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

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The latest results on production of Higgs boson pairs at 13 TeV by the ATLAS experiment are reported, including a combination of six different decay modes. Results include $b\bar{b}\tau^+\tau^-$, $b\bar{b}b\bar{b}$, $b\bar{b}\gamma\gamma$, $b\bar{b}W^+W^-$, $W^+W^-W^+W^-$, and $W^+W^-\gamma\gamma$ final states, and they are interpreted both in terms of sensitivity to the SM and as limits on k_λ, a scaling of the triple-Higgs interaction strength. The strongest constraints to date on the $VVHH$ coupling are shown. Future prospects of testing the Higgs self-couplings at the High Luminosity LHC (HL-LHC) will also be presented.

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Introduction

With the discovery of the Higgs boson (H) at the Large Hadron Collinder (LHC) the Brout-Englert-Higgs (BEH) mechanism of spontaneous electroweak-symmetry breaking and mass generation was experimentally confirmed. The BEH mechanism predicts the Higgs boson to couple to itself and the form of the Higgs field potential to depend on the strength of its self-coupling. Therefore, the observation of di-Higgs production and the measurement of the Higgs self-coupling is a crucial test of the BEH mechanism. Any deviation from the Standard Model (SM) prediction would open a window on new physics.

In the SM, the gluon–gluon fusion process (ggF) accounts for more than 90% of the Higgs boson pair production cross-section. The Feynman diagrams contributing to this process can be classified based on the absence, cf. Figure 1 (a,b), or presence, cf. Figure 1 (c), of the Higgs self-coupling vertex. The SM predicts a destructive interference between these two types of contributions and a resulting cross-section of $\sigma^{\mathrm{SM}}_{\mathrm{ggF}}(pp \to HH) = 31.05^{+2.2\%}_{-5.0\%}$ fb at $\sqrt{s} = 13$ TeV [1].

Even if the SM predicts the di-Higgs production to be rare and beyond the current sensitivity of LHC experiments, various theories beyond the SM (BSM) predict significantly higher di-Higgs production cross-sections. Enhanced non-resonant Higgs boson pair production could come from anomalous Higgs couplings. Alternatively, extensions of the Higgs sector, such as the two-Higgs-doublet models [2], predict a second, heavier, CP-even scalar that can resonantly decay into two SM Higgs bosons. Furthermore, Randall–Sundrum (RS) models of warped extra dimensions [3] predict spin-2 gravitons that can decay into Higgs boson pairs.

In this contribution, the latest results on the search for di-Higgs production performed by the ATLAS collaboration are shown. The most recent results exploiting data collected by the ATLAS [4] experiment during LHC Run 2 are presented in Section 1, whereas Section 2 focuses on the latest predictions for the High Luminosity LHC (HL-LHC).

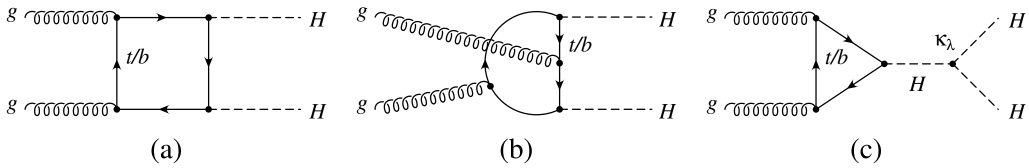


Figure 1: Example of leading-order Feynman diagrams for di-Higgs ggF production: the diagrams (a) and (b) are proportional to the square of the top Yukawa coupling, while the diagram (c) is proportional to the product of the top Yukawa coupling and the Higgs self-coupling [5].

1. Search for di-Higgs production with the ATLAS experiment at the LHC

In this section, the latest results on the di-Higgs search by the ATLAS collaboration are shown. First, the combination of all results published by the ATLAS collaboration on di-Higgs searches using pp collision data at $\sqrt{s} = 13$ TeV, collected during 2015 and 2016 is presented [5]. Afterwards, two searches performed on the pp collision dataset collected with the ATLAS experiment during the full LHC Run 2 are shown. The former is a search for di-Higgs production where one of the Higgs bosons decays via the $H \to b\bar{b}$ channel and the other produces two leptons (electrons or muons) with opposite electric charge in the final state via either of the $H \to WW^*/ZZ^*/\tau\tau$ decay channels [6]. The latter focuses on the search for di-Higgs events produced via vector boson fusion (VBF) in the $b\bar{b}b\bar{b}$ final state [7].

1.1 Combination of di-Higgs production searches

The combination of results from searches for both non-resonant and resonant Higgs boson pair production in pp collisions at $\sqrt{s} = 13\,\text{TeV}$, first published in [5], is herein presented. The combination includes all published di-Higgs searches using data collected with the ATLAS experiment during the first two years of LHC Run 2, corresponding to an integrated luminosity of up to $36.1\,\text{fb}^{-1}$. Namely, the combination includes the analyses targeting $b\bar{b}b\bar{b}$ [8], $b\bar{b}W^+W^-$ [9], $b\bar{b}\tau^+\tau^-$ [10], $W^+W^-W^+W^-$ [11], $b\bar{b}\gamma\gamma$ [12], and $W^+W^-\gamma\gamma$ [13] final states.

The statistical interpretation is based on a simultaneous fit to the data for the cross-section of the signal process using the CL_s approach. The branching fractions of the Higgs boson are assumed to be equal to the SM predictions. Signal regions are either constructed to be mutually orthogonal or are shown to have a negligible overlap.

For the SM di-Higgs search, upper limits are extracted for the gluon fusion (ggF) cross-section assuming that all kinematic properties of the HH pair are those predicted by the SM. The observed and expected limits for all different analyses and their combination are shown in Figure 2 (left). The combined observed 95% confidence level (CL) upper limit on the SM di-Higgs production is $6.9 \times \sigma^{\text{SM}}_{\text{ggF}}(pp \to HH)$, with $\sigma^{\text{SM}}_{\text{ggF}}(pp \to HH) = 33.5^{+2.4}_{-2.8}\,\text{fb}$ [14] being the best theoretical estimation at the time of [5]. This is a more stringent limit than expected, but within the 2σ uncertainty band.

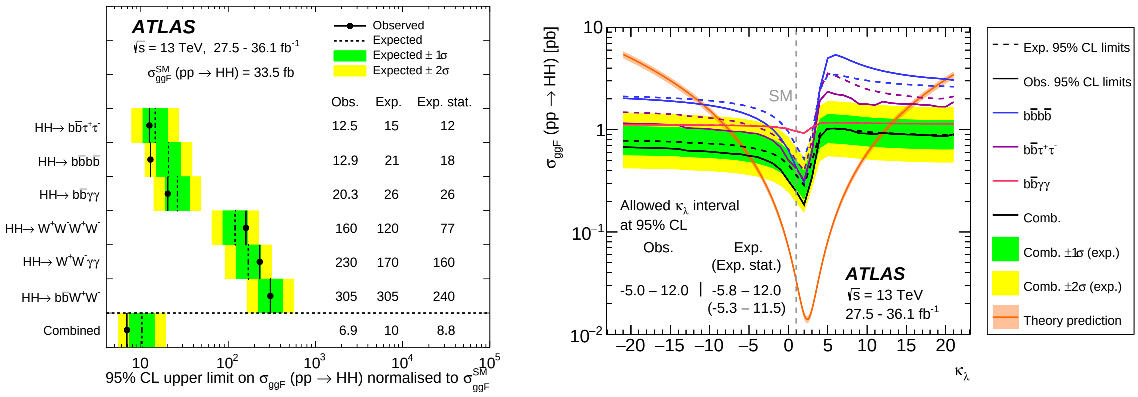
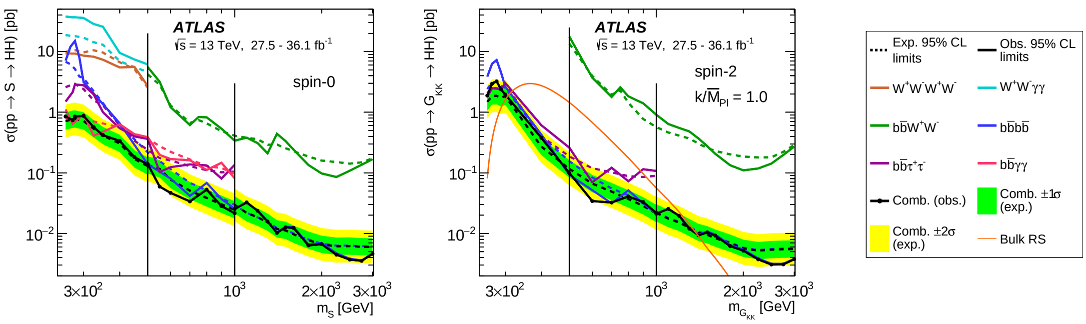


Figure 2: **Left:** Upper limits at 95% CL on the cross-section of the ggF SM HH production normalised to the SM expectation [5]. **Right:** Upper limits at 95% CL on the cross-section of the ggF non-resonant SM HH production as a function of k_λ. The observed (expected) limits are shown as solid (dashed) lines. The theoretical prediction of the cross-section as a function of k_λ is also shown [5].

Additionally, constraints on the Higgs boson self-coupling are derived through a scan of the Higgs self-coupling modifier $k_\lambda = \lambda_{HHH}/\lambda^{SM}_{HHH}$, keeping all other Higgs couplings to the SM values. The scan takes into account the dependence of the di-Higgs production cross-section and kinematic distributions on k_λ, whereas its effect on Higgs boson decay branching fractions due to NLO electroweak corrections is neglected. Only the three most sensitive channels, namely $b\bar{b}b\bar{b}$, $b\bar{b}\tau^+\tau^-$, and $b\bar{b}\gamma\gamma$, are combined in this case. The observed and expected upper limits at 95% CL on the cross-section of the ggF non-resonant SM HH production as a function of k_λ are shown in Figure 2 (right). The theoretical prediction on the cross-section as a function of k_λ is also shown. The observed (expected) confidence interval at 95% CL for k_λ is $-5.0 < k_\lambda < 12.0$ ($-5.8 < k_\lambda < 12.0$) setting the strongest direct limit to date on k_λ. Notably, indirect limits on k_λ from single Higgs differential production and decay measurements were also assessed by the ATLAS collaboration using a dataset of pp collisions at $\sqrt{s} = 13\,\text{TeV}$ corresponding up to $80\,\text{fb}^{-1}$ and are documented in [15]. The observed (expected) 95% confidence interval is $-3.2 < k_\lambda < 11.9$ ($-6.2 < k_\lambda < 14.4$).

Alternatively, di-Higgs events could be produced at the LHC via a heavy spin-0 scalar particle with a narrow width or a spin-2 Kaluza-Klein (KK) graviton. The resonance width changes with the graviton mass and depends on the parameter $k/\overline{M}_{\text{Pl}}$, where k is the curvature of the warped extra dimension in the bulk RS model and $\overline{M}_{\text{Pl}} = 2.4\times10^{18}\,\text{GeV}$ is the effective four-dimensional Planck mass. The scalar (spin-2) resonance search is performed in the range $260(300)-3000\,\text{GeV}$. Within these ranges no statistically significant excess is observed. The combined 95% upper limit on the cross-section is shown as a function of the resonance mass in Figure 3. Further interpretations in the context of the hMSSM and EW-singlet models can be found in [5].



(a) (b)

Figure 3: Upper limits at 95% CL on the cross-section of the resonant Higgs boson pair production for a spin-0 heavy scalar (a) and a spin-2 KK graviton with $k/\overline{M}_{\text{Pl}} = 1$ (b) [5].

1.2 Search for non-resonant Higgs boson pair production in the $bb\ell\nu\ell\nu$ final state

A search for non-resonant di-Higgs production in the $bb\ell^+\nu\ell^-\nu$ final state [6], where ℓ refers either to an electron or a muon, is herein presented. The analysis uses data collected with the ATLAS experiment during the full pp LHC Run 2 period and corresponding to an integrated luminosity of $139\,\text{fb}^{-1}$. The signal is composed of di-Higgs events in which one Higgs decays to a $b\bar{b}$ pair and the other to WW^* (90%), $\tau\tau$ (9%), or ZZ^* (1%).

A machine-learning method based on the feedforward neural network architecture is used to construct a classifier to distinguish the HH signal from the SM backgrounds. The main backgrounds, namely events from the production of $t\bar{t}$ pairs and a single Z boson in association with heavy flavour quarks, account for roughly 80% of the total expected background yield. They are irreducible backgrounds and are estimated from Monte Carlo simulation normalized in dedicated control regions. The remaining part of the background comes from non-prompt leptons from heavy flavour hadron and is estimated with a data-driven method using events with same sign leptons.

A counting experiment is performed with a profile-likelihood fit across signal and control regions, simultaneously using the predicted and observed event counts in each region as inputs. No significant excess over the expected SM background is observed and upper limits are set on non-resonant Higgs boson pair production at 95% CL with the $\mathrm{CL_s}$ method. The observed (expected) limit is 1.2 (0.9) pb, corresponding to 40(29) times the SM prediction, as detailed in Table 1.

	-2σ	-1σ	**Expected**	$+1\sigma$	$+2\sigma$	**Observed**
$\sigma\,(gg \to HH)$ [pb]	0.5	0.6	0.9	1.3	1.9	1.2
$\sigma\,(gg \to HH)\,/\sigma^{\mathrm{SM}}\,(gg \to HH)$	14	20	29	43	62	40

Table 1: Observed and expected upper limits on the ggF-initiated non-resonant HH production cross-section at 95% CL and their ratios to the SM prediction $\sigma^{\mathrm{SM}}_{\mathrm{ggF}}(pp \to HH) = 31.05^{+2.2\%}_{-5.0\%}$ fb. The $\pm 1\sigma$ and $\pm 2\sigma$ variations about the expected limit are also shown [6].

1.3 Search for the $HH \to b\bar{b}b\bar{b}$ process via vector boson fusion production

The di-Higgs production via VBF in pp collisions is characterized by the presence of two jets with a large rapidity gap resulting from the quarks from which a vector boson is radiated. Such a topology is uniquely sensitive to the $VVHH$ vertex, cf. Figure 4 (left), because in the dominant ggF production mode the Higgs bosons can be produced only through quarks.

Events collected during LHC pp runs at $\sqrt{s} = 13$ TeV with the ATLAS experiment are scrutinized to search for di-Higgs VBF production and the subsequent decay of each Higgs boson to a $b\bar{b}$ pair [7]. The total dataset corresponds to 126 fb^{-1}, recorded during stable beam conditions and fully efficient operation of the detector components. In particular, a significant fraction of events

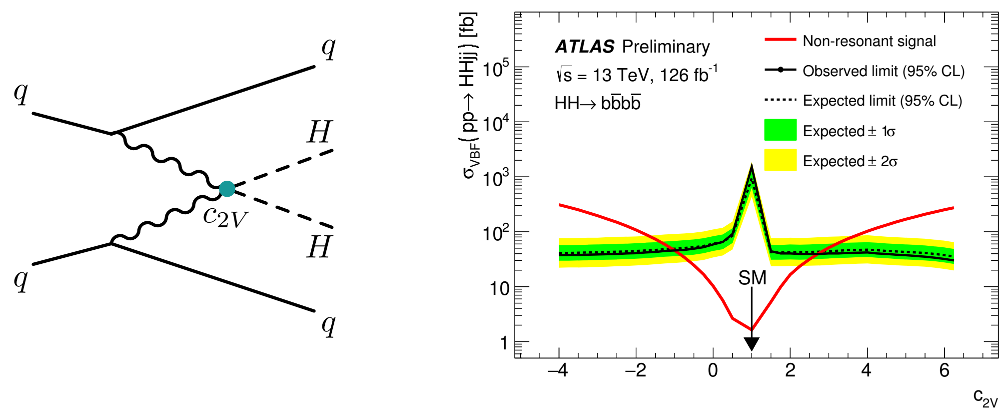


Figure 4: **Left:** Tree-level Feynman diagrams contributing to non-resonant di-Higgs production via VBF through the $VVHH$ vertex (b) [7]. **Right:** Observed and expected upper limits at 95% CL on the cross-section of the VBF non-resonant SM HH production as a function of c_{2V}. The theoretical cross-section prediction is also shown [7].

collected during 2016 and affected by inefficiencies in the vertex reconstruction at the HLT level is discarded due to the resulting reduction in b-jet identification efficiency.

Jets are reconstructed with the anti-k_t algorithm with $R = 0.4$. To select events compatible with VBF production of Higgs pairs, at least four central b-tagged jets with $p_T > 40\,\text{GeV}$ and $|\eta| < 2.0$, and at least two forward jets with $p_T > 30\,\text{GeV}$, $|\eta| > 2.0$ and opposite sign of η are required. After applying an event selection that exploits the kinematic properties of the signal to distinguish it against the SM background processes, the background is dominated by multijet (about 95%) and $t\bar{t}$ events. The multijet process is estimated through a data-driven method consisting in reweighting events with lower b-jet multiplicity to model events in the signal region. The normalization of the all-hadronic $t\bar{t}$ background is determined from data, whereas the rest of the $t\bar{t}$ background is normalised to the SM prediction. The SM di-Higgs ggF production is herein considered as a background, being expected to give a small contribution compared to other background processes, but about three times higher than the expected SM VBF production.

The mass of the four selected b-jets is used as the final discriminant. As no significant excess is observed over the background prediction, exclusion limits are computed based on the CL_s method. The observed (expected) 95% CL limit on the production cross-section times branching ratio is set to 1966 (1210) fb, meaning 1210 (702) times the SM expected value. Bounds on the $VVHH$ coupling strength modifier c_{2V} are presented in Figure 4 (right). The observed and expected 95% CL confidence intervals are $-1.02 < c_{2V} < 2.71$ and $-1.09 < c_{2V} < 2.82$, respectively. Further interpretations in the context of resonant di-Higgs VBF production can be found in [7].

2. Di-Higgs production with the ATLAS experiment at the High-Luminosity LHC

The latest projections of di-Higgs physics at the HL-LHC were published in the CERN Yellow Report by a joint ATLAS, CMS, and theory effort [16]. The ATLAS contribution consists of three analyses targeting the most promising channels, namely $b\bar{b}b\bar{b}$, $b\bar{b}\tau^+\tau^-$, and $b\bar{b}\gamma\gamma$.

The expected performance for the $b\bar{b}b\bar{b}$ and $b\bar{b}\tau^+\tau^-$ channels is assessed through an extrapolation of LHC Run 2 measurements performed by the ATLAS collaboration and published in [8] and [10], respectively. The expected performance of the $b\bar{b}\gamma\gamma$ channel is assessed through a dedicated analysis that exploits truth-level Monte Carlo samples with parametric smearing based on upgraded detector performance and assuming an average pile-up rate of 200 simultaneous interactions per bunch crossing. Of particular importance is the di-photon invariant mass resolution which is estimated to be 1.6 GeV by dedicated upgrade studies and set to this value in simulation.

A pp collision dataset of $\mathscr{L} = 3000\,\text{fb}^{-1}$ is assumed for the projection herein presented. The combined discovery significance of the three channels is 3.5σ and 3.0σ with and without systematic uncertainties included, when the SM HH signal is injected. The combined sensitivity to k_λ is quantified by generating an Asimov dataset containing the background plus SM signal. The maximum likelihood for k_λ divided by the maximum likelihood of a fit under the $k_\lambda = 1$ hypothesis is shown in Figure 5. The resulting 68% confidence intervals for k_λ is $0.4 < k_\lambda < 1.7$ and $0.25 < k_\lambda < 1.9$ with and without systematic uncertainties respectively. Under the assumption of SM di-Higgs production, the expected exclusion significance for the $k_\lambda = 0$ hypothesis is 1.4σ and 1.8σ standard deviations with and without systematic uncertainties respectively.

Improvements on such predictions are to be expected given the fact that some inputs and systematic uncertainties have large unknowns, such as the multijet background modelling for the $b\bar{b}b\bar{b}$ analysis and the τ-fake rate.

The combination with CMS projection are expected to lead to a discovery significance of 4.5σ and 4.0σ with and without systematic uncertainties included, when the SM Higgs self-coupling are considered. Under the same assumptions, the di-Higgs production cross-section is expected to be measured with 30% accuracy and k_λ with 50% accuracy at 68% CL.

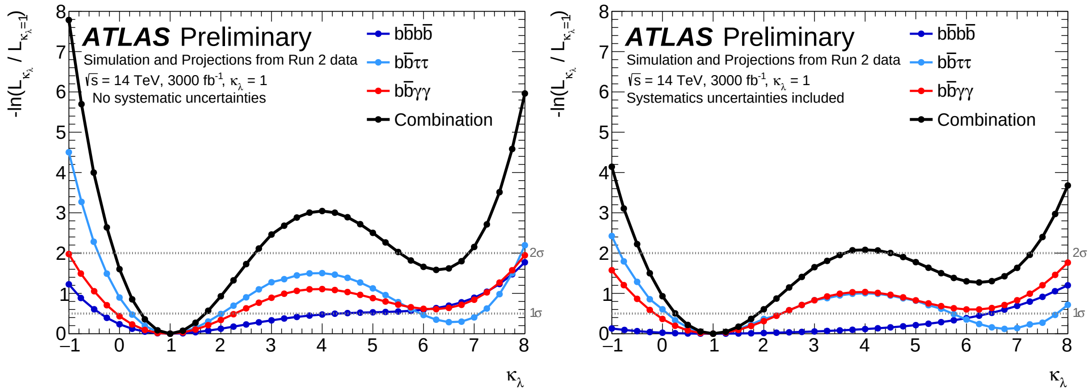


Figure 5: Maximum likelihood for k_λ divided by the maximum likelihood for $k_\lambda = 1$ for (left) the fits with only statistical uncertainties and (right) the fits with all systematic uncertainties as nuisance parameters [16].

Conclusion

The study of di-Higgs production is one of the main goals of the (HL-)LHC physics programme. The most recent results by the ATLAS collaboration on the topic have been presented including a combination of all 2015-2016 ATLAS analyses, two analyses performed on the full *pp* LHC Run 2 dataset, and prospects for the HL-LHC.

No observation for enhanced di-Higgs production has been found. The ATLAS *HH* combination analysis sets the most stringent constraints to date on the di-Higgs production cross-section assuming $k_\lambda = 1$ and the SM model value of Higgs self-coupling, with an observed (expected) 95% CL upper limit of $6.9(10) \times \sigma^{\text{SM}}_{\text{ggF}}$. The observed (expected) confidence interval at 95% CL for k_λ is $-5.0 < k_\lambda < 12.0$ ($-5.8 < k_\lambda < 12.0$). The results of a search for di-Higgs VBF production have been presented, setting the strongest limits to date on the $VVHH$ coupling strength.

The first comprehensive assessment of the HL-LHC physics programme has been recently published in the Yellow Report by a joint ATLAS, CMS, and theory effort. The projection of the state-of-the-art analyses by the ATLAS and CMS collaborations leads to a di-Higgs production discovery significance of 4σ and an uncertainty on the k_λ measurement of 50%, with ATLAS and CMS results combined. Areas for improvement have also been identified.

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