Higgs pair production and heavy Higgs searches at the HL-LHC

Amit Adhikary* (IISc), Shankha Banerjee (CERN), Rahool K. Barman (OSU), Biplob Bhattacherjee (IISc), Saurabh Niyogi (GMC)

Abstract

In our work, 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

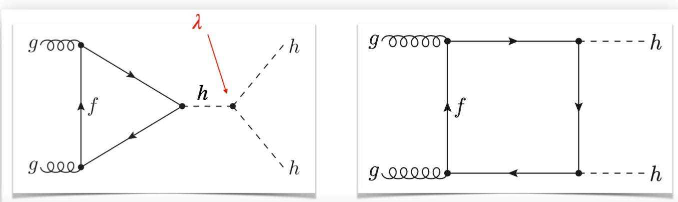
After the discovery of the Higgs boson at the Large Hadron Collider (LHC) by the ATLAS and CMS collaboration in 2012, the following open questions arise:

- **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 study these issues in our work.

Higgs self-coupling

Challenging task

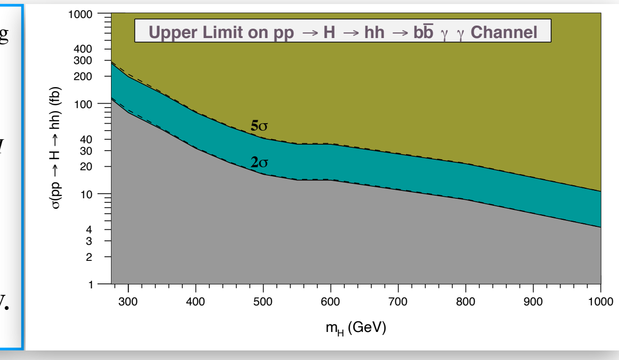


- To directly probe the Higgs boson self coupling λ, we need to observe two Higgs boson production from one Higgs boson, known as non-resonant Higgs pair production, pp → hh.
- **Cancellation between the triangle and box diagram leads to very small rate for Higgs pair production.**

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 $b\bar{b}\gamma\gamma$ 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.**



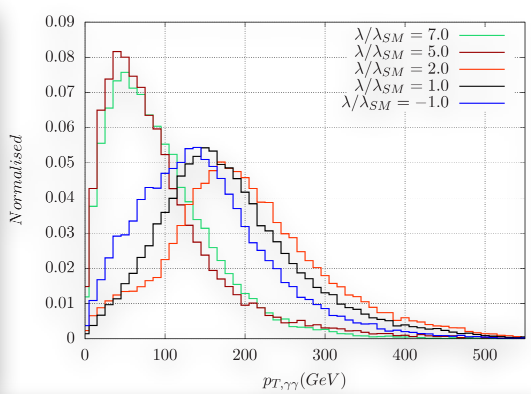
Higgs pair production at the HL-LHC

- HL-LHC: 14 TeV @ 3 ab^{-1}. The following 11 final states are chosen based on the production rate and cleanliness. Cut based and BDT analysis.

1. $b\bar{b}\gamma\gamma$: $S/\sqrt{B}$ **= 1.76**
2. $b\bar{b}\tau_h\tau_h$, $b\bar{b}\tau_h\tau_l$, $b\bar{b}\tau_l\tau_l$: $S/\sqrt{B}$ **= 0.74, 0.49, 0.08**
3. $b\bar{b}WW^* \to$ (a) $b\bar{b}ljj + \not{E}_T$, (b) $b\bar{b}ll + \not{E}_T$: $S/\sqrt{B}$ **= 0.13, 0.62**
4. $WW^*\gamma\gamma \to$ (a) $ljj\gamma\gamma + \not{E}_T$, (b) $ll\gamma\gamma + \not{E}_T$: $S/\sqrt{B}$ **< 1,** S/B **= 0.11, 0.40**
5. $WW^*WW^* \to$ (a) $2l4j + \not{E}_T$, (b) $3l2j + \not{E}_T$ and (c) $4l + \not{E}_T$: **more lepton means lower rate, more jets → lose cleanliness,** $S/\sqrt{B} < 1$

- **Combined Signal significance** ~ 2.1σ .

- Changing the Higgs self-coupling from its SM value, $\kappa_\lambda = \frac{\lambda}{\lambda_{SM}}$.
- 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.**

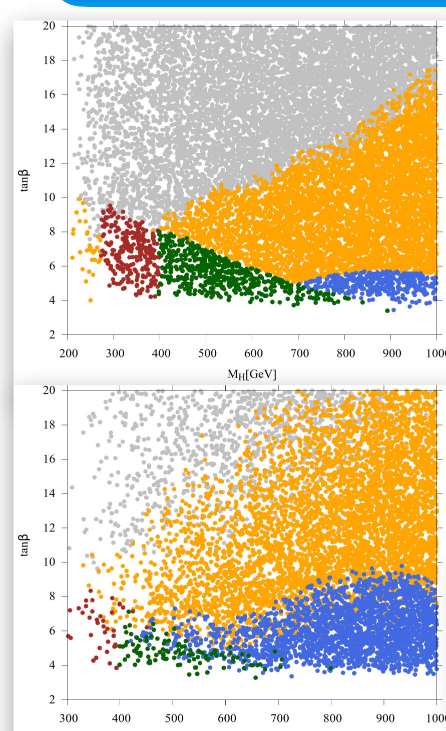


- New physics can contaminate di-Higgs final states via, (a) overlapping Kinematics of new physics process with the SM, (b) production rate is larger than the SM.
- Considered new physics processes:

1. $pp \to hh$ $(+X)$: (a) $pp \to H \to hh$, (b) $pp \to \tilde{q}_L\tilde{q}_L$, $\tilde{q}_L \to q_L\chi_2^0$, $\chi_2^0 \to h\chi_1^0$.
2. $pp \to h + X$: (a) $pp \to A \to Zh$, (b) $pp \to \chi_2^0\chi_1^\pm$, $\chi_2^0 \to h\chi_1^0$, $\chi_1^\pm \to W^\pm\chi_1^0$.
3. $pp \to X$: (a) $pp \to H \to t\bar{t}$, (b) $pp \to \bar{t}bH^+/t\bar{b}H^-$ and (c) $pp \to \tilde{t}_1\tilde{t}_1^*$, $\tilde{t}_1 \to b\chi_1^+ \to bW^+\chi_1^0$.

- **The channel 2(b) contaminates the semi-leptonic $b\bar{b}WW^*$ channel with yield ~ 383 as compared to SM di-Higgs production with yield ~ 134, at the HL-LHC.**

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.**

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

Bottom 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.

Journal Ref:

1. JHEP 1807 (2018) 116, arXiv: 1712.05346.
2. JHEP 1909 (2019) 068, arXiv: 1812.05640.

*amitadhikary@iisc.ac.in

HPNP2021, 25-27 March 2021, Osaka University, Japan