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 $b\bar{b}\tau^-\tau^+$, $b\bar{b}b\bar{b}$, $b\bar{b}\gamma\gamma$, $b\bar{b}WW$, $WWWW$ and $WW\gamma\gamma$ final states, and they are interpreted both in terms of sensitivity to the SM and as limits on κ_λ , 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 κ_λ 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 $b\bar{b}b\bar{b}$ 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.

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 Figure 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 Figure 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 ($t\bar{t}X$ 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.

Figure 1: Diagrams (a) and (b) illustrate the tree-level Feynman diagrams contributing to SM non-resonant Higgs boson pair production via ggF. Diagram (c) illustrates the resonant BSM production of a new scalar state X .

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.

Figure 2: Diagrams (a), (b) and (c) illustrate the tree-level Feynman diagrams contributing to SM non-resonant Higgs boson pair production via VBF. The non-resonant production modes scale with $\kappa_V \kappa_\lambda$, κ_V^2 and κ_{2V} , respectively. Diagram (d) illustrates the resonant production mode of a new scalar state X .

The analysis has been performed in the processes $HH \rightarrow b\bar{b}b\bar{b}$ [8], $b\bar{b}\tau^-\tau^+$ [9], $b\bar{b}\gamma\gamma$ [10], $WWWW$ [11], $WW\gamma\gamma$ [12], and $b\bar{b}WW$ [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.

Table 1: The branching ratios of the HH decay. The column and row are categorized with the pattern of the decays of the two Higgs bosons.

	$H \rightarrow b\bar{b}$	$H \rightarrow WW$	$H \rightarrow \tau\tau$	$H \rightarrow ZZ$	$H \rightarrow \gamma\gamma$
$H \rightarrow b\bar{b}$	34%	25%	7%	3%	0.3%
$H \rightarrow WW$	-	5%	3%	1%	0.1%
$H \rightarrow \tau\tau$	-	-	0.4%	0.3%	0.03%
$H \rightarrow ZZ$	-	-	-	0.07%	0.01%
$H \rightarrow \gamma\gamma$	-	-	-	-	0.0005%

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.

Figure 3: Distributions of m_{HH} in the signal region of (a) the resolved analysis and (b) the boosted analysis [8].

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 τ -lepton. In this analysis, the $\tau_{\text{lep}}\tau_{\text{had}}$ and $\tau_{\text{had}}\tau_{\text{had}}$ channels are considered, where the subscripts (lep = electron or muon, had = hadrons) indicate the decay mode of the τ -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 , $b\bar{b}$, and $\tau\tau$, the angles of the $b\bar{b}$ 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 results exclude an enhancement of the SM expectation by more than a factor of 12.7 at 95% CL [9].

2.3. Combination of different channels

The combination of the analyses of $HH \rightarrow b\bar{b}b\bar{b}$, $b\bar{b}\tau^-\tau^+$, $b\bar{b}\gamma\gamma$, $WWWW$, $WW\gamma\gamma$, and $b\bar{b}WW$ has been performed [14]. Figure 4 shows the 95% CL upper limit on the $\sigma_{\text{ggF}}(pp \rightarrow HH)$ as a function of κ_λ , 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 κ_λ is constrained in the range $-5 - 12$ at 95% CL. Figure 5 shows the 95% CL upper limit on the $\sigma_{\text{ggF}}(pp \rightarrow HH)$ 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_A (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].

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

3. New analyses exploiting the full Run2 dataset

3.1. Search for $HH \rightarrow b\bar{b}l\nu l\nu$ 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 $HH \rightarrow b\bar{b}WW$, $b\bar{b}ZZ$, and $b\bar{b}\tau^-\tau^+$ [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].

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 pannel indicate mass intervals where different final states are combined [14].

3.2. Search for $HH \rightarrow b\bar{b}b\bar{b}$ 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 $HH \rightarrow b\bar{b}b\bar{b}$ analysis. Figure 6 shows the invariant mass of the $4b$ -jets, m_{4b} . 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 κ_{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 $\sqrt{s} = 14 \text{ TeV}$ 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 $27 - 36 \text{ fb}^{-1}$, has been combined with extrapolated statistics and expected systematics. The signal significance on the SM is expected to be 4σ and κ_λ constraint is expected to be $0.1 < \kappa_\lambda < 2.3$ at 95% CL with combined ATLAS and CMS results. Note that the new analysis with full Run2 dataset are not included in this predictions. The limit on κ_{2V} is also expected to

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].

Figure 7: Observed and expected 95% CL upper limits on the production cross-section for (a) resonant HH production via VBF as a function of the X mass, m_X , and (b) non-resonant HH production via VBF as a function of the $VVHH$ coupling, κ_{2V} [16].

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 κ_λ 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 4σ for the SM di-Higgs production process and κ_λ 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.

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