Search for Di-Higgs Production at ATLAS

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Di-Higgs makes possible measurement of Higgs self coupling and hence fully reconstruct Higgs potential:

\[ V(\phi) = \frac{1}{2} \mu^2 \phi^2 + \frac{1}{4} \lambda \phi^4 = \lambda v^2 h^2 + \lambda v h^3 + \frac{1}{4} \lambda h^4 \]

- Mass term
- Self coupling terms

Destructive interference between diagrams reduces cross section

Measurements of \( p_T(H) \) can enhance sensitivity to \( \lambda \)

- Rare process: 33.4 fb\(^{-1}\) at 13 TeV
Various models expect a new particle decaying into a Higgs boson pair
Can reconstruct each Higgs boson and di-Higgs resonance
Randall-Sundrum graviton (spin 2) $G \rightarrow HH$
2HDM CP-even heavy Higgs boson $X \rightarrow HH$
Which decays?

High branching fractions

Precise $H \rightarrow \gamma\gamma$ mass reconstruction

Run 1 Results:

<table>
<thead>
<tr>
<th>Analysis</th>
<th>$\gamma\gamma bb$</th>
<th>$\gamma\gamma WW^*$</th>
<th>$b\bar{b}\tau\tau$</th>
<th>$bbbb$</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Upper limit on the cross section [pb]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Expected</td>
<td>1.0</td>
<td>6.7</td>
<td>1.3</td>
<td>0.62</td>
<td>0.47</td>
</tr>
<tr>
<td>Observed</td>
<td>2.2</td>
<td>11</td>
<td>1.6</td>
<td>0.62</td>
<td>0.69</td>
</tr>
<tr>
<td></td>
<td>Upper limit on the cross section relative to the SM prediction</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Expected</td>
<td>100</td>
<td>680</td>
<td>130</td>
<td>63</td>
<td>48</td>
</tr>
<tr>
<td>Observed</td>
<td>220</td>
<td>1150</td>
<td>160</td>
<td>63</td>
<td>70</td>
</tr>
</tbody>
</table>
b tagging

- b-Hadrons decay with a lifetime of $\tau \approx 450\mu m$
- Secondary vertex and lifetime-based ID
- Information combined using MVA algorithms

**Efficiency measured in situ using $tt$ events**

**Excellent light and charm rejection**

- Explicit secondary decay vertex
- Large impact parameter

![Diagram of b tagging with secondary vertex and displaced tracks](image)
Data split into resolved and boosted regions

- b jet triggers for resolved and fat-jet trigger for boosted

Resolved region ($260 < M < 1400$ GeV) has 4 clearly separated b tagged R=0.4 jets

Boosted region ($800 < M < 3000$ GeV) has 2 R=1.0 fat-jets each containing 1 or 2 tagged R=0.2 track-jets
Main multijet background taken from data using 4 jet, 2 tag events
Weights applied by comparing 2 tag to 4 tag events in the sideband to account for different jet multiplicities and b-tagging efficiency
Validation region used for checking background modelling
Multijet background taken from lower tagged samples in sideband
Background modelling checked in the validation region
2,3,4 tagged signal regions
HH → bbb

- No clear excess observed
- Largest deviation for resonant search is 3.6σ local significance at M=280 GeV (2.3σ global)
- Slightly tighter limits on non-resonant limits than expected.

Resonant

Not resonant. 95% CL limits as ratio to SM

<table>
<thead>
<tr>
<th></th>
<th>Observed</th>
<th>$-2\sigma$</th>
<th>$-1\sigma$</th>
<th>Expected</th>
<th>$+1\sigma$</th>
<th>$+2\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>13.0</td>
<td>11.1</td>
<td>14.9</td>
<td>20.7</td>
<td>30.0</td>
<td>43.5</td>
</tr>
</tbody>
</table>
Tau tagging

Hadronic $\tau$ id based on
- collimated jet
- 1 or 3 tracks
- Both EM and Had energy

In situ calibration using Z and events with $\tau$s

Probability of misidentifying jets as $\tau$s also measured from data

Good separation of taus from background
\( \tau_{lep}\tau_{had} \) and \( \tau_{had}\tau_{had} \) channels analysed

Major background from \( t\bar{t} \to b\tau\nu b\tau\nu \) taken from Monte Carlo

\( t\bar{t} \) background with jets faking \( \tau \)s taken from data (\( \tau_{lep}\tau_{had} \)) or from Monte Carlo corrected for jet to \( \tau \) fake rate as measured from data (\( \tau_{had}\tau_{had} \)).

Validate fake \( \tau \) treatment by looking at same sign control regions

\( Z \to \tau\tau + \) heavy flavour Monte Carlo normalised on \( Z \to \mu\mu + \) heavy flavour control region

Combine kinematic information using boosted decisions trees (next slide)

**Same Sign** \( \tau_{lep}\tau_{had} \)

**Same Sign** \( \tau_{had}\tau_{had} \)
HH → bbττ: Boosted Decision Tree (BDT)

Combine masses, $E_T^{\text{miss}} +$ angular variables to discriminate signal and background

Non-resonant

Resonant e.g. G(500)

Different training for each mass + non-resonant
HH $\rightarrow$ bb$\tau\tau$: Results

- No excess seen in either channel
- Rules out a wide parameter space in BSM models
- Non-resonant limit is the best individual channel to date

Non Resonant limit

<table>
<thead>
<tr>
<th>Channel</th>
<th>Observed</th>
<th>$-1\sigma$</th>
<th>Expected</th>
<th>$+1\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_{lep}$ $\tau_{had}$</td>
<td>$\sigma(HH \rightarrow bb\tau\tau)$ [fb]</td>
<td>57.3</td>
<td>49.9</td>
<td>69.2</td>
</tr>
<tr>
<td></td>
<td>$\sigma/\sigma_{SM}$</td>
<td>23.5</td>
<td>20.5</td>
<td>28.4</td>
</tr>
<tr>
<td>$\tau_{had}$ $\tau_{had}$</td>
<td>$\sigma(HH \rightarrow bb\tau\tau)$ [fb]</td>
<td>39.9</td>
<td>30.5</td>
<td>42.4</td>
</tr>
<tr>
<td></td>
<td>$\sigma/\sigma_{SM}$</td>
<td>16.4</td>
<td>12.5</td>
<td>17.4</td>
</tr>
<tr>
<td>Combination</td>
<td>$\sigma(HH \rightarrow bb\tau\tau)$ [fb]</td>
<td>30.9</td>
<td>26.0</td>
<td>36.0</td>
</tr>
<tr>
<td></td>
<td>$\sigma/\sigma_{SM}$</td>
<td>12.7</td>
<td>10.7</td>
<td>14.8</td>
</tr>
</tbody>
</table>
2 photons +2 jets (1 or 2 b-tags)
Parameterised fit to data distribution to obtain limits
Set limits on resonant + non-resonant production
Also set limits on Higgs self coupling
No significant excess seen
Observed non-resonant limit $22 \times \text{SM}$ (28 expected)
2 photons +1 e or µ + 2 jets
Parameterised fit to data distribution to obtain limits
$p_T^{\gamma\gamma} > 100$ GeV for non-resonant and higher mass search
No significant excess seen
Observed non-resonant limit $230 \times$ SM (160 expected)
 Searches presented of di-Higgs production in 4 channels using 13 TeV data

Best limit on non-resonant production is $13 \times$ the SM

Plenty more results to come $\rightarrow 3$-$4 \times$ more data from Run II (2017+2018)