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Research Article

LHC Signals of the Next-to-Lightest Scalar Higgs State of the NMSSM in the 4τ Decay Channel

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We study the a_1a_1 and Za_1 decay channels of the next-to-lightest CP-even Higgs boson h_2 of the NMSSM at the LHC, where the h_2 is produced in gluon fusion. It is found that while the h_2 discovery is impossible through the latter channel, the former one in the 4τ final state is a promising channel to discover the h_2 with masses up to around 250 GeV at the LHC. Such a discovery of the h_2 is mostly accompanied with a light a_1, which is a clear evidence for distinguishing the NMSSM from the MSSM since such a light a_1 is impossible in the MSSM.

1. Introduction

The discovery of the standard model- (SM-) like Higgs boson with a mass around 125 GeV at the LHC [1–4] can be accommodated in the framework of the next-to-minimal supersymmetric standard model (NMSSM) [5–16] without much fine tuning and as a consequence, it has acquired increasing attention. In this model, one Higgs singlet field is added to the two MSSM-type Higgs doublets in order to give a natural explanation of the μ-problem of the MSSM [17]. So, the Higgs sector of the NMSSM is phenomenologically richer than that of the MSSM due to the existence of this extra Higgs singlet.

The Higgs spectrum of the NMSSM after electroweak symmetry breaking contains seven Higgs mass states, assuming CP conservation: two pseudoscalar Higgses $a_{1,2}(m_{a_1} < m_{a_2})$, three scalar Higgses $h_{1,2,3}(m_{h_1} < m_{h_2} < m_{h_3})$, and a pair of charged Higgses $h^{\pm}$. Following the discovery of the SM-like Higgs boson in 2012, the observation of additional Higgs bosons, if they exist, would point to the existence of supersymmetric extensions of the SM. In the NMSSM framework, the search for light Higgs bosons has been done by many authors, aiming to establish the so-called "no-lose theorem" of the NMSSM stating that one or more of the Higgs bosons of the NMSSM should be discovered at the LHC throughout the entire NMSSM parameter space [18–27]. All these studies were performed before the discovery of the Higgs boson at the LHC in 2012. Many studies have also been done on the discovery potential of other Higgs bosons of the NMSSM following the 2012 discovery [28–51].

One of the interesting features of the NMSSM is that Higgs-to-Higgs decays are dominant over large regions of parameter space if they are kinematically allowed. The importance of such decays in the framework of the NMSSM has long been emphasized in the literature (see, e.g., Ref. [52]). It was found that Vector Boson Fusion (VBF) could be a suitable production channel to detect $h_{1,2} \longrightarrow a_1a_1$ at the LHC, in which the Higgs pair decays into $jj\tau^+\tau^-$ [19]. Both the Vector Boson Fusion and Higgs-Strahlung production mechanisms could also be useful to discover such Higgses in the 4τ final states [53]. Furthermore, some scope could be afforded by 4μ and $2\tau 2\mu$ signatures in the gluon-fusion production channel [22, 54]. Higgs production in association with a $b\bar{b}$ pair could also be a good means to search for the $h_{1,2} \longrightarrow Za_1$ at the LHC [55]. All these studies were performed prior to the Higgs discovery in 2012.

In this paper, we study the LHC discovery potential for the next-to-lightest CP-even Higgs boson h_2, which is not a SM-like Higgs, decaying either into two light CP-odd Higgs bosons $a_1 a_1$ or into a light a_1 and a gauge boson $a_1 Z$ through the gluon fusion $gg \longrightarrow h_2$ in the 4τ final state in the NMSSM framework. We calculate the signal rates of the two processes $gg \longrightarrow h_2 \longrightarrow a_1 a_1 \longrightarrow 4\tau$ and $gg \longrightarrow h_2 \longrightarrow Z a_1 \longrightarrow 4\tau$ to examine whether or not there are some regions of NMSSM parameter space where the h_2 and a_1 states can simultaneously be observed at the LHC (we do not consider the case of both $b\bar{b}b\bar{b}$ and $b\bar{b}\tau^+\tau^-$ final states because these channels are burdened by large SM backgrounds). We perform a partonic signal-to-background analysis of the h_2 production. It is found that there are parameter regions of the NMSSM where the h_2 and a_1 signals may be found at the LHC through the process $gg \longrightarrow h_2 \longrightarrow a_1 a_1 \longrightarrow 4\tau$.

The paper is planned as follows. In the next section, we briefly discuss the Higgs sector of the NMSSM, describing the NMSSM parameter space scans performed under current constraints. In Section 3, we present the inclusive production rates of the h_2 at the LHC in the 4τ final states as well as signal-to-background analysis for some benchmark points. Finally, conclusions are given in Section 4.

2. The Higgs Sector of the NMSSM

The scale invariant superpotential of the NMSSM in terms of the usual two MSSM-type Higgs doublet superfields $\widehat{H}_u$ and $\widehat{H}_d$ as well as the singlet one $\widehat{S}$ is given by [8, 9].

$$W_{\text{NMSSM}} = \text{MSSM Yukawa terms} + \lambda \widehat{S} \widehat{H}_u \widehat{H}_d + \frac{1}{3} \kappa S \wedge^3, \quad (1)$$

where both λ and κ are dimensionless couplings. The term $\lambda \widehat{S} \widehat{H}_u \widehat{H}_d$ is introduced to solve the μ-problem of the MSSM superpotential. When the singlet superfield develops a vacuum expectation value (VEV) $\langle S \rangle = (1/\sqrt{2}) v_s$ upon spontaneous symmetry breaking, an "effective" μ-parameter given by $\mu_{\text{eff}} = \lambda \langle S \rangle$ of the order of the electroweak scale will be automatically generated. The last term of the above equation is introduced to avoid the Peccei-Quinn symmetry [56, 57]. The soft breaking terms for both the doublet and singlet fields read

$$\begin{aligned} V_{\text{NMSSM}} = {} & m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 + m_S^2 |S|^2 \\ & + \left(\lambda A_\lambda S H_u H_d + \frac{1}{3} \kappa A_\kappa S^3 + \text{h.c.} \right), \end{aligned} \quad (2)$$

where A_λ and A_κ are the trilinear coupling parameters of the order of SUSY mass scale m_{SUSY}.

The physical Higgs bosons arise after the Higgs fields acquire vacuum expectation values (VEVs), $\langle H_u \rangle = (1/\sqrt{2}) v_u$, $\langle H_d \rangle = (1/\sqrt{2}) v_d$, and $\langle S \rangle = (1/\sqrt{2}) v_s$, and eliminating the Goldstone boson states. As a result, the potential has terms for the nonzero mass modes for the scalar fields $S_i (i = 1, 2, 3)$, pseudoscalar fields $P_i (i = 1, 2)$, and charged fields $h^\pm$ given by

$$V_{\text{mass}} = \frac{1}{2} (S_1 S_2 S_3) \mathcal{M}_S \begin{pmatrix} S_1 \\ S_2 \\ S_3 \end{pmatrix} + \frac{1}{2} (P_1 \quad P_2) \mathcal{M}_P \begin{pmatrix} P_1 \\ P_2 \end{pmatrix} + m_{h^\pm}^2 h^+ h^-. \quad (3)$$

One can obtain physical mass eigenstates with tree-level masses as follows. First, the elements of the mass matrix for the CP-even Higgs states at tree-level are given by [58]

$$\begin{aligned} \mathcal{M}_{S11} &= m_A^2 + \left(m_Z^2 - \frac{1}{2} (\lambda v)^2 \right) \sin^2 2\beta, \\ \mathcal{M}_{S12} &= -\frac{1}{2} \left(m_Z^2 - \frac{1}{2} (\lambda v)^2 \right) \sin 4\beta, \\ \mathcal{M}_{S13} &= -\frac{1}{2} \left(m_A^2 \sin 2\beta + 2 \frac{\kappa \mu_{\text{eff}}^2}{\lambda} \right) \left(\frac{\lambda v}{\sqrt{2} \mu_{\text{eff}}} \right) \cos 2\beta, \\ \mathcal{M}_{S22} &= m_Z^2 \cos^2 2\beta + \frac{1}{2} (\lambda v)^2 \sin^2 2\beta, \\ \mathcal{M}_{S23} &= \frac{1}{2} \left(4\mu_{\text{eff}}^2 - m_A^2 \sin^2 2\beta - \frac{2\kappa \mu_{\text{eff}}^2 \sin 2\beta}{\lambda} \right) \frac{\lambda v}{\sqrt{2} \mu_{\text{eff}}}, \\ \mathcal{M}_{S33} &= \frac{1}{8} m_A^2 \sin^2 2\beta \frac{\lambda^2 v^2}{\mu_{\text{eff}}^2} + 4 \frac{\kappa^2 \mu_{\text{eff}}^2}{\lambda^2} + \frac{\kappa A_\kappa \mu_{\text{eff}}}{\lambda} - \frac{1}{4} \lambda \kappa v^2 \sin 2\beta, \end{aligned} \quad (4)$$

where $m_A^2 = \sqrt{2} (\mu_{\text{eff}} / \sin 2\beta)(A_\lambda + (\kappa \mu_{\text{eff}} / \lambda))$, $\tan \beta = v_u / v_d$, and $v^2 = v_u^2 + v_d^2$.

Second, the elements of the mass matrix for the CP-odd Higgs states at tree-level are [58]

$$\begin{aligned} \mathcal{M}_{P11} &= m_A^2, \\ \mathcal{M}_{P12} &= \frac{1}{2} \left(m_A^2 \sin 2\beta - 6 \frac{\kappa \mu_{\text{eff}}^2}{\lambda} \right) \frac{\lambda v}{\sqrt{2} \mu_{\text{eff}}}, \\ \mathcal{M}_{P22} &= \frac{1}{8} \left(m_A^2 \sin 2\beta + 6 \frac{\kappa \mu_{\text{eff}}^2}{\lambda} \right) \frac{\lambda^2 v^2}{\mu_{\text{eff}}^2} \sin 2\beta - 3 \frac{\kappa \mu_{\text{eff}} A_\kappa}{\lambda}. \end{aligned} \quad (5)$$

Third, the mass of charged Higgs fields at tree level is given by [58]

$$m_{h^\pm}^2 = m_A^2 + m_W^2 - \frac{1}{2} (\lambda v)^2. \quad (6)$$

It is clear from the above equations that the Higgs sector of the NMSSM at the tree level is described by the six parameters: λ, κ, $\tan \beta$, μ_{eff}, A_λ, and A_κ. Assuming CP conservation, the upper mass bound for the lightest CP-even Higgs boson of the NMSSM, if it is the SM-like Higgs, at the tree level is given by [8, 9]

$$m_{h_1}^2 < m_Z^2 \cos^2(2\beta) + \frac{\lambda^2 v^2}{2} \sin^2(2\beta). \quad (7)$$

The last term in this expression can lift m_{h_1} with up to 10-

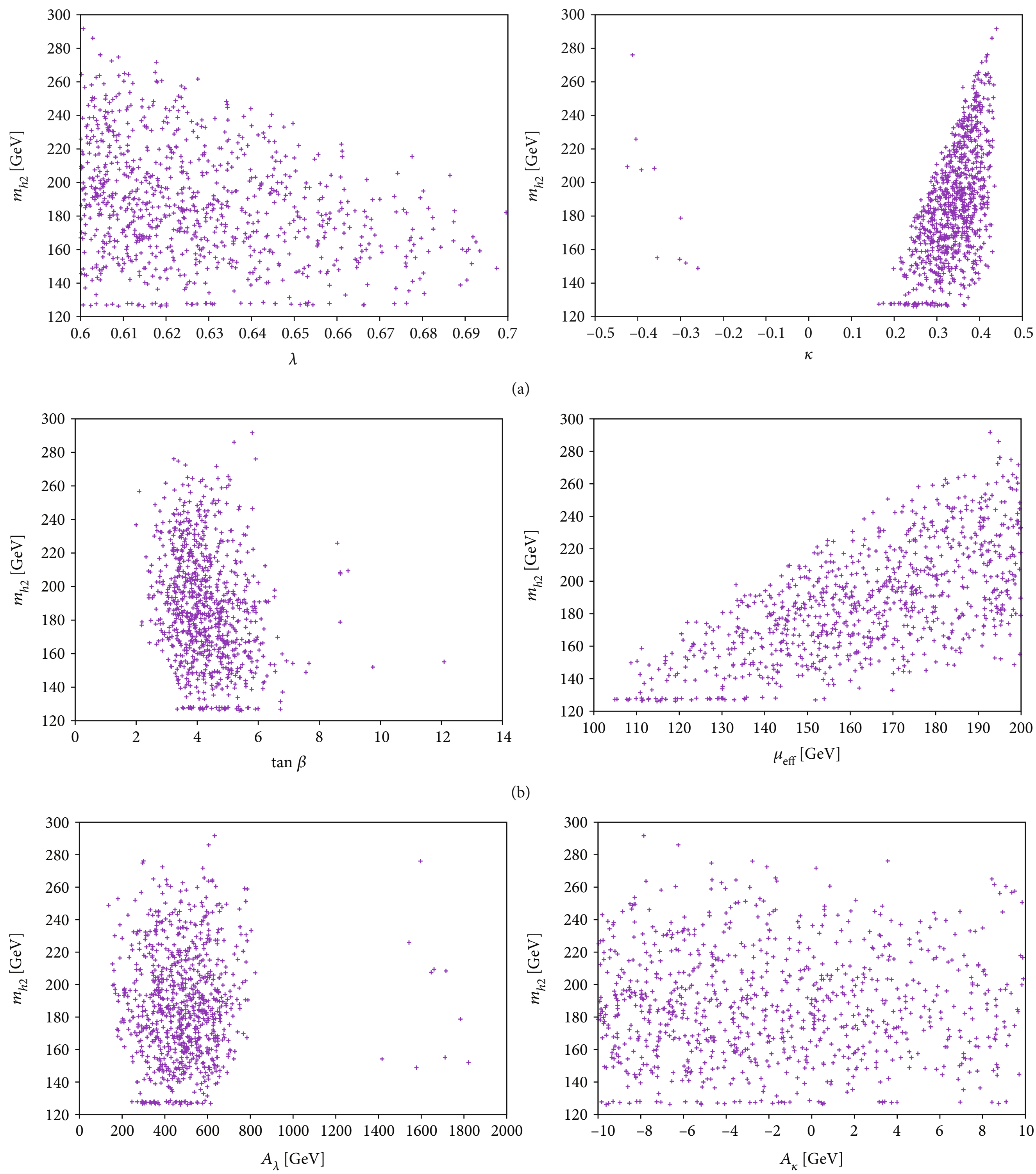


Figure 1: The next-to-lightest CP-even Higgs mass m_{h_2} as a function of λ and κ (a), tan β and μ_{eff} (b), and A_λ and A_κ (c).

15 GeV higher than the corresponding one of the MSSM. So, less loop corrections are required to get the lightest Higgs, h_1, to be SM-like with a mass around 125 GeV. Clearly, large values of λ and low values of tanβ are preferred to obtain a large value of the h_1 at the tree level. The scenarios with $m_{h_1} < 125$ GeV mean that the h_1 is highly singlet-like so it

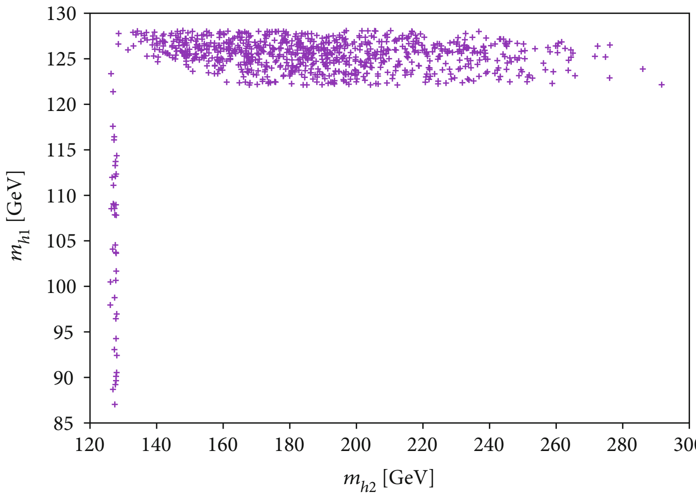


Figure 2: The mass distribution for the next-to-lightest CP-even Higgs, m_{h_2}, versus the lightest CP-even Higgs mass, m_{h_1}.

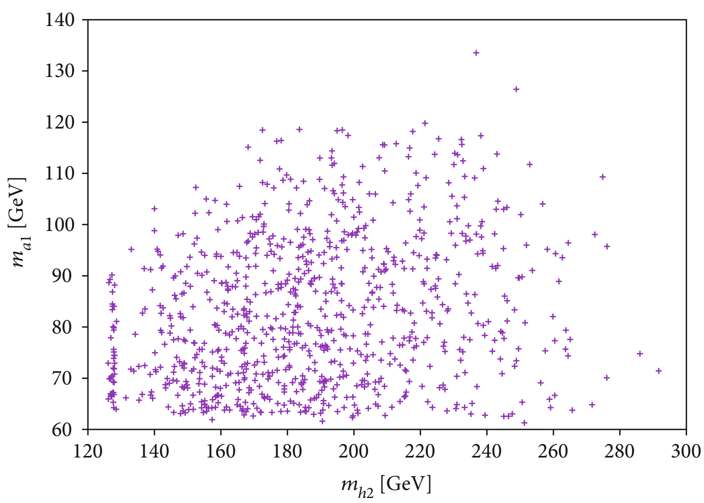


Figure 3: The mass distribution for the next-to-lightest CP-even Higgs, m_{h_2}, versus the lightest CP-odd Higgs mass, m_{a_1}.

can escape the constraints coming from LEP, the Tevatron, and the LHC. In this case, the next-to-lightest CP-even Higgs boson h_2 is the SM-like Higgs of a mass around 125 GeV.

In this paper, we are interested in the production of the next-to-lightest scalar Higgs boson h_2, which is not the SM-like Higgs, and its decays into either two light CP-odd Higgs bosons, $a_1 a_1$, or a light CP-odd Higgs and a gauge boson, $a_1 Z$, in the mass region $m_{h_2} \lesssim 300$ GeV. We use the package NMSSMTools5.1.2 [59–61] which computes the masses, couplings, and decay widths of all the Higgs bosons in addition to the spectrum of supersymmetric particles. This package takes into account various theoretical and experimental constraints such as constraints from negative Higgs searches at LEP, the Tevatron, and the LHC, as well as SUSY mass limits as implemented in the package. Moreover, it takes into account constraints of upsilon, B, and K decays and also the bounds on the mass of the SM-like Higgs and its signal rates. More details about the constraints can be found on the website of the package. We have ignored the constraints on the dark matter because its nature is still unknown. We also do not take into account the constraints on the muon anomalous magnetic moment because such constraints have large theoretical uncertainties.

In our parameter space, we scan by varying the tree level parameters of the NMSSM within the following ranges:

$$\begin{gathered} 0.6 \le \lambda \le 0.7, \\ -0.65 \le \kappa \le 0.65, \\ 1.6 \le \tan\beta \le 60, \\ 100 \le \mu_{\text{eff}} \le 200\,\text{GeV}, \\ -2000 \le A_\lambda \le 2000\,\text{GeV}, \\ -10 \le A_\kappa \le 10\,\text{GeV}. \end{gathered} \tag{8}$$

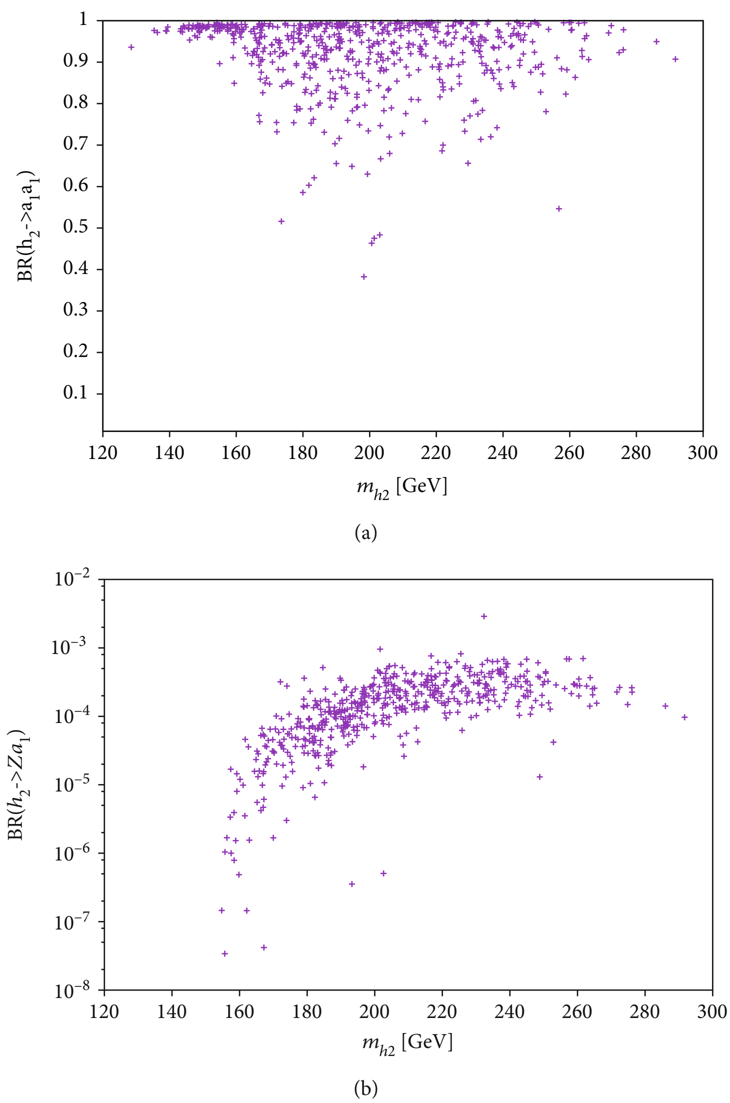


FIGURE 4: The next-to-lightest CP-even Higgs mass m_{h_2} plotted against both BR($h_2 \longrightarrow a_1 a_1$) (a) and BR($h_2 \longrightarrow Z a_1$) (b).

Notice that we focus here on scenarios with large values of λ and small values of both μ_{eff} and A_κ to simultaneously obtain the h_2 with $m_{h_2} \lesssim 300$ GeV and a light a_1. Remaining soft mass parameters for the scalars and gauginos in addition to the trilinear soft SUSY coupling parameters, contributing at higher order level, are set to

(i) $m_Q = m_U = m_D = m_L = m_E = m_{Q_3} = m_{U_3} = m_{D_3} = m_{L_3} = m_{E_3} = 3000$ GeV

(ii) $M_1 = 500$ GeV, $M_2 = 1000$ GeV, $M_3 = 3000$ GeV

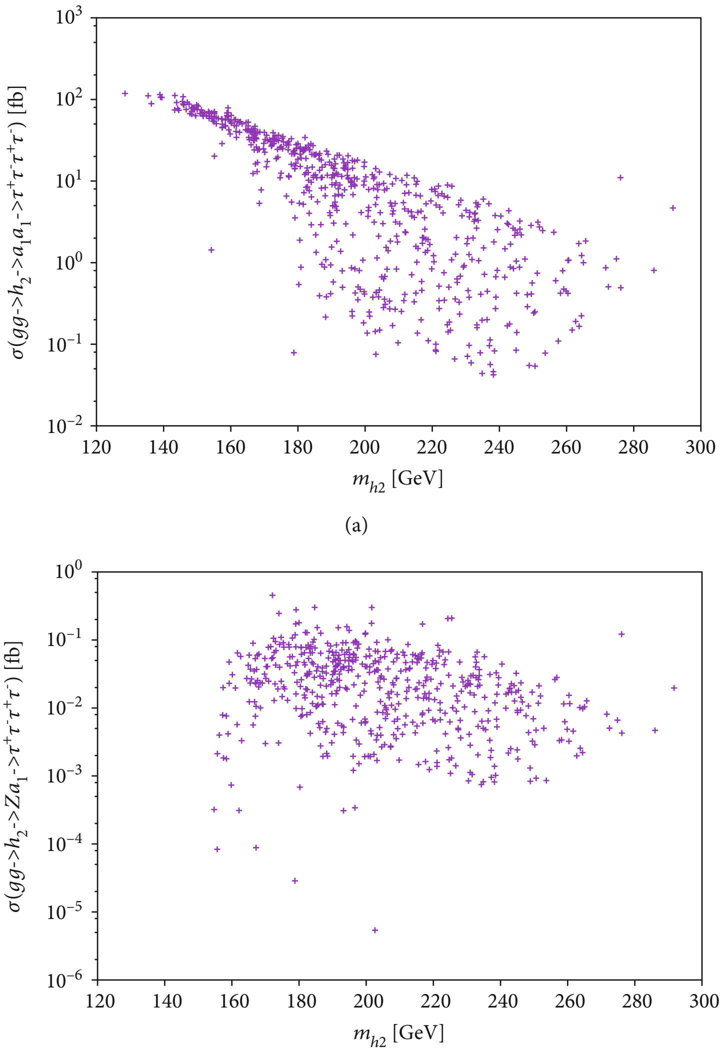
(iii) $A_{U_3} = A_{D_3} = A_{E_3} = 3000$ GeV

We randomly perform a scan over the above mentioned parameters and identify the parameter space of the NMSSM that passed all theoretical and experimental constraints. The outcome of our scan contains masses and branching ratios of the NMSSM Higgs bosons for all the surviving data points which have passed the constraints. As mentioned above, we have ignored the constraints on dark matter relic density. To know the effects of these constraints on the NMSSM parameter space, see, for example, Ref. [62] and references therein.

3. Higgs Boson Signal Rates

In this section, we discuss the discovery potential of the h_2 produced in the gluon fusion $gg \longrightarrow h_2$ at the LHC in the mass region $m_{h_2} \lesssim 300$ GeV. The region with $m_{h_2} \gtrsim 300$ GeV is less promising since the cross sections for the h_2 production fall quickly with increasing h_2 masses. For the surviving data points obtained from the random scan, we calculate the inclusive cross sections for the h_2 production by using CalcHEP [63] for the following processes:

$$gg \longrightarrow h_2 \longrightarrow a_1 a_1 \longrightarrow \tau^+\tau^-\tau^+\tau^- \text{ and } gg \longrightarrow h_2 \longrightarrow Z a_1 \longrightarrow \tau^+\tau^-\tau^+\tau^-. \quad (9)$$



(a)

(b)

FIGURE 5: The production rates in fb for $\sigma(gg \longrightarrow h_2) \cdot \mathrm{BR}(h_2 \longrightarrow a_1 a_1 \longrightarrow \tau^+\tau^-\tau^+\tau^-)$ (a) and $\sigma(gg \longrightarrow h_2) \cdot \mathrm{BR}(h_2 \longrightarrow Z a_1 \longrightarrow \tau^+\tau^-\tau^+\tau^-)$ (b) as functions of m_{h_2}.

Here, we consider a center-of-mass energy $\sqrt{s} = 14\,\mathrm{TeV}$ for the LHC.

In Figure 1, we present the mass of the next-to-lightest CP-even Higgs boson m_{h_2} against the tree-level parameters of the NMSSM. One finds that for the surviving points, the m_{h_2} decreases by increasing λ whereas it increases by increasing both κ and μ_{eff}. Also, it is found that for our parameter space, most of the surviving points correspond to the region with $2 \lesssim \tan\beta \lesssim 7$ and $200 \lesssim A_\lambda \lesssim 800$ while the distribution in A_κ is quite uniform.

Looking at Figures 2 and 3, showing the correlations between m_{h_2} and the lightest CP-even Higgs mass m_{h_1} and between m_{h_2} and the lightest CP-odd Higgs mass m_{a_1} for the surviving points, it is clear that in most regions of our parameter space, the h_1 is the SM-like Higgs and the h_2 can only play the role of the SM-like Higgs in a small region of the parameter space. The h_2 is a mixture of doublet and singlet components for the majority of points selected in our parameter space. Figure 3 shows that the smaller the m_{a_1}, the smaller the m_{h_2}. Since the surviving points have small values of A_κ, only small values of m_{a_1} are allowed. One noteworthy feature of the figure is that the h_2 can be the SM-like Higgs with mass around 125 GeV, which corresponds to a light a_1 with $m_{a_1} \lesssim 90\,\mathrm{GeV}$.

Due to the mixing between the Higgs doublets and singlet, Higgs-to-Higgs decays are kinematically allowed for large area of the NMSSM parameter space, even for small masses of Higgs bosons. Also, one distinguished landmark of the NMSSM is that the existence of the lightest CP-odd Higgs boson a_1 with mass values less than m_Z is quite natural, which is impossible in the context of the MSSM. In Figure 4, we display the correlations between m_{h_2} and the h_2 decays into light CP-odd Higgs pairs $h_2 \longrightarrow a_1 a_1$ (a) and into an a_1 and a gauge boson Z (b). It is clear from panel (a) of the figure that the decay $h_2 \longrightarrow a_1 a_1$ is the dominant one whenever it is kinematically open. It is found that the $\mathrm{BR}(h_2 \longrightarrow a_1 a_1)$ ranges

Table 1: Four benchmark points P1, P2, P3, and P4 used in the $S/\sqrt{B}$ analysis.

	P1	P2	P3	P4
λ	0.615706	0.650828	0.637590	0.617789
κ	0.261287	0.264725	0.339134	0.387478
$\tan\beta$	5.2247	3.78738	3.82514	3.70979
μ_{eff} (GeV)	153.678	198.766	198.201	199.224
A_λ (GeV)	646.778	517.464	464.215	426.835
A_κ (GeV)	-8.00937	5.1126	-9.72344	9.09329
m_{h_2} (GeV)	140	180	220	260
m_{a_1} (GeV)	66	64	99	67
S (fb) with 300 fb^{-1}	3.168×10^4	8.61×10^3	2.364×10^3	3.21×10^2
B (fb) with 300 fb^{-1}	3.9×10^4	3.9×10^4	3.9×10^4	3.9×10^4
$S/\sqrt{B}$ with 300 fb^{-1}	160.4	43.6	12	1.6
$S/\sqrt{B}$ with 1000 fb^{-1}	292.9	79.6	21.9	3

from around 40% to 100% see panel (a) of the figure), while the maximum BR($h_2 \longrightarrow Za_1$) is 0.1% (see the panel (b) of the figure). In fact, the dominance of $a_1 a_1$ decay channel causes a suppression to other decay channels such as $b\bar{b}$ and other channels.

Figure 5 illustrates the inclusive h_2 production rates ending up with $a_1 a_1 \longrightarrow \tau^+\tau^-\tau^+\tau^-$ (a) and $Za_1 \longrightarrow \tau^+\tau^-\tau^+\tau^-$ (b) as functions of m_{h_2}. It is shown from the figure that the h_2 production rates decrease rapidly with increasing m_{h_2}. It is clear that the production rates $\sigma(gg \longrightarrow h_2 \longrightarrow a_1 a_1 \longrightarrow \tau^+\tau^-\tau^+\tau^-)$ are sizable, reaching up to 100 fb for small values of m_{h_2}, while the production rates $\sigma(gg \longrightarrow h_2 \longrightarrow Za_1 \longrightarrow \tau^+\tau^-\tau^+\tau^-)$ is quite small, reaching around 0.5 fb at the most. The latter production rates are clearly not enough to detect the h_2 at the LHC, taking into account that leptonic tau decays are around 17.5%. In short, the inclusive production rates for h_2 decaying into $a_1 a_1 \longrightarrow \tau^+\tau^-\tau^+\tau^-$ are promising and could allow discovery of both h_2 and a_1 at the LHC while the production rates for h_2 decaying into $Za_1 \longrightarrow \tau^+\tau^-\tau^+\tau^-$ are quite small. So, we will analyze signal-to-background for the former channel as the latter channel is useless.

To claim discovery at the LHC, we have done a partonic signal-to-background (S/B) analysis based on CalcHEP. The dominant standard model backgrounds are the irreducible background coming from $pp \longrightarrow \tau^+\tau^-\tau^+\tau^-$(via γ and Z exchange). Here, we assume the double leptonic decay channels of the τ's. In Table 1, we give 4 points as benchmark points for various masses of the h_2 to do our analysis. Here, we assume that the tagging efficiency is 50% for tau jets, by scaling of the total cross sections. As it is shown in the table ,we have calculated the cross sections for both the signal and background processes and also the significance $S/\sqrt{B}$ at a center-of-mass energy $\sqrt{s} = 14$ TeV for the LHC. We have done that for 300 fb^{-1} and 1000 fb^{-1} of accumulated luminosity (we do such analysis without assuming any cuts. Of course, the proper cuts could improve the signal to background ratio, which we leave for the experimentalist to do). It is obvious that there is a good potential to detect the h_2 decaying into $a_1 a_1 \longrightarrow \tau^+\tau^-\tau^+\tau^-$ at the LHC in the mass region $140 \lesssim m_{h_2} \lesssim 220$ GeV. The corresponding signal events are quite large of order 31680 events for $m_{h_2} = 140$ GeV and 2364 events for $m_{h_2} = 220$ events with 300 fb^{-1} of integrated luminosity. Again, these results are given without assuming any cuts, which of course is reducing the number of signal rates. Thus, we conclude that the LHC with integrated luminosity of 1000 fb^{-1} has the potential to discover the h_2, if it is not a SM-like Higgs, with masses up to around 250 GeV. Such a discovery of the h_2 is mostly accompanied with a light a_1. The existence of such a light a_1 is a direct evidence for distinguishing the NMSSM from the MSSM.

4. Conclusions

In this paper, we have explored the discovery prospects of the next-to-lightest CP-even Higgs state, h_2, at the LHC with $\sqrt{s} = 14$ TeV. We have studied the detectability of the h_2 in the two processes $gg \longrightarrow h_2 \longrightarrow a_1 a_1 \longrightarrow \tau^+\tau^-\tau^+\tau^-$ and $gg \longrightarrow h_2 \longrightarrow Za_1 \longrightarrow \tau^+\tau^-\tau^+\tau^-$. We have shown that while the h_2 discovery of the latter channel is impossible due to smallness of the inclusive production rates, the former channel is promising as the $\sigma(gg \longrightarrow h_2 \longrightarrow a_1 a_1 \longrightarrow \tau^+\tau^-\tau^+\tau^-)$ is sizable and should help discovering the h_2 signals with masses up to around 250 GeV at the LHC with integrated luminosity of 1000 fb^{-1}.

After doing some analysis for signals and dominant backgrounds in the partonic level, we have proven that the discovery of both the h_2 and a_1 is possible at the LHC. Such a discovery of the h_2 is mostly accompanied with a light a_1 with $m_{a_1} \lesssim m_Z$. The existence of such a light a_1 is a direct evidence for the NMSSM as such a light a_1 is impossible in the MSSM. Of course, more experimental analyses including τ-decays, detector effects, parton shower, and hadronization are needed to claim the actual discovery potential of such Higgses at the LHC. However, we believe that our results are valuable for scientists interested in determining the NMSSM Higgs signals at the LHC.

The discovery of Higgs states through the process $gg \longrightarrow h_2 \longrightarrow a_1 a_1 \longrightarrow \tau^+\tau^-\tau^+\tau^-$ has in fact two merits. On the one hand, it can be a good alternative to discover both h_2 and a_1 that could be difficult to be discovered in a direct production. On the other hand, it can be exploited to measure the trilinear Higgs self-coupling $h_2 a_1 a_1$.

Data Availability

The author confirms that the data supporting the results of this work are available within the article.

Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this paper.

Acknowledgments

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