Constraints on the Higgs boson self-coupling from the combination of single-Higgs and double-Higgs production analyses performed with the ATLAS experiment

The ATLAS Collaboration

Constraints on the Higgs boson self-coupling are set by combining the single Higgs boson analyses targeting the $\gamma\gamma$, $ZZ^*$, $WW^*$, $\tau^+\tau^-$ and $b\bar{b}$ decay channels with the double Higgs boson analyses in the $b\bar{b}b\bar{b}$, $b\bar{b}\tau^+\tau^-$ and $b\bar{b}\gamma\gamma$ decay channels, using data collected at $\sqrt{s} = 13$ TeV with the ATLAS detector at the LHC. The data used in these analyses correspond to an integrated luminosity of up to 79.8 fb$^{-1}$ for single Higgs boson analyses and up to 36.1 fb$^{-1}$ for the double Higgs boson analyses. With the assumption that new physics affects only the Higgs boson self-coupling ($\lambda_{HHH}$), values outside the interval $-2.3 < \lambda_{HHH}/\lambda_{SM} < 10.3$ are excluded at 95% confidence level. Results with less stringent assumptions are also provided, introducing additional coupling modifiers for the Higgs boson interactions with the other Standard Model particles.

*This note has been updated with respect to the version released on the 11th October 2019 adding References [37, 38].

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1 Introduction

After the discovery of the Higgs boson by the ATLAS and CMS experiments [1, 2], the focus has shifted to measuring its properties and testing their compatibility with the predictions of the Standard Model (SM). During the first two runs of data-taking of the Large Hadron Collider (LHC) at CERN, the Higgs boson production cross sections and decay branching fractions in various channels have been measured with increasing precision [3–5]. Nevertheless the Higgs scalar potential is still largely unconstrained, including the Higgs boson trilinear self-coupling $\lambda_{HHH}$.

Constraints on $\lambda_{HHH}$ have been set from searches for double Higgs boson production (here referred to as double-Higgs) and from the measurements of single Higgs boson productions and decays (here referred to as single-Higgs). Results are reported in terms of $\kappa_4 = \lambda_{HHH}/\lambda_{HHH}^{SM}$, which is the ratio of the Higgs boson self-coupling to its SM prediction, derived from the Higgs boson mass [6, 7] and the Fermi constant [8] measurements. Using double-Higgs boson searches, the value of $\kappa_4$ is constrained at 95% confidence level (CL) to be in the range $-5.0 < \kappa_4 < 12.0$ [9] by ATLAS using up to 36.1 fb$^{-1}$ of Run-2 data and in the range $-11.8 < \kappa_4 < 18.8$ [10] by CMS. Indirect constraints on the Higgs boson self-coupling using single-Higgs measurements, following the approach proposed in Refs. [11–16], have been set by ATLAS constraining $\kappa_4$ in the range $-3.2 < \kappa_4 < 11.9$ at 95% CL [17] using up to 79.8 fb$^{-1}$ of Run-2 data. These constraints are derived under the assumption that new physics affects only the Higgs boson self-coupling.

This note describes a global fit to $\kappa_4$ and other modifiers affecting the Higgs boson couplings to fermions and vector bosons, based on the combined measurements of single-Higgs [4] and double-Higgs boson [9] production and decay rates. The results presented are obtained using data collected at $\sqrt{s} = 13$ TeV with an integrated luminosity ranging from 27.5 to 36.1 fb$^{-1}$ for the double-Higgs analyses and from 36.1 to 79.8 fb$^{-1}$ for the single-Higgs analyses.

2 Data and input measurements

The results presented in this note are obtained using data collected by the ATLAS experiment [18–20] in 2015, 2016 and 2017 from LHC 13 TeV $pp$ collisions. The integrated luminosities of the datasets used in each input analysis to the combination are summarised in Table 1. Details about the individual analyses can be found in the references reported in the same table. Each analysis separates the selected events into orthogonal kinematic and topological regions, called categories. Most of the single-Higgs analyses are designed to be orthogonal and the residual overlaps between them are found to be negligible [4]. In the double-Higgs analyses, the $bb\tau\tau$ categories are orthogonal to both the $bb\gamma\gamma$ and $bb\gamma\gamma$ categories by definition, while a negligible overlap is present between the $bb\gamma\gamma$ analyses [9].

The single-Higgs and double-Higgs categories combined in this note have not been designed to be orthogonal to each other. The overlap between them has been studied for this combination. Following the results of the study, the $t\bar{t}H, H \rightarrow \gamma\gamma$ categories included in Ref. [17] have been removed because there are categories where up to 50% of the selected $t\bar{t}H, H \rightarrow \gamma\gamma$ events are also selected by the $HH \rightarrow b\bar{b}\gamma\gamma$ analysis. When removing the $t\bar{t}H, H \rightarrow \gamma\gamma$ categories, the expected $\kappa_4$ 95% CL interval increases by 4%; this is significantly smaller than the expected interval increase due to the removal of the $HH \rightarrow b\bar{b}\gamma\gamma$ categories. The remaining categories have a maximum overlap of less than 2% of the events in the double-Higgs categories, with the maximum being between the $VH, H \rightarrow b\bar{b}$ and $H \rightarrow \tau^+\tau^-$ single-Higgs categories and the $HH \rightarrow b\bar{b}\tau^+\tau^-$ categories. The impact of this overlap on the results has been checked.
removing separately the $VH, H \rightarrow b\bar{b}$ and $H \rightarrow \tau^+\tau^-$ categories overlapping with the $HH \rightarrow b\bar{b}\tau^+\tau^-$ ones from the combined fit and it was found to be about 1%, thus it can be considered negligible and all these categories are included in this combination.

In summary, the categories included in this combination are those described in Refs. [9, 17] for the double-Higgs and single-Higgs analyses with the exception of the $t\bar{t}H, H \rightarrow \gamma\gamma$ categories, which are not included in this work.

# 3 Theoretical model and signal samples

Double-Higgs production analyses are directly sensitive to the Higgs boson self-coupling starting at the lowest order in the electroweak (EW) couplings expansion. In the SM, the gluon–gluon fusion $pp \rightarrow HH$ process (ggF) accounts for more than 90% of the Higgs boson pair production cross section, and only this production mode has been considered here. At lowest order in perturbation theory, it proceeds via two amplitudes: the first ($A_1$) represented by the diagrams (a) and (b), and the second ($A_2$) represented by the diagram (c) in Figure 1. The $A_1$ amplitude is proportional to the square of the Higgs boson coupling to the top-quark, $g_t$, and the $A_2$ amplitude to the product of $g_t$ and the Higgs boson self-coupling $\lambda_{HHH}$. In the SM, the interference between these two amplitudes is destructive and yields an overall cross section of $\sigma_{ggF}(pp \rightarrow HH) = 33.5^{+3.4}_{-2.8} \text{ fb}$ at $\sqrt{s} = 13 \text{ TeV}$, calculated at NLO in QCD with the measured value of the top-quark mass and corrected at NNLO in QCD matched to NNLL resummation using the heavy top-quark limit\[34–41\].

The dependence of the ggF $pp \rightarrow HH$ cross section on $\kappa_1$ is obtained by multiplying the SM cross section above by the ratio $\sigma_{ggF}(\kappa_1)/\sigma_{ggF}^\text{SM}$, where $\sigma_{ggF}^\text{SM} = \sigma_{ggF}(\kappa_1 = 1)$\[34–41\]. Recent computations have been performed inducing a small reduction of the SM cross section to $31.05 \text{ fb}$ and a stronger dependence on $\kappa_1$\[42–44\]. To keep consistency with the published double-Higgs results\[9\], these recent calculations have not been used in this work, but their impact on the Higgs boson self-coupling constraints has been evaluated to be less than 2%. The value of the Higgs boson mass used in these calculations and for all results in this note is $m_H = 125.09 \text{ GeV}$\[45\]. In the SM, the $b$-quark loop contribution to the ggF cross section is negligible\[34, 46, 47\], so its contribution has been neglected in this analysis.
Figure 1: Examples of leading-order Feynman diagrams for Higgs boson pair production: the diagrams (a) and (b) are proportional to the square of the top-quark Yukawa coupling, while the diagram (c) is proportional to the product of the top-quark Yukawa coupling and the Higgs boson self-coupling.

Beyond-the-Standard-Model (BSM) scenarios can bring substantial enhancement of the \( pp \rightarrow HH \) cross section by modifying the relative sign of \( A_1 \) and \( A_2 \), and by increasing the contributions of \( A_1 \) or \( A_2 \) through modifications of the couplings \( g_t \) and \( \lambda_{HHH} \). The \( HH \) amplitude can then be written as:

\[
\mathcal{A}(\kappa_t, \kappa_A) = \kappa_t^2 A_1 + \kappa_t^2 \kappa_A A_2,
\]

where \( \kappa_t = g_t / g_t^{\text{SM}} \). Higher order QCD corrections do not add further \( t\bar{t}H \) or \( HHH \) vertices to the diagrams shown in Figure 1, implying that Equation 1 is applicable to any order in QCD (i.e., also when the amplitudes \( A_1 \) and \( A_2 \) are modified to include their higher order QCD corrections). Calculations at higher orders in electroweak (EW) are not available for double-Higgs production.

From Equation 1, after integration over the final-state phase space and over the PDFs, the \( ggF \) double Higgs boson cross section \( \sigma_{ggF}(pp \rightarrow HH) \) can be parameterised in terms of \( \kappa_A / \kappa_t \) and \( \kappa_t \) as:

\[
\sigma_{ggF}(pp \rightarrow HH) \propto \int \kappa_t^4 \left[ |A_1|^2 + 2 \left( \frac{\kappa_A}{\kappa_t} \right) \Re(\mathcal{A}_1 \mathcal{A}_2^*) + \left( \frac{\kappa_A}{\kappa_t} \right)^2 |A_2|^2 \right].
\]

This expression shows that the kinematic distributions depend only on the ratio \( \kappa_A / \kappa_t \), and, consequently, the signal acceptance also depends only on \( \kappa_A / \kappa_t \), while the \( \kappa_t^4 \) factor affects only the total cross section.

Using Equation 2 it is thus possible to parameterise the \( ggF \) double-Higgs signal distributions as a function of \( \kappa_A / \kappa_t \). In the \( b\bar{b}b\bar{b} \) and \( b\bar{b}\tau^+\tau^- \) cases, the distributions of the analysis observables depend on \( \kappa_A / \kappa_t \). For these two channels, three samples with different set of parameters \( \kappa_A / \kappa_t \) were simulated and combined to reproduce the signal distributions included in the fit for any value of \( \kappa_A / \kappa_t \), as described in Ref. [9]. The \( b\bar{b}\gamma \gamma \) analysis, instead, is based on a smooth parameterisation of the analysis observable, the diphoton invariant mass, that does not depend on \( \kappa_A / \kappa_t \). The analysis acceptance does depend on \( \kappa_A / \kappa_t \) and the dependence described in Ref. [9] is taken into account in the fit procedure.

A complementary approach to study the Higgs boson self-coupling has been proposed in Refs. [11–16]. Single-Higgs processes do not depend on \( \lambda_{HHH} \) at leading order (LO), but the Higgs boson trilinear self-coupling contributes to the calculation of the complete next-to-leading order (NLO) EW corrections. In
Figure 2: Examples of one loop $\lambda_{HHH}$-dependent diagrams for the Higgs boson self-energy (a) and the single-Higgs production in the $ggF$ (b), VBF (c), $VH$ (d), and $t\bar{t}H$ (e) modes. The self-coupling vertex is indicated by the filled circle.

In particular, $\lambda_{HHH}$ contributes at NLO EW via Higgs boson self energy loop corrections and via additional diagrams, examples of which are shown in Figure 2. Therefore, an indirect constraint on $\lambda_{HHH}$ can be extracted by comparing precise measurements of single-Higgs production and decay yields and the SM predictions corrected for the $\lambda_{HHH}$-dependent NLO EW effects. A framework for a global fit to constrain the Higgs boson trilinear coupling and the other coupling modifiers $\kappa_m = g_m/g_{m}^{SM}$, where $g_m$ is a coupling of the Higgs boson to fermions or vector bosons altered by BSM physics, has been proposed in Refs. [11, 12]; the model dependent assumptions of this parameterisation are described in the same references. In this work inclusive production cross sections, decay branching ratios and differential cross sections are exploited to increase the sensitivity of the single-Higgs analyses to $\kappa_\lambda$ and $\kappa_m$. The differential information is encoded through the simplified template cross-section (STXS) framework [34, 48]. The signal yield in a specific decay channel and STXS bin is then proportional to:

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

where $\mu_i$ and $\mu_f$ 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 fraction ($\text{BR}_{\text{SM},f}$) as a function of the values of the trilinear Higgs boson self-coupling modifier $\kappa_\lambda$ and the LO-inspired modifiers $\kappa_m$. The $(\epsilon \times A)_{i,f}$ coefficients take into account the analysis acceptance times efficiency in each production and decay mode.

The functional dependence of $\mu_i(\kappa_\lambda, \kappa_m)$ and $\mu_f(\kappa_\lambda, \kappa_m)$ on $\kappa_\lambda$ and $\kappa_m$ varies according to the production mode, the decay channel and, in particular for the $VH$ production mode, on the STXS bin. Therefore STXS information of the VBF, $WH$ and $ZH$ production modes are exploited here to constrain $\kappa_\lambda$ and $\kappa_m$. For the
ggF production mode only the inclusive cross section dependence on $\kappa_4$ is currently available and it has been used in this study, while the STXS bin dependence has not been considered\(^1\). For the $t\bar{t}H$ production mode no differential information from the ATLAS analyses is available, hence only the inclusive yield measurement is used.

In this work, the single-Higgs signals are simulated using samples generated in the SM hypothesis. This is possible because at the lowest order in the electroweak expansion only one diagram per process participates in the single-Higgs production, therefore the cross-section modifiers $\kappa_m$ can be factorised out of the expression of the total cross section. This holds also for all decays with the exception of the $H \to \gamma\gamma$ decay, where two amplitudes interfere at the lowest order. However, even in this case, since $H \to \gamma\gamma$ is a two-body decay of a narrow scalar particle and thus no dynamics can affect the distribution of the decay products, the $\kappa$-modifiers only affect the total branching ratio.

Conversely, the $\kappa_4$-modifier can affect the Higgs boson production kinematics by modifying the analysis acceptance in a given STXS bin. This residual dependence was evaluated and found to be negligible, as described in Ref. [17]. Thus the single-Higgs selection efficiencies are assumed to be constant as a function of $\kappa_4$ in each STXS bin.

In this work, only the coupling modifiers $\kappa_t$, $\kappa_b$, $\kappa_\ell$, $\kappa_W$ and $\kappa_Z$ are considered. They describe the modifications of the SM Higgs boson coupling to up-type quarks, to down-type quarks, to leptons and to $W$ and $Z$ vector bosons, respectively. In this parameterisation the interactions between the Higgs boson and the gluons and photons are resolved in terms of the coupling modifiers of the SM particles that enter in the loop-level diagrams. New particles contributing to these diagrams are therefore not considered. The Higgs boson total width is also parameterised in terms of the coupling modifiers of the individual SM particles, assuming no BSM contributions. As discussed in Ref. [12], for small deviations of $\kappa_m$ from one, the dependence of NLO EW corrections on these coupling modifiers can be neglected. The model under discussion does not allow for any new physics beyond that encoded in the aforementioned $\kappa_b, \kappa_m$ parameters.

### 4 Statistical model and systematic uncertainty correlations

The statistical treatment used in this note follows the procedures described in Refs. [3, 4]. The result is obtained from a likelihood function $L(\vec{\alpha}, \vec{\theta})$, where $\vec{\alpha}$ represents the vector of the parameters of interest (POI) of the model and $\vec{\theta}$ is the set of nuisance parameters, including the systematic uncertainty contributions and background parameters that are constrained by sidebands or control regions in data. The global likelihood function $L(\vec{\alpha}, \vec{\theta})$ is obtained as the product of the likelihoods of each input analysis. These are, in turn, products of likelihoods computed in the single analysis categories.

The number of signal events in each analysis category $j$ is given by:

$$n_{j,\text{signal}}(\kappa_4, \kappa_t, \kappa_b, \kappa_\ell, \kappa_W, \kappa_Z, \vec{\theta}) = L_j(\vec{\theta}) \sum_i \sum_f \sigma_i(\kappa_4, \kappa_t, \ldots, \vec{\theta}) \times \text{BR}_f(\kappa_4, \kappa_t, \ldots, \vec{\theta}) \times (\epsilon \times A)_{i,f,j}(\kappa_4, \vec{\theta}), \quad (4)$$

where the index $i$ runs over all the single-Higgs production regions (defined by the STXS stage-1 framework) and the double-Higgs production regions, and the index $f$ includes all the considered decay channels,

\(^1\) The STXS bin dependence on $\kappa_4$ is expected to be small in the heavy top-quark approximation [49].
\( i.e. \ f = \gamma\gamma, ZZ^*, WW^*, \tau^+\tau^-, b\bar{b} \) for the single-Higgs regions while \( f = b\bar{b}b\bar{b}, b\bar{b}\tau^+\tau^-, b\bar{b}\gamma\gamma \) for the double-Higgs regions. \( \mathcal{L}_j \) is the integrated luminosity of the dataset used in the category \( j \), and \((\epsilon \times A)_{if,j}\) represents the acceptance times efficiency for the category \( j \), the production process \( i \) and the decay channel \( f \). All these terms depend also on a set of nuisance parameters \( \bar{\theta} \), accounting for theoretical and experimental systematic uncertainties that can affect the luminosity, the cross section and branching fraction prediction, the efficiency estimation, and the background estimation.

The results presented in this note are based on the profile-likelihood test statistics \( \Lambda(\bar{\sigma}, \bar{\theta}) \), and 68% as well as 95% CL intervals are derived in the asymptotic approximation [50].

The correlation model adopted for the systematic uncertainties within the single-Higgs and double-Higgs individual combinations is described in detail in Refs. [4, 9]. In this note the additional correlation of systematic uncertainties between single-Higgs and double-Higgs analyses has been investigated and implemented. Experimental uncertainties have been correlated whenever relevant; these include the uncertainty on the integrated luminosity. Experimental uncertainties that are related to the same physics object but determined with different methodologies or implemented with different parameterisations have been kept uncorrelated. The impact on the final results of correlating some of the largest experimental uncertainties (for example the \( \tau \) identification efficiency and the jet energy resolution) have been investigated and found to be negligible. Signal theory uncertainties between the single-Higgs and double-Higgs production modes have been kept uncorrelated while the systematic uncertainties on the decay branching ratios have been correlated. The single-Higgs contribution to the double-Higgs analyses is properly taken into account in the combination, including the \( \kappa_4 \) parameterisation and the main theory systematic uncertainties. For the double-Higgs analyses, the most important uncertainties are related to background estimates with data driven methodologies (derived from data sidebands or control regions) and are therefore not correlated with the single-Higgs analyses. The correlation between systematic uncertainties is implemented in the fit by associating them to the same nuisance parameter in the combined likelihood function. In this work, theoretical uncertainties on the \( pp \rightarrow HH \) cross section have been included in the fit, using as uncertainties for all \( \kappa_4 \) values those computed for the SM case (\( \kappa_4 = 1 \)). The impact of such uncertainties on the 95% CL \( \kappa_4 \) interval is about 1%.

In some cases the results in the note are presented with the uncertainty decomposed into separate components. The value of the uncertainty for each component is derived iteratively by fixing a given set of nuisance parameters to their best fit values. The value of each component is then evaluated as the quadratic difference between the uncertainty at a given step and the uncertainty obtained in the previous step, where for the initial step the total uncertainty is considered. This procedure is repeated sequentially for each uncertainty component in the following order: theoretical uncertainties affecting the background processes, theoretical uncertainties affecting the Higgs boson signal, experimental uncertainties and statistical uncertainties.

5 Results

In this section, the results of the analysis are presented. The \( \kappa_3, \kappa_m \) modifiers are fitted under several assumptions. The most general model presented allows for independent modifications of the coupling of the Higgs boson to the W and Z bosons, through the modifiers \( \kappa_W \) and \( \kappa_Z \), of the up-type quark and down-type quark couplings, through \( \kappa_t \) and \( \kappa_b \), of the lepton couplings, through \( \kappa_{\ell} \), and of the Higgs boson self-coupling \( \kappa_4 \). The impact of the coupling modifiers of the first- and second-generation fermions is negligible. In Sec. 5.1 a model where only \( \kappa_4 \) is allowed to vary is discussed, while in Sec. 5.2 more general models are probed.
where the total uncertainty is decomposed into components for statistical uncertainties, experimental
systematic uncertainties, and theory uncertainties on signal and background modelling, following the

These models have been implemented by setting all coupling modifiers to the SM values (\( \kappa_W = \kappa_Z = \kappa_t = \kappa_b = \kappa_\ell = 1 \)) with the exception of the Higgs self-coupling modifier \( \kappa_\lambda \). The \( \kappa_\lambda \) self-coupling modifier is probed in the range \(-20 < \kappa_\lambda < 20\), because outside this range the calculation in Refs. [11, 12] loses its validity.

The value of \(-2 \ln \Lambda\) is shown as a function of \( \kappa_\lambda \) in Figure 3, separately for the observed data and the Asimov dataset with \( \kappa_\lambda = 1 \). Results are shown for the single-Higgs production, the double-Higgs production, and their combination. The double-Higgs analyses are more sensitive than the single-Higgs measurement for \( \kappa_\lambda >> 1 \) and show similar sensitivity for negative \( \kappa_\lambda \).

The combined single-Higgs and double-Higgs fit result for the \( \kappa_\lambda \) modifier is:

\[
\kappa_\lambda = 4.6^{+3.2}_{-3.8} = 4.6^{+2.9}_{-3.5} \, \text{(stat.)} \times 1.2^{+1.2}_{-1.2} \, \text{(exp.)} \times 0.6^{+0.7}_{-0.5} \, \text{(sig. th.)} \times 0.6^{+0.6}_{-1.0} \, \text{(bkg. th.)} \, \text{[observed]},
\]

\[
\kappa_\lambda = 1.0^{+7.3}_{-3.8} = 1.0^{+6.2}_{-3.0} \, \text{(stat.)} \times 3.0^{+1.8}_{-1.2} \, \text{(exp.)} \times 1.7^{+1.7}_{-1.1} \, \text{(sig. th.)} \times 1.7^{+1.7}_{-1.1} \, \text{(bkg. th.)} \, \text{[expected]},
\]

where the total uncertainty is decomposed into components for statistical uncertainties, experimental systematic uncertainties, and theory uncertainties on signal and background modelling, following the

5.1 \( \kappa_\lambda \)-only model

In a variety of BSM models new physics is expected to only appear at the LHC as a modification of the Higgs boson self-coupling, as for example in the Higgs boson portal models in the alignment limit [51]. In these BSM scenarios, the constraints on \( \kappa_\lambda \), derived through the combination of single-Higgs measurements, can be directly compared to the constraints set by double-Higgs production analyses and the sensitivity gain from their combination can be evaluated.

These models have been implemented by setting all coupling modifiers to the SM values (\( \kappa_W = \kappa_Z = \kappa_t = \kappa_b = \kappa_\ell = 1 \)) with the exception of the Higgs self-coupling modifier \( \kappa_\lambda \). The \( \kappa_\lambda \) self-coupling modifier is probed in the range \(-20 < \kappa_\lambda < 20\), because outside this range the calculation in Refs. [11, 12] loses its validity.

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\]

\[
\kappa_\lambda = 1.0^{+7.3}_{-3.8} = 1.0^{+6.2}_{-3.0} \, \text{(stat.)} \times 3.0^{+1.8}_{-1.2} \, \text{(exp.)} \times 1.7^{+1.7}_{-1.1} \, \text{(sig. th.)} \times 1.7^{+1.7}_{-1.1} \, \text{(bkg. th.)} \, \text{[expected]},
\]

where the total uncertainty is decomposed into components for statistical uncertainties, experimental systematic uncertainties, and theory uncertainties on signal and background modelling, following the
procedure described in Section 4. The total uncertainty is dominated by the statistical component. The observed (expected) 95% CL interval constraint on $\kappa_4$ is found to be $-2.3 < \kappa_4 < 10.3$ ($-5.1 < \kappa_4 < 11.2$). The observed central value of $\kappa_4$ and its uncertainty differ from the expected values because the measured yields from single-Higgs and double-Higgs processes are slightly different than the expectation and the dependence of their cross sections on $\kappa_4$ is non-linear. As a check, the fit was performed using an Asimov dataset [50] produced setting the signal strengths close to the observed values, giving a fit result very similar to the one obtained from data.

### 5.2 More generic models

As described in Sec. 3, the $HH$ cross section depends both on $\kappa_t$ and $\kappa_4$, therefore its measurement cannot constrain both parameters simultaneously. At the same time, the inclusion of a dependence on $\kappa_4$ in the single-Higgs production cross section and branching fractions slightly affects the constraining power of single-Higgs measurements to $\kappa_t$. In order to quantify these effects, a fit has been performed setting all coupling modifiers other than $\kappa_t$ and $\kappa_4$ to their SM values of one. The fit results are shown in Fig. 4. Despite the fact that the double–Higgs analyses alone cannot constrain $\kappa_t$ and $\kappa_4$ simultaneously [44], the combination with the single–Higgs measurements allows, even for $\kappa_t$ values deviating from the SM prediction, the determination of $\kappa_t$ to a sufficient precision to restore most of the ability of the double-Higgs analyses to constrain $\kappa_4$. As a result, the constraining power on $\kappa_4$ of the combined single- and double-Higgs analyses is only slightly worse than in the $\kappa_4$-only model, where the assumption $\kappa_t = 1$ was made. In turn, exploiting the correlation between $\kappa_4$ and $\kappa_t$ in the single-Higgs measurements, the improved constraint on $\kappa_4$ also enhances the constraining power on $\kappa_t$.

![Figure 4](image)

Figure 4: Negative log-likelihood contours at 68% and 95% CL in the ($\kappa_4$, $\kappa_t$) plane on data (a) and on the Asimov dataset [50] generated under the SM hypothesis (b). The best fit value ($\kappa_4 = 4.7$, $\kappa_t = 1.03$) is indicated by a cross while the SM hypothesis is indicated by a star. The $\kappa_t = 1$ line is shown. These results are produced under the assumption that the approximations in Refs. [11, 12] are valid inside the contours shown.

A more generic model is also considered, where $\kappa_W$, $\kappa_Z$, $\kappa_t$, $\kappa_b$, $\kappa_4$ and $\kappa_4$ are fitted simultaneously. This allows the test of BSM models that can modify at the same time the Higgs boson self-coupling and other Higgs boson couplings. The value of $-2 \ln \Lambda$ as a function of $\kappa_4$ for this model is shown in Fig. 5 together with that obtained in the $\kappa_t$-only model. It is worth stressing that the combination of the single- and
double-Higgs analyses provides substantial constraints on the $\kappa_4$ parameters even in this more generic model. The results for the $\kappa_4$-only model and for the more generic model are summarised in Table 2.

Figure 5: Value of $-2 \ln \Lambda$ as a function of $\kappa_4$ with $\kappa_W$, $\kappa_Z$, $\kappa_t$, $\kappa_b$, $\kappa_\ell$ profiled (i.e., the generic model) for the data (a) and the Asimov dataset [50] generated assuming $\kappa_4 = 1$ with the likelihood distribution $\Lambda$ evaluated with nuisance parameters fixed to the best-fit values obtained from data and the parameters of interest fixed to the SM hypothesis (b). The curves are compared to the $\kappa_4$-only model (where all $\kappa_m$ modifiers are set to unity). The intersections of the dashed horizontal lines, corresponding to $-2 \ln \Lambda = 1$ and $-2 \ln \Lambda = 3.84$, with the profile likelihood curve are used to define the $\pm 1\sigma$ sigma uncertainty on $\kappa_4$ and the 95% CL interval, respectively.

Table 2: Best-fit values for the $\kappa$-modifiers with $\pm 1\sigma$ uncertainties for the $\kappa_4$-only and generic models. The 95% CL interval for $\kappa_4$ is also reported. For each model the upper row corresponds to the observed results, and the lower row to the expected results obtained using Asimov datasets [50] generated under the SM hypothesis.

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<td>1.10^{+0.09}_{-0.09}</td>
<td>1.00^{+0.12}_{-0.11}</td>
<td>1.03^{+0.20}_{-0.18}</td>
<td>1.06^{+0.16}_{-0.16}</td>
<td>5.5^{+3.5}_{-5.2}</td>
<td>[-3.7, 11.5]</td>
</tr>
<tr>
<td></td>
<td>1.00^{+0.08}_{-0.08}</td>
<td>1.00^{+0.08}_{-0.08}</td>
<td>1.00^{+0.12}_{-0.12}</td>
<td>1.00^{+0.21}_{-0.19}</td>
<td>1.00^{+0.16}_{-0.15}</td>
<td>1.0^{+0.7}_{-0.5}</td>
<td>[-6.2, 11.6]</td>
</tr>
</tbody>
</table>

6 Conclusion

The Higgs boson self-coupling modifier $\kappa_4 = \lambda_{HHH}/\lambda_{SM}^{HHH}$ has been constrained with a combination of single-Higgs analyses using data collected at $\sqrt{s} = 13$ TeV with an integrated luminosity of up to
and double-Higgs analyses with an integrated luminosity of up to 36.1 fb$^{-1}$ [9].

Under the assumption that new physics affects only the Higgs boson self-coupling, the best fit value of the coupling modifier is $\kappa_4 = 4.6^{+1.2}_{-1.8}$, excluding values outside the interval $-2.3 < \kappa_4 < 10.3$ at 95% CL while the expected excluded range assuming the SM predictions is $-5.1 < \kappa_4 < 11.2$. This constitutes a significant improvement on the constraints on $\kappa_4$ obtained from single-Higgs and double-Higgs analyses alone [9, 17].

A less model dependent parameterisation has also been considered, including coupling modifiers for the Higgs boson self-coupling, the up- and down-type quarks, leptons and for the $W$ and $Z$ bosons. In this more generic study the self-coupling modifier has been constrained at the 95% CL value to the interval $-3.7 < \kappa_4 < 11.5$, while the expected excluded interval assuming the SM predictions is $-6.2 < \kappa_4 < 11.6$. All other coupling modifiers are compatible with the SM predictions.
Appendix A

Fig. 6 and Fig. 7 show the expected dependence of \(-2 \ln \Lambda\) on \(\kappa_\lambda\) for the \(\kappa_\lambda\)-only model (obtained in the \(\kappa_\lambda = 1\) hypothesis) for the different production modes and decay channels, respectively.

To obtain these results, the signal yields of a given channel (produced via the production mode \(i\) and decaying into final state \(f\)) are parametrised as a function of the corresponding \(\kappa_\lambda\) (the dependence of the total width on the \(\kappa_\lambda\) from different channels is also taken into account) as shown in Eq. 5.

\[
h^\text{signal}_{i,f}(\kappa^i_\lambda, \kappa^f_\lambda, \ldots) \propto \sigma_i(\kappa^i_\lambda) \times \frac{\Gamma_f(\kappa^f_\lambda)}{\Gamma_{\text{tot}}(\kappa^f_\lambda, \kappa'^f_\lambda, \ldots)}. \tag{5}\]

When showing a specific production channel, all the \(\kappa_\lambda\) involved in the parametrisation of the corresponding signal yields (including those entering in the parametrisation of the branching ratios) are correlated in the \(-2 \ln \Lambda\) scan, while all the others are profiled. Similarly, for a specific decay channel all \(\kappa_\lambda\) that are used to parametrise the signal yields of that decay channel (including those entering in the parameterisation of the production mode part) are correlated in the \(-2 \ln \Lambda\) scan, while all the others are profiled.

Figure 6: Expected value of \(-2 \ln \Lambda\) as a function of \(\kappa_\lambda\) with \(\kappa_W = \kappa_Z = \kappa_t = \kappa_b = \kappa_\ell = 1\) (\(\kappa_\lambda\)-only model) obtained in the \(\kappa_\lambda = 1\) hypothesis for each production mode.

Fig. 8 shows the \(pp \rightarrow H\) cross section for several production modes and the \(pp \rightarrow HH\) cross section for the gluon–gluon fusion production mode as a function of \(\kappa_\lambda\).
Figure 7: Expected value of $-2 \ln \Lambda$ as a function of $\kappa_4$ with $\kappa_W = \kappa_Z = \kappa_t = \kappa_\ell = 1$ ($\kappa_3$-only model) obtained in the $\kappa_4 = 1$ hypothesis for the single-Higgs and double-Higgs decay modes.

Figure 8: Single-Higgs and double-Higgs production cross section as a function of $\kappa_4$ [11, 12, 34]. The dashed line intercepts the values corresponding to the SM hypothesis ($\kappa_4 = 1$).
References


