Prospects of non-resonant Higgs pair production at the HL-LHC and HE-LHC

Amit Adhikary
Indian Institute of Science,
Bangalore, India


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Higgs boson has been discovered at the LHC in 2012 which is more or less consistent with Standard Model.

The coupling to gauge bosons and fermions are being measured with great precision.

In Standard Model, the Higgs self coupling ($\lambda$) has a value, fixed by the Higgs mass and VEV.

The value of $\lambda$ determines the structure of the Higgs potential.

There is no direct measurement of Higgs self-coupling till now.
Motivation

- To probe Higgs self coupling → Higgs pair production
- Cancellation between triangle and box diagrams → small production cross-section
Di-Higgs production at HL-LHC

- HL-LHC: 14 TeV @ 3 ab⁻¹, $\sigma(gg \rightarrow hh) = 36.69$ fb [CERN Twiki]
- Channels based on production rate and cleanliness
- 11 possible final states:
  - $b\bar{b}\gamma\gamma$
  - $b\bar{b}\tau\tau \rightarrow (a) \tau_h\tau_h, (b) \tau_h\ell_\tau$ and (c) $\tau_\ell\tau_\ell$
  - $b\bar{b}WW^* \rightarrow (a) b\bar{b}\ell jj + E_T$ and (b) $b\bar{b}\ell\ell + E_T$
  - $WW^*\gamma\gamma \rightarrow (a) \ell jj\gamma\gamma + E_T$ and (b) $\ell\ell\gamma\gamma + E_T$
  - $WW^*WW^* \rightarrow (a) 2\ell 4j + E_T$, (b) $3\ell 2j + E_T$ and (c) $4\ell + E_T$
- Standard cut-based analysis (Follow CMS/ATLAS analysis whenever available)
- Multivariate analysis using Boosted Decision Tree (BDT) algorithm
Di-Higgs production at HL-LHC: The $b\bar{b}\gamma\gamma$ channel

- $pp \rightarrow hh \rightarrow b\bar{b}\gamma\gamma$: Clean channel but low production rate

- Major backgrounds: $b\bar{b}\gamma\gamma$, $t\bar{t}h$, $b\bar{b}h$, $Zh$

- Fake backgrounds: $b\bar{b}jj$, $b\bar{b}j\gamma$, $jj\gamma\gamma$, $c\bar{c}jj$, $c\bar{c}j\gamma$

Cut-based Analysis:

<table>
<thead>
<tr>
<th>Selection cuts</th>
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<tbody>
<tr>
<td>$N_j &lt; 6$</td>
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<tr>
<td>$0.4 &lt; \Delta R_{\gamma\gamma} &lt; 2.0$, $0.4 &lt; \Delta R_{bb} &lt; 2.0$, $\Delta R_{\gamma b} &gt; 0.4$</td>
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<tr>
<td>$100 \text{ GeV} &lt; m_{bb} &lt; 150 \text{ GeV}$</td>
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<tr>
<td>$122 \text{ GeV} &lt; m_{\gamma\gamma} &lt; 128 \text{ GeV}$</td>
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<tr>
<td>$p_{T,bb} &gt; 80 \text{ GeV}$, $p_{T,\gamma\gamma} &gt; 80 \text{ GeV}$</td>
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* Signal Significance, $S/\sqrt{B} = 1.46$

BDT Analysis:

$m_{bb}$, $p_{T,\gamma\gamma}$, $\Delta R_{\gamma\gamma}$, $p_{T,bb}$, $\Delta R_{b_1\gamma_1}$, $p_{T,\gamma_1}$, $\Delta R_{bb}$, $p_{T,\gamma_2}$, $\Delta R_{b_2\gamma_1}$, $\Delta R_{b_2\gamma_2}$, $p_{T,b_1}$, $\Delta R_{b_1\gamma_2}$, $p_{T,b_2}$, $E_T$

* Signal Significance, $S/\sqrt{B} = 1.76$
Di-Higgs production at HL-LHC: The $b\bar{b}\gamma\gamma$ channel

Fig. Normalised distributions of $m_{bb}$, $p_{T,\gamma\gamma}$, $\Delta R_{b1\gamma1}$, $\Delta R_{bb}$
Di-Higgs production at HL-LHC: The other channels

- \(b\bar{b}\tau\tau: t\bar{t}\), Significance: \(\tau_h\tau_h = 0.74, \tau_h\tau_\ell = 0.49, \tau_\ell\tau_\ell = 0.08\)

- \(b\bar{b}WW^*: t\bar{t}\), Significance: leptonic = 0.62, semi-leptonic = 0.13

- \(WW^*\gamma\gamma: t\bar{t}h\), < 5 Signal events, S/B: leptonic = 0.40, semi-leptonic = 0.11

- \(WW^*WW^*\): more lepton → low rate, more jets → lose cleanliness, Significance < 1

- Combined significance \(\sim 2.1\sigma\)

Q. How much contamination is possible once multivariate analysis performed to maximise SM di-Higgs?

Ans. Kinematics of new physics may overlap with SM / Overlap is not significant but overall rate is large
Di-Higgs production at HE-LHC

- HE-LHC: 27 TeV @ 15 ab\(^{-1}\), \(\sigma(gg \rightarrow hh) = 139.9\) fb [CERN Twiki]

- 7 possible final states:
  
  - \(b\bar{b}\gamma\gamma\)
  - \(b\bar{b}\tau\tau \rightarrow \tau_h\tau_h\)
  - \(b\bar{b}WW^* \rightarrow b\bar{b}\ell\ell + E_T\)
  - \(WW^*\gamma\gamma \rightarrow \ell\ell\gamma\gamma + E_T\)
  - \(b\bar{b}ZZ^* \rightarrow \text{(a) } b\bar{b}4\ell + E_T\text{ and } \text{(b) } b\bar{b}2e2\mu + E_T\)
  - \(b\bar{b}\mu\mu\)

- Multivariate analysis:
  
  - Boosted Decision Tree (BDT) algorithm
  - XGBoost toolkit
  - Deep Neural Network (DNN)
Di-Higgs production at HE-LHC: The $b\bar{b}\gamma\gamma$ channel

<table>
<thead>
<tr>
<th>Acceptance cuts</th>
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<tbody>
<tr>
<td>$N_{b\text{ jets}} = 2$, $N_\gamma = 2$</td>
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<tr>
<td>$122$ GeV $&lt; m_{\gamma\gamma} &lt; 128$ GeV</td>
</tr>
<tr>
<td>$\Delta R_{b\gamma} &gt; 0.2$</td>
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<td>$m_{bb} &gt; 50$ GeV</td>
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Signal Significance, $S/\sqrt{B}$:

- BDT = 9.8
- DNN = 10.4
- XGBoost = 13.1 (97% probability cut)
  = 9.7 (95% probability cut)

Kinematic variables in BDT, XGBoost and DNN Analysis:

- $m_{bb}$, $\Delta R_{\gamma\gamma}$, $\Delta R_{bb}$, $p_{T,bb}$, $p_{T,\gamma\gamma}$, $\Delta R_{bb\gamma\gamma}$, $p_{T,hh}$, $\Delta R_{b_1\gamma_1}$, $m_{hh}$, $p_{T,b_{1,2}}$, $p_{T,\gamma_{1,2}}$, $E_T$, $\cos\theta^*$, $\cos\theta_{\gamma_{1}h}$

Fig. Variation of significance and $S/B$ with the probability cut on XGBoost output.
Di-Higgs production at HE-LHC: The $b\bar{b}\gamma\gamma$ channel

Fig. Normalised distributions of $m_{bb}$, $p_{T,\gamma\gamma}$, $p_{T,\gamma_1}$, $m_{hh}$
Di-Higgs production at HE-LHC: The other channels

- $b\bar{b}\tau\tau$: Significance: BDT = 2.8, DNN = 4.3, XGBoost = 4.8

- $b\bar{b}WW^*$: Significance: BDT = 1.5, DNN = 1.4, XGBoost = 2.7, Extra new variables used:
  
  \[
  \log T, \log H, M_T^{(b)}, M_T^{(\ell)}, \sqrt{s_{\text{min}}^{(\ell\ell)}}, \sqrt{s_{\text{min}}^{(bb\ell\ell)}}, p_T, E_T, m_{\ell\ell}, m_{bb}, \\
  \Delta R_{\ell\ell}, \Delta R_{bb}, p_{T,bb}, p_{T,\ell\ell}, \Delta \phi_{bb\ell\ell}.
  \]

- $WW^*\gamma\gamma$: Significance: BDT = 1.7, XGBoost = 2.1

- $b\bar{b}ZZ^*$: $t\bar{t}h$, Combined significance from both final states: BDT = 1.2, XGBoost = 1.4

- $b\bar{b}\mu\mu$: $t\bar{t}$, $b\bar{b}\mu\mu$, Significance < 1

- Combined significance $\sim 10\sigma$ (BDT), $\sim 14\sigma$ (XGBoost)

- Changing $k_\lambda = \lambda/\lambda_{SM}$ modifies the kinematics of di-Higgs final state. Our projections indicate that the HE-LHC would be sensitive to the entire range of $k_\lambda = [-2,4]$ through direct searches in the non-resonant di-Higgs search channels.
Summary

- It is very important to directly probe Higgs pair production to understand the Higgs potential.
- At the HL-LHC, the di-Higgs search yields a combined signal significance of $\sim 2.1\sigma$.
- New physics can contaminate the small number of events from di-Higgs signal.
- $\text{HL-LHC} \rightarrow \text{HE-LHC} : \text{di-Higgs production rate can improve by a factor of } \sim 4$.
- The Higgs pair production can be probed with discovery potential at the HE-LHC.
- At the HE-LHC, di-Higgs search will be sensitive to variation in $k_\lambda = [-2,4]$. 