Fermionic decays of NMSSM Higgs bosons under LHC 13 TeV constraints

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ABSTRACT

This paper investigates the impact of the recent LHC constraints on the Higgs sector in the semi-constrained version of the Next-to-Minimal Supersymmetric Standard Model. Our analysis focuses on the parameter space for which the value of the Higgs doublet-singlet coupling, $\lambda$, is large as possible, while the ratio between the vacuum expectation values of the two Higgs doublets, $v_1/v_2$, is small as possible. Under the current constraints, we present the possible fermionic decay channels and reduced cross-section into fermions final states for the lightest neutral Higgs bosons in the NMSSM, $(h_1, h_2, a_1)$. We found that the branching ratios of the non SM-like Higgs ($a_1$ and $h_2$) into a pair of bottom quarks are near 90% level when the Higgs mass below 400 GeV. Moreover, the branching ratio of $h_2/a_1 \rightarrow t\bar{t}$ can reach unity for all mass ranges when these bosons are mostly singlet.

Introduction

In 2012, ATLAS and CMS at the Large Hadron Collider announced the detection of a Higgs-like particle with a mass of around 125 GeV and its measurements consistent with the Standard Model’s prediction [1,2]. However, several new physics models with extended Higgs sector can also accommodate 125 GeV Higgs boson, such as the Minimal Supersymmetric Standard Model (MSSM) [3,4]. The Higgs sector in the MSSM involves two Higgs doublets, which the mixing of their components leads to five Higgs states, one of them is the SM-like Higgs. To obtain a 125 GeV Higgs, the MSSM needs large quantum corrections from the scale of the electroweak scale to ensure that the two Higgs doublets get a non-zero vacuum after EWSB; this leads to the well-known “μ problem” [5,6]. Also, in the MSSM Lagrangian, there is a supersymmetric term, the μ-term. This term should be of a scale of the electroweak scale to ensure that the two Higgs doublets get a non-zero vacuum after EWSB; this leads to the well-known “μ problem” [7]. However, in the Next-to-minimal supersymmetric standard model (NMSSM) [8,9], these issues can be fixed. This model was proposed as an extension of MSSM with an additional Higgs singlet field, $\tilde{\phi}$, that generates a μ parameter dynamically of the SUSY breaking scale, solving the “μ-problem” [10,11]. Moreover, this new singlet scalar gives the NMSSM particle spectrum additional degrees of freedom. In the Higgs sector of the NMSSM, there are seven massive states: three CP-even $h_i$ ($i=1,2,3$), two CP-odd $a_j$ ($j=1,2$), two charged $h^\pm$. Furthermore, the introduction of an extra Higgs singlet in the NMSSM has many implications that cause interesting phenomena. Thus, the NMSSM was widely proposed to interpret the results of the LHC [12–34]. The singlet components’ presence causes all Higgs bosons measurements to deviate from the Higgs boson’s expected values in the SM, which may change the particle (and sparticle) decay width and signals at the LHC [35,36]. Based on this observation, the constraints of the recent LHC Higgs data on the lightest neutral Higgs states’ properties are discussed in this paper. This method was used in a previous paper to investigate the effect of the latest LHC constraints on bosonic decays of possible lightest neutral Higgs bosons in the semi-constrained NMSSM (scNMSSM) with Grand unification boundary conditions [37] and will be shortly described in Section “Scan strategy”. In this paper, we will apply this method to predict the effect of the recent constraints of the LHC on fermionic decays of neutral Higgs particles in scNMSSM.

The structure of this paper is as follows. Section “Higgs Sector in the NMSSM” briefly introduces the Higgs sector in the NMSSM model. Section “Scan Strategy” is devoted to present the analyzed parameter space of the NMSSM at the GUT scale and the imposed theoretical and experimental constraints. In Section “Results”, our results are derived and analyzed. Finally, Section “Conclusion” contains brief conclusions of our findings.

Higgs sector in the NMSSM

The NMSSM represents the simplest extension of the MSSM by additional gauge chiral superfield which is singlet under $SU(3)_c \times SU(2)_L \times U(1)_Y$. To solve the μ-problem of the MSSM, $Z_3$-symmetry is...
imposed. Thus, the scale-invariant NMSSM superpotential reads [8],

$$W_{\text{NMSSM}} = W_{\text{Yukawa}} + \lambda \tilde{H}_u \tilde{H}_d + \frac{1}{3} \kappa S^3. \quad (1)$$

The first line in Eq. (1) represents the Yukawa couplings of the Higgs doublet fields ($\tilde{H}_u$ and $\tilde{H}_d$) to the lepton and quark superfields. On the other hand, the Higgs mass term in the MSSM is replaced by a linear coupling of $S \to \tilde{H}_u$ and $\tilde{H}_d$ plus the self-coupling term ($\frac{1}{3} \kappa S^3$). Once the singlet superfield gets a vacuum expectation value ($S = s$), the second term in NMSSM superfield generates an efficient $\mu$-term; to solve the $\mu$-problem [8].

$$\mu_{\text{eff}} = ks. \quad (2)$$

The most general NMSSM soft Lagrangian consists of mass terms for all scalars, the Higgs and sfermion fields ($m^2_{\tilde{H}_u}$, $m^2_{\tilde{H}_d}$, $m^2_{\tilde{S}}$, $m^2_{\tilde{\nu}_L}$, $m^2_{\tilde{\nu}_R}$, $m^2_{\tilde{\nu}_e}$), the gaugino mass terms ($m_1$, $m_2$, and $m_3$), and finally, the trilinear soft SUSY breaking interaction between the sfermions and Higgs fields.

$$-\mathcal{L}_{\text{soft}} = m^2_{\tilde{H}_u} |H_u|^2 + m^2_{\tilde{H}_d} |H_d|^2 + m^2_{\tilde{S}} |S|^2 + m^2_{\tilde{\nu}_L} |\tilde{\nu}_L|^2 + m^2_{\tilde{\nu}_R} |\tilde{\nu}_R|^2 + m^2_{\tilde{\nu}_e} |\tilde{\nu}_e|^2 + |A|$$(4)

To present the tree-level mass matrices of the Higgs fields physically, the expansion of the full scalar potential around the vacuum expectation values (VEVs), $v_u$, $v_d$, and $s$, is required. Thus, the neutral Higgs doublets and singlet components are labeled by,

$$H_u^0 = v_u + \frac{1}{\sqrt{2}}(R_u^0 + iP_u^0), \quad H_d^0 = v_d + \frac{1}{\sqrt{2}}(R_d^0 + iP_d^0),$$

$$S = s + \frac{1}{\sqrt{2}}(R_s + iP_s). \quad (5)$$

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$$S = s + \frac{1}{\sqrt{2}}(R_s + iP_s). \quad (6)$$

In scNMSSM, we assume that the soft SUSY breaking terms (the gaugino masses, sfermion masses, and the trilinear couplings) are equal at the GUT scale.

$$m_1 = m_2 = m_3 \equiv m_{1/2},$$

$$m^2_{\tilde{H}_u} = m^2_{\tilde{H}_d} = m^2_{\tilde{S}} = m^2_{\tilde{\nu}_L} = m^2_{\tilde{\nu}_R} = m^2_{\tilde{\nu}_e},$$

$$A_t = A_b = A_\tau \equiv A_0.$$
Results

Branching Ratios

Lightest CP-even Higgs ($h_1$)

Fig. 1 shows the allowed fermionic decays of $h_1$ as a function of their mass. There are some excluded points because the values of the Higgs couplings to top quarks, photons, vector bosons, gluons ($C_t$, $C_γ$, $C_V$, $C_g$) and the branching ratio of the SM-like Higgs to new physics ($B_{BSM}$) are 2 $σ$ away from the practically measured values, which represented by violet, green, black, red, and cyan colors, respectively. While the limitations from $h\to aa\to4l/2l+2b$ and $h\to aa\toγγ$ resulted in the exclusion of

Fig. 2. The branching ratios of $h_2\to tt$, $h_2\to bb$, $h_2\to ττ$, $h_2\to Jets$, $h_2\to cc$, and $h_2\toμμ$ plotted against the next to lightest CP-even Higgs mass $M_{h_2}$ for $A_0 ≠ A_i ≠ A_c$. 

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orange and red points, respectively. Finally, the blue dots express the surviving points that exceeded all recent constraints. Please note that the deviations from the SM predictions are computed with the assumption that there is only one underlying state at 125 GeV ($h_{\text{SM}}$). According to the results shown in this figure, this boson represents the SM-like Higgs with a mass ranging from 122 GeV to 128 GeV. Therefore, the branching ratios and the reduced cross-sections of this particle are supposed to be close to what was expected in the SM. As seen from this figure (in the top panels), for the allowed range mass, the branching ratio of $h_1 \rightarrow bb$, $h_1 \rightarrow \tau\tau$, and $h_1 \rightarrow \text{Jets}$ may vary from 0.4 to 0.7, 0.05 to 0.08, and 0.06 to 0.12, respectively. Next, the bottom panels shows $Br\ (h_1 \rightarrow cc)$ runs from 0.02 to 0.03, while for $h_1 \rightarrow \mu\mu$, the allowed band indicates the expected branching ratio at 0.00025. This figure also shows that some points violate the LHC constraints. The constraints with the most considerable impact are $h \rightarrow aa \rightarrow 4l/2l \rightarrow 2b$ and $B_{\text{BSM}}(h_{\text{SM}})$, with the branching ratios below the accepted value in the SM. It should be noted that, in the scanned parameter space, if a region contains both good points and ruled-out points, then we plot the good points on top of the bad points scanned parameter space, if a region contains both good points and.

Second lightest CP-even Higgs ($h_2$)

Fig. 2 shows the permitted fermionic decays of the second lightest CP-even Higgs boson, $h_2$. The results illustrate that the dominant decay mode is to $\tau\tau$ for mass values above 300 GeV for this boson. On the other hand, when the Higgs mass below 300 GeV, $h_2 \rightarrow bb$ can be dominant with a branching ratio of about 0.9. The branching ratio of the channels $h_2 \rightarrow \tau\tau, h_2 \rightarrow \text{Jets}$ are about 0.1 for $m_{h_2} < 300$ GeV, then decreases to 0.01 and 0.001, respectively, as $m_{h_2} \sim 2$ TeV. For $m_{h_2}$ below 200 GeV, the branching ratio of $h_2$ to $cc$ is around 0.01, then sharply decreases to $10^{-5}$. Finally, for the low mass range ($m_{h_2} < 200$ GeV), the value of the Higgs’s branching ratio to $\rightarrow \mu\mu$ can not exceed 0.001. Moreover, the region where $m_{h_2} \leq 250$ GeV and branching ratios below 0.01, the impact of the constraints are more visible due to violating the constraint on $C_i(h_{\text{BSM}})$ (as clearly shown for $h_2 \rightarrow \tau\tau/\mu\mu$), $B_{\text{BSM}}$. $C_i(h_{\text{SM}})$, and from $h \rightarrow aa \rightarrow 4l/2l \rightarrow 2b$ (as shown for $h_2 \rightarrow \text{Jets/}cc$).

Lightest CP-odd Higgs ($a_1$)

The branching ratios of allowed fermionic decays of $a_1$ are presented in Fig. 3. As shown in the right top panel, with $m_{a_1}$ above 350 GeV, the dominant decay mode is to $\tau\tau$. For $m_{a_1} < 400$ GeV, the branching ratio of $a_1 \rightarrow bb$ reaches a maximum value of 0.9 then decreases with mass increasing to about 0.45. Moving now to $a_1 \rightarrow cc$, when the mass below 400 GeV, this decays also has a maximum value of 0.01 then sharply drops to about $10^{-5}$ for the allowed range mass. Next, The decay of $a_1 \rightarrow Jets$ is possible for mass below 350 GeV with branching ratios dramatically increases from 0 to about 0.6 at $m_{a_1} \sim 350$ GeV. Finally, for the allowed range mass of the lightest CP-odd, $m_{a_1}$, the expected value of the branching ratios to $\tau\tau$ and $\mu\mu$ can reach about 0.1 and $1.5 \times 10^{-4}$, respectively. There are some points that are excluded due to the LHC constraints on $C_i(h_{\text{BSM}})$ and $C_i(h_{\text{SM}})$, with $m_{a_1} < 300$ GeV and BR below $10^{-5}$ (as shown for $a_1 \rightarrow cc/\mu\mu$).

Reduced cross-sections

Fig. 4 shows the reduced cross-section of the lightest CP-even and CP-odd Higgs bosons ($h_1, h_2,$ and $a_1$) into bottom quarks via tH production mode (top panels), and via VBF and VH production modes (bottom panels). While the reduced cross-sections of the these neutral Higgs bosons into $\tau\tau$ via ggF production mode (top panels) and via VBF and VH production modes (bottom panels) are presented in Fig. 5. 

As we mentioned before, the results showed that the SM-like Higgs is the lightest of CP-even Higgs boson during this range of the scan. Therefore, the left panels in Figs. 4 and 5 show that the permissible values for the reduced cross-section of $h_1$ into $bb$ and $\tau\tau$ via various production modes are near unity. These plots also show that when the cross-section values are between 0.1 and 0.0012, there are points that were excluded due to their violation of the restrictions of LHC (specifically from $B_{\text{BSM}}(h_{\text{SM}})$ and $h \rightarrow aa \rightarrow 4l/2l + 2b$), while near the permissible values there are points that were excluded due to the constraints on $C_i(h_{\text{BSM}}), C_i(h_{\text{SM}})$, and $C_i(h_{\text{SM}})$.
From the middle panels of Figs. 4 and 5, the results show that when the mass of $h_2 < 200$ GeV, the reduced cross-section into $b\bar{b}$ and $\tau\tau$ is around the unity. With mass increasing, the reduced cross-section may get enhanced by over 100 via $ttH$ production mode and get decreased to below 0.5 via VBF or VH. We noted that when the reduced cross-section is between $10^{-4}$ and $10^{-6}$, some points were excluded due to the constraints from $h \rightarrow aa \rightarrow 4l/2l + 2b$, $B_{SM}(h_{SM})$, $C_{l}(h_{SM})$, and $C_{t}(h_{SM})$. Moreover, $R(ggF \rightarrow h_2 \rightarrow \tau\tau)$ and $R(VBF/VH \rightarrow h_2 \rightarrow \tau\tau)$ have similar properties of $R(ttH \rightarrow h_2 \rightarrow bb)$ and $R(VBF/VH \rightarrow h_2 \rightarrow bb)$, respectively.

The reduced cross-section of $a_1$ into $b\bar{b}$, via $ttH$, and $\tau\tau$, via VBF or
For the lightest neutral Higgs bosons in the NMSSM ($h_1, h_2$, and $a_1$), we examined the reduced cross-section and possible decay modes to the fermions in a region where $\lambda$ is large as possible, and tan$\beta$ is small. The results show that in future searches the following channels could be most promising. For example, the decays of $h_2 \rightarrow b\bar{b}$, and $a_1 \rightarrow b\bar{b}$, can be dominant with a branching ratio of 0.9 when the Higgs mass below 300 GeV and 400 GeV, respectively, due to the high values of the doublet components of $h_2$ and $a_1$. Thus, the coupling between these Higgs states and $b$ quarks will get enhanced. Moreover, the branching ratio of $h_2$ and $a_1$ to a pair of top quarks, if kinematically allowed, would be dominant. This is because the doublet component of $h_2$ and singlet component of $a_1$ have high values, which leads to a strong coupling between these particles and the top quarks. The results also showed a similar behavior of a reduced cross-section of the neutral Higgs bosons into $b\bar{b}$ and $\tau\tau$ final states.

In summary, the discovery of a SM-like Higgs boson with a mass of about 125 GeV may indicate the existence of extended Higgs sectors predicted by new physics models, such as the NMSSM. The measured couplings of the SM-like Higgs can indirectly affect the parameter space of the other non-SM Higgs bosons in the model as is shown by the findings of this paper, which can provide a deeper insight into the model and suggest new directions for future research.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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