have divided the points which survive all the constraints defined above into two distinct scenarios.

(i) *Scenario 1*.—The heavier Higgs boson h_2 is in the mass range [124, 127] GeV, whereas the lightest pseudoscalar a_1 has a mass less than half the mass of h_2. The lightest *CP*-even Higgs boson h_1 is lighter than h_2.

(ii) *Scenario 2*.—As before, h_2 is in the mass range [124, 127] GeV, with the lightest *CP*-even scalar h_1 less than half the mass of h_2. The lightest pseudoscalar a_1 can be lighter than h_1 satisfying the experimental constraints or heavier than h_2.

The $98 + 126$ GeV Higgs boson case can be obtained in the first scenario, but we separately give the parameter points which satisfy this. We show in Figs. 4–6 the different parameters that lead to the scenarios of interest considered here. The points in the plots as discussed before satisfy all the experimental constraints. It can be seen from Fig. 4 that smaller values of λ and κ are preferred for the scenarios we are considering. A lot of work has been done in the context

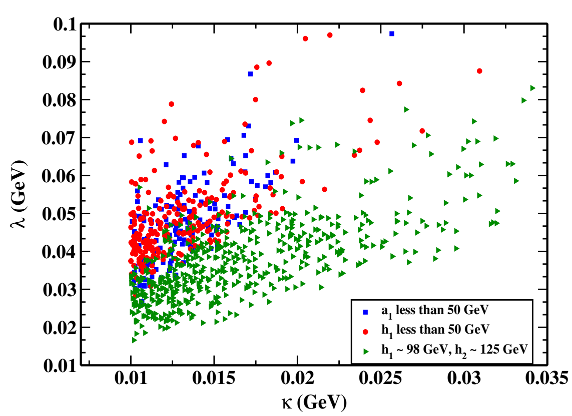

FIG. 4 (color online). Point satisfying all the experimental constraints in the $\lambda - \kappa$ plane.

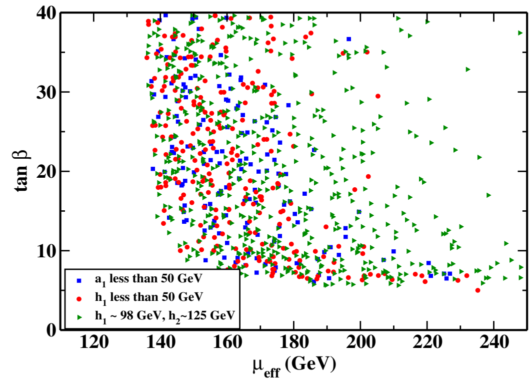

FIG. 5 (color online). Point satisfying all the experimental constraints in the $\tan\beta - \mu_{\rm eff}$ plane.

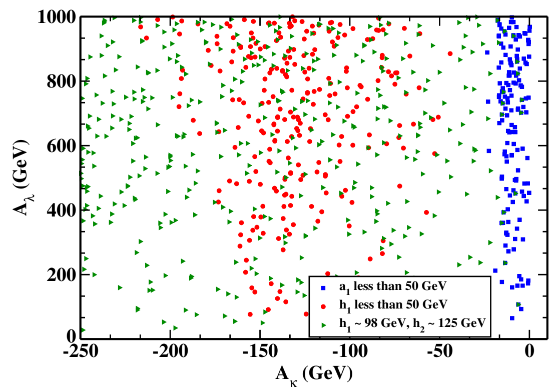

FIG. 6 (color online). Point satisfying all the experimental constraints in the $A_\lambda - A_\kappa$ plane.

of large doublet singlet mixing in the Higgs sector, i.e., concentrating on regions of the parameter space with large values of λ, leading naturally to a SM-like Higgs boson h_2 in the 126 GeV range [57–60]. But we are mainly interested in the case where the Higgs decay channels to nonstandard particles are open, such as $h_2 \to a_1 a_1, Z a_1, h_1 h_1$, along with the neutralinos. Most of the points which satisfy the above constraints are concentrated in the low $\kappa - \lambda$ plane; therefore, we show them here. Moreover, scenario 1 is distinct from the others in the $A_\lambda - A_\kappa$ plane, since M_{a_1} is sensitive to A_κ.

With the universal gaugino masses at the GUT scale, and from (3.4), we find that it is not possible to get a massless neutralino in the NMSSM, with $M_{h_2} \approx 126$ GeV. This result holds in the entire parameter space considered in our analyses. In the range of the parameter space

TABLE III. Input parameters for the benchmark points in the case of the NMSSM.

	λ	κ	A_λ	A_κ	$\tan\beta$	$\mu_{\rm eff}$	$A_{t,b,\tau}$
Scenario 1	0.055	0.013	875.76	−0.174	19.97	169.47	−2500
Scenario 2	0.037	0.013	978.21	−168.44	18.69	149.77	−2500

TABLE IV. The Higgs mass spectrum for the different benchmark scenarios in the case of the NMSSM.

	M_{h_1}	M_{h_2}	M_{h_3}	M_{a_1}	M_{a_2}	$M_{h^\pm}$
Scenario 1	76.28	126.47	1716.62	5.23	1716.6	1718.2
Scenario 2	47.69	124.58	1657.66	164.07	1657.63	1659.38

considered by us, for the NMSSM with universal boundary conditions of gaugino masses at the GUT scale, the decay $h_2 \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0$ is kinematically possible in some regions. Since analysis with the GUT relation between M_1 and M_2 will result in confining to a particular case, we do not consider that possibility here but instead concentrate on the general case with M_1 and M_2 as independent parameters. We consider a benchmark point for the different scenarios listed above and present the results here. The spectra of the sparticles and the gluinos are considered similar to the case of the MSSM. We list in Table III the parameters for the two different benchmark scenarios considered here. The corresponding Higgs spectrum is listed in Table IV.

We show in Fig. 7 the contours of constant branching ratios of $h_2 \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0$ (black line) and $h_2 \rightarrow \tilde{\chi}_1^0\tilde{\chi}_2^0$ (red dashed line) in the $\mu_{\rm eff} - M_1$ plane with the values of the other parameters fixed as given in Table III for scenario 1. Since M_{h_2} is sensitive to $\mu_{\rm eff}$, we have varied $\mu_{\rm eff}$ in the range such that $M_{h_2} \approx 124$–127 GeV. The blue shaded region is the area where the h_2 decay to the lightest neutralinos is kinematically not accessible. The lightest neutralino has a dominant gaugino component, in the entire $\mu_{\rm eff} - M_1$ plane. The singlino component is absent for low M_1 values and opens up at higher values of M_1. The gray shaded area shows the region where the lightest neutralino satisfies the relic density constraint. The relic density is satisfied in the region where the neutralino is a gaugino-Higgsino mixture but has a dominant gaugino component. We see that, for the region allowed by the relic density, the invisible branching ratio can vary in the range of 15%–20%. As invisible BRs less that 38% are still allowed by the global fits, the NMSSM parameter space cannot be constrained by the present LHC Higgs data. In the future with the upgraded

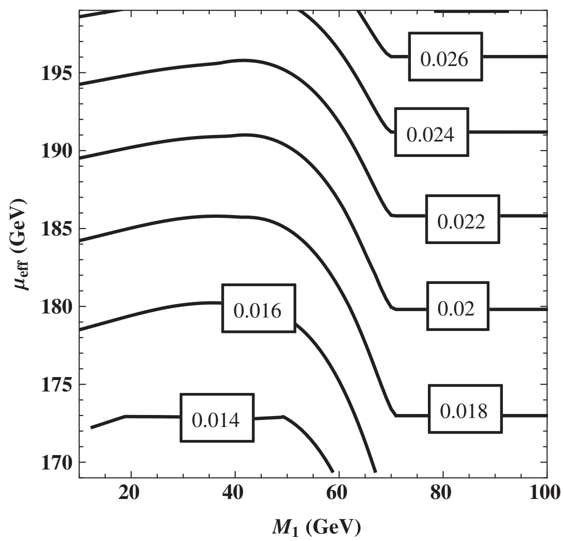

FIG. 8. Contours of the constant branching ratio of $(h_2 \rightarrow a_1 a_1)$ in the NMSSM in the $\mu_{\rm eff} - M_1$ plane for a fixed value of $M_2 = 200$ GeV and the other parameters fixed to values in Table III for scenario 1.

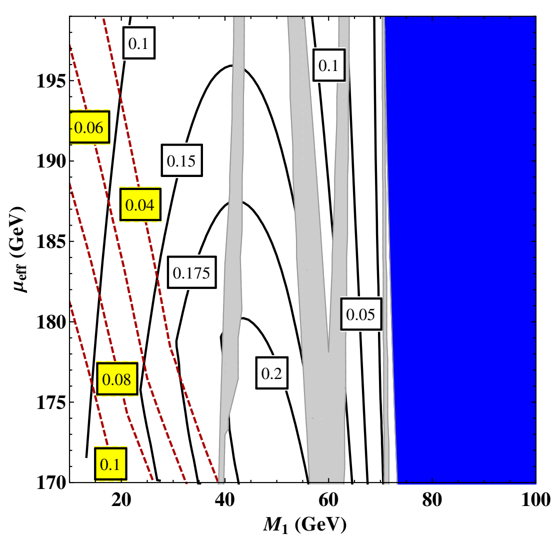

FIG. 7 (color online). Contours of the constant branching ratio of $(h_2 \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0)$ (black solid line) and $(h_2 \rightarrow \tilde{\chi}_1^0\tilde{\chi}_2^0)$ (red dashed line) in the NMSSM in the $\mu_{\rm eff} - M_1$ plane for a fixed value of $M_2 = 200$ GeV and the other parameters fixed to values in Table III for scenario 1.

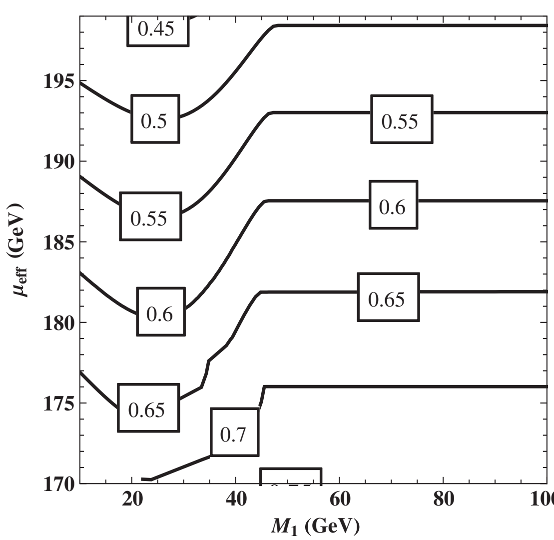

FIG. 9. Contours of the constant branching ratio of $(h_1 \rightarrow a_1 a_1)$ in the NMSSM in the $\mu_{\rm eff} - M_1$ plane for a fixed value of $M_2 = 200$ GeV and the other parameters fixed to values in Table III for scenario 1.

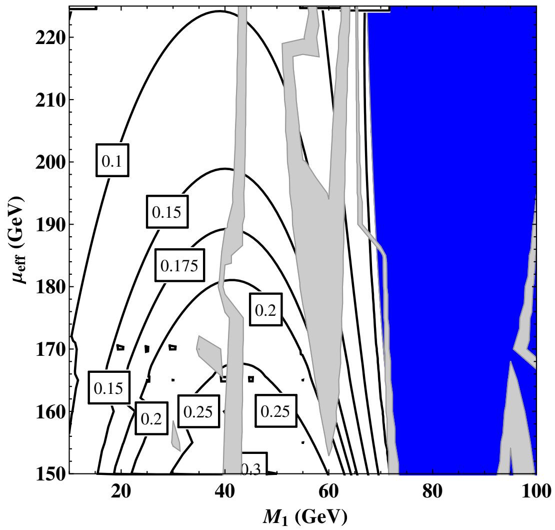

FIG. 10 (color online). Contours of the constant branching ratio of ($h_2 \to \tilde{\chi}_1^0 \tilde{\chi}_1^0$) in the NMSSM in the $\mu_{\rm eff} - M_1$ plane for a fixed value of $M_2 = 200$ GeV and the other parameters fixed to values in Table III for scenario 2.

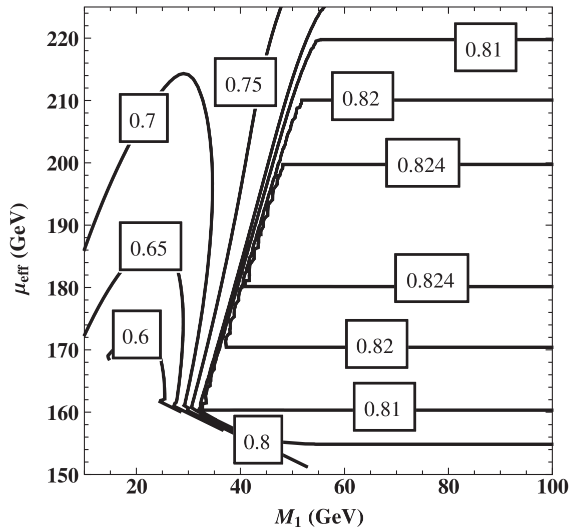

FIG. 11. Contours of the constant branching ratio of ($h_1 \to b\bar{b}$) in the NMSSM in the $\mu_{\rm eff} - M_1$ plane for a fixed value of $M_2 = 200$ GeV and the other parameters fixed to values in Table III for scenario 2.

LHC results, it will be possible to constrain the parameter space from the Higgs data. The nature of the contours in Fig. 7 can be readily understood from the fact that, since $M_{\tilde{\chi}_2^0}$ also depends on $\mu_{\rm eff}$ and M_1, at low values of M_1, the decay channel $h_2 \to \tilde{\chi}_1^0 \tilde{\chi}_2^0$ is kinematically accessible. This is shown by red dashed lines which decrease with increasing M_1 due to the increase in mass of $\tilde{\chi}_2^0$ and the opening of the channel $h_2 \to \tilde{\chi}_1^0 \tilde{\chi}_1^0$. The second lightest neutralino is mostly a singlino. Since in this scenario the lightest pseudoscalar is very light, $M_{a_1} \approx 6$ GeV, we show in Fig. 8 the branching ratio of h_2 to a pair of a_1 in the $\mu_{\rm eff} - M_1$ plane. The decay channel $h_2 \to Z a_1$ is also open, but the branching ratio is very small. So we do not consider it here. The nature of the contour in Fig. 8 can be understood from the fact that at high values of M_1, since the neutralino decay channel is not there, the BR is constant, whereas for lower values of M_1 due to the invisible branching ratio the contours show a curved nature. Here a_1 will mostly decay into a pair of τ's, which can be easily detected in the collider. So we do not include them in the calculation of the invisible branching ratio. We also show in Fig. 9 the decay of the light CP-even Higgs boson h_1 to a pair of a_1. Here h_1 predominantly decays to a_1 with around 50%–60% branching ratio. The dip in the contours at lower values of M_1 is due to the presence of light neutralinos, leading to the decay channel $h_1 \to \tilde{\chi}_1^0 \tilde{\chi}_1^0$. The lighter Higgs boson h_1 in this case can be observed in the collider through the decay mode $h_1 \to a_1 a_1 \to 4\tau$. We next show our results for scenario 2, where $M_{h_1} \le M_{h_2}/2$. The nature of Fig. 10 is similar to Fig. 7, showing the contours of constant branching ratios of $h_2 \to \tilde{\chi}_1^0 \tilde{\chi}_1^0$. The value of λ in scenario 2 is smaller compared to that of scenario 1, as can be seen from Table III. Since the neutralino mass ($M_{\tilde{\chi}_{1,2}^0}$) increases with decreasing λ, the neutralinos in this case are more massive. Therefore, the decay channel $h_2 \to \tilde{\chi}_1^0 \tilde{\chi}_2^0$ is kinematically not accessible. The allowed parameter space can be constrained only by the future LHC results. We would further add that the composition of the lightest and the second lightest neutralino is similar to scenario 1. Finally, we show in Fig. 11 the contours of the constant branching ratio of the lightest CP-even Higgs boson to a pair of b quarks, which is the dominant decay mode. The BR can be as high as 80% for most of the $\mu_{\rm eff} - M_1$ parameter space. When the neutralino is light enough to allow for the invisible decay mode of the light Higgs (h_1), the BR decreases by about 20%. It will be possible to observe this state at the LHC, through the $b\bar{b}$ decay mode. The lightest pseudoscalar Higgs boson in this scenario is heavier than h_1 and h_2 but is considerably lighter to be observed at the LHC. Nevertheless, the dominant decay mode of a will be to a pair of neutralinos, and the second dominant mode will be to a pair of b quarks. The pseudoscalar a will therefore be difficult to be observed in the LHC, due to a large invisible BR. This shows that the global fits from the recent LHC data are unable to constrain the neutralino sector of the NMSSM, when the second lightest scalar is identified as the 126 GeV Higgs boson. We add that the analysis carried out in this work can also be repeated for negative values of κ. However, we have found that in this case, for most of the parameter space with h_2 around 126 GeV, the limits on the invisible branching ratio cannot constrain the parameter space as is the case with positive values of κ. A more detailed precision study in the Higgs sector is allowed so as to constrain the parameter space in this case.

IV. CONCLUSION

In this work, we have considered the possibility of the invisible decays of the second lightest CP-even Higgs boson in the context of both the MSSM and NMSSM. The second lightest Higgs boson behaves as the SM-like Higgs boson with mass in the allowed mass range $\approx[124, 127]$ GeV. The neutralino sector in the past few years has been studied in detail and also constrained by the data from different astrophysical, cosmological, and collider experiments. The recent LHC results on the Higgs branching ratio have independently constrained the Higgs invisible branching ratio, through global fits. The Higgs boson can decay to a pair of neutralinos giving rise to an invisible decay branching ratio provided $M_{\tilde{\chi}_1^0} < M_H$. This invisible Higgs decay channel is also looked for through direct searches at the LHC. It will therefore be important to consider the implications of the current information on Higgs bosons from the LHC, on the neutralino sector of the supersymmetric models. In the context of the MSSM, we discuss in brief whether it will be possible for the SM-like Higgs boson to decay to a pair of neutralinos, with both universal and nonuniversal gaugino masses at the GUT scale. We find that, with universal gaugino masses, the invisible decay channel $H \to \tilde{\chi}_1^0\tilde{\chi}_1^0$ is kinematically not allowed. Nevertheless, in the case of nonuniversal gaugino masses, for certain representations of $SO(10)$ and E_6, the 126 GeV Higgs boson will have a considerable invisible branching ratio. We have then analyzed the possibility of having a large invisible branching ratio in the context of the NMSSM which has a richer neutralino and Higgs sector compared to the MSSM. We find that in the case of the NMSSM it is possible to have the invisible decay channel ($h_2 \to \tilde{\chi}_1^0\tilde{\chi}_1^0$) with universal gaugino masses at the GUT scale. The assumption of the GUT relation between M_1 and M_2 being largely model dependent, we have considered a more general case and have done our analyses by treating M_1 and M_2 as two independent parameters in the case of both the MSSM and the NMSSM. With this assumption, there is an additional freedom of the neutralino being very light.

We have then studied the decay of the Higgs bosons (h and H) to a pair of lightest neutralinos in the context of the nondecoupling scenario of the MSSM. We have considered the possibility that the 126 GeV scalar (H) observed at the LHC along with the 98 GeV scalar (h) from the LEP excess in the $b\bar{b}$ final state can be concurrently explained in the MSSM framework. We find that there are regions in the MSSM parameter space where such scenarios exist. The neutralino sector being dependent on the parameters μ, M_1, M_2, and $\tan\beta$, we give our results for a fixed value of $\tan\beta$ and M_2 in the $\mu - M_1$ plane, because we are mainly interested in the Higgs decay channel to a pair of neutralinos. We find the invisible BR in this case is too small to be constrained by the recent LHC fits from the Higgs data. This is in contrast to the case when the lightest CP-even Higgs boson (h) was SM-like [17,28], the decoupling scenario. There it was found that, with $h \approx 126$ GeV, a large portion of the $\mu - M_1$ parameter space for a fixed value of $\tan\beta$ and M_2 allowed a large invisible branching ratio in conflict with the latest LHC fits from the Higgs sector, thereby constraining the neutralino parameter space. Therefore, if the nondecoupling scenario exists, the parameter space of the neutralino sector cannot be constrained by the recent LHC data. Higher precision Higgs physics is required to constrain the parameter space in the scenario. This scenario can be alternatively tested by looking for the other Higgs boson production, $M_h \approx 98$ GeV, $M_A \approx 100$–150 GeV, and $M_{H^\pm} \approx 150$–200 GeV at the LHC. We do not consider the possibility here. The dependence of our results on the other input parameters is also discussed in detail.

An analogous analysis is then performed in the context of the NMSSM. The number of independent parameters in the neutralino and the Higgs sector is greater than that of the MSSM. We have performed a scan over the parameters contributing to the neutralino sector of the NMSSM and have plotted the points which pass the various theoretical and experimental constraints discussed in the text, along with the condition that the second lightest Higgs boson h_2 behaves like the SM Higgs boson. The points which survive these constraints are then divided into three scenarios, depending on the mass of the other Higgs bosons. We first separately isolate the points where both M_{h_1,a_1} are less than m_{h_2}, but only the decay of h_2 to a pair of CP-odd Higgs bosons a_1 is kinematically allowed. Second, we consider the case when the mass of the lightest Higgs boson (h_1) is less than half the mass of h_2; that is, the decay $h_2 \to h_1h_1$ is kinematically allowed. We have considered a single benchmark point for these two scenarios and have exclusively worked out the results. The dependence of the results on the other points can be suitably interpreted. There are regions in the parameter space which also satisfy the $98(h_1) + 126(h_2)$ GeV Higgs scenario, so as to account for the LEP excess along with the Higgs data from the LHC. We list the points which fall in this parameter space, but we do not consider a benchmark point in this case, as the results will be similar to the first scenario. We see that the invisible branching ratio reaches a maximum of 20% for the two scenarios considered here, still too small to be constrained by the recent LHC fits from the Higgs data. The result is thus similar to the MSSM, where, with the second lightest scalar being 126 GeV, it is currently not possible to constrain the neutralino parameter space from the Higgs data. The situation will improve with more data from the next LHC run.

Overall, we find that in the context of both the MSSM and NMSSM it is not possible to constrain the neutralino sector from the recent Higgs data, if the second lightest scalar is identified with the one observed at the LHC. The presence of the other light Higgs boson will, however, lead to interesting collider signals at the LHC, which will alternatively test these scenarios. It will be worthwhile to do a detailed collider study of these light Higgs bosons and find the reach of the LHC. The direct detection of some SUSY particles in the 13 and 14 TeV runs of the LHC would significantly cut down the arbitrariness of extensions of the SM to its SUSY variants, after which a precision Higgs era could be pursued at the LHC. Hopefully, this can be pursued in the near future.

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