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Probing the nature of electroweak symmetry breaking with Higgs boson pairs in ATLAS

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In the Standard Model, the ground state of the Higgs field is not found at zero but instead corresponds to one of the degenerate solutions minimising the Higgs potential. In turn, this spontaneous electroweak symmetry breaking provides a mechanism for the mass generation of nearly all fundamental particles. The Standard Model makes a definite prediction for the Higgs boson self-coupling and thereby the shape of the Higgs potential. Experimentally, both can be probed through the production of Higgs boson pairs (HH), a rare process that presently receives a lot of attention at the LHC. In this talk, the latest HH searches by the ATLAS experiment are reported, with emphasis on the results obtained with the full LHC Run 2 dataset at 13 TeV. Non-resonant HH search results are interpreted both in terms of sensitivity to the Standard Model and as limits on the Higgs boson self-coupling and the quartic $VVHH$ coupling. The Higgs boson self-coupling can be also constrained by exploiting higher-order electroweak corrections to single Higgs boson production. A combined measurement of both results yields the overall highest precision, and reduces model dependence by allowing for the simultaneous determination of the single Higgs boson couplings. Results for this combined measurement are also presented. Finally, extrapolations of recent HH results towards the High Luminosity LHC upgrade are also discussed.

1 Introduction

After the Higgs boson discovery in 2012, a major effort targets the measurement of properties and interactions of the Higgs boson, like the Higgs boson self-coupling, with data from the LHC experiments. The determination of the Higgs boson self-coupling probes the Higgs boson potential shape and sheds light on some open theory questions on the Higgs boson nature [1]. Experimentally, the tri-linear Higgs boson self-coupling λ_3 can be inferred by measuring the di-Higgs production. The cross section and some kinematic observables, like the di-Higgs invariant mass m_{HH}, are sensitive to λ_3. The coupling strength is measured with respect to the Standard Model (SM) tri-Higgs coupling, λ_3^{SM}, using as metric the coupling modifier $\kappa_\lambda = \frac{\lambda_3}{\lambda_3^{SM}}$. In current non-resonant di-Higgs searches, two types of di-Higgs production processes are considered: gluon-gluon-fusion (ggF) with a cross section of $\sigma_{ggF} = 31.05$ fb at NNLO [2] and vector-boson fusion (VBF) with $\sigma_{VBF} = 1.72$ fb at N3LO [3]. Different couplings can be inferred through ggF and VBF production: the triple Higgs vertex with coupling κ_λ and the Htt vertex coupling κ_t in ggF production, κ_{2V} parameterizes the $VVHH$ coupling in VBF production. In single Higgs production, sensitivity to λ_3 comes from higher order electroweak corrections. There is a huge effort in the ATLAS [4] collaboration to constrain non-resonant di-Higgs production and κ_λ with multiple decay channels to increase the sensitivity in combination. Most sensitivity is expected to come from the decays $HH \to bb\gamma\gamma$, $HH \to bb\tau\tau$ and $HH \to bbbb$. The latest results on the di-Higgs production cross section σ_{HH} and self-coupling measurements in these decay channels

Analysis	Observed (expected) limit on $\sigma_{HH}/\sigma_{HH}^{SM}$, 95% CL	κ_λ observed limit	κ_{2V} observed limit
$HH \to bb\tau\tau$	4.7 (3.9)	[-2.7,9.5]	n.a.
$HH \to bb\gamma\gamma$	4.2 (5.7)	[-1.5,6.7]	n.a.
$HH \to bbbb$	5.4 (8.1)	[-3.9,11.1]	[-0.03,2.11]
Combination	2.4 (2.9)	[-0.6,6.6]	[0.1,2.0]

Table 1: Overview over the main results from $HH \to bb\tau\tau, bb\gamma\gamma, bbbb$ analyses by ATLAS: Observed (expected) limits of the HH (ggF and VBF) cross section normalized by the SM cross section (σ_{HH}^{SM}). The observed limits on the couplings κ_λ and κ_{2V} are also shown. From [5,6,7].

are presented using 139 fb^{-1} of data collected by the ATLAS experiment, along with interpretations within the scope of Effective Field Theories and prospects for the high-luminosity run of the LHC (HL-LHC).

2 Recent non-resonant HH searches

The most recent ATLAS publications on di-Higgs non-resonant searches are presented in the following. Important results are presented as an overview in Table 1.

2.1 $HH \to bb\tau\tau$

This analysis [5] selects events with exactly two b-tagged jets and with either two hadronically decaying τ-leptons ($\tau_{had} + \tau_{had}$) and no electron or muon, or each one hadronic and leptonic τ ($\tau_{had} + \tau_{lep}$) whereas one τ_{had} and one electron or muon are required. The $t\bar{t}$ and multijet background with fake τ-leptons are estimated with semi-data-driven methods and backgrounds containing true τs are estimated with simulation. Multivariate discriminants are constructed to separate the background from the signal. A binned maximum likelihood fit to a control region and the multivariate discriminant score in the signal region is performed and the signal strength, the normalizations of $t\bar{t}$ and Z-boson production in association with heavy flavour jets are floated. The limit on the HH cross section improves w.r.t the previous ATLAS result in this channel by a factor of four, which is mostly due to the increased data set and improvements in τ and b-jet reconstruction and identification. The reconstruction of the di-τ system from the visible τ decay production and the missing transverse momentum constitutes the main challenge of the analysis, due to the presence of additional neutrinos from the b-hadron decay. The sensitivity is limited by the statistical uncertainty of data in the signal region.

2.2 $HH \to bb\gamma\gamma$

The $HH \to bb\gamma\gamma$ channel profits from a good $H \to \gamma\gamma$ mass resolution. The analysis [6] selects events with exactly two b-tagged jets, at least two photons and no leptons. The invariant mass of the di-photon system $m_{\gamma\gamma}$ is required to be within $105 < m_{\gamma\gamma} < 160$ GeV, whereas the sensitive region is in the range $120 < m_{\gamma\gamma} < 130$ GeV. The mass sideband is used to normalize the di-photon+jet production model, whose functional form is determined using simulation. A multivariate discriminant is trained to enhance the signal over the background. The signal region is divided into four regions in the plane defined by the multivariate score and the reconstructed di-Higgs invariant mass, $m^*_{bb\gamma\gamma}$, which can discriminate between SM and Beyond Standard Model (BSM) HH production, defined such that a better mass resolution is achieved. A combined maximum likelihood fit to $m_{\gamma\gamma}$ is performed in all regions. The HH signal and the single Higgs background are modelled with Crystal Ball functions. The analysis sensitivity is limited by statistical precision. The limit on σ_{HH} w.r.t the result using 36 fb^{-1} of Run-2 data has been improved by a factor of five, mostly due to the increased dataset, the categorization in $m^*_{bb\gamma\gamma}$, the multivariate event selection and better object reconstruction and calibration.

Wilson coefficient (observed)	c_{gghh}	c_{tthh}
$HH \to bbbb$	[-0.36,0.78]	[-0.55,0.51]
$HH \to bb\gamma\gamma$	[-0.4,0.5]	[-0.3,0.8]
$HH \to bb\tau\tau$	[-0.4,0.4]	[-0.3,0.7]
$HH \to bb\tau\tau$ & $HH \to \gamma\gamma$ combined	[-0.3,0.5]	[-0.2,0.6]

Table 2: ATLAS observed results on the HEFT Wilson coefficients c_{gghh} (gluon-gluon-HH-vertex) and c_{tthh} (tt-HH vertex). The coefficients are zero in the Standard Model. From [7,10].

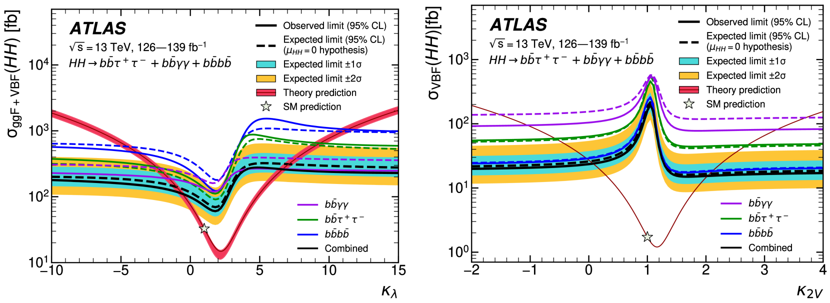

Figure 1 – Combined expected and observed limits on κ_λ (left) and κ_{2V} (right). The expected and observed limits of the single analyses and the theory prediction are superimposed. From [11].

2.3 $HH \to bbbb$

The $H \to bbbb$ analysis [7] defines additional regions targeted at constraining VBF production, thus, limits on κ_λ as well as κ_{2V} are set. Events with at least 4 b-tagged jets are selected and the two Higgs bosons are reconstructed from the four b-tagged jets leading in p_T and their masses are required to be compatible with the Higgs mass. For the VBF regions, two non-b-tagged jets with large invariant mass and large separation in pseudo-rapidity are required in addition. The background is estimated by re-weighting events in a control region with weights derived using a neural network. A combined maximum likelihood fit is performed to the reconstructed m_{HH} distribution. Limits on ggF production improved by a factor of two w.r.t the previous analysis with a data set of 27 fb^{-1}, also due to improved background estimation and object reconstruction. The limits on the VBF production cross section are more than 75% lower w.r.t the previous VBF analysis on the full Run-2 data, the improvements come alone from the analysis strategy and object reconstruction. The sensitivity is limited by systematics on the background modeling and theoretical predictions.

3 Higgs coupling interpretation in Effective Field Theories

Anomalous couplings can be expressed in terms of effective field theories (EFTs), like the Standard Model EFT (SMEFT) [9] or the Higgs EFT (HEFT) [8]. Wilson coefficients expressing couplings in HEFT and SMEFT are measured in all three channels and the results of $HH \to bb\gamma\gamma$ and $HH \to bb\tau\tau$ are combined [10]. Table 2 shows the limits on the HEFT Wilson coefficients related to the BSM $gghh$ and $ttbb$ vertices for $H \to bbbb$ and the $H \to bb\gamma\gamma$ - $HH \to bb\tau\tau$ combination. Limits are as well set on seven benchmark models in which different HEFT coefficients are varied simultaneously. $HH \to bbbb$ also sets limits on the SMEFT coefficients.

4 Inferring the self-coupling using H and HH production

The upper limits on the HH production cross section and the couplings κ_λ and κ_{2V} of the $HH \to bb\tau\tau, bb\gamma\gamma, bbbb$ analyses are combined and the results are shown in Table 1 and Figure 1 [11]. Single Higgs measurements can provide additional sensitivity to κ_λ and assumptions on the Higgs couplings to other particles can be dropped to provide limits in a more generic model. Single Higgs measurements with several final states are considered. Figure 2 shows the principal

Combination assumption	Obs. 95% CL	Exp. 95% CL	Obs. value$^{+1\sigma}_{-1\sigma}$
HH combination	$-0.6 < \kappa_\lambda < 6.6$	$-2.1 < \kappa_\lambda < 7.8$	$\kappa_\lambda = 3.1^{+1.9}_{-2.0}$
Single-H combination	$-4.0 < \kappa_\lambda < 10.3$	$-5.2 < \kappa_\lambda < 11.5$	$\kappa_\lambda = 2.5^{+4.6}_{-3.9}$
HH+H combination	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
HH+H combination, κ_t floating	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
HH+H combination, κ_t, κ_V, κ_b, κ_τ floating	$-1.4 < \kappa_\lambda < 6.1$	$-2.2 < \kappa_\lambda < 7.7$	$\kappa_\lambda = 2.3^{+2.1}_{-2.0}$

Figure 2 – Expected and observed limits on κ_λ for different combination scenarios: Combination of HH analyses, single H analyses, HH and H analyses fixing or floating other Higgs couplings to SM particles. From [11].

results, comparing the different combinations. These combinations provide the most stringent limits on κ_λ to date. The result of the single-Higgs combination shows that these measurements can only provide very limited constraints on κ_λ.

5 HH non-resonant searches: HL-LHC prospects

The expected sensitivity with the future HL-LHC data set is probed [12]. The HL-LHC runs with increased instantaneous luminosity start in 2029 and the ATLAS experiment is expected to collect 3000 fb^{-1} of data at a collision energy of 14 TeV. The $HH \to bbbb$ search is extrapolated to HL-LHC data set luminosity and combined with the extrapolated $HH \to bb\gamma\gamma, bb\tau\tau$ analyses assuming different systematic uncertainty scenarios, namely a baseline scenario where relevant systematics are scaled down according to expected improvements at the HL-LHC. In the $bbbb$ final state, an upper limit of 2.0 on the HH signal strength at 95% CL is expected in the baseline scenario. A reduction of the background estimation uncertainty and an increase of the b-tagging performance have the largest potential to improve the limits. A 68% confidence interval (CI) for κ_λ of [-0.5,6.1] and for κ_{2V} of [0.7,1.4] for the baseline scenario is estimated. A combination of the extrapolated results of all three presented channels yield an expected discovery significance of 3.4 σ for the baseline scenario and a 1 σ CI on κ_λ of [0.5,1.6].

6 Conclusion

ATLAS searches for di-Higgs non-resonant production in multiple final states using data from the full LHC Run-2 data set. The latest results in the final states $bbbb, bb\tau\tau, bb\gamma\gamma$ on limits on the production cross section, the triple Higgs coupling and the VVHH coupling are presented, along with a rich interpretation of the results in terms of Effective Field Theories. The combination of the three HH analyses and with single Higgs measurements provide the most stringent limits to date. Extrapolating the results of these three channels to 3000 fb^{-1} of HL-LHC data and combining them for different uncertainty scenarios, yields an expected discovery significance of 3.4 σ in the most realistic scenario.

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