Search for di-Higgs production at 13 TeV and prospects for HL-LHC

F. Costanza on behalf of the ATLAS Collaboration
EPS-HEP2019 July 10th-17th, Ghent
Motivation

Non-resonant HH production

- Sensitive to Higgs trilinear coupling $\lambda_{HHH}$.
- Its value in SM is determined by the v.e.v. and $m_H$.
- Its measurement is a test of the shape of the Higgs potential.
- SM cross-section for $pp$ collisions at 13TeV is $\sigma_{ggF}^{SM} = 31.05\text{fb}$.
- Possible BSM enhancements due to modified $\lambda_{HHH}$.

Resonant HH production

- Models containing a heavy spin-0 particle coupling to SM Higgs:
  - Singlet extension;
  - 2HDM;
  - hMSSM;
  - ...
- Models with heavy spin-2 particle:
  - Randall-Sundrum Graviton.
### ATLAS Run2 publication summary

<table>
<thead>
<tr>
<th>Channel</th>
<th>$L \ [fb^{-1}]$</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b\bar{b}b\bar{b}$</td>
<td>27.5-36.1</td>
<td>[JHEP 01 (2019) 030]</td>
</tr>
<tr>
<td>$b\bar{b}W^+W^- \ (b\bar{b}\ell\nu qq)$</td>
<td>36.1</td>
<td>[JHEP 04 (2019) 092]</td>
</tr>
<tr>
<td>$b\bar{b}\tau^+\tau^-$</td>
<td>36.1</td>
<td>[Phys. Rev. Lett. 121 (2018) 191801]</td>
</tr>
<tr>
<td>$b\bar{b}\gamma\gamma$</td>
<td>36.1</td>
<td>[JHEP 11 (2018) 40]</td>
</tr>
<tr>
<td>combination</td>
<td>36.1</td>
<td>[1906.02025]</td>
</tr>
</tbody>
</table>

#### Di-Higgs decay BR
- Assuming SM Higgs BR and $m_H = 125 \text{ GeV}$
  - $\gamma\gamma$: 34%
  - $WW$: 25%
  - $\tau\tau$: 7%
  - $ZZ$: 3%
  - $b\bar{b}$: 0.3%

### New!
- $b\bar{b}\ell\nu\ell\nu$: 139
- VBF $b\bar{b}b\bar{b}$: 126

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Ghent, 11/07/2018

Search for di-Higgs production with ATLAS

F. Costanza
**HH Combination**

**HH → bbaru: JHEP 01 (2019) 030**

- To recover efficiency at high reconstructed $m_{HH}$:
  - **Resolved**: 4 *anti*-k$_t$ jet with $R=0.4$ tagged as *b*-jet.
  - **Boosted**: 2 *anti*-k$_t$ jets with $R=1.0$ both with at least a sub-jet with $R=0.2$ tagged as *b*-jet.
- Main background: QCD multijet production.
- **Data-driven** estimation in CRs with reduced b-tagging.
- Signal extraction by means of a fit on reconstructed $m_{HH}$.


- Considering $\tau^+\tau^-$ final states.
- Main source of uncertainties comes from $t\bar{t}$ modelling ($\pm17\%$) and MC statistics ($\pm16\%$).
- Signal extraction by means of a fit on BDT output used to separate signal vs SM background.
- Single channel with the most stringent constraints on non-resonant SM HH production.
HH → b̅bγγ: JHEP 11 (2018) 40

- **Loose selection**: (sub-)leading jet $p_T > 40(25)$ GeV used for $\lambda_{HHH}$ analysis and resonances with $m_X < 500$ GeV.
- **Tight selection**: (sub-)leading jet $p_T > 100(30)$ GeV used $m_X > 500$ GeV.
- Signal extracted by means of a fit on $m_{HH}$ ($m_{yy}$) for (non-)resonant production.
- Analysis dominated by statistical uncertainties.

- Simultaneous fit to data for cross-section of the signal process and nuisance parameters modelling statistical and systematic uncertainties, using the CLs approach.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Discriminant: Resonant [non-resonant]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b\bar{b}b\bar{b}$</td>
<td>$m_{HH}$ [$m_{HH}$]</td>
</tr>
<tr>
<td>$b\bar{b}W^+W^-$ ($b\bar{b}\ell\nu qq$)</td>
<td>c.e. [$m_{HH}$]</td>
</tr>
<tr>
<td>$b\bar{b}\tau^+\tau^-$</td>
<td>BDT [BDT]</td>
</tr>
<tr>
<td>$W^+W^-W^+W^-$</td>
<td>c.e. [c.e.]</td>
</tr>
<tr>
<td>$b\bar{b}γγ$</td>
<td>$m_{yy}$ [$m_{HH}$]</td>
</tr>
<tr>
<td>$W^+W^-γγ$</td>
<td>$m_{yy}$ [$m_{yy}$]</td>
</tr>
</tbody>
</table>
Combination results: non-resonant production

**HH production cross-section:**

- **ATLAS**
  - $\sigma_{ggF}^{SM}(pp \rightarrow HH) = 33.5$ fb
  - $\sigma_{ggF}^{SM}(pp \rightarrow HH) = 33.5$ fb

- Observed
  - $\sigma_{ggF}^{SM}(pp \rightarrow HH) = 33.5$ fb

- Expected
  - $\sigma_{ggF}^{SM}(pp \rightarrow HH) = 33.5$ fb

- Expected ± 1σ
  - $\sigma_{ggF}^{SM}(pp \rightarrow HH) = 33.5$ fb

- Expected ± 2σ
  - $\sigma_{ggF}^{SM}(pp \rightarrow HH) = 33.5$ fb

95% CL upper limit for $k_\lambda \equiv \frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}} = 1$:

- $6.9 \times \sigma_{ggF}^{SM}$ (obs)
- $10.0 \times \sigma_{ggF}^{SM}$ (exp)

**Higgs trilinear coupling:**

- Indirect limits from single Higgs differential production and decay measurement (80fb⁻¹):
  - $K_\lambda \in [-3.2, 11.9]$ (obs), $[-5.8, 12.0]$ (exp)

95% CL confidence intervals:

- $K_\lambda \in [-5.0, 12]$ (obs), $[-5.8, 12]$ (exp)

**ATL-PHYS-PUB-2019-009**
Combination results: resonant production

- Same statistical treatment as described for non-resonant production.

**Singlet:**
- First ATLAS interpretation of HH results within this model.
- Exclusion in \((m_s, \sin \alpha)\) and \((\sin \alpha, \tan \beta)\).

**hMSSM:**
- Exclusion in \((m_A, \tan \beta)\).
- Exclusion more than twice as Run1 in both \(m_A\) and \(\tan \beta\).
**bbℓℓνν: Analysis Strategy**

- New channel in ATLAS addressing the $2\ell$ decay of $HH\rightarrow bbWW^*/ZZ^*/\tau^+\tau^-$.  
- First HH published analysis exploiting the full LHC-Run2 dataset (139fb$^{-1}$).

- Main backgrounds:
  - **Irreducible** (~80%): Top ($t\bar{t}$ and $tW$), $Z+HF$.
    - Normalization from control regions.
  - **Reducible**: non-prompt leptons from heavy flavour hadrons.
    - Data-driven estimate from events with same sign leptons.

- The analysis relies on a **DNN classifier** to distinguish the **signal** from the main backgrounds: Top, $Z\rightarrow e^+e^-/\mu^+\mu^-$, and $Z\rightarrow \tau^+\tau^-$. 

- The four outputs of the DNN, are combined:
  
  $$d_{hh} = \ln\left(\frac{p_{HH}}{p_{Top} + p_{Z-\ell\ell} + p_{Z-\tau\tau}}\right)$$

- $m_{bb}$ and $m_{ee}$ are uncorrelated to $d_{hh}$ and are used to define SR.
Search for di-Higgs production with ATLAS

- Observation is consistent with no enhanced di-Higgs production hypothesis.

**95% CL upper limit at $k_\lambda = 1$ (SM)**

<table>
<thead>
<tr>
<th></th>
<th>$-2\sigma$</th>
<th>$-1\sigma$</th>
<th>Expected</th>
<th>$+1\sigma$</th>
<th>$+2\sigma$</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma (gg \rightarrow HH)$ [pb]</td>
<td>0.5</td>
<td>0.6</td>
<td>0.9</td>
<td>1.3</td>
<td>1.9</td>
<td>1.2</td>
</tr>
<tr>
<td>$\sigma (gg \rightarrow HH) / \sigma^{SM} (gg \rightarrow HH)$</td>
<td>14</td>
<td>20</td>
<td><strong>29</strong></td>
<td>43</td>
<td>62</td>
<td><strong>40</strong></td>
</tr>
</tbody>
</table>
Search for di-Higgs production with ATLAS

**Target signature:** \( HH \rightarrow b\bar{b}b\bar{b} \) process with 2 final state VBF jets.

**Motivation:** first study of VVHH vertex.

**Similar analysis strategy as in inclusive \( HH \rightarrow b\bar{b}b\bar{b} \).**

- Additional selection of 2 VBF jets: \(|\eta| > 2\) and in opposite hemispheres.
- Main background is QCD multijet: data-driven estimation in 2b-CR.

**Improved b-jet energy resolution** (~25%) with BDT-based regression.

**Signal extracted from fit on \( m_{4b} \). No statistically significant excess found.**

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**New! Full Run2**

**Results for the search of resonant production in the talk by R. Jansky [link].**

**Stringent limits on \( c_{2V} \)!**

\( 95\% \) CL intervals:

\[ c_{2V} \in [-1.0, 2.7] \text{ obs.} \]

\[ c_{2V} \in [-1.1, 2.8] \text{ exp.} \]
HL-LHC projections: \( HH \rightarrow b\bar{b}b\bar{b} / b\bar{b}\tau^+\tau^- / b\bar{b}\gamma\gamma \)

Latest HL-LHC projections published in the *Yellow Report* by a joint ATLAS+CMS+Theory effort.

**\( HH \rightarrow b\bar{b}b\bar{b} \): Extrapolation** from Run2 analysis.
- Fit of \( m_{HH} \) distribution.
- Main systematic: **data-driven** multijet modelling.
  - Conservative assumption: uncertainty as in Run2.
  - Alternative assumption: scale as \( 1/\sqrt{L} \).

**\( HH \rightarrow b\bar{b}\tau^+\tau^- \): Extrapolation** from Run2 analysis.
- BDT output used as final discriminant.
- Main source of uncertainty in Run2 analysis is MC statistics: included in extrapolation.

**\( HH \rightarrow b\bar{b}\gamma\gamma \): Dedicated** analysis with **parametric smearing** based on upgraded detector performance.
- \( m_{\gamma\gamma} \) resolution \( \sim 1.6 \text{GeV} \).
- BDT to reject continuum background and single Higgs background (mainly \( t\bar{t}H \)).
- Very small impact from systematic uncertainties.
**ATLAS + CMS HH combination**

- Combined values channel-by-channel:
  - No correlation considered (shown to have negligible impact).
  - Systematic uncertainties included.
- Signal (SM) significance:
  - $4\sigma$ expected for ATLAS+CMS!
- Signal (SM) injection test:
  - $\mu_{\text{inj}} = 1$: $\mu$ measured with $\sim30\%$ unc.
  - $\mu_{\text{inj}} = 0$: SM di-Higgs production excluded at 95% CL.
- $k_\lambda$ measurement (assuming SM value):
  - $0.1 < k_\lambda < 2.3$ [95% CL]
  - $0.5 < k_\lambda < 1.5$ [68% CL]
  - 2$^{\text{nd}}$ minimum excluded at 99.4% CL thanks to $m_{hh}$ shape information.

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**Table:**

<table>
<thead>
<tr>
<th>Process</th>
<th>Statistical-only ATLAS</th>
<th>Statistical-only CMS</th>
<th>Statistical + Systematic ATLAS</th>
<th>Statistical + Systematic CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$HH \rightarrow bbbb$</td>
<td>1.4</td>
<td>1.2</td>
<td>0.61</td>
<td>0.95</td>
</tr>
<tr>
<td>$HH \rightarrow b\tau\tau$</td>
<td>2.5</td>
<td>1.6</td>
<td>2.1</td>
<td>1.4</td>
</tr>
<tr>
<td>$HH \rightarrow b\bar{b}\gamma\gamma$</td>
<td>2.1</td>
<td>1.8</td>
<td>2.0</td>
<td>1.8</td>
</tr>
<tr>
<td>$HH \rightarrow b\bar{b}VV(ll\nu\nu)$</td>
<td>-</td>
<td>0.59</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$HH \rightarrow b\bar{b}ZZ(4l)$</td>
<td>-</td>
<td>0.37</td>
<td>-</td>
<td>0.37</td>
</tr>
<tr>
<td>combined</td>
<td>Combined 3.5</td>
<td>2.8</td>
<td>3.0</td>
<td>2.6</td>
</tr>
</tbody>
</table>

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**4$\sigma$ expected for ATLAS+CMS!**

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**Graph:**

- ATLAS and CMS
- HL-LHC prospects
- 3000 fb$^{-1}$ (14 TeV)
- $-2\Delta\ln(L)$
- Higgs-like candidates
- Combination
Conclusions

- The discovery of di-Higgs production and the measurement of the Higgs trilinear self-coupling are among the main goals of the (HL-)LHC physics programme.
- The most recent results of the ATLAS collaboration on the topic have been presented.

LHC Run2

- A combination of all 2015-2016 ATLAS analyses and two new analyses performed on the full LHC-Run2 dataset (bb\ell\ell\nu and VBF-HH→b\bar{b}bb) have been presented.
- No observation for enhanced di-Higgs production has been found up to now.
- The most stringent constraint on di-Higgs production cross-section assuming k_\lambda=1 (SM) is set by the ATLAS HH combination and is $6.9 \times 10^{-1} \times \sigma_{ggF}^{SM}$ obs (exp).
- Strong constraints on the VVHH vertex have been set.

HL-LHC

- The first comprehensive assessment of the HL-LHC physics programme has been recently published in the Yellow Report.
- The YR predicts that the full HL-LHC potential is going to be needed for ATLAS+CMS to reach a discovery significance of 4\sigma and an uncertainty on K_\lambda measurement of 50%.
- Past experience tells us that these results will be outperformed with the help of new ideas on object reconstruction and physics analysis.