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

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Abstract
The latest results on production of Higgs boson pairs at 13 TeV by the ATLAS experiment at LHC are reported, including a combination of six different decay modes. Results include \( bb\tau\tau \), \( bbbb \), \( bb\gamma\gamma \), \( bbWW \), \( WWWW \) and \( WW\gamma \) final states, and they are interpreted both in terms of sensitivity to the SM and as limits on \( \kappa_3 \), a scaling of the triple-Higgs interaction strength. The most stringent constraint on di-Higgs production cross-section is set at 6.9 times SM cross-section and \( \kappa_3 \) is constrained in the range \(-5\)–\( -12 \) at 95% confidence level. A new search dedicated to the Vector-Boson-Fusion production was performed in the \( bbbb \) final state. No significant excess, relative to the background-only Standard Model expectation, is observed and interpretation in terms of the coupling between a Higgs boson pair and two vector bosons is also provided: coupling values normalized to the Standard Model expectation of \( \kappa_{2V} < -0.56 \) and \( 2.89 < \kappa_{2V} \) are excluded at the 95% confidence level. Future prospects of testing the Higgs self-couplings at the High Luminosity LHC are also reported.

Keywords: ATLAS, di-Higgs production, LHC

(Some figures may appear in colour only in the online journal)

1. Introduction
The Higgs boson (\( H \)) was discovered by the ATLAS and CMS collaborations in 2012 using proton–proton (\( pp \)) collisions at the Large Hadron Collider (LHC) [1, 2]. Since then a lot of studies have been performed in order to investigate with increasing precision the properties of the Higgs boson. Even if up to now no significant discrepancy has been observed with respect to the Standard Model (SM) expectations, studies of Higgs Boson final states offer new opportunities in searching for new physics beyond the SM (BSM). In particular, many models predict enhanced cross-sections of Higgs pair production in \( pp \) collision. Spin-0 resonances that may decay into Higgs boson pairs, appear in scenarios beyond the SM [3, 4]. Enhanced non-resonant Higgs boson pair production is predicted by many models, for example those featuring light coloured scalars [5] or new contact interactions, such as direct \( t\bar{t}HH \) vertices [6, 7].

In \( pp \) collisions at LHC, \( HH \) production is mainly due to two processes. The first one is the gluon-gluon Fusion (ggF) process whose diagrams are shown in figure 1. In the SM, the non-resonant processes of figures 1(a) and (b) appear, and the interference between the two diagrams is destructive. However, the amplitude of the diagram (a) is proportional to the Higgs self-coupling (\( HHH \)) and the cross-section can be enhanced significantly by new physics. The possible ggF resonant production of a hypothetical new heavy scalar state \( X \) is shown in figure 1(c). The second process is Vector Boson Fusion (VBF) whose diagrams are shown in figure 2. The VBF process (\( pp \rightarrow HHjj \)) is characterized by the presence of two jets (\( j \)) with a large rapidity gap resulting from quarks from which a vector boson (\( V \)) is radiated. In the SM, three different types of couplings are involved in non-resonant \( HH \) production via VBF: \( HHH \) coupling, the Higgs-boson–di-vector-boson coupling (\( VVH \)) and the quartic (di-vector-boson–di-Higgs-boson, or \( VVHH \)) coupling, and the amplitudes of figures 2(b) and (c) are canceled out by negative interference. The amplitude of the diagram (c) is proportional to the \( VVHH \) coupling and the cross-section can be enhanced significantly due to possible new physics effects. The resonant production via VBF of a possible
new BSM scalar state $X$ is shown in figure 2(d). The resonant productions via ggF and VBF are complementary to each other for the specific parameters of the model due to the different couplings ($ttX$ in ggF and $VVX$ in VBF) involved in the production, as we can see in the diagrams.

In the ATLAS experiment, the search for the Higgs pair production via ggF and VBF are conducted using Run2 datasets of integrated luminosities in the range 27–139 fb$^{-1}$ at $\sqrt{s} = 13$ TeV. The significant analyses will be reported.

2. Searches for $HH$ production via ggF using 2015–16 data

The searches for the $HH$ production via ggF have been performed using datasets of integrated luminosities 27–36 fb$^{-1}$ taken in 2015–2016 with $\sqrt{s} = 13$ TeV at LHC. Table 1 shows the branching ratios in the different channels of the $HH$ decay. The process $HH \rightarrow b\bar{b}b\bar{b}$ has the largest branching ratio but suffer from high backgrounds from QCD multi-jet. On the other hand, the other processes which contain leptons or photons in the final state, have lower statistics than $HH \rightarrow b\bar{b}b\bar{b}$ but much lower background. Therefore, we can search for the $HH$ production in various final states. The analysis has been performed in the processes $HH \rightarrow b\bar{b}b\bar{b}$ [8], $b\bar{b}\gamma\gamma$ [9], $bb\gamma\gamma$ [10], $WWW\gamma\gamma$ [11], $WW\gamma\gamma$ [12], and $bbWW$ [13].

In order to search for the $HH$ process, the analyses have to be well designed depending on the characteristic kinematics of the signal. For example, since the Higgs bosons are boosted in the hard scattering event, the analysis should be optimized for the $HH$ invariant masses ($m_{HH}$) correlated with the energy of the parton scattering in the $pp$ collision. Furthermore, the component of the backgrounds is different for each process. Therefore, the selection criteria should be well designed according to the kinematics of the signals and the backgrounds, specific to each process. In the following, the selected analyses and the combination results of all analyses are overviewed.

2.1. Search for $HH \rightarrow b\bar{b}b\bar{b}$ process via ggF

The feature of $HH \rightarrow b\bar{b}b\bar{b}$ process is high statistics due to the largest branching ratio of the $HH$ decay. In this search,
two approaches for the regions of low $m_{HH}$ and high $m_{HH}$ are pursued. The first one for the low $m_{HH}$ region, called ‘resolved analysis’, requires the presence of four $b$-jets. Resolved analysis has sensitivity in the region of $260 \text{ GeV} < m_{HH} < 1400 \text{ GeV}$. On the other hand, the angle between the two $b$-jets from boosted Higgs boson become small in high $m_{HH}$ region making it difficult to experimentally resolve the two $b$-jets. For this reason, in order to get a reasonable signal efficiency, the analysis in the high $m_{HH}$ region, called ‘boosted analysis’, requires two large radius jets with at least one $b$-tagged small radius jet matched to it. The boosted analysis has sensitivity in the region of $800 \text{ GeV} < m_{HH} < 3000 \text{ GeV}$. In both cases, the backgrounds are QCD multi-jet (about 95%) and $t\bar{t}$ (about 5%). The QCD multi-jet is modeled using data driven method with reduced $b$-tagging dataset and the $t\bar{t}$ is estimated using Monte Carlo (MC) sample. Figure 3 shows the distribution of $m_{HH}$ in the signal region of the Resolved analysis and the Boosted analysis. We observe no significant excess. The 95% confidence level (CL) upper limit on the non-resonant production is 147 fb, which corresponds to 12.9 times the SM expectation.

2.2. Search for $HH \rightarrow b\bar{b}\tau^+\tau^-$ process via ggF

The $HH \rightarrow b\bar{b}\tau^+\tau^-$ process has fairly high statistics and quite clean final states in case of leptonic decay of the $\tau$-lepton. In this analysis, the $\tau_{\ell}p$ and $\tau_{\ell}n$ channels are considered, where the subscripts (lep = electron or muon, had = hadrons) indicate the decay mode of the $\tau$-lepton. To distinguish the signal and the backgrounds of $t\bar{t}$, single-top-quark, QCD multi-jet, and $W$ or $Z$ bosons associated with jets in the entire range of $m_{HH}$, a Boosted Decision Tree (BDT) is used. Several variables have been used as input to the BDT: among them the invariant masses of $HH$, $bb$, and $\tau\tau$, the angles of the $bb$ and $\tau\tau$ (for more details see [9]). The uncertainty is dominated by the data statistics and the observation was consistent with no enhanced di-Higgs production. The 95% CL upper limit on the non-resonant production is 12.7 times the SM expectation [9].

![Figure 3. Distributions of $m_{HH}$ in the signal region of (a) the resolved analysis and (b) the boosted analysis (Reproduced from [8]. CC BY 4.0. Open Access, Copyright CERN, for the benefit of the ATLAS Collaboration). The expected distributions of spin-2 Kaluza-Klein graviton ($G_{KK}$) resonances, scalar samples and SM $HH$ production ($\times 100$) are also shown.](image)

![Figure 4. Upper limits at 95% CL on the cross-section of the ggF non-resonant SM $HH$ production as a function of $\kappa_\chi$. The observed (expected) limits are shown as solid (dashed) lines. The combined result and the leading analyses of $bb\bar{b}$, $b\bar{b}\tau^+\tau^-$, and $b\bar{b}\gamma\gamma$ are shown. The theoretical prediction of the cross-section is also shown [14]. Reproduced from [14]. CC BY 4.0.](image)

2.3. Combination of different channels

The combination of the analyses of $HH \rightarrow bb\bar{b}$, $b\bar{b}\tau^+\tau^-$, $bb\gamma\gamma$, $WWWW$, $WW\gamma\gamma$, and $bbWW$ has been performed [14]. Figure 4 shows the 95% CL upper limit on the cross-section of the ggF non-resonant SM $HH$ production as a function of $\kappa_\chi$, the strength of the Higgs self-coupling, normalized to the SM value. The combination results in an observed (expected) upper limit of about 6.9 (10) times the SM cross-section. The coupling $\kappa_\chi$ is constrained in the range $-5.12$ at 95% CL.

Figure 5 shows the 95% CL upper limit on the cross-section of the ggF resonant $HH$ production as a function of the mass of a heavy scalar decaying to $HH$. The limits on the heavy scalar resonance have been interpreted as constraints on the EWK-singlet model [3] and on hMSSM. Regarding the hMSSM, the exclusion region in the plane $m_\chi$ (mass of the pseudo-scalar Higgs boson)–tan $\beta$ (ratio of the two vacuum expectation values) has been considerably extended with respect to Run1 results [4].
3. New analyses exploiting the full Run2 dataset

3.1. Search for HH → b \bar{b} WW process via ggF

For precise measurement of the Higgs coupling, it is important to exploit different channels and combine their results. ATLAS focused on the 2-leptons final states to study the processes \( HH → b \bar{b}WW, b \bar{b}ZZ, \) and \( b \bar{b}τ^+τ^- \) [15]. In order to distinguish the signal from the main backgrounds of top and Z/γ processes, a discriminant has been constructed exploiting a deep neural network (DNN). The input variables for the DNN include the transverse momentum of leptons and b-jets and the angle between the leptons (for more details see [15]). Observation is consistent with SM hypothesis. An observed (expected) upper limit at 95% CL of about 40 (29) times the SM cross-section has been obtained, which means a factor 10 improvement on previous \( b \bar{b}WW \) result [13].

3.2. Search for HH → bbbb process via VBF

This analysis focuses on the \( HH \) production via VBF and has been performed adding the VBF jet selections to the di-Higgs selection from ggF resolved analysis [16]. Furthermore, the b-jet energy correction based on BDT is implemented to account for energy loss due to semi-leptonic decays and soft particles result in out-of-cone leakage. As a result, the resolution of the mass of the reconstructed Higgs boson is improved by 25%. The background is dominated by the QCD multi-jet and it is estimated by data-driven method with reduced b-tagging as well as in ggF \( HH → bb \bar{b}b \) analysis. Figure 6 shows the invariant mass of the 4b-jets, \( m_{bb} \). No significant deviation was observed.

Figure 7(a) shows the 95% CL upper limit on the cross-section of the production of a spin-0 resonance decaying into two Higgs bosons via VBF. This result is complementary with the ggF analysis. Figure 7(b) shows the 95% CL upper limit on the cross-section of the non-resonant signal with VVHH coupling modifier \( \kappa_{2V} \). The excluded region at 95% CL for the VVHH coupling normalized to the SM expectation is \( \kappa_{2V} < -0.56 \) and 2.89 < \( \kappa_{2V} \).

4. HL-LHC prospects

High luminosity LHC (HL-LHC) will deliver more than 3000 fb\(^{-1}\) at \( \sqrt{s} = 14 \) TeV by late 2030’s. The latest studies for the Higgs physics at HL-LHC are presented in [17], thanks to a joint ATLAS+CMS+Theory effort. Regarding the di-Higgs production, the analyses of Run2 datasets, using integrated luminosities of 27–36 fb\(^{-1}\), has been combined with extrapolated statistics and expected systematics. The signal significance on the SM is expected to be 4σ and \( \kappa_3 \) constraint is expected to be 0.1 < \( \kappa_3 < 2.3 \) at 95% CL with combined ATLAS and CMS results. Note that the new analysis with full Run2 dataset are not included in this.

Figure 5. Upper limits at 95% CL on the cross-section of the resonant Higgs boson pair production for a spin-0 heavy scalar. The observed (expected) limits are shown as solid (dashed) lines. The vertical black lines in each panel indicate mass intervals where different final states are combined [14]. Reproduced from [14]. CC BY 4.0.

Figure 6. Post-fit mass distribution of the \( HH \) candidates in the signal region. The expected background is shown after the profile-likelihood fit to data with the background-only hypothesis; the narrow-width resonant signal at 800 GeV and the non-resonant signal at \( \kappa_{2V} = 3 \) are overlaid, both normalized to the corresponding observed upper limits on the cross-section [16].
predictions. The limit on $\kappa_{2V}$ is also expected to be improved not only for the much larger statistics but also for the inclusion of more channels and the improved detector performances.

5. Conclusion

The $HH$ studies can access the SM Higgs couplings and new physics beyond the SM. A combination of all 2015–16 ATLAS analyses and two new analyses performed on the full LHC-Run2 dataset are summarized. No observation for enhanced $HH$ production has been found up to now. The most stringent constraint on $HH$ production cross-section is set as 6.9 times the SM cross-section and the $\kappa_{\lambda}$ is constrained in the range $-5$–$12$ at 95% CL by ggF analyses. The first constraint on $VVHH$ coupling modifier has been set to be $\kappa_{2V} < -0.56$ and $2.89 < \kappa_{2V}$ by the VBF analysis of $HH \rightarrow b\bar{b}b\bar{b}$ process. The HL-LHC prospects with a total integrated luminosity of the order of $3000 fb^{-1}$ at 14 TeV will allow a discovery significance of 4 for the SM di-Higgs production process and $\kappa_{\lambda}$ constraints of $0.1 < \kappa_{\lambda} < 2.3$ at 95% CL with combined ATLAS and CMS results. Inclusion of new channels, new ideas for physics analysis, and improved detector performances can further improve the measurement.

References

[1] ATLAS Collaboration 2012 Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC Phys. Lett. B 716 1
[2] CMS Collaboration 2012 Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC Phys. Lett. B 716 30
[3] de Florian D et al 2017 Handbook of LHC Higgs cross sections: 4 Deciphering the Nature of the Higgs Sector, CERN-2017-002-M arXiv:1610.07922 [hep-ph]
[4] Djouadi A 2008 The anatomy of electroweak symmetry breaking Tome II: The Higgs bosons in the minimal supersymmetric model Phys. Rept. 459 1
[5] Kribs G D and Martin A 2012 Enhanced di-Higgs production through light colored scalars Phys. Rev. D 86 095023
[6] Gröber R and Mühlleitner M 2011 Composite Higgs boson pair production at the LHC J. High Energy Phys. JHEP06 (2011)020
[7] Contino R et al 2012 Anomalous couplings in double Higgs production J. High Energy Phys. JHEP08(2012)154
[8] ATLAS Collaboration 2019 Search for pair production of Higgs bosons in the $b\bar{b}b\bar{b}$ final state using proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector J. High Energy Phys. 01(2019)030
[9] ATLAS Collaboration 2018 Search for Resonant and Nonresonant Higgs Boson pair production in the $b\bar{b}\tau^+\tau^-$ decay channel in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector Phys. Rev. Lett. 121 191801
[10] ATLAS Collaboration 2018 Search for Higgs boson pair production in the $\gamma h h$ final state with 13 TeV $pp$ collision data collected by the ATLAS experiment J. High Energy Phys. 11(2018)040
[11] ATLAS Collaboration 2019 Search for Higgs boson pair production in the $WW(*)WW(*)$ decay channel using ATLAS data recorded at $\sqrt{s} = 13$ TeV J. High Energy Phys. 05(2019)124
[12] ATLAS Collaboration 2018 Search for Higgs boson pair production in the $\gamma ^* h h$ channel using $pp$ collision data collected at $\sqrt{s} = 13$ TeV with the ATLAS detector Eur. Phys. J. C 78 1007
[13] ATLAS Collaboration 2019 Search for Higgs boson pair production in the $b\bar{b}WW^*$ decay mode at $\sqrt{s} = 13$ TeV with the ATLAS detector J. High Energy Phys. 04(2019)092
[14] ATLAS Collaboration 2020 Combination of searches for Higgs boson pairs in $pp$ collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector Phys. Lett. B 800 135103
[15] ATLAS Collaboration 2020 Search for non-resonant Higgs boson pair production in the $b\bar{b}l\bar{l}v$ final state with the ATLAS detector in pp collisions at $\sqrt{s} = 13$ TeV Phys. Lett. B 801 135145
[16] ATLAS Collaboration Search for the $HH \rightarrow b\bar{b}b\bar{b}$ process via vector-boson fusion production using proton–proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector arXiv:2001.05178 [hep-ex]
[17] Cepeda M et al Higgs Physics at the HL-LHC and HE-LHC arXiv:1902.00134 [hep-ph]