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The non-resonant and resonant Higgs pair production at the HL-LHC

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Direct measurement of the Higgs self-coupling is crucial to understanding the nature of electroweak symmetry breaking, which requires observation of Higgs pair production. We study the prospects of observing the non-resonant Higgs pair production at the high luminosity run of the 14 TeV LHC (HL-LHC) upon considering various di-Higgs final states. A search is also performed for the heavy resonant scalars (H/A) via their decay into SM final states at the HL-LHC. We set upper limits on the production cross-section of heavy scalar times its branching ratio into final state products for different heavy scalar masses. Finally, we translate these limits and put constraints on the $m_A - \tan\beta$ parameter space in the context of the Minimal Supersymmetric Standard Model (MSSM).

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1. Introduction

The discovery of the Higgs boson at the Large Hadron Collider (LHC) by ATLAS [1] and CMS [2] collaboration has led to many open questions in the Higgs sector. For example, is this the Higgs boson of Standard Model (SM)? A way to answer this question is to measure precisely the properties of the Higgs boson, *viz.*, its coupling with other SM particles, width, spin and CP. The Higgs sector in several well-motivated beyond the SM (BSM) models consists of additional Higgs bosons and the SM-like Higgs boson. Does the discovered Higgs boson have any similarities with these BSM Higgs bosons? To unravel this question, what kind of features of the discovered Higgs boson we should look for? Should we devise new strategies for those additional Higgs bosons? One important feature of the SM Higgs boson is its self-coupling, and this coupling can be measured by the Higgs pair or di-Higgs production. Measuring this coupling precisely at the collider can confirm the electroweak symmetry breaking (EWSB) mechanism. However, a direct measurement of this coupling is challenging at the current LHC as the di-Higgs production rate is very small. The dominant di-Higgs production channel at the LHC is the gluon fusion process. This channel suffers from a small production rate because of the destructive interference between the triangle and box diagram.

We study various final states arising from Higgs pair production at the HL-LHC, at $\sqrt{s}$ = 14 TeV with 3 ab^{-1} of integrated luminosity [3]. We perform usual cut-based analysis as well as multivariate analysis using Boosted Decision Tree (BDT) algorithm in the `TMVA` framework [4]. We further search for heavy Higgses in the context of Minimal Supersymmetric Standard Model (MSSM) and put limits in the MSSM parameter space at the HL-LHC [5].

2. The non-resonant Higgs pair production

A direct probe to measure the Higgs boson self-coupling is observing non-resonant Higgs pair production, $pp \to hh$. The final states coming from di-Higgs production is rich. For example, we choose the following possible final states, $b\bar{b}\gamma\gamma$, $b\bar{b}\tau\tau$, $b\bar{b}WW^*$, $WW^*\gamma\gamma$ and $4W$. We perform cut-based and BDT analysis to evaluate the prospect of these di-Higgs channels at the HL-LHC.

One Higgs boson decays to photons in case of the $b\bar{b}\gamma\gamma$ final state. So, this channel is clean but lacks in total rates. The di-photon invariant mass has a nice peak around the Higgs boson mass, where a cut of 122 GeV $< m_{\gamma\gamma} <$ 128 GeV is applied. This cut reduces the QCD-QED $b\bar{b}\gamma\gamma$ background. In the case of signal, the final state decay products come from the Higgs boson, and they are collimated. A cut on angular separation in the $\eta - \phi$ plane of $0.4 < \Delta R_{\gamma\gamma/b\bar{b}} < 2.0$ reduces the dominant QCD-QED $b\bar{b}\gamma\gamma$ and $t\bar{t}h$ backgrounds. Further, the $b\bar{b}$ invariant mass, and transverse momentum reconstructed from the $\gamma\gamma$ and $b\bar{b}$ system are good kinematic variables for signal and background separation. We perform the BDT analysis with similar kinematic variables, and the signal significance improves about 20%.

The $b\bar{b}\tau\tau$ channel has the advantage of having three final states, which comes from leptonic or hadronic decays of τ's. This channel's main difficulty lies in the reconstruction of the Higgs boson from τ leptons because their decay always comes with neutrinos. There are several techniques in this regard, *viz.* missing mass calculator (MMC), collinear mass approximation, transverse mass, Higgs-bound technique. We adopt the collinear mass approximation technique. The major background here is the $t\bar{t}$. The best kinematic variables consist of collinear mass of $\tau\tau$ system, stransverse mass, invariant mass and transverse momentum constructed from $b\bar{b}$ system. The BDT analysis slightly improves over the cut based results.

The $b\bar{b}WW^*$ channel can be subdivided into three final states. We choose the fully-leptonic and semi-leptonic channels. The $t\bar{t}$ is the dominant background here too. The transverse momentum and invariant mass of $b\bar{b}$ system, transverse momentum of the final state leptons, missing energy falls under the best kinematic variables in this channel. We further analyse the $WW^*\gamma\gamma$ channel. This channel is clean as the final state contains leptons and photons. This signal over background ratio is good here. This final state might have great potential at higher energy collider as the event yield is very low the HL-LHC. We further explore the $4W$ channel. Increasing the number of leptons in the final state lowers the event yield, and considering the final state with jets increases the QCD backgrounds. We perform an analysis in the same-sign di-lepton, three lepton and four lepton final states.

3. The resonant Higgs pair production

We further specifically search for heavy Higgs bosons in various SM final states, *viz.* $pp \to H \to hh$, $pp \to H \to t\bar{t}$ and $pp \to b\bar{b}H, H \to \tau\tau$. The $pp \to H \to hh$ channel is called resonant Higgs pair production, which we divide in various final states as in the previous section. The $pp \to H \to t\bar{t}$ channel is divided into fully leptonic and semi-leptonic final states. We consider hadronic τ decays and b-tag category in $pp \to b\bar{b}H, H \to \tau\tau$ channel. We perform cut-based and multivariate analysis using BDT algorithm in all these channels. Upper limit (UL) at 95% CL on the heavy Higgs production cross-section is placed. The UL on $\sigma(pp \to H \to hh)$ is shown in Fig. 1. The $H \to hh \to b\bar{b}\gamma\gamma$ channel gives stronger limit below heavy Higgs mass (m_H) of 600 GeV. After that, the $H \to hh \to b\bar{b}b\bar{b}$ channel provides stronger UL. The semi-leptonic mode in $H \to t\bar{t}$ channel gives stronger UL of $\sigma(pp \to H \to t\bar{t}) \sim [187, 33]$ fb between $m_H = [400, 1000]$ GeV. The $pp \to b\bar{b}H, H \to \tau\tau$ channel places an UL on $\sigma(pp \to b\bar{b}H) \times Br(H \to \tau\tau)$ between $[22, 4]$ fb for $m_H = [300, 500]$ GeV.

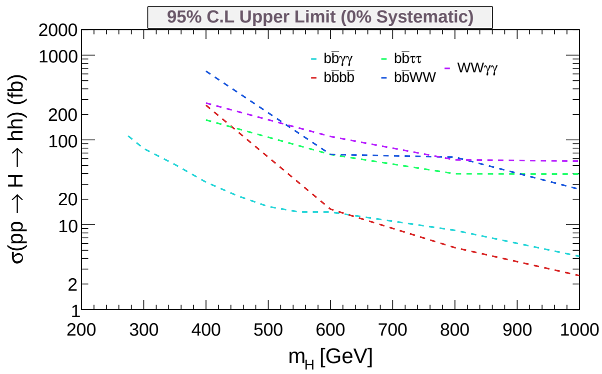

Figure 1: Upper limit on $\sigma(pp \to H \to hh)$ at 95% CL with no systematic uncertainty.

The Higgs sector in MSSM can be parametrised by only two parameters, the pseudoscalar Higgs mass m_A and the ratio of two vacuum expectation values of the two Higgs doublets $\tan\beta$.

We translate these 95% CL upper limits on resonant Higgs production cross-section into projected reaches in the $m_A - \tan\beta$ plane. They are shown in Fig. 2. The plot on the left shows the projected HL-LHC reach of heavy Higgs searches at 95% confidence level (CL). The grey coloured points are excluded by searches in $\sigma_{b\bar{b}H/A} \times Br(H/A \to \tau\tau)$ from ATLAS and CMS Run-II data with 36 fb^{-1} of integrated luminosity. The brown, green and orange coloured points are within the projected reach of $H \to hh \to b\bar{b}\gamma\gamma$, $H \to t\bar{t}$ and $b\bar{b}H, H \to \tau\tau$ final states respectively, at 95% CL. The blue coloured points will remain allowed even after the heavy Higgs searches at the HL-LHC.

The heavy Higgs can further have non-SM decay modes, which has an interesting impact on the final result. If kinematically allowed, the heavy Higgs can decay into neutralinos and charginos. Having these decay modes, the branching ratio of heavy Higgs to SM particles gets modified. It can impact the projected limits placed in the $m_A - \tan\beta$ plane. This effect is shown on the right plot of Fig. 2. In this case, the allowed blue coloured points increase, which corresponds to weaker limits in the presence of these additional non-SM decay modes.

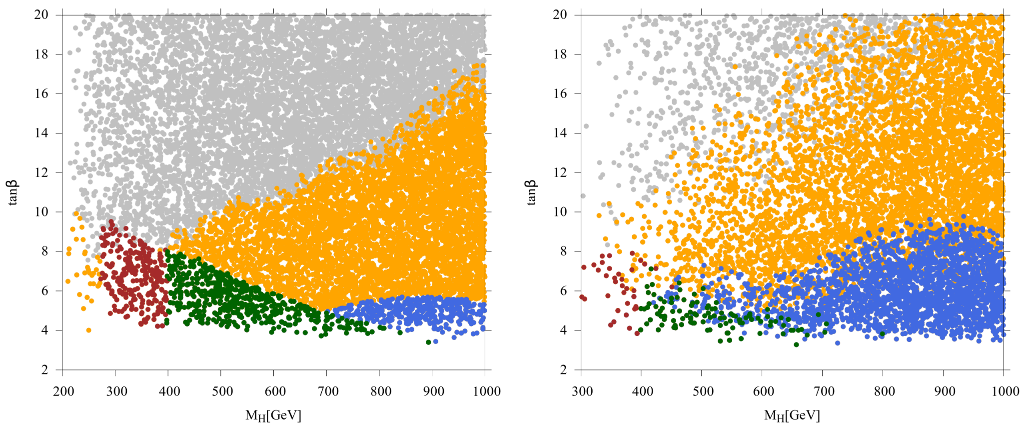

Figure 2: Projected limits at HL-LHC in the $m_A - \tan\beta$ plane for heavy Higgs decaying to, only SM final states (left) and SM+supersymmetic decays (right).

4. Conclusion and outlook

The search for non-resonant Higgs pair production is significant in understanding the EWSB mechanism and confirming the observed Higgs boson's SM-like nature. One efficient way for measuring the Higgs self-coupling at the HL-LHC would be to consider multifarious di-Higgs final states and combine them. Further, the ATLAS and CMS results can be combined to improve the final result. The proposed higher energy colliders will provide much better signal significance. The heavy Higgs searches can confirm/rule out the existence of possible frameworks in search for BSM physics. These searches have the advantage of the resonant peaks in the invariant mass distribution. The low m_A and low $\tan\beta$ region can be probed with $pp \to H \to hh/t\bar{t}$ channel. While the $pp \to b\bar{b}H, H \to \tau\tau$ final state can probe the high $\tan\beta$ region. In the kinematically allowed region, the supersymmetric decays of the heavy Higgs boson can modify the search limits in the $m_A - \tan\beta$ plane.

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