Combination of searches for resonant and non-resonant Higgs boson pair production in the $b\bar{b}\gamma\gamma$, $b\bar{b}\tau^+\tau^-$, and $bb\bar{b}b$ decay channels with the ATLAS detectors

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On behalf of the ATLAS collaboration

Introduction

What are we looking for?

- In the Standard Model (SM), the Higgs boson (H) can self-interact and results in the simultaneous production of two Higgs bosons ($HH$). The $HH$ production is a very rare process with a SM predicted cross-section three orders of magnitude smaller than the single Higgs production.

I. Non-resonant $HH$ production

- The dominant SM $HH$ production mode is the gluon–gluon fusion (ggF) process with a cross-section of 31.05 fb at 13 TeV with $m_H=125$ GeV. The next leading production mode proceeds with the vector boson fusion (VBF) with a cross-section of 1.726 fb.

- The SM ggF and VBF productions are referred to as the non-resonant $HH$ production. They provide a direct probe of the Higgs trilinear self-coupling ($\kappa_3 = \lambda_{HHH}/\lambda_{SM}$), which affects the $HH$ production cross-section. A deviation from the SM predicted self-coupling value may point to physics Beyond the Standard Model (BSM).

II. Resonant $HH$ production

- $HH$ production can be mediated by a heavy scalar (spin-0) resonance $X$ as predicted by several BSM models (e.g. hMSSM).

- For the resonant production, only the dominant ggF production mode is considered.

Combination input analyses

- ATLAS has released the $HH$ combination result using the full Run 2 (139 fb$^{-1}$) dataset of $pp$ collisions at $\sqrt{s}=13$ TeV.

- Statistically independent decay channels are combined to maximize sensitivity:

  - Non-resonant production: $b\bar{b}\tau^+\tau^-$, $b\bar{b}\gamma\gamma$
  - Resonant production: $bb\bar{b}b$, $b\bar{b}\tau^+\tau^-$, $bb\gamma\gamma$

(Reference: ATLAS-CONF-2021-035)

- $b\bar{b}\gamma\gamma$: Small branching ratio, but clean diphoton signature for triggering. (Reference: ATLAS-CONF-2021-016)

- $b\bar{b}\tau^+\tau^-$: Higher production rate than $b\bar{b}\gamma\gamma$ and lower background rates than $bb\bar{b}b$. However, tau leptons can decay in many ways, making them sometimes tricky to identify. (Reference: ATLAS-CONF-2021-030)

Systematic Uncertainties

In the combination, common systematic sources are correlated across channels.

<table>
<thead>
<tr>
<th>Source</th>
<th>Channels</th>
<th>Correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity</td>
<td>$b\bar{b}\tau^+\tau^-$, $bb\gamma\gamma$</td>
<td>Correlated</td>
</tr>
<tr>
<td>Pile-up</td>
<td>$b\bar{b}\tau^+\tau^-$, $bb\gamma\gamma$</td>
<td>Correlated</td>
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<tr>
<td>Electron</td>
<td>$b\bar{b}\tau^+\tau^-$, $bb\gamma\gamma$</td>
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<tr>
<td>Muon</td>
<td>$b\bar{b}\tau^+\tau^-$, $bb\gamma\gamma$</td>
<td>-</td>
</tr>
<tr>
<td>Tau</td>
<td>$b\bar{b}\tau^+\tau^-$, $bb\gamma\gamma$</td>
<td>-</td>
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<tr>
<td>Photon</td>
<td>$b\bar{b}\tau^+\tau^-$, $bb\gamma\gamma$</td>
<td>-</td>
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<tr>
<td>JES</td>
<td>$b\bar{b}\tau^+\tau^-$, $bb\gamma\gamma$</td>
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<tr>
<td>MET</td>
<td>$b\bar{b}\tau^+\tau^-$, $bb\gamma\gamma$</td>
<td>Partly Correlated</td>
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<tr>
<td>Boosted JES</td>
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<td>MET</td>
<td>$b\bar{b}\tau^+\tau^-$, $bb\gamma\gamma$</td>
<td>Correlated</td>
</tr>
</tbody>
</table>

*Correlated uncertainties

Results

Limit on non–resonant $HH$ production

- The observed (expected) exclusion upper limits on the signal strength from $b\bar{b}\gamma\gamma$ and $b\bar{b}\tau^+\tau^-$ lie at 4.3 (3.9) and 4.6 (5.7) times the SM prediction individually, and goes down to 3.1 (3.1) when combined.

- Improved by a factor of three with respect to the previous ATLAS results using partial Run 2 dataset.

Constraints on $\kappa_3$

- The cross-section upper limits on the non–resonant production are set as a function of the Higgs self-coupling modifier ($\kappa_3$). Exclusion on $\kappa_3$ is derived from the intersection with the theory prediction.

- The value of $\kappa_3$ has been excluded outside the range $-1.0 \leq \kappa_3 \leq 6.6$ ($-1.2 \leq \kappa_3 \leq 7.2$) in observation (expectation).

Limit on resonant $HH$ production

- Upper limits are set on the production rates of the heavy scalar $X$ decaying into Higgs boson pairs as a function of its mass $m_X$.

- The $b\bar{b}\gamma\gamma$ search is most sensitive at low $m_X$, the $b\bar{b}\tau^+\tau^-$ search is most sensitive in the 400–800 GeV range and the $bb\bar{b}b$ search dominates for high $m_X$, demonstrating the complementary of these searches.

Reference: ATLAS-CONF-2021-052