HH non-resonant searches at the LHC

XXVII Workshop on Deep-Inelastic Scattering and Related Subjects - DIS2019

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For ATLAS and CMS Collaborations
Di-Higgs in SM

- Higgs couplings to fermions and gauge bosons so far compatible with SM.
- What happens to the Higgs Self coupling?
- Are they relevant, how can we measure them?

\[ V^{SM}(h) = \frac{m_h^2}{2} h^2 + \frac{m_h^2 v}{2 v^2} h^3 + \frac{1}{4} \frac{m_h^2}{2 v^2} h^4 \]

Trilinear Coupling: \( \lambda_{hhh} = \frac{m_h^2}{2 v^2} \)
Higgs so far

ATLAS-CONF-2019-005

CMS-HIG-17-031

ATLAS Preliminary

\[ \sqrt{s} = 13 \text{ TeV}, \, 24.5 - 79.8 \text{ fb}^{-1} \]

\[ m_H = 125.09 \text{ GeV}, \, |y_H| < 2.5 \]

\[ p_{\text{SM}} = 76\% \]

- **ggF**: $1.04 \pm 0.09$ (stat.) $\pm 0.07$ (syst.) $+0.07$ (SM)
- **VBF**: $1.21 \pm 0.22$ (stat.) $+0.18$, $-0.17$ (syst.) $-0.06$ (SM)
- **WH**: $1.30 \pm 0.38$ (stat.) $+0.26$, $-0.27$ (syst.) $-0.27$ (SM)
- **ZH**: $1.05 \pm 0.31$ (stat.) $+0.19$, $-0.17$ (syst.)
- **ttH+H**: $1.21 \pm 0.24$ (stat.) $+0.20$, $-0.18$ (syst.)

Cross-section normalized to SM value

CMS

35.9 fb$^{-1}$ (13 TeV)

\[ \frac{m_{F}^2}{\sqrt{K_{F}V}} \]

\[ \text{Ratio to SM} \]

Particle mass [GeV]
In SM, non-resonant production

- Destructive interference of box and triangle contributions
- Cross-section is very low
- Modification to $\kappa \lambda = \lambda_{HHH} / \lambda_{SM}$.
- Measurement of sub-leading channels are very difficult

\[ \sigma_{(gg \rightarrow HH)}^{SM} = 33.53 \text{ fb}^{+4.3\%}_{-6.0\%} \text{(scale)} \pm 5.9\% \text{ (PDF)} \]
\[ \sigma_{(VBF HH)}^{SM} = 1.64^{+0.05}_{-0.06} \text{ fb} \]
Di-Higgs Decays

- $bbbb$: highest BR, high QCD and $tt$ contamination
- $bbWW$: high BG, large irreducible $tt$ background
- $bb\tau\tau$: relatively low background and low BR
- $bb\gamma\gamma$: high purity, very low BR
hh $\rightarrow$ 4b
hh $\rightarrow$ 4b (ATLAS)

- Non-resonant search uses ‘resolved’ channel:
- Construct two Higgs boson candidates from the 4 jets identified most probably to contain a b-hadron.
- Dominant background is multijet events, estimated by a data-driven method
- Shape estimated by a region with fewer b-tagged jets
- Observed (exp.) 95% CL upper limit $\sigma(pp \rightarrow HH \rightarrow bbbb) < 147$ (234) fb.

$\frac{\sigma_{HH}}{\sigma_{SM}}$ HH limits:

<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>12.9</td>
<td>11.1</td>
<td>14.9</td>
<td>20.7</td>
<td>30.0</td>
<td>43.6</td>
</tr>
</tbody>
</table>
hh → 4b (CMS)

- Final state of 4 identified b-jets.
- A hemisphere mixing technique is used to provide samples for BDT training and for predicting the background BDT shape.
- BDT modelling checked using data sidebands which exclude m(bb) around the Higgs boson mass.
- Observed (Exp.) 95% CL upper limit \( \sigma_{HH}/\sigma_{SM} \) HH = 75 (37).
- Cross-section limits (fb):

<table>
<thead>
<tr>
<th>Category</th>
<th>Observed</th>
<th>Expected</th>
<th>-2 s.d.</th>
<th>-1 s.d.</th>
<th>+1 s.d.</th>
<th>+2 s.d.</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM HH → bbbb</td>
<td>847</td>
<td>419</td>
<td>221</td>
<td>297</td>
<td>601</td>
<td>834</td>
</tr>
</tbody>
</table>

CMS-HIG-17-017
hh $\rightarrow$ bb$\tau\tau$
hh \rightarrow bb\tau\tau (CMS)

- Select events with 1+ isolated $\tau_{\text{had}}$ with a second lepton of opposite charge ($e/\mu$ or $\tau_{\text{had}}$).
- Categorise according to 1/2 b-jets.
- Boosted category for events with a Higgs-bb jet candidate.
- BDT discriminant trained on kinematic variables used to reduce the $tt$ background in the semi-leptonic channel.

$m_{T2}$ used for signal-background separation - bounded by the top mass for $tt$ processes

- Observed (Expected) 95% CL upper limit $\sigma_{HH}/\sigma_{SM} \text{HH} = 30(25)$. 

PLB 778(2018)101
hh $\rightarrow$ bb$\tau\tau$ (ATLAS)

- Final states with an e/\(\mu\) and hadronically decaying \(\tau\) candidate (\(\tau_{had}\)) or two \(\tau_{had}\) candidates, in association with two b-jets and missing ET.
  - Two search channels (\(\tau_{lep}\)\(\tau_{had}\) and \(\tau_{had}\)\(\tau_{had}\))
- Background:
  - Primary: \(tt\), QCD multi-jets, \(Z+HF\) (b, c)
  - Secondary: Single Higgs : ZH
- Discrimination signal/background: BDT

<table>
<thead>
<tr>
<th></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</td>
<td>49.9</td>
<td>69</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>40.0</td>
<td>30.6</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>36.1</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>
$hh \rightarrow bb\gamma\gamma$
\( hh \rightarrow bb\gamma\gamma \) (CMS)

- 2D fit of the diphoton and di(b) jet invariant mass distributions.
- Estimate the \( n\gamma+\text{jet} \) continuum from the mass sidebands.
- Signal purity estimated by a BDT using jet b-tagging scores, the HH system helicity angles and H candidate \( pT \).

- Observed (expected) 95% CL upper limit \( \sigma(pp\rightarrow HH\rightarrow \gamma\gamma bb) < 2.0 \text{ fb} \) (1.6 fb), 24 (19)\( \times \) \( \sigma \) SM HH.
- 95% CL limits on coupling: \(-11 < \kappa\lambda < 17\)
**hh → bbγγ (ATLAS)**

- Events with 2 isolated photons and two jets with an invariant mass compatible with $m_H$ and at least one b-tag.
- Categorise according to the number of b-tagged jets.

95% CL limits on coupling: $-8.2 < \kappa \lambda < 13.2$, in line with expectation.

<table>
<thead>
<tr>
<th>$\sigma_{gg\rightarrow HH}$ [pb]</th>
<th>Observed</th>
<th>Expected</th>
<th>$-1\sigma$</th>
<th>$+1\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>As a multiple of $\sigma_{SM}$</td>
<td>22</td>
<td>28</td>
<td>20</td>
<td>40</td>
</tr>
</tbody>
</table>

**JHEP 11(2018)040**
hh → bblvlvlv
hh $\rightarrow$ bblνlν (CMS)

- Exclude di-lepton events in case the mass is compatible with Z boson
- Large irreducible background from ttbar processes
- Deep Neural Network used to aid discrimination of signal against background.
- No significant excess over background prediction
- Observed (exp.) 95% CL upper limit signal strength: \( \text{obs(exp)} = 79(89) \times \text{SM} \)
hh \rightarrow bbWW (ATLAS)

- Search for bbllqq final state only
- Events passing e/\mu triggers, with two b-tagged jets,
- Construct W boson candidate from untagged jets, reconstruct W_{lept} with l+E miss
- Further kinematic requirements suppress tt; constraints from data control regions.
- Observed 95% CL upper limit \( \sigma(pp\rightarrow HH\rightarrow bbllqq) < 2.5 \text{ pb}, \sim 300 \times \sigma \text{ SM HH (at 95% CL)} \)
- Coupling limit: \(-11 < \kappa \lambda < 17\) at 95% CL.
Combination
Combination (ATLAS)

ATLAS-CONF-2018-043

$\kappa_\lambda = \frac{\lambda_{HHH}}{\lambda_{SM}}$

Limits on $k_\lambda$

Observed $-5.0 < k_\lambda < 12.1$

Expected $-5.8 < k_\lambda < 12.0$

Observed 6.7

Expected 10.4
Combination (CMS)

Limits on $k_{\lambda}$

- Observed $-11.8 < k_{\lambda} < 18.8$
- Expected $-7.1 < k_{\lambda} < 13.6$

Limits on Signal Strength

- Observed 22.2
- Expected 12.8
HL-LHC Projections
HH at HL-LHC

CMS-PAS-FTR-18-019

3000 fb\(^{-1}\) of data
ATLAS, significance of 3.0\(\sigma\)
CMS, significance 2.6\(\sigma\)

ATL-PHYS-PUB-2018-053
Summary

• Various Di-Higgs searches for Run-II for both CMS and ATLAS.
• Not sensitive to SM production yet.
• Apart from this, various BSM scenarios are being tested.
• Limits from the combination increasing.
• New search channels are being investigated
• Much to come in the future, Run-3 and HL-LHC
• ATLAS and CMS now have \( \sim 150 \) fb\(^{-1}\) of data recorded from LHC Run-2.
• Many powerful 13 TeV results to come!
Thank you all for you attention
BackUp
hh $\rightarrow$ 4b (ATLAS)

- QCD Multijets bkg (95% in SR): shape from 2-tags selection: `=2b` + `=2j` weight 2 >> 4-tags: sidebands (validation CR) (add. jet activity, and kinematics diff.)
- tt bkg (5% in SR) shape from simulation
- Norm. bkg: fit m4j in sidebands

```
ATLAS
$\sqrt{s} = 13$ TeV, 24.3 fb$^{-1}$
Resolved, 2016
```
Hemisphere mixing

- Similarity condition ~ multi-dimentional distance.
- Destroys any correlation in the jet distribution
- Decay of a heavy object into jet pairs, is washed out in the artificial samples
- Unaffected by the presence of a small signal contamination in the original data
- Verified by signal injection tests
- Signal fraction 0.1%, — 0.0001%
**hh $\rightarrow$ bbττ (ATLAS)**

Discrimination signal/background: BDT

<table>
<thead>
<tr>
<th>Variable</th>
<th>$\tau_{lep}\tau_{had}$ channel (SLT resonant)</th>
<th>$\tau_{lep}\tau_{had}$ channel (SLT non-resonant &amp; LTT)</th>
<th>$\tau_{had}\tau_{had}$ channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{HH}$</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$m_{MMC}$</td>
<td></td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>$m_{\tau\tau}$</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>$m_{bb}$</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>$\Delta R(\tau, \tau)$</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>$\Delta R(b, b)$</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>$E_T^{\text{miss}}$</td>
<td></td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>$E_T^{\text{miss}} \phi$</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_W$</td>
<td></td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>$\Delta \phi(H, H)$</td>
<td></td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>$\Delta p_T(\text{lep}, \tau_{had-vis})$</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sub-leading $b$-jet $p_T$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
**bbγγ (ATLAS)**

Loose Selection:
- $p_T j > 40$, 25 GeV
- $80 < m_{jj} < 140$ GeV

Tight Selection:
- $p_T j > 100$, 30 GeV
- $90 < m_{jj} < 140$ GeV
## HH at HL-LHC

Upper limit at the 95% confidence level (CL) and the significance for the SM HH signal

<table>
<thead>
<tr>
<th>Channel</th>
<th>Significance</th>
<th>95% CL limit on $\sigma_{HH}/\sigma_{HH}^{SM}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>bbbb</td>
<td>0.95</td>
<td>1.2</td>
</tr>
<tr>
<td>bb$\tau\tau$</td>
<td>1.4</td>
<td>1.6</td>
</tr>
<tr>
<td>bbWW($\ell\nu\nu$)</td>
<td>0.56</td>
<td>0.59</td>
</tr>
<tr>
<td>bb$\gamma\gamma$</td>
<td>1.8</td>
<td>1.8</td>
</tr>
<tr>
<td>bbZZ($\ell\ell\ell\ell$)</td>
<td>0.37</td>
<td>0.37</td>
</tr>
<tr>
<td>Combination</td>
<td>2.6</td>
<td>2.8</td>
</tr>
</tbody>
</table>

**Note:** CMS-PAS-FTR-18-019

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<table>
<thead>
<tr>
<th>Channel</th>
<th>Statistical-only</th>
<th>Statistical + Systematic</th>
</tr>
</thead>
<tbody>
<tr>
<td>$HH \rightarrow b\bar{b}b\bar{b}$</td>
<td>1.4</td>
<td>0.61</td>
</tr>
<tr>
<td>$HH \rightarrow b\bar{b}\tau^+\tau^-$</td>
<td>2.5</td>
<td>2.1</td>
</tr>
<tr>
<td>$HH \rightarrow b\bar{b}\gamma\gamma$</td>
<td>2.1</td>
<td>2.0</td>
</tr>
<tr>
<td>Combined</td>
<td>3.5</td>
<td>3.0</td>
</tr>
</tbody>
</table>

**Note:** ATL-PHYS-PUB-2018-053
**Di-Higgs Production**

- **Gluon fusion** Main production channel
- Measurement of sub-leading channels are very difficult
$hh \rightarrow bb\tau\tau$ (ATLAS)

- **Final Discriminant Variable**

- **Yields**

<table>
<thead>
<tr>
<th></th>
<th>$\tau_{lep}\tau_{had}$ channel</th>
<th>$\tau_{had}\tau_{had}$ channel</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(SLT)</td>
<td>(LTT)</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>$17800 \pm 1100$</td>
<td>$1475 \pm 94$</td>
</tr>
<tr>
<td>Single top</td>
<td>$1130 \pm 110$</td>
<td>$72.9 \pm 7.6$</td>
</tr>
<tr>
<td>Multi-jet fake-$\tau_{had}$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$t\bar{t}$ fake-$\tau_{had}$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Fake-$\tau_{had}$</td>
<td>$9000 \pm 1100$</td>
<td>$475 \pm 76$</td>
</tr>
<tr>
<td>$Z \rightarrow \tau\tau + (cc, bc, bb)$</td>
<td>$416 \pm 97$</td>
<td>$117 \pm 28$</td>
</tr>
<tr>
<td>Other</td>
<td>$197 \pm 32$</td>
<td>$14.5 \pm 2.3$</td>
</tr>
<tr>
<td>SM Higgs</td>
<td>$38 \pm 10$</td>
<td>$4.1 \pm 1.0$</td>
</tr>
<tr>
<td>Total Background</td>
<td>$28610 \pm 180$</td>
<td>$2159 \pm 46$</td>
</tr>
</tbody>
</table>

|                  | Data                            | $G_{KK}(300 \text{ GeV}, k/M_{Pl} = 1)$ | $G_{KK}(500 \text{ GeV}, k/M_{Pl} = 1)$ | $G_{KK}(1000/800(\text{LTT}) \text{ GeV}, k/M_{Pl} = 1)$ | $G_{KK}(300 \text{ GeV}, k/M_{Pl} = 2)$ | $G_{KK}(500 \text{ GeV}, k/M_{Pl} = 2)$ | $G_{KK}(1000/800(\text{LTT}) \text{ GeV}, k/M_{Pl} = 2)$ | $X(300 \text{ GeV})$ | $X(500 \text{ GeV})$ | $X(1000/800(\text{LTT}) \text{ GeV})$ | NR $HH$ |
|------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
|                  | $28612$                         | $23.6 \pm 3.7$                 | $7.5 \pm 1.2$                  | $13.1 \pm 2.6$                 | $42.4 \pm 6.4$                 | $9.9 \pm 1.5$                  | $36.3 \pm 7.0$                  | $2.6 \pm 0.4$                  | $1.06 \pm 0.16$                 | $2.11 \pm 0.43$                 | $327 \pm 50$                    | $82 \pm 13$                    | $240 \pm 46$                   |
|                  | $2161$                          | $193 \pm 29$                  | $39.7 \pm 6.1$                 | $187 \pm 36$                   | $39.1 \pm 6.3$                 | $11.8 \pm 1.9$                 | $17.9 \pm 3.6$                 | $8.6 \pm 1.3$                  | $3.63 \pm 0.56$                 | $7.9 \pm 1.6$                   | $3.41 \pm 0.52$                 | $0.88 \pm 0.13$                | $2.84 \pm 0.54$                |
|                  |                                 | $0.0267 \pm 0.0041$           | $0.0228 \pm 0.0035$            | $0.0222 \pm 0.0044$            | $0.99 \pm 0.13$                | $0.225 \pm 0.033$              | $0.75 \pm 0.14$                |
ATLAS combination

- **Non-resonant, Run 1**

\[ h(bb)h(\tau\tau), h(\gamma\gamma)h(WW^*), h(\gamma\gamma)h(bb), h(bb)h(bb) \]

<table>
<thead>
<tr>
<th>Channel</th>
<th>Experiment</th>
<th>Observed (pb)</th>
<th>Expected (pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\gamma\gamma b\bar{b} )</td>
<td>ATLAS</td>
<td>2.2</td>
<td>1.0</td>
</tr>
<tr>
<td>(\gamma\gamma b\bar{b} )</td>
<td>CMS</td>
<td>0.71</td>
<td>0.60</td>
</tr>
<tr>
<td>(\tau\tau b\bar{b} )</td>
<td>ATLAS</td>
<td>1.6</td>
<td>1.3</td>
</tr>
<tr>
<td>(\tau\tau b\bar{b} )</td>
<td>CMS</td>
<td>0.59</td>
<td>0.94</td>
</tr>
<tr>
<td>(b\bar{b} b\bar{b} )</td>
<td>ATLAS</td>
<td>0.62</td>
<td>0.62</td>
</tr>
<tr>
<td>(\gamma\gamma WW^* )</td>
<td>ATLAS</td>
<td>11.0</td>
<td>6.7</td>
</tr>
<tr>
<td><strong>Combination</strong></td>
<td>ATLAS</td>
<td>0.69 (70xSM)</td>
<td>0.47 (48xSM)</td>
</tr>
</tbody>
</table>