Invisible decays of the lightest Higgs boson in supersymmetric models

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We consider supersymmetric models in which the lightest Higgs scalar can decay invisibly consistent with the constraints on the 126 GeV state discovered at the CERN LHC. We consider the invisible decay in the minimal supersymmetric standard model (MSSM), as well as its extension containing an additional chiral singlet superfield, the so-called next-to-minimal or nonminimal supersymmetric standard model (NMSSM). We consider the case of MSSM with both universal as well as nonuniversal gaugino masses at the grand unified scale, and find that only an $\mathcal{E}_6$ grand unified model with unnaturally large representation can give rise to sufficiently light neutralinos which can possibly lead to the invisible decay $h^0 \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0$. Following this, we consider the case of NMSSM in detail, where also we find that it is not possible to have the invisible decay of the lightest Higgs scalar with universal gaugino masses at the grand unified scale. We delineate the regions of the NMSSM parameter space where it is possible to have the lightest Higgs boson to have a mass of about 126 GeV, and then concentrate on the region where this Higgs can decay into light neutralinos, with the soft gaugino masses $M_1$ and $M_2$ as two independent parameters, unconstrained by grand unification. We also consider, simultaneously, the other important invisible Higgs decay channel in the NMSSM, namely the decay into the lightest CP odd scalars, $h^0 \rightarrow a_1 a_1$, which is studied in detail. With the invisible Higgs branching ratio being constrained by the present LHC results, we find that $\mu_{a_1 f} < 170$ GeV and $M_1 < 80$ GeV is disfavored in NMSSM for fixed values of the other input parameters. The dependence of our results on the parameters of NMSSM is discussed in detail.

PACS numbers: 12.60.Jv, 14.80.Da, 14.80.Ly, 14.80.Nb

I. INTRODUCTION

There is now a possible signal for a Higgs boson at a mass of around 126 GeV from the ATLAS [1, 2] and CMS [3, 4] collaborations. Attention is focused on to check whether the decay widths of this particle are in accordance with the predictions of the Standard Model (SM) or its extensions, especially the supersymmetric extensions of the SM. It may, however, turn out that the SM is only a low-energy effective theory and that there are indeed particles of low masses that have evaded detection in the past due to their weak coupling to the SM particles. Candidates include such particles as the lightest neutralino in the minimal supersymmetric (MSSM) extension of the SM, and also the lightest CP-odd neutral Higgs boson of the next-to-minimal or nonminimal supersymmetric standard model (NMSSM). The Higgs sector in MSSM is extended compared to the SM and includes two Higgs doublets $H_1$ and $H_2$ leading to five physical Higgs states, which include two CP even Higgs bosons $h$ and $H$ ($m_h < m_H$), a CP odd Higgs, $A$, and a pair of charged Higgs bosons, $H^\pm$. The recent discovery of the Higgs like particle (with mass $m_h \approx 126$ GeV) at the LHC, requires a significant degree of fine-tuning in the parameters in the context of MSSM. This fine-tuning can be evaded in case of the NMSSM, which is a extension of the MSSM, supplemented by a chiral singlet superfield ($S$). In the NMSSM the role of the $\mu$ parameter of the MSSM is played by $\lambda < S >$, which is generated from a trilinear superpotential coupling $\lambda H_1 H_2 S$, when $S$ obtains a vacuum expectation value $< S >$. This 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 existence of the singlet chiral superfield not only has implications for the Higgs sector, but also for the neutralino sector, where the spectrum has an additional state when compared to the neutralino sector of the MSSM. It has been found that certain regions of the parameter space of MSSM allow a Higgs boson ($h$) with a mass of 126 GeV, albeit with fine tuning, satisfying the LHC results.

Since the identification of the state with mass of 126 GeV at the LHC with the Higgs boson depends on the measurement of its couplings to different particles, it is important to study all its decay channels in the context of the SM and its supersymmetric extensions. In the allowed parameter space there are regions where the Higgs decay to the lightest neutralinos is kinematically allowed. This in turn will lead to invisible decay modes. Detailed studies have been carried out, where by assuming the discovered particle to be the SM Higgs boson, global fits have been performed to place upper bounds on its invisible decay width. The fits are performed for several cases, (a) with the assumption that the invisible Higgs width is the only new physics; (b) the couplings of Higgs to gluons and photons are considered as free parameters, keeping the couplings to fermions and vector bosons to their SM values. We quote here the upper bound on the invisible decay rates of the state discovered at the LHC:
consistent with the current data at 95% confidence level. In Ref. [8], it has been pointed out that these limits can be further improved in the near future with an integrated luminosity \( \mathcal{L} > 300 \text{ fb}^{-1} \) at \( \sqrt{s} = 14 \text{ TeV} \) at the LHC. The discovery potential of the 7 and 8 TeV LHC in probing the invisible decaying Higgs has been studied for different final states, where the invisible Higgs is produced in association with a hard jet (from gluon fusion), 2 jets in the forward direction (from vector boson fusion) or the leptonic decay of \( Z^0 \) (from associated \( Z^0 \) production) [11, 12].

As mentioned above, since the Higgs and neutralino sector of NMSSM is quite different from that of MSSM, conclusions about the invisible Higgs decay in MSSM need to be reconsidered in the context of the NMSSM, particularly in relation to the neutralino sector, as well as the additional possibility of decay into CP odd Higgs bosons. In the light of the discovery of the SM-like Higgs boson at the LHC, considerable work has been done in the context of the Higgs sector of the NMSSM [15, 20]. These studies have scanned various regions of the parameter space, mainly focussing on the regions favored by the results from LHC and the flavour physics. These studies have also considered the case where the lightest Higgs \( h_1 \) has a mass of around 100 GeV, and the second lightest scalar \( h_2 \) is identified with the state of mass around 126 GeV observed at the LHC. This is mainly in light of the fact that with this assumption the LEP bound on the chargino mass has set lower limits on the invisible branching fraction at 95% confidence level. They have considered the associated \( ZH \) production, with \( Z \) decaying leptonically, and have excluded invisible branching fractions greater than 65%.

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Since there is no lower experimental bound on this very light neutralino from collider experiments, bounds on their properties have been obtained from other sources. For instance, in very light neutralinos together with R-parity violation, consistent with all the experiments, have been proposed as an explanation for the KARMEN time anomaly. Supernova 1987A data has been used to set bounds on the mass of a nearly pure bino like light neutralino \((m_{\chi^0} < 200 \text{ MeV})\) in the context of MSSM, while gravitino cosmology with such light neutralinos has been studied in by taking into account astrophysical and cosmological bounds. Moreover a general survey on the bound of the mass of this lightest neutralino in the context of MSSM with R-parity conservation has been discussed in where all the collider data along with the constraints from cosmological observations has been considered. Overall these studies show that a very light neutralino in the context of non universal gaugino masses is not ruled out by current experimental observations.

The plan of the paper is as follows. In Sec. II we consider different patterns of gaugino masses that arise in grand unified theories based on \(SU(5), SO(10)\) and \(E_6\) gauge groups. We study the existence of a massless neutralino in these theories with appropriate boundary conditions as dictated by grand unification. In Sec. III the decay of the lightest Higgs to neutralinos is considered in the MSSM case, with the relevant experimental constraints. The case of the invisible decay of the lightest Higgs boson for the NMSSM is considered in detail in Sec. IV. The parameter space which supports the lightest Higgs(ino) mass parameter, \(m\), is explored. In this Section we also consider the decay of the lightest Higgs boson to the lightest CP odd Higgs. Finally, we summarize our results in Sec. V. In Appendix A, we briefly summarize some of the details regarding non-universal gaugino masses in GUTs.

**II. MINIMAL SUPERSYMMETRIC STANDARD MODEL WITH GUT BOUNDARY CONDITIONS**

We begin our analysis with a brief review of the existence of a massless or a light neutralino in the minimal supersymmetric standard model. We recall that the neutralinos are 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. When the electroweak symmetry is broken, the physical mass eigenstates are obtained from the diagonalization of the neutralino mass matrix \([28, 29]\)

\[
M_{\text{MSSM}} = \begin{pmatrix}
M_1 & 0 & -m_Z \sin \theta_W \cos \beta & -m_Z \sin \theta_W \sin \beta \\
0 & M_2 & m_Z \cos \theta_W \cos \beta & m_Z \cos \theta_W \sin \beta \\
-m_Z \sin \theta_W \cos \beta & m_Z \cos \theta_W \cos \beta & -m_Z \cos \theta_W \sin \beta & -\mu \\
m_Z \sin \theta_W \sin \beta & -m_Z \cos \theta_W \sin \beta & -\mu & 0
\end{pmatrix},
\]

where \(M_1\) and \(M_2\) are the \(U(1)_Y\) and the \(SU(2)_L\) soft supersymmetry breaking gaugino mass parameters, \(\mu\) is the Higgs(ino) mass parameter, \(m_Z\) is the \(Z\) boson mass, \(\theta_W\) 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 \(H_2\). We are interested in having a light neutralino eigenstate of the neutralino mass matrix \((II.1)\). For this purpose we consider the limiting case of the massless neutralino, which, at the tree level, arises when the determinant of the matrix \((II.1)\) is zero. This leads to the condition \([28]\)

\[
\mu \left[ m_Z^2 \sin 2\beta \left( M_1 \cos^2 \theta_W + M_2 \sin^2 \theta_W \right) - M_1 M_2 \right] = 0.
\]

The solution with \(\mu = 0\) is excluded by the lower bounds on the chargino mass from the LEP experiments \([30]\), which impose the constraint

\[
|\mu|, \quad M_2 \geq 100 \text{ GeV}.
\]

The other possible solution to \((II.2)\) can be written as

\[
M_1 = \frac{M_2 m_Z^2 \sin^2 \theta_W \sin 2\beta}{\mu M_2 - m_Z^2 \cos^2 \theta_W \sin 2\beta}.
\]

Therefore, with fixed values of \(\mu, M_2\) and \(\tan \beta\), for a massless neutralino, one must find a value of \(M_1\) consistent with \((II.3)\). The condition \((II.3)\) can be expressed in terms of \(r \equiv M_1/M_2\), so as to check whether a massless neutralino is allowed in the MSSM. In terms of \(r\) the condition \((II.3)\) can be written as

\[
\mu M_2 = \frac{m_Z^2}{r} \sin 2\beta (\sin^2 \theta_W + r \cos^2 \theta_W),
\]

where \(r\) is the ratio of the vacuum expectation values of the neutral components of the two Higgs doublet fields \(H_1\) and \(H_2\).
which must be satisfied, consistent with the experimental constraints (II.3), in order to have a massless neutralino.

It is known that the condition (II.5) is not satisfied in MSSM with universal gaugino masses at the grand unified scale [23]. In next section we briefly recall this and then proceed to study whether this condition can be satisfied in MSSM with nonuniversal boundary conditions on the gaugino mass parameters at the grand unified scale.

A. Gaugino Masses in Grand Unified Theories

In the MSSM, with universal gaugino masses at the grand unified scale, usually referred to as mSUGRA, the soft supersymmetry breaking gaugino mass parameters \( M_1, M_2, \) and \( M_3 \) satisfy the boundary condition

\[
M_1 = M_2 = M_3 = m_{1/2},
\]

at the grand unified scale \( M_G \). Furthermore, the three gauge couplings corresponding to the gauge groups

\( U(1)_Y, SU(2)_L \) and \( SU(3)_C \)

satisfy (\( \alpha_i = g_i^2 / 4\pi, i = 1, 2, 3 \))

\[
\alpha_1 = \alpha_2 = \alpha_3 = \alpha_G,
\]

at the GUT scale \( M_G \). Using the one-loop renormalization group equations [31] for the gaugino masses and the gauge couplings this leads to the ratio

\[
M_1 : M_2 : M_3 \simeq 1 : 2 : 7.1,
\]

for the soft gaugino masses at the electroweak scale \( m_Z \). In the following, for definiteness, we shall consider the value of \( \tan \beta = 10 \). From Eq. (II.8), we see that the value of \( r \) is 0.5. Using this in Eq. (II.5), we conclude that either \( \mu \approx M_2 \approx m_Z \), or \( \mu \gg m_Z \) and \( M_2 \ll m_Z \), or \( \mu \ll m_Z \) and \( M_2 \gg m_Z \). None of these conditions are consistent with the LEP constraint (II.3). Thus, a massless neutralino is excluded in the case of MSSM with universal gaugino masses at the GUT scale.

We recall here that universal soft supersymmetry breaking gaugino masses are not the only possibility in a grand unified theory. In fact, non universal boundary conditions for the soft gaugino masses can naturally arise in a grand unified supersymmetric theory. It is, therefore, important to study whether it is possible to have a light neutralino with nonuniversal boundary conditions at the grand unified scale. To this end we recall the essential features of the boundary conditions on the gaugino masses in a grand unified theory.

B. Nonuniversal Gaugino Masses in Grand Unified Theories

We now consider the neutralino masses and mixing in the minimal supersymmetric standard model with nonuniversal boundary conditions at the GUT scale, which arise in \( SU(5) \), \( SO(10) \) and \( E_6 \) grand unified theories. As discussed in subsection II A, in the simplest supersymmetric model with universal gaugino masses \( M_i (i = 1, 2, 3) \) are taken to be equal at the grand unified scale. However, in supersymmetric theories with an underlying grand unified gauge group, the gaugino masses need not necessarily be equal at the GUT scale.

In Appendix A, we recall the essential features of the embedding of the SM gauge group in different grand unified gauge groups, namely \( SU(5) \), \( SO(10) \) and \( E_6 \), these being the only ones which support the chiral structure of weak interactions as observed in nature [32]. The gaugino mass parameters for the different representations, that arise in the symmetric product of the adjoint representations of the respective gauge groups are shown in the Tables IV, V, VI, VII, VIII, IX, X, XI, XII, XIII of Appendix A. Using the value of the ratio \( r \) at the electroweak scale from the respective Tables, and following the same procedure as in the case of MSSM with universal gaugino masses in the previous subsection, we see from Eq. (II.5) and Tables IV, V, VI, VII that none of the representations of \( SU(5) \) and \( SO(10) \) can have a massless neutralino in the light of experimental constraints (II.3). We also find that in case of \( E_6 \), for all the representations except one, there can be no massless neutralino which satisfies the condition (II.8). Only the higher dimensional 2430 representation of \( E_6 \), as shown in Tables X and XI with the 770 dimensional representation of \( SO(10) \) and a singlet of \( SU(4) \), allows the possibility of a light neutralino consistent with the phenomenological constraint (II.3). We shall not consider this possibility any further in this paper.
III. DECAY OF HIGGS TO NEUTRALINOS IN THE MSSM

In the previous section, we have seen that in MSSM with universal gaugino mass parameters at the GUT scale, with \( r = 0.5 \) at the weak scale, it is not possible obtain a massless neutralino. Since \( r \leq 0.04 \) for a massless neutralino, it is not possible to obtain a massless neutralino in a GUT even with nonuniversal gaugino masses \( M_i \) at the GUT scale. The only possible exception is the higher dimensional representation 2430 of \( E_6 \), with \( r = 0.02 \), and this is not an appealing possibility. Thus, in order to obtain a massless neutralino, we must consider arbitrary gaugino masses in the MSSM. If the neutralino is sufficiently light, then the invisible decay \( h^0 \rightarrow \chi_1^0 \chi_1^0 \) will be kinematically allowed in MSSM.

Recalling that in the MSSM, the decay width of the lightest Higgs boson to a pair of lightest neutralinos can be written as [33]

\[
\Gamma(h^0 \rightarrow \chi_1^0 \chi_1^0) = \frac{G_F m_W^2 m_h}{2\sqrt{2} \pi} (1 - 4m_{\chi_1^0}/m_h^2)^{3/2} [(Z_{12} - \tan \theta_W Z_{11})(Z_{13} \sin \alpha + Z_{14} \cos \alpha)]^2 , \tag{III.1}
\]

where \( Z_{ij} \) are the elements of the matrix \( Z \) which diagonalizes the neutralino mass matrix, and \( \alpha \) is the mixing angle in the \( CP \) even Higgs sector. In the decoupling limit, when the mass \( m_A \) of the pseudoscalar Higgs boson is large compared to the \( Z \) boson mass \( m_Z \), with \( \alpha \rightarrow \beta - \pi/2 \), the decay width (III.1) can be written as [13]

\[
\Gamma(h^0 \rightarrow \chi_1^0 \chi_1^0) = \frac{G_F m_W^2 m_h}{2\sqrt{2} \pi} (1 - 4m_{\chi_1^0}^2/m_h^2)^{3/2} [(Z_{12} - \tan \theta_W Z_{11})(Z_{14} \sin \beta - Z_{13} \cos \beta)]^2 . \tag{III.2}
\]

The invisible decay of the lightest Higgs boson to the lightest neutralinos, if kinematically allowed, is mainly constrained by the \( Z \) invisible decay rate. This invisible decay width has been measured very precisely by the LEP experiments [34] with

\[
\Gamma(Z^0 \rightarrow \chi_1^0 \chi_1^0) < 3 \text{ MeV} . \tag{III.5}
\]

The \( Z \) width to a pair of lightest neutralinos can be written as [35]

\[
\Gamma(Z^0 \rightarrow \chi_1^0 \chi_1^0) = \frac{G_F m_Z^2}{6\sqrt{2} \pi} (Z_{13}^2 - Z_{14}^2) \left( 1 - 4m_{\chi_1^0}^2/m_Z^2 \right)^{3/2} . \tag{III.6}
\]

For our analysis we have used the program CalcHEP [36], with \( \tan \beta = 10 \). The trilinear soft supersymmetry breaking coupling \( A_t \) has been adjusted in order to obtain a lightest Higgs boson of mass \( \approx 126 \) GeV. The gluino mass is taken to be 1400 GeV [37], and the squarks are assumed to have a mass above 1 TeV [38], thereby respecting the current experimental bounds. We have presented our results for a fixed value of \( M_2 \), with the parameters \( \mu \) and \( M_1 \) being varied. Since the results don’t change significantly as a function of \( M_2 \), only a particular value of \( M_2 \) is considered. In Fig. 1 we show the contour plots of the constant lightest neutralino mass in MSSM, and in Fig. 2 the corresponding contours of constant invisible branching ratio of the lightest Higgs boson. In our calculations we have imposed the constraint of the lightest chargino mass bound \( m_{\tilde{\chi}^+} > 94 \) GeV from the LEP experiments as well as the bound from invisible \( Z^0 \) decay width coming from \( Z^0 \) decay into neutralinos. Our results agree with those of Ref. [13]. This sets the stage for our analysis of the invisible decay of the lightest Higgs boson in the NMSSM, which we carry out in the next section.

IV. DECAY OF THE LIGHTEST HIGGS TO NEUTRALINOS AND PSEUDOSCALARS IN THE NMSSM

The NMSSM is characterized by the presence of the gauge singlet superfields \( S \) in addition to the two Higgs doublets \( H_1 \) and \( H_2 \) of the minimal supersymmetric standard model. The Higgs(ino) mass term \( \mu H_1 H_2 \) in
where the superpotential of the MSSM is replaced by the trilinear coupling $\lambda SH_1H_2$ where $\lambda$ is a dimensionless coupling $\lambda [34–45]$. In addition there is also a trilinear self coupling of the singlet, namely $S^3$. The part of the superpotential involving only the Higgs superfields has the form

$$W_{NMSSM} = \lambda SH_1H_2 - \frac{\kappa}{3}S^3. \quad \text{(IV.1)}$$

After the electroweak symmetry breaking, the vacuum expectation value (VEV) of the singlet field, $<S>$ generates an effective $\mu$ parameter, $\mu_{\text{eff}} = \lambda x$, which is naturally of order of the electroweak scale, thus providing a solution to the $\mu$ problem of the MSSM. Thus, compared to the two independent parameters in the Higgs sector of the MSSM at tree level ($\tan \beta, M_A$), the Higgs sector of NMSSM is described by six parameters $\mu_{\text{eff}}, \lambda, \kappa, \tan \beta, A_\lambda$ and $A_\kappa$, where $A_\lambda$ and $A_\kappa$ are the trilinear supersymmetry breaking couplings. Due to the addition of the singlet, the neutralino mass matrix in NMSSM is a 5×5 matrix, which in the bino, wino, Higgsino and singlino basis can be written as $[46–48]$

$$M_{NMSSM} = \begin{pmatrix}
M_1 & 0 & -m_Z \sin \theta_W \cos \beta & m_Z \sin \theta_W \sin \beta & 0 \\
0 & M_2 & m_Z \cos \theta_W \cos \beta & -m_Z \cos \theta_W \sin \beta & 0 \\
-m_Z \sin \theta_W \cos \beta & m_Z \cos \theta_W \cos \beta & 0 & -\mu_{\text{eff}} & -\lambda v_2 \\
m_Z \sin \theta_W \sin \beta & -m_Z \cos \theta_W \sin \beta & -\mu_{\text{eff}} & 0 & -\lambda v_3 \\
0 & 0 & -\lambda v_2 & -\lambda v_3 & 2\kappa x
\end{pmatrix}. \quad \text{(IV.2)}$$

The neutralino sector in this case is described by six parameters, $\mu_{\text{eff}}, M_1, M_2, \tan \beta, \lambda$ and $\kappa$. For a massless neutralino the determinant of the mass matrix $\text{[IV.2]}$ should be zero, which leads to $\text{[22]}$

$$2\kappa x \mu_{\text{eff}} (\Delta_0 \sin 2\beta - \mu_{\text{eff}} M_1 M_2) + \lambda^2 v^2 [\Delta_0 - \mu_{\text{eff}} M_1 M_2 \sin 2\beta] = 0, \quad \text{(IV.3)}$$

where $\Delta_0 = m_Z^2 (M_1 \cos^2 \theta_W + M_2 \sin^2 \theta_W)$. Eq. $\text{[IV.3]}$ in turn leads to the following condition

$$\kappa = \frac{\lambda}{2} \left( \frac{\lambda v}{\mu_{\text{eff}}} \right)^2 \frac{\Delta_0 - \mu_{\text{eff}} M_1 M_2 \sin 2\beta}{\Delta_0 \sin 2\beta}. \quad \text{(IV.4)}$$

for a massless neutralino in the NMSSM. The composition of the lightest neutralino $\chi_1^0$ in terms of the gauginos, Higgsinos and the singlino is in turn given by

$$\chi_1^0 = Z_{1i} \tilde{B} + Z_{12} \tilde{W}^3 + Z_{13} \tilde{H}_1^0 + Z_{14} \tilde{H}_2^0 + Z_{15} S, \quad \text{(IV.5)}$$

where

$$Z_{1i}' = \begin{pmatrix}
\frac{\lambda v M_Z \cos 2\beta \sin \theta_W M_2}{\Delta_1} & \frac{\lambda v M_Z \cos 2\beta \cos \theta_W M_1}{\Delta_1} \\
\frac{v (\sin \beta \Delta_0 - \mu_{\text{eff}} M_1 M_2 \cos \beta)}{x \Delta_1} & \frac{v (\cos \beta \Delta_0 - \mu_{\text{eff}} M_1 M_2 \sin \beta)}{x \Delta_1}
\end{pmatrix}. \quad \text{(IV.6)}$$
and $\Delta_t = \mu_{eff} M_1 M_2 - \Delta_0 \sin 2\beta$. Here $Z'$ is the matrix which diagonalizes the $5 \times 5$ neutralino mass matrix of the NMSSM. As in the case of MSSM, we have assumed CP conservation in the neutralino sector in our analysis.

We have performed our analysis for the NMSSM with the set of relevant parameters varied in the following ranges:

1. $4 \leq \tan \beta \leq 11$, 100 GeV $\leq \mu_{eff} \leq 200$ GeV,
2. $0.55 \leq \lambda \leq 0.7$, $0.33 \leq \kappa \leq 0.8$,
3. $\pm 10$ GeV $\leq A_\lambda \leq 10$ GeV, 500 GeV $\leq A_\kappa \leq 1000$ GeV.

This range is considered, because we are mainly interested in the region where the lightest CP even Higgs $(h_1)$ of the NMSSM will lead to a SM like Higgs in the mass range 124 GeV $\leq m_{h_1} \leq 127$ GeV. We have restricted ourselves to small values of $\tan \beta$, since it is difficult to get a SM like lightest Higgs in the mass window of 124 - 127 GeV with large values of $\tan \beta$. The range for $\lambda$ and $\kappa$ are chosen by imposing the theoretical constraint that there are no charge and color breaking global minima of the scalar potential and that a Landau pole does not develop below the GUT scale. We are interested mainly in relatively large values of $\lambda$, so as to increase the tree level mass of the CP-even Higgs boson, leading naturally to a SM like Higgs bosons. This in turn implies a large doublet singlet mixing in the Higgs sector. The lightest Higgs boson with mass $\approx 126$ GeV can also be achieved in NMSSM, as in MSSM through loop level corrections coming from stop, with large values of $A_\kappa$. In this case $\lambda$ can be small ($\lambda \approx 0.1$), typically preferred for negative values of $A_\kappa$. Here we have considered the former case, where the Higgs mass is obtained naturally at tree level. Since we are mainly interested in large $\lambda$, the other NMSSM parameters are considered accordingly so as to satisfy the constraints from precision electroweak measurements, see Ref. [49]. In addition we have also taken into account the latest experimental constraints from the LHC on the gluino and other sparticle masses. The gluino mass is chosen above 1400 GeV, and the squark masses are set to 1 TeV or more, as in the MSSM analysis. Additional constraints from $B$ physics and the anomalous magnetic moment of muon are taken into account using CalcHEP, which has inbuilt NMSSMTools package [50, 51]. In Table I we summarize the values of the various input parameters used for our analysis. Considering the relation between $m_{h_1}$, $m_{\lambda, \kappa}$ respectively. The gaugino plus Higgsino, and the singlino components are respectively given by $Z_{1/2}' + Z_{1/2}'$, $Z_{1/3}' + Z_{1/4}'$, and $Z_{1/5}'$. The decay width of $h_1$ to the lightest neutralino in NMSSM can be written as [52, 53]:

$$\Gamma(h_1 \rightarrow \chi^0_1 \chi^0_1) = \frac{m_{h_1}}{16 \pi} (1 - 4 m_{\chi^0_1}^2 / m_{h_1}^2)^{1/2} \Omega_{\chi^0_1}^2$$  \hspace{1cm} (IV.7)
where we see that there is a significant singlino component in the lightest neutralino. For lower values of the contours of constant singlino component, in the case with universal gaugino masses at the GUT scale, available, since in practice either sign solutions for the singlino matrix element are found. We show in Fig. 3, the constraint on the gluino mass, the gaugino and Higgsino components decrease, with the neutralino being

\[ Q'_{111} = \left[ \frac{g}{\sqrt{2} v} Z'_{12} \left( U_{11}^s \cos \beta + U_{12}^s \sin \beta \right) Z'_{13} + (U_{11}^s \sin \beta - U_{12}^s \cos \beta) Z'_{14} \right. \]
\[ \left. + \sqrt{2} \lambda Z'_{15} \left( U_{11}^s \cos \beta + U_{12}^s \sin \beta \right) Z'_{14} - (U_{11}^s \sin \beta - U_{12}^s \cos \beta) Z'_{13} \right] \]
\[ - 2 \sqrt{2} \kappa Z'_{13} |Z'_{15}|^2 \]  
(IV.8)

where \( U^s \) is the matrix that diagonalizes the \( 3 \times 3 \) scalar Higgs mass matrix of the NMSSM. It is clear from Eq. (IV.8), that as the singlino contribution appears with a negative sign in the decay width, the invisible decay width of \( h_1 \) would decrease, as the singlino composition increases. Nevertheless no simple explanation is available, since in practice either sign solutions for the singlino matrix element are found. We show in Fig. 3 the contours of constant singlino component, in the case with universal gaugino masses at the GUT scale, where we see that there is a significant singlino component in the lightest neutralino. For lower values of \( M_1 \), the lightest neutralino has a dominant gaugino component. Since in this case \( M_1 \) is around 180 GeV, due to the constraint on the gluino mass, the gaugino and Higgsino components decrease, with the neutralino being dominantly a singlino.

**TABLE II:** The mass of the lightest CP even Higgs \( h_1 \), lightest neutralino \( \tilde{\chi}^0_1 \) and the lightest CP odd pseudoscalar Higgs \( a_1 \), in the NMSSM with universal gaugino masses at the GUT scale, for the parameter space considered in Table [I] and with \( M_1 = 197 \) GeV, \( M_2 = 395 \) GeV.

| \( \lambda \) | \( m_{h_1} \) | \( m_{\tilde{\chi}^0_1} \) | \( m_{a_1} \) | \( m_{h_1} \) | \( m_{\tilde{\chi}^0_1} \) | \( m_{a_1} \) | \( m_{h_1} \) | \( m_{\tilde{\chi}^0_1} \) | \( m_{a_1} \) | \( m_{h_1} \) | \( m_{\tilde{\chi}^0_1} \) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.55 | 113 | 73.7 | 46.1 | 122 | 82.9 | 51.4 | 125 | 88.7 | 55.7 | 125.6 | 92.5 | 59.2 |
| 0.58 | 108.3 | 69.5 | 50 | 120 | 79.1 | 55.9 | 124 | 85.5 | 60.9 | 125 | 89.8 | 65 |
| 0.61 | 102.6 | 65.4 | 53.5 | 117.9 | 75.4 | 60 | 123 | 82.2 | 62.5 | 124.9 | 69.5 | 70.1 |
| 0.64 | 96.4 | 61.4 | 56.7 | 114.9 | 71.6 | 63.8 | 121.7 | 78.8 | 69.7 | 124.3 | 83.9 | 74.8 |
| 0.67 | 89.8 | 57.5 | 59.7 | 111.1 | 67.8 | 67.2 | 119.9 | 75.3 | 73.5 | 123.4 | 80.9 | 79.1 |
| 0.7 | 82.7 | 53.9 | 62.4 | 106.5 | 64.1 | 70.3 | 117.7 | 71.9 | 77.1 | 122 | 77.7 | 82.9 |

**TABLE III:** The relic density of the lightest neutralino, for different values of \( M_1 \), for the parameter space considered in Table [II] and with \( M_2 = 200 \) GeV.

| \( \lambda \) | \( m_{h_1} \) | \( m_{\tilde{\chi}^0_1} \) | \( m_{a_1} \) | \( m_{h_1} \) | \( m_{\tilde{\chi}^0_1} \) | \( m_{a_1} \) | \( m_{h_1} \) | \( m_{\tilde{\chi}^0_1} \) | \( m_{a_1} \) | \( m_{h_1} \) | \( m_{\tilde{\chi}^0_1} \) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.55 | 4.67 | 0.33 | 0.02 | 3.08 | 0.21 | 0.04 | 2.43 | 0.13 | 0.03 | 2.1 | 0.10 | 0.01 |
| 0.58 | 6.33 | 0.14 | 0.34 | 3.77 | 0.16 | 0.04 | 2.83 | 0.13 | 0.05 | 2.36 | 0.09 | 0.05 |
| 0.61 | 9.13 | 0.10 | 0.13 | 4.80 | 0.13 | 0.02 | 3.37 | 0.09 | 0.05 | 3.17 | 0.10 | 0.05 |
| 0.64 | 14.3 | 0.05 | 0.11 | 6.40 | 0.02 | 0.02 | 4.15 | 0.03 | 0.02 | 3.17 | 0.07 | 0.05 |
| 0.67 | 25.8 | 0.44 | 0.05 | 9.01 | 0.42 | 0.08 | 5.29 | 0.40 | 0.03 | 3.83 | 0.33 | 0.04 |
| 0.7 | 68.3 | 0.68 | 0.08 | 13.65 | 0.79 | 0.02 | 70.57 | 0.73 | 0.06 | 4.76 | 0.51 | 0.01 |

Here it is important to consider the possibility that our parameter choice could lead to over closure of the
We use MicroOmegas\cite{54,55} implemented in NMSSMTools to compute the dark matter relic density of the lightest neutralino, $\tilde{\chi}_0^0$. We show in Table III the corresponding relic density for different values of $M_1$, in the $\kappa - \lambda$ parameter space. The measurements from WMAP has constrained the relic density of dark matter\cite{56}, i.e. $(0.0925 < \Omega h^2 < 0.1287)$. It can be seen from the Table, that the relic density constrains most of the $(\lambda - \kappa)$ parameter space, depending on the value of $M_1$. When the lightest neutralino is mostly a bino, due to a small value of $M_1$, the relic density is sufficiently large at smaller values of $\kappa$ and larger values of $\lambda$. This has to do with the dependence of neutralino mass on $\lambda$ and $\kappa$, which will be discussed later. The relic density mostly constrains smaller values of $M_1 < 50$ GeV, and as will be seen later this region is disfavored by the Higgs invisible branching ratio. Thus we see that our choice does not come in conflict with the cosmological relic density constraint.

FIG. 3: Contours of constant singlino composition $|Z'_{13}|^2$ in the $\kappa - \lambda$ plane for NMSSM, with universal gaugino masses at the GUT scale with fixed values of $M_1 = 197$ GeV, $M_2 = 395$ GeV, and the other input parameters as given in Table I.

FIG. 4: Dependence of $m_{h_1}$ [green-solid], $m_{a_1}$ [blue-dashed] and $m_{\tilde{\chi}_0^0}$ [brown-dot-dashed] on $\mu_{\text{eff}}$, for $M_1 = 120$ GeV, $M_2 = 200$ GeV, $\lambda = 0.55$ and $\kappa = 0.33$ with the other input parameters fixed to the values given in Table I (colours in on-line version).

FIG. 5: Dependence of $m_{h_1}$ [green-solid], $m_{a_1}$ [blue-dashed] and $m_{\tilde{\chi}_0^0}$ [brown-dot-dashed] on $\tan \beta$ for $M_1 = 120$ GeV, $M_2 = 200$ GeV, $\lambda = 0.55$ and $\kappa = 0.33$ with the other input parameters fixed to the values given in Table I (colours in on-line version).

With the universal gaugino masses at the GUT scale, the Higgs invisible decay to the lightest neutralinos is kinematically not allowed in the NMSSM. We, therefore, use $M_1$ and $M_2$ as two independent parameters. Before proceeding further we would like to comment on the dependence of our results on the various input parameters considered in our analysis. For this we consider the dependence of the mass of the lightest CP even Higgs $h_1$, the lightest pseudoscalar Higgs $a_1$ and the lightest neutralino $\tilde{\chi}_0^0$ on different NMSSM parameters, $\mu_{\text{eff}}$, $\lambda$, $\kappa$, $\tan \beta$, $A_\lambda$ and $A_\kappa$. We consider the mass of the lightest pseudoscalar Higgs because for certain regions of the parameter space it is rather light, in fact $a_1$ can be lighter than $h_1$. This could lead to additional decay channels for the lightest CP even Higgs, mainly the channel $h_1 \to a_1 a_1$, and $h_1 \to a_1 Z^0$. In the observed universe.
mass window of the Higgs, the decay to $b\bar{b}$ is dominant, but with the additional decay channel $h_1 \to a_1 a_1$ and $a_1 \to b\bar{b}, \tau^+\tau^-, \mu^+\mu^-, \tilde{\chi}_1^0\tilde{\chi}_1^0$, depending on the mass of the lightest pseudoscalar, the branching fraction $h_1 \to b\bar{b}$ can be significantly reduced. It may be emphasized that the LHC sensitivity in case of Higgs decay to light pseudoscalars depend on the decay mode of the pseudoscalars. For the parameter space considered in our analyses, $a_1$ mainly decays to $b\bar{b}$. At the LHC, this channel will be dominated by a large QCD background. The $b\bar{b}$ channel in the Higgs decay has been searched for at the LHC, and indicates weak SM Higgs signal of around 1–2 $\sigma$. This particular decay channel of $h_1$ decaying to pseudoscalar $a_1$ pairs has also been discussed in [57–62].

![Graph](image)

**FIG. 6:** Dependence of $m_{h_1}$ [green-solid], $m_{a_1}$ [blue-dashed] and $m_{\tilde{\chi}_1^0}$ [brown-dot-dashed] on $\lambda$ for $M_1 = 120$ GeV, $M_2 = 200$ GeV and $\kappa = 0.33$ with the other input parameters fixed to the values given in Table I (colours in on-line version).

FIG. 7: Dependence of $m_{h_1}$ [green-solid], $m_{a_1}$ [blue-dashed] and $m_{\tilde{\chi}_1^0}$ [brown-dot-dashed] on $\kappa$ for $M_1 = 120$ GeV, $M_2 = 200$ GeV and $\lambda = 0.55$ with the other input parameters fixed to the values given in Table I (colours in on-line version).

Most of the studies in the context of the lightest pseudoscalar have been carried out in the light of the LEP constraints on the Higgs mass, $m_h > 114$ GeV, along with the LEP excess for a lighter Higgs around 100 GeV, through $Z^0h$ production, where $h$ decays primarily to $b\bar{b}$ quarks. It has been concluded that if in the NMSSM, the Higgs boson decays mainly into $a_1$ pairs, and with $m_{a_1} < 2m_h$, then the LEP constraints can be evaded. It will be possible to have a lighter Higgs of mass less than 105 GeV, satisfying all precision electroweak results. This is often referred to as the “ideal” Higgs Boson scenario. The BABAR [63] and BELLE [64] experiments have placed limits on $m_{a_1}$, using the data collected at the $\Upsilon$ resonances but it is based on the “ideal” Higgs Boson scenario.

In Figs. 4–6, 7, 8, and 9 we show the dependence of the mass of $h_1$, $a_1$, $\tilde{\chi}_1^0$ on various parameters of NMSSM. While displaying the dependence on a particular parameter, the other parameters are kept fixed at their values in Table I with $\lambda$ and $\kappa$ fixed to the lowest acceptable values of 0.55 and 0.33, respectively. We have fixed the value of the soft gaugino mass parameter $M_2 = 200$ GeV, with $M_1 = 120$ GeV. Since the mass $m_{h_1}$, of CP even, and the mass $m_{a_1}$ of the pseudoscalar Higgs are independent of the soft gaugino mass parameters, the dependence of their mass on various input parameters is independent of the universal gaugino masses at the GUT scale. The mass of the lightest neutralino being sensitive to gaugino masses can be scaled up and down, with its mass as low as 1 GeV for $M_1 = 5$ GeV. It is seen from Figs. 4 and 5 that $m_{a_1}$ and $m_{\tilde{\chi}_1^0}$ are sensitive to both $\mu_{\text{eff}}$ and $\tan \beta$, with $m_{a_1}$ being comparatively more sensitive. Both these masses decrease with $\mu_{\text{eff}}$. In case of NMSSM for large $\lambda$, where $\lambda \approx 0.5$ to 0.7, small values of $\tan \beta$ are preferred in order to obtain $m_{h_1}$ in the desired mass window of 123–127 GeV. The mass of the lightest neutralino increases, as expected, with increasing $\mu_{\text{eff}}$, and is almost independent of $\tan \beta$. Similarly, we can draw conclusions from Figs. 4–6, 7, 8, and 9 regarding the dependence of the mass of the lightest scalar Higgs, lightest pseudoscalar Higgs and the lightest neutralino on different parameters of the NMSSM.

Before discussing the branching ratios of the lightest Higgs scalar to neutralinos and the lightest pseudoscalars, with $M_1$ and $M_2$ treated as independent parameters, in the following we summarize the dependence of our results on the various parameters of NMSSM:

- Dependence on $M_1$, $M_2$: If the value of $M_1$ is lowered below 30 GeV, the neutralino becomes sufficiently light, with $h_1 \to \tilde{\chi}_1^0\tilde{\chi}_1^0$ dominating over the decay $h_1 \to a_1a_1$ for the entire parameter space considered.
Here. If we decrease the value of $M_2$, the chargino mass bound from the LEP results in larger values of $\mu_{\text{eff}}$ being disfavored.

- **Dependence on $\mu_{\text{eff}}$:** Increasing the value of the $\mu_{\text{eff}}$, in the considered range, $m_{a_1}$ reduces whereas $m_{\tilde{\chi}^0_1}$ increases. Therefore the invisible branching ratio for $h_1 \to \tilde{\chi}^0_1 \tilde{\chi}^0_1$ decreases, while the branching ratio of $h_1 \to a_1 a_1$ increases.

- **Dependence on $\tan \beta$:** In this case $h_1 \to \tilde{\chi}^0_1 \tilde{\chi}^0_1$ decreases due to the increase of the branching ratio to lightest pseudoscalars, as the value of $m_{a_1}$ decreases and $m_{\tilde{\chi}^0_1}$ remains constant.

- **Dependence on $\lambda, \kappa$:** Increasing the value of $\lambda$ increases the value of $m_{a_1}$ and decreases $m_{\tilde{\chi}^0_1}$. Since $\lambda$ also substantially affects the mass of $m_{h_1}$, other parameters need to be changed accordingly, so as to obtain the lightest CP even Higgs $h_1$ in the required mass range. The dependence of $h_1 \to \tilde{\chi}^0_1 \tilde{\chi}^0_1$ on $\lambda$ and $\kappa$ will be discussed in what follows.

- **Dependence on $A_\lambda, A_\kappa$:** The pseudoscalar and the neutralino mass is almost insensitive to $A_\lambda$. We have therefore performed our analyses for a fixed value of $A_\lambda$ so as to have $h_1$ in the required mass range. The pseudoscalar mass is sensitive to $A_\kappa$, therefore the decay $h_1 \to a_1 a_1$ can be dominant for small $|A_\kappa|$.

We now consider the case when the soft gaugino masses are treated as independent parameters. In Fig. 10 we show contours of constant neutralino mass in the $\mu_{\text{eff}} - M_1$ plane. We have taken into account the LEP
constraint on the chargino mass \((m_{\tilde{\chi}_1^+} \geq 105 \text{ GeV})\) as well as the invisible \(Z^0\) decay width \(\Gamma_{\text{inv}}\). For the parameter space considered here, the \(Z^0\) invisible decay width is less than 3 MeV. It can be seen from Fig. 10 that most of the parameter region with low \(M_1\) allows a low mass neutralino, making the Higgs invisible decay kinematically possible. The values in this Fig. are obtained with \(\lambda = 0.55\) and \(\kappa = 0.6\), with other parameter values as given in Table I with \(M_2 = 200 \text{ GeV}\). The dependence of the constant contours on other parameters can be inferred from Figs. 5, 7, 8 and 10.

Before considering the invisible decay width, we show the contours of constant singlino composition in the non GUT scenario, with \(M_1\) and \(M_2\) treated as independent parameters. In Figs. 11 and 12 we show the constant singlino composition contours for two different values of \(M_1 = 5 \text{ GeV}\) and 120 GeV, respectively, with a fixed value of \(M_2 = 200 \text{ GeV}\). The behavior of the constant contours can be understood from the fact that for low \(M_1\), the neutralino is dominantly a gaugino type, with small singlino composition. Therefore, as discussed earlier, due to the small singlino composition, the invisible decay width of \(h_1\) will be large compared to the GUT case. This can be seen in Fig. 13 where we show the invisible branching ratio of the Higgs decay to the lightest neutralinos satisfies the experimental constraints for the entire \(\mu_{\text{eff}} - M_1\) plane. We have fixed \(M_2 = 200 \text{ GeV}\), \(\lambda = 0.55\), \(\kappa = 0.6\), with other input parameters as given in Table I. The LEP constraint on the chargino mass excludes the parameter region below \(\mu_{\text{eff}} = 120 \text{ GeV}\), for \(M_2 = 200 \text{ GeV}\) and is shown by the blue-dot-dashed line. This limit on \(\mu_{\text{eff}}\) will decrease, with the increase in the value of \(M_2\). The invisible decay width of the \(Z^0\) to the lightest neutralinos satisfies the experimental constraints for the entire \(\mu_{\text{eff}} - M_1\) plane considered here. We see that in the allowed parameter space, the invisible branching ratio can be as large as 70%. The shape of the contours can be understood from Fig. 13 where we see that \(m_{a_1}\) decreases and \(m_{\tilde{\chi}_1^0}\) increases, with increasing \(\mu_{\text{eff}}\), leading to \(h_1 \rightarrow a_1 a_1\) at high \(\mu_{\text{eff}}\). At low \(\mu_{\text{eff}}\) and \(M_1\), \(\tilde{\chi}_1^0\) is sufficiently light, therefore the decay \(h_1 \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0\) is kinematically possible. This explains the kinks in the contours. The second lightest neutralino \(\tilde{\chi}_2^0\) is mostly a higgsino, at low \(\mu_{\text{eff}}\) and \(M_1\). The bino component increases, with the increase in value of \(M_1\), for a fixed \(\mu_{\text{eff}}\). The dominant branching ratio is seen for values of \(M_1\) in the range of 40 - 70 GeV, where \(m_{\tilde{\chi}_2^0}\) in turn varies from 30 - 60 GeV. In the region excluded by the chargino mass bound, it is seen that the branching ratio of Higgs to neutralinos can reach around 90% for \(M_1 > 70 \text{ GeV}\) and low \(\mu_{\text{eff}}\). This is mainly because in this parameter region both \(m_{\tilde{\chi}_2^0} < (m_{h_1} - m_{\tilde{\chi}_1^0})\) and \(m_{a_1} < m_{h_1}/2\). Thus, if the bound on invisible branching ratio is considered to be less than 30%, most of the region with \(\mu_{\text{eff}} < 170 \text{ GeV}\) and \(M_1 < 80 \text{ GeV}\) is disfavored by the invisible Higgs decay.

In order to fully understand the dependence of the invisible branching ratio on other input parameters of the NMSSM, in Fig. 14 we show its behavior in the \(\mu_{\text{eff}} - \tan \beta\) plane for \(M_2 = 200 \text{ GeV}, M_1 = 60 \text{ GeV}, \lambda = 0.55\) and \(\kappa = 0.6\). The other input parameters are fixed at values as in Table I. We have shown the result for \(M_1 = 60 \text{ GeV}\), as we see from Fig. 13 the dominant branching ratio is seen for values of \(M_1\) in the region of 40 - 70 GeV. The area between the green-dotted lines in Fig. 14 shows the parameter region which allows \(h_1\) to be in the allowed mass range 123 - 127 GeV. The blue-dot-dashed line represents the chargino mass bound from the LEP. We see that in the constrained space, the invisible branching ratio can be as high as 90%. At small values of \(\tan \beta(< 10)\), when the value of \(\mu_{\text{eff}}\) is increased, the invisible branching ratio decreases as \(m_{\tilde{\chi}_2^0}\) increases. The invisible branching ratio is small for \(\tan \beta > 10\) and low \(\mu_{\text{eff}}\), due to the opening of the decay channel \(h_1 \rightarrow a_1 a_1\), as \(m_{a_1}\) decreases with \(\tan \beta\). This can be seen from Fig. 4. Therefore, considering the
bound on $h \rightarrow \tilde{\chi}^0_1 \tilde{\chi}^0_1$ to be less than 30%, $\mu_{\text{eff}} < 180$ GeV and $\tan \beta > 10$ is disfavored. When $M_1$ is less than 40 GeV, the channel $h \rightarrow \tilde{\chi}^0_1 \tilde{\chi}^0_2$ is kinematically accessible for low values of $\mu_{\text{eff}}$. The invisible branching ratio in this case being small, a large parameter region in the $LHC$ experiments.

The sensitivity of our results on the parameters $\lambda$ and $\kappa$ can be understood from the behavior of the invisible branching ratio in the $\kappa - \lambda$ plane. This behavior depends on the composition of the lightest neutralino and can be easily understood from Figs. 6, 7. Since $m_{\tilde{\chi}_1}$ is sensitive to the gaugino mass parameter $M_1$, we discuss the behavior for different values of $M_1$. At low values of $M_1 < 30$ GeV, as discussed earlier, the channel $h \rightarrow \tilde{\chi}^0_1 \tilde{\chi}^0_2$ becomes kinematically accessible. Therefore the Higgs invisible branching ratio is less than 30% for most of the $\kappa - \lambda$ parameter space. With $40 < M_1 < 70$ GeV, as can be seen from Fig. 13, the branching ratio of $h \rightarrow \tilde{\chi}^0_1 \tilde{\chi}^0_1$ is the largest. As $m_{\tilde{\chi}_1}$ decreases with $\lambda$, Fig. 6 the neutralino becomes light ($m_{\tilde{\chi}_1} < m_{h_1}/2$), and the mass of the lightest pseudoscalar Higgs increases ($m_{a_1} > m_{h_1}/2$), with $\lambda > 0.6$, even in case of large $M_1$. Therefore the dominant decay mode is $h \rightarrow \tilde{\chi}^0_1 \tilde{\chi}^0_1$, with the branching ratio greater the 90% for $\lambda > 0.6$. This result is practically independent of $\kappa$ as can be seen from Fig. 7 where $m_{\tilde{\chi}_2}, m_{a_1}$ is seen not to depend on $\kappa$. Again for large $M_1$ and $\lambda < 0.6$, with $m_{a_1} < m_{\tilde{\chi}_2}$, the branching ratio of $h \rightarrow \tilde{\chi}^0_2 \tilde{\chi}^0_2$ is smaller.

The invisible decay width mainly depends on the neutralino composition. The neutralino should have a small singlino component and a dominant bino component, i.e. $M_1$ should be small, in order to have a large invisible decay width. The decay width is also sensitive to the mass of the pseudoscalar Higgs $a_1$ and next to the lightest neutralino $\tilde{\chi}^0_1$. The dependence of the width on the other input parameters $\tan \beta, \kappa$ and $\lambda$ is sensitive to the gaugino mass parameter $M_1$ and behaves differently for smaller and larger values of $M_1$. This is mainly because $m_{\tilde{\chi}_2}$ is also sensitive to $M_1$, leading to the opening of new decay channels.

**V. SUMMARY AND CONCLUSIONS**

We now summarize the results obtained in this work. We have considered the possibility of the invisible decays of the lightest CP even Higgs boson in MSSM and in NMSSM. In the MSSM, we have considered both the universal as well as nonuniversal gaugino masses at the GUT scale. In both cases we have seen that it is not possible to have a light neutralino, so that the decay of the lightest Higgs boson to lightest neutralinos does not take place. Our results show that in virtually all realistic scenarios, the non-universality is not sufficient to generate sufficiently light neutralinos. We have parametrized such non-universality in terms of a parameter $r$ which we have studied in detail. The details of such non-universality are briefly summarized in the Appendix A.

We have then analyzed the possibility of having a light neutralino in the NMSSM extension of MSSM. We note that in the NMSSM, both the Higgs as well as the neutralino sectors are significantly richer, which provides us with greater possibilities. We have considered the neutralino sector of NMSSM, and in particular the phenomenon of the mixing of the singlino, and concluded that even in this case massless neutralinos cannot
be realized with universal boundary conditions on the gaugino masses at the GUT scale, since the lightest Higgs is too heavy in conflict with the LHC result. Furthermore, with universal boundary conditions the lightest Higgs $m_{h_1} \approx 126$ GeV would not decay to the lightest neutralinos. A related consideration is the “ideal” Higgs scenario motivated by LEP constraints, where the next to lightest CP even Higgs $h_2$ can decay to lightest neutralinos. Departing from the assumption of universal gaugino masses, we have investigated the invisible branching ratio of the Higgs, as a function of the various parameters of NMSSM. We have concentrated on the case with the lightest scalar as the SM Higgs boson $h_1$, and have considered the dependence on parameters which are relevant to the Higgs and neutralino sector.

As is well known, the Higgs sector of the NMSSM itself is richer than the corresponding one in the MSSM. Thus, there is the intriguing possibility that the Higgs can decay into a pair of CP odd lightest Higgs particles $a_1$. It is seen that for higher values of $\tan \beta$, the invisible branching ratio decreases, with the largest contribution coming from the Higgs decaying to two light pseudoscalar Higgs bosons. The present Higgs decay uncertainties can constrain NMSSM but these constraints are strongly correlated with the composition of the lightest neutralino. The invisible branching ratio is found to be relatively independent of $\lambda$ and $\kappa$, for $40 \text{ GeV} < M_1 < 60 \text{ GeV}$. In the NMSSM, the constraints on the Higgs mass results in small values of $\tan \beta$ being favored for large $\lambda$. We have discussed the dependence of our results on the parameters which enter the neutralino and the Higgs sectors of the NMSSM. From the dependence of the invisible branching ratio in the $\mu_{eff} - M_1$ plane, with other parameters fixed, we have shown that most of the parameter space is constrained by considering invisible branching ratio $< 30\%$. The dependence of this result on the other input parameters has also been discussed. For large values of $\tan \beta$, the invisible branching ratio decreases as $a_1$ becomes lighter with $h_1 \rightarrow a_1 a_2$ kinematically possible. Therefore at large $\tan \beta$, $M_1 < 40 \text{ GeV}$ is favored in the $\mu_{eff} - M_1$ plane, for all values of $\mu_{eff}$. The allowed parameter region with $M_1 > 80 \text{ GeV}$ remains unchanged. The sensitivity of the results on the input parameters $\lambda$, $\kappa$ has also been discussed in detail. We have shown that for $M_1 < 70 \text{ GeV}$, the results do not change significantly as a function of of $\lambda$ and $\kappa$. But with large $M_1$ and $\lambda > 0.6$, the neutralinos becomes very light. In that case the $\mu_{eff} - M_1$ parameter space is more tightly constrained. Further data from LHC may be able to shed light on the question of the invisible decays of the lightest Higgs boson.

VI. ACKNOWLEDGEMENTS

PNP would like to thank the Centre for High Energy Physics, Indian Institute of Science, Bangalore for hospitality while this work was initiated, as well as the Inter-University Centre for Astronomy and Astrophysics, Pune, for hospitality where part of this work was done. The work of PNP is supported by the J. C. Bose National Fellowship of the Department of Science and Technology, India, and by the Council of Scientific and Industrial Research, India.

Appendix A: Nonuniversal gaugino masses in GUTS

In this Appendix we briefly discuss non-universal gaugino masses as they arise in grand unified models [67]. In grand unified supersymmetric models, non-universal gaugino masses are generated by a non-singlet chiral superfield $\Phi^0$ that appears linearly in the gauge kinetic function $f(\Phi)$, which is an analytic function of the chiral superfields $\Phi$ in the theory [68]. The gaugino masses are generated from the coupling of the field strength superfield $W^a$ with $f(\Phi)$, when the auxiliary part $F_\Phi$ of a chiral superfield $\Phi$ in $f(\Phi)$ gets a VEV. The Lagrangian for the coupling of gauge kinetic function to the gauge field strength can be written as

$$\mathcal{L}_{g.k.} = \int d^2 \theta f_{ab}(\Phi)W^a W^b + h.c.,$$

(A.1)

where $a$ and $b$ refer to gauge group indices, and repeated indices are summed over. The gauge kinetic function $f_{ab}(\Phi)$ is given by

$$f_{ab}(\Phi) = f_0(\Phi^*) \delta_{ab} + \sum_n f_n(\Phi^*) \frac{\Phi^n}{M_P} + \cdots.$$  

(A.2)

Here $\Phi^*$ and the $\Phi^n$ are the singlet and the non-singlet chiral superfields, respectively. Furthermore, $f_0(\Phi^*)$ and $f_n(\Phi^*)$ are functions of gauge singlet superfields $\Phi^*$, and $M_P$ denotes some large scale. When $F_\Phi$ gets a VEV $\langle F_\Phi \rangle$, the interaction (A.1) generates gaugino masses:

$$\mathcal{L}_{g.k.} \supset \frac{\langle F_\Phi \rangle_{ab}}{M_P} \lambda^a \lambda^b + h.c.,$$

(A.3)
where $\lambda^{a,b}$ are gaugino fields. Here, we denote by $\lambda^1$, $\lambda^2$ and $\lambda^3$ as the $U(1)$, $SU(2)$ and $SU(3)$ gaugino fields, respectively. Since the gauginos belong to the adjoint representation of the gauge group, $\Phi$ and $F_\Phi$ can belong to any of the representations appearing in the symmetric product of the two adjoint representations of unified gauge group.

In the case where the SM gauge group is embedded within the grand unified gauge group $SU(5)$. For the symmetric product of the two adjoint $(24$ dimensional) representations of $SU(5)$, we have

$$(24 \otimes 24)_{\text{Symm}} = 1 \oplus 24 \oplus 75 \oplus 200.$$  \hfill (A.4)

In Table IV we show the ratios of gaugino masses which result when $F_\Phi$ belongs to different representations of $SU(5)$ in the decomposition (A.4).

Next we consider the embedding of the SM gauge group in a $SO(10)$ grand unified theory. The adjoint representation of $SO(10)$ being $(45)$, $\Phi$ and $F_\Phi$ can belong to the symmetric product of two adjoint $(45)$ dimensional representations

$$(45 \times 45)_{\text{Symm}} = 1 \oplus 54 \oplus 210 \oplus 770.$$  \hfill (A.5)

In Table V we have shown the gaugino mass parameters for the different representations that arise in the symmetric product (A.5) for the $SO(10)$ group. We note from Table V that the ratios of gaugino masses for the different representations of $SO(10)$ in the symmetric product (A.5) with the unflipped embedding $SU(5) \subset SO(10)$ are identical to the corresponding gaugino mass ratios in Table IV for the embedding of SM in $SU(5)$. In case of the flipped embedding $SU(5)' \times U(1) \subset SO(10)$, as seen from Table VI the gaugino mass ratios for the $210$ and $770$ dimensional representations of the grand unified gauge groups is different from the corresponding ratios for $SU(5)$. The ratio $r$, used for our analyses in Section II B is obtained in this case from the Tables V, VI, VII respectively.

Finally we consider the grand unified group $E_6$, which has $78$ as the adjoint representation. The possible $E_6$ symmetric irreducible representations are

$$(78 \times 78)_{\text{Symm}} = 1 \oplus 650 \oplus 2430.$$  \hfill (A.6)

The corresponding quantities of interest for this case are tabulated in Tables VIII, IX, XI, XII and XIII.
TABLE V: Ratios of the gaugino masses at the GUT scale in the normalization $M_1(GUT) = 1$, and at the electroweak scale in the normalization $M_1(EW) = 1$ for $F$-terms in representations of $SU(5) \subset SO(10)$ with the normal (nonflipped) embedding. These results have been obtained at the 1-loop level.

| $SO(10)$ | $SU(5)$ | $M_{1}^{\tilde{g}}$ | $M_{2}^{\tilde{g}}$ | $M_{3}^{\tilde{g}}$ | $M_{1}^{\tilde{w}}$ | $M_{2}^{\tilde{w}}$ | $M_{3}^{\tilde{w}}$ |
|----------|----------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 1        | 1        | 1               | 1               | 1               | 2               | 7.1             |
| 54       | 24       | 1               | 3               | -2              | 1               | 6               | -14.3           |
| 210      | 1        | 1               | 1               | 1               | 2               | 7.1             |
| 75       | 1        | $-\frac{7}{6}$ | $-\frac{1}{6}$ | 1               | -1.18           | -1.41           |
| 24       | 1        | 1               | 3               | -2              | 1               | 6               | -14.3           |
| 75       | 1        | $-\frac{3}{5}$ | $-\frac{1}{5}$ | 1               | -1.18           | -1.14           |
| 200      | 1        | 1               | $\frac{1}{2}$  | 1               | 0.4             | 0.71            |

TABLE VI: Ratios of the gaugino masses at the GUT scale in the normalization $M_1(GUT) = 1$, and at the electroweak scale in the normalization $M_1(EW) = 1$ at the 1-loop level for flipped $SU(5)' \times U(1) \subset SO(10)$.

| $SO(10)$ | $SU(5)' \times U(1)$ | $f_{\text{flipped}}$ | $M_{1}^{\tilde{g}}$ | $M_{2}^{\tilde{g}}$ | $M_{3}^{\tilde{g}}$ | $M_{1}^{\tilde{w}}$ | $M_{2}^{\tilde{w}}$ | $M_{3}^{\tilde{w}}$ |
|----------|-----------------------|----------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 1        | (1.0)                 | 1                    | 1               | 1               | 2               | 7.1             |
| 54       | (24.0)                | 1                    | 3               | -2              | 1               | 6               | -14.3           |
| 210      | (1.0)                 | 1                    | $\frac{1}{6}$  | $\frac{5}{6}$  | 1               | -0.52           | -1.85           |
| 75       | (24.0)                | 1                    | $\frac{1}{6}$  | $\frac{5}{6}$  | 1               | -4.2            | 10              |
| 770      | (1.0)                 | 1                    | -15             | -5              | 1               | -28             | -33.33          |
| 24       | (75.0)                | 1                    | $\frac{1}{6}$  | $\frac{5}{6}$  | 1               | 0.13            | 0.46            |
| 770      | (24.0)                | 1                    | $\frac{1}{6}$  | $\frac{5}{6}$  | 1               | 0.3             | -0.70           |
| 200      | (75.0)                | 1                    | -15             | -5              | 1               | -28             | -33.33          |
| 1        | (200.0)               | 1                    | 5               | $\frac{1}{2}$  | 1               | 9.33            | 16.67           |

TABLE VII: Ratios of the gaugino masses at the GUT scale in the normalization $M_1(GUT) = 1$, and at the electroweak scale in the normalization $M_1(EW) = 1$ at the 1-loop level for $F$-terms in representations of $SU(4) \times SU(2)_L \times SU(2)_R \subset SO(10)$.

| $SO(10)$ | $SU(4) \times SU(2)_R$ | $M_{1}^{\tilde{g}}$ | $M_{2}^{\tilde{g}}$ | $M_{3}^{\tilde{g}}$ | $M_{1}^{\tilde{w}}$ | $M_{2}^{\tilde{w}}$ | $M_{3}^{\tilde{w}}$ |
|----------|-------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 1        | (1.1)                   | 1               | 1               | 1               | 2               | 7.1             |
| 54       | (1.1)                   | 1               | 3               | 2               | 1               | 6               | -14.3           |
| 210      | (1.1)                   | 1               | $\frac{5}{6}$  | 0               | 1               | -3.35           | 0               |
| 770      | (1.1)                   | 1               | 25              | $\frac{10}{11}$| 1               | 2.6             | 3.7             |
| 24       | (15.1)                  | 1               | 0               | $\frac{5}{6}$  | 1               | 0               | -9.09           |
| 770      | (15.3)                  | 1               | 0               | 0               | 1               | 0               | 0               |
| 200      | (84.1)                  | 1               | 0               | $\frac{5}{6}$  | 1               | 0               | 1.11            |

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TABLE VIII: Ratios of the gaugino masses at the GUT scale in the normalization $M_1(GUT) = 1$, and at the electroweak scale in the normalization $M_1(EW) = 1$ at the 1-loop level for $F$-terms in representations of $SU(5)^c \times U(1)^f \times U(1) \subset [SO(10)^f \times U(1)]_{\text{flipped}} \subset E_6$.

**TABLE IX:** Ratios of the gaugino masses at the GUT scale in the normalization $M_1(GUT) = 1$, and at the electroweak scale in the normalization $M_1(EW) = 1$ at the 1-loop level for $F$-terms in representations of $SU(4)^f \times SU(2)_L \times SU(2)_X \times U(1) \subset [SO(10)^f \times U(1)]_{\text{flipped}} \subset E_6$.

[References and data for Tables VIII and IX are not provided in the text. Additional details would be necessary to fully understand the context and implications of these tables.]
| $E_6$ | $SU(3)_L \times SU(3)_R$ | $M_1^U$ | $M_2^U$ | $M_3^U$ | $M_1^E$ | $M_2^E$ | $M_3^E$ |
|-------|-----------------|--------|--------|--------|--------|--------|--------|
| 1     | (1, 1)          | 1      | 1      | 1      | 1      | 1      | 2      |
| 650   | (1, 1), (1, 8)  | 1      | $\frac{-7}{3}$ | 0      | 1      | $-3.35$ | 0      |
|       | (8, 1)          | 1      | 0      | $\frac{-7}{3}$ | 1      | 0      | $-8.86$ |
| 2430  | (1, 1)          | 1      | 1      | 1      | 2      | 7.1    |        |
|       | (1, 8)          | 1      | 0      | 0      | 1      | 0      | 0      |
|       | (8, 8)          | 1      | 0      | 0      | 1      | 0      | 0      |
|       | (1, 1)          | 1      | 1      | 1      | 1      | 2      | 7.1    |
|       | (8, 1)          | 1      | 0      | 0      | 1      | 0      | 0      |
|       | (8, 8)          | 1      | 0      | 0      | 1      | 0      | 0      |
|       | (1, 27)         | 1      | 0      | 0      | 1      | 0      | 0      |
|       | (27, 1)         | 1      | $\frac{7}{3}$ | 0      | 1      | 1.12   | 0      |

TABLE X: Ratios of the gaugino masses at the GUT scale in the normalization $M_1(GUT) = 1$, and at the electroweak scale in the normalization $M_1(EW) = 1$ at the 1-loop level for $F$-terms in representations of the trinification subgroup $SU(3)_C \times SU(3)_L \times SU(3)_R \subset E_6$.

| $E_6$ | $SU(6) \times SU(2)_X$ | $SU(3)_L$ | $M_1^U$ | $M_2^U$ | $M_3^U$ | $M_1^E$ | $M_2^E$ | $M_3^E$ |
|-------|-----------------|--------|--------|--------|--------|--------|--------|--------|
| 1     | (1, 1)          | 1      | 1      | 1      | 1      | 1      | 2      | 7.1    |
| 650   | (1, 1), (35, 1) | 1      | 1      | 5      | -5     | 1      | 10.0   | -35.5  |
|       | (189, 1)        | 1      | $\frac{-7}{3}$ | 0      | 1      | 3.35   | 0      |
| 2430  | (1, 1)          | 1      | 1      | 1      | 1      | 2      | 7.1    |        |
|       | (189, 1)        | 1      | $\frac{-7}{3}$ | $-\frac{7}{3}$ | 1      | -0.67  | -2.36  |
|       | (405, 1)        | 1      | $\frac{1}{3}$ | $-\frac{1}{3}$ | 1      | -0.67  | -2.36  |
|       | (405, 1)        | 1      | $\frac{1}{3}$ | $-\frac{1}{3}$ | 1      | -0.67  | -2.36  |
|       | (27, 1)         | 1      | $\frac{7}{3}$ | 0      | 1      | 1.12   | 0      |

TABLE XI: Ratios of the gaugino masses at the GUT scale in the normalization $M_1(GUT) = 1$, and at the electroweak scale in the normalization $M_1(EW) = 1$ at the 1-loop level for $F$-terms in representations of $SU(3)_C \times SU(3)_L \times U(1) \times SU(2)_X \subset SU(6) \times SU(2)_X \subset E_6$.

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### TABLE XII: Ratios of the gaugino masses at the GUT scale in the normalization $M_1(GUT) = 1$, and at the electroweak scale in the normalization $M_1(EW) = 1$ at the 1-loop level for $F$-terms in representations of $SU(3)_C \times SU(3)_L \times U(1) \times SU(2)_R \subset SU(6)' \times SU(2)_R \subset E_6$.

| $E_6$ | $SU(6)' \times SU(2)_R$ | $SU(3)_L$ | $M_1^{\tilde{e}}$ | $M_2^{\tilde{e}}$ | $M_3^{\tilde{e}}$ | $M_1^{\tilde{\tau}}$ | $M_2^{\tilde{\tau}}$ | $M_3^{\tilde{\tau}}$ |
|-------|------------------------|-----------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 1     | (1, 1)                 | 1         | 1               | 1               | 1               | 1               | 2               | 7.1             |
| 650   | (1, 1)                 | 1         | 1               | $\frac{5}{7}$   | $\frac{5}{7}$   | 1               | -0.77           | 2.73            |
|       | (35, 1)                | 1         | 1               | 5               | -5              | 1               | 10.0            | -35.5           |
|       | (35, 3)                | 1         | 1               | 0               | 0               | 1               | 0               | 0               |
|       | (189, 1)               | 1         | 1               | $\frac{5}{7}$   | $\frac{5}{7}$   | 1               | -3.35           | -11.8           |
|       | (405, 1)               | 1         | 1               | 5               | 0               | 1               | 10.0            | 0               |
| 2430  | (1, 1)                 | 1         | 1               | $\frac{15}{11}$ | $\frac{15}{11}$ | 1               | 0.73            | 2.59            |
|       | (1, 5)                 | 1         | 0               | 0               | 0               | 1               | 0               | 0               |
|       | (35, 3)                | 1         | 0               | 0               | 0               | 1               | 0               | 0               |
|       | (189, 1)               | 1         | 1               | $\frac{5}{7}$   | $\frac{5}{7}$   | 1               | -3.35           | -11.8           |
|       | (405, 1)               | 1         | 5               | 0               | 0               | 1               | 0.73            | 0               |

### TABLE XIII: Ratios of the gaugino masses at the GUT scale in the normalization $M_1(GUT) = 1$, and at the electroweak scale in the normalization $M_1(EW) = 1$ at the 1-loop level for $F$-terms in representations of $SU(3)_C \times SU(3)_R \times U(1) \times SU(2)_L \subset SU(6)' \times SU(2)_L \subset E_6$.

| $E_6$ | $SU(6)' \times SU(2)_L$ | $SU(3)_R$ | $M_1^{\tilde{e}}$ | $M_2^{\tilde{e}}$ | $M_3^{\tilde{e}}$ | $M_1^{\tilde{\tau}}$ | $M_2^{\tilde{\tau}}$ | $M_3^{\tilde{\tau}}$ |
|-------|------------------------|-----------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 1     | (1, 1)                 | 1         | 1               | 1               | 1               | 1               | 2               | 7.1             |
| 650   | (1, 1)                 | 1         | 1               | -5              | 1               | 1               | 10.0            | 7.1             |
|       | (35, 1)                | 1         | 1               | 0               | $\frac{5}{7}$   | 1               | 0               | -8.86           |
|       | (189, 1)               | 1         | 0               | 0               | 1               | 0               | 0               | 1               |
|       | (405, 1)               | 1         | 1               | $\frac{15}{11}$ | 1               | 7.81            | 7.1             |
| 2430  | (1, 1)                 | 1         | 1               | $\frac{15}{11}$ | 1               | 7.81            | 7.1             |
|       | (189, 1)               | 1         | 0               | 0               | 1               | 0               | 0               | 1               |
|       | (405, 1)               | 1         | 1               | $\frac{5}{7}$   | 1               | 0               | 2.95            |

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