The second lightest CP-even Higgs boson signals in the NMSSM at the LHC

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We study the signal rates of the second lightest CP-even Higgs boson, h_2 , of the NMSSM produced in gluon fusion, in association with bottom quarks and in association with top quarks, which is not the SM-like Higgs boson, at the LHC. We evaluate the production rates of h_2 in the SM fermionic and bosonic final states in addition to $a_1 a_1$, $h_1 h_1$ and $Z a_1$ final states. It is observed that the size of the signal rates in some regions of the NMSSM parameter space is quite large and that could help extracting h_2 signals at the LHC through a variety of decay channels.

Keywords: NMSSM; CP-even Higgs boson; Higgs signals.

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1. Introduction

Assuming CP-conservation in the Higgs sector, the Next-to-Minimal Supersymmetric Standard Model (NMSSM)^{1–11} predicts one or more light CP-even Higgs boson, either the lightest Higgs boson h_1 or the second lightest Higgs boson h_2 , which could be the Higgs particle with a mass around 125 GeV discovered by the Large Hadron Collider (LHC).^{12–15} This discovered SM-like Higgs can be accommodated in the context of the NMSSM without much fine tuning, see Refs. 16–33 for more details.

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Within the NMSSM, the Higgs field consists of the two MSSM-type Higgs doublets in addition to the Higgs singlet, giving rise to seven Higgs states: three CP-even Higgses $h_{1,2,3}$ ($m_{h_1} < m_{h_2} < m_{h_3}$), two CP-odd Higgses $a_{1,2}$ ($m_{a_1} < m_{a_2}$) and a pair of charged Higgses $h^\pm$. When the singlet field acquires a vacuum expectation value (VEV), an “effective” μ -term, μ_{eff} , is generated automatically, which is naturally of the order of the electroweak scale.⁴ Moreover, due to the presence of the singlet field, the phenomenology of the NMSSM Higgs sector is richer than that of the MSSM, which has only five Higgs states: h , H , A and $H^\pm$. The phenomenology of the NMSSM Higgs sector has been studied by many authors, for a review and details, see Refs. 34–36 and references therein. For the latest studies about the NMSSM Higgs sector, see Refs. 37–40.

Following the discovery of the SM-like Higgs boson at the LHC, looking for other Higgs bosons at the LHC, if they exist, would point to the existence of supersymmetric models. Searches for additional heavy neutral Higgs bosons have been carried out by the ATLAS and CMS Collaborations in $b\bar{b}$,^{41,42} $\tau\tau$,^{43–50} and gauge boson, WW and ZZ ,^{51,52} final states. No signal has been found so far, putting some constraints on such Higgs bosons.

In this paper, we study the production rates of the second lightest Higgs boson h_2 , if it is not the SM-like Higgs boson, of the NMSSM at the LHC through the following production channels: gluon fusion $gg \rightarrow h_2$ and associated production with bottom–antibottom pair $gg \rightarrow b\bar{b}h_2$ and top–antitop pair $gg \rightarrow t\bar{t}h_2$ for the most promising final states. We calculate the inclusive cross-section of h_2 . It is observed that there exist some regions of the NMSSM parameter space where the cross-section times branching ratios are quite sizable and could help extracting h_2 signals at the LHC through the above production channels.

The paper is organized as follows. In Sec. 2, we briefly discuss the NMSSM Higgs sector, describing the NMSSM parameter space scans performed and the allowed decay channels of h_2 . In Sec. 3, we present the inclusive event rates of h_2 production at the LHC for various decay channels. Finally, we summarize our results in Sec. 4.

2. The Higgs Sector of the NMSSM

The scale-invariant superpotential of the NMSSM, including only the third generation fermions, is given by

$$W = h_t \hat{Q} \hat{H}_u \hat{t}_R^c - h_b \hat{Q} \hat{H}_d \hat{b}_R^c - h_\tau \hat{L} \hat{H}_d \hat{\tau}_R^c + \lambda \hat{S} \hat{H}_u \hat{H}_d + \frac{1}{3} \kappa \hat{S}^3, \quad (1)$$

where h_t , h_b , h_τ , λ and κ are dimensionless couplings. The term $\lambda \hat{S} \hat{H}_u \hat{H}_d$ is required to solve the μ -problem.⁵³ The last term, which is cubic in the singlet superfield, has been introduced to break the Peccei–Quinn (PQ) symmetry.^{54,55}

The soft SUSY-breaking potential containing only the Higgs fields is given by

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

where A_λ and A_κ are dimensionful parameters of the order of the mass scale of supersymmetric particles.

The NMSSM Higgs sector is fully described by six independent parameters: κ , A_κ , λ , A_λ , $\tan \beta$ (the ratio of the VEVs of the two Higgs doublets, H_u and H_d) and $\mu_{\text{eff}} = \lambda \langle S \rangle$ (where $\langle S \rangle$ is the VEV of the singlet field).

For our study of the NMSSM Higgs sector, we have used the package NMSSM-Tools5.1.2^{56–58} to compute the masses, couplings and decay widths of all the NMSSM Higgs bosons. The package systematically takes into account various theoretical and experimental constraints. We use the package to scan over some regions of the NMSSM parameter space in order to obtain a general view of the phenomenology of the second lightest CP-even Higgs boson, h_2 , at the LHC. We have set the six tree level parameters in the following ranges:

$$0.001 \leq \lambda \leq 0.1, \quad -0.1 \leq \kappa \leq 0.1, \quad 1.6 \leq \tan \beta \leq 60,$$

$$100 \leq \mu \leq 1000 \text{ GeV}, \quad -1000 \leq A_\lambda \leq 1000 \text{ GeV}, \quad -1000 \leq A_\kappa \leq 1000 \text{ GeV}.$$

Note that we focus here on scenario with small values of λ and κ in order to increase the probability of getting a lot of surviving data points with $m_{h_2} \lesssim 500 \text{ GeV}$. In such scenario, the PQ symmetry is slightly broken,^a which is favored by the renormalization group flow from the grand unification scale down to the electroweak scale, see Ref. 59 for more details. Further information about the effect of λ and κ on the two lightest CP-even Higgs boson masses can be obtained from the following sum rule:⁵⁹

$$m_{h_1}^2 + m_{h_2}^2 \approx M_Z^2 + \frac{1}{2} \kappa \langle S \rangle (4\kappa \langle S \rangle + \sqrt{2} A_\kappa), \quad (3)$$

where $\langle S \rangle = \sqrt{2} \mu / \lambda$.

Remaining terms, contributing at higher order level, which are soft SUSY breaking right- and left-handed masses for the first two generations and the third generation, soft SUSY breaking trilinear couplings and gaugino soft SUSY breaking masses have been set as

- $m_Q = m_U = m_D = m_L = m_E = m_{Q_3} = m_{U_3} = m_{D_3} = m_{L_3} = m_{E_3} = 1000 \text{ GeV}$,
- $A_{U_3} = A_{D_3} = A_{E_3} = 2000 \text{ GeV}$,
- $M_1 = 250 \text{ GeV}$, $M_2 = 500 \text{ GeV}$, $M_3 = 1500 \text{ GeV}$.

^aThe PQ symmetry is slightly broken when κ is small, i.e. $\kappa \ll 1$.

Fig. 1. The correlations between the second lightest CP-even Higgs mass, m_{h_2} and the lightest CP-odd Higgs masses, m_{a_1} .

In our study for looking for h_2 at the LHC, we focus on the following decay channels:

$$h_2 \rightarrow \tau^+ \tau^-, \quad h_2 \rightarrow b\bar{b}, \quad h_2 \rightarrow t\bar{t}, \quad h_2 \rightarrow \gamma\gamma, \quad h_2 \rightarrow Z\gamma, \\ h_2 \rightarrow W^+ W^-, \quad h_2 \rightarrow ZZ, \quad h_2 \rightarrow a_1 a_1, \quad h_2 \rightarrow h_1 h_1, \quad h_2 \rightarrow Z a_1.$$

We perform a random scan over some fraction of the NMSSM parameter space. The output of the scan contains masses, branching ratios and couplings of both the NMSSM Higgses and SUSY particles for all the surviving data points which have passed the various experimental and theoretical constraints implemented in the package NMSSMTools5.1.2.^{56–58}

3. Higgs Boson Signal Rates

In order to investigate the discovery prospects for h_2 at the LHC,^b we calculate the cross-sections for h_2 production for the surviving data points by using CalcHEP.⁶⁰ We focus here on the following production channels:

- (i) gluon fusion $gg \rightarrow h_2$;
- (ii) associated production with a pair of bottom quarks $gg \rightarrow b\bar{b}h_2$;
- (iii) associated production with a pair of top quarks $gg \rightarrow t\bar{t}h_2$.^c

Figure 1 displays the correlation between the lightest CP-odd Higgs boson mass m_{a_1} and the second lightest CP-even Higgs boson mass m_{h_2} . It is shown that a_1 can be very light, ~ 7 GeV.^d It is also interesting to note that the smaller the m_{h_2} , the smaller the m_{a_1} . Furthermore, it is obvious that there are some points of the

^bWe assume a center-of-mass energy $\sqrt{s} = 14$ TeV for the LHC.

^cThe production modes $q\bar{q} \rightarrow b\bar{b}h_2$ and $q\bar{q} \rightarrow t\bar{t}h_2$ are negligible at the LHC with $\sqrt{s} = 14$ TeV.

^dFor the mass region $m_{a_1} < 2m_b$, the decay into $\tau^+ \tau^-$ is dominant compared to the decay into $c\bar{c}$ or $\mu^+ \mu^-$.

NMSSM parameter space where the two Higgs states h_2 and a_1 can simultaneously have the same mass around 125 GeV.

As an initial step of our analysis, we show in Fig. 2 the cross-sections for h_2 produced in gluon fusion (left), in association with bottom quarks (middle) and in association with top quarks (right) against λ (top) and κ (bottom). It is clear that in our chosen parameter space, the positive values of κ are favored, while the distributions in λ are nearly uniform. Also, it is clear that the maximum values of cross-sections do not only occur in the region with nearly vanishing λ and κ , MSSM-limit,^e but also in the other regions because a combination of all the six tree level parameters jointly affects m_{h_2} , which in turn affects the values of cross-sections. The maximum cross-sections occur when the h_2 becomes more doublet-like than the singlet-like.

As a second step, we calculate the total cross-section times branching ratios of h_2 production at the LHC in femtobarn (fb):

$$\begin{aligned}\sigma(gg \rightarrow h_2) \times \text{Br}(h_2 \rightarrow XX), \\ \sigma(gg \rightarrow b\bar{b}h_2) \times \text{Br}(h_2 \rightarrow XX), \\ \sigma(gg \rightarrow t\bar{t}h_2) \times \text{Br}(h_2 \rightarrow XX),\end{aligned}$$

where $h_2 \rightarrow XX$ represents h_2 decay channels with $XX = \tau^+\tau^-$, $b\bar{b}$, $t\bar{t}$, $\gamma\gamma$, $Z\gamma$, W^+W^- , ZZ , a_1a_1 , h_1h_1 and Za_1 .

Figure 3 displays the signal rates for h_2 produced in gluon fusion (left), in association with bottom quarks (middle) and in association with top quarks (right) for $\tau^+\tau^-$ (top), $b\bar{b}$ (middle) and $t\bar{t}$ (bottom) final states as functions of m_{h_2} . We note that there is a gap in the figure with only few points between the upper region and lower region of the parameter space in the mass range $m_{h_2} \gtrsim 480$ GeV. This is because the decay $h_2 \rightarrow a_1a_1$, which is dominant in large area of the NMSSM parameter space, is closed or suppressed in the upper region. It is clear from the figure that the cross-section times branching ratio for the gluon fusion process is the highest one in general, reaching up to 2600 fb, 26,000 fb and 60 fb for $\tau^+\tau^-$, $b\bar{b}$ and $t\bar{t}$ final states, respectively, see the left panels of the figure. The inclusive cross-section for the production in association with bottom quarks is the second largest one, topping 30 fb, 300 fb and 25 fb in case of $\tau^+\tau^-$, $b\bar{b}$ and $t\bar{t}$ final states, respectively, see the middle panels of the figure.^f However, there is some region

^eThe MSSM limit can be obtained by simultaneously taking $\lambda \rightarrow 0$ and $\kappa \rightarrow 0$ while keeping the parameters μ_{eff} , A_λ and A_κ fixed, which is not applied in our study.

^fSearches at the LHC for additional neutral MSSM Higgs bosons set some limits for the production of such bosons. For τ lepton final states, these range from 18,000 fb at 90 GeV to 3.5 fb at 3.2 TeV for production via gluon fusion and from 15,000 fb at 90 GeV to 2.5 fb at 3.2 TeV for production in association with b quarks at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 35.9 fb^{-1} , see Ref. 50. For b quark final states, the upper limits on Higgs boson produced in association with at least one additional b quark range from about 250,000 fb at 100 GeV to about 1000 fb at 900 GeV at a center-of-mass energy of 8 TeV at the LHC, corresponding to an integrated luminosity of 19.7 fb^{-1} , see Ref. 42.

Fig. 2. The cross-section for the second lightest CP-even Higgs boson h_2 produced in gluon fusion $\sigma(gg \rightarrow h_2)$ (left), in association with bottom quarks $\sigma(gg \rightarrow b\bar{b}h_2)$ (middle) and in association with top quarks $\sigma(gg \rightarrow t\bar{t}h_2)$ (right) as functions of λ (top) and κ (bottom).

Fig. 3. The signal rates for the second lightest CP-even Higgs boson h_2 produced in gluon fusion $\sigma(gg \rightarrow h_2)$ (left), in association with bottom quarks $\sigma(gg \rightarrow b\bar{b}h_2)$ (middle) and in association with top quarks $\sigma(gg \rightarrow t\bar{t}h_2)$ (right) times $\text{Br}(h_2 \rightarrow \tau^+\tau^-)$ (top), $\text{Br}(h_2 \rightarrow b\bar{b})$ (middle) and $\text{Br}(h_2 \rightarrow t\bar{t})$ (bottom) as functions of m_{h_2} .

of the NMSSM parameter space in the mass range $m_{h_2} \gtrsim 480$ GeV where the production in association with bottom quarks can give the largest signal rate. This is because h_2 in this region has a large H_d component, which can be substantial for large values of $\tan \beta$, so its couplings to down-type fermions are enhanced compared to the SM. In fact, h_2 production in association with bottom quarks has an extra advantage where the associated $b\bar{b}$ pair can be tagged, allowing a useful handle for background rejection. The production in association with a top-quark pair has only a considerable signal rate for the low mass range $m_{h_2} \lesssim 2m_W$, giving maximum rates of about 15 fb and 150 fb in case of $\tau^+\tau^-$ and $b\bar{b}$ final states, respectively, see the top left and middle left panels of the figure. In short, the size of the signal rates in some regions of the parameter space is quite large and that could help discovering h_2 in $\tau^+\tau^-$ and $b\bar{b}$ final states. Also, $t\bar{t}$ final states may be exploited to discover h_2 in gluon fusion and in association with bottom-quark pair for $m_{h_2} \sim 480$ GeV or slightly above, though challenging due to large backgrounds and a complicated $t\bar{t}$ final state.

In Figs. 4 and 5, we present the production rates for h_2 into the SM bosonic particles. It is shown that $\gamma\gamma$ and $Z\gamma$ final states have only sizable signal rates for the low mass range $m_{h_2} \lesssim 2m_W$, see Fig. 4. It is clear that the largest production rate comes from gluon fusion channel, reaching maximum 70 fb for the former and 45 fb for the latter, see the left panels of the figure. The production rates for h_2 produced in association with bottom quarks and top quarks are quite small below 1 fb level for both $\gamma\gamma$ and $Z\gamma$ final states. Although the signal rates for $\gamma\gamma$ and $Z\gamma$ final states are not so large, these final states offer clean signatures with manageable backgrounds at the LHC, so one may exploit these channels to discover h_2 in the low mass range especially in gluon fusion production channel. Figure 5 shows the signal rates in W^+W^- and ZZ final states. It is shown that these rates reach up to 10,000 fb for the former and 1000 fb for the latter in gluon fusion channel, see the left panels of the figure.[§] The h_2 production in association with both bottom and top quarks has approximately two orders of magnitude less than that of the gluon fusion production channel, see the middle and right panels.

It is interesting to note that h_2 decays into lighter Higgs pairs or into Higgs plus gauge boson are kinematically open in large areas of the NMSSM parameter space, see Fig. 6 which shows the signal rates in the presence of the following decays: $h_2 \rightarrow a_1 a_1$ (top), $h_2 \rightarrow h_1 h_1$ (middle) and $h_2 \rightarrow Z a_1$ (bottom) for the gluon fusion production (left), the production in association with bottom quarks (middle) and the production in association with top quarks (right). It is shown from the figure that the largest signal rates also come from the gluon fusion production channel, reaching maximum about 1000 fb for light m_{h_2} in case of both $a_1 a_1$ and $h_1 h_1$ final

[§]The CMS collaboration published results of searches for a heavy neutral Higgs boson decaying into WW and ZZ bosons with up to 19.7 fb^{-1} of data collected at a center-of-mass energy of 8 TeV. It was found that such a heavy Higgs boson with SM-like couplings and decays in the mass ranging from 145 GeV to 1000 GeV was excluded, see Ref. 51.

Fig. 4. The signal rates for the second lightest CP-even Higgs boson h_2 produced in gluon fusion $\sigma(gg \rightarrow h_2)$ (left), in association with bottom quarks $\sigma(gg \rightarrow b\bar{b}h_2)$ (middle) and in association with top quarks $\sigma(gg \rightarrow t\bar{t}h_2)$ (right) times $\text{Br}(h_2 \rightarrow \gamma\gamma)$ (top) and $\text{Br}(h_2 \rightarrow Z\gamma)$ (bottom) as functions of m_{h_2} .

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Fig. 5. The signal rates for the second-to-lightest CP-even Higgs boson h_2 produced in gluon fusion $\sigma(gg \rightarrow h_2)$ (left), in association with bottom quarks $\sigma(gg \rightarrow b\bar{b}h_2)$ (middle) and in association with top quarks $\sigma(gg \rightarrow t\bar{t}h_2)$ (right) times $\text{Br}(h_2 \rightarrow W^+W^-)$ (top) and $\text{Br}(h_2 \rightarrow ZZ)$ (bottom) as functions of m_{h_2} .

Fig. 6. The signal rates for the second lightest CP-even Higgs boson h_2 produced in gluon fusion $\sigma(gg \rightarrow h_2)$ (left), in association with bottom quarks $\sigma(gg \rightarrow b\bar{b}h_2)$ (middle) and in association with top quarks $\sigma(gg \rightarrow t\bar{t}h_2)$ (right) times $\text{Br}(h_2 \rightarrow a_1 a_1)$ (top), $\text{Br}(h_2 \rightarrow h_1 h_1)$ (middle) and $\text{Br}(h_2 \rightarrow Z a_1)$ (bottom) as functions of m_{h_2} .

states and 5 fb for $m_{h_2} \sim 480$ GeV in case of Za_1 final state. The signal rates for h_2 production in association with both bottom and top quarks are quite small in most NMSSM parameter space except for small region where both a_1a_1 and h_1h_1 final states reach maximum signal rates of about 20 fb for the production channel $gg \rightarrow b\bar{b}h_2$ (two top middle panels) and 10 fb for the production channel $gg \rightarrow t\bar{t}h_2$ (two top left panels). The Za_1 final state can only give sizable signal rates in the mass range $m_{h_2} \gtrsim 480$ GeV, reaching up to 3 fb for the production channel $gg \rightarrow h_2$ (bottom left panel) and 5 fb for the production channel $gg \rightarrow b\bar{b}h_2$ (bottom middle panel). It is remarkable to note that a_1a_1 , h_1h_1 and Za_1 final states will further decay into quarks or leptons. The promising channels which may be exploited to discover h_2 are $2\tau 2b$ and 4τ final state as $4b$ final state may be difficult to exploit because of the large background. Such extracted signals may require very large integrated luminosities of 300 fb^{-1} or higher.^h

4. Conclusions

The discovered SM-like Higgs boson can be accommodated in the framework of the NMSSM. In this model, by assuming CP-conservation, there are seven Higgses: three CP-even Higgses $h_{1,2,3}$ ($m_{h_1} < m_{h_2} < m_{h_3}$), two CP-odd Higgses $a_{1,2}$ ($m_{a_1} < m_{a_2}$) and a pair of charged Higgses $h^\pm$. We have computed the cross-section for h_2 produced in gluon fusion, in association with a $b\bar{b}$ pair and in association with a $t\bar{t}$ pair in the following final states: $\tau^+\tau^-$, $b\bar{b}$, $t\bar{t}$, $\gamma\gamma$, $Z\gamma$, W^+W^- , ZZ , a_1a_1 , h_1h_1 and Za_1 at the LHC with $\sqrt{s} = 14$ TeV. It has been found that the size of the signal rates in some regions of the parameter space is quite large and that could help discovering the h_2 through $\tau^+\tau^-$, $b\bar{b}$, $\gamma\gamma$ and $Z\gamma$ final states in the low mass range $m_{h_2} \lesssim 2m_W$. Also, it has been found that W^+W^- and ZZ final states can give considerable signal rates for the mass range $m_{h_2} \lesssim 500$ GeV. For most of the NMSSM parameter space, the dominant contribution to the h_2 production comes from the gluon fusion production channel. Furthermore, it has been noted that there exist some regions of the NMSSM parameter space where the production rates of the h_2 in the mass range $m_{h_2} \gtrsim 480$ GeV are quite sizable, and may be exploited to discover h_2 in $\tau^+\tau^-$, $b\bar{b}$ and $t\bar{t}$ final states through its production in association with $b\bar{b}$ pair, which has the dominant contribution to the h_2 production in this mass range, or through the gluon fusion channel.

Finally, we have calculated the signal rates of h_2 , decaying into a_1a_1 , h_1h_1 and Za_1 final states. Although h_2 production rates are quite small in most of the NMSSM parameter space, it has been found that there exist some regions where the signal rates of h_2 are sizable and that could help discovering h_2 at the LHC in a_1a_1 , h_1h_1 and Za_1 final states, but such discovery may require very large integrated luminosities of 300 fb^{-1} or higher.

^hThe h_2 decays to SUSY particles, if kinematically possible, can be dominant, making searching for h_2 at the LHC very complicated.

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