

Combination of ATLAS and CMS Searches for Higgs Boson Pair Production at $\sqrt{s} = 13$ TeV

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This Letter presents a combination of searches for Higgs boson pair (HH) production performed by the ATLAS and CMS Collaborations using proton-proton collision datasets recorded at $\sqrt{s} = 13$ TeV during the Large Hadron Collider Run 2, corresponding to integrated luminosities ranging between 126 and 140 fb⁻¹. The upper limit at the 95% confidence level on the total HH signal strength, defined as the ratio of the measured cross section to the standard model (SM) prediction, corresponds to 2.5, with an expected value of 1.7 (2.8) assuming the absence (presence) of the SM HH signal. The strength of the HH signal is measured to be $0.8^{+0.9}_{-0.7}$ relative to the SM prediction. The observed significance is found to be 1.1 standard deviations whereas 1.3 are expected for the SM HH signal. Constraints are set on the Higgs boson trilinear self-coupling and on the couplings of two Higgs bosons to two vector bosons, both normalized to the SM predictions and denoted as κ_λ and κ_{2V} , respectively. The observed individual constraints at the 95% confidence level are $-0.71 < \kappa_\lambda < 6.1$ and $0.73 < \kappa_{2V} < 1.3$, while the expected constraints assuming the presence of the SM HH signal are $-1.3 < \kappa_\lambda < 6.7$ and $0.66 < \kappa_{2V} < 1.4$.

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The standard model (SM) of particle physics [1–3] includes a doublet of complex scalar fields, Φ , that is subject to a potential which is symmetric under the $SU(2) \times U(1)$ electroweak gauge group. This potential has the form $V(\Phi^\dagger \Phi) = -\mu^2 \Phi^\dagger \Phi + \lambda(\Phi^\dagger \Phi)^2$, with parameters $\mu^2 > 0$ and $\lambda > 0$. In the mechanism postulated by Brout, Englert, Higgs, and others [4–7], the electroweak symmetry is spontaneously broken when Φ acquires a nonzero vacuum expectation value $v = |\mu|/\sqrt{\lambda} \approx 246$ GeV, giving rise to the longitudinal polarizations of the W and Z vector bosons and resulting in a physical scalar field h whose associated quantum excitations are Higgs bosons (H). In the SM, the Higgs boson mass m_H depends on the curvature of the potential at its minimum, $m_H^2 = 2\lambda v^2$. The SM also predicts the existence of a Higgs boson trilinear self-coupling (HHH) in the form $\lambda v h^3$ and of a coupling between two Higgs bosons and two vector bosons ($VVHH$, with $V = W, Z$), whose strength depends on $(m_V/v)^2$, where m_V is the V boson mass, and is directly proportional to the strength of the coupling between one Higgs and two vector bosons

(VVH). The spontaneous breaking of the electroweak symmetry and the resulting properties of the scalar sector are thus determined by the form of the potential via the value of λ .

The existence of the Higgs boson was established by the ATLAS and CMS Collaborations in 2012 [8–10]. Since then, all measurements performed to characterize its properties have yielded observations compatible with the SM predictions [11,12]. These measurements inform us about the behavior of the h field near the minimum of the potential. However, the global structure of the potential, which in the SM is controlled by the value of λ , is largely unknown. Its study represents one of the main goals of the CERN Large Hadron Collider (LHC) [13] physics program.

The Higgs boson trilinear self-coupling, whose strength depends on λ , can be directly measured through the production of Higgs boson pairs (HH). In the SM, the leading HH production mode in proton-proton (pp) collisions at the LHC is gluon fusion (ggF), with a cross section of $\sigma_{HH}^{\text{ggF}} = 30.8^{+2.0}_{-7.1}$ fb [14–21], followed by vector boson fusion (VBF) with a cross section $\sigma_{HH}^{\text{VBF}} = 1.687 \pm 0.046$ fb [22–27]. Both predictions are computed for a center-of-mass energy of 13 TeV and for $m_H = 125$ GeV, using the PDF4LHC21 parton distribution function (PDF) set [28].

These processes exhibit a quadratic dependence of their total cross section at the leading electroweak order on the

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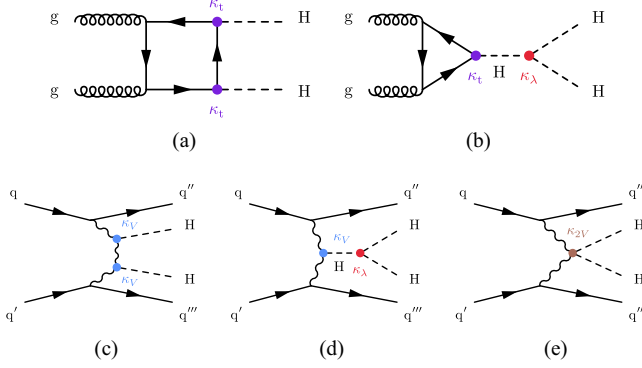


FIG. 1. Leading order Feynman diagrams for (a),(b) ggF and (c)–(e) VBF HH production. The Higgs boson coupling modifiers are indicated on the relevant vertices: in (b) and (d) the trilinear Higgs boson self coupling modifier κ_λ , in (e) the quartic $VVHH$ coupling modifier κ_{2V} , in (a) and (b) the top Yukawa coupling modifier k_t , and in (c) and (d) the VVH coupling modifier κ_V .

value of the Higgs boson trilinear self-coupling relative to the SM prediction, which is referred to as κ_λ . Modifications of κ_λ also lead to nontrivial kinematic changes of the HH processes because of the interference between the contributions involving the Higgs boson trilinear self-coupling and the ones only involving other Higgs boson interactions [29,30]. The total ggF cross section exhibits a minimum for $\kappa_\lambda \approx 2.3$ [31–33], where the interference effects are strongest [34,35]. Large values of κ_λ result in an enhancement of the cross section in the region with low HH invariant mass

(m_{HH}), close to the kinematic production threshold. The VBF production cross section also features a quadratic dependence on the strength of the $VVHH$ interaction, whose value normalized to the SM prediction is referred to as κ_{2V} . A single parameter is considered in this Letter to scale simultaneously the $WWHH$ and $ZZHH$ couplings, since these are not distinguished experimentally in VBF HH analyses. Scenarios with $\kappa_{2V} \neq 1$ are characterized by a strong increase in the signal cross section at large values of m_{HH} and the resulting production of Higgs bosons with large transverse momenta (p_T^H) [36], a phase space region offering enhanced experimental sensitivity. Leading order Feynman diagrams for ggF and VBF HH production and their dependence on these coupling modifiers are shown in Fig. 1.

Both the ATLAS and CMS Collaborations have performed searches for HH production using the pp Run 2 datasets collected at $\sqrt{s} = 13$ TeV between 2015 and 2018, corresponding to integrated luminosities ranging between 126 and 140 fb $^{-1}$, depending on the experiment and the analysis considered. Searches have been performed by both experiments in a variety of final states [37–49] and combined independently by the two collaborations. In terms of the total signal strength μ_{HH} , defined as the ratio of the measured and predicted values of $\sigma_{HH}^{\text{ggF}} + \sigma_{HH}^{\text{VBF}}$, the observed (expected) upper limits assuming the absence of HH production are 2.9 (2.4) for ATLAS [50] and 3.5 (2.5) for CMS [51] at the 95% confidence level (CL).

This Letter presents the combination of ATLAS and CMS searches for HH production using the LHC Run 2

TABLE I. Summary of the observed and expected results from the individual input analyses considered, the single experiment combinations, and the LHC combination presented in this Letter. The upper limit on $\mu_{HH} = \sigma_{HH}/\sigma_{HH}^{\text{SM}}$ and the constraints on κ_λ and κ_{2V} are reported. All values quoted are defined at 95% CL. The expected limits on μ_{HH} are computed assuming the absence of HH signal. The references indicate the original publication where the corresponding analyses are documented, and the results were recomputed following the modifications to input analyses described in the text.

	Channel	Details	Expected			Observed		
			μ_{HH}	κ_λ	κ_{2V}	μ_{HH}	κ_λ	κ_{2V}
ATLAS	$bbbb$	[38,40]	< 8.1	$[-5.3, 12]$	$[0.38, 1.7]$	< 5.4	$[-3.4, 11]$	$[0.55, 1.5]$
	$bb\tau\tau$	[42]	< 3.3	$[-2.6, 9.2]$	$[-0.24, 2.4]$	< 5.8	$[-3.3, 9.1]$	$[-0.51, 2.7]$
	$bb\gamma\gamma$	[44]	< 5.2	$[-3.0, 7.9]$	$[-1.1, 3.3]$	< 4.1	$[-1.6, 7.0]$	$[-0.48, 2.7]$
	$bb\ell\ell + E_T^{\text{miss}}$	[46]	< 14	$[-11, 17]$	$[-0.50, 2.7]$	< 9.6	$[-6.5, 13]$	$[-0.19, 2.4]$
	Multilepton	[53]	< 11	$[-4.5, 9.6]$	$[-1.9, 4.1]$	< 17	$[-6.4, 12]$	$[-2.5, 4.7]$
	Combined	[50]	< 2.4	$[-1.7, 7.2]$	$[0.41, 1.7]$	< 2.9	$[-1.3, 7.2]$	$[0.57, 1.5]$
CMS	$bbbb$	[37,39]	< 4.3	$[-4.6, 12]$	$[0.63, 1.4]$	< 7.0	$[-5.0, 12]$	$[0.66, 1.4]$
	$bb\tau\tau$	[41]	< 5.4	$[-4.2, 11]$	$[-0.64, 2.8]$	< 3.5	$[-1.9, 8.9]$	$[-0.32, 2.5]$
	$bb\gamma\gamma$	[43]	< 5.7	$[-3.5, 8.8]$	$[-0.94, 3.1]$	< 8.7	$[-3.5, 8.0]$	$[-1.4, 3.6]$
	$bbWW$	[45]	< 19	$[-9.4, 16]$	$[-1.4, 3.5]$	< 15	$[-6.1, 13]$	$[-1.0, 3.1]$
	Multilepton	[52]	< 20	$[-8.0, 12]$	$[-2.5, 4.6]$	< 22	$[-5.8, 10]$	$[-3.4, 5.6]$
	Combined	[51]	< 2.6	$[-2.2, 8.0]$	$[0.63, 1.4]$	< 3.5	$[-1.4, 6.6]$	$[0.66, 1.4]$
ATLAS + CMS combined			< 1.7	$[-1.3, 6.7]$	$[0.66, 1.4]$	< 2.5	$[-0.71, 6.1]$	$[0.73, 1.3]$

datasets. The input analyses correspond to the $bbbb$ [37–40], $bbWW$ [45,46], $bb\tau\tau$ [41,42], $bb\gamma\gamma$ [43,44], and multilepton [52,53] searches, where the latter refers collectively to topologies with multiple leptons. Charge conjugation is implied in the notation used throughout this Letter. These searches, as included in the CMS and ATLAS only combinations, have the leading sensitivity to SM HH production, κ_λ , and κ_{2V} in both experiments. The ATLAS multilepton search targets additional final states such as $bbZZ(4\ell)$, with $\ell = e, \mu$, and signatures with both multiple leptons and photons. CMS covers this additional phase space with dedicated searches in $\tau\tau\gamma\gamma$ [47], $bbZZ(4\ell)$ [48], and $WW\gamma\gamma$ [51]. These CMS analyses as well as the $bbWW$ (hadronic) [51] and VHH ($HH \rightarrow bbbb$) [49] searches originally included in the CMS combination are not considered for this Letter. This choice reduces the technical complexity of the combination with an expected impact of about 1% on the combined sensitivity to the SM HH signal strength. The included analyses and their relative sensitivities are summarized in Table I.

The ATLAS [54] and CMS [55,56] experiments are the two multipurpose particle detectors at the LHC. Both detectors have a nearly hermetic design with a forward-backward symmetric cylindrical geometry, and are designed to reconstruct and identify electrons, muons, photons, and hadronic objects that are used as inputs to the analyses. The ATLAS detector consists of an inner tracking detector based on silicon pixel, silicon microstrip, and transition radiation detectors. It is surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, lead plus liquid-argon sampling electromagnetic calorimeters, steel plus scintillator-tile and liquid-argon hadronic calorimeters with lead, tungsten, or copper absorbers, and a muon spectrometer based on superconducting air-core toroidal magnets. The CMS apparatus features a 3.8 T superconducting solenoid of 6 m internal diameter. An all-silicon inner tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass plus scintillator hadron calorimeter are contained within the solenoid volume, and gas-ionization muon detectors are embedded in the flux-return yoke outside the solenoid.

The $bbbb$ final state has a branching fraction of about 34% [57], the largest among the HH decay modes, but faces a challenging multijet background. The selection of signal events relies heavily on the use of modern heavy-flavor jet taggers and dedicated b -jet trigger algorithms. Both experiments target resolved-jet [37,38] and merged-jet [39,40] signatures, where the $H \rightarrow bb$ decays are respectively reconstructed as two separate small-radius jets with a jet cone radius parameter $R = 0.4$, or as a single large-radius jet with $R = 0.8$ for CMS and $R = 1$ for ATLAS. In both cases, jets are reconstructed with the anti- k_t algorithm [58,59]. The merged-jet topology has leading sensitivity to VBF HH production in anomalous κ_{2V} scenarios where the signal is characterized by large m_{HH}

and large p_T^H . The ATLAS merged-jet analysis only searches for VBF HH production with dedicated selections on additional jets in the event, while the CMS merged-jet analysis covers both ggF and VBF HH production modes. All four analyses estimate background contributions, mostly consisting of multijet production, using data in background enriched control regions, and simulation for the remaining processes in the merged-jet CMS analysis. The final results are extracted using a template fit either to a boosted decision tree (BDT) classifier output or the reconstructed m_{HH} and merged-jet mass distributions.

The $bb\tau\tau$ final state combines a sizable total branching fraction of about 7.3% [57] with reasonable selection purity from the identification of the $\tau\tau$ decay products. Both ATLAS and CMS analyses [41,42] target the decay channels of the $\tau\tau$ system where at least one τ -lepton decays to hadrons and a neutrino (τ_h). Events are classified in a variety of signal regions based on the final state and the corresponding single-lepton, di- τ_h , and lepton + τ_h triggers (ATLAS) or on the presence of one or two small-radius b -tagged jets or a single large-radius jet (CMS). Categories enriched in VBF HH events are also defined. The results are extracted using BDT or deep neural network (DNN) classifier scores for the ATLAS and CMS searches, respectively. Templates for the distributions of the background are mostly derived from simulation, and control regions in data are used to model the contribution from misidentified τ_h objects.

The $bb\gamma\gamma$ final state compensates an extremely low branching fraction of 0.26% [57] with a clean experimental signature from the $H \rightarrow \gamma\gamma$ decay. The signal extraction strategies in the ATLAS and CMS analyses [43,44] are similar and feature a parametric fit to the data in the diphoton invariant mass (ATLAS and CMS) and the dijet mass observable (CMS). These fits are performed in a number of subcategories of different signal purity. Categories are built based on the modified four-body invariant mass $m_{bb\gamma\gamma}^* = m_{bb\gamma\gamma} - (m_{bb} - 125 \text{ GeV}) - (m_{\gamma\gamma} - 125 \text{ GeV})$ and BDT outputs separating the signal from the continuum diphoton background and, in the case of ATLAS, also from single H production processes. For ATLAS a BDT is separately trained in the high- and low- $m_{bb\gamma\gamma}^*$ regions. In the CMS analysis, additional categories targeting VBF HH production are used, and the resonant single H background is reduced by applying a selection requirement based on a dedicated multivariate analysis (MVA) classifier in the ggF categories.

The $bbWW$ decay channel offers the second-highest branching fraction of all HH decay modes at about 25% [57]. The CMS $bbWW$ [45] and ATLAS $bb\ell\ell + E_T^{\text{miss}}$ [46] analyses target this final state in semileptonic (CMS) and dileptonic (ATLAS and CMS) $bbWW$ final states, with additional contributions from $bb\tau\tau$ and $bbZZ$ decays. The final state leptons (ℓ) considered are electrons and muons, and the symbol E_T^{miss} denotes the magnitude of the missing

transverse momentum. In the CMS case, events in the semileptonic and dileptonic categories are further split based on the number of b -tagged jets, their reconstruction as a merged large-radius jet, or as resolved small-radius jets and the output of a multiclass DNN separating ggF HH , VBF HH , $t + H$, and other backgrounds. For ATLAS, events are divided into signal and control regions based on the presence of a ggF- or VBF-like topology, $m_{\ell\ell}$, m_{bb} , and the lepton flavor. For the ggF-like case a multivariate DNN is trained to classify events into signal, $t\bar{t} + Wt$, and other backgrounds, while in the VBF-like case a BDT is used to separate the signal from backgrounds. In both the ATLAS and CMS analyses, the signal is extracted from the MVA discriminator outputs of the various categories.

Analyses targeting final states with multiple leptons (electrons, muons, τ_h) in combination with other objects benefit from high trigger efficiencies and low reconstruction thresholds, resulting in large acceptances for signal hypotheses with soft m_{HH} spectra and low p_T^H . The CMS multilepton analysis [52] targets the $WWWW$, $WW\tau\tau$, and $\tau\tau\tau\tau$ decay channels, while the ATLAS analysis [53] additionally targets the decays to $bbZZ$, and to a $\gamma\gamma$ pair plus a WW , ZZ , or a $\tau\tau$ pair. The total branching fraction of all these decay modes is about 9% [57], with the various final states included in the ATLAS and CMS analyses corresponding to a branching fraction of about 5% due to lepton requirements. The signal is extracted in categories based on how many light lepton, τ_h , and photon (ATLAS) objects are present. In each category, a fit is performed to the output of dedicated BDTs or to the diphoton invariant mass for $\gamma\gamma$ final states. Signal and background templates are obtained from a combination of estimations based on simulation and control regions in data.

The overlap between the selection criteria of the input analyses within each experiment was studied as part of the individual combinations. It was found to be negligible and treated as described in Refs. [50,51].

Signals in the input analyses are normalized to the predictions based on the PDF4LHC15 PDF set [60]. Compared to the newer cross-section calculations reported earlier, based on the PDF4LHC21 PDF set [14–21], the predictions used for this Letter are less than 1% larger for the ggF production mode, independent of the κ_λ hypothesis. For the VBF production mode, the predictions used for this Letter are about 2% larger compared to the newer ones presented in [27], which use the updated PDF set and include next-to-leading order electroweak corrections. The corresponding total SM cross section for HH production is 32.8 fb. The ggF HH signal prediction [35,61], for each of the analyses used in this combination, is rescaled by a function of κ_λ to adjust its normalization following the correction of the two-loop amplitude in the POWHEG [62,63] simulation described in Refs. [33,64]. The effect of this modification on the distributions of simulated HH

events is not taken into account in the ATLAS and CMS input analyses, but its impact was estimated [50] to be less than 4% on the constraints for κ_λ , and the SM result is not affected.

Processes involving the production of a single H boson constitute a relevant background for most input analyses. The production cross section of these processes and the branching fractions of H bosons depend on κ_λ through loop-level effects [65,66], which is strongest for H production in association with top quark pairs and for H decays into weak bosons. The ATLAS $bb\tau\tau$ and all CMS input analyses include these effects through a parametrization of the total single H cross sections and the H branching fractions as a function of κ_λ . The same parametrization was added for this Letter to the background modeling of the ATLAS $bb\gamma\gamma$ and $bbbb$ analyses where it was not originally implemented. These effects are not considered for the ATLAS analyses in the multilepton and $bb\ell\ell + E_T^{\text{miss}}$ final states, because their statistical models do not contain a parametrization of individual single H processes, preventing the implementation of the process-specific κ_λ dependence. Considering that their implementation in the ATLAS $bb\gamma\gamma$ and $bbbb$ input analyses has an impact smaller than 1% on the combined κ_λ sensitivity, the effects from the missing corrections in the ATLAS multilepton and $bb\ell\ell + E_T^{\text{miss}}$ inputs on the overall inference are estimated to be negligible.

Results are obtained using a profile likelihood ratio test statistic with systematic uncertainties modeled as nuisance parameters and making use of the asymptotic approximation [67]. The combined likelihood is the product of the individual likelihoods and the signal predictions are parametrized by the HH signal strength parameter, μ_{HH} , and by the κ_λ and κ_{2V} parameters, common to both experiments. In fitting to the data either the signal strength or the coupling modifiers are allowed to float, but not both. Upper limits on μ_{HH} are computed using the modified frequentist CL_s criterion [68,69] with the profile likelihood ratio modified for upper limits [67,70] as the test statistic. Asimov datasets [67] are generated by setting all nuisance parameters to their best-fit value and μ_{HH} , κ_λ , and κ_{2V} according to the assumed hypothesis, and are used to compute expected results. Results are derived and cross-checked by the two collaborations using different software. The ATLAS Collaboration uses HISTFACTORY [71] and the CMS Collaboration uses COMBINE [70], both of which are based on the ROOFIT [72] and ROOSTATS [73] packages.

Theoretical uncertainties in the HH signal production cross sections are related to the limited knowledge of the PDFs and α_s , variations of the factorization and renormalization scales and, for ggF HH , the scale and the choice of the renormalization scheme for the top quark and missing finite top-quark mass effects at NNLO QCD. These uncertainties are considered as fully correlated across all the input analyses and the two experiments. Since they

affect theoretical predictions, they are not considered when computing upper limits on the HH production cross section, while they are accounted for when deriving the other results. Similarly, the corresponding sources of uncertainties on the single H processes are correlated between the two experiments. Such uncertainties are related to the cross section of H production via ggF, via VBF, and in association with top quarks, to the normalization of ggF and VBF H production in association with heavy flavor jets, and to the branching fractions for $H \rightarrow b\bar{b}$, $H \rightarrow \tau\tau$, and $H \rightarrow \gamma\gamma$ decays. Uncertainties for the other decay modes are considered but not correlated across experiments since they follow a different grouping because of the final states considered in the $b\bar{b}WW$ and multilepton analyses. All other uncertainties considered in the input analyses are not correlated between the two experiments, while correlations across different analyses from the same experiment follow their original treatment [50,51]. Scenarios with a correlated uncertainty in the integrated luminosity and with a different correlation scheme between groups of single H processes have been studied and were found to have a negligible effect on the results. The magnitude of the uncertainty in the normalization of single H production in association with heavy flavor jets [74] is 100% for ATLAS analyses and 50% for CMS analyses. The choice to retain two different values of this uncertainty follows from the small impact in the present results and for consistency with previously published results [50,51] that are used as input to this Letter. Considering a common correlated uncertainty of 100% for both experiments increases the observed 95% CL upper limit on the HH signal strength by 1% without significant change to the expected limit, and has similar effects at the percent level or below on the best-fit value of μ_{HH} and the 95% CL constraints on κ_λ . These uncertainties are treated as fully correlated between the two experiments, while the change in the μ_{HH} and κ_λ sensitivities if they are considered as uncorrelated is about 1%.

The individual per-experiment best-fit values on the total signal strength μ_{HH} , obtained from individual fits to each set of results, are $\hat{\mu}_{HH}^{\text{ATLAS}} = 0.5^{+1.2}_{-1.1}$ and $\hat{\mu}_{HH}^{\text{CMS}} = 1.0^{+1.3}_{-1.0}$. The combined best-fit signal strength for HH production is found to be $\hat{\mu}_{HH} = 0.8^{+0.9}_{-0.7} = 0.8^{+0.7}_{-0.6}(\text{stat})^{+0.4}_{-0.2}(\text{theory})^{+0.3}_{-0.3}(\text{exp})$, where the breakdown of the uncertainty is into the statistical, theoretical, and experimental components, computed as detailed in Ref. [75]. The expected best-fit value is $\hat{\mu}_{HH}^{\text{exp}} = 1.0^{+0.9}_{-0.8} = 1.0^{+0.7}_{-0.6}(\text{stat})^{+0.5}_{-0.3}(\text{theory})^{+0.3}_{-0.3}(\text{exp})$. The leading theoretical uncertainties are those on the ggF HH signal normalization from the choice of the renormalization scheme and scale of the top quark mass, and from the production of single H in association with heavy flavor jets, the latter impacting mostly the $b\bar{b}\gamma\gamma$ and $b\bar{b}\tau\tau$ analyses. The leading experimental uncertainties are related to the background modeling in the CMS $b\bar{b}b\bar{b}$ merged-jet and ATLAS $b\bar{b}\tau\tau$

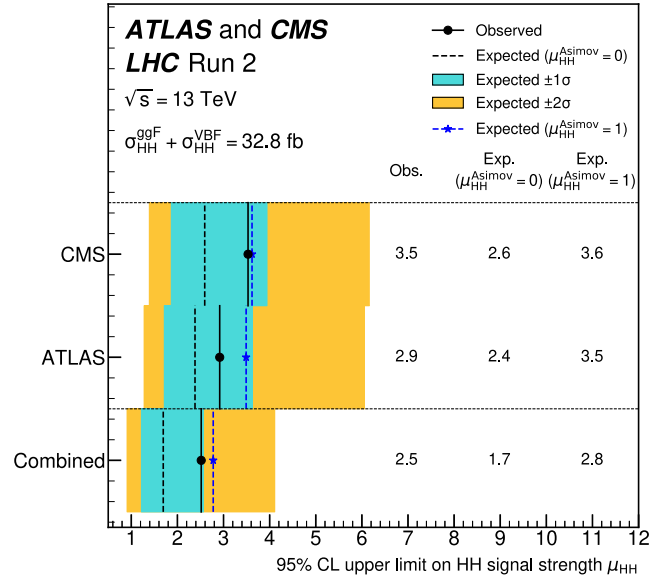


FIG. 2. Expected and observed 95% CL upper limits on the total HH signal strength, defined as the ratio of the measured cross section to the sum of the ggF and VBF HH SM cross sections, for ATLAS, CMS, and the combination from both experiments. The median expected limits on μ_{HH} are obtained under the hypotheses of no HH signal ($\mu_{HH}^{\text{Asimov}} = 0$) or assuming the presence of the SM HH signal ($\mu_{HH}^{\text{Asimov}} = 1$). The $\pm 1\sigma$ and $\pm 2\sigma$ bands are computed under the $\mu_{HH}^{\text{Asimov}} = 0$ hypothesis.

analyses. The combined observed (expected) significance for the HH signal is 1.1 (1.3) standard deviations.

Upper limits are placed on the total HH production cross section assuming the absence of HH production ($\mu_{HH}^{\text{Asimov}} = 0$). The observed combined limit at 95% CL corresponds to 73 fb with an expected limit of 50 fb. Taking into account uncertainties in the HH signal cross section, this translates into an observed 95% CL upper limit on the HH signal strength of 2.5, with an expected limit of 1.7, as shown in Fig. 2. With limits approaching the SM range, it can be insightful to also compare with the expected upper limit computed assuming SM HH production ($\mu_{HH}^{\text{Asimov}} = 1$), which is 2.8 times the SM prediction, slightly closer to the observed limit. An upper limit on the individual signal strength of the VBF HH production mode, μ_{HH}^{VBF} , is obtained by fixing the ggF HH signal to the SM prediction. The observed combined limit at 95% CL on μ_{HH}^{VBF} is 35 with an expected value of 41 assuming the absence of the VBF HH signal.

Figure 3 shows the expected and observed likelihood values as a function of κ_λ and κ_{2V} obtained from individual fits to the ATLAS and CMS data, and their combination. Only the Higgs boson coupling considered in the corresponding fit is allowed to vary while the others are fixed to their SM predictions. The observed combined constraints at 95% CL on the coupling modifier values are $-0.71 < \kappa_\lambda < 6.1$ and $0.73 < \kappa_{2V} < 1.3$, while the expected

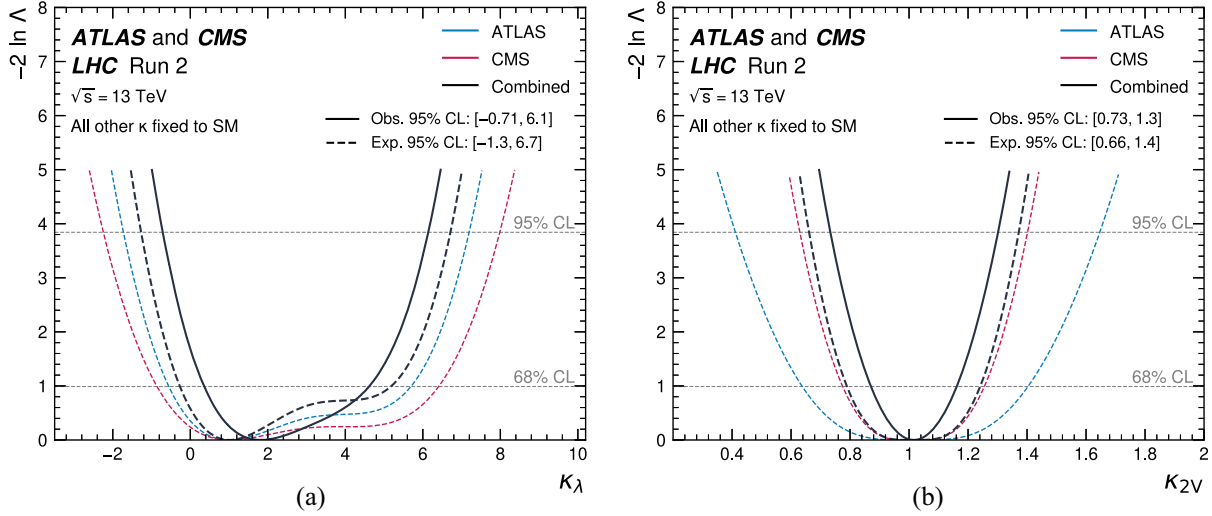


FIG. 3. Expected negative log-likelihood ($-2 \ln \Delta$) values as functions of (a) κ_λ and (b) κ_{2V} for ATLAS, CMS, and the expected and observed values for the combination from both experiments. All the other Higgs boson couplings are fixed to their SM predictions.

constraints are $-1.3 < \kappa_\lambda < 6.7$ and $0.66 < \kappa_{2V} < 1.4$ assuming the presence of the SM HH signal. The observed best-fit values for the coupling modifiers from the individual fits are $\hat{\kappa}_\lambda = 1.8^{+2.8}_{-1.5}$ and $\hat{\kappa}_{2V} = 1.02^{+0.14}_{-0.15}$ while the expected values are $\hat{\kappa}_\lambda^{\text{exp}} = 1.0^{+4.2}_{-1.3}$ and $\hat{\kappa}_{2V}^{\text{exp}} = 1.00^{+0.24}_{-0.21}$. The channels with leading sensitivity on κ_λ are $bb\gamma\gamma$ and $bb\tau\tau$, while the κ_{2V} result is driven by the $bbbb$ analyses in the merged-jet topologies because of the increase in the average p_T^H in scenarios with $\kappa_{2V} \neq 1$, resulting in much stronger sensitivities to these signals compared to the SM VBF HH production. The difference between the ATLAS and CMS CL intervals arises from the sensitivities of these channels in each experiment. The smaller observed κ_{2V} interval relative to the expected one is primarily driven by the ATLAS $bbbb$ analysis, which reports a deficit of events in the merged-jet topology, thereby driving the fit towards κ_{2V} near one, where the VBF HH production cross section is smallest. The presented combination improves the expected sensitivity on κ_λ by 10% and on κ_{2V} by 8% with respect to the best results to date, as given by the ATLAS and CMS individual combinations, respectively. The 95% CL contours, obtained from a fit where κ_λ and κ_{2V} are allowed to vary simultaneously, are shown in Fig. 4. The best-fit point in this plane corresponds to 1.8 for κ_λ and 1.0 for κ_{2V} . All results are compatible with the SM predictions.

Table I presents a summary of the individual sensitivities of the channels considered, of the single experiment combinations, and of the ATLAS and CMS combination presented in this Letter. Results from the individual channels and the single experiment combinations have been recomputed with respect to the original references following the modifications to the signal normalization and κ_λ dependence for the HH and H processes described above.

In summary, this Letter presents the first combination of ATLAS and CMS searches for Higgs boson pair production. The searches are performed using the LHC Run 2 datasets with integrated luminosities ranging between 126 and 140 fb^{-1} . The upper limit at 95% CL on the total HH signal strength, defined as the ratio of the measured cross section to the SM prediction, corresponds to 2.5, with an expected value of 1.7 (2.8) in the absence (presence) of SM HH production. The best fit of the signal strength is observed to be $0.8^{+0.9}_{-0.7}$, corresponding to an observed significance of 1.1 standard deviations, while the expected significance is 1.3 standard deviations. The observed 95% CL constraints on the κ_λ and κ_{2V} coupling modifiers are $-0.71 < \kappa_\lambda < 6.1$ ($-1.3 < \kappa_\lambda < 6.7$ expected) and

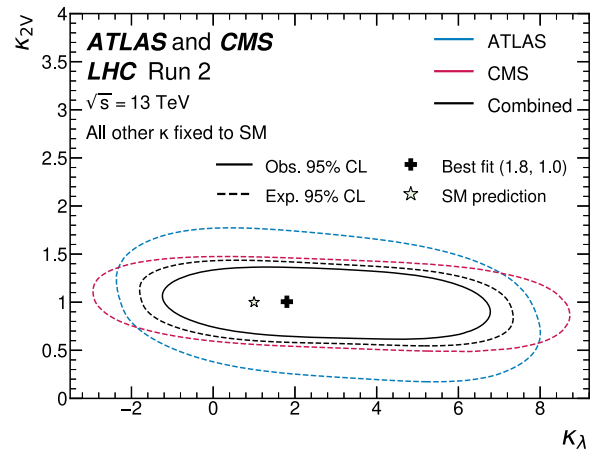


FIG. 4. Observed and expected 95% CL contours for the simultaneous scan of the profile likelihood as a function of κ_λ and κ_{2V} . The expected constraints from the individual experiments are also shown. All the other Higgs boson couplings are fixed to their SM predictions.

$0.73 < \kappa_{2V} < 1.3$ ($0.66 < \kappa_{2V} < 1.4$ expected). The results of the combination are compatible within their uncertainties with the SM predictions and represent the most comprehensive and most sensitive constraints on HH production to date.

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