The role of MSSM heavy Higgs production in the self coupling measurement of 125 GeV Higgs boson at the LHC

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Abstract

Measurement of the self coupling of 125 GeV Higgs boson is one of the most crucial task for high luminosity run of the LHC and it can only be measured in the di-Higgs final state. In the minimal supersymmetric standard model, heavy CP even Higgs ($H$) can decay into lighter 125 GeV Higgs boson ($h$) and therefore influence the di-Higgs production. We investigate the role of single $H$ production in the measurement of self coupling of $h$. We find that $H \rightarrow hh$ decay can nontrivially affect the $h$ self coupling measurement in low tan$\beta$ regime when the mass of the heavy Higgs boson lies between 250 - 600 GeV and depending on the parameter space it may be seen as an enhancement of the self coupling of 125 GeV Higgs boson.

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I. INTRODUCTION

One of the long standing problems of the particle physics is the origin of mass of fundamental particles. In the standard model (SM), a scalar doublet is introduced, neutral component (called Higgs boson) of which spontaneously breaks the electroweak symmetry by acquiring the non-zero vacuum expectation value (vev) and consequently generates masses for all SM particles. The mass of the Higgs boson is a free parameter in the SM and it is determined by the vev of the Higgs field and Higgs quartic self coupling ($\lambda$). A new boson with mass about 125-126 GeV has been recently observed by ATLAS [1] and CMS [2] collaborations of Large Hadron Collider (LHC) experiment which may be the sole missing piece of the SM, i.e., the Higgs boson. The next crucial step is to measure the properties of the newly discovered boson and establish the connection between this particle and the electroweak symmetry breaking mechanism. The measured couplings of the new boson with fermions and gauge bosons are found to be quite compatible with those of the SM Higgs boson [3, 4] and more accurate measurement will be performed in near future at the 13/14 TeV LHC [5]. In order to reconstruct the full profile of the Higgs boson, we also need to measure the Higgs self coupling along with other couplings. In the framework of SM, it is possible to determine Higgs self-coupling $\lambda$ from the accurate measurement of Higgs mass and vev of the Higgs field. However, we should note that this type of estimation is indirect in nature and independent confirmation is indeed required to prove the existence of SM Higgs boson. The direct way to determine the coupling $\lambda$ is to produce three Higgs bosons through Higgs boson quartic coupling $\lambda$ in collider experiments. However, triple Higgs boson production cross section is too small to observe at the LHC even with very high luminosity and therefore the only probe is to observe di-Higgs production via Higgs trilinear coupling. Higgs trilinear coupling is generated by the electroweak symmetry breaking and it is proportional to $\lambda$ and vev of the Higgs field. It is thus possible to measure the Higgs quartic self coupling $\lambda$ from the di-Higgs production cross section in the SM [6,8]. The Higgs pair production cross section in SM is also small (a few tens of fb at the 14 TeV LHC) and it is accessible at the very high luminosity LHC, called HL-LHC.

In 2015, LHC will start to operate at 13/14 TeV center of mass energy and after 2018 it is expected that LHC will be upgraded for high luminosity operation. At HL-LHC, prospect of
SM Higgs self-coupling measurement has been studied extensively in Ref [9–15] using Higgs pair production process. Although, we can have various final states like $b\bar{b}b\bar{b}$, $b\bar{b}W^+W^-$, $b\bar{b}\gamma\gamma$, $b\bar{b}\tau\tau$, $W^+W^-W^+W^-$ etc. from Higgs pair production, phenomenological studies show that $b\bar{b}\gamma\gamma$ channel is the most promising one [10, 12]. A recent study [5] by ATLAS Collaboration has also confirmed the importance of $b\bar{b}\gamma\gamma$ channel for the measurement of SM Higgs self-coupling.

Precise measurement of Higgs self-coupling and the reconstruction of Higgs potential is necessary to prove the correctness of the SM as there are many well motivated scenarios beyond the standard model (BSM) which can have extended Higgs sector and/or non-standard couplings [16–19]. The presence of new particles and couplings can potentially change the value of Higgs self coupling $\lambda$ compared to that of SM. In case, we observe deviation of $\lambda$ from its SM value, this can be the indication of new physics beyond the SM.

In minimal version of supersymmetric standard model (MSSM), which is one of the most favourable BSM models, there are five Higgs bosons: one CP even light Higgs ($h$), one CP even heavy Higgs ($H$), one CP odd Higgs ($A$) and two charged Higgs bosons ($H^\pm$). In this scenario, the lightest CP even Higgs boson ($h$) can be identified with the observed 125 GeV Higgs boson and other Higgs bosons may be discovered in future LHC run. In the MSSM scenario, tree level couplings of Higgs bosons depend on two parameters: Higgs mixing angle $\alpha$ and $\beta$, where $\tan\beta$ is the ratio of the vacuum expectation values of two Higgs doublets. This means that Higgs couplings can be significantly different from the SM depending on the parameter space of the model.

In MSSM, one of the important consequence of the presence of heavy Higgs boson is that $H$ can decay to lighter Higgs boson $h$ and in that case, single production of heavy Higgs can be seen as a pair production of lighter Higgs bosons. We already mentioned that the observation of pair production of Higgs boson is the only direct way to measure the self coupling of $h$ and therefore, the production of heavy Higgs boson and its decay to $h$ can potentially affect the measurement of $\lambda$. In this paper we study the effect of heavy Higgs ($H$) production on self coupling measurement of SM-like Higgs boson $h$ in the context of MSSM. We assume that the observed Higgs with mass 125 GeV is indeed MSSM lightest
Higgs boson and the couplings of $h$ is such that it behaves like SM Higgs boson. The plan of
the paper is as follows: in Sec. II we briefly discuss the production of heavy CP even MSSM
Higgs and its decay to lighter Higgs boson. In Sec. III we illustrate how the production of $H$
can influence the self coupling measurement of lighter (SM like) Higgs boson. Summary of
our work and possible issues are discussed in Sec. IV.

II. MSSM $H$ PRODUCTION AND ITS DECAY TO 125 GEV HIGGS

The couplings of the MSSM Higgs bosons are determined by two parameters: $\alpha$ and $\beta$
defined in the introduction. The couplings of gauge bosons with $h$ and $H$ are proportional
to $\sin(\beta - \alpha)$ and $\cos(\beta - \alpha)$ respectively. As the experimental data shows that the observed
Higgs boson, which is assumed to be $h$, couples to W/Z gauge boson similar to SM Higgs,
$\sin(\beta - \alpha)$ should be close to unity in order to satisfy the above mentioned constraint. In
our work we simply assume $\sin(\beta - \alpha)=1$ which means that $h$ couples to fermions and gauge
bosons exactly like SM Higgs boson. The effect of this assumption is quite similar to the
case of decoupling limit in which lightest MSSM Higgs boson behaves like SM Higgs boson.
In this case, heavier CP even Higgs $H$ does not couple to electroweak gauge bosons and
coupling to up and down type fermions are either suppressed or enhanced by $\tan\beta$. For
large values of $\tan\beta$, the coupling of $H$ (also $H^{\pm}$ and $A$) to $b$ quark becomes strong as it
scales with $m_b \tan\beta$ while its coupling with the top quark, which is $\propto m_t/\tan\beta$, becomes
rather weak. In that case, $H$ dominantly decays to $b$ quarks and $\tau$s. In other words, $H \to hh$
branching is negligible for high value of $\tan\beta$.

Here, we are interested to study the effect of heavy MSSM Higgs $H$ production which
decays into a pair of $h$. In MSSM this decay mode is particularly important in the mass
window $250 \text{ GeV} < M_H < 400 \text{ GeV}$ for low value of $\tan\beta$. Above $M_H > 350 \text{ GeV}$, its
decay to top quark opens up and eventually becomes the dominant one. To illustrate this
point, we present the plot for branching ratio of $H$ for two values of $\tan\beta = 3$, and 5 in
Fig. 1 assuming $\sin(\beta - \alpha)=1$. For spectrum generation and decay/branching calculations
we use SUSY-HIT [20]. It is clear from Fig. 1 that for $\tan\beta = 3$ (5) BR$(H \to hh)$ can be
as high as 64 (25)%$. For $\tan\beta = 2$, branching to lighter Higgs can go up to 83% while at
moderate $\tan\beta (=10)$ its maximum value reduces to only 2%. For small $\tan\beta$, $H$ branching
FIG. 1. Branching Ratios for heavy CP even Higgs ($H$) for $\tan\beta = 3$ and 5. Results are given in the limit $\beta - \alpha = \pi/2$.

to $t\bar{t}$ is important when it is kinematically allowed, but for large $\tan\beta$, $\text{BR}(H \rightarrow b\bar{b})$ always dominates (for example, $\text{BR}(H \rightarrow b\bar{b})$ varies between 70 to 90% for $\tan\beta=10$). In Table I we present a few benchmark points with different $M_H$ values and their branching ratios ($\text{Br}(H \rightarrow hh)$) for $\tan\beta = 2, 3$ and 5 respectively.
TABLE I. $\sigma_{NNLO}$ is the NNLO cross-section of single $H$ production from gluon fusion and bottom quark annihilation. Branching ratios of heavy CP even Higgs to di-Higgs final state ($Br(H \to hh)$) is calculated for different values of $\tan \beta$ assuming $\beta - \alpha = \pi/2$ with $M_h = 125$ GeV.

| $M_H$ (GeV) | $\sigma_{NNLO}$ (pb) | $Br(H \to hh)$ |
|------------|----------------------|----------------|
|            | $\tan \beta = 2$    | $\tan \beta = 3$ | $\tan \beta = 5$ |
| 250        | 3.970                | 0.55           | 0.43           | 0.12           |
| 275        | 3.347                | 0.82           | 0.62           | 0.22           |
| 300        | 2.936                | 0.83           | 0.64           | 0.25           |
| 350        | 2.854                | 0.51           | 0.50           | 0.22           |
| 400        | 2.558                | 0.08           | 0.13           | 0.11           |
| 450        | 1.792                | 0.04           | 0.07           | 0.07           |
| 500        | 1.191                | 0.03           | 0.05           | 0.05           |

Production cross-section of $H$ depends on $\tan \beta$ through heavy quark couplings. The dominant contribution to single $H$ production mainly comes from gluon-gluon fusion although, for large or moderate $\tan \beta$, the bottom quark annihilation to $H$ ($b\bar{b} \to H$) cross section can be substantial. We compute the NNLO cross-section of single $H$ production coming from gluon fusion and bottom-quark annihilation using SusHi (version 1.3.0) \cite{21} with MSTW 2008 (NNLO) PDF\cite{22}. The single production cross section of $H$ can be much larger than SM $hh$ production, for example, $\sigma(gg + b\bar{b} \to H)$ is $1635$ fb for $M_H = 300$ GeV with $\tan \beta = 3$. For the same $H$ mass, this cross section reduces to $1371$ fb for $\tan \beta = 5$. The total cross section $\sigma(gg + b\bar{b} \to H)$ for different benchmark points are presented in Table I.

Before closing this section, we are interested to point out that the low $\tan \beta$ region in the MSSM is not well favoured due to the fact that in this region of the parameter space, it is very difficult to raise the lighter Higgs mass to $\sim 125$ GeV assuming low supersymmetry (SUSY) breaking scale ($M_S$). For example, with $M_S = 1$ TeV and for $\tan \beta = 3$, the lightest Higgs boson mass is just about $\sim 99$ GeV (assuming trilinear coupling $A_t$ to be equal to 0 GeV). However, it is possible to get 125 GeV Higgs mass by lifting the SUSY scale to 10
- 100 TeV even with small tan β [23]. This type of high scale SUSY scenario has become particularly attractive in the context of recent discovery of 125 GeV Higgs boson which requires somewhat higher value of SUSY scale in contrast to the pre-LHC era (typically $M_S > 1$ TeV), the absence of flavour changing neutral current and the non observation of supersymmetric particles at the LHC.

III. ANALYSIS AND RESULTS

At the leading order, SM Higgs pair production occurs either through gluon fusion to $hh$ (via top quark box diagram) or gluon gluon to virtual Higgs (mediated by top quark triangle diagram) and its splitting into a pair of Higgs bosons. The contribution of the box diagram is independent of the Higgs self coupling and this also interfere destructively with the later one. At present, the SM Higgs pair cross section is known at the NLO level and it is about 34 fb at the 14 TeV LHC for $M_h = 125$ GeV [24].

Let us now discuss potentially detectable final states from Higgs pair production at the LHC. In spite of the large cross section of $b\bar{b}b\bar{b}$ final state, it is very difficult to observe the di-Higgs signal in this channel due to the huge QCD background. On the other hand, fully leptonic final states from $h$ to gauge boson decay, i.e., $h \to ZZ/WW \to$ leptons, is not very promising due to small branching fractions of $W/Z$ bosons to leptons. Recent studies using jet substructure technique show that $b\bar{b}\tau^+\tau^-$ [11] and $bbW^+W^−$ [25] channels may be encouraging at the HL-LHC. So far, the most promising channel to observe di-Higgs production is $bb\gamma\gamma$ final state, although the branching to this particular channel is very small (about 0.27 %). Observation of this channel is possible due to the high identification efficiency as well as excellent energy measurement of photons so that Higgs candidate in the di-photon invariant mass distribution can be easily separated from the background. The ATLAS collaboration has performed a detailed analysis [5] in this channel closely following the Ref. [10] and according to their estimation di-Higgs ($hh$) production signal can be observed at $\sim 3\sigma$ level at the HL-LHC. In this work we only focus on the most promising final state, i.e., $bb\gamma\gamma$ channel.

By comparing cross sections of single $H$ production (see Table [1]) and direct pair production of $h$, we can see that single $H$ cross section can be up to two orders in magnitude
higher than the $hh$ cross section. Depending on the branching $H \rightarrow hh$, $H$ production can, in principle, contaminate the signal of direct $hh$ production and therefore affect the measurement of self coupling of 125 GeV Higgs ($h$). For illustration purpose, we take three benchmark points assuming different values of $M_H$ and $\tan \beta$: $BP_1(275$ GeV,$5)$, $BP_2(350$ GeV,$2)$, $BP_3(450$ GeV,$6)$ respectively and compare with SM $hh$ production in the $b\bar{b}\gamma\gamma$ channel.

SM parton level $hh$ events with $M_h = 125$ GeV have been generated using MadGraph5 [28] at the 14 TeV LHC using the model file of “Higgs Pair Production” [29] which includes both top quark box and triangle diagrams. For generating MSSM signal (i.e., single $H$ production) we have used the MC generator PYTHIA [30]. All SM and SUSY events are showered and hadronized by PYTHIA and cross sections are scaled to NLO/NNLO values given in Table I for different benchmark points.

For object reconstruction, we use fast detector simulator package Delphes3 [31]. Details of the analysis cuts and efficiencies, following the ATLAS analysis [5], are discussed below.

Events containing two $b$-jets and two photons are selected. Selection requirements of $b$-jets are $p_T > 40$ (25) GeV for leading (sub-leading jets) and $|\eta| < 2.5$. It is assumed that $b$-tagging efficiency is 80%. Photons are selected with $p_T > 25$ GeV, $|\eta| < 2.5$ and they satisfy isolation requirement. Following ATLAS analysis [32] photon candidate is removed if more than 4 GeV of transverse energy is observed within a cone with $\Delta R = 0.4$ surrounding the photon. The photon identification efficiency is assumed to be 80%. Separation cuts between $b\bar{b}, b\gamma, \gamma\gamma$ pair ($\Delta R(b,b)$, $\Delta R(b,\gamma)$, $\Delta R(\gamma\gamma)$) are greater than 0.4. Criteria for reconstructing the Higgs mass are: $50$ GeV $< M_{b\bar{b}} < 130$ GeV, $120$ GeV $< M_{\gamma\gamma} < 130$ GeV, where $M_{b\bar{b}}$ and $M_{\gamma\gamma}$ are the invariant masses of $b\bar{b}$ and di-photon respectively. Finally, a lepton veto is also applied. After imposing the above cuts we obtain approximately 13.5 SM $hh$ events at the 14 TeV LHC with integrated luminosity $L = 3000$ fb$^{-1}$ which is fairly consistent with the ATLAS result [5]. On the other hand, the same cuts select 161, 410 and 9 events for $BP_1$, $BP_2$, $BP_3$ respectively with the same luminosity. We find that the MSSM single $H$ production can change the di-Higgs production cross section and this effect

1. All these benchmark points are well below the current LHC bound on heavy Higgs [26, 27].
2. NNLO cross section for $BP_3$ is 0.404 pb and $\text{Br}(H \rightarrow hh)$ is 5 %.
3. Jets are reconstructed with anti-$k_t$ algorithm with $R = 0.4$. 

8
is significant in the $H$ mass range 250-600 GeV in the low $\tan \beta$ region.

Counting of the number of $b\bar{b}\gamma\gamma$ events in all these benchmark points shows moderate to huge excess over SM cross section, although it is not possible to identify the origin of the excess from this counting itself. It is therefore important to separate out the direct $hh$ cross section from the MSSM heavy Higgs contribution. As the decay width of $H$ is small (at most a few GeV), one may try to separate out the direct $hh$ events from the MSSM $H$ events by identifying it in the $b\bar{b}\gamma\gamma$ invariant mass ($M_{hh}$) distribution \[16\] [17].

![Graph showing invariant mass distribution of SM $hh$ events and SUSY events for different SUSY benchmark points.](image)

**FIG. 2.** Invariant mass distribution of SM $hh$ events and the events coming from single $H$ production for different SUSY benchmark points. Events are obtained after the basic cuts/Higgs reconstruction (see text) with $\mathcal{L} = 3000 \, fb^{-1}$ at 14 TeV HL-LHC.

In Fig 2, we present the invariant mass distribution of reconstructed $hh$ pair of SM events and SUSY events for three benchmark points. We can identify the clear peaks of heavy Higgs for $BP1$ and $BP2$. We can see that the $hh$ invariant mass distribution spreads over 100-150 GeV range, although, the $H$ decay width is small (about a few GeV). This broadening mainly comes from the reconstructed $h$ from the $b$ quark pair and this can not be reduced further because of the limitation of the hadronic calorimeter. It is therefore not
possible to sharpen the $H$ mass peak in this channel. However, one can remove most of the $H$ events by putting a cut on the $hh$ invariant mass distribution around $H$ peak, although, the same cut may remove some amount of direct $hh$ events. Depending on the values of $M_H$ and $\tan \beta$ we may think of three possibilities:

**Scenario A:** MSSM contribution is very large compared to SM (for example, consider $BP1$). The excess events over direct $hh$ events can be separated by imposing a cut on di-Higgs invariant mass and in that case direct $hh$ pair events may be marginally affected by this cut. In case of $BP1$, one can remove almost all of the SUSY contribution (160 out of 161) by rejecting the events in the $M_{hh}$ bin of 200-300 GeV. However, this cut only reduces the SM events by one. Here we can separately measure both contributions and the determination of parameters in the Higgs sector may be possible in this case.

**Scenario B:** In this case SUSY contribution is also large (for example, see $BP2$) although invariant mass cut may not help us to separate out these two contributions. The position of the $H$ peak is such that the events coming from the direct $hh$ production also large around $M_H$. In case of $BP2$, there are 408 events (total events = 410) in the region $250 \text{ GeV} < M_{hh} < 400 \text{ GeV}$ and if we reject events of these bins, the SM $hh$ events reduces to 7 from 13.5. One possibility to separate these two contributions is to fit the $H$ peak and continuum $hh$ events simultaneously. However, the number of direct $hh$ events may not be statistically sufficient for this procedure. However, we can clearly identify existence of $H$ from this measurement.

**Scenario C:** SUSY contribution is comparable or slightly smaller than SM in this case (for example, see $BP3$). Identification of clear reconstructed peak of $H$ is difficult because of the poor statistics. The slight excess which comes from $H$, can be manifested as an enhancement of $h$ self coupling. However many different new physics models can give rise to enhancement of $h$ self-coupling and it is thus difficult to identify the presence of heavy Higgs in this scenario. Invariant mass cut also do not help to identify the MSSM contribution in this case. For example, a cut $300 \text{ GeV} < M_{hh} < 500 \text{ GeV}$ can remove 8 events of $BP3$ while it also removes 9 direct $hh$ events. This should be regarded as the most challenging scenario in the context of the measurement of $h$ self coupling.
IV. DISCUSSIONS

In this paper we have studied how the decay of heavy MSSM Higgs can contribute the measurement of self coupling of lighter Higgs boson. The branching ratio $H \rightarrow hh$ can be sizeable in the low tan $\beta$ region and it can affect the direct $hh$ signal if the mass of the H lies in between 250-600 GeV. Depending on the parameter space, MSSM signal can be very large compared to direct $hh$ production and in that case, clear identification of heavy Higgs boson is possible. However, we have identified a region in the parameter space corresponding to $M_H = 400 - 600$ GeV with low tan $\beta$ where the MSSM contribution is small but non-negligible. In such scenarios, the identification of $H$ is difficult and an excess in cross sections may be explained in terms of enhancement of $h$ self coupling. This should be regarded as the most challenging scenario and further studies are required in this direction. Before concluding we are interested to point out a few relevant issues:

- In our work we rely on the default smearing parameters implemented in Delphes3. However, in case of HL-LHC, there can be some changes in the LHC detector design and one may expect more smearing effect compared to conventional case. To check the effect of smearing we increase the default ATLAS smearing parameters of ECAL and HCAL by a factor of 25% and study its effect. We find that our result is almost unaffected under this change.

- One may think of discovering heavy Higgs bosons in different channel, for example $t\bar{t}$ final state which is the dominant decay mode for $M_H > 350$ GeV. However, in that case, the main background is SM top quark production. Assuming that the reconstructed heavy Higgs mass may lie within 100 GeV mass range, our naive estimation shows that the ratio of SM $t\bar{t}$ background and signal can be as large as 100-1000 at the parton level, which makes it hard to detect in this mass range and it requires a dedicated study. It is also important to identify the other Higgs bosons $A$ and $H^\pm$ in this mass range and jet substructure technique can be useful in this purpose [33].

- In this paper we present our result assuming $\beta - \alpha = \pi/2$ which forces the lighter Higgs
boson to couple to fermions and gauge bosons exactly like SM Higgs boson. However, current bound allows some amount of deviations from SM couplings. Depending on the parameter space, \( \cos(\beta - \alpha) \) can have small non zero value which opens up several potentially observable decay modes \[34, 35\]. The detailed study is beyond the scope of this paper and this issue will be considered in a separate work\[33\].

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