Constraining the Higgs boson self-coupling in a combined measurement of single and double Higgs boson channels at the ATLAS experiment

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The most precise measurements of single and double Higgs boson production cross sections are obtained from a combination of measurements performed in different Higgs boson production and decay channels. While double Higgs production can be used to directly constrain the Higgs boson self-coupling, this parameter 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 presented based on pp collision data collected at a centre-of-mass energy of 13 TeV with the ATLAS detector.

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1. Introduction

After the discovery of the Higgs boson by the ATLAS [1, 2] and CMS Collaborations [3, 4] at the Large Hadron Collider (LHC), the measurement of its properties has become of major importance for the physics program of the LHC experiments in order to verify their compatibility with the prediction of the Standard Model (SM) of particle physics. One of the most important features of the Higgs boson is its self-interaction, characterised by the trilinear self-coupling λ_{HHH}, and related to the shape of the Higgs potential [5–7]. This property influences the SM prediction of the non-resonant Higgs boson pair (HH) production cross-section. The observation of this process will be able to test the SM description of the Englert-Brout-Higgs mechanism and provide a measurement of the Higgs boson self-coupling value. Results on Higgs boson self-coupling are usually expressed using the kappa-framework coupling modifier $\kappa_\lambda = \lambda_{HHH}/\lambda_{HHH}^{SM}$. HH production is directly sensitive to the Higgs boson self-coupling starting at the lowest order in perturbation theory. In the SM, the gluon-gluon fusion process (ggF HH) accounts for more than 90% of the $pp \to HH$ cross-section, while the second most abundant process is the VBF HH production, accounting for only 5% of the total HH production. Feynman diagram examples of these two production modes are shown in Figure 1, where the coupling modifiers accessible via each diagram are highlighted.
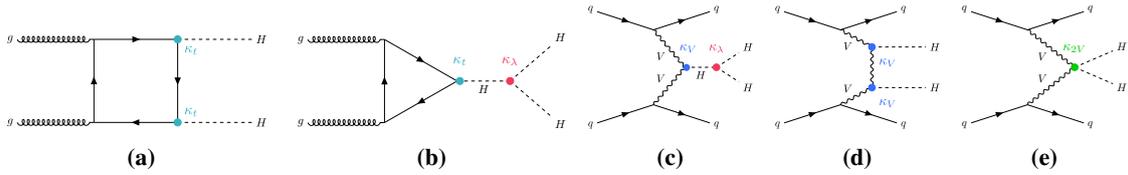
Figure 1: Examples of leading-order Feynman diagrams for Higgs boson pair production for ggF mode (a,b), and VBF mode (c,d,e). The Higgs coupling modifiers are also shown for the HHVV (κ_{2V}), HVV (κ_V), Higgs self-coupling (κ_λ), and top quark Yukawa coupling modifier (κ_t). [20].

Single-Higgs processes are indirectly sensitive to κ_λ via next-to-leading-order (NLO) electroweak (EW) corrections. A universal correction of $O(\kappa_\lambda^2)$ is possible through Higgs loops, as visible from Figure 2(a), while linear corrections of the order of $O(\kappa_\lambda)$ are process and kinematic dependent, as visible from Figure 2(b,c,d,e). As a result, production cross sections and branching ratios vary as a function of κ_λ [8, 9], and precise measurements of inclusive and differential single-Higgs production cross sections and decays provide indirect constraints on κ_λ.

In this work the combination of the three most sensitive double-Higgs decay channels, $b\bar{b}\gamma\gamma$ [10], $b\bar{b}\tau\tau$ [11], and $b\bar{b}b\bar{b}$ [12], using the dataset collected by ATLAS at $\sqrt{s} = 13$ TeV between 2015 and 2018, corresponding to an integrated luminosity of 126-139 fb^{-1}, is reported. This combination is used to set constraints on the HH production cross-section and on κ_λ. More stringent constraints on κ_λ are also reported, from the combination of HH results with the combination of recent single-Higgs analyses in the $\gamma\gamma$, ZZ^*, $\tau^+\tau^-$, WW^*, and $b\bar{b}$ [13–19] decay channels at ATLAS. The single-Higgs measurements of the simplified template cross-sections (STXS) and the HH results have been parameterised to take into account the impact of κ_λ and the other coupling modifiers. This combination allows to measure κ_λ, relaxing the assumptions on the Higgs boson interactions with the other SM particles, thus obtaining a less model dependent result.
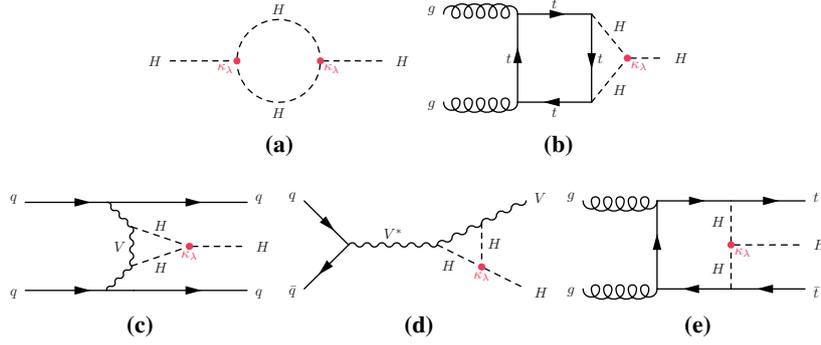
Figure 2: Examples of one loop κ_λ-dependent diagrams for the Higgs boson self-energy (a) and the single-Higgs production in the ggF (b), VBF (c), VH (d), and ttH (e) modes [20].

2. Statistical model

The parameterisation of ggF HH production is provided generating the signal samples at different values of κ_λ, and for the VBF production also κ_V and κ_{2V}. The inclusive production cross-sections, decay branching ratios and differential cross-sections are exploited to increase the sensitivity of the single-Higgs analyses to κ_λ and the other coupling modifiers κ_m. The differential information of single-Higgs analyses is encoded in the STXS framework, with a signal yield in a specific decay channel and STXS bin being proportional to:

$$n_{i,f}^{\text{signal}}(\kappa_\lambda, \kappa_m) \propto \mu_i(\kappa_\lambda, \kappa_m) \times \mu_f(\kappa_\lambda, \kappa_m) \times \sigma_{\text{SM},i} \times \text{BR}_{\text{SM},f} \times (\varepsilon \times A)_{i,f} \tag{1}$$

where μ_i and μ_f describe respectively the multiplicative corrections of the expected SM Higgs boson production cross-sections in an STXS bin ($\sigma_{\text{SM},i}$) and each decay-channel branching ratio ($\text{BR}_{\text{SM},f}$), as a function of the values of κ_λ and κ_m. The $(\varepsilon \times A)_{i,f}$ coefficients take into account the analysis efficiency times acceptance in each production and decay mode. The results are obtained from a likelihood function, with the systematic uncertainties and background parameters that are constrained by sidebands or control regions in data treated as nuisance parameters. The global likelihood function is obtained as the product of the likelihoods of each input analysis, which are products of likelihoods computed in the single analysis categories as well. The results presented here are based on the profile likelihood ratio test statistic Λ, and 68% as well as 95% confidence level (CL) intervals are derived in the asymptotic approximation. The detailed discussion of the sources of systematic uncertainty implemented in the individual analyses is described in Ref. [10–19], and the correlation model adopted for the systematic uncertainties within the single-Higgs combination is described in detail in Ref. [21]. The additional correlation of systematic uncertainties between HH analyses and between the single-Higgs and HH combination has been investigated and implemented, and are described in detail in Ref. [20].

3. Double-Higgs analyses combination results

The double-Higgs boson analyses are combined in order to extract constraints on the production cross-section and on the Higgs-boson self-coupling. The value of the signal strength μ_{HH}, defined as the HH cross-section, only including the ggF HH and VBF HH processes, normalised to its

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SM prediction, is determined. This combination yields an observed (expected) upper limit on μ_{HH} of 2.4 (2.9) at 95% CL assuming no HH production. The limits on the μ_{HH} obtained from the individual channels and their combination are shown in Figure 3(a). The best fit value obtained from the fit to the data is $\mu_{HH} = -0.73 \pm 1.25$, which is compatible with the SM prediction of unity with a p-value of 0.2. The observed (expected) limit can be translated into an upper limit on $\sigma(pp \to HH)$ of 73 fb (85 fb) at 95% CL, assuming no HH production. The cross-section limit as a function of κ_λ is shown in Figure 3(b), exhibiting a strong dependence of the HH signal acceptance on κ_λ. The combined HH channels are also sensitive to the VBF HH process and to the $HHVV$ quartic interaction, and the 95% CL observed VBF HH cross-section upper limit as a function of κ_{2V} is shown in Figure 3(c).
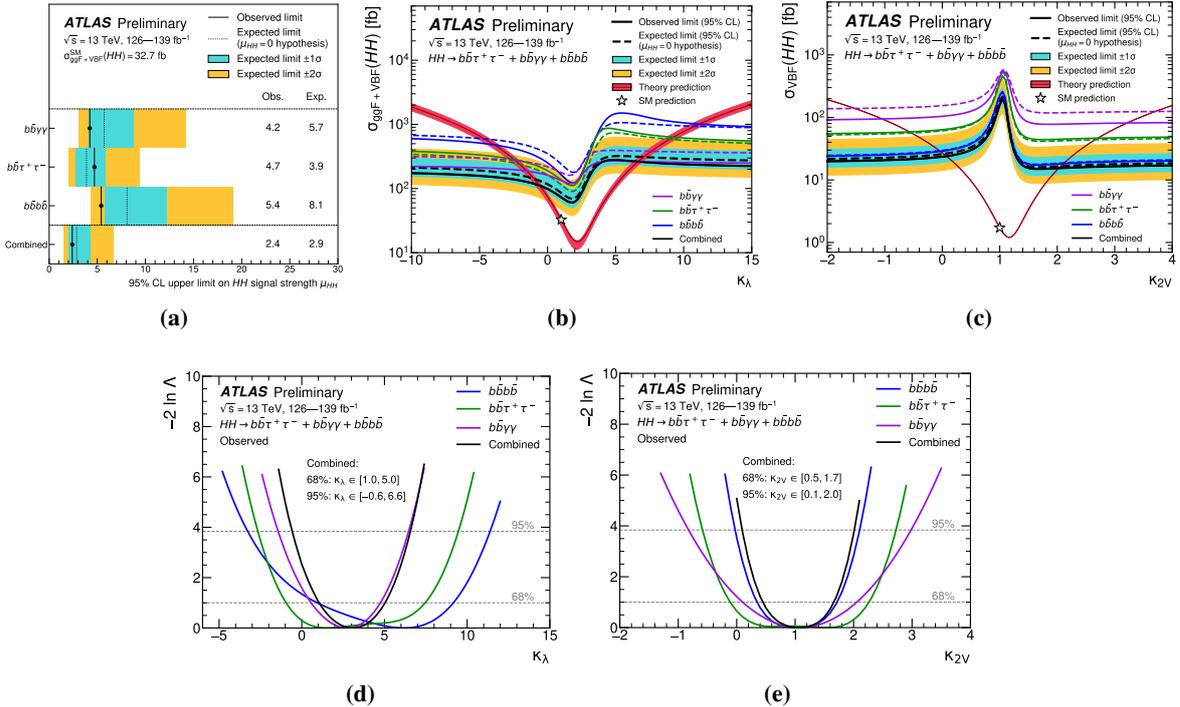

Figure 3: Observed and expected 95% CL upper limits on μ_{HH} from the three double-Higgs search channels, and their combination (a). Observed and expected 95% CL exclusion limits on the production cross-sections of (b) the combined ggF HH and VBF HH as a function of κ_λ and (c) the VBF HH process as a function of κ_{2V}, for the three HH search channels and their combination. The expected limits assume no HH production (a,b) or no VBF HH production (c). The red line shows the theory prediction for (b) the combined ggF HH and VBF HH cross-section as a function of κ_λ, and (c) the VBF HH cross-section as a function of κ_{2V}, with the surrounding band indicating the theoretical uncertainty on the predicted cross-section. Observed value of the test statistic ($-2 \ln \Lambda$), as a function of the κ_λ (d), and κ_{2V} (e) parameter for the three HH search channels and their combination, where all other coupling modifiers are fixed to their SM value [20].

Constraints on the coupling modifiers are obtained by using the values of the test statistic $-2 \ln \Lambda$ as a function of κ_λ and κ_{2V}, shown in Figure 3(d,e), in the asymptotic approximation and including the theoretical uncertainty on the cross-section predictions. The observed (expected) constraints at 95% CL are $-0.6 < \kappa_\lambda < 6.6$ ($-2.1 < \kappa_\lambda < 7.8$), and $0.1 < \kappa_{2V} < 2.0$ ($0.0 < \kappa_{2V} < 2.1$), with the expected values derived under the SM hypothesis.

4. Single- and double-Higgs analyses combination results

The *HH* and single-Higgs analyses are combined to derive constraints on κ_λ. Several fits to data are performed with different assumptions on the Higgs coupling modifiers, summarised in Table 1. Considering only possible deviations from the SM of κ_λ and assuming that all other Higgs boson interactions proceed as predicted by the SM, the observed values of the test statistic $-2 \ln \Lambda$ as a function of κ_λ are obtained and shown in Figure 4(a) for the single-Higgs, *HH* analyses, and their combination. The combined observed (expected) constraints obtained under this hypothesis are $-0.4 < \kappa_\lambda < 6.3$ ($-1.9 < \kappa_\lambda < 7.5$) at 95% CL. The addition of the single-Higgs analyses gives the possibility to relax assumptions on the coupling modifiers to other SM particles. Removing the assumption on the coupling modifier κ_t between the Higgs and the top quark, and allowing it to float freely in the fit, allows to obtain the two dimensional contours of the test statistic in the $\kappa_\lambda - \kappa_t$ plane. These contour plots are shown in Figure 4(b,c), fixing all the other coupling modifiers to unity. Thanks to the strong constraints on κ_t from single-Higgs measurements visible in the contour plots, the constraints on κ_λ obtained from a fit with a free floating value of κ_t are similar to those obtained with its value fixed to unity, as reported in Table 1.

| (a) | (b) | (c) |
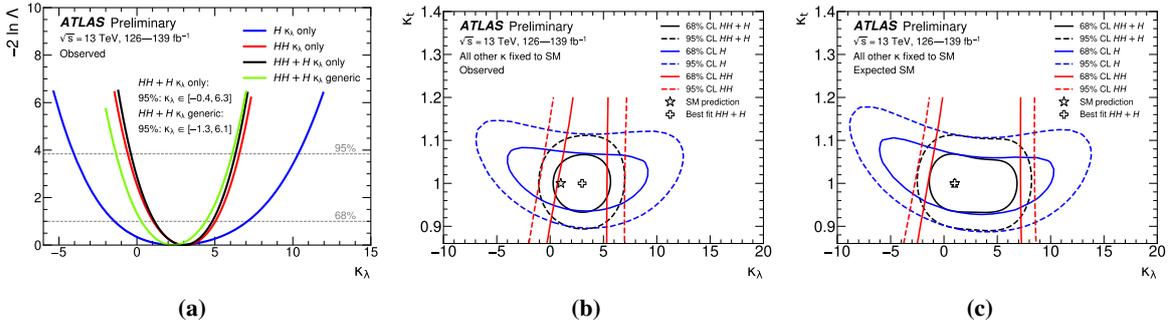
Figure 4: Observed value of the test statistic ($-2 \ln \Lambda$) as a function of κ_λ (a), and observed (b) and expected (c) constraints in the $\kappa_\lambda - \kappa_t$ plane, from single-Higgs (blue), *HH* (red) and their combination (black). The combined result for the generic model is also shown in (a) (green curve) [20].

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+Single-*H* combination	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
HH+Single-*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+Single-*H* combination, $\kappa_t, \kappa_V, \kappa_b, \kappa_\tau$ floating	$-1.4 < \kappa_\lambda < 6.1$	$-2.2 < \kappa_\lambda < 7.7$	$\kappa_\lambda = 2.3^{+2.1}_{-2.0}$

Table 1: Summary of κ_λ observed and expected constraints and corresponding observed best fit values with their uncertainties for different combination assumptions [20].

The most generic model allows all coupling modifiers implemented in this parameterisation, κ_λ, κ_t, κ_b, κ_τ, and κ_V, to freely float in the fit, with the exception of κ_{2V} that is fixed to unity, since there is no available parameterisation of single-Higgs NLO EW correction as a function of this coupling modifier. In this combination, an observed (expected) exclusion of $-1.3 < \kappa_\lambda < 6.1$ ($-2.1 < \kappa_\lambda < 7.6$) is obtained at 95% CL in this less model-dependent fit. The post-fit values of all the other coupling modifiers are in agreement with the SM prediction within uncertainties.

5. Conclusions

The single-Higgs and double-Higgs boson analyses based on the full Run 2 LHC dataset collected with the ATLAS detector have been combined to investigate the Higgs boson self-interaction. Using the three most sensitive HH channels, $b\bar{b}\gamma\gamma$, $b\bar{b}\tau\tau$, and $b\bar{b}b\bar{b}$, an observed (expected) upper limit of 2.4 (2.9) at 95% CL has been set on the HH signal strength, defined as the sum of the ggF HH and VBF HH production cross-sections normalised to its SM prediction. A constraint of $-0.6 < \kappa_\lambda < 6.6$ at 95% CL on the Higgs boson self-coupling modifier has been set, assuming that the other Higgs boson interactions are as predicted by the SM. In addition, thanks to the sensitivity of the VBF HH process, a constraint of $0.1 < \kappa_{2V} < 2.0$ at 95% CL on the κ_{2V} coupling modifier has been derived. The HH channels results have been combined with the single-Higgs boson cross-section measurements from the $\gamma\gamma$, ZZ^*, $\tau^+\tau^-$, WW^*, and $b\bar{b}$ decay channels, to derive less model dependent constraints on κ_λ. Using this combination and assuming that κ_λ is the only source of physics beyond the SM, an observed (expected) exclusion limit of $-0.4 < \kappa_\lambda < 6.3$ ($-1.9 < \kappa_\lambda < 7.5$) at 95% CL has been set. A less model-dependent result is obtained relaxing the assumptions on the other coupling modifiers, κ_t, κ_b, κ_τ, and κ_V, with an observed (expected) constraint of $-1.3 < \kappa_\lambda < 6.1$ ($-2.1 < \kappa_\lambda < 7.6$) at 95% CL. To date, this study provides the most stringent constraints on the Higgs boson self-interactions.

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