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

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on behalf of the ATLAS
What we can access using HH production
~Non resonant signals~

gluon gluon Fusion (ggF)

Negative interference with box diagram
Possible BSM enhancements due to modified coupling strength of $\kappa \lambda$

Vector Boson Fusion (VBF)

In SM, each coupling strength is $c_{2V}=1$ and $c_{V}=1$, $\kappa \lambda=1$.

$\mathcal{A}(V_L V_L \rightarrow hh) \approx \frac{\hat{s}}{v^2}(c_{2V} - c_{V}^2)$ [Eur. Phys. J. C (2017) 77:481]

Possible BSM enhancements due to modified coupling strength of $c_{2V}$
What we can access using HH production
~BSM resonant signals~

Models with a heavy spin-0 particle: “Singlet extension”, “2HDM”, “hMSSM”
Models with a heavy spin-2 particle: “Randall-Sundrum Graviton”

ggF and VBF are complementary to each other for the specific parameters due to different couplings at production.
# Studied channels at 13 TeV

Various decay channels in HH:

<table>
<thead>
<tr>
<th>Decay Channels</th>
<th>J_L [fb^-1]</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>bbbb</td>
<td>27.5-36.1</td>
<td>JHEP 01 (2019) 030</td>
</tr>
<tr>
<td>bbγγ</td>
<td>36.1</td>
<td>JHEP 11 (2018) 40</td>
</tr>
<tr>
<td>WWWWWW</td>
<td>36.1</td>
<td>JHEP 05 (2019) 124</td>
</tr>
<tr>
<td>bbWW</td>
<td>36.1</td>
<td>JHEP 04 (2019) 092</td>
</tr>
<tr>
<td>combination</td>
<td>36.1</td>
<td>1906.02025</td>
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</tbody>
</table>

**New this summer**

<table>
<thead>
<tr>
<th>Analysis</th>
<th>J_L</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>bblvlv</td>
<td>139</td>
<td>-</td>
</tr>
<tr>
<td>VBF bbbb</td>
<td>126</td>
<td>ATLAS-CONF-2019-030</td>
</tr>
</tbody>
</table>

Today, will report “★” that are the selected ggF analyses and the combination of them, two new analyses, and HL-LHC prospect of ggF analyses.
Feature: **high statistics**
- Two approaches for low mass and high mass regions

Resolved:
- 4 R=0.4 jets (“small-R jets”)
- Relies critically on b-jet triggers

Backgrounds
- **Multijet (95%)**: Data-driven estimation in CRs with reduced b-tagging for multijet bkg.
- **ttbar (5%)**: MC

Uncertainty: dominated by QCD modeling unc.
- Observation is consistent with no enhanced di-Higgs production hypothesis.
- The limits on $\kappa \lambda$ will be shown at the combination results.

Boosted:
- 2 R=1.0 jets (“large-R jets”)
- 3 categories (2, 3, 4 b-tags), based on number of b-tagged “track jets” associated with the large-R jets

Resolved SR
ggF $HH\rightarrow bb\tau\tau$  

36.1 fb$^{-1}$  


- Feature: **Fairly high statistics, clean with lepton channel**
- Two channels, based on decays of the tau leptons: $\tau_{\text{lep}}\tau_{\text{had}}$, $\tau_{\text{had}}\tau_{\text{had}}$
  - Boosted Decision Trees (BDT) used to enhance the analysis sensitivity
- Backgrounds: ttbar (MC), QCD multijet (data driven), Z+HF(MC)
- Uncertainty: dominated by statistical uncertainties
- Observation is consistent with no enhanced di-Higgs production hypothesis.
ggF $\text{HH} \to \text{bb}\gamma\gamma$ \hfill 36.1 fb$^{-1}$

JHEP 11 (2018) 40

- Feature: **Low background**
- Two categories for low mass and high mass regions
  - **Loose selection:** (sub-)leading jet $p_T > 40(25)$ GeV used for $\kappa \lambda$ analysis and resonances with $m_x < 500$ GeV.
  - **Tight selection:** (sub-)leading jet $p_T > 100(30)$ GeV used for $m_x > 500$ GeV.
- Background: single higgs (MC), continuum $m_{\gamma\gamma}$ (data driven)
- Uncertainty: dominated by statistical uncertainties
- Observation is consistent with no enhanced di-Higgs production hypothesis.
Results of the $ggF$ combination

~Interpretation on non-resonant signal~

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

SM HH production cross-section

<table>
<thead>
<tr>
<th>Process</th>
<th>Obs.</th>
<th>Exp.</th>
<th>Exp. stat.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$HH \rightarrow b\bar{b}+\gamma+\gamma$</td>
<td>160</td>
<td>120</td>
<td>77</td>
</tr>
<tr>
<td>$HH \rightarrow b\bar{b}$</td>
<td>230</td>
<td>170</td>
<td>160</td>
</tr>
<tr>
<td>Combined</td>
<td>306</td>
<td>305</td>
<td>240</td>
</tr>
</tbody>
</table>

95% CL upper limit

- $6.9 \times \sigma_{ggF}^{SM}$ (obs)
- $10 \times \sigma_{ggF}^{SM}$ (exp)

Higgs trilinear coupling

$\kappa_\lambda \equiv \frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}} = 1$

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

Indirect limits from single Higgs differential production and decay measurement (80fb$^{-1}$):

$\kappa_\lambda \in [-3.2, 11.9]$
Results of the ggF combination
~Interpretation on resonant signal~

- The limits on the cross-section for each model are set close to the expected values.
- Enlarged excluded region for spin-0/2 models.

First ATLAS interpretation of HH results within this model

Over double the Run 1 exclusion in both mA and tanβ.
ggF $HH \to bblvlv$

- New channel in ATLAS addressing the 2l decay of $HH \to bbWW^*/ZZ^*/\tau^+\tau^-$
- The analysis relies on a **DNN classifier** to distinguish the **signal** from the main backgrounds: Top, $Z \to e^+e^-/\mu^+\mu^-$, and $Z \to \tau^+\tau^-.$
- The four outputs of the DNN, are combined: $d_{HH} = \ln \left( \frac{p_{HH}}{p_{Top} + p_{Z \to ll} + p_{Z \to \tau\tau}} \right)$
- Observation is consistent with no enhanced di-Higgs production hypothesis.
- The factor 10 improvement on previous $bbWW$ result of upper limit at $\kappa^\lambda = 1$.

95% CL upper limit at $k^\lambda = 1$ (SM)

<table>
<thead>
<tr>
<th>$\sigma(gg \to HH)$ [pb]</th>
<th>$-2\sigma$</th>
<th>$-1\sigma$</th>
<th><strong>Expected</strong></th>
<th>$+1\sigma$</th>
<th>$+2\sigma$</th>
<th><strong>Observed</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma(gg \to HH)$</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>$\sigma(gg \to HH)/\sigma^{SM}(gg \to HH)$</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>
New VBF HH analysis in LHC, using the full Run-2 dataset
- The VBF jet selections are added to di-Higgs selection from ggF resolved analysis.
- The invariant mass of 4b is reconstructed.

The b-jet energy regression based on BDT is implemented to account for energy loss due to:
- Neutrinos in b-jets due to semi-leptonic B decays
- Soft particles result in out-of-cone leakage

Background: ~90% Multijet, ~10% ttbar
- Data-driven estimation in CRs with reduced b-tagging.
VBF HH→4b: Results

- No significant deviation observed. Local 1.5σ excess at ~550 GeV is largest deviation and set limits near expected values.
- World’s first limit on VVHH coupling strength: c_{2V} < -1.02 and 2.71 < c_{2V} is excluded with 95% CLs.

Spin-0 resonant production XS

Non-resonant production XS
HL-LHC prospects on SM non-resonant

- HL-LHC will deliver ~3000 fb⁻¹ at 14 TeV by late 2030’s
  - HH→bbbb and HH→bbττ: Extrapolation from Run2 analysis
  - HH→bbγγ: Dedicated analysis with parametric smearing based on upgraded detector performance
  - Systematics are estimated with expected potential gains in technique
- HH combination
  - No correlation considered (shown to have negligible impact).
  - Signal (SM) significance: 4σ expected for ATLAS+CMS
  - κλ measurement (assuming SM value):
    - 0.1 < κλ < 2.3 [95% CLs]
Summary

• HH studies can access the SM higgs couplings and BSM physics.
• A combination of all 2015-16 ATLAS analyses and two new analyses performed on the full LHC-Run2 dataset (bbl ν l ν and VBF HH→4b) 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 (SM) is set and is $6.9(10) \times \sigma^{\text{SMggF obs (exp)}}$.
  – The first constraint on VVHH coupling strength has been set: $c_{2V} < -1.02$ and $2.71 < c_{2V}$ is excluded with 95% CLs.
  – Limits on heavy spin-0/2 particles are set
• Stay tuned for more & more results with the full Run-2 dataset.
• The HL-LHC prospects at 3000 fb$^{-1}$ at 14 TeV shows discovery significance of $4\sigma$ and $\kappa \lambda$ measurement of $0.1 < \kappa \lambda < 2.3$ by ATLA+CMS. New channels, ideas for physics analysis, and improved detector performances can improve the measurement.