

Probing new physics in the boosted $HH \rightarrow b\bar{b}\gamma\gamma$ channel at the LHC

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This paper presents the first dedicated study of the boosted $HH \rightarrow b\bar{b}\gamma\gamma$ topology as a key probe of physics beyond the Standard Model (SM) in the high-energy double-Higgs boson regime. The analysis presented in this paper focuses on two classes of new-physics scenarios: nonresonant deviations of the quartic gauge-Higgs interaction, parametrized by the coupling modifier κ_{2V} , and resonant enhancement arising from the decay of a heavy scalar state, modeled within a two-Higgs-doublet framework. We demonstrate that the boosted reconstruction category enhances sensitivity to beyond SM effects that populate the high- m_{HH} tail, yielding improved constraints on κ_{2V} and extending the discovery reach for heavy resonances.

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I. INTRODUCTION

Understanding the interactions that govern the Higgs sector remains a central challenge in particle physics. Although a decade of precision measurements has established the properties of the Higgs boson discovered at the LHC [1–7] to be compatible with the SM, the form of the Higgs potential and the structure of its couplings are still only loosely constrained. In particular, the trilinear Higgs self-coupling λ_3 which governs the shape of the Higgs potential and the interactions between the Higgs field and electroweak gauge bosons plays a key role in electroweak symmetry breaking and in a wide range of extensions of the Standard Model (SM) [8–12].

At the LHC proton-proton collisions, the Higgs boson pair production ($pp \rightarrow HH$) provides a unique laboratory to probe these interactions. While the dominant gluon-gluon fusion (ggF) process is mainly sensitive to the self-coupling modifier $\kappa_\lambda = \lambda_3/\lambda_3^{\text{SM}}$, the vector-boson fusion (VBF) production mode provides the unique direct test of the gauge-Higgs sector through the VVH and $VVHH$ vertices. Many theoretical frameworks, including two-Higgs-doublet models, singlet extensions, and supersymmetric scenarios [13–30], predict deviations in double Higgs boson production either through the new resonant decaying to two Higgs bosons or through deviations in the quartic gauge-Higgs interaction, commonly parametrized by the modifier κ_{2V} . The VBF channel is particularly

sensitive to these deviations, especially in the high-energy regime where the two forward jets and the Higgs system exhibit large boosts [31–38]. The search for new resonances in the double Higgs boson production and constraining κ_{2V} has therefore emerged as a priority for Higgs physics program at the LHC.

The $HH \rightarrow b\bar{b}\gamma\gamma$ channel provides one of the most experimentally powerful probes of Higgs pair production due to its relatively clean final state and high trigger efficiency compared to the fully hadronic channels. Despite its small branching ratio of roughly 0.26% for $m_H = 125$ GeV [39], the final state combines the large $H \rightarrow b\bar{b}$ branching fraction with the exceptionally clean diphoton signature, where the narrow $m_{\gamma\gamma}$ peak enables strong suppression of the dominant nonresonant continuum $\gamma\gamma + \text{jets}$ background. Both ATLAS and CMS collaborations have exploited this final state extensively, setting stringent limits on both nonresonant and resonant HH productions [35,40–44]. All the $HH \rightarrow b\bar{b}\gamma\gamma$ analyses to date have operated in the fully *resolved* reconstruction regime, where the two b -quarks emerging from $H \rightarrow b\bar{b}$ are reconstructed as separate small-radius jets. This configuration provides good sensitivity to the double Higgs boson production cross-section limit and to variations of κ_λ , and moreover has been the foundation for recent machine-learning-enhanced studies, including our earlier works employing graph neural networks [45] and hybrid quantum machine learning [46]. However, the resolved topology probes moderate kinematic scales and thus has limited sensitivity to the boosted high-energy regime where the deviations in κ_{2V} or new scalar resonance decaying to two Higgs bosons are expected.

In the boosted regime, where the Higgs boson is produced with large transverse momentum (p_T), the decay products of $H \rightarrow b\bar{b}$ become highly collimated, yielding to a single large-radius jet with a distinctive two-prong

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substructure. Such boosted Higgs boson configurations have become essential in analyses involving hadronic Higgs decays, especially for the $HH \rightarrow b\bar{b}b\bar{b}$ [47–49], offering improved reconstruction efficiencies and enabling access to extreme kinematic regions. Recently, the CMS Collaboration used the boosted topology to exclude the $\kappa_{2V} = 0$ scenario with a significance of 6.3σ , demonstrating the strong discriminating power of the boosted phase space and further motivating dedicated studies in this regime [50]. The boosted category enables sensitivity to both modifications of κ_{2V} and to heavy resonance decaying to Higgs boson pairs.

Despite the strong theoretical motivation, the $HH \rightarrow b\bar{b}\gamma\gamma$ channel has thus far been explored primarily in the resolved regime, and the potential of a dedicated boosted category has not yet been systematically assessed. In this paper, we present the first detailed study of the boosted $HH \rightarrow b\bar{b}\gamma\gamma$ topology for both nonresonant and resonant searches. Building on the simulation framework of Refs. [45,46], we define two mutually exclusive analysis regimes: a resolved category, in which the b -jets from $H \rightarrow b\bar{b}$ are reconstructed separately as two small-radius jets, and a boosted category, where the Higgs boson decay is captured as a single large-radius jet. An XGBoost classifier is used in the nonresonant analysis to define signal-enriched score bins within each category. For the resonant search, the available statistics at high transverse momentum are limited, and the signal topology is already highly distinctive. Thus, a simple rectangular-cut selection is adopted instead of a machine-learning approach. The central goal of the study is not to optimize classification performance, but to demonstrate the importance of accessing the high-energy VBF-like phase space through boosted Higgs reconstruction in the $HH \rightarrow b\bar{b}\gamma\gamma$ channels.

This paper is organized as follows: Sec. II introduces the theoretical framework. The Monte Carlo event generation is described in Sec. III. Object reconstruction and event definition are detailed in Sec. IV. The event selection strategy is presented in Sec. V. The results are presented and discussed in Sec. VI. Finally, the conclusions are given in Sec. VII.

II. THEORETICAL FRAMEWORK

Higgs boson pair production in proton-proton collisions proceeds primarily through the ggF production mode, with a smaller but theoretically important contribution from VBF production mode. The leading-order diagrams contributing to ggF and VBF production are shown in Fig. 1.

In the nonresonant case, the ggF process receive contribution from two leading amplitudes: the *box* diagram [Fig. 1(a)] and the *triangle* diagram [Fig. 1(b)]. The latter depends explicitly on the trilinear Higgs self-coupling and interferes destructively with the box contribution, making the total cross section strongly dependent on the modifier κ_t .

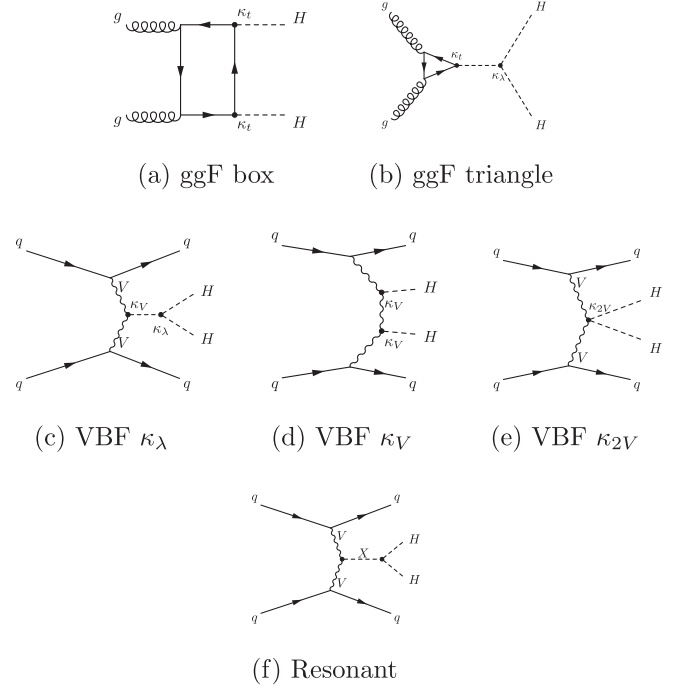


FIG. 1. Leading-order Feynman diagrams for gluon-gluon fusion [(a), (b)] and VBF Higgs boson pair production [(c)–(e)]. The resonant production mode is illustrated in (f).

The VBF production mode probes a different sector of the Higgs potential. In addition to κ_λ , its amplitude receives contributions from both the VVH and $VVHH$ vertices, making the process sensitive to modifications of the Higgs-vector boson couplings (κ_V) and, critically, to the quartic gauge-Higgs interaction parametrized by κ_{2V} . Modifications in the κ_{2V} alter the high-energy behavior of the VBF amplitude and affect both the inclusive rate and the kinematic distributions of the Higgs boson pair.

In the resonant case, many theories predict the existence of heavy scalar states that can decay into a pair of Higgs bosons, producing a resonant enhancement in the HH invariant-mass spectrum [14,51]. At leading order [Fig. 1(f)], the resonant production mechanism corresponds to a heavy state X being produced through VBF, followed by the decay $X \rightarrow HH$, yielding kinematics characterized by two highly boosted Higgs bosons whenever $m_X \gg 2m_H$. In this analysis, we consider the presence of such a resonant as a benchmark to illustrate the sensitivity of the boosted $HH \rightarrow b\bar{b}\gamma\gamma$ topology to heavy beyond SM (BSM) particles. For simulation purposes, we adopt a simplified scenario inspired by the type II two-Higgs-doublet model (2HDM) in which the SM-like Higgs H is accompanied by a heavier neutral scalar X that decays dominantly into HH . No model-dependent constraints, parameter scans, or couplings are used in the interpretation; the 2HDM framework serves only as a generator-level tool to produce representative kinematics for different scalar resonant masses m_X . As the resonant mass increases, the two Higgs bosons recoil back-to-back with

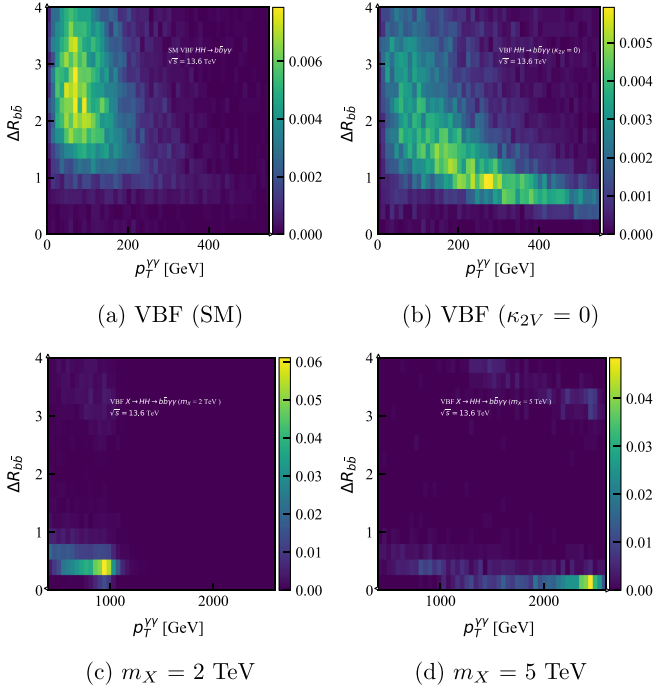


FIG. 2. Two-dimensional truth-level distribution of $\Delta R_{b\bar{b}}$ as a function of $p_T^{\gamma\gamma}$ for SM (a), $\kappa_{2V} = 0$ (b), resonant $m_X = 2$ TeV (c), and $m_X = 5$ TeV (d) at $\sqrt{s} = 13.6$ TeV.

large transverse momentum, and their hadronic decays become increasingly collimated. This places the bulk of the signal in precisely the region where the resolved selection loses efficiency and the boosted reconstruction becomes essential.

Figure 2 shows the two-dimensional distribution of the angular separation between the two b quarks, $\Delta R_{b\bar{b}}$, as a function of the diphoton transverse momentum $p_T^{\gamma\gamma}$ at the truth level. At moderate Higgs transverse momenta such as for SM [Fig. 2(a)], the two b quarks from $H \rightarrow b\bar{b}$ are well separated, typically with $\Delta R_{b\bar{b}} \gtrsim 0.4$, and are reconstructed as two distinct small-radius (small- R) jets. This defines the resolved regime, which has been the focus of most existing experimental and phenomenological studies [35,40–46]. However, we focus on the *semiboosted* regime (hereafter referred to simply as the boosted regime), in which only the $H \rightarrow b\bar{b}$ decay products become collimated while the diphoton system remains well resolved. In this configuration, the characteristic angular separation of the b quarks decreases approximately as

$$\Delta R_{b\bar{b}} \simeq \frac{2m_H}{p_T^H}. \quad (1)$$

Once $\Delta R_{b\bar{b}} \lesssim R_{\text{jet}}$, both b quarks are captured inside a single large-radius (large- R) jet, as shown in Fig. 2 for BSM scenarios. The resulting jet exhibits a distinctive two-prong substructure, a feature that has been extensively exploited in a variety of hadronic Higgs analyses [47,48].

III. MONTE CARLO EVENT GENERATION

The Monte Carlo (MC) samples used in this analysis correspond to simulated proton-proton collisions at a c.m. energy of $\sqrt{s} = 13.6$ TeV. The simulation setup is designed to model the kinematics of Higgs boson pair production in the $H(\rightarrow b\bar{b})H(\rightarrow \gamma\gamma)$ final state and to provide sufficient statistical precision to evaluate the performance of the boosted and resolved reconstruction strategies introduced in this work. Both signal and background samples are normalized to the most accurate cross-section predictions available in the literature. An integrated luminosity of 308 fb^{-1} is assumed, representative of the combined Run 2 and partial Run 3 dataset recorded by the LHC experiments.

For the nonresonant signal, the ggF process is generated using the Powheg-Box v2 framework [52], including finite top-quark mass effects and full next-to-leading-order (NLO) QCD corrections. The generated events are subsequently normalized to the next-to-next-to-leading-order (NNLO) cross-section prediction with top-mass dependence following Refs. [31,32]. The VBF signal sample is produced at leading order using MadGraph5_aMC@NLO v3.3.0 [53], and the normalization is set using the next-to-next-to-next leading order QCD + NLO electroweak prediction from Refs. [33,34]. All signal samples are generated with the Higgs boson mass fixed to $m_H = 125$ GeV and SM couplings ($\kappa_\lambda = 1$, $\kappa_{2V} = 1$). Additional VBF samples are generated with varied κ_{2V} parameter from its SM value including $\kappa_{2V} = 0, 0.5, 1.5, -1$ and -2.5 . The VBF resonant BSM samples are generated at leading order using MadGraph5_aMC@NLO v3.3.0 using the type II 2HDM model for eight mass points $m_X = 1, 1.5, 2, 2.5, 3, 3.5, 4$, and 5 TeV. The generated samples are normalized to a cross section equal to 1 fb.

Backgrounds contributing to the $b\bar{b}\gamma\gamma$ final state are experimentally known to arise from the nonresonant continuum photon component and from resonant single Higgs production. In the CMS or ATLAS analyses, backgrounds are classified into resonant and nonresonant components. Resonant backgrounds originate from single Higgs boson production followed by the decay $H \rightarrow \gamma\gamma$. The dominant production mechanisms—ggF, VBF, ZH , and $t\bar{t}H$ —are generated with Powheg-Box v2, using identical settings to those employed for the ggF signal simulation. The cross sections are taken from the most recent LHC Higgs Working Group recommendations [39]. The dominant nonresonant background arises from direct QCD production of continuum $\gamma\gamma$ events accompanied by jets. This background is produced with MadGraph5_aMC@NLO, including matrix elements with up to two additional partons in the final state to ensure an accurate modeling of the jet multiplicity and the kinematic tails relevant for this analysis. In the selected phase space, the continuum $\gamma\gamma$ + jets contribution is the dominant background component, while single Higgs production is subdominant. Top + γ contributions are expected to be

TABLE I. Summary of the generated signal and background samples used in this analysis, together with their nominal cross sections.

Process	Events	Cross section [pb]
ggF HH (SM)	50k	0.3413 [34]
VBF HH (SM)	100k	0.001874 [34]
VBF HH ($\kappa_{2V} = 0$)	100k	0.02885 [34]
VBF $X \rightarrow HH$	100k	1 fb
ggF H	500k	52.17 [39]
VBF H	550k	4.075 [39]
$qq \rightarrow ZH$	50k	1.834×10^{-3} [39]
$gg \rightarrow ZH$	100k	3.087×10^{-4} [39]
$t\bar{t}H$	100k	5.688×10^{-1} [39]
$\gamma\gamma$ + jets	2.5M	48.1

negligible after the analysis selections and are therefore not included. Contributions such as hadronic Z/W +continuum-photon production or $Z \rightarrow b\bar{b}$ with continuum photons are effectively included in the inclusive nonresonant photon + jets background class, and photon-fake backgrounds are represented primarily by the γ + jet component. Table I summarizes the generated processes, along with the corresponding numbers of simulated events and nominal cross sections.

All parton-level events are processed through Pythia 8.186 [54] for parton showering, hadronization, and underlying-event modeling. The detector response is emulated using the Delphes fast-simulation framework [55], configured with an ATLAS detector card tuned for Run 3 performance.

IV. OBJECT RECONSTRUCTION AND EVENT SELECTION

The final state targeted in this analysis contains two isolated photons and the hadronic decay of a Higgs boson into a $b\bar{b}$ pair. Depending on the transverse momentum of the hadronically decaying Higgs, the two b quarks may be reconstructed either as two distinct small- R jets (resolved topology) or as a single large- R jet (boosted topology). All reconstructed objects are obtained from the Delphes fast simulation of the ATLAS detector and follow Run 3 object definitions.

A. Object reconstruction

Photon candidates are built from clusters in the electromagnetic calorimeter and are required to satisfy a transverse momentum threshold of $p_T > 20$ GeV and a pseudorapidity acceptance of $|\eta| < 2.37$. The region $1.37 < |\eta| < 1.52$ is excluded to avoid reduced calorimeter response. A dedicated emulation of the ATLAS Run 3 photon identification efficiency is applied using the efficiency maps provided in Ref. [56]. When two photon seeds

are nearly coincident in (η, ϕ) space ($\Delta R < 0.01$), only the higher- p_T photon is retained, ensuring the isolation of photon candidates.

Small- R jets used in the resolved analysis are formed using the anti- k_t algorithm with radius parameter $R = 0.4$, as implemented in FastJet [57,58]. Reconstructed jets are required to satisfy $p_T > 25$ GeV and $|y| < 4.5$. A parametrized b -tagging response corresponding to 85% efficiency [59] is applied to identify jets originating from b -hadrons. This working point corresponds to mistag rates of 0.17 for c -jets and 0.01 for light-flavor jets. Only b -tagged small- R jets within the inner-detector coverage ($|\eta| < 2.5$) are considered.

To capture merged $H \rightarrow b\bar{b}$ decays in the boosted regime, a second jet collection is constructed using the anti- k_t algorithm with $R = 1.0$. To reflect modern ATLAS grooming and substructure practices, several procedures are applied at the Delphes level to improve the stability of the large- R jet mass and suppress contamination from soft radiation and pileup [60]. Each jet is first trimmed by reclustering its constituents into subjets of size $R_{\text{trim}} = 0.2$ and removing subjets carrying less than 5% of the original jet p_T . Pruning is then applied using $z_{\text{cut}} = 0.1$ and $R_{\text{cut}} = 0.5$ to eliminate soft, large-angle contributions. In addition, the jet undergoes soft-drop grooming with $\beta_{\text{SD}} = 0$, a symmetry threshold of $z_{\text{cut}} = 0.1$, and characteristic radius $R_0 = 0.8$, providing a groomed mass that is less sensitive to soft QCD effects [61,62]. Large- R jets used as boosted Higgs candidates are required to satisfy a transverse momentum in the range $250 \text{ GeV} < p_T < 3 \text{ TeV}$ and a rapidity acceptance of $|y| < 2$, ensuring that the jet is fully contained within the inner detector tracker. After grooming, the jet mass is required to lie within $80 < m_J < 250 \text{ GeV}$, a broad window chosen to retain signal-like two-prong configurations while suppressing soft QCD backgrounds; Fig. 3 shows the groomed large- R jet mass. Identification of jets originating from a merged $b\bar{b}$ system is performed

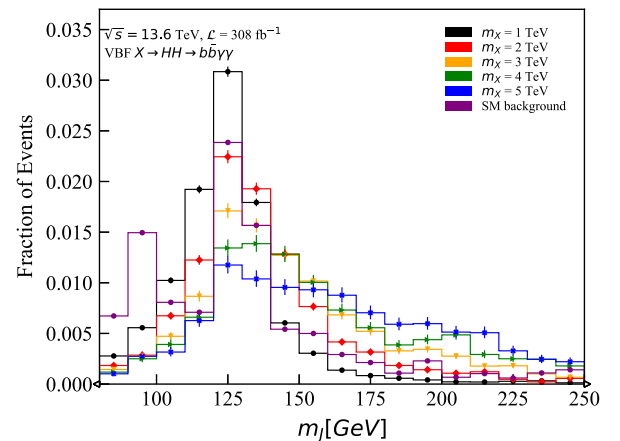


FIG. 3. Groomed jet mass distribution for different m_X mass points and SM backgrounds.

using a parametrized double- b tagging efficiency of 60%, with a corresponding mistag probability of approximately 6% for light-flavor and gluon-initiated jets [63].

Electrons and muons are reconstructed from the particle-flow track collection. They are used exclusively for vetoing backgrounds with leptonic activity. Electrons must satisfy $p_T > 10$ GeV and $|\eta| < 2.47$, excluding the ATLAS barrel-endcap transition region. Muon candidates are required to have $p_T > 10$ GeV and $|\eta| < 2.7$.

To ensure a unique assignment of reconstructed objects and to prevent double counting of calorimeter deposits or tracks, a fixed overlap-removal sequence is applied. Jets that lie within $\Delta R < 0.4$ of any reconstructed photon are discarded, and jets overlapping with electrons within $\Delta R < 0.2$ are also removed. After the jet cleaning step, electrons found within $\Delta R < 0.4$ of any remaining jet are removed, as are muons satisfying the same condition. Photon candidates overlapping with electrons or muons within $\Delta R < 0.4$ are subsequently discarded, guaranteeing that photons used in the analysis are isolated from charged leptons. This procedure yields mutually exclusive collections of jets, photons, and leptons, providing a clean object definition for the resolved and boosted reconstruction strategies used in this study.

B. Common event selection

All events considered in this analysis must satisfy a diphoton trigger designed to select final states containing two energetic photons. The trigger thresholds correspond to transverse energy (E_T) requirements of approximately 35 GeV for the leading photon and 25 GeV for the subleading one, and the associated efficiencies are applied to the simulated events using the measured trigger efficiency obtained in ATLAS Run 3 data at $\sqrt{s} = 13.6$ TeV [64]. Only events that pass this trigger emulation and the object selections described in Sec. IV A are retained.

To form a Higgs boson candidate decaying into two photons, the two highest- p_T photons in the event are selected and required to satisfy an invariant mass window,

$$105 \text{ GeV} < m_{\gamma\gamma} < 160 \text{ GeV},$$

which defines the signal-enriched diphoton region. In addition, scaled p_T requirements are imposed to ensure a uniform selection efficiency across the diphoton mass range. Specifically, the leading photon must satisfy $p_T^{Z_1} > 0.35m_{\gamma\gamma}$, and the subleading photon must meet $p_T^{Z_2} > 0.25m_{\gamma\gamma}$. These normalized thresholds suppress events with soft photons and preserve the shape of the $m_{\gamma\gamma}$ spectrum near the Higgs boson mass, preventing distortions that would otherwise complicate the background modeling [65]. The photon pair passing these criteria defines the reconstructed $H \rightarrow \gamma\gamma$ candidate.

Events containing reconstructed electrons or muons are vetoed to suppress contributions from top-associated and electroweak processes. Furthermore, to reduce

contamination from hadronic $t\bar{t}H$ backgrounds, events with more than six central jets are rejected. This set of requirements defines the common selection applied to both the resolved and boosted categories.

C. Resolved category selection

In the resolved topology, the hadronic Higgs boson candidate is reconstructed from two well-separated b -tagged small- R jets. Events entering this category must contain at least two jets identified as originating from b -quarks, and the pair with the highest transverse momenta is taken to represent the $H \rightarrow b\bar{b}$ decay. No additional constraints are imposed on the angular separation of the two jets beyond the requirements already included in the object definitions; the resolved configuration is naturally selected by the absence of collimation between the two b quarks. To characterize the VBF event topology, additional jets not used in the Higgs reconstruction are examined. If such jets are present, the two highest- p_T remaining jets are designated as VBF candidates and may be used to probe the forward-jet kinematics typical of VBF production mode. This identification is auxiliary and not required for an event to be accepted: events without a pair of suitable forward jets are kept in the sample, ensuring that the resolved selection remains inclusive and highly sensitive to the SM cross-section limit.

D. Boosted category selection

The boosted category targets events in which the hadronic Higgs decay is reconstructed as a single large- R jet. The highest- p_T large- R jet meeting the criteria described in Sec. IV A is selected as the Higgs $H \rightarrow b\bar{b}$ candidate. The boosted category is required to have at least two VBF jets. To identify a VBF-like topology, the remaining small- R jets in the event are examined. Only jets that are well separated from the Higgs candidate, $\Delta R(j, J) > 1.4$, are considered. Among all possible jet pairs fulfilling this condition, the pair with the largest pseudorapidity separation ($|\Delta\eta|$) is chosen as the VBF-jet system. Table II summarizes the selection criteria, while the corresponding event yields for signal and background processes after each selection step are presented in the outflow Table III.

E. Orthogonality

To ensure orthogonality between the two analysis categories, an exclusive event-assignment rule is applied. In events where a suitable large- R jet is identified, the hadronic Higgs decay is represented by this single boosted jet and the event is assigned to the boosted category. If no such jet is found, but the event contains two distinct b -tagged small- R jets consistent with a resolved $H \rightarrow b\bar{b}$ configuration, the event is assigned to the resolved category. This boosted-priority arbitration guarantees that the two fit categories are disjoint. The overlap fractions quoted here (8.7% for $\kappa_{2V} = 0$ and 2.2% for the SM

TABLE II. Summary of the common event selection and the category-specific requirements for the resolved and boosted analyses.

Common selection	
Diphoton trigger	
Two photons with $p_T > 20$ GeV and $ \eta < 2.37$, excluding $1.37 < \eta < 1.52$	
$105 < m_{\gamma\gamma} < 160$ GeV	
$p_T^{\gamma_1} > 0.35m_{\gamma\gamma}$ and $p_T^{\gamma_2} > 0.25m_{\gamma\gamma}$	
Lepton veto (e, μ)	
$N_{\text{jet}}^{\text{small-}R} \geq 2$ and $N_{\text{jet}}^{\text{small-}R} < 6$	
Resolved category	
$N_{b\text{-jet}}^{\text{small-}R} \geq 2$	
Remaining leading 2-jets, when present, are used as VBF jets	
Exclude boosted category events	
Boosted category	
$N_{b\text{-jet}}^{\text{large-}R} \geq 1$	
$N_{\text{VBF-jet}}^{\text{small-}R} \geq 2$	
VBF jets are selected among small- R jets satisfying $\Delta R(j, J) > 1.4$	
The VBF pair is chosen as the pair with the largest $ \Delta\eta $	

TABLE III. Cutflow table for continuum background, single Higgs, ggF SM HH , VBF SM HH , VBF ($\kappa_{2V} = 0$) HH , BSM $X \rightarrow HH$ ($m_X = 2$) TeV and BSM $X \rightarrow HH$ ($m_X = 5$) TeV. Event yields are normalized to integrated luminosity of 308 fb⁻¹.

Cut	Background		Nonresonant HH			Resonant BSM HH	
	$\gamma\gamma$ + jets	Single H	ggF	VBF	$\kappa_{2V} = 0$	$m_X = 2$ TeV	$m_X = 5$ TeV
All	1.48×10^7	4.05×10^4	27.8	1.53	23.5	3.08×10^5	3.08×10^5
Trigger	8.07×10^6	2.23×10^4	15.82	0.85	15.39	2.47×10^5	2.57×10^5
≥ 2 tight photon	5.63×10^6	1.55×10^4	13.00	0.70	13.21	2.23×10^5	2.35×10^5
Photon p_T cut	4.70×10^6	1.42×10^4	11.53	0.55	10.90	1.80×10^5	1.96×10^5
$m_{\gamma\gamma} \in [105, 160]$ GeV	2.59×10^6	1.40×10^4	11.30	0.55	10.84	1.79×10^5	1.95×10^5
Veto lepton	2.57×10^6	1.39×10^4	9.83	0.33	8.70	1.03×10^5	1.12×10^5
$N_{\text{jet}} \geq 2$ & $N_{\text{jet}} < 6$	9.49×10^5	2.01×10^3	8.53	0.30	7.89	9.74×10^4	1.07×10^5
Resolved category	1.35×10^4	54.2	3.88	0.15	2.47	1.94×10^3	5.01×10^3
Boosted category	1.14×10^4	23.4	0.46	0.09	1.42	1.96×10^4	8.51×10^3

sample) correspond to the preassignment candidate level, before this final event arbitration.

Figure 4 shows the reconstructed di-Higgs invariant mass distributions for (a) the nonresonant analysis and (b) the resonant analysis after applying the full event selection described above. The distributions are shown separately for the boosted reconstruction category (solid histograms) and the resolved reconstruction category (dashed histograms). In the nonresonant case, the boosted category demonstrates an enhanced sensitivity to deviations in κ_{2V} in the high- m_{HH} tail, where contributions from BSM effects are expected to be largest. A similar behavior is observed in the resonant analysis, where the boosted reconstruction dominates the sensitivity at large resonant masses m_X .

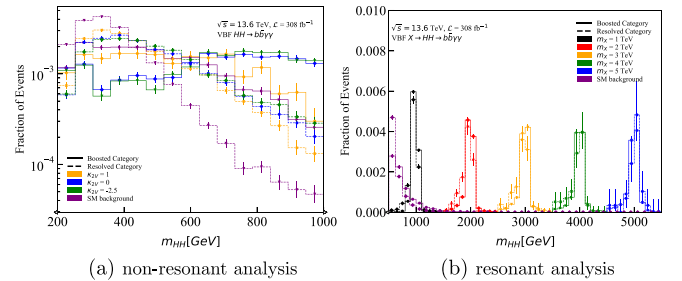


FIG. 4. Reconstructed di-Higgs invariant mass m_{HH} in both nonresonant (a) and resonant (b) analysis. The boosted reconstruction category is shown with solid histograms, while the resolved category is shown with dashed histograms.

V. EVENT CATEGORIZATION

This section describes the strategy used to categorize events and construct a lightweight classifier aimed at improving the separation between signal and background for the nonresonant study. The emphasis of the analysis is not on developing an advance Machine Learning (ML) model, but rather on demonstrating how a dedicated boosted reconstruction of the $HH \rightarrow b\bar{b}\gamma\gamma$ final state can strengthen the sensitivity to BSM physics—an aspect that has not been systematically explored in previous studies. Due to the lack of background events in the high- p_T m_{HH} spectrum, the resonant analysis will rely only on the rectangular cuts described before and no ML based categorization will be considered.

Before training the XGBoost classifier [66], a uniform preprocessing procedure is applied to all selected events to ensure consistent inputs and to reduce detector-related asymmetries. In particular, events that satisfy either of the Higgs reconstruction paths (resolved or boosted) are transformed by rotating the final-state momenta in the transverse plane so that the leading photon is placed at a fixed azimuthal reference direction. This operation leverages the approximate cylindrical symmetry of the ATLAS detector and removes arbitrary variations in ϕ , enabling the classifier to concentrate on physically relevant geometric correlations rather than on random orientation differences [67]. All remaining objects in the event are rotated coherently to preserve their internal angular relationships. For the purposes of training and validating the classifier, the full event sample is partitioned into two nonoverlapping subsets. A randomly selected fraction of 75% is used to optimize the model parameters, while the remaining 25% is held out and serves exclusively for performance validation. All physics results presented in this work rely solely on the latter subset, ensuring that the quoted performance is derived from events not used during training and is therefore free from training-induced bias. Each simulated event carries a weight proportional to its generator-level cross section, allowing the effective event composition to reproduce the expected yields in data. Because the background samples greatly exceed the signal in raw statistics, an additional per-class normalization factor is applied to counteract the imbalance.

Separate XGBoost classifiers are trained for the resolved and boosted event categories. In the resolved case, the signal sample consists of the SM ggF and VBF Higgs boson pair production. For the boosted classifier, the signal definition is extended to include events generated with $\kappa_{2V} = 0$ and $\kappa_{2V} = 0.5$, providing additional statistics in the kinematic region where merged $H \rightarrow b\bar{b}$ decays are most frequent. Both classifiers rely on a common set of high-level kinematic variables describing the diphoton system, including p_T , η , and ϕ angles of the two leading photons, as well as the four-vector properties of the reconstructed $H_{\gamma\gamma}$

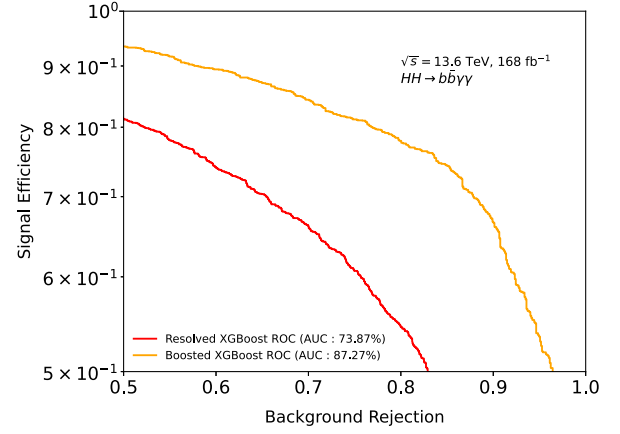


FIG. 5. Weighted ROC curves for resolved (red) and the boosted (orange) categories. The ROC curves are computed using event weights on the test datasets.

candidate ($p_T^{\gamma\gamma}$, $\eta^{\gamma\gamma}$, $\phi^{\gamma\gamma}$, and $m_{\gamma\gamma}$). Kinematic quantities associated with the VBF-tagged jets are also included: the p_T , η , and ϕ angle of each jet, together with the dijet angular separation $\Delta\eta_{jj}$ and invariant mass m_{jj} . The two categories differ only in the representation of the hadronic Higgs candidate. In the resolved regime, the classifier receives as input the four-vector components of the two b -tagged small- R jets, the corresponding reconstructed $H_{b\bar{b}}$ system ($p_T^{b\bar{b}}$, $\eta^{b\bar{b}}$, $\phi^{b\bar{b}}$, and $m_{b\bar{b}}$) and the reconstructed HH system ($p_T^{b\bar{b}\gamma\gamma}$, $\eta^{b\bar{b}\gamma\gamma}$, $\phi^{b\bar{b}\gamma\gamma}$, and $m_{b\bar{b}\gamma\gamma}$). In the boosted regime, the hadronic Higgs is instead identified with the leading large- R jet, and the classifier uses the jet kinematics (p_T^J , η^J , ϕ^J , and m^J) as the $H \rightarrow b\bar{b}$ representation and the $\gamma\gamma$ + large R jet kinematic ($p_T^{J\gamma\gamma}$, $\eta^{J\gamma\gamma}$, $\phi^{J\gamma\gamma}$, and $m_{J\gamma\gamma}$) as the representation of the HH system in the boosted regime. The XGBoost algorithm includes a set of hyperparameters [68] that significantly influence model performance and require careful tuning. In this analysis, both XGBoost classifier rely on the random grid search approach for the hyperparameter optimization. Figure 5 shows the XGBoost receiver operating characteristic (ROC) curves for both resolved and boosted categories. The boosted model exhibits a higher accuracy of 87% compared to 74% for the resolved model.

The output of each XGBoost model is used to define two signal-enriched bins above the 0.5 threshold, with the bin boundaries optimized to maximize the expected sensitivity using the Asimov approximation to the profile likelihood ratio [69] defined as

$$Z = \sqrt{2 \times ((s + b) \times \ln(1 + s/b) - s)},$$

where s is the total signal yield and b corresponds to the total background yield. The defined bins are used in the binned likelihood fit. Figure 6 shows the XGBoost output scores for both resolved and boosted regimes.

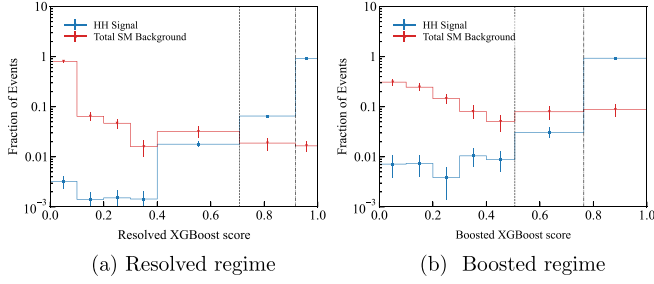


FIG. 6. XGBoost classifier output score for resolved (a) and boosted (b) regimes. The dashed vertical lines indicates the optimized binning threshold.

VI. RESULTS AND DISCUSSION

The purpose of this study is to highlight the sensitivity gain obtained by introducing a dedicated boosted $HH \rightarrow b\bar{b}\gamma\gamma$ category, particularly in the high mass region where many BSM scenarios predict enhancements. Two classes of new-physics effects are examined: (i) nonresonant deviations from the quartic gauge-Higgs interaction, parametrized through variations of κ_{2V} , and (ii) heavy resonances decaying into Higgs boson pairs, as predicted in extended scalar sectors. Both mechanisms increase the population of events with highly boosted Higgs bosons, making the boosted reconstruction highly sensitive over the resolved.

A. Nonresonant analysis

A binned likelihood fit is performed in each analysis category using the optimized classifier output bins. The statistical inference relies on the `pyhf` framework [70] to derive the 95% confidence level (CL) upper limit on the signal strength, as follows:

$$\mu_{HH} = \frac{\sigma(pp \rightarrow HH)}{\sigma_{SM}(pp \rightarrow HH)}.$$

In the likelihood model, the background is separated into process components (continuum $\gamma\gamma + \text{jets}$ and single Higgs), each with an independent normalization nuisance of 10% and a per-bin shape nuisance. The per-bin shape term is implemented with `shapesys` using binwise MC statistical uncertainties. The observed data constructed by assuming the SM expectation (background plus SM ggF + VBF HH yields). Because the statistical model is built from the final exclusive event assignment, the combined likelihood of the two categories factorizes as

$$\mathcal{L}_{\text{combined}} = \mathcal{L}_{\text{resolved}} \times \mathcal{L}_{\text{boosted}}.$$

Figure 7 shows the extracted limits for each category. The resolved channel provides the strongest individual constraint, excluding a signal strength of $\mu_{HH} = 2.7$ at 95% CL, consistent with its high efficiency near threshold where the SM contribution peaks. The boosted channel

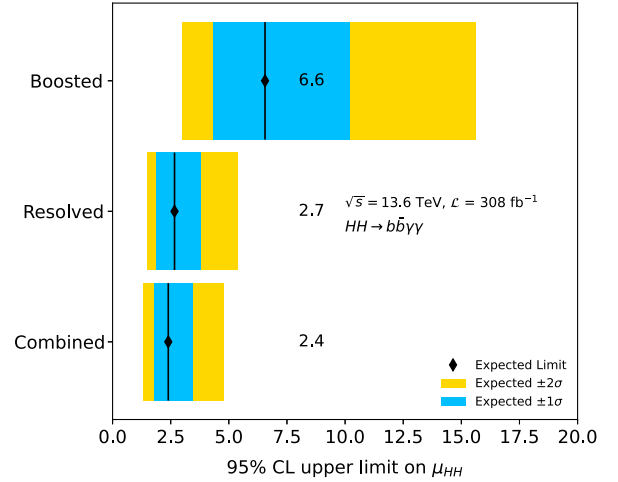


FIG. 7. Expected 95% CL upper limit on the signal strength μ_{HH} for the resolved, boosted, and combined categories.

yields a weaker limit of $\mu_{HH} = 6.6$, reflecting the much smaller SM contribution in the high-mass region. When combined, the analysis achieves a limit of 2.4 times the SM predictions, dominated by the resolved region but benefiting from the complementary boosted acceptance. The improvement with respect to a resolved-only strategy is driven primarily by the reconstruction efficiency recovery of the high- p_T topology.

While the inclusive SM sensitivity is dominated by the resolved selection, the primary goal of this work is to probe deviations at high m_{HH} induced by variations of the κ_{2V} coupling in the nonresonant scenario. A one-dimensional profile-likelihood scan of κ_{2V} is performed using the same statistical model as above. Here, only the impact of κ_{2V} on the overall event rate is considered, without modeling shape modification. Figure 8 shows the resulting likelihood profiles for the boosted, resolved, and combined categories. The boosted selection exhibits a pronounced response to non-SM values of κ_{2V} , significantly outperforming the

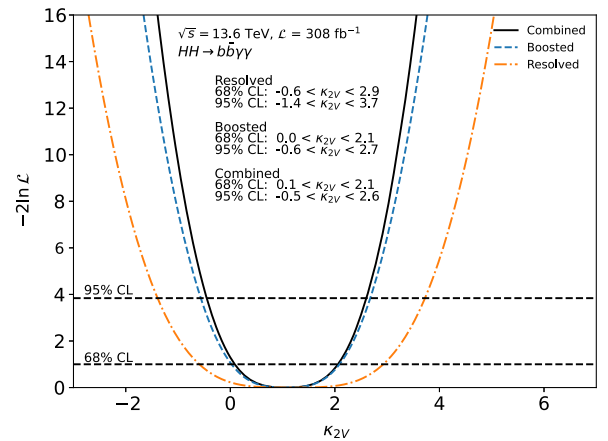


FIG. 8. Profile-likelihood scan of the κ_{2V} modifier for the resolved, boosted, and combined analysis categories.

resolved category in the large- $|\kappa_{2V} - 1|$ region. This behavior reflects the strong correlation between κ_{2V} variations and the high- p_T phase space where the boosted topology dominates. The combined result inherits the strengths of both categories, providing superior constraints across the full parameter range.

The strongest current Run-2 ATLAS + CMS combination, which includes the $b\bar{b}\gamma\gamma$, $b\bar{b}b\bar{b}$ and $b\bar{b}\tau\tau$ channels, set a limit on the signal strength μ_{HH} of 2.5. The same combination also constrains the quartic gauge-Higgs coupling to $0.73 < \kappa_{2V} < 1.3$ at 95% CL at 13 TeV [71]. The individual $b\bar{b}\gamma\gamma$ channel gives a wider allowed interval on κ_{2V} in the range of $[-0.48, 2.7]$ at 95% CL [35,72]. A large part of the combined sensitivity comes from the $b\bar{b}b\bar{b}$ final states where boosted event categories play an important role in increasing the sensitivity to BSM deviations of κ_{2V} . Including a boosted category in the $b\bar{b}\gamma\gamma$ analysis would therefore make this golden final state a more competitive probe of quartic gauge-Higgs interactions.

B. Resonant analysis

Since the resonant analysis does not rely on the ML classifier, the likelihood is binned on the $m_{\gamma\gamma}$ in the range [120, 130] GeV with a bin width of 2 GeV. Similarly to the nonresonant analysis, the 95% CL upper limit is derived on the signal strength,

$$\mu = \frac{\sigma_{VBF}(X \rightarrow HH)}{1 \text{ fb}},$$

with a background uncertainty including both normalization and shape uncertainties as implemented for the nonresonant analysis, and the observed data are constructed in the same way. The 95% CL upper limit is evaluated for the eight generated mass points and a quadratic interpolation is used to interpolate between the mass point in the range 1 to 5 TeV.

Figure 9 shows the 95% CL upper limit on the VBF cross section for the resonant process as a function of the heavy scalar mass m_X for the boosted, resolved, and combined cases. In the whole considered mass range, the boosted category provides significantly stronger limits than the resolved selection. This effect originates from the fact that resonant production manifests as enhancement to the high- p_T , high- m_{HH} phase space where the Higgs boson decay products are highly collimated, whereas the resolved regime suffers from vanishing acceptance once the two b -quarks merge. Consequently, for all mass points, the limits set by the resolved category are well above the ones obtained with the boosted selection. The boosted category is able to set a limit on the cross section about a factor 1 to 2 better depending on the mass point. This reflects the key role played by the boosted analysis in BSM searches. The combined limit is highly dominated, with the boosted

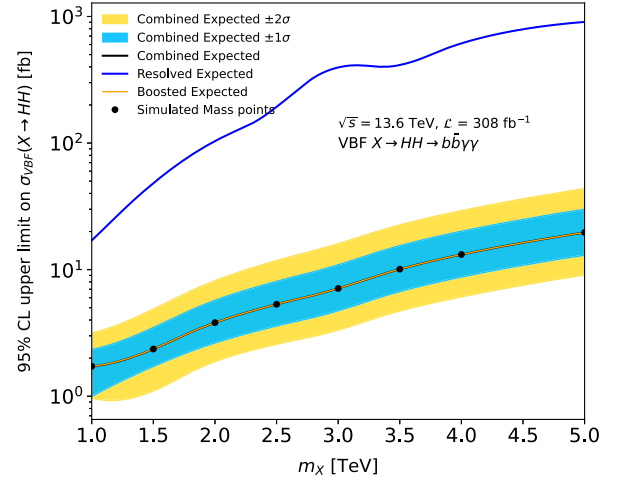


FIG. 9. Expected 95% CL upper limits on the VBF production cross section $\sigma(X \rightarrow HH)$ as a function of the resonant mass m_X for the resolved (blue), boosted (orange), and combined (black) analysis categories. The combined expectation band includes the $\pm 1\sigma$ and $\pm 2\sigma$ variations, while the points represent the simulated mass hypotheses.

analysis setting limit ranging from 1.9 fb for 1 TeV and 100 fb at 5 TeV.

The ATLAS Run-2 combination of resonant Higgs-pair searches probes narrow scalar resonances in the mass range 251 GeV to 5 TeV, with observed 95% CL upper limits between 0.96 and 600 fb [73]. The sensitivity degrades rapidly in the high-mass region, where the Higgs bosons become highly boosted and the hadronic decay products increasingly collimated. This is precisely the kinematic regime targeted in the present work to improve the acceptance of heavy resonances.

VII. CONCLUSION

This work presents the first dedicated analysis of the boosted $HH \rightarrow b\bar{b}\gamma\gamma$ topology, with a specific focus on understanding the relevance of these processes with regards to BSM theories that can extend the high-energy phase space region. Both nonresonant BSM signals associated with modifications to the quartic couplings involving the gauge and Higgs boson, κ_{2V} modifier, and resonantly produced Higgs pairs via heavy scalar decay (X), are considered. Both scenarios preferentially generate regions with large Higgs transverse momentum and high di-Higgs mass, with the hadronic Higgs system being reconstructed as large- R jets instead of two separate b -jets.

To exploit this kinematic regime, two mutually exclusive and orthogonal reconstruction categories are defined: a resolved category conserving the sensitivity to SM Higgs boson pair production, and a boosted category—introduced here for the first time in the $b\bar{b}\gamma\gamma$ final state—targeting BSM-induced high-energy enhancements. The results demonstrate that the boosted category enhances the sensitivity of the golden di-Higgs channel to new-physics effects that

modify the high- m_{HH} tail of the spectrum. In the nonresonant case, the boosted selection exhibits a strong dependence on κ_{2V} away from the SM value, providing constraints that are not accessible with the resolved category alone. For heavy scalar resonances, the boosted reconstruction retains high acceptance across the mass range considered, while the resolved selection rapidly loses efficiency once the two b -quarks become collimated.

Consequently, it becomes clear that the resolved and boosted analysis combined greatly enhances the search region beyond what would have been achieved via a resolved-only analysis, establishing the $b\bar{b}\gamma\gamma$ channel as a competitive and complementary probe for BSM di-Higgs searches. This channel uniquely benefits from an efficient trigger strategy, well-understood backgrounds, and a clean experimental signature.

Overall, this study establishes the boosted $HH \rightarrow b\bar{b}\gamma\gamma$ topology as an essential tool for the BSM searches for the

future Run-3 and the High-Luminosity LHC physics program.

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DATA AVAILABILITY

The data that support the findings of this article are publicly available [74], and the code used in this analysis can be provided by the corresponding author upon reasonable request.

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