Double Higgs boson searches overview

Dinko Ferenček*
Ruđer Bošković Institute, Zagreb
on behalf of
ATLAS and CMS Collaborations

LHC Days in Split
September 17, 2018
Split, Croatia

*supported by
Introduction and motivation

- Di-Higgs production provides an important test of the Standard Model (SM) electroweak symmetry breaking

Higgs field potential

Potential expanded around minimum

\[ V^{\text{SM}}(h) = \frac{m_h^2}{2} h^2 + \lambda_3^{\text{SM}} h^3 + \lambda_4^{\text{SM}} h^4 \]

- mass term
- trilinear self-coupling
- quartic self-coupling

\[
\lambda_3^{\text{SM}} = \frac{m_h^2}{2v^2} \quad \lambda_4^{\text{SM}} = \frac{m_h^2}{8v^2}
\]
Di-Higgs production

- In general, di-Higgs production can be resonant or non-resonant

SM di-Higgs production dominated by non-resonant gluon-gluon fusion production

- Two diagrams below interfere destructively

At the leading order (LO), probing the trilinear Higgs coupling $\lambda_3$ requires di-Higgs production

In addition, the SM di-Higgs production provides access to the top-Higgs Yukawa coupling $y_t$

$\sigma(pp \rightarrow HH)_{\text{SM}}@13$ TeV $\sim 30$ fb

$\sim 1000 \times$ less than single Higgs
Di-Higgs production (cont’d)

- BSM production can be resonant and non-resonant

Resonant BSM production proceeds through the production of a new heavy resonance $X$ that decays into two Higgs bosons
- Production cross section significantly enhanced

Non-resonant BSM production can arise from anomalous couplings $\kappa_\lambda$ and additional contact interactions → Can lead to large modifications in the production cross section and shapes of kinematic distributions
Final state signatures

- Higgs boson decay modes

\[ h \rightarrow b\bar{b} \]
most frequent

Di-Higgs final state signatures

- Searches prioritize on high branching fractions and clean final states
- Main final states include b jets → b tagging algorithms play an important role

\[ m_h = 125 \text{ GeV} \]
Recent experimental results

• In the following slides recent experimental results for different final states from ATLAS and CMS will be presented
  • Results mostly based on 2015 and 2016 data

• Due to limited time, focus on the final results without going into various analysis details
  • Trigger strategy, Monte Carlo sample production, event selection, background estimation, definition of sideband and control regions, use of MVA techniques,…

• More details can be found in provided references
hh→4b

**References**

<table>
<thead>
<tr>
<th>ATLAS</th>
<th>arXiv:1804.06174</th>
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</thead>
</table>
Both resonant and non-resonant signatures being looked for
Final state topology can be resolved, semi-resolved or merged

Resolved
Semi-resolved
Merged
Resolved resonant

Resolved

Resolved non-resonant
hh→4b (merged)

Semi-resolved

Merged

ATLAS

Events / 0.1 TeV

ATLAS

Events / 0.1 TeV

ATLAS

Events / 0.1 TeV

(a) Two-tag

(b) Three-tag

(c) Four-tag

Data

Multijet

tt

Scalar (2 TeV)

G_{1,2} (2 TeV k_{T}>1) × 30

Stat+Syst Uncertainties

G_{0} (2 TeV k_{T}>1) × 30

Stat+Syst Uncertainties

Data

Multijet

tt

Scalar (2 TeV)

G_{1,2} (2 TeV k_{T}>1) × 30

Stat+Syst Uncertainties

G_{0} (2 TeV k_{T}>1) × 30

Stat+Syst Uncertainties

Data

Multijet

tt

Scalar (2 TeV)

G_{1,2} (2 TeV k_{T}>1) × 30

Stat+Syst Uncertainties

G_{0} (2 TeV k_{T}>1) × 30

Stat+Syst Uncertainties

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

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

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

September 17, 2018

LHC Days in Split
**Resolved resonant**

- **LHC Days in Split**
- **September 17, 2018**

**Merged resonant**

- **Resolved resonant**
  - Observed upper limit
  - Expected upper limit
  - 68% Expected
  - 95% Expected
  - Bulk Graviton $\sqrt{m_X} = 0.5$

- **Merged resonant**
  - 95% CL upper limits
    - Observed
    - Median expected
    - 68% expected
    - 95% expected
    - Bulk KK graviton ($\sqrt{m_X} = 0.5$)
    - Radion ($\Lambda_R = 3000$ GeV)

**Resonant**

- ATLAS
  - $\sqrt{s}=13$ TeV, 27.5-36.1 fb$^{-1}$
  - Observed 95% CL limit
  - Expected 95% CL limit
  - $\pm 1\sigma$
  - $\pm 2\sigma$
  - Bulk RS, $k/R_s = 1$

- Scalar → HH → bbb6
  - $m(G_{\chi\chi})$ [TeV]
  - $m(Scalar)$ [TeV]
hh→4b (non-resonant)

ATLAS

<table>
<thead>
<tr>
<th></th>
<th>Observed</th>
<th>−2σ</th>
<th>−1σ</th>
<th>Expected</th>
<th>+1σ</th>
<th>+2σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>σ/σ_{SM}</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>

Limit on σ/σ_{SM}
Observed: 74
Expected: 37
hh → bbττ

References

<table>
<thead>
<tr>
<th>Group</th>
<th>Reference</th>
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<tbody>
<tr>
<td>ATLAS</td>
<td>arXiv:1808.00336</td>
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</table>
**hh→bbττ**

- Third largest branching fraction and relatively clean compared to other final states

- To maximize the analysis sensitivity, using both leptonic and hadronic τ decay modes (approx. 88% of all ττ decays)

- As in the 4b case, looking for resonant and non-resonant signatures in both resolved and boosted (currently CMS only) final state topologies
$hh \rightarrow bb\tau\tau$ (resonant)
$hh \rightarrow bb\tau\tau$ (non-resonant)

**ATLAS**

<table>
<thead>
<tr>
<th>Variable</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>$\sigma$</td>
<td>57</td>
<td>49.9</td>
<td>69</td>
</tr>
<tr>
<td>$\sigma/\sigma_{SM}$</td>
<td>23.5</td>
<td>20.5</td>
<td>28.4</td>
<td>39.5</td>
</tr>
<tr>
<td>$\tau_{had}$ $\tau_{had}$</td>
<td>$\sigma$</td>
<td>40.0</td>
<td>30.6</td>
<td>42.4</td>
</tr>
<tr>
<td>$\sigma/\sigma_{SM}$</td>
<td>16.4</td>
<td>12.5</td>
<td>17.4</td>
<td>24.2</td>
</tr>
<tr>
<td>Combination</td>
<td>$\sigma$</td>
<td>30.9</td>
<td>26.0</td>
<td>36.1</td>
</tr>
<tr>
<td>$\sigma/\sigma_{SM}$</td>
<td>12.7</td>
<td>10.7</td>
<td>14.8</td>
<td>20.6</td>
</tr>
</tbody>
</table>
hh → bbγγ

- Small branching fraction but clean final state due to the presence of photons
- Good energy resolution for photons
- Fully reconstructible final state

Resonant

Non-resonant

Observed limits
\( \sigma/\sigma_{SM} < 24 \)
\(-11 < \kappa_\lambda < 17 \)

Observed limits
\( \sigma/\sigma_{SM} < 22 \)
\(-8.2 < \kappa_\lambda < 13.2 \)
Other final states

- $hh \rightarrow WW\gamma\gamma$
  - ATLAS: arXiv:1807.08567 (NR $\sigma/\sigma_{SM} < 230$@95% CL)
- $hh \rightarrow bbWW$
  - ATLAS: Preliminary result (NR $\sigma/\sigma_{SM} < 300$@95% CL)
  - CMS: JHEP 01 (2018) 054 (NR $\sigma/\sigma_{SM} < 79$@95% CL)

- Other more exotic final states being explored as well
  - $bbZZ$
  - $\tau\tau\tau\tau$
  - $WWWW$
Combination

• Different channels combined to improve sensitivity to the di-Higgs production

References

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<tr>
<td>ATLAS</td>
<td>Higgs Summary Plots</td>
</tr>
<tr>
<td>CMS</td>
<td>Higgs Summary Plots, CMS-PAS-HIG-17-030</td>
</tr>
</tbody>
</table>
Combination (resonant production)
Combination (SM hh production)

Combined limit on $\sigma/\sigma^{SM}$
- Observed: 22.2
- Expected: 12.8

Combined limit on $\sigma/\sigma^{SM}$
- Observed: 6.7
- Expected: 10.4
Combination (trilinear self-coupling)

**Combined limits on $\kappa_\lambda$**
- Observed: $-11.8 < \kappa_\lambda < 18.8$
- Expected: $-7.1 < \kappa_\lambda < 13.6$

**Expected limits**
- Combined (exp.): $-7.1 < \kappa_\lambda < 13.6$
- Combined (obs.): $-5.8 < \kappa_\lambda < 12.0$
Summary and outlook

- Rich phenomenology of di-Higgs production and decay
- Equally rich program of di-Higgs searches established at both experiments
  - Sophisticated reconstruction and analysis techniques developed
  - New final states being explored
- So far no signs of new physics
- Not yet sensitive to the Standard model di-Higgs production
  - Best sensitivity from $bb\gamma\gamma$ and $bb\tau\tau$ (but also some differences between ATLAS and CMS in this regard)
- Important to exercise existing analyses and test their reach in preparation for future larger data sets
Backup Slides
hh→WWγγ

Resonant

Non-resonant

<table>
<thead>
<tr>
<th></th>
<th>+2σ</th>
<th>+1σ</th>
<th>Median</th>
<th>−1σ</th>
<th>−2σ</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper limits on $\sigma(HH)$ [pb]</td>
<td>12</td>
<td>8.0</td>
<td>5.4</td>
<td>3.9</td>
<td>2.9</td>
<td>7.7</td>
</tr>
<tr>
<td>Upper limits on $\sigma(HH) \times B(γγWW^*)$ [fb]</td>
<td>12</td>
<td>7.8</td>
<td>5.3</td>
<td>3.8</td>
<td>2.8</td>
<td>7.5</td>
</tr>
<tr>
<td>Ratios of limits over the SM $\sigma(HH)$</td>
<td>360</td>
<td>240</td>
<td>160</td>
<td>120</td>
<td>87</td>
<td>230</td>
</tr>
</tbody>
</table>
**hhh → bbWW**

**CMS:** \(hhh \rightarrow bbWW \rightarrow bblvln\)

**ATLAS:** \(hhh \rightarrow bbWW \rightarrow bblvqq\)

### Resonant

**CMS**

- Observed 95% upper limit
- Expected 95% upper limit
- 68% expected
- 95% expected
- Resonant \((\chi = 1\text{ TeV}, k_l = 35)\)

**ATLAS**

- Observed
- Expected
- Expected \(\pm 1\sigma\)
- Expected \(\pm 2\sigma\)

### Non-resonant

**CMS limit on \(\sigma/\sigma^{SM}\)**

- Observed: 79
- Expected: 89

**ATLAS limit on \(\sigma/\sigma^{SM}\)**

- Observed: 300