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Combination of searches for Higgs boson decays into a photon and a massless dark photon using pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector



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ABSTRACT: A combination of searches for Higgs boson decays into a visible photon and a massless dark photon ($H \rightarrow \gamma\gamma_d$) is presented using 139 fb^{-1} of proton-proton collision data at a centre-of-mass energy of $\sqrt{s} = 13 \text{ TeV}$ recorded by the ATLAS detector at the Large Hadron Collider. The observed (expected) 95% confidence level upper limit on the Standard Model Higgs boson decay branching ratio is determined to be $\mathcal{B}(H \rightarrow \gamma\gamma_d) < 1.3\% (1.5)\%$. The search is also sensitive to higher-mass Higgs bosons decaying into the same final state. The observed (expected) 95% confidence level limit on the cross-section times branching ratio ranges from $16 \text{ fb} (20 \text{ fb})$ for $m_H = 400 \text{ GeV}$ to $1.0 \text{ fb} (1.5 \text{ fb})$ for $m_H = 3 \text{ TeV}$. Results are also interpreted in the context of a minimal simplified model.

KEYWORDS: Hadron-Hadron Scattering , Higgs Physics

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1 Introduction

The existence of dark matter is supported by a series of astrophysical observations [1–8], but its unknown fundamental nature remains one of the central questions in particle physics. The discovery of a Higgs boson (H) [9, 10] with a mass of 125 GeV at the Large Hadron Collider (LHC) [11] has initiated an extensive effort aimed at investigating its possible connection with physics beyond the Standard Model (BSM). In particular, an upper limit of the order of 10% on the undetected Higgs boson decay branching ratio [12, 13] motivates searches for elusive BSM dark sector particles coupled to the Higgs boson. One example of such particles is an undetectable, massless dark photon (γ_d), which acts as the force carrier of an extra $U(1)_d$ gauge group of the dark sector. Dark photons may introduce dark matter self-interactions that can potentially solve the small-scale structure formation problem [14] and the PAMELA-Fermi-AMS2 anomaly [15]. They may also play a role in enhancing the light dark matter annihilation rate to reach the required phenomenological threshold, thereby making asymmetric dark matter scenarios phenomenologically viable [16]. A potential approach to search for this particle is through the Higgs boson decaying into a visible photon and a massless dark photon ($H \rightarrow \gamma\gamma_d$) [17–23]. This scenario can involve either the Standard Model (SM) Higgs boson (H_{125}) or additional high-mass Higgs bosons predicted in some BSM theories (H_{BSM}). As the produced γ_d is invisible to the detector, its signature is characterised by missing transverse momentum, whose magnitude is denoted E_T^{miss} . The same behaviour is also exhibited by ultra-light dark photons with masses below the threshold to decay into SM particles or by the lightest supersymmetry particles in a cascaded Higgs-boson decay [24, 25]. In this paper, the Higgs boson is assumed to be produced via three different processes, including gluon-gluon fusion (ggF), vector-boson fusion (VBF), and in association with a Z boson (ZH), with the SM-like production cross-sections [26]. Their leading-order Feynman diagrams, including the Higgs boson decay, are shown in figure 1.

The CMS experiment reported searches for such Higgs boson decays exploiting the ZH production mechanism, with an integrated luminosity of 137 fb^{-1} [27], or via VBF production

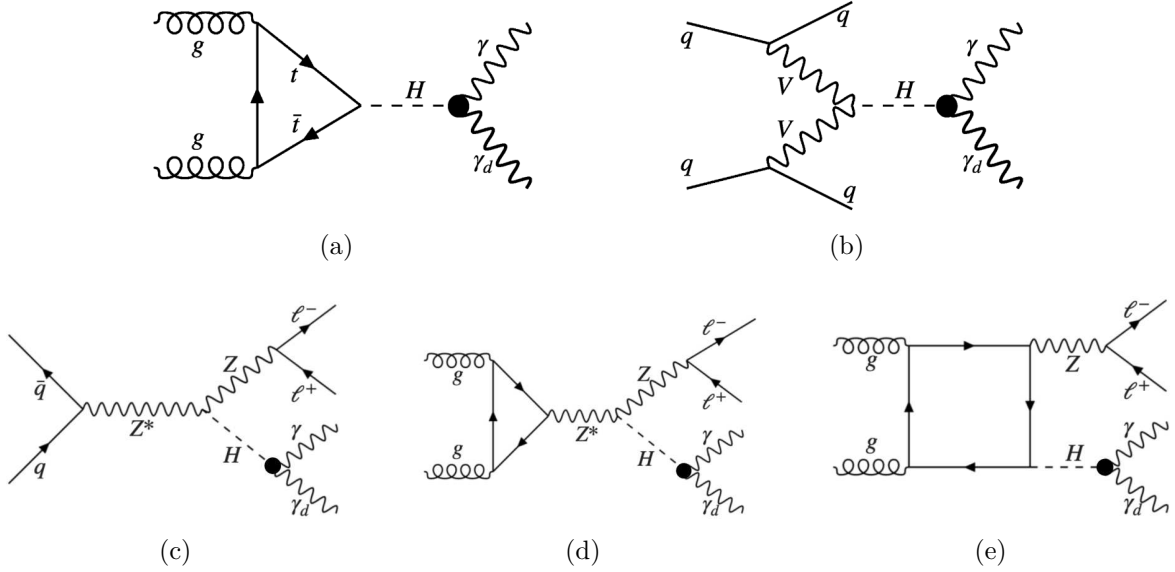


Figure 1. Leading-order Feynman diagrams for Higgs boson production decaying into a visible photon and a massless dark photon. The Higgs boson is produced via different processes: (a) ggF, (b) VBF, (c) $q\bar{q} \rightarrow ZH$ and (d) and (e) $gg \rightarrow ZH$.

with an integrated luminosity of 130 fb^{-1} [28], where a combination of the two searches is also performed. Using the 8 TeV collision data, the ATLAS and CMS collaborations also reported various searches targeting the same $\gamma + E_{\text{T}}^{\text{miss}}$ final states [29–31].

This paper presents a combined search for $H \rightarrow \gamma\gamma_d$ produced in three distinct final-state signatures: $\gamma + E_{\text{T}}^{\text{miss}}$ + VBF jets (VBF channel¹), $\gamma + E_{\text{T}}^{\text{miss}}$ + $Z(\rightarrow \ell\ell, \ell = e, \mu)$ (ZH channel) and $\gamma + E_{\text{T}}^{\text{miss}}$ (ggF channel). The searches under consideration use the full LHC Run 2 data sample corresponding to an integrated luminosity of 139 fb^{-1} [32, 33] of proton-proton (pp) collision data recorded with the ATLAS detector at a centre-of-mass energy of $\sqrt{s} = 13 \text{ TeV}$. The results from the VBF channel are derived based on the analysis described in ref. [34], with an extension to higher-mass Higgs bosons and the inclusion of the ggF process contributions. The results for the ZH channel are taken from ref. [35]. The results for the ggF channel are based on the reinterpretation of the mono- γ results in ref. [36] using the RECAST technique [37]. Using the available results in the individual publications, the VBF and ZH channels are combined under the SM Higgs boson assumption, and the VBF and ggF channels are combined under the additional high-mass Higgs boson hypothesis in the narrow width approximation. The range of the H_{BSM} masses probed starts at 400 GeV, as the sensitivity of the ggF channel decreases for lower masses, and goes up to 3 TeV.

The ATLAS detector [38] is a multipurpose particle detector with cylindrical geometry. It consists of an inner tracking detector surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, electromagnetic and hadronic sampling calorimeters, and a muon spectrometer with three toroidal superconducting magnets, providing a near

¹In this paper, the term ‘channel’ is used to refer to the final-state signature that defines the event selections. The term ‘process’ refers to the production mode of the Higgs boson. Events from multiple processes can contribute to a given channel and they are all treated as signal events.

4π coverage in solid angle.² An extensive software suite [39] is used in data simulation, in the reconstruction and analysis of real and simulated data, in detector operations, and in the trigger [40] and data acquisition systems of the experiment.

Monte Carlo (MC) samples of simulated signal events for the ggF, VBF, and ZH via both the $q\bar{q} \rightarrow ZH$ and $gg \rightarrow ZH$ processes were generated at next-to-next-to-leading order (NNLO) for ggF, next-to-leading order (NLO) for VBF and $q\bar{q} \rightarrow ZH$ or leading order (LO) for $gg \rightarrow ZH$ in quantum chromodynamics (QCD) using POWHEG v2 [41–44], interfaced to PYTHIA 8 [45] for parton showering, hadronisation, and underlying event modelling, with the AZNLO set of tuned parameters [46]. The signal predictions from these MC samples were normalised to the NNLO (VBF and ZH) or next-to-NNLO (ggF) cross-section in QCD plus electroweak corrections at NLO [26, 47–56]. The Higgs boson mass was set to 125 GeV for the SM scenario. For the additional higher-mass Higgs boson scenarios, the mass takes values in the 400 GeV–1000 GeV range, in steps of 200 GeV, and in the 1000 GeV–3000 GeV range, in steps of 500 GeV. For the BSM Higgs boson samples, the detector response was simulated using a fast parameterised simulation of the ATLAS calorimeters and the full GEANT4 [57, 58] simulation was used for the SM Higgs boson samples. Additional pp collisions simulated using PYTHIA 8 [59] with the A3 set of tuned parameters [60] were overlaid to simulate the effect of multiple interactions in the same and neighbouring bunch crossings (pile-up). The simulated events are weighted to reproduce the distribution of the pile-up observed in the data. These samples are used to check the orthogonality of the channels and produce the final results. Descriptions of the data and simulation samples used to model backgrounds from SM processes can be found in refs. [34–36].

2 Description of the input analyses

The detailed information about the reconstruction, identification and calibration of physics objects used for analysis selections described below is given in refs. [34–36, 61–69]. A brief overview of the already published Run 2 searches relevant to the combination performed here is given below. The $H_{125} \rightarrow \gamma\gamma_d$ search is performed in the VBF and ZH channels while $H_{\text{BSM}} \rightarrow \gamma\gamma_d$ is probed in the VBF and ggF channels. No significant deviation from the SM prediction is observed in any of these studies. All searches utilise the signature of an isolated photon and $E_{\text{T}}^{\text{miss}}$, with variations on the number of selected leptons and jets.

Events in the VBF channel were selected with the $E_{\text{T}}^{\text{miss}}$ trigger algorithm [70]. They are further required to have $E_{\text{T}}^{\text{miss}} > 150$ GeV and two VBF jets. The VBF jets are the leading and subleading transverse momentum (p_{T}) jets, denoted j_1 and j_2 , satisfying $p_{\text{T}}^{j_1} > 60$ GeV and $p_{\text{T}}^{j_2} > 50$ GeV, respectively. In addition, they are required to have a large pseudorapidity separation ($|\Delta\eta_{j_1 j_2}| > 3$, $\eta_{j_1} \cdot \eta_{j_2} < 0$), a large invariant mass ($m_{j_1 j_2} > 250$ GeV) and not be back-to-back in azimuthal angle ($\Delta\phi_{j_1 j_2} < 2$). An additional jet is allowed with $p_{\text{T}}^{j_3} > 25$ GeV

²ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z -axis along the beam pipe. The x -axis points from the IP to the centre of the LHC ring, and the y -axis points upwards. Polar coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the z -axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln \tan(\theta/2)$ and is equal to the rapidity $y = \frac{1}{2} \ln \left(\frac{E+p_z c}{E-p_z c} \right)$ in the relativistic limit. Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta y)^2 + (\Delta\phi)^2}$.

and a centrality³ of $C_{j_3} < 0.7$. Events with a reconstructed lepton ($\ell = e, \mu$) are rejected. The photon must be isolated and lie in the electromagnetic calorimeter acceptance $|\eta^\gamma| < 2.37$ but not in the transition region ($1.37 < |\eta^\gamma| < 1.52$) between the barrel and endcap. These isolation and η requirements on the photon are used in all three analyses in addition to energy-related criteria specific to the different analyses. In the VBF analysis discussed here, the photon is required to have $15 \text{ GeV} < E_T^\gamma < \max(110 \text{ GeV}, 0.733 \times m_T)$, where the transverse mass m_T is defined as $m_T(\gamma, E_T^{\text{miss}}) = \sqrt{2E_T^\gamma E_T^{\text{miss}} [1 - \cos(\phi_\gamma - \phi_{E_T^{\text{miss}}})]}$, bounded above by the Higgs boson mass. The centrality of the photon is required to be $C_\gamma > 0.4$. To increase the sensitivity of the search, events are categorised in ten signal regions (SRs) based on m_{jj} and m_T . The dominant backgrounds are $W(\rightarrow \ell\nu)\gamma + \text{jets}$ events, in which the lepton from the W boson decay is lost if it falls outside of the acceptance, and $Z(\rightarrow \nu\nu)\gamma + \text{jets}$ events. Four dedicated control regions (CRs) are designed to capture the background contributions from $W(\rightarrow e\nu)\gamma + \text{jets}$, $W(\rightarrow \mu\nu)\gamma + \text{jets}$, $Z(\rightarrow \nu\nu)\gamma + \text{jets}$ and processes where electrons are misidentified as fake photons. Backgrounds due to jets misidentified as fake photons are estimated by using a data-driven method. Contribution from the ggF process was not considered in the original analysis [34] but is included for this combination. All SRs and CRs are simultaneously fitted using the profile likelihood fit method to constrain the background contributions and to extract the signal contribution.

In the ZH channel, $Z \rightarrow \ell^+ \ell^-$ events were selected with single-lepton and dilepton triggers [71, 72]. Events are required to contain two same-flavour, oppositely charged (SFOC) leptons with invariant mass $76 \text{ GeV} < m_{\ell\ell} < 116 \text{ GeV}$. Furthermore, they are required to have $E_T^{\text{miss}} > 60 \text{ GeV}$ and a photon with $E_T^\gamma > 25 \text{ GeV}$ satisfying the isolation and η selections. The selected objects are required to satisfy $\Delta\phi(E_T^{\text{miss}}, p_T^{\ell\ell\gamma}) > 2.4$ and $m_{\ell\ell\gamma} > 100 \text{ GeV}$. Events with a third lepton with $p_T > 10 \text{ GeV}$ or any b -tagged jet (77% working point [73]) are rejected. To enhance the sensitivity of the search, a boosted decision tree (BDT) algorithm is applied to separate the signal from the backgrounds. The dominant background contribution comes from E_T^{miss} mismeasurement in mainly $Z\gamma + \text{jets}$ and $Z + \text{jets}$ processes due to undetected particles or hadronic jets not fully contained in the detector acceptance. Another major background is from electrons misidentified as photons in the SM diboson processes. Both of these backgrounds are estimated with data-driven techniques. The irreducible $VV\gamma$ ($V = W, Z$) background with both V decaying leptonically is constrained in the fit by a dedicated CR. Backgrounds from top quark and Higgs boson production are found to be minor and estimated from MC simulations. Contributions from ggF and VBF produced Higgs boson processes to the ZH channel are assumed to be negligible and therefore not considered. A simultaneous fit exploiting the distribution of the BDT discriminant and the single bin $VV\gamma$ CR is performed.

Events in the ggF channel were selected with a single photon trigger with a threshold of $E_T^\gamma > 140 \text{ GeV}$ [71]. Events are required to have $E_T^{\text{miss}} > 200 \text{ GeV}$ and at least one photon satisfying the isolation and η selections. The leading photon in the events is required to fulfil the following criteria: the transverse energy $E_T^\gamma > 150 \text{ GeV}$, the separation between its

³The centrality of an object i in this channel is defined as $C_i = \exp \left[-\frac{4}{(\eta_{j_1} - \eta_{j_2})^2} \left(\eta_i - \frac{\eta_{j_1} + \eta_{j_2}}{2} \right)^2 \right]$. When the object i is centred between the two jets, C_i reaches the maximum value of 1. When the object i is aligned with one of the two jets, C_i decreases to $1/e$.

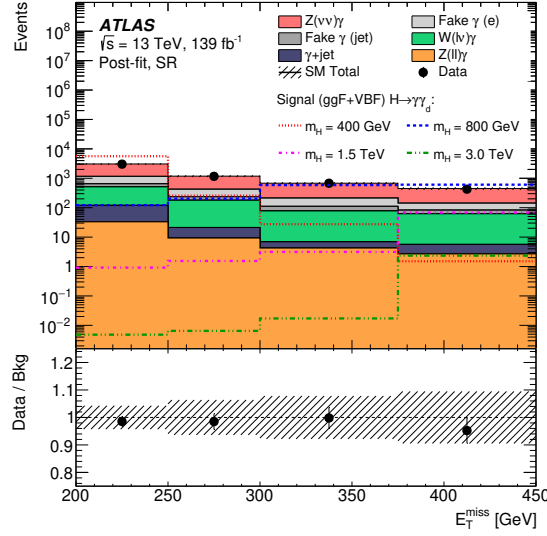


Figure 2. Number of events in each E_T^{miss} bin in the SR of the ggF channel after a background-only fit. The signals $H_{\text{BSM}} \rightarrow \gamma\gamma_d$ are superimposed onto the observed data and the expected SM background. The ggF and VBF processes are considered, assuming $\mathcal{B}(H_{\text{BSM}} \rightarrow \gamma\gamma_d) = 5\%$ and the production cross-sections from ref. [26]. The error bars on data represent the statistical uncertainty, and the shaded band includes statistical and systematic uncertainties determined from the fit. The lower panel shows the ratio of observed data to expected SM background yields. The last bin includes the overflow. This analysis is reinterpreted from the mono- γ results in ref. [36].

extrapolated origin and primary vertex of the event along the beam axis $|\Delta z_\gamma| < 250$ mm and $\Delta\phi(\gamma, E_T^{\text{miss}}) > 0.4$. At most one jet is allowed in the selection if $p_T^j > 30$ GeV, $|\eta_j| < 4.5$ and $\Delta\phi(j, E_T^{\text{miss}}) > 0.4$. Events that contain leptons ($\ell = e, \mu$, hadronically decaying τ) are rejected. To improve the sensitivity, four SRs are defined corresponding to different E_T^{miss} ranges. The SM background arises from several processes with either true photons or fake photons from misidentified electrons or jets. The background with true photons is dominated by the SM $Z(\rightarrow \nu\nu)\gamma$ process. Secondary contributions come from $\gamma + \text{jets}$ events and from $W(\rightarrow \ell\nu)\gamma$ and $Z(\rightarrow \ell\ell)\gamma$ production with unidentified electrons, muons or with hadronically decaying τ -leptons. Four CRs are defined to estimate the contributions of these true-photon processes in the SRs through the profile likelihood fit. The fake photon backgrounds are estimated with control samples that contain electrons or jets, scaled by misidentification rates determined from data. Signal contributions from both the ggF and VBF Higgs boson processes are considered. Figure 2 shows the E_T^{miss} distribution in the SR after a background-only fit to data. Signals with higher mass tend to have larger E_T^{miss} . The highest E_T^{miss} SR captures about 30% of the events for signal benchmarks with $m_H \geq 1.0$ TeV.

Theoretical uncertainties due to the QCD factorisation and renormalisation scales, and the choice of parton distribution functions are included. Uncertainties in initial- and final-state radiation due to the choice of parton shower parameters are estimated through simulations with alternative sets of tuned parameters.

The event selections for the input channels are summarised in table 1. To perform the combination, a few adjustments are made. In the VBF channel, the contribution of the ggF

Channels	VBF	ZH	ggF
Trigger	E_T^{miss}	Lepton(s)	Photon
Photons	$= 1, C_\gamma > 0.4$	$= 1$	≥ 1
E_T^γ [GeV]	$\in (15, \max(110, 0.733 \times m_T))$	> 25	> 150
E_T^{miss} [GeV]	> 150	> 60	> 200
Jets	$2 \text{ or } 3, m_{j_1 j_2} > 250 \text{ GeV}, \Delta\eta_{j_1 j_2} > 3$ $\eta_{j_1} \cdot \eta_{j_2} < 0, \Delta\phi_{j_1 j_2} < 2, C_{j_3} < 0.7$	≤ 2	≤ 1
Leptons	$= 0 \text{ (} e, \mu \text{)}$	$= 2, \text{SFOC}$ $m_{\ell\ell} \in (76, 116) \text{ GeV}$	$= 0 \text{ (} e, \mu, \tau \text{)}$
Disc. variables	m_{jj} and m_T in SR and 4 CRs	BDT score and 1 CR	E_T^{miss}
Reference	[34]	[35]	[36]
Processes considered in the combination	VBF, ggF	ZH	ggF, VBF
Combination scenario	SM, BSM	SM	BSM

Table 1. Summary of the main event selections, discriminating variables and processes considered in the input channels. The definition of the variables is provided in the text.

process to the BSM Higgs boson decay search is included using the RECAST technique. The contribution to the signal yields is up to 30% for the low masses and decreases to 1% for the high masses. Additional BSM Higgs boson signal samples are generated to align with the masses probed in the ggF analysis. The fit regions used in the three analyses are either orthogonal due to variations in the number and type of physics objects required in their final states or have a negligible number of overlapping events due to different jet algorithms being used. They are therefore treated as statistically independent.

3 Statistical combination

The results of the combination presented in this paper are obtained from a likelihood function $L(\mu, \vec{\theta})$, where μ denotes the parameter of interest (POI) of the model, and $\vec{\theta}$ constitutes a set of nuisance parameters, encoding the systematic uncertainty contributions and background normalisation factors that are constrained by CRs in data. The final likelihood function $L(\mu, \vec{\theta})$ is the product of the likelihoods from individual channels within the combination, which are themselves products of likelihoods computed from the final observables in various categories in a single analysis. To derive upper limits on the POI, the profile-likelihood-ratio test statistic is used with the CL_s method [74] following the asymptotic formulae [75].

All systematic uncertainties that are considered in the individual analyses are included in the combination and those that stem from common sources are treated as correlated among the input searches. A complete discussion of their sources can be found in the individual channel

publications [34–36]. Systematic uncertainties related to the data-taking conditions, such as those associated with the integrated luminosity and the modelling of pile-up, are treated as correlated. Experimental uncertainties related to physics objects used by multiple searches are treated as correlated where appropriate, with the following exceptions. Uncertainties related to the same object but implemented with different reduced uncertainty schemes are treated as uncorrelated. In addition, uncertainties that were heavily constrained or pulled in the original input channel are treated as uncorrelated, and the impact on the final upper limits would be $\leq 3\%$ if they were correlated. These constraining powers come from the special phase space probed in certain channels and therefore passing these constraints to the other channels should be avoided. Uncertainties related to background modelling are considered as uncorrelated since the composition and phase space of the backgrounds are different. Uncertainties related to signal modelling, stemming from the choice of parton distribution functions and QCD calculations, have minor impact on the final results and are treated as uncorrelated. Ignoring correlations of the systematic uncertainties between the input channels is found to impact the upper limits by $\leq 2\%$. The $H_{125} \rightarrow \gamma\gamma_d$ search has similar impacts from the data statistical (66%) and systematic (75%) uncertainties, where the values are relative to the total uncertainty. The dominant contributions to the systematic uncertainties stem from the background modelling (47%), jet and E_T^{miss} calibration (40%), followed by the MC statistical uncertainty (36%) and fake-background estimate (35%). All of these impacts are evaluated from the quadratic differences of the fitted errors in the POI before and after fixing the considered nuisance parameters to their best-fit values. In the $H_{\text{BSM}} \rightarrow \gamma\gamma_d$ search, the statistical uncertainty increases from 75% to 86% for the higher Higgs boson mass assumptions. The dominant contributions come from the fake-background estimate, which decreases from 52% to 29% depending on the mass, and background modelling uncertainty, ranging from 27%–38%. The uncertainties related to jet and E_T^{miss} , leptons, and MC sample size share a similar $\sim 20\%$ impact each.

4 Results and interpretation

This combination yields an observed (expected) 95% confidence level (CL) upper limit on the branching ratio $\mathcal{B}(H_{125} \rightarrow \gamma\gamma_d)$ is 1.3% (1.5%). Relative to the most stringent result from the VBF analysis, this combination brings an improvement of 29% (14%) in the sensitivity. The limits are displayed in figure 3(a). The observed (expected) 95% CL upper limits on the BSM Higgs boson production cross-section times $\mathcal{B}(H_{\text{BSM}} \rightarrow \gamma\gamma_d)$ as a function of the BSM Higgs boson mass m_H , obtained from this combination, are shown in figure 3(b). The observed (expected) limit ranges from 16 fb (26 fb) for $m_H = 400$ GeV to 1.0 fb (1.5 fb) for $m_H = 3000$ GeV. Assuming a branching ratio $\mathcal{B}(H_{\text{BSM}} \rightarrow \gamma\gamma_d)$ of 5% and theoretically predicted cross-sections for H_{BSM} production from ref. [26], masses of H_{BSM} below around 1600 GeV (1500 GeV) are excluded. Relative to the leading ggF channel, the combination with the VBF channel yields an improvement of 33% (14%) on the cross-section times $\mathcal{B}(H_{\text{BSM}} \rightarrow \gamma\gamma_d)$ at $m_H = 1500$ GeV.

Additionally, the results on $\mathcal{B}(H_{125} \rightarrow \gamma\gamma_d)$ are interpreted under a minimal simplified model described in refs. [17, 76]. The model assumes the SM prediction for the cross-section and its systematic uncertainties for all Higgs boson production modes. It introduces a generic

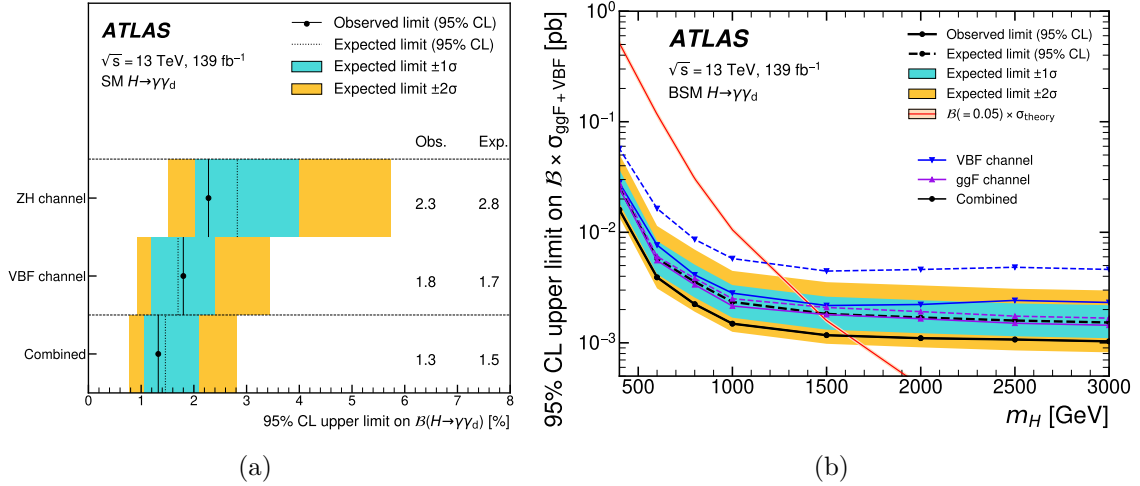


Figure 3. Observed and expected 95% CL upper limits on (a) the branching ratio $\mathcal{B}(H_{125} \rightarrow \gamma\gamma_d)$ and (b) $\mathcal{B}(H_{\text{BSM}} \rightarrow \gamma\gamma_d)$ times the BSM Higgs boson ggF + VBF production cross-section $\sigma_{\text{ggF} + \text{VBF}}$ as a function of the Higgs boson mass m_H . Results obtained from the input channels are overlaid. The expected limit and the corresponding error bands are derived assuming the absence of the $H \rightarrow \gamma\gamma_d$ process and with all nuisance parameters profiled to the observed data. The theory predictions and their error band are taken from ref. [26] assuming a branching ratio $\mathcal{B}(H_{\text{BSM}} \rightarrow \gamma\gamma_d) = 5\%$.

messenger sector consisting of one left-doublet and one right-singlet of the $\text{SU}(2)_L$ gauge group connecting the dark and the observable sectors. A minimal scenario can be realised under mass universality in the left and right messenger sector with a mixing parameter ξ . Under this scenario, the messenger sector couples to both $\text{U}(1)$ and $\text{U}(1)_d$ gauge fields, allowing three Higgs boson decay modes: $\gamma\gamma_d$, $\gamma_d\gamma_d$ and $\gamma\gamma$. Their branching ratios are all interconnected and can be expressed using two free, dimensionless parameters: ξ and the fine structure constant α_d associated with the $\text{U}(1)_d$ gauge group [76], whose values are zero in the SM. Hence, setting upper limits on, or measuring the value of the branching ratio of the Higgs boson decaying into $\gamma\gamma$, $\gamma\gamma_d$, and $\gamma_d\gamma_d$ can be translated into restrictions on the allowed parameter space in the (α_d, ξ) plane. The range $0 < \alpha_d < 1$ and $0 \leq \xi < 1$ is explored in this study. An extra parameter $\chi = \pm 1$ accounts for the relative sign of the new physics and SM contributions in the amplitudes of the $H_{125} \rightarrow \gamma\gamma$ and $H_{125} \rightarrow gg$ decays. It provides two scenarios with either constructive ($\chi = +1$) or destructive ($\chi = -1$) interference between the messenger sector and the SM particles affecting the $\mathcal{B}(H_{125} \rightarrow \gamma\gamma)$.

Figure 4 shows the observed exclusion limits derived from the combination of the VBF and ZH channels for $H_{125} \rightarrow \gamma\gamma_d$ and from the reinterpretation of the ATLAS search for $H_{125} \rightarrow$ invisible [77]. In addition, the ATLAS measurement of $\mathcal{B}(H_{125} \rightarrow \gamma\gamma) = 0.247^{+0.022}_{-0.020}\%$ [12] provides a one standard deviation (σ) upper bound. The SM predicted $\mathcal{B}(H_{125} \rightarrow \gamma\gamma)$ defines a region in the (α_d, ξ) parameter space of the minimal model that is not allowed when assuming a positive interference from the messenger sector in the $\gamma\gamma$ final state ($\chi = +1$).

From the reinterpretation of the $\mathcal{B}(H_{125} \rightarrow \text{invisible})$ result in terms of a $H_{125} \rightarrow \gamma_d\gamma_d$ signal, values down to about $\xi \simeq 0.7$ at $\alpha_d = 1$ are excluded for $\chi = +1$. The $H_{125} \rightarrow \gamma\gamma_d$ combination presented here provides additional sensitivity in the low α_d region, which is also disfavoured by the $\mathcal{B}(H_{125} \rightarrow \gamma\gamma)$ measurement. The $\chi = -1$ scenario has also been investigated but no constraints can be placed in this case.

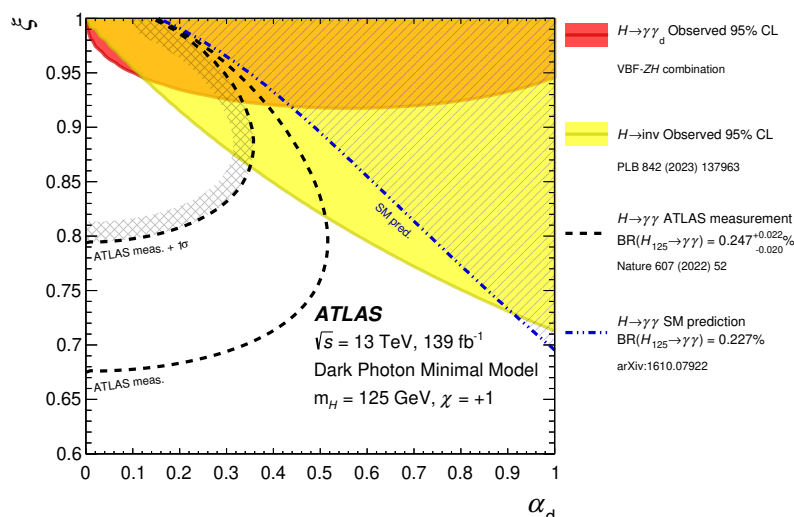


Figure 4. Observed 95% CL exclusion regions in the (α_d, ξ) parameter space from the VBF- ZH combination of $H_{125} \rightarrow \gamma\gamma_d$ searches (dark coloured area) and the reinterpretation of the ATLAS measured limit of $\mathcal{B}(H_{125} \rightarrow \text{invisible})$ as $H_{125} \rightarrow \gamma_d\gamma_d$ (light coloured area). Both the central value (dashed line) and the $+1\sigma$ upper bound (dashed-hashed line) show the less favoured (α_d, ξ) plane obtained from the current ATLAS measurement of $\mathcal{B}(H_{125} \rightarrow \gamma\gamma)$. The dash-dotted line and the associated dashed area show the parameter space that is not allowed by the SM $\mathcal{B}(H_{125} \rightarrow \gamma\gamma)$ predictions assuming positive interference with the minimal messenger sector. The parameter $\chi = +1$ parameterises the relative sign of the new physics and SM contributions in the amplitudes of the $H_{125} \rightarrow \gamma\gamma$ and $H_{125} \rightarrow gg$ decays.

5 Conclusion

In conclusion, this paper reports a combined search for $H \rightarrow \gamma\gamma_d$ produced in ggF, VBF, and ZH processes using 139 fb^{-1} of pp collision data at $\sqrt{s} = 13 \text{ TeV}$ collected by the ATLAS detector at the LHC. Various Higgs boson mass assumptions are probed including the SM value of 125 GeV and higher values ranging from 400 GeV to 3 TeV. The combined analysis sets an observed (expected) 95% CL upper limit on $\mathcal{B}(H_{125} \rightarrow \gamma\gamma_d)$ at 1.3 (1.5)%. The observed (expected) 95% confidence level limit on the cross-section times branching ratio ranges from 16 fb (26 fb) for $m_H = 400 \text{ GeV}$ to 1.0 fb (1.5 fb) for $m_H = 3 \text{ TeV}$. This study provides the most stringent constraints on Higgs bosons decaying into a photon and a massless dark photon to date. The results are also interpreted in the context of a minimal simplified model, providing complementary exclusion in the parameter space obtained from other searches for this model.

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B.T. Carlson ^{132,p}, E.M. Carlson ^{168,159a}, J. Carmignani ⁹⁴, L. Carminati ^{72a,72b},
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B. Chen ¹⁵⁴, B. Chen ¹⁶⁸, H. Chen ^{114a}, H. Chen ³⁰, J. Chen ^{63c}, J. Chen ¹⁴⁵, M. Chen ¹²⁹,
S. Chen ⁸⁹, S.J. Chen ^{114a}, X. Chen ^{63c}, X. Chen ^{15,ab}, Y. Chen ^{63a}, C.L. Cheng ¹⁷³,
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