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

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Abstract

We study the prospects of observing the non-resonant Higgs pair production at the high luminosity run of the 14 TeV LHC (HL-LHC). We choose multiple final states based on the event rate and cleanliness and do a collider study by employing a cut-based as well as multivariate analyses using the Boosted Decision Tree (BDT) algorithm. Next, we specifically search for the heavy resonant scalars (H/A) in SM final states at the HL-LHC. After doing the BDT analysis, we set upper limits on the production cross-section of heavy scalar times its branching ratio into final state products for different values of heavy scalar masses. Finally, we translate these limits and put strong constraints on the $m_A - \tan\beta$ parameter space.

Motivation

After the discovery of the Higgs boson at the Large Hadron Collider (LHC) by the ATLAS and CMS collaboration in 2012, the following open questions arise:

- ✦ Is this the Standard Model (SM) Higgs boson?
- ✦ Are there other Higgs bosons which appear in many beyond the Standard Model (BSM) theories?
- ✦ Are we missing any search strategies to look for those additional Higgs bosons?

We address these questions in our work.

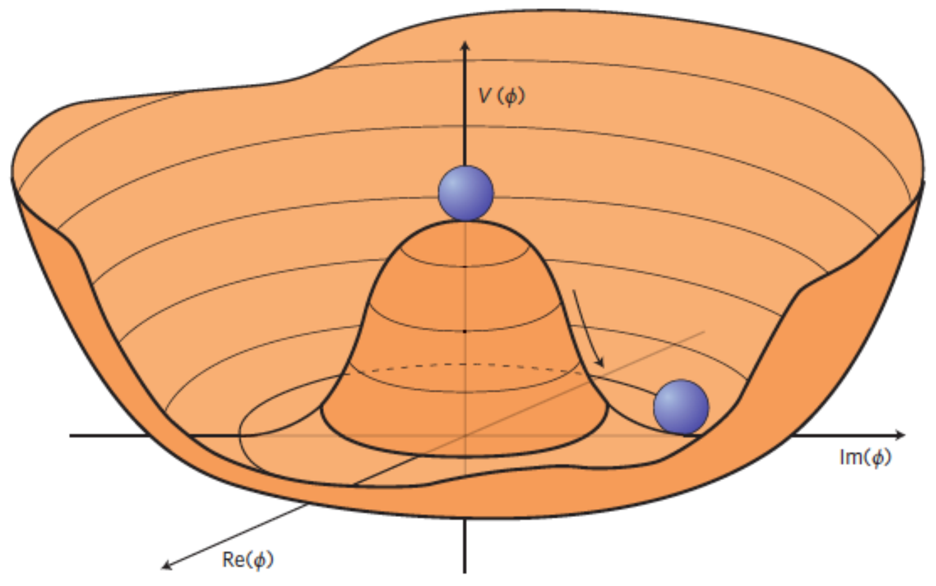
Importance of Higgs self-coupling

✦ The choice of the Higgs potential,

$$V(\Phi) = \mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$$

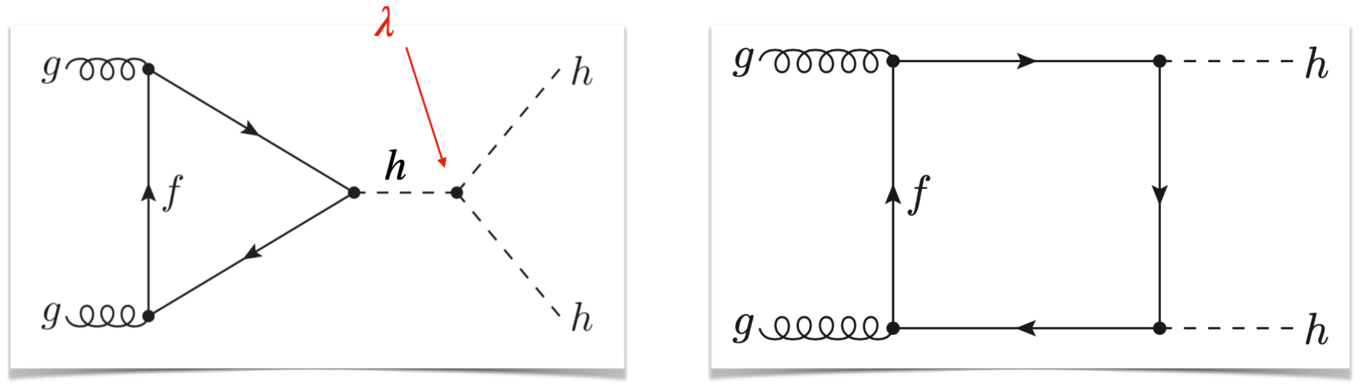
was completely arbitrary choice.

✦ The only way to reconstruct this potential is by knowing the exact value of λ, Higgs boson self-coupling.



Difficulty in measuring Higgs self-coupling

Challenging Task



✦ To directly probe the Higgs boson self-coupling λ, we need to observe two Higgs boson production from one Higgs boson, called non-resonant Higgs pair production, $pp \rightarrow hh$.

✦ Destructive interference between the triangle and box diagram leads to very small rate for Higgs pair production. This makes the task very challenging.

Higgs pair production at the HL-LHC

✦The analysis is done at the centre of mass energy of 14 TeV with 3 ab^{-1} of integrated luminosity, called High Luminosity Large Hadron Collider (HL-LHC). The following 11 di-Higgs final states are chosen based on the production rate and cleanliness. We perform both the cut based and multivariate analysis using Boosted Decision Tree.

1. The $pp \to hh \to b\bar{b}\gamma\gamma$ channel: The signal significance ($S/\sqrt{B}$) after cut based analysis is 1.46 and after BDT analysis is 1.76 (20% improvement over cut based analysis).
2. The $pp \to hh \to b\bar{b}\tau\tau$ channel: This final state is divided into 3 final states of $b\bar{b}\tau_h\tau_h$, $b\bar{b}\tau_h\tau_l$, $b\bar{b}\tau_l\tau_l$, where τ_h and τ_l corresponds to hadronically and leptonically decaying τ respectively. The signal significance after the BDT analysis are 0.74, 0.49, 0.08 respectively.
3. The $pp \to hh \to b\bar{b}WW^*$ channel: This channel is divided into $b\bar{b}ljj + \not{E}_T$ and $b\bar{b}ll + \not{E}_T$, depending on the W boson decay products. The signal significance after the BDT analysis are 0.13 and 0.62 respectively.
4. The $pp \to hh \to WW^*\gamma\gamma$ channel: Similar to the previous channel, this channel is also divided into two final states, $ljj\gamma\gamma + \not{E}_T$ and $ll\gamma\gamma + \not{E}_T$. We got < 5 signal events. However, the signal over background ratio is good in this channel, S/B = 0.11, 0.40 .
5. $pp \to hh \to WW^*WW^*$: Three final states considered, $2l4j + \not{E}_T$ and $3l2j + \not{E}_T$ and (c) $4l + \not{E}_T$. The drawback in this channel are: (a) Increasing the number of leptons lowers the production rate and (b) with more number of jets in the final state the channel becomes contaminated with huge QCD backgrounds. We got a signal significance of < 1 in this final state.

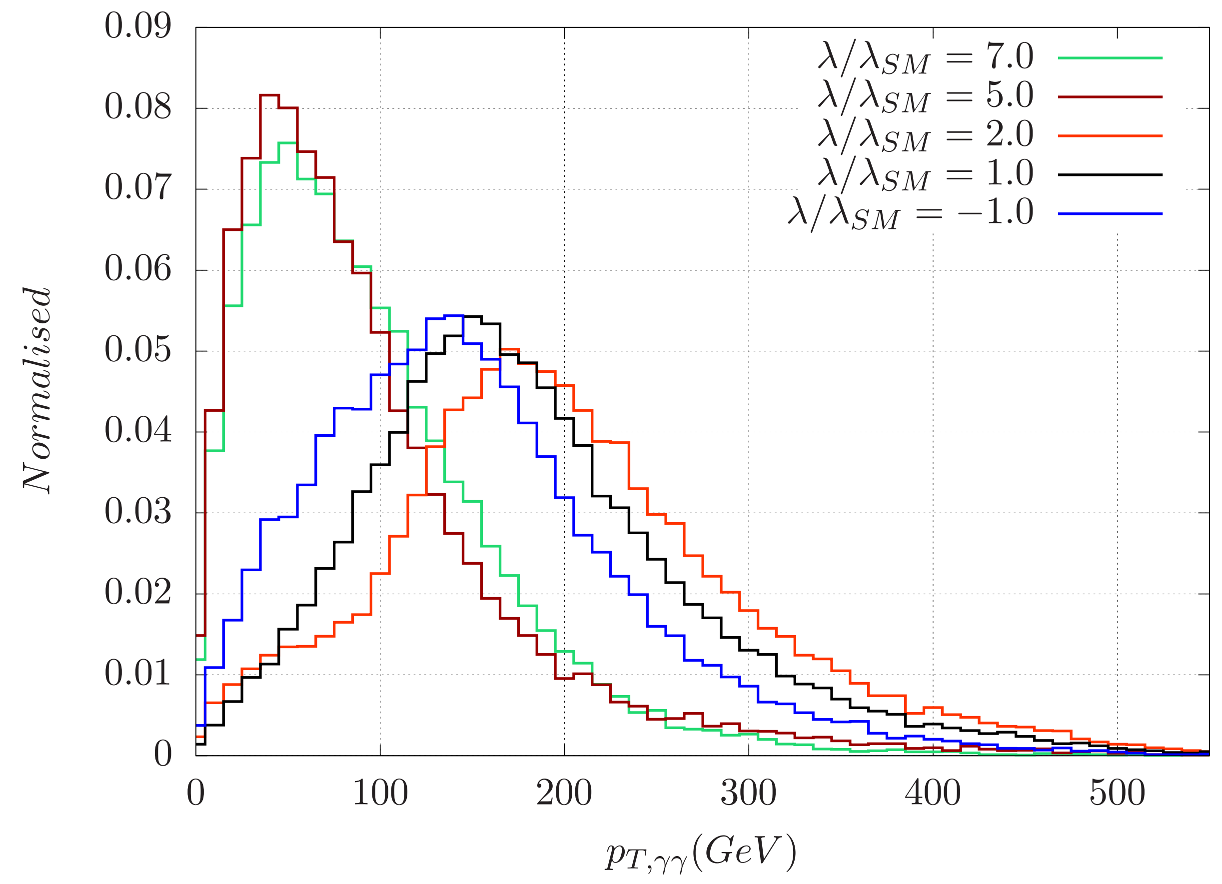
✦Combined Signal significance (Combining all the final states considered): $\sim 2.1\sigma$.

Ramification of varying the Higgs self-coupling from Standard Model value

✦Changing the Higgs self-coupling from its SM value is quantified as the ratio of the measured to the SM value: $\kappa_\lambda = \dfrac{\lambda}{\lambda_{SM}}$.

✦This modifies the kinematics of the di-Higgs final states.

✦Upon using the BDT optimisation for κ_λ =1, the Higgs self-coupling modifier can be constrained in the range [-0.63, 8.07] after the HL-LHC runs.



Heavy Higgs search

✦ Cut-based and BDT analysis at the HL-LHC with the following channels:

1. $pp \to H \to hh$: $b\bar{b}\gamma\gamma$, $b\bar{b}b\bar{b}$, $b\bar{b}\tau_h\tau_h$, $b\bar{b}ljj + \not{E}_T$, $b\bar{b}ll + \not{E}_T$, $ljj\gamma\gamma + \not{E}_T$ and $ll\gamma\gamma + \not{E}_T$ channels. The upper limits at 95% confidence level for these final states are shown in the bottom figure.

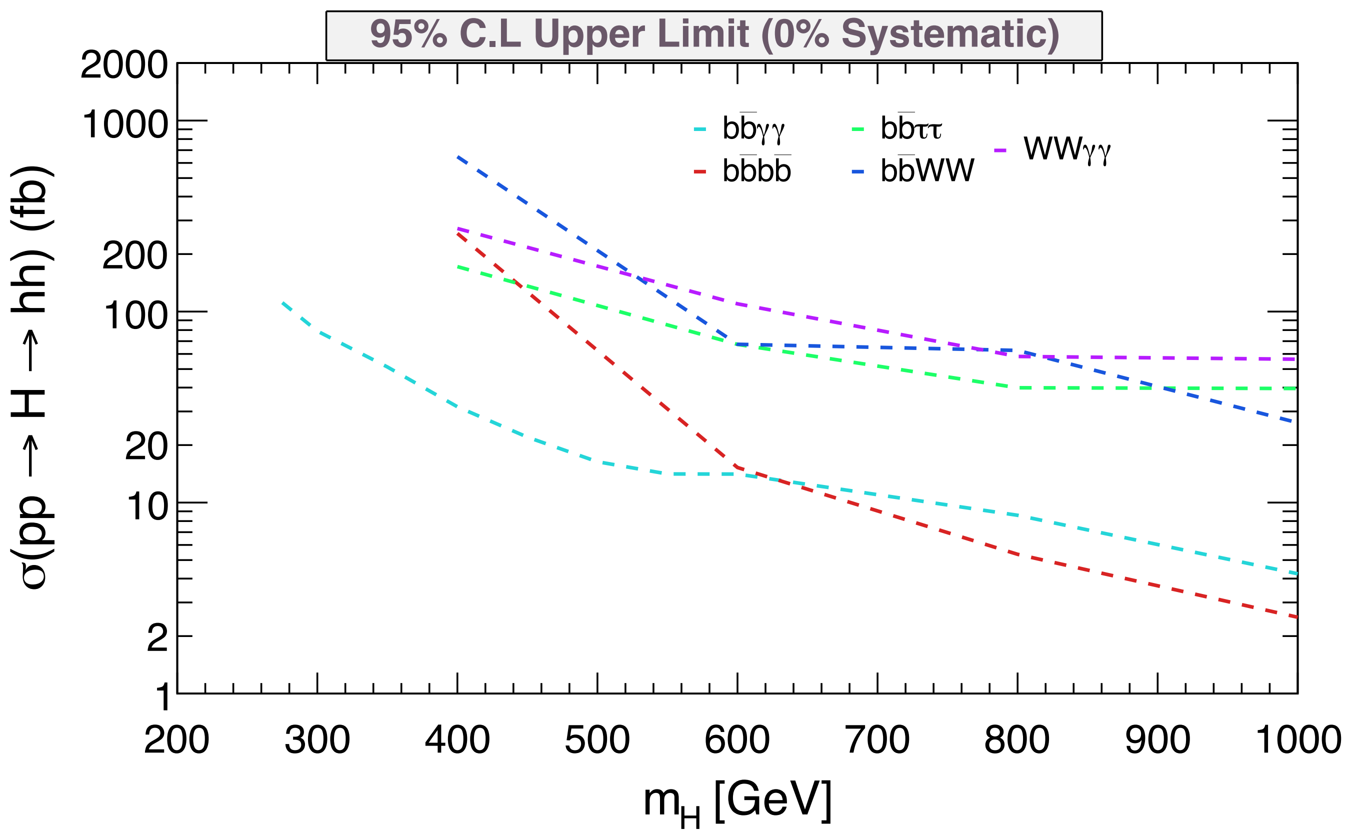
➢ The $b\bar{b}\gamma\gamma$ gives strongest upper limit upto m_H = 600 GeV. After m_H = 600 GeV, the $b\bar{b}b\bar{b}$ yields stronger limit.

2. $pp \to H \to t\bar{t}$: fully leptonic and semi-leptonic channels.

➢ The semi-leptonic channel gives stronger upper limit between ~ [187, 33] fb for m_H = [400, 1000] GeV.

3. $pp \to b\bar{b}H, H \to \tau_h\tau_h$: b-tag category.

➢ The upper limit varies between ~ [22, 4] fb for m_H = [300, 500] GeV.



Future of the pMSSM parameter space

The Higgs sector of Minimal Supersymmetric Standard Model (MSSM) can be parametrised by two parameters: mass of the pseudoscalar (m_A) and the ratio of the vacuum expectation values of the two Higgs doublets ($\tan\beta$). The colour codes for the figures on the left are the following:

✦ Grey : Excluded by Run-II ATLAS and CMS data in $pp \to b\bar{b}H$, $H \to \tau\tau$.

Our projected limits:

✦ Brown: Within projected reach of $pp \to H \to hh \to b\bar{b}\gamma\gamma$.

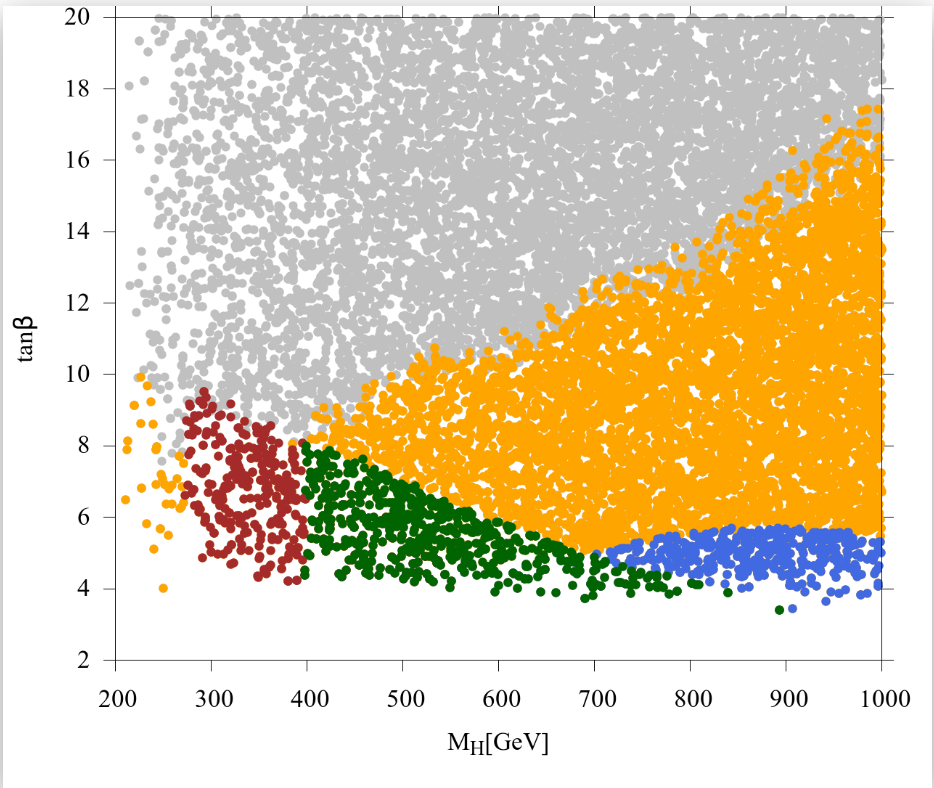
✦ Green: Within projected reach of $pp \to H \to t\bar{t}$.

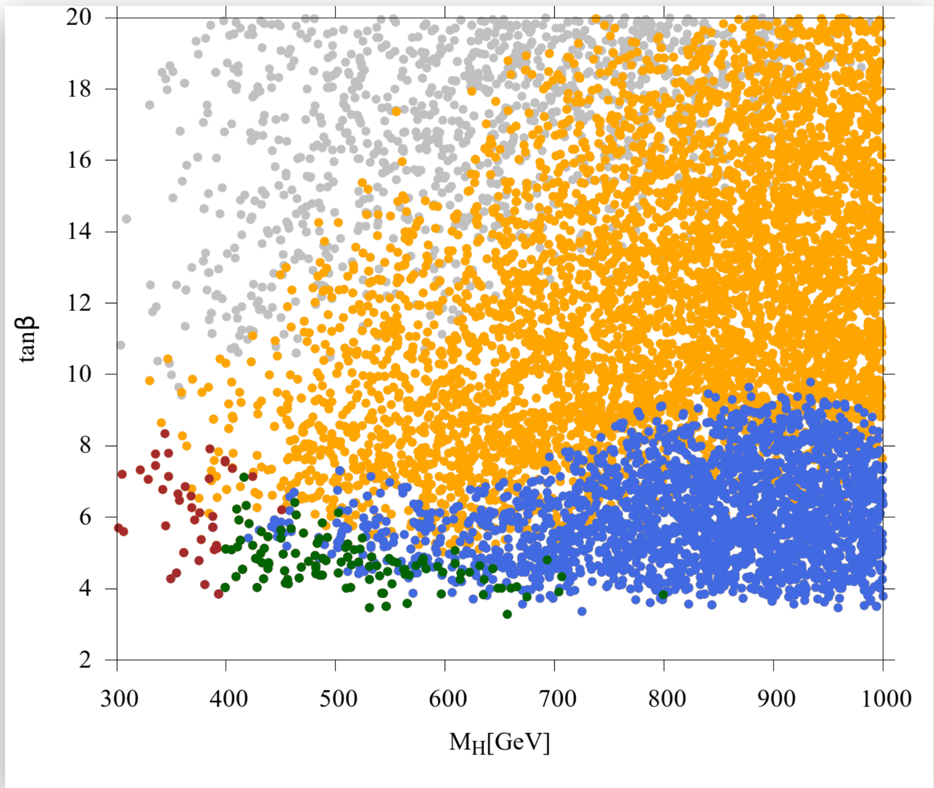
✦ Orange: Within projected reach of $pp \to b\bar{b}H$, $H \to \tau\tau$.

✦ Blue: Remains allowed after the HL-LHC runs.

Left figure: Our projected limit at 95% confidence level (CL) in the $M_A - \tan\beta$ parameter space.

Right figure: The projected limits weaken after adding heavy Higgs to electroweakino (chargino and neutralino) decays, e.g. $pp \to H \to \tilde{\chi}_1^0\,\tilde{\chi}_2^0$. The heavy Higgs to SM branching ratios gets modified in presence of these supersymmetric decays and limits get weaken.





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1. A. Adhikary, S. Banerjee, R. K. Barman, B. Bhattacherjee and S. Niyogi, "Revisiting the non-resonant Higgs pair production at the HL-LHC", JHEP 07 (2018) 116, arXiv: 1712.05346 [hep-ph].
2. A. Adhikary, S. Banerjee, R. K. Barman and B. Bhattacherjee, "Resonant heavy Higgs searches at the HL-LHC", JHEP 1909 (2019) 068, arXiv: 1812.05640 [hep-ph].