Study of a Light NMSSM CP-Odd Higgs Produced via Bottom-Quark Annihilation in the Di-Photon Channel at the LHC

M. M. Almarashi

Physics Department, Faculty of Science, Taibah University, P. O. Box 344, Medina, KSA

Abstract

We study the production of a low mass CP-odd Higgs through bottom-quark annihilation in the $\gamma\gamma$ final state at the LHC in the framework of the NMSSM. This production channel is significantly enhanced at large values of tanβ. We provide some results about the inclusive cross section of this production mode, which may help for extracting the a_1 signal at the LHC.

Keywords: supersymmetric models, CP-odd Higgs bosons, NMSSM, LHC
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1. INTRODUCTION

The discovery of the a Standard-Model-like Higgs boson with a mass of approximately 125 GeV at the CERN Large Hadron Collider (LHC) [1, 2] opens up a new window to explore an extended Higgs sector, with additional (pseudo)scalar Higgs bosons, predicted by several theories such as the Next-to-Minimal Supersymmetric Standard Model (NMSSM) [3, 4, 5, 6, 7, 8]. The NMSSM is quite an attractive model. First, it provides a natural solution to the mu-problem of the MSSM by adding a chiral singlet superfield to the MSSM [3]. Second, it can relieve the Little Hierarchy Problem and Fine-tuning [9, 10]. Third, the phenomenology of the NMSSM is really richer than that of the MSSM, particularly in the the Higgs sector. Hence, the NMSSM deserves more attention.

After electroweak symmetry breaking (EWSB), the NMSSM Higgs sector consists of seven Higgs bosons, three of which are CP-even, two are CP-odd and two charged states. The tree-level Higgs sector of this model can be described by six parameters: the Yukawa couplings λ and κ, the associated trilinear soft-breaking parameters A_λ and A_κ, the parameters $\mu_{\text{eff}} = \lambda s$ with s being the vacuum expectation value of the singlet field and tan$\beta \equiv v_u/v_d$ with v_u and v_d being the vacuum expectation values of the Higgs doublets.

Following the discovery of the Higgs boson in 2012 at the LHC, looking for non SM Higgs bosons, if exist, is crucial in probing physics beyond the SM. Of particular interest is a light CP-odd Higgs boson. A recent detailed study of search for a light CP-odd Higgs boson via its production in bottom-gluon fusion in the framework of the NMSSM at the LHC can be found in [11].

In this paper we study the potential discovery of a light CP-odd Higgs particle at the LHC through bottom quark fusion $b\bar{b} \to a_1$, followed by the decay $a_1 \to \gamma\gamma$, Figure 1, in the NMSSM framework. The initial bottom quarks reside in the proton sea, and the bottom-quark sea is generated from the splitting of gluons into nearly-collinear bottom-antibottom pairs. The a_1 decay into two photons is mediated by loops of fermions. If the a_1 is a singlet-like then the chargino contribution is the dominant one. This work is complementary to the one carried out in Ref. [12], in which we explored the production channel $b\bar{b} \to a_1 \to \tau^+\tau^-$ of such a low-mass a_1 state. In the next section we give a brief review of the NMSSM, focusing on the light CP-odd Higgs particle inside this model. The results and discussions are presented in section 3. Finally, conclusions are given in section 4.

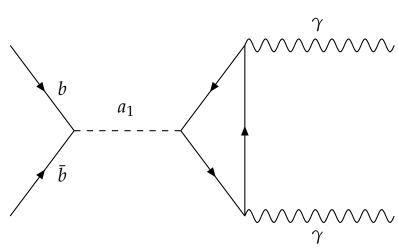

FIGURE 1: Representative Feynman diagram for the lightest CP-odd Higgs production with subsequent decay to a pair of photons $b\bar{b} \to a_1 \to \gamma\gamma$.

2. LIGHT CP-ODD HIGGS BOSON OF THE NMSSM

The NMSSM superpotential depends on the usual two Higgs doublets superfields of the MSSM $\hat{H}_u$ and $\hat{H}_d$ and the additional singlet one $\hat{S}$. It is given by

$$W_{NMSSM} = W_{MSSM} + \lambda \hat{S}\hat{H}_u\hat{H}_d + \frac{1}{3}\kappa\hat{S}^3, \tag{1}$$

where W_{MSSM} is known MSSM superpotential. Correspondingly, the soft supersymmetric breaking terms for the NMSSM Higgs sector read

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

The lightest CP-odd Higgs boson of the NMSSM results from the mixing between the CP-odd Higgs state of the MSSM a_{MSSM} and the CP-odd singlet state of the NMSSM:

$$a_1 = a_{\rm MSSM}\cos\theta_A + a_{\rm S}\sin\theta_A, \qquad (3)$$

where θ_A is the mixing angle.

A light a_1 is naturally accommodated in the NMSSM parameter space , which is of great interest. The tree-level mass-squared of the a_1, to a good approximation, are given by the following expressions:

$$m_{a_1}^2 = -\frac{3\kappa\mu_{\rm eff}A_\kappa}{\lambda} + v^2 sin2\beta(2\lambda\kappa + \frac{A_\lambda\lambda^2}{\sqrt{2}\mu_{eff}}), \qquad (4)$$

where $v \equiv \sqrt{{v_u}^2 + {v_d}^2}$, with v_u and v_d are the vacuum expectation values for up-type and down type Higgs doublets as mentioned above. One can see from Eq. 4 that all the tree-level Higg sector parameters affects on m_{a_1}.

We try to find the region of the NMSSM parameter space that offers a light a_1. We randomly scan the parameter space by using the NMSSMTools_5.5.2 package [13, 14, 15, 16] with the goal of finding such the light a_1. Details of our parameter space scan including theoretical and experimental constraints can be found in Ref. [12].

3. RESULTS AND DISCUSSIONS

The $\gamma\gamma$ signal may be the most ideal decay mode to search for a light a_1 at the LHC as a hadron collider suffering from large hadron backgrounds. The light a_1 dominantly decays to $b\bar{b}$ with branching ratio close to 90% for most points of the NMSSM parameter space but this channel suffers from large QCD backgrounds. The branching ratio of the light a_1 decay into di-tau decay channel is $\lesssim$ 10% in most of the parameter space when the $b\bar{b}$ decay channel is kinematically open. The di-tau decay channel was studied for the a_1 production via the bottom-quark fusion, see [12]. In this work we study the production process $b\bar{b} \to a_1$ followed by $a_1 \to \gamma\gamma$. Presence of the two photons in the final state is very encouraging since it provides a very clean signature for probing a_1 properties such as its mass.

As a first step, we show in Fig. 2 the correlations between the mass of the lightest CP-odd Higgs boson, m_{a_1}, and the lightest two CP-even Higgs masses, m_{h_1} and m_{h_2}, (top two panels) and between the former one and the branching fraction BR$(a_1 \to \gamma\gamma)$. It is clear from the top-panel that in our parameter space the h_1 is mostly the SM-like Higgs with masses between 122 and 128 GeV though one can not generalize this to the entire parameter space where the h_1 can also be a singlet-like with masses less than that of the SM Higgs boson. It is also obvious from the middle-panel of the figure that the h_2 can play the role of the SM-like Higgs in a small region of the parameter space. Moreover, it is also noticeable that the smaller m_{a_1} the smaller m_{h_2} Furthermore, it is remarkable that there is a certain region of the NMSSM parameter space in which the $BR(a_1 \to \gamma\gamma)$ is dominant, reaching up to 100%, see the bottom-panel of the figure. The reason behind this is the singlet nature of the a_1 leading to suppressions of the a_1 decays to fermion-antifermion at the tree level like $a_1 \to b\bar{b}$ and $a_1 \to \tau^+\tau^-$ in which case the $a_1\chi_1^+\chi_1^-$ coupling generating through the $\lambda H_1 H_2 S$ Lagrangian term is enhanced, inducing the enhancement of the $\gamma\gamma$ decay channel. It is further noticed that the BR$(a_1 \to \gamma\gamma)$ ranges from 10^{-3} to 10^{-6} for most points in our parameter space.

In order to study the discovery potential of the a_1 at 14 TeV center-of-mass energy at the LHC, we evaluate the inclusive production rates of the a_1 by using CalcHEP [17] for the points surviving the constraints in the scan. We focus on the production channel $b\bar{b} \to a_1$. This channel is significantly enhanced at large values of tanβ. Figure 3 presents the production rates $\sigma(b\bar{b} \to a_1)$BR$(a_1 \to \gamma\gamma)$ as functions of a_1 mass (top), BR$(a_1 \to \gamma\gamma)$ (middle) and tanβ (bottom). The top-panel of the figure shows that the production rates decreases by increasing the a_1 mass, as expected. This production rates reach up to 10^8 fb for large values of tanβ, see the bottom-panel of the figure. The middle-panel of the figure shows that the BR$(a_1 \to \gamma\gamma)$ can be enhanced in some region of the NMSSM parameter space, reaching up to 100%. This enhancement of the BR$(a_1 \to \gamma\gamma)$ is a characteristic feature of the NMSSM compared with the other SUSY models. Unfortunately, this region does not correspond to the one that maximizes the inclusive production rates $\sigma(b\bar{b} \to a_1)$BR$(a_1 \to \gamma\gamma)$. This is because the production channel $b\bar{b} \to a_1$ is suppressed in contrast to the decay channel $a_1 \to \gamma\gamma$ which is enhanced. In fact, the maximum cross sections occurs when the BR$(a_1 \to \gamma\gamma)$ ranges from 10^{-4} to 5×10^{-5}. In summary, we conclude that although the details of signal-to-background analysis is required to make the final conclusion about the discovery potential of a_1 via the process $b\bar{b} \to a_1 \to \gamma\gamma$ at the LHC, the total production rates for the production channel $b\bar{b} \to a_1$ followed by the decay $a_1 \to \gamma\gamma$ are quite large, and may help extracting the a_1 signals at least at high-Luminosities of the LHC.

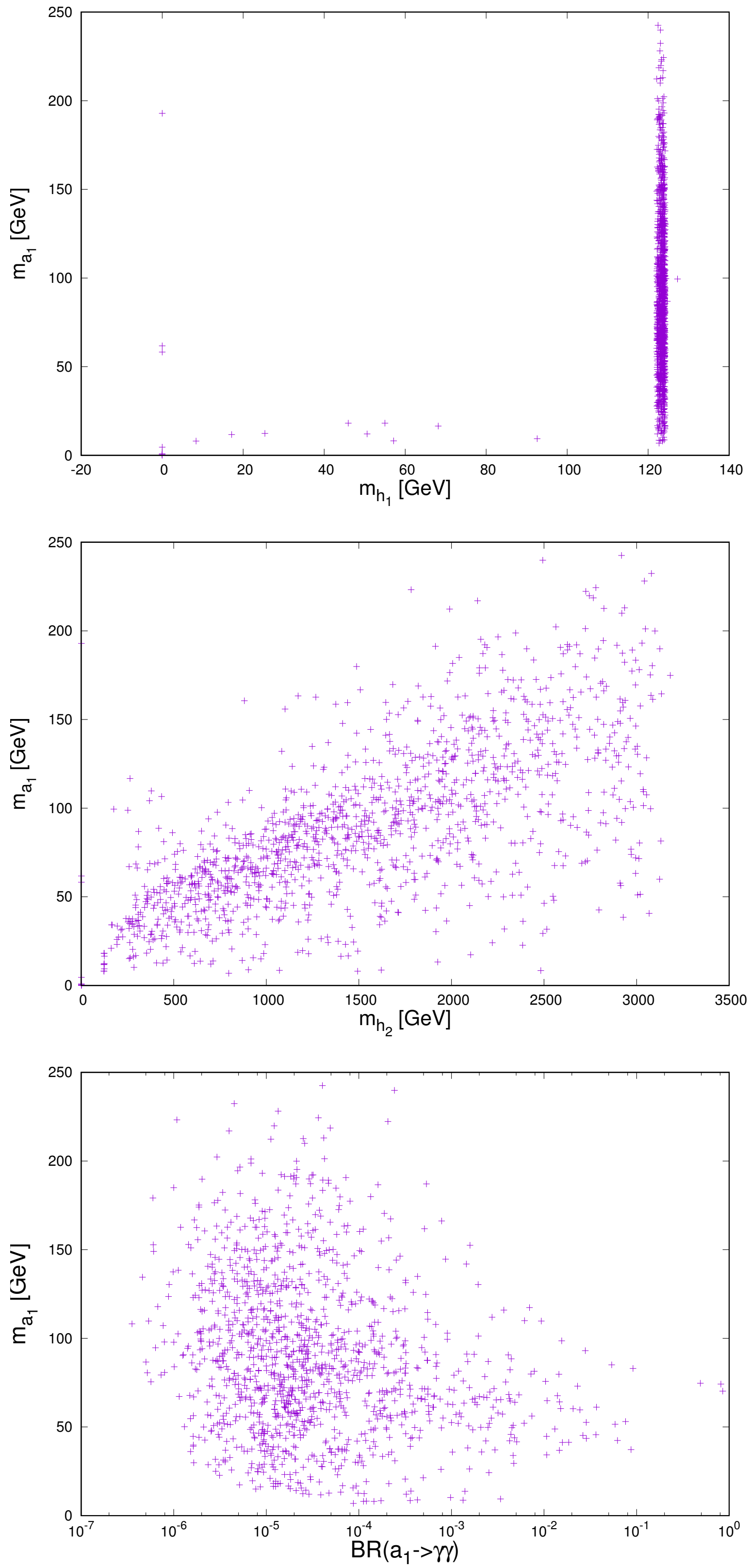

FIGURE 2: The correlations between the lightest CP-odd Higgs mass, m_{a_1} and the lightest two CP-even Higgs masses, m_{h_1} and m_{h_2} and between the former one and and the di-photon decay rate.

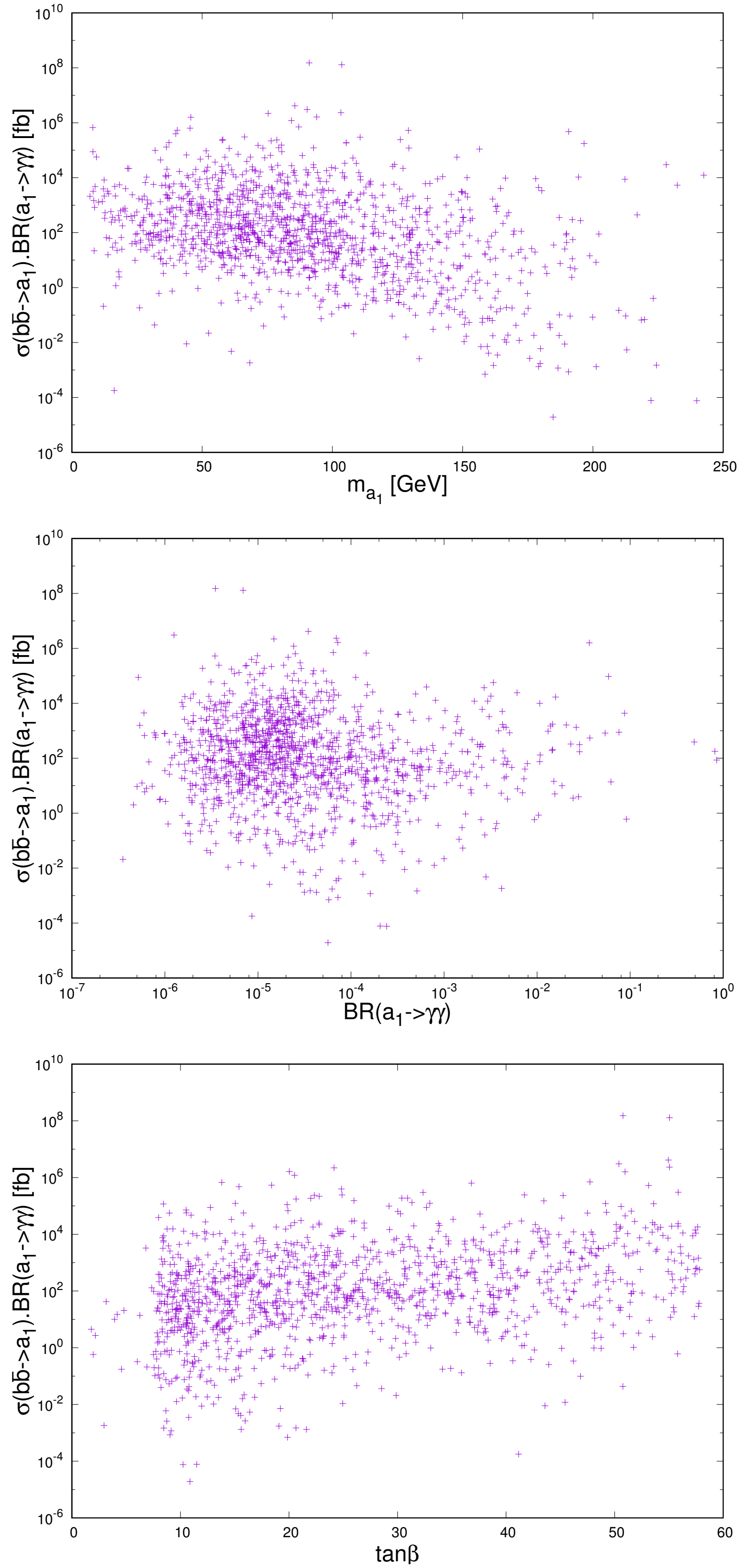

FIGURE 3: The production rates of the lightest CP-odd Higgs boson a_1 produced in bottom-gluon fusion $\sigma(gg \to a_1)\text{BR}(a_1 \to \gamma\gamma)$ versus a_1 mass (top), $\text{BR}(a_1 \to \gamma\gamma)$ (middle) and tanβ (bottom) at 14 TeV LHC for the points surviving the constraints in the random scan.

4. CONCLUSIONS

In this work, we have studied the production of a light CP-odd Higgs boson, a_1, of the Next-to-Minimal Supersymmetric Standard Model (NMSSM), which contains a singlet superfields in addition to the two doublet ones of the MSSM, at the LHC. We have estimated the inclusive production rates for the a_1 produced in bottom-quark fusion through di-photon decay channel. We have found that these production rates are quite large, and could help extracting the di-photon a_1 signal, at least at the High-Luminosity LHC. The discovery of such a light a_1 with mass less than Z mass is not only an evidence of supersymmetric models but it can also distinguish the NMSSM from the MSSM. The a_1 production through bottom-quark fusion in the di-photon final state is enhanced at large values of tanβ, and can be exploited to measure both the a_1-to-bottom-antibottom $a_1 b\bar{b}$ coupling and the effective a_1-to-diphoton coupling at the LHC.

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