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Combination of Searches for Higgs Boson Pair Production in *pp* Collisions at $\sqrt{s} = 13$ TeV with the ATLAS Detector

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This Letter presents results from a combination of searches for Higgs boson pair production using 126–140 fb^{-1} of proton-proton collision data at $\sqrt{s} = 13$ TeV recorded with the ATLAS detector. At 95% confidence level (CL), the upper limit on the production rate is 2.9 times the standard model (SM) prediction, with an expected limit of 2.4 assuming no Higgs boson pair production. Constraints on the Higgs boson self-coupling modifier $\kappa_\lambda = \lambda_{HHH}/\lambda_{HHH}^{\mathrm{SM}}$, and the quartic $HHVV$ coupling modifier $\kappa_{2V} = g_{HHVV}/g_{HHVV}^{\mathrm{SM}}$, are derived individually, fixing the other parameter to its SM value. The observed 95% CL intervals are $-1.2 < \kappa_\lambda < 7.2$ and $0.6 < \kappa_{2V} < 1.5$, respectively, while the expected intervals are $-1.6 < \kappa_\lambda < 7.2$ and $0.4 < \kappa_{2V} < 1.6$ in the SM case. Constraints obtained for several interaction parameters within Higgs effective field theory are the strongest to date, offering insights into potential deviations from SM predictions.

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Since the discovery of the Higgs boson (H) by the ATLAS and CMS Collaborations at the Large Hadron Collider (LHC) in 2012 [1,2], understanding its intrinsic properties and interactions has been a priority. The Higgs self-coupling is directly related to the shape of the Higgs scalar field potential, which is important for understanding the mechanism of electroweak symmetry breaking and serves as an essential test of the electroweak theory. After the symmetry breaking, the Higgs potential predicted in the standard model (SM) can be expanded in the Higgs boson field H near its minimum: $V(H) = \frac{1}{2} m_H^2 H^2 + \lambda_{HHH} v H^3 + \mathcal{O}(H^4)$, where m_H is the Higgs boson mass and $v \approx 246$ GeV is the field's vacuum expectation value [3]. The Higgs boson's trilinear self-coupling $\lambda_{HHH}^{\mathrm{SM}}$ is equal to $m_H^2/2v^2$, its coupling g_{HVV}^{SM} to vector bosons ($V = W$, Z) is equal to $2m_V^2/v$, and its coupling $g_{Hf\bar{f}}^{\mathrm{SM}}$ to fermions is equal to m_f/v. The quartic coupling between two Higgs bosons and two vector bosons, g_{HHVV}^{SM}, is equal to g_{HVV}^{SM}/v [3]. The production of Higgs boson pairs (HH) via gluon-gluon fusion (ggF) and vector-boson fusion (VBF) provides a direct probe of λ_{HHH} and g_{HHVV}, which affects the pair-production differential cross section at tree level. Observed (expected) 95% confidence level (CL) upper limits on the HH production cross section have been set at 2.4 (2.9) and 3.4 (2.5) times the SM prediction by previous ATLAS [4] and CMS [5] search combinations, respectively.

Deviations from the SM can be expressed in terms of coupling modifiers κ_i [6,7] or Wilson coefficients c_i in the Higgs effective field theory (HEFT) [8,9], as illustrated in Fig. 1. In the κ framework, the coupling modifiers κ_λ, k_t, κ_V, and κ_{2V} are each defined as the ratio of the Higgs boson coupling to its SM value, e.g., $\kappa_\lambda = \lambda_{HHH}/\lambda_{HHH}^{\mathrm{SM}}$. In the HEFT framework, new physics in the electroweak sector is described through anomalous couplings of the Higgs boson. The organization of the HEFT Lagrangian is guided by chiral perturbation theory, with the low-energy dynamics of electroweak symmetry breaking described using a nonlinear realization of the gauge symmetry group $\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$. One advantage of the HEFT framework is that the anomalous single-Higgs-boson and HH couplings are defined separately, allowing simplified HH interpretations. In the HEFT Lagrangian, ggF HH production is described at leading order by five relevant operators, and their associated Wilson coefficients are c_{tth}, c_{ggh}, c_{hhh}, c_{gghh}, and c_{tthh}. In this formalism, c_{tth} and c_{hhh} are equivalent to k_t and κ_λ. In this analysis, κ_V, k_t (c_{tth}), and c_{ggh} are set equal to the SM predictions, because those parameters are constrained by precise measurements of single-Higgs-boson production [5,10].

In the SM, destructive interference between the ggF HH production diagrams in Figs. 1(a) and 1(b) makes softer Higgs bosons more sensitive for constraining κ_λ. For $m_H = 125$ GeV and $\sqrt{s} = 13$ TeV proton-proton collisions, the predicted cross section is $\sigma_{\mathrm{ggF}}^{\mathrm{SM}}(HH) = 31.1^{+1.9}_{-7.1}(\mathrm{scale} + m_{\mathrm{top}}) \pm 0.9(\mathrm{PDF} + \alpha_s)$ fb [11–18] at next-to-next-to-leading order

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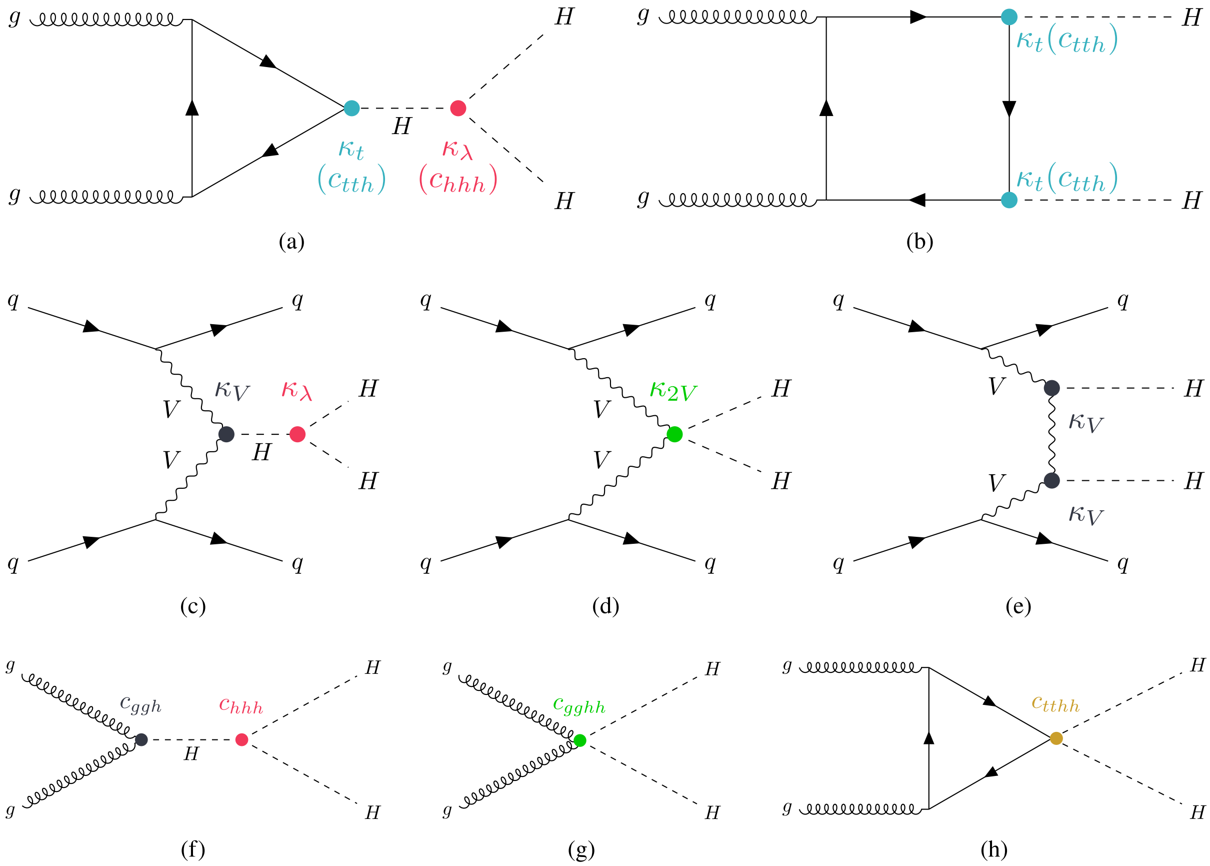

FIG. 1. Leading-order Feynman diagrams showing the production of Higgs boson pairs via the ggF (a),(b),(f)–(h) and VBF (c)–(e) processes. Each diagram is sensitive to specific coupling factors, denoted by κ_i in the κ framework or c_i in the HEFT. Diagrams (a)–(e) occur in the SM predictions, while diagrams (f)–(h) manifest only when deviations from the SM predictions are present in the coefficients c_{ggh}, c_{gghh}, or c_{tthh}.

in α_s and including an uncertainty related to the choice of the virtual top-quark mass scheme [18]. The "PDF + α_s" uncertainty accounts for uncertainties in the parton distribution functions and strong coupling constant, the "scale" uncertainty is due to the finite order of quantum chromodynamics (QCD) calculations, and the "m_{top}" uncertainty is related to the top-quark mass scheme. For SM VBF HH production, divergences in the diagrams shown in Figs. 1(d) and 1(e) cancel out due to perturbative unitarity. If κ_{2V} deviates from the SM prediction, this cancellation no longer occurs, leading to a linear dependence of the cross section on the effective center-of-mass energy of the incoming vector bosons [19]. Consequently, the Higgs bosons are expected to be more energetic in non-SM scenarios. The cross section for VBF HH production is $\sigma_{\text{VBF}}^{\text{SM}}(HH) = 1.73 \pm 0.04$ fb at next-to-next-to-next-to-leading order in QCD [20–24].

This Letter presents a combination of results from the $b\bar{b}b\bar{b}$ [25,26], $b\bar{b}\tau^+\tau^-$ [27], $b\bar{b}\gamma\gamma$ [28], multilepton [29], and $b\bar{b}\ell\ell$ [30] decay channels, probing more than half of the HH decays. The first three analyses have been improved since the previous combination [4], and the other two are newly included. The $HH \to b\bar{b}b\bar{b}$ decay mode has the advantage of having the largest SM HH decay branching fraction (33.9%), but it also has the largest SM background, due to the abundance of QCD multijet events. Given its capability to probe relatively high-energy Higgs bosons, both the resolved [25] and boosted topologies [26] are now used to reconstruct the Higgs bosons. The $HH \to b\bar{b}\tau^+\tau^-$ decay mode has one of the larger branching fractions (7.3%) among the investigated HH decay channels and benefits from having only moderate background contamination. In the corresponding search [27], one of the τ leptons is required to decay hadronically, ensuring orthogonality with the $b\bar{b}\ell\ell + E_{\text{T}}^{\text{miss}}$ search. Although the $HH \to b\bar{b}\gamma\gamma$ decay mode has a small branching fraction (0.26%), it has high trigger efficiency and a clean experimental signature. The $b\bar{b}\tau^+\tau^-$ [27] and $b\bar{b}\gamma\gamma$ [28] analyses have been improved through optimized classification of selected events to enhance the sensitivity to the Higgs boson couplings. Furthermore, the $b\bar{b}\tau^+\tau^-$ analysis now benefits from more accurate background modeling and larger samples of simulated events. The multilepton analysis is designed to select HH events in $b\bar{b}ZZ^*$, VV^*VV^* ($V = W$ or Z), $VV^*\tau^+\tau^-$, $\tau^+\tau^-\tau^+\tau^-$,

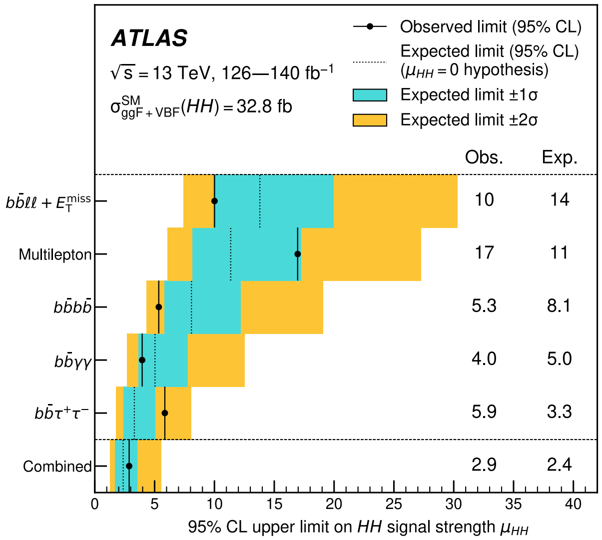

FIG. 2. Observed and expected 95% CL upper limits on the signal strength for inclusive ggF HH and VBF HH production from the $b\bar{b}\tau^+\tau^-$, $b\bar{b}\gamma\gamma$, $b\bar{b}b\bar{b}$, multilepton, and $b\bar{b}\ell\ell + E_T^{miss}$ decay channels and their statistical combination. The predicted SM cross section assumes $m_H = 125$ GeV. The expected limit, along with its associated $\pm1\sigma$ and $\pm2\sigma$ bands, is calculated for the assumption of no HH production and with all NPs profiled to the observed data.

$\gamma\gamma VV^*$, and $\gamma\gamma\tau^+\tau^-$ decay channels with leptons in the final states; the total branching fraction is around 6.5%. The $b\bar{b}\ell\ell + E_T^{miss}$ search targets final states arising from HH decay channels where one of the Higgs bosons decays to a b-quark pair and the other to either a boson pair (ZZ^*, WW^*) or a τ-lepton pair, which then decays to a pair of opposite-sign leptons ($\ell = e$, μ) and neutrinos, for a total branching fraction of 2.9%. Depending on the analysis, the final discriminating variable can be the HH invariant mass, the diphoton invariant mass, or the multivariate classifiers used to separate signal from background.

The analyses under consideration use the full sample of $\sqrt{s} = 13$ TeV proton-proton (pp) collision data recorded with the ATLAS detector during run 2 of the LHC. The integrated luminosity ranges from 126 to 140 fb^{-1} depending on the trigger selection [31]. The ATLAS experiment is a multipurpose particle detector with a forward-backward symmetric cylindrical geometry and nearly 4π coverage in solid angle [32–34]. A software suite [35] is used in data simulation, in the reconstruction and analysis of real and simulated data, in detector operations, and in the trigger and data acquisition systems of the experiment. The searches use a common set of event generators to describe ggF and VBF HH production in the pp collisions. Reweighting methods are used to estimate the total and differential signal yields at a given value of κ_i from samples simulated for different values of κ_λ and κ_{2V} [4] or to estimate the particle-level m_{HH} distributions for alternative values of the Wilson coefficients using parameters from Ref. [36].

The results are derived from a likelihood function $L(\boldsymbol{\alpha},\boldsymbol{\theta})$, where $\boldsymbol{\alpha}$ denotes the vector of parameters of interest (POIs) in the statistical model and $\boldsymbol{\theta}$ is a set of nuisance parameters (NPs), including systematic uncertainty contributions and background parameters. This global likelihood function is the product of individual search likelihoods. The profile-likelihood-ratio test statistic $-2\ln\Lambda(\boldsymbol{\alpha},\boldsymbol{\theta}) = -2\ln[L(\boldsymbol{\alpha},\hat{\hat{\boldsymbol{\theta}}}(\boldsymbol{\alpha}))/L(\hat{\boldsymbol{\alpha}},\hat{\boldsymbol{\theta}})]$ is used to determine the 68% and 95% CL intervals and local significance in the asymptotic approximation [37]. The $\mathrm{CL_s}$ method [38] is utilized to derive upper limits on the HH production cross section. To evaluate the expected limits, Asimov datasets [37] are generated, setting all NPs to their best-fit values in data and fixing the POIs to those posited in the hypothesis under test. The event samples from the combined searches are scrutinized for overlaps in both real and simulated data; they are found to be less than 1% in the signal regions and, thus, considered negligible.

Complete discussions of the systematic uncertainties considered in the individual searches are provided in Refs. [25–30]. Correlations of these uncertainties between different searches are investigated. Uncertainties related to the data-taking conditions, such as those associated with the integrated luminosity and the mismodeling of the multiple pp interactions per bunch crossing, are assumed to be correlated across the searches. An exception is the integrated luminosity uncertainty in the resolved $b\bar{b}b\bar{b}$ analysis [25], which employs a different calibration version. Where applicable, uncertainties associated with physics objects common to two or more searches are considered correlated. Correlations are also assumed for theoretical uncertainties affecting simulated signal and background processes, such as uncertainties in the QCD scale, proton parton distribution functions, and Higgs boson decay branching fractions. Systematic uncertainties that significantly influence the individual searches but are strongly constrained or pulled in the data fitting are treated as uncorrelated to prevent undue influence on the other searches. However, the impact of treating them as correlated or uncorrelated in the combination was checked and found to be negligible.

The signal strength μ_{HH} is defined as the ratio of the measured inclusive ggF and VBF HH production cross section to the SM prediction $\sigma^{\mathrm{SM}}_{\mathrm{ggF+VBF}}(HH) = 32.8^{+2.1}_{-7.2}$ fb. This μ_{HH} measure assumes that the relative ggF and VBF production cross sections, Higgs boson decay branching fractions, and relative kinematic distributions correspond to the SM predictions. The fit to data indicates a value of $\mu_{HH} = 0.5^{+1.2}_{-1.0} = 0.5^{+0.9}_{-0.8}(\mathrm{stat})^{+0.7}_{-0.6}(\mathrm{syst})$, where “stat” and “syst” denote the statistical and systematic uncertainties, respectively. The result is compatible with the SM prediction, with a p value of 0.64. Assuming $\sigma_{\mathrm{ggF+VBF}}(HH) = \sigma^{\mathrm{SM}}_{\mathrm{ggF+VBF}}(HH)$, the expected value is $\mu_{HH} = 1.0^{+1.2}_{-1.0} = 1.0^{+1.0}_{-0.9}(\mathrm{stat})^{+0.7}_{-0.5}(\mathrm{syst})$. The primary systematic uncertainty arises from an estimated uncertainty of 100% in modeling

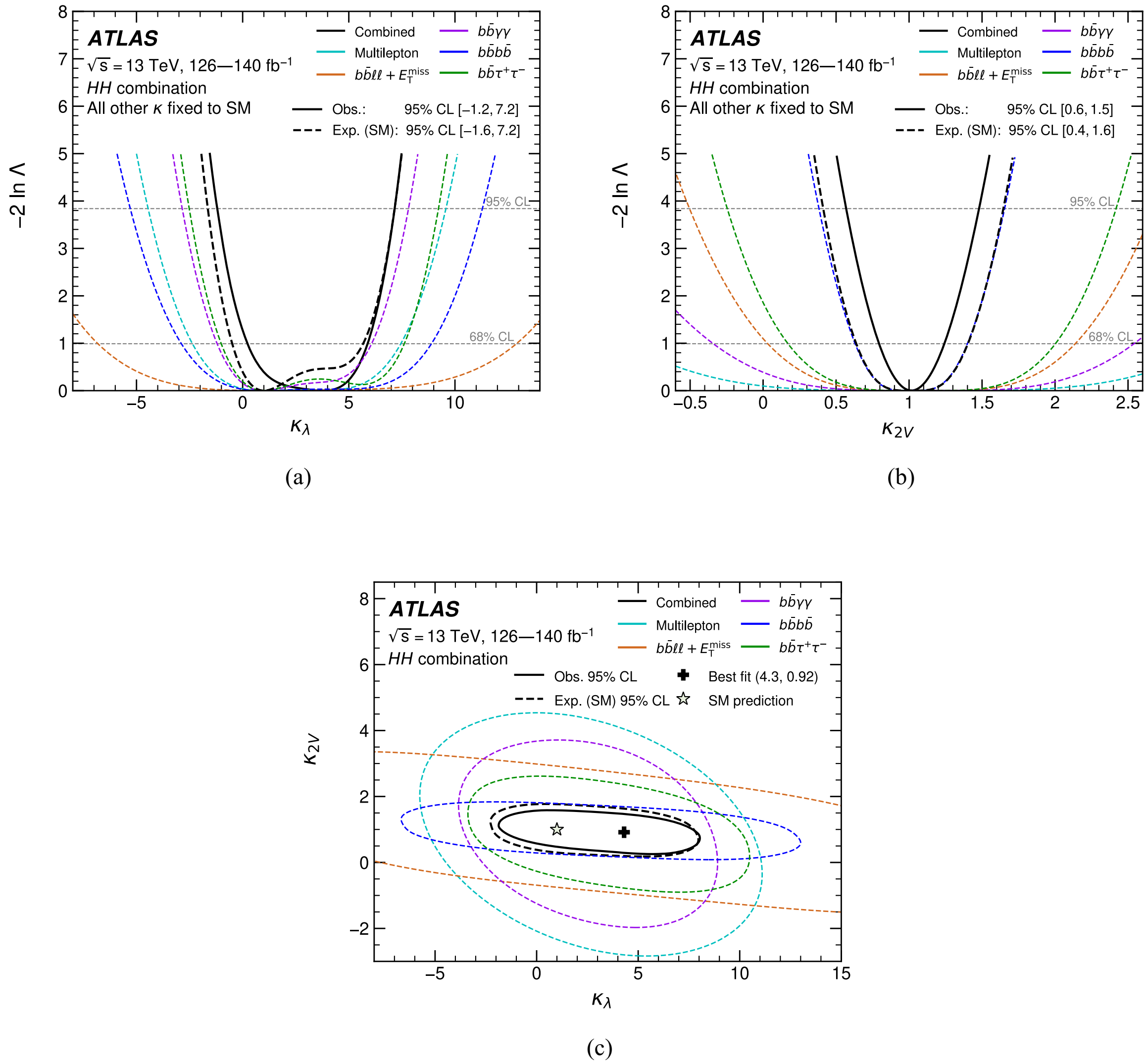

FIG. 3. Expected values (dashed lines) of the test statistic ($-2 \ln \Lambda$) as functions of (a) κ_λ and (b) κ_{2V}. These results are shown for the decay channels $b\bar{b}\gamma\gamma$ (purple), $b\bar{b}\tau^+\tau^-$ (green), multilepton (cyan), $b\bar{b}b\bar{b}$ (blue), and $b\bar{b}\ell\ell + E_T^{miss}$ (brown), as well as their combination (black). The observed values from the combined data are depicted by solid black lines. These results are computed with the assumption that all other Higgs boson couplings follow the SM predictions. (c) The expected 95% CL contours in the κ_{2V}-κ_λ plane, corresponding to the individual decay channels and their combination, are illustrated using dashed lines. The observed contour from the combined results is depicted by a solid black line. The SM prediction is marked by a star, and the combined best-fit value is indicated by a cross.

the radiation of additional heavy-flavor jets in the ggF single-Higgs-boson background production process [39–43], affecting μ_{HH} by 25%. The observed (expected) significance of μ_{HH} is 0.4 (1.0) standard deviations, with respect to the hypothesis of no HH production. No significant HH signal is observed above the expected background, and a 95% CL upper limit of 2.9 is placed on μ_{HH}. If HH production is absent, the expected 95% CL upper limit is 2.4, and in the SM case ($\mu_{HH} = 1$) the expected upper limit is 3.4. The expected upper limit is 17% lower than in the previous combination [4]: 13% from improvements in the $b\bar{b}\tau^+\tau^-$, $b\bar{b}\gamma\gamma$, and $b\bar{b}b\bar{b}$ analyses and an additional 4% from the inclusion of the multilepton and $b\bar{b}\ell\ell + E_T^{miss}$ channels. This combination provides the best expected sensitivity to the HH production cross section to date. Figure 2 displays the limits from the individual searches and their combination [44] highlighting the $b\bar{b}\tau^+\tau^-$ channel as the one expected to constrain μ_{HH} the most. The p value for compatibility between the μ_{HH} value measured in the combination and those measured in the individual searches is 0.16. The observed and expected 95% CL upper limits on $\sigma_{ggF+VBF}(HH)$ from the combination are 86 and 71 fb, respectively, derived in this case excluding theoretical uncertainties in the HH production cross section.

The self-coupling modifier κ_λ is explored in the ggF and VBF HH production processes. The impact of κ_λ on the single-Higgs-boson background productions and the Higgs

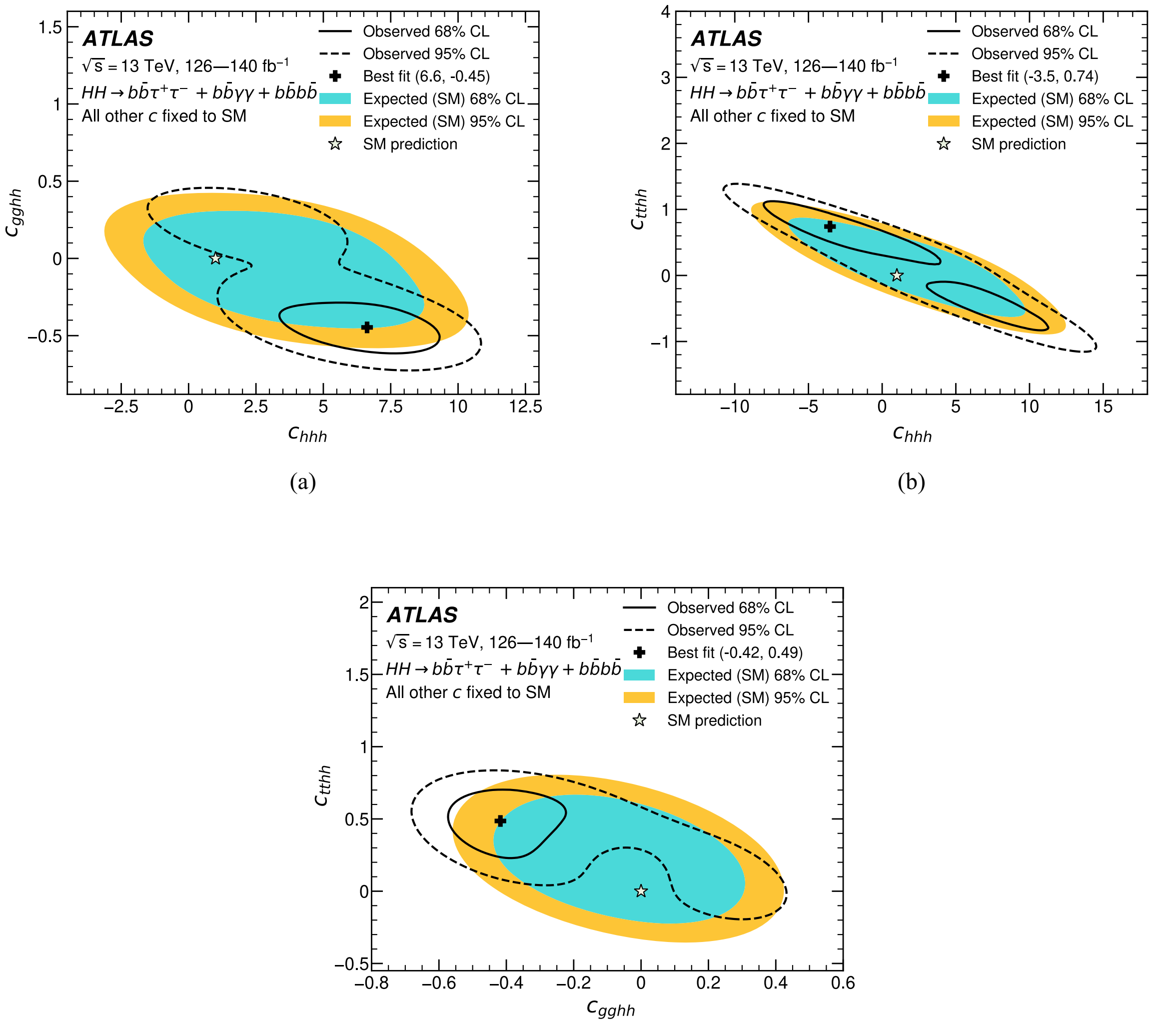

FIG. 4. Two-dimensional test-statistic contours at 68% CL (solid line) and 95% CL (dashed line) in the (a) c_{gghh}-c_{hhh}, (b) c_{tthh}-c_{hhh}, and (c) c_{tthh}-c_{gghh} HEFT parameter spaces, with c_{tthh}, c_{gghh}, and c_{hhh} fixed to their SM values, respectively. The corresponding SM expected contours are shown by the inner and outer shaded regions. The SM prediction is indicated by the star, while the best-fit value is shown by the cross.

decay widths is neglected. Assuming that other Higgs boson couplings conform to the SM predictions, a fit to data yields $\kappa_\lambda = 3.8^{+2.1}_{-3.6}$, which is compatible with the SM prediction, with a p value of 0.53. The expected value of κ_λ is $1.0^{+4.7}_{-1.5}$ when assuming SM HH production. The observed (expected) 95% CL interval is $-1.2 < \kappa_\lambda < 7.2$ ($-1.6 < \kappa_\lambda < 7.2$), representing the best expected sensitivity to the Higgs boson self-coupling to date. The values of the test statistic as a function of κ_λ are shown in Fig. 3(a) for both the individual searches and their combination, highlighting the $b\bar{b}\gamma\gamma$ channel as the most sensitive. Similarly, κ_{2V} is explored in the VBF HH production process. Assuming the SM predictions for other Higgs boson couplings, the observed (expected) value is $\kappa_{2V} = 1.02^{+0.22}_{-0.23}$ ($\kappa_{2V} = 1.00^{+0.40}_{-0.36}$). The observed (expected) 95% CL interval is $0.6 < \kappa_{2V} < 1.5$ ($0.4 < \kappa_{2V} < 1.6$). The values of the test statistic as a function of κ_{2V} are shown in Fig. 3(b), highlighting the $b\bar{b}b\bar{b}$ analysis as the most sensitive, mainly due to the boosted channel [26]. A deficit of data events in this channel results in stronger constraints on κ_{2V} than expected. To reduce model dependence, two-dimensional contours of $-2\ln\Lambda$ in the κ_{2V}-κ_λ plane are presented in Fig. 3(c). The p value for compatibility of the combined measurement and the SM prediction is 0.78.

For the HEFT interpretation the three most sensitive HH decay channels, $b\bar{b}\tau^+\tau^+$, $b\bar{b}\gamma\gamma$, and $b\bar{b}b\bar{b}$, are combined. The VBF HH process is ignored, since it is sensitive only to c_{hhh} and the predictions for this Wilson coefficient are not available for this process. One-dimensional constraints are evaluated separately for the coefficients c_{gghh} and c_{tthh}, with all other coefficients fixed to the SM predictions.

At 95% CL, the observed interval on c_{gghh} is $-0.38 < c_{gghh} < 0.49$; if the SM value $c_{gghh} = 0$ is assumed, the expected 95% CL interval is $-0.36 < c_{gghh} < 0.36$. Similarly, the observed (expected) 95% CL interval on c_{tthh} is $-0.19 < c_{tthh} < 0.70$ ($-0.27 < c_{tthh} < 0.66$). These represent the most stringent constraints to date on c_{gghh} and c_{tthh}. The results are compatible with the SM predictions, with p values of 0.087 and 0.16, respectively. Figure 4 displays the two-dimensional test-statistic contours in the coefficient spaces of (c_{gghh}, c_{hhh}), (c_{tthh}, c_{hhh}), and (c_{gghh}, c_{tthh}), with each plot fixing c_{tthh}, c_{gghh}, or c_{hhh}, respectively, to its SM value. Two minima are expected because of the quadratic dependence of the cross section on the coefficients. The p values for compatibility of the c_{gghh}-c_{hhh}, c_{tthh}-c_{hhh}, and c_{gghh}-c_{tthh} measurements with the SM predictions are 0.044, 0.21, and 0.031, respectively. The relatively low p values are primarily due to the $b\bar{b}b\bar{b}$ analysis [25], where the data-driven background modeling cannot perfectly describe the background distribution in data, making non-SM signals more favorable in the fit. Because of insufficient sensitivity, the combination does not allow simultaneous constraints to be placed on c_{hhh}, c_{gghh}, and c_{tthh} in a more model-independent manner [45].

In summary, this Letter presents a combination of the results of searches for HH production in the $b\bar{b}\tau^+\tau^-$, $b\bar{b}\gamma\gamma$, $b\bar{b}b\bar{b}$, multilepton, and $b\bar{b}\ell\ell + E_{\mathrm{T}}^{\mathrm{miss}}$ decay channels, utilizing the complete LHC run 2 dataset of 13 TeV proton-proton collisions recorded with the ATLAS detector. This new combination provides the best expected sensitivities to the HH production cross section and the Higgs boson self-coupling, superseding the results on the di-Higgs measurements of Ref. [4]. The results agree well with the SM predictions. When using Higgs effective field theory to interpret the measurements, unprecedented constraints are placed on the effective $ggHH$ and $t\bar{t}HH$ interactions.

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