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Letter

Constraints on the Higgs boson self-coupling from the combination of single and double Higgs boson production in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$

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ABSTRACT

The Higgs boson (H) trilinear self-coupling, λ_3, is constrained via its measured properties and limits on the HH pair production using the proton-proton collision data collected by the CMS experiment at $\sqrt{s} = 13\,\text{TeV}$. The combination of event categories enriched in single-H and HH events is used to measure κ_λ, defined as the value of λ_3 normalized to its standard model prediction, while simultaneously constraining the Higgs boson couplings to fermions and vector bosons. Values of κ_λ outside the interval $-1.2 < \kappa_\lambda < 7.5$ are excluded at 2σ confidence level, which is compatible with the expected range of $-2.0 < \kappa_\lambda < 7.7$ under the assumption that all other Higgs boson couplings are equal to their standard model predicted values. Relaxing the assumption on the Higgs couplings to fermions and vector bosons the observed (expected) κ_λ interval is constrained to be within $-1.4 < \kappa_\lambda < 7.8$ $(-2.3 < \kappa_\lambda < 7.8)$ at 2σ confidence level.

1. Introduction

Significant progress has been made in the study of the properties of the Higgs boson (H) since its discovery [1–5]. The characterization of the Higgs boson is one of the primary goals of the CERN LHC physics program. This includes the measurement of its couplings to the vector bosons and fermions to test the compatibility with the standard model (SM) predictions. The Higgs boson plays a special role in several theories beyond the standard model (BSM), which could lead to deviations of the Higgs boson couplings from the SM predictions [6–10]. A crucial property of the Higgs boson predicted by the SM which is still only weakly constrained by the LHC data is its self-coupling. At low energy the potential V of the Higgs boson field H in the SM Lagrangian can be expressed as:

$$V(H) = \frac{1}{2} m_{\mathrm{H}}^2 H^2 + \lambda_3 v H^3 + \frac{\lambda_4}{4} H^4, \tag{1}$$

where m_{H} is the mass of the Higgs boson and $v \simeq 246$ GeV is the vacuum expectation value of the Higgs field. The form of the Higgs potential, hence the self-coupling constant, is tightly connected to the cosmological evolution of the Universe [11]. The second and third term of Eq. (1) correspond to the trilinear and a quartic self-interactions of the Higgs boson. The parameters λ_3 and λ_4 control the strength of the trilinear and quartic self-interactions of the Higgs boson, respectively. In the SM the strength of the quartic interaction λ_4^{SM} is fully determined by the trilinear interaction λ_3^{SM} as:

$$\lambda_4^{\mathrm{SM}} = \lambda_3^{\mathrm{SM}} = \frac{m_{\mathrm{H}}^2}{2v^2} \simeq 0.13. \tag{2}$$

The modifier of the Higgs boson trilinear self-coupling with respect to the SM prediction is defined as $\kappa_\lambda = \lambda_3/\lambda_3^{\mathrm{SM}}$. The κ_λ value can be determined from the measurement of the Higgs boson pair production (HH) cross section. In the SM, the main production mechanism for HH in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$ is gluon fusion (ggF HH) with a cross section of $31.0^{+2.1}_{-7.2}$ fb [12–19]. The second-largest HH production mechanism is via vector boson fusion (VBF HH) with a cross section of 1.726 ± 0.036 fb [20–24]. The Feynman diagrams corresponding to the ggF HH and VBF HH productions at the leading order (LO) are shown in Figs. 1 and 2, respectively. The diagrams show that both mechanisms depend at the LO on κ_λ. A deviation of κ_λ from unity could significantly modify the cross sections and change the HH kinematics. The most stringent observed (expected) upper limit on the HH inclusive cross section previously set by the CMS Collaboration is 3.4 (2.5) times the SM prediction, and the observed constraint on κ_λ is $[-1.24, 6.49]$ at 95%

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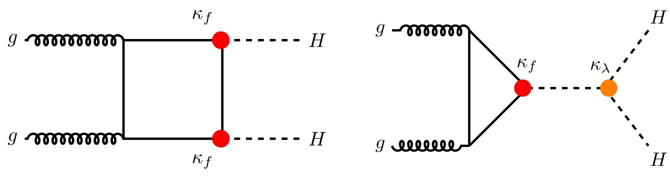

Fig. 1. Feynman diagrams for the LO HH production via gluon fusion. κ_f corresponds to the modifier of the Higgs boson coupling strength (Section 4) to fermions.

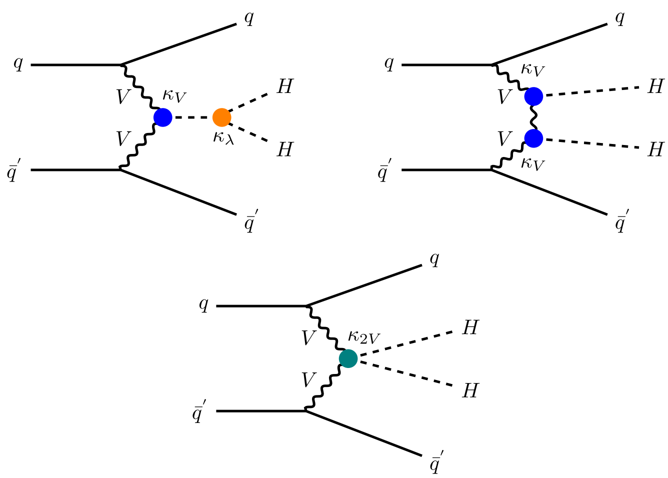

Fig. 2. Feynman diagrams for the LO HH production via vector boson fusion. κ_V and κ_{2V} correspond to the modifiers of the Higgs boson coupling strength (Section 4) to one and a pair of vector bosons, respectively.

confidence level (CL) assuming all the other Higgs boson couplings fixed to their SM value [4].

Another property of the Higgs boson predicted by the SM which can be probed through HH searches is the coupling between two Higgs bosons and two massive vector bosons. The modifier of the HHVV coupling strength (Section 4), which is referred to as κ_{2V}, affects the cross section of the VBF HH mechanism, and it is tightly related to the modifier of the strength of the coupling between one Higgs boson and a pair of massive vector bosons, κ_V. In particular, the conservation of the asymptotic unitarity of the VBF HH process imposes $\kappa_{2V} = \kappa_V^2$. A deviation from this relationship would require the presence of BSM physics, e.g. a BSM particle, to maintain the asymptotic unitarity of the process or could significantly increase the rate of the VBF HH production. Allowing for such a deviation and assuming all the other Higgs boson couplings equal to their SM-predicted values, κ_{2V} values smaller than or equal to zero are excluded at a CL corresponding to more than 5 standard deviations [4].

Other Higgs boson couplings also affect the HH production cross sections. In particular at LO, the HH cross section in the ggF production mode depends on the Higgs boson coupling to the top quark and the VBF HH cross section depends on the couplings of the Higgs boson to the vector bosons. Further dependencies on Higgs boson couplings arise when considering different HH decay channels. The searches for HH production generally provide weaker constraints on the Higgs boson couplings to fermions and vector bosons compared to single-H measurements because of the much smaller cross sections.

An alternative way to determine κ_λ is from the cross sections of the main single-H production mechanisms utilizing next-to-LO (NLO) electroweak corrections that depend on κ_λ because of the appearance of loops and vertices with three Higgs bosons [25]. These corrections affect the single-H production cross sections and partial decay widths, as well as the Higgs boson propagator, as visible in the example Feynman diagrams of Fig. 3.

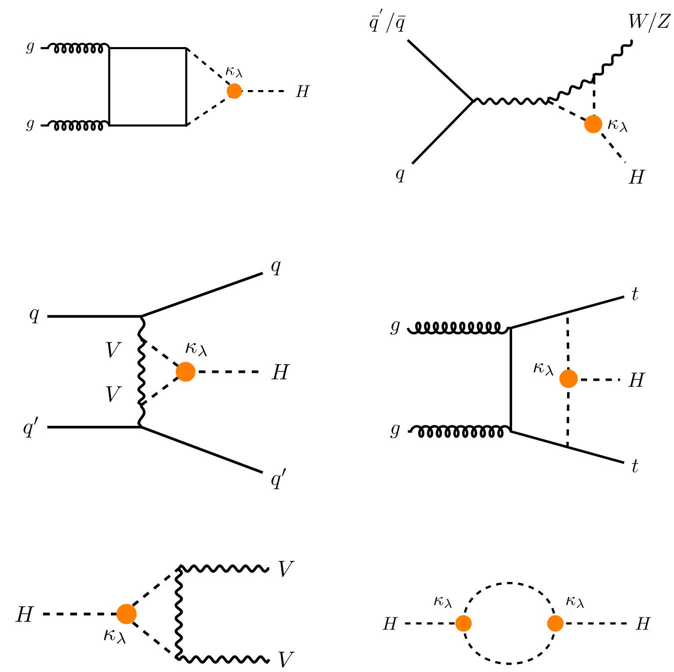

Fig. 3. Feynman diagrams corresponding to κ_λ-dependent NLO corrections to the main single-H production mechanisms (in the two top rows), to the H → VV decay width (bottom left) and to the Higgs boson propagator (bottom right).

The parametrizations of the Higgs boson production cross section and branching fraction variations as functions of κ_λ are provided in Refs [25,26]. The largest corrections affect the Higgs boson production in association with a Z or a W boson (ZH and WH, respectively, or generally VH), a top quark-antiquark pair ($t\bar{t}$H), or a single top quark (tH). In particular, the variation of the $t\bar{t}$H cross section is up to about ±10% for κ_λ between −2 and 6. The variations of the Higgs boson production cross sections via gluon fusion (ggF H) and via vector boson fusion (VBF H) are milder but still relevant, i.e. up to about −3%/+2% for the same variation of κ_λ. Additional information can be extracted from the single-H differential cross sections. Some kinematic variables that are experimentally accessible, such as the Higgs boson transverse momentum (p_T^H), are particularly sensitive to κ_λ. The single-H production mechanisms that receive the largest κ_λ-dependent corrections to the p_T^H spectrum are $t\bar{t}$H and VH.

A framework to study the single-H production cross sections with a well-defined phase space granularity is provided by the simplified template cross sections (STXS) [27,28]. The phase space divisions, known as *stages*, provide varying levels of granularity, with the most detailed being *stage* 1.2. Depending on the production mode, the measurements are performed in intervals of numbers of jets and p_T^H, or for the VH processes in intervals of the transverse momentum of the vector boson. The variations of the single-H cross sections as functions of κ_λ with the granularity defined by the STXS of *stage* 1.2 are provided in Ref. [29].

The constraints on the Higgs boson couplings from the measurement of the single-H cross sections are complementary to those from the HH searches. In particular, the single-H measurements provide stringent constraints on the Higgs boson couplings to fermions and vector bosons and a mild constraint on κ_λ, while the HH searches provide tighter constraints on κ_λ. Therefore, the inclusion of single-H measurements improves the sensitivity with respect to HH searches, where other Higgs boson couplings are assumed equal to their SM values, and it also enables more generic interpretations where constraints on κ_λ and other Higgs boson couplings are obtained from data simultaneously.

The combination of measurements and searches for the single-H and HH processes performed by the ATLAS Collaboration [30] excludes values of κ_λ outside the range $-0.4 < \kappa_\lambda < 6.3$ or $-1.4 < \kappa_\lambda < 6.1$ at 95%

Table 1
Analyses targeting single-H production modes and decay channels included in the combination and the corresponding data set sizes, in terms of integrated luminosity. The production modes targeted with dedicated analysis categories and the maximum phase space granularity of each cross section measurement are also reported.

Analysis	Integrated luminosity (fb^{-1})	Targeted H production modes	Maximum granularity	References
$H \to 4l$	138	ggF, VBF, VH, $t\bar{t}H$	STXS 1.2	[51]
$H \to \gamma\gamma$	138	ggF, VBF, VH, $t\bar{t}H$, tH	STXS 1.2	[52,53]
$H \to WW$	138	ggF, VBF, VH	STXS 1.2	[54]
$H \to$ leptons ($t\bar{t}H$)	138	$t\bar{t}H$	Inclusive	[55]
$H \to b\bar{b}$ (ggF)	138	ggF	Inclusive	[56]
$H \to b\bar{b}$ (VH)	77	VH	Inclusive	[48]
$H \to b\bar{b}$ ($t\bar{t}H$)	36	$t\bar{t}H$	Inclusive	[57]
$H \to \tau\tau$	138	ggF, VBF, VH	STXS 1.2	[58]
$H \to \mu\mu$	138	ggF, VBF	Inclusive	[59]

Table 2
The HH searches included in the combination and the corresponding data set sizes, in terms of integrated luminosity. The HH production modes targeted with dedicated event categories are also reported.

Analysis	Int. luminosity (fb^{-1})	Targeted HH production modes	References
$HH \to \gamma\gamma b\bar{b}$	138	ggF and VBF	[53]
$HH \to \tau\tau b\bar{b}$	138	ggF and VBF	[60]
$HH \to b\bar{b}b\bar{b}$	138	ggF, VBF, and VHH	[61–63]
$HH \to$ leptons	138	ggF	[64]
$HH \to WWb\bar{b}$	138	ggF and VBF	[65]

CL assuming the other Higgs boson couplings at their SM values or by treating the coupling modifiers κ_t, κ_b, κ_τ, and κ_V as unconstrained parameters, respectively.

This letter presents a statistical combination of single-H measurements and HH searches to constrain the Higgs boson trilinear self-coupling under minimal assumptions on the Higgs boson couplings to fermions and to vector bosons. Constraints on κ_λ are also set assuming all the other Higgs boson couplings fixed to their SM values. The analyses considered are based on data from proton-proton (pp) collisions produced by the LHC at $\sqrt{s} = 13\,\text{TeV}$ and collected by the CMS experiment, corresponding to integrated luminosities of up to $138\,\text{fb}^{-1}$ [31–33]. The tabulated results are provided as HepData records [34].

The CMS apparatus [35,36] is a multipurpose, nearly hermetic detector, designed to trigger on [37,38] and identify electrons, muons, photons, and (charged and neutral) hadrons [39–41]. A global "particle-flow" algorithm [42] aims to reconstruct all individual particles in an event, combining information provided by the all-silicon inner tracker and by the crystal electromagnetic and brass-scintillator hadron calorimeters, operating inside a 3.8 T superconducting solenoid, with data from the gas-ionization muon detectors embedded in the flux-return yoke outside the solenoid. The reconstructed particles are used to build tau leptons, jets, and missing transverse momentum [43–45].

2. Analysis channels

The single-H analyses considered are summarized in Table 1, which includes information on the production modes targeted by dedicated event categories and the maximum available phase space granularity of the cross section measurements, while the HH searches included in the combination are listed in Table 2. A more detailed description can be found in the references listed in Tables 1 and 2. Most of the analyses considered are based on the pp collision data collected between 2016 and 2018 with the CMS detector, corresponding to an integrated luminosity of 138 fb^{-1}, while two analyses use a subset of this data set.

The $H \to c\bar{c}$ searches [46,47] are not included because major overlaps are expected with the considered $H \to b\bar{b}$ analysis [48]. Searches sensitive to the Higgs couplings to the strange quark and first generation fermions [49,50] are not considered, since their contribution in constraining the corresponding Higgs boson couplings would be negligible in a combined fit.

The contribution of HH events in the signal regions targeting single-H events is also studied. This can be nonnegligible for the $t\bar{t}H$-enriched categories because the $t\bar{t}H$ cross section is about 16 times larger than the HH cross section, and because the HH events with one Higgs boson decaying to a $b\bar{b}$ quark pair have a final state similar to the $t\bar{t}H$ events. The categories targeting $t\bar{t}H$ events in the $H \to \gamma\gamma$ and multilepton final states are the most sensitive to this process among the $t\bar{t}H$ categories considered for this combination. The HH contamination in the $t\bar{t}H$-enriched categories is either modeled, as in the $H \to \gamma\gamma$ ($t\bar{t}H$) categories, or its impact on the results is studied and found to be small. In particular, a possible HH contamination in the $H \to$ leptons ($t\bar{t}H$) analysis categories is estimated to be at most 5% with respect to the total $t\bar{t}H$ signal yield in the categories. This possible contamination is expected to cause a shift of the allowed 2σ κ_λ interval for the combination of single-H channels and for the combination of single-H and HH channels of at most 2% and 1% with respect to the width of the interval towards higher values of κ_λ, respectively.

3. Changes to the analyses in the combination

One of the main challenges of this combination is estimating the overlaps between the signal regions considered in different analyses and optimizing a strategy for the removal of the nonnegligible overlaps. This is crucial to avoid significant double-counting, ensuring accurate constraints on the Higgs boson trilinear self-coupling and its couplings to fermions and vector bosons. The overlap of single-H analyses targeting similar final states has been checked and found to be negligible [4], while analyses targeting different final states are designed to be orthogonal to each other. The study of the overlap between the different HH analysis signal regions was performed for the HH combination presented in Ref. [4] and the only relevant overlap was found between the searches for $HH \to b\bar{b}b\bar{b}$ in the resolved-jet and merged-jet final states. An additional veto on events with large-radius jets with $p_T > 300$ GeV is applied in the resolved-jet analysis to remove the overlap with minimal impact on the final results. The study of the overlap between HH analysis regions has been extended to the additional HH channels introduced in this combination. An additional overlap is found between categories of the HH → $\mathrm{b\bar{b}b\bar{b}}$ (VHH) analysis targeting fully hadronic V decays and signal regions of the HH → $\mathrm{b\bar{b}b\bar{b}}$ (ggF) analysis. Since the ggF analysis sets stronger constraints on κ_λ, the hadronic-V categories of the VHH analysis are removed.

Overlaps between single-H and HH analyses are identified by comparing the event selection criteria of the analysis subcategories. Two analysis regions are considered to be overlapping if both categories in single-H and HH analyses select more than 1% of the same events in simulated single-H or HH event samples. The overlap of HH events in single-H analyses is negligible because of the low yield of the HH signal in the single-H analysis categories, while significant overlaps are identified for single-H events reconstructed in the HH regions. In case two analysis regions are considered overlapping, one of the two is dropped. The removal of the overlap is optimized to provide the highest sensitivity to κ_λ, without significantly compromising the sensitivity to the Higgs boson couplings to fermions and vector bosons. The HH → $\mathrm{b\bar{b}ZZ(4l)}$ analysis [66] has not been included in this combination because of its comparatively low sensitivity and high expected overlap with the H → 4l analysis.

Significant overlaps are generally found between the categories targeting $\mathrm{t\bar{t}H}$ events and the ones targeting HH events. In the H → $\gamma\gamma$ final state, the $\mathrm{t\bar{t}H}$ STXS 1.2 categories defined in Ref. [52] are replaced by the inclusive $\mathrm{t\bar{t}H}$ categories defined in Ref. [53] for the combined measurement of the H → γγ ($\mathrm{t\bar{t}H}$) and HH → $\gamma\gamma\mathrm{b\bar{b}}$ cross sections, which are by construction orthogonal to each other. In the H → leptons ($\mathrm{t\bar{t}H}$) analysis, categories with subleading sensitivity to the $\mathrm{t\bar{t}H}$ signal are removed because they target final states with the same lepton multiplicity as the signal regions defined in the HH → $\mathrm{WWb\bar{b}}$ or HH → $\tau\tau\mathrm{b\bar{b}}$ analyses. In the H → $\mathrm{b\bar{b}}$ ($\mathrm{t\bar{t}H}$) analysis, the signal regions targeting fully-hadronic decays of the top quark-antiquark pair are removed to prevent overlaps with the HH → $\mathrm{b\bar{b}b\bar{b}}$ analysis categories.

Overlaps are also found between HH → $\gamma\gamma\mathrm{b\bar{b}}$ analysis categories and some H → $\gamma\gamma$ analysis categories enriched in ggF H, VBF H, or VH events. The overlapping H → $\gamma\gamma$ analysis categories target ggF H or VBF H events with large $p_{\mathrm{T}}^{\mathrm{H}}$, or VH events with hadronic decays of the vector boson. Those categories are removed. The H → WW analysis categories targeting VH events in final states with either two same-sign leptons or three leptons are expected to have a nonnegligible overlap with the HH → leptons analysis categories targeting the same lepton multiplicities. The three-lepton categories of the H → WW analysis and the same-sign dilepton category of the HH → leptons analysis are dropped. The impact on the coupling constraints of interest is negligible because those categories play a subdominant role in their respective analyses. Overlaps are also found between most of the H → ττ analysis categories and the HH → $\tau\tau\mathrm{b\bar{b}}$ ones which target HH events with a H → $\mathrm{b\bar{b}}$ candidate reconstructed as a pair of jets with exactly one of them identified as a b jet. The overlapping HH → $\tau\tau\mathrm{b\bar{b}}$ categories are removed to preserve the sensitivity to the H coupling to the tau lepton with minimal impact on the constraints on κ_λ. Furthermore, the HH → $\tau\tau\mathrm{b\bar{b}}$ analysis categories enriched in single-H events are removed, along with a few remaining H → ττ categories targeting ggF H and VBF H events with large $p_{\mathrm{T}}^{\mathrm{H}}$ or with two additional jets in the final state.

Finally, overlaps in control regions, which are used to constrain background processes, are studied by comparing selected data events. In cases of significant overlap, one of the overlapping control regions is removed. The removal strategy is optimized to preserve the constraints from data on the background processes and on the related systematic uncertainties. Control regions of the H → $\mathrm{b\bar{b}}$ (VH) and HH → $\mathrm{WWb\bar{b}}$ analyses enriched in $\mathrm{t\bar{t}}$ events are removed because of overlaps with control regions of the HH → $\mathrm{b\bar{b}b\bar{b}}$ (VHH) and H → WW analyses, respectively, which target similar phase space. The control regions of the HH → leptons analysis enriched in ZW and ZZ events are also removed because of expected overlaps with the signal regions of the H → WW analysis enriched in VH events.

4. Statistical procedure

The statistical interpretation of the data is based on the methodology common to the ATLAS and CMS Collaborations [67,68] and the results have been obtained using the CMS statistical analysis tool COMBINE [69]. A profile likelihood ratio q is used as a test statistic to estimate the parameters of interest (POIs) $\vec{\alpha}$ of the model and their associated confidence intervals, taking into account the systematic uncertainties (Section 5) as independent nuisance parameters $\vec{\theta}$:

$$q(\vec{\alpha}) = -2\log\left(\frac{L(\vec{\alpha}, \hat{\hat{\vec{\theta}}}(\vec{\alpha}))}{L(\hat{\vec{\alpha}}, \hat{\vec{\theta}})}\right), \tag{3}$$

where L is the likelihood function, which is built as the product of the individual Poisson probability functions, accounting for the observed data and expected number of events across all the analysis channels, and additional terms representing constraints on the nuisance parameters from external measurements. The POIs and nuisance parameter values maximizing the likelihood function are given by $(\hat{\vec{\alpha}}, \hat{\vec{\theta}})$, while $\hat{\hat{\vec{\theta}}}(\vec{\alpha})$ is the set of nuisance parameter values that maximize the likelihood function for a given set of POI values. Each source of systematic uncertainty corresponds to a nuisance parameter in the likelihood function, possibly correlated among all the input channels affected by that uncertainty.

The $\hat{\vec{\alpha}}$ are taken as the best-fit values of the considered POIs. The intervals at 68.3% and 95.4% CL correspond to one (1σ) and two (2σ) standard deviations, respectively. For one-dimensional measurements, the 1σ and 2σ intervals are identified as the regions of POI values for which $q < 1$ and $q < 4$, respectively, while for two-dimensional measurements they correspond to the regions where $q < 2.30$ and $q < 6.18$, respectively.

In addition to κ_λ, this combination takes into consideration the modifiers of the H couplings to fermions or vector bosons. The modifiers of the H couplings to a pair of fermions or vector bosons, which are referred to as κ_f and κ_{V}, respectively, have been introduced in the κ-framework [70] to parametrize possible deviations of the Higgs boson production cross sections and decay branching fractions from the SM predictions. The κ_f and κ_{V} parameters are defined in such a way that the deviations from the SM prediction for a single-H production mechanism i and its cross section σ_i, or a H decay channel j and the corresponding partial decay width Γ_j, is parametrized as:

$$\frac{\sigma_i}{\sigma_i^{\mathrm{SM}}} = \kappa_i^2 \text{ or } \frac{\Gamma_j}{\Gamma_j^{\mathrm{SM}}} = \kappa_j^2. \tag{4}$$

The loop-induced H production via gluon fusion and H decay to a pair of photons or gluons are parametrized as a function of the H couplings to the fermions or vector bosons entering in the loop. This combination alternatively considers the κ_f parameter, which coherently modifies the H couplings to all fermions, or the κ_{t}, κ_{b}, κ_{μ}, and κ_{τ} parameters which independently modify the couplings to the corresponding fermions. In this second case, the H couplings to the remaining fermions are assumed to be fixed to their SM predictions because no analyses sensitive to such parameters are included in the combination.

The modifier of the SM couplings between two Higgs bosons and two massive vector bosons, $\kappa_{2\mathrm{V}}$, is used to describe possible deviations from the SM expectation for the HH production from VBF mechanism. The cross sections of the single-H processes considered in this combination do not depend on $\kappa_{2\mathrm{V}}$ at the leading order, while effects at higher perturbative orders are assumed negligible. One or at most two coupling modifiers among κ_λ, κ_{t}, $\kappa_{2\mathrm{V}}$, and κ_{V} are chosen as the POIs in this combination. The remaining coupling modifiers are assumed to be either equal to the SM prediction or treated as unconstrained nuisance parameters.

The modeling of the dependence of the single-H cross sections and branching fractions on κ_λ are provided in Refs [25,26,29]. Those parametrizations are valid under the assumption of small deviations of

κ_V and κ_f from unity. The reason is that the parametrizations are based on an incomplete perturbative order expansion, which is at LO in κ_V and κ_f and at NLO in electroweak theory in κ_λ. This is a good approximation for deviations of κ_V and κ_f within a few percent from unity because in this range the missing higher-order terms would have a negligible effect on the cross sections and branching fractions compared to the experimental and theoretical uncertainties.

5. Systematic uncertainties

The systematic uncertainties, which affect the modeling of a signal or a background process, are described as uncertainties in the shape of the distributions or normalization uncertainties in the yield of the affected processes. The systematic uncertainties may originate either from the theoretical predictions or from the measurement. The most important uncertainties are described in the next paragraphs. The HH production searches are limited by the statistical power of the data. In the combination of HH channels, the overall impact of the systematic uncertainties on the constraints on κ_λ is about 8% of the total uncertainty. The most impactful systematic uncertainties are in the theory predictions of the ggF HH cross section, and in the estimations from data of important background components in the $b\bar{b}b\bar{b}$ and $\tau\tau b\bar{b}$ channels. In the single-H channels, the systematic uncertainties tend to be more important. The overall impact of the systematic uncertainties on the constraints on κ_λ from the combination of single-H channels is about 30%. The leading uncertainties are in the theory predictions of the ggF H and $t\bar{t}H$ production cross sections [27]. Several modifications to the input channels are performed to use a consistent uncertainty model similar to the uncertainty model in the single-H combination presented in Ref. [4]. The impact of all these modifications on the results is found to be negligible.

The uncertainties in the theory predictions of the single-H and HH cross sections are among the dominant sources of systematic uncertainty on κ_λ. The uncertainties in the HH and single-H cross sections originate from the renormalization and factorization scales, the parton distribution functions (PDF), as well as the branching fraction predictions. An additional important source of uncertainty in the ggF HH cross section is related to the renormalization scheme and scale dependence of the virtual top quark mass [19]. Such theory uncertainties are fully correlated among all affected channels as are the uncertainties in the theoretical prediction of the cross section of a background process, whenever a similar phase space is considered. In the single-H channels the uncertainty scheme for the ggF H cross section is defined according to Ref. [27]. This consists of a set of nuisance parameters that cover for the uncertainty in the total ggF H cross section, as well as the cross sections in the exclusive phase space regions targeted by the STXS framework. The HH analyses with a nonnegligible contamination from ggF H production do not perform any explicit classification of the ggF H events in STXS bins. Therefore, in the HH channels only the uncertainty in the total ggF H cross section is taken into account and correlated with the single-H channels.

Uncertainties affecting multiple channels such as those in the integrated luminosity, in the reconstruction and identification of photons, electrons, muons, hadronically decaying tau leptons, in the b jet identification, and in the jet energy scale and resolution are correlated among multiple channels, following the same procedure as for the combinations presented in Ref. [4]. Additional experimental uncertainties related to measurement procedures specific to each channel, which are detailed in the dedicated publications (listed in Tables 1 and 2), are uncorrelated among the channels.

6. Results

The profile likelihood scan of the κ_λ parameter is shown in Fig. 4, comparing the separate combinations of the single-H or HH channels to the full combination of the two, assuming in all cases the other H couplings equal to their SM predictions. The observed best-fit κ_λ from the combination of the HH channels is found very close to unity, and the observed 2σ allowed interval is found to be $-1.7 < \kappa_\lambda < 7.0$, in agreement with the expected interval of $-2.3 < \kappa_\lambda < 8.0$, assuming the other Higgs boson couplings fixed to the SM prediction. The observed best-fit κ_λ from the combination of the single-H channels is larger than one, although compatible with the SM within the 2σ uncertainty. The observed and expected 2σ allowed intervals are $-1.8 < \kappa_\lambda < 12.0$ and $-4.5 < \kappa_\lambda < 11.7$, respectively. The profile likelihood obtained considering both the single-H and HH channels is qualitatively flat around the minimum. The shift in the κ_λ interval from the single-H combination is mostly driven by the $H \to \gamma\gamma$ ($t\bar{t}H$) channel. The observed (expected) 2σ allowed interval from single-H and HH combination is $-1.2 < \kappa_\lambda < 7.5$ ($-2.0 < \kappa_\lambda < 7.7$). The observed allowed interval on κ_λ can be compared to the corresponding one from the HH combination of Ref. [4]. The lower bounds are compatible, while the upper bound from this combination is weaker because of the single-H channels shifting the interval towards higher values of κ_λ. The observed allowed interval on κ_λ from the combination of only the HH channels can also be compared to Ref. [4]. The differences, including the change in the observed best-fit κ_λ value, which moves closer to the SM prediction, are the result of the changes described in Section 3 and most notably the removal of categories from the $HH \to \tau\tau b\bar{b}$ in favor of the $H \to \tau\tau$ analysis. It should be noted that any loss of sensitivity in the HH combination as a result of those changes is fully recovered in the combination with the single-H channels.

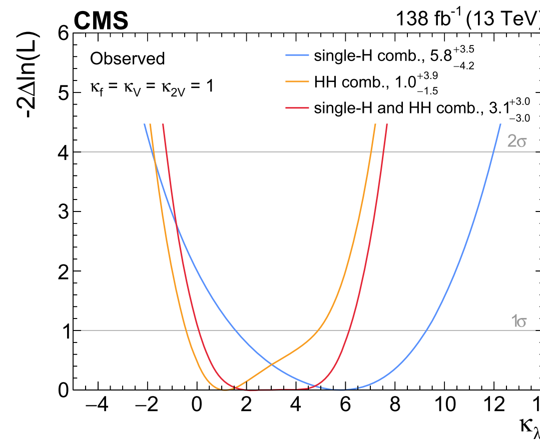

Fig. 4. Observed profile likelihood scans of κ_λ comparing the full combination of single-H and HH (red) to the combinations of only single-H (blue) or only HH (yellow) channels. The legend includes the best-fit values and the 1σ uncertainties.

The two-dimensional likelihood scan of the κ_λ and κ_t parameters is shown in Fig. 5. A large degeneracy of the ggF HH cross section with respect to κ_λ and κ_t limits the κ_λ sensitivity of the HH channels. In that case, the constraints on κ_t arise mostly from the contamination of single-H events in the HH enriched categories, and from the κ_t dependence of the H branching fractions, especially in the $H \to \gamma\gamma$ channel. Instead, the single-H combination provides a stringent constraint on κ_t, which is utilized in the combination of the single-H and HH channels.

The complementarity of the single-H and HH channels is also employed in the simultaneous measurement of the κ_V and κ_{2V} parameters. The two-dimensional likelihood scan of the κ_V and κ_{2V} parameters is shown in Fig. 6. The constraint on κ_{2V} is driven by the HH categories enriched in VBF HH events. However, the VBF HH cross section has a large degeneracy with respect to the κ_V and κ_{2V} parameters. The single-H channels have no sensitivity on the κ_{2V} parameter but provide a stringent constraint on κ_V. This allows the exclusion of $\kappa_{2V} \leq 0$ for any value of κ_V with a significance larger than five standard deviations, under the assumption that κ_{2V} contributions to the single H cross section are negligible in the considered range.

Table 3
Expected and observed constraints on κ_λ at 2σ and best fit values from the combination of the single-H and HH channels under different assumptions on the Higgs boson couplings to fermions and vector bosons. The floating coupling parameters are either treated as POIs or as unconstrained nuisance parameters in the fit. The parameters that are not listed as floating are always assumed fixed to the SM prediction.

Hypothesis	Best fit κ_λ value $\pm 1\sigma$		2σ interval	
	Expected	Observed	Expected	Observed
Other couplings fixed to the SM prediction	$1.0^{+4.6}_{-1.7}$	$3.1^{+3.0}_{-3.0}$	[−2.0, 7.7]	[−1.2, 7.5]
Floating (κ_V, κ_{2V}, κ_f)	$1.0^{+4.7}_{-1.8}$	$4.5^{+1.8}_{-4.7}$	[−2.2, 7.8]	[−1.7, 7.7]
Floating (κ_V, κ_t, κ_b, κ_τ)	$1.0^{+4.8}_{-1.8}$	$4.7^{+1.7}_{-4.1}$	[−2.3, 7.7]	[−1.4, 7.8]
Floating (κ_V, κ_{2V}, κ_t, κ_b, κ_τ, κ_μ)	$1.0^{+4.8}_{-1.8}$	$4.7^{+1.7}_{-4.2}$	[−2.3, 7.8]	[−1.4, 7.8]

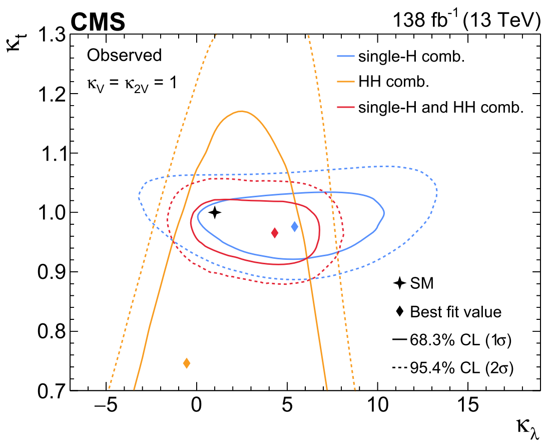

Fig. 5. Observed two-dimensional likelihood scans of $(\kappa_\lambda, \kappa_t)$ comparing the full combination of single-H and HH (red) to the combinations of only single-H (blue) or only HH (yellow) channels.

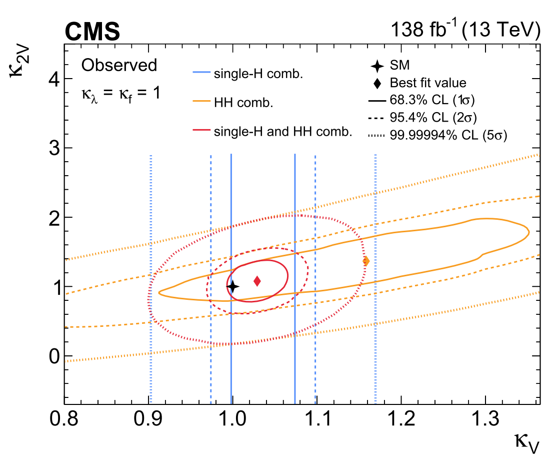

Fig. 6. Observed two-dimensional likelihood scans of (κ_V, κ_{2V}) comparing the full combination of single-H and HH (red) to the combinations of only single-H (blue) or only HH (yellow) channels. The single-H combination has no sensitivity on the κ_{2V} parameter.

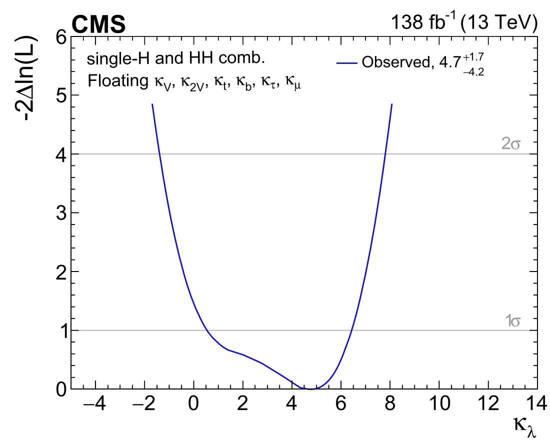

Fig. 7. Observed likelihood scans of κ_λ assuming κ_V, κ_{2V}, κ_t, κ_b, κ_τ, and κ_μ as unconstrained nuisance parameters. The legend includes the best-fit value and the 1σ uncertainty.

Constraints on κ_λ are also set under less restrictive assumptions on the Higgs boson couplings to the fermions and vector bosons. In particular, the κ_λ likelihood scan treating κ_V, κ_{2V}, κ_t, κ_b, κ_τ, and κ_μ as unconstrained nuisance parameters is shown in Fig. 7. The degeneracy that would be present if only HH categories were considered is fully resolved in the combination of the single-H and HH channels. The resulting expected constraint on κ_λ is comparable to the one expected from the HH combination assuming the other Higgs boson couplings equal to their SM value. The constraints on κ_λ under the aforementioned assumptions, along with some alternative assumptions, including the ones used by the ATLAS Collaboration in Ref. [30], are summarized in Table 3. The results are found to be consistent with the combination of single-H and HH measurements and searches from the ATLAS Collaboration [30].

7. Summary

A combination of Higgs boson (H) measurements and searches for Higgs boson pair production (HH) to constrain the Higgs boson trilinear self-coupling has been presented. Proton-proton collision data at $\sqrt{s} = 13\,\text{TeV}$, collected by the CMS experiment between 2016 and 2018, were analyzed. This is the first combination of single-H and HH channels from the CMS Collaboration. The complementarity of the constraints on the Higgs boson couplings of the single-H and HH channels is employed in the combination. The single-H channels lessen the assumptions on the measurements on the modifier of the Higgs boson trilinear self-coupling κ_λ, allowing for simultaneous constraint of the Higgs boson couplings to fermions and vector bosons. The observed (expected) interval at 2σ confidence level on κ_λ under the assumption that the other Higgs boson couplings are fixed to the standard model prediction, is found to be $-1.2 < \kappa_\lambda < 7.5$ ($-2.0 < \kappa_\lambda < 7.7$). Relaxing the assumption on the Higgs couplings to fermions and vector bosons the corresponding observed (expected) interval on κ_λ is $-1.4 < \kappa_\lambda < 7.8$ ($-2.3 < \kappa_\lambda < 7.8$).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Release and preservation of data used by the CMS Collaboration as the basis for publications is guided by the CMS data preservation, re-use and open access policy.

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