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Letter

Search for exclusive Higgs and Z boson decays to $\omega\gamma$ and Higgs boson decays to $K^*\gamma$ with the ATLAS detector

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ABSTRACT

Searches for the exclusive decays of the Higgs boson to an ω meson and a photon or a K^* meson and a photon can probe flavour-conserving and flavour-violating Higgs boson couplings to light quarks, respectively. Searches for these decays, along with the analogous Z boson decay to an ω meson and a photon, are performed with a pp collision data sample corresponding to integrated luminosities of up to 134 fb^{-1} collected at $\sqrt{s} = 13$ TeV with the ATLAS detector at the CERN Large Hadron Collider. The obtained 95% confidence-level upper limits on the respective branching fractions are $\mathcal{B}(H \to \omega\gamma) < 5.5 \times 10^{-4}$, $\mathcal{B}(H \to K^*\gamma) < 2.2 \times 10^{-4}$ and $\mathcal{B}(Z \to \omega\gamma) < 3.9 \times 10^{-6}$. The limits for $H \to \omega\gamma$ and $Z \to \omega\gamma$ are 370 times and 140 times the Standard Model expected values, respectively. The result for $Z \to \omega\gamma$ corresponds to a two-orders-of-magnitude improvement over the limit obtained by the DELPHI experiment at LEP.

1. Introduction

The discovery of a Higgs boson H with a mass of approximately $m_H = 125$ GeV [1,2] by the ATLAS and CMS collaborations at the Large Hadron Collider (LHC) has led to a variety of measurements to determine its properties, which so far have found no deviations from the Standard Model (SM) [3,4]. In the SM, fermion masses are generated via Yukawa interactions between the Higgs and fermion fields. The Higgs boson couplings to the fermions are subject to substantial modifications in various theories beyond the SM [5]. Theories that modify the couplings of the Higgs boson to quarks include the Minimal Flavour Violation framework [6], the Froggatt–Nielsen mechanism [7], the Higgs-dependent Yukawa couplings model [8], the Randall–Sundrum family of models [9], and the possibility of the Higgs boson being a composite pseudo-Goldstone boson [10]. Measurements of Higgs boson production in association with top-quark pairs [11] and decays of Higgs bosons into pairs of τ-leptons [11–13] or bottom-quarks [14,15] have been performed and were found to be consistent with the SM expectations, providing clarity on third-generation fermion interactions with the Higgs boson. Evidence has been reported for the Higgs boson coupling to the second generation through the $H \to \mu^+\mu^-$ decay [16,17], but there is no further experimental evidence of interactions with fermions of the first and second generations. Searches have also been performed for the decay $H \to c\bar{c}$ by the ATLAS and CMS collaborations [18–21].

Currently, the light (u, d, s) quark couplings to the Higgs boson are loosely constrained by existing data on the total Higgs boson width and combined measurements of Higgs boson production and decays [3,4], while the large multi-jet background at the LHC inhibits the study of such couplings with inclusive $H \to q\bar{q}$ decays. Rare decays of the Higgs boson into a meson and a photon have been suggested as a probe of the couplings of the Higgs boson to light quarks. Higgs boson decays into a heavy quarkonium state, J/ψ, $\psi(2S)$ and $\Upsilon(nS)$ with $n = 1, 2, 3$, and a photon have been suggested for probing the charm- and bottom-quark couplings to the Higgs boson [22–25]. These have already been searched for by the ATLAS and CMS collaborations [26–30]. Higgs boson decays into a ϕ or ρ meson and a photon are potential probes for the u, d and s quark couplings to the Higgs boson [31–33]. Searches have already been performed for these decays by the ATLAS Collaboration [34,35] and the CMS Collaboration [36]. The current constraints with the corresponding predictions are given in Ref. [37]. The partial widths for these decays are driven by two (interfering) contributions: one known as "direct", which scales with the Yukawa couplings, and the other known as "indirect", which mimics $H \to \gamma\gamma$ but with one photon fragmenting into a quark–antiquark pair, forming the meson. These contributions are shown in Fig. 1. The interference between these two amplitudes is rather strong and typically destructive. In the case of the Υ channel, almost complete destructive interference occurs, reversing the expected scaling with quark mass.

This paper describes a search for Higgs boson decays into the exclusive final states $\omega\gamma$ and $K^*\gamma$. These decays can probe the flavour-conserving coupling of the Higgs boson to up and down quarks, and the flavour-violating coupling of the Higgs boson to down and strange quarks, respectively. Two calculations of the expected SM branching fractions for the ω channel are available: $\mathcal{B}(H \to \omega\gamma) = (1.48 \pm 0.08) \times$

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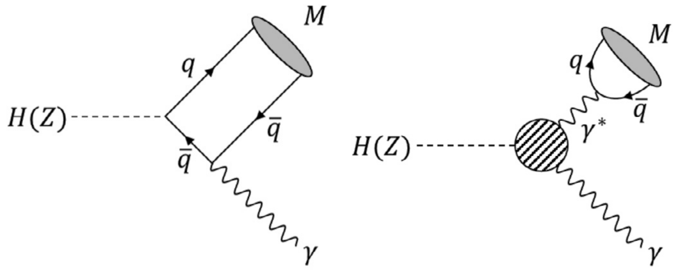


(a) (b)

Fig. 1. Feynman diagrams for the (a) direct and (b) indirect contributions to the $H/Z \to \mathcal{M}\gamma$ decays.

10^{-6} [31] and $\mathcal{B}(H \to \omega\gamma) = (1.6 \pm 0.2) \times 10^{-6}$ [32]. For the $K^*\gamma$ decay, which arises from loop contributions, only the expected branching fraction of $H \to d\bar{s} + \bar{d}s$ is available, with a value of $\mathcal{B}(H \to d\bar{s} + \bar{d}s) = 1.19 \times 10^{-11}$ [38]. The branching fraction for $H \to K^*\gamma$ is expected to be much smaller. This is the first exclusive decay analysis to target flavour-changing interactions of the Higgs boson. Earlier searches for flavour-changing neutral currents via the top-quark decays $t \to uH$ and $t \to cH$ were performed by the ATLAS and CMS collaborations [39–42], with no evidence found for these decays.

The decay $\omega \to \pi^+\pi^-\pi^0$ is used to reconstruct the ω meson, and the decay $K^* \to K^+\pi^-$ is used to reconstruct the K^* meson. The branching fractions of the respective meson decays are accounted for when calculating the expected signal yields. A search for the analogous decay of the Z boson into a ω meson and a photon is also presented. The channel has been studied theoretically [25,43] as a unique precision test of the SM and the factorisation approach in quantum chromodynamics (QCD), in an environment where the power corrections in terms of the QCD energy scale divided by the mass of the vector boson are small [25]. The large Z boson production cross section at the LHC means that rare Z boson decays can be probed at branching fractions much smaller than for Higgs boson decays into the same final states. The SM branching fraction prediction for the decay considered in this paper is $\mathcal{B}(Z \to \omega\gamma) = (2.82 \pm 0.40) \times 10^{-8}$ [25]. A previous search was performed at the DELPHI experiment, yielding an upper limit on the branching fraction of $\mathcal{B}(Z \to \omega\gamma) < 6.5 \times 10^{-4}$ [44].

2. ATLAS detector

The ATLAS detector [45] is a multi-purpose particle physics detector with an approximately forward-backward symmetric cylindrical geometry and near 4π coverage in solid angle.[1] It consists of an inner tracking detector surrounded by a thin superconducting solenoid, electromagnetic and hadronic calorimeters, and a muon spectrometer. The inner tracking detector (ID) covers the pseudorapidity range $|\eta| < 2.5$, and is surrounded by a thin superconducting solenoid providing a 2 T magnetic field. At small radii, a high-granularity silicon pixel detector covers the vertex region and typically provides three measurements per track. A new innermost pixel-detector layer, the insertable B-layer, was added before 13 TeV data-taking began in 2015 and provides an additional measurement at a radius of about 33 mm around a new and thinner beam pipe [46,47]. The pixel detectors are followed by a silicon microstrip tracker, which typically provides four space-point measurements per track. The silicon detectors are complemented by a gas-filled straw-tube transition radiation tracker, which enables radially extended track reconstruction up to $|\eta| = 2.0$, with typically 35 measurements per track. The calorimeter system covers the pseudorapidity range $|\eta| < 4.9$. A high-granularity lead/liquid-argon (LAr) sampling electromagnetic calorimeter covers the region $|\eta| < 3.2$, with an additional thin LAr presampler covering $|\eta| < 1.8$ to correct for energy losses upstream. The electromagnetic calorimeter is divided into a barrel section covering $|\eta| < 1.475$ and two endcap sections covering $1.375 < |\eta| < 3.2$. For $|\eta| < 2.5$ it is divided into three layers in depth, which are finely segmented in η and ϕ. A steel/scintillator-tile calorimeter provides hadronic calorimetry in the range $|\eta| < 1.7$, while in the endcap region, $1.5 < |\eta| < 3.2$, a copper/LAr calorimeter is used. The solid-angle coverage is completed with forward copper/LAr and tungsten/LAr calorimeter modules in $3.1 < |\eta| < 4.9$, optimised for electromagnetic and hadronic measurements, respectively. The muon spectrometer surrounds the calorimeters and comprises separate trigger and high-precision tracking chambers measuring the deflection of muons in a magnetic field provided by three air-core superconducting toroids.

A two-level trigger and data acquisition system is used to provide an online selection and record events for offline analysis [48]. The level-1 trigger is implemented in hardware and uses a subset of detector information to reduce the event rate to 100 kHz or less from the maximum LHC collision rate of 40 MHz. It is followed by a software-based high-level trigger which filters events using the full detector information and records events for detailed offline analysis at an average rate of 1 kHz. An extensive software suite [49] 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.

3. Data and Monte Carlo simulation

The searches are performed in two distinct decay modes, $\omega\gamma$ and $K^*\gamma$, using a pp collision data sample collected at a centre-of-mass energy $\sqrt{s} = 13$ TeV. Following the requirement that events must be collected under stable LHC beam conditions and that all relevant detector components are in good operating condition, the total integrated luminosity available is 89.5 and 134 fb^{-1} for the $\omega\gamma$ and $K^*\gamma$ final states, respectively, with an uncertainty of 1.7% [50,51]. The data samples were recorded by a combination of dedicated triggers, which were integrated into the trigger menu at different times. This is reflected in the different integrated luminosities. Namely, the trigger for the $\omega\gamma$ final state recorded data from July 2017 to the end of data taking in 2018, whilst the triggers for the $K^*\gamma$ final state recorded data from May 2016 to the end of data taking in 2018. These require a photon at the level-1 trigger, and a photon and an isolated pair of ID tracks at the high-level trigger. At the high-level trigger, an isolated photon with a transverse momentum $p_{\mathrm{T}}^{\gamma} > 35$ GeV [48] is required in general, with the exception of data recorded for the $K^*\gamma$ final state in 2017–2018, where the threshold was reduced to $p_{\mathrm{T}}^{\gamma} > 25$ GeV. For the ID tracks a modified version of the τ-lepton trigger algorithms [52] is used. The triggers for the $K^*\gamma$ final state require at least one track to have a p_{T} greater than 15 GeV, whilst the triggers for the $\omega\gamma$ final state require at least one track to have a p_{T} greater than 25 GeV. In each case, the track is required to be associated with a topological cluster of calorimeter cells [53] with a transverse energy greater than 25 GeV. Different requirements on the invariant mass of the pair of tracks are applied, depending on the mass of each targeted meson. For $\omega \to \pi^+\pi^-\pi^0$ an invariant mass of the pair of tracks in the range 279 to 648 MeV is required, under the charged-pion hypothesis. For $K^* \to K^+\pi^-$ an invariant mass of 790 to 990 MeV, under the $K^{\pm}\pi^{\mp}$ hypothesis, is required. The trigger efficiency with respect to the offline selection, as described in Section 4, is approximately 78% for the $K^*\gamma$ final state and 52% for the $\omega\gamma$ final state.

Higgs boson production through the gluon–gluon fusion (ggH) and vector-boson fusion (VBF) processes was modelled up to next-to-leading order (NLO) in α_{s} using the Powheg Box v4 Monte Carlo (MC) event generator [54–58]. Powheg Box v4 was interfaced with the Pythia

[1] ATLAS 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 upward. Cylindrical 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 $\eta = -\ln\tan(\theta/2)$.

8.244 MC event generator [59,60] to model the parton shower, hadronisation and underlying event, with parameter values set according to the AZNLO tune [61] and using CTEQ6L1 parton distribution functions (PDFs) [62]. Additional contributions from the associated production of a Higgs boson and a $W^{\pm}$ or Z boson (denoted by WH and ZH, respectively) were modelled by Pythia 8.244 with NNPDF2.3lo PDFs [63] and the A14 tune for hadronisation and the underlying event [64]. Higgs boson production through associated production with top quarks ($t\bar{t}H$) was modelled using Pythia 8.244, and aMC@NLO to model the parton shower [65], again with the NNPDF2.3lo PDFs and A14 tune. The production rates and kinematic distributions for the SM Higgs boson with $m_H = 125$ GeV are assumed throughout. These were obtained from Ref. [66] and are summarised below. The ggH production rate is normalised such that it reproduces the total cross section predicted by a next-to-next-to-next-to-leading-order QCD calculation with NLO electroweak corrections applied [67,68]. The VBF production rate is normalised to an approximate next-to-next-to-leading-order (NNLO) QCD cross section with NLO electroweak corrections applied [69–71]. The WH and ZH production rates are normalised to cross sections calculated at NNLO in QCD with NLO electroweak corrections [72] including the NLO QCD corrections for $gg \to ZH$. Powheg Box v4 was also used to model inclusive Z boson production with CT10 PDFs. Pythia 8.244 with CTEQ6L1 PDFs and the AZNLO tune was used to simulate the parton showering and hadronisation. The prediction is normalised to the total cross section obtained from the measurement in Ref. [73]. The Higgs and Z boson decays were simulated as a cascade of two- and three-body decays, accounting for angular momentum conservation. The meson invariant mass distributions were simulated by Pythia. The branching fraction for the decay $\omega \to \pi^+\pi^-\pi^0$ is $(89.2 \pm 0.7)\%$. The decay $K^* \to K\pi$ has a branching fraction close to 100%, of which two-thirds correspond to decays to a charged kaon and a charged pion [74]. The simulated events were passed through a detailed Geant4 simulation of the ATLAS detector [75,76] and processed with the same software used to reconstruct the data. Simulated additional pp collisions in the same or neighbouring bunch crossings (pile-up events) are also included and the distribution of these is matched to the conditions observed in the data.

4. Object and event selections

The similarities of the final states in these searches allow common event selections to be used. A pair of oppositely charged reconstructed ID tracks is required for both, with the addition of a neutral pion in the reconstruction of the $\omega\gamma$ final state.

Events with a pp interaction vertex reconstructed from at least two ID tracks with $p_{\mathrm{T}} > 500$ MeV are considered in the analysis. Within an event, the primary vertex is defined as the reconstructed vertex with the largest $\sum p_{\mathrm{T}}^2$ of associated ID tracks.

Photons are reconstructed from clusters of energy in the electromagnetic calorimeter. Reconstructed photon candidates are required to have $p_{\mathrm{T}}^{\gamma} > 35$ GeV, $|\eta^{\gamma}| < 2.37$, excluding the barrel/endcap calorimeter transition region $1.37 < |\eta^{\gamma}| < 1.52$, and to satisfy "tight" photon identification criteria [77]. An isolation requirement is imposed to further suppress contamination from jets. The sum of the transverse momenta of all tracks within $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.2$ of the photon direction, excluding those associated with the reconstructed photon, is required to be less than 5% of p_{T}^{γ}. Moreover, the sum of the transverse momenta of all calorimeter energy deposits within $\Delta R = 0.4$ of the photon direction, excluding those associated with the reconstructed photon, is required to be less than $2.45\ \mathrm{GeV} + 0.022 \times p_{\mathrm{T}}^{\gamma}$. To mitigate the effects of multiple pp interactions in the same or neighbouring bunch crossings, only ID tracks consistent with originating from the primary vertex are considered in the photon track-based isolation. For the calorimeter-based isolation the effects of the underlying event and multiple pp interactions are also accounted for on an event-by-event basis using an average underlying-event energy density determined from data [77].

Charged-hadron candidates are reconstructed from ID tracks which are required to have $|\eta| < 2.5$, $p_{\mathrm{T}} > 3$ GeV and to satisfy basic quality criteria, including a requirement on the number of hits in the silicon detectors [78]. For the $\omega\gamma$ analysis, the combination of a pair of charged-hadron candidates with opposite charge and a neutral-pion candidate is denoted by $\mathcal{M}$, whereas for the $K^*\gamma$ analysis, $\mathcal{M}$ denotes the combination of a pair of charged-hadron candidates with opposite charge. Within a pair, the charged-hadron candidate with the higher p_{T}, referred to as the leading charged-hadron candidate, is required to have $p_{\mathrm{T}} > 20$ GeV for the $K^*\gamma$ analysis and $p_{\mathrm{T}} > 25$ GeV for the $\omega\gamma$ analysis. The selection of candidates for the charged-particle pair in $\mathcal{M}$ is based on their invariant masses. Charged-hadron pairs satisfying these requirements are assumed to be a $\pi^+\pi^-$ pair in the $\omega\gamma$ analysis. In the $K^*\gamma$ channel, tracks are assigned a particular mass hypothesis by calculating the invariant mass of the di-track system for both possible assignments (K/π or π/K). The combination which results in an invariant mass closer to m_{K^*} is chosen. Additionally, the p_{T} of the di-track system must satisfy $p_{\mathrm{T}} > 35$ GeV. For the $\omega\gamma$ channel, charged-hadron pairs with an invariant mass of 279 to 648 MeV are selected as candidates. For the $K^*\gamma$ channel, charged-hadron pairs with an invariant mass of 790 to 990 MeV are selected as candidates. Selected charged-hadron pair candidates are required to satisfy an isolation requirement: the sum of the p_{T} of the reconstructed ID tracks from the primary vertex that are within $\Delta R = 0.2$ of the leading charged-hadron candidate (excluding from the sum the charged-hadron candidate defining the pair) is required to be less than 10% of the p_{T} of the charged-hadron pair candidate for the $\omega\gamma$ channel, and less than 20% for the $K^*\gamma$ channel.

Neutral-pion candidates are expected to leave a signature of a pair of overlapping clusters in the electromagnetic calorimeter. In the case of $H \to \omega\gamma$ decays, the π^0 is expected to be very close in ΔR to the $\pi\pi$ system. Tau particle-flow object (TauPFO) algorithms [79] optimised to search for neutral pions in τ-like decay signatures, using boosted decision trees, are used to reconstruct the neutral pion in the ω decay. The τ-jets are searched for, with no identification requirements, within $\Delta R = 0.1$ of the $\pi^+\pi^-$ system. The presence of neutral-pion particle-flow objects is then examined within each τ-jet object. The closest particle-flow object consistent with a π^0 is taken to be the π^0 candidate, which is then added to the charged-hadron candidates to form $\mathcal{M}$ for the $\omega\gamma$ channel. An additional mass requirement of 650 to 850 MeV is then imposed on the fully reconstructed ω meson.

The $\mathcal{M}$ candidates are subsequently combined with the reconstructed photons. When multiple combinations are possible, a situation that arises only in a few percent of the events, the combination of the highest-p_{T} photon and the $\mathcal{M}$ candidate with an invariant mass closest to the respective meson mass is selected. The event is retained for further analysis if the requirement $\Delta\phi(\mathcal{M},\gamma) > \pi/2$ on the azimuthal angular separation between the meson candidate and the photon is satisfied. This selection defines the "signal region".

For the $\omega\gamma \to \pi^+\pi^-\pi^0\gamma$ final state, the total signal efficiency (kinematic acceptance, trigger and reconstruction efficiencies) is 2.2% and 0.4% for the Higgs and Z boson decays, respectively. The corresponding efficiency for the $K^*\gamma$ final state in Higgs boson decay is 12.1%.[2] The difference in efficiency between the Higgs and Z boson decays arises primarily from the softer p_{T} distributions of the photon and charged-hadron candidates from $Z \to \omega\gamma$ production. The efficiency difference between the two final states is due to the presence of the neutral pion in the decay of the ω. This arises both from the reconstruction efficiency of the neutral pion itself, and from the softer p_{T} distributions of the charged hadrons in the decay of the ω compared to the K^*, caused by the neutral pion taking a portion of the decay energy.

The Higgs boson signal $m_{\mathcal{M}\gamma}$ distribution for the $H \to \omega\gamma$ decay is modelled with a sum of a Crystal Ball distribution and a Gaussian dis-

[2] This efficiency is estimated with respect to K^* decays to a charged kaon and a charged pion.

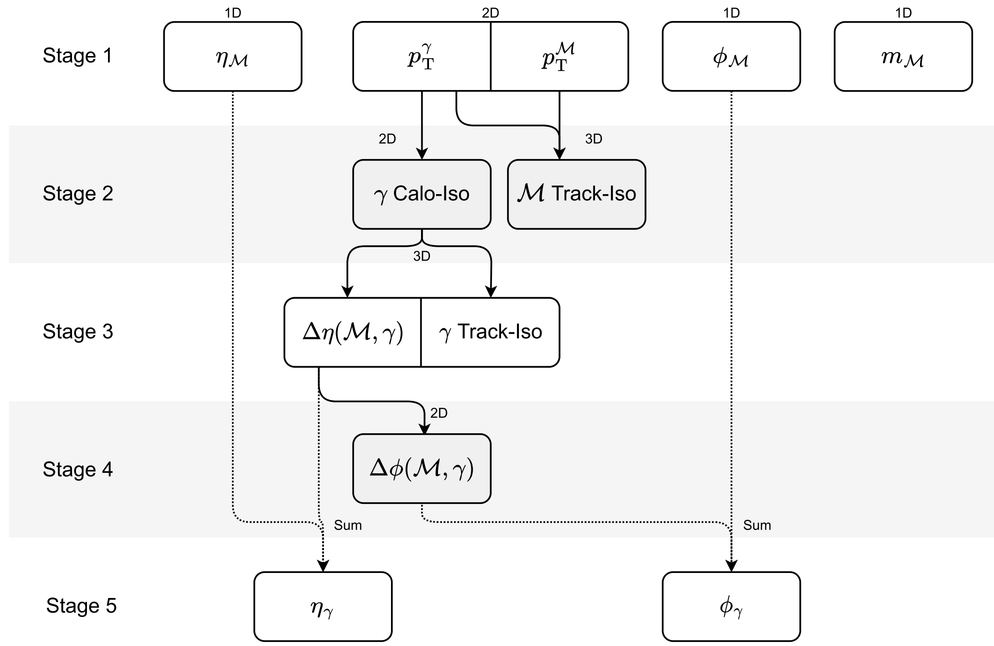


Fig. 2. A schematic diagram showing the stages of the background model used for the analyses presented. Variables are drawn using a combination of 1D, 2D and 3D histograms in order to retain the correlations between them. Solid arrows correspond to where variables have been sampled from the previous stage. Dashed arrows correspond to where previous variables have been summed to produce a new variable. Joined cells indicate variables that have been simultaneously sampled from the previous stage.

tribution, while for $H \to K^*\gamma$ a sum of two Gaussian probability density functions (pdf) with a common mean value is used. For the Z boson signal the $m_{\mathcal{M}\gamma}$ distribution is modelled with a double Voigtian pdf (a convolution of relativistic Breit–Wigner and Gaussian pdfs) corrected with a mass-dependent efficiency factor.

Additionally, sideband meson mass datasets are defined for both analyses, where the full set of selection criteria is imposed except for different invariant mass requirements on $\mathcal{M}$. For the $H \to \omega\gamma$ decay channel, the requirement is $m_\omega < 650$ MeV or $850 \text{ MeV} < m_\omega < 2000$ MeV. For $H \to K^*\gamma$ the requirement is $m_{K^*} < 790$ MeV or $m_{K^*} > 990$ MeV. These requirements produce datasets that are orthogonal to the signal region, but still provide a useful description of the background processes.

5. Background estimation

For both the $\omega\gamma$ and $K^*\gamma$ final states, the main sources of background in the searches are events involving inclusive γ + jet or multi-jet processes, where an $\mathcal{M}$ system is reconstructed from ID tracks originating from a jet. From the selection criteria discussed earlier, the shape of this background exhibits a kinematic turn-on structure in the $m_{\mathcal{M}\gamma}$ distribution around 100 GeV, in the region of the Z boson signal, and a smoothly falling background in the region of the Higgs boson signal. These processes are modelled inclusively with a non-parametric data-driven approach using templates to describe the relevant distributions [80]. The background normalisation and shape are simultaneously extracted from a fit to the data. A similar procedure was used in the searches for Higgs and Z boson decays into $\phi\gamma$ and $\rho\gamma$ [34,35] and the searches for Higgs and Z boson decays into $J/\psi\gamma$, $\psi(2S)\gamma$ and $\Upsilon(nS)\gamma$ [26–28].

5.1. Background modelling

The background modelling procedure for each final state uses a sample of approximately 16 000 $\pi^+\pi^-\pi^0\gamma$ and 280 000 $K^+\pi^-\gamma$ candidate events in data. These events pass all the kinematic selection requirements described previously, except that the photon and $\mathcal{M}$ candidates are not required to satisfy the nominal isolation requirements. This selection defines the "generation region" (GR), which is background-dominated. From these events, pdfs are constructed to describe the distributions of the relevant kinematic and isolation variables and their most important correlations. In this way, in the absence of appropriate simulations, pseudocandidates are generated, from which the background shape in the discriminating variable is derived. This ensemble of pseudocandidates is produced by randomly sampling the distributions of the relevant kinematic and isolation variables, which are estimated from the data in the GR. Each pseudocandidate is described by $\mathcal{M}$ and γ four-momentum vectors and the associated $\mathcal{M}$ and photon isolation variables. The $\mathcal{M}$ four-momentum vector is constructed from sampled $\eta_{\mathcal{M}}$, $\phi_{\mathcal{M}}$, $m_{\mathcal{M}}$ and $p_{\mathrm{T}}^{\mathcal{M}}$ values. For the γ four-momentum vector, the η_γ and ϕ_γ values are determined from the sampled $\Delta\phi(\mathcal{M},\gamma)$ and $\Delta\eta(\mathcal{M},\gamma)$ values, whereas p_{T}^{γ} is sampled directly. The most important correlations among these kinematic and isolation variables in background events are retained in the generation of the pseudocandidates. This is achieved through the following sampling scheme, also depicted in Fig. 2, where the steps are performed sequentially, following the magnitude of the observed correlations:

i) Initially, values for $p_{\mathrm{T}}^{\mathcal{M}}$ and p_{T}^{γ} are drawn from a two-dimensional pdf of ($p_{\mathrm{T}}^{\mathcal{M}}$, p_{T}^{γ}). The values of $\eta_{\mathcal{M}}$ and the ϕ angle of the meson are sampled from one-dimensional pdfs of the variables. Finally, a value for the meson mass is sampled from a one-dimensional pdf of $m_{\mathcal{M}}$.

ii) The isolation of the meson candidate is sampled from a three-dimensional pdf based on the values of $p_{\mathrm{T}}^{\mathcal{M}}$ and p_{T}^{γ} obtained in the previous step. Then, the photon's relative calorimeter isolation is sampled from a two-dimensional pdf, based on the value of p_{T}^{γ} obtained in the previous step.

iii) From this value of the photon's relative calorimeter isolation, the values of the pseudorapidity difference between the $\mathcal{M}$ and γ candidates, $\Delta\eta(\mathcal{M},\gamma)$, and the photon's relative track isolation are sampled simultaneously from a three-dimensional pdf.

iv) The value of the azimuthal angular separation, $\Delta\phi(\mathcal{M},\gamma)$, is sampled from a two-dimensional pdf based on the value of $\Delta\eta(\mathcal{M},\gamma)$ drawn in the previous step.

v) Given these sampled values, and the values sampled previously for $\Delta\eta(\mathcal{M},\gamma)$ and $\Delta\phi(\mathcal{M},\gamma)$, the values of $\eta_{\mathcal{M}}$ and ϕ_γ are then defined.

The nominal selection requirements are imposed on the ensemble, and the surviving pseudocandidates are used to construct templates for the $m_{\mathcal{M}\gamma}$ distribution, which are then smoothed using Gaussian kernel density estimation [81]. Signal injection tests were performed to ensure that the background model is not affected by any potential signal contamination.

5.2. Background validation

To validate the background model, the $m_{\mathcal{M}\gamma}$ distributions in validation regions, defined by kinematic and isolation requirements looser than the nominal signal requirements, are used to compare the prediction of the background model with the data. Three validation regions are defined, each based on the GR selection and adding one of the following: the meson isolation requirement (VR1), the calorimeter component of the photon isolation requirements (VR2a), or the track component of the photon isolation requirements (VR2b). The $m_{\mathcal{M}\gamma}$ distributions in these validation regions are shown in Fig. 3. The background model is found to describe the data well in all regions within uncertainties.

To allow the shape of the background model for the three-body mass to adjust to the observed data, variations around the nominal shape are derived. Three variations are included to allow this adjustment to occur. Firstly, a scale variation of the p_T distribution of either $\mathcal{M}$ or γ is used to allow the peak of the three-body mass distribution to shift upwards or downwards in mass. Secondly, a variation is produced via a polynomial distortion of the shape of the $\Delta\phi(\mathcal{M},\gamma)$ distribution, which allows the width of the three-body mass distribution to vary. Finally, a global tilt of the three-body mass distribution is included, which allows the model to account for slopes with respect to the data. The first two variations are simple alterations to the kinematics of the pseudocandidates, resulting in changes to the three-body mass distribution. The corresponding nuisance parameters are assigned a Gaussian constraint in the likelihood. The third variation is directly applied to the three-body mass template and is not constrained by a Gaussian term in the fit. The uncertainty band in Fig. 3 corresponds to the uncertainty envelope derived from these variations, which are set sufficiently large to allow the shape to adapt in the fit to the data.

6. Systematic uncertainties

The photon identification and isolation uncertainties are estimated to be 1.7% for the Higgs and Z boson signals. An uncertainty of 3.0% per $\mathcal{M}$ candidate is assigned to the track reconstruction efficiency and accounts for effects associated with the modelling of ID material and also with the track reconstruction algorithms if there is a charged particle near the photon. This uncertainty is derived conservatively by assuming the uncertainty to be fully correlated between the two tracks of the $\mathcal{M}$ candidate.

The systematic uncertainty in the expected signal yield arising from the photon component of the trigger efficiency is estimated to be 0.7% [82]. Uncertainties to account for the "τ"-component of the trigger turn on are assigned in accord with the studies described in Ref. [83], and are 7.3% (2.1%) for the $H(Z) \to \omega\gamma$ channels, and 4.1% for the $H \to K^*\gamma$ channel.

The Higgs boson production cross sections and decay branching fractions, as well as their uncertainties, are taken from Refs. [5,84,85]. The effect of QCD scale uncertainties on the cross section for a 125 GeV H boson [5] amounts to a 5.0% uncertainty. The uncertainties in the production cross section due to uncertainties in the PDFs and the strong coupling constant, α_s, are combined for the separate processes and amount to 2.9%. The shape component of the uncertainties was found to be negligible. The efficiency to reconstruct the neutral pion in the decay using the TauPFO algorithms is approximately 65%. The uncertainty in this reconstruction efficiency, based on Ref. [77], is 5.0%.

Table 1
Numbers of observed and expected background events for the $m_{\mathcal{M}\gamma}$ ranges of interest. Each expected background and the corresponding uncertainty of its mean is obtained from a background-only fit to the data; the uncertainty does not take into account statistical fluctuations in each mass range. Expected Z and Higgs boson signal contributions, with their corresponding total systematic uncertainty, are shown for reference branching fractions of 10^{-6} and 10^{-4}, respectively. Entries are marked with a dash when there is no signal of that type in the specified range.

Channel	Mass range [GeV]	Observed (Expected) background	H signal $\mathcal{B}=10^{-4}$	Z signal $\mathcal{B}=10^{-6}$
$H \to \omega\gamma$	115–135	686 (730 ± 17)	9 ± 1	–
$Z \to \omega\gamma$	80–100	388 (386 ± 16)	–	18 ± 2
$H \to K^*\gamma$	120–130	9526 (9630 ± 50)	53 ± 4	–

Table 2
Expected and observed branching fraction limits at the 95% CL for $H/Z \to \omega\gamma$ and $H \to K^*\gamma$.

Channel	95% CL upper limit	
	Expected	Observed
$H \to \omega\gamma$ [10^{-4}]	$10.4^{+3.8}_{-2.9}$	5.5
$Z \to \omega\gamma$ [10^{-6}]	$4.7^{+2.0}_{-1.3}$	3.9
$H \to K^*\gamma$ [10^{-4}]	$3.7^{+1.5}_{-1.0}$	2.2

The shape of the background model is allowed to vary around the nominal shape, and the parameters controlling these systematic variations are treated as nuisance parameters in the maximum-likelihood fit used to extract the signal and background yields, as described in Section 5.2.

7. Results

After the full selection is applied, 4264 events are observed in the $H/Z \to \omega\gamma$ signal region, and 114 707 events are observed in the $H \to K^*\gamma$ signal region. The data are compared with background and signal predictions using an unbinned maximum-likelihood fit to the $m_{\mathcal{M}\gamma}$ distribution. The parameters of interest are the Higgs and Z boson signal normalisations. Systematic uncertainties are modelled using additional nuisance parameters in the fit; in particular, the background normalisation is a free parameter in the model. The fit uses the selected events with $m_{\mathcal{M}\gamma} < 300$ GeV. Upper limits are set on the branching fractions for the Higgs and Z boson decays into $\mathcal{M}\gamma$ using the $\mathrm{CL_s}$ modified frequentist formalism [86] with the profile-likelihood-ratio test statistic and the asymptotic approximations derived in Ref. [87]. For the upper limits on the branching fractions, the SM production cross section is assumed for the Higgs boson, while the ATLAS measurement of the inclusive Z boson cross section is used for the Z boson signal, as discussed in Section 6. Tests of the fit on sideband meson-mass data demonstrate good agreement and modelling of the background processes and serve as further validation of the background modelling.

The expected and observed numbers of background events within regions of $m_{\mathcal{M}\gamma}$ around the Higgs and Z boson masses are given in Table 1. The expected numbers of background events are taken from background-only fits. Table 1 also shows the expected number of signal events for branching fractions near the sensitivity of the analyses. Fits to the signal region data are shown in Fig. 4. Signals are shown normalised to branching fraction values of the order of the expected sensitivity. The observed and expected limits are summarised in Table 2.

8. Conclusion

A search for the decays $H/Z \to \omega\gamma$ and $H \to K^*\gamma$ has been performed with 13 TeV pp collision data samples collected with the AT-

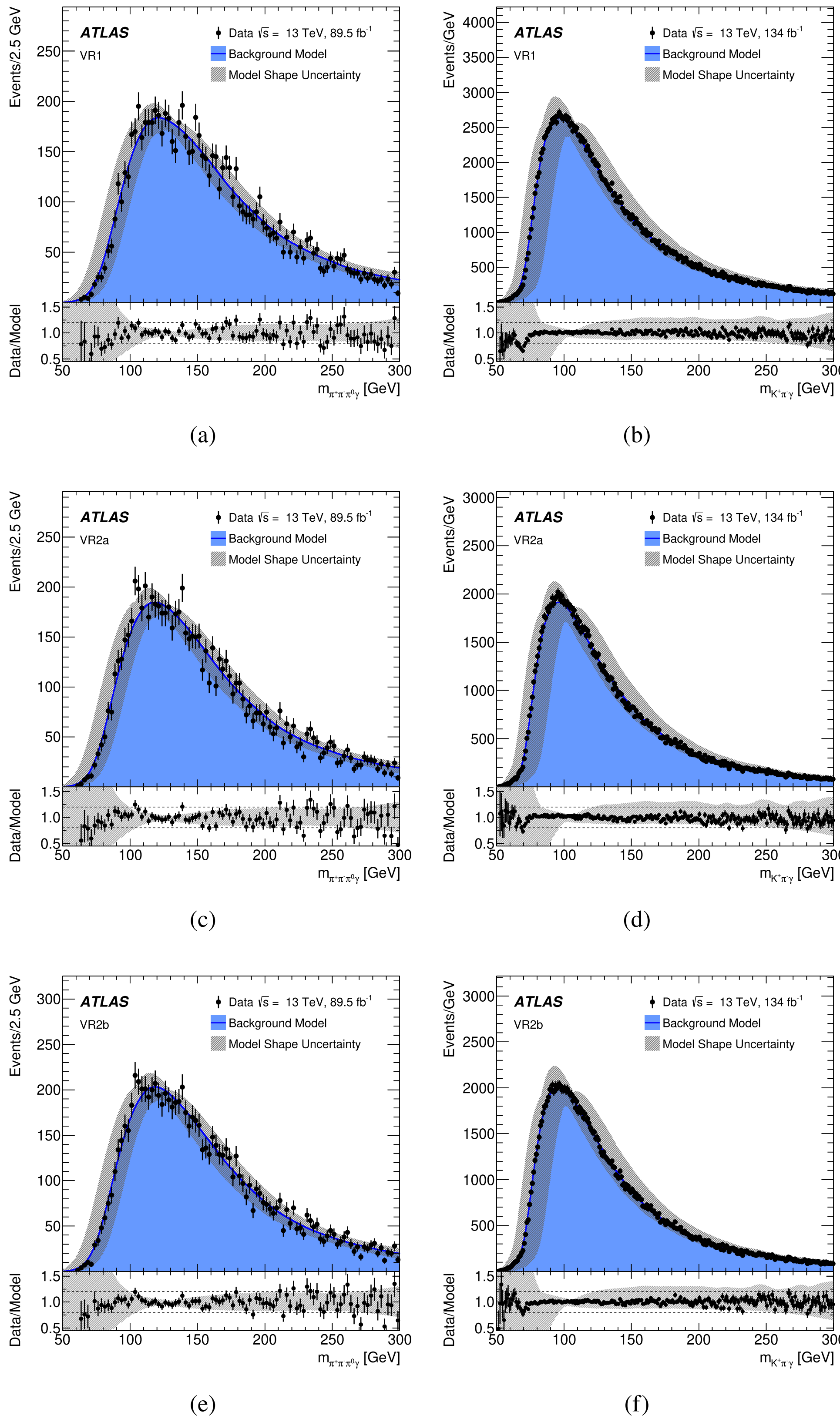
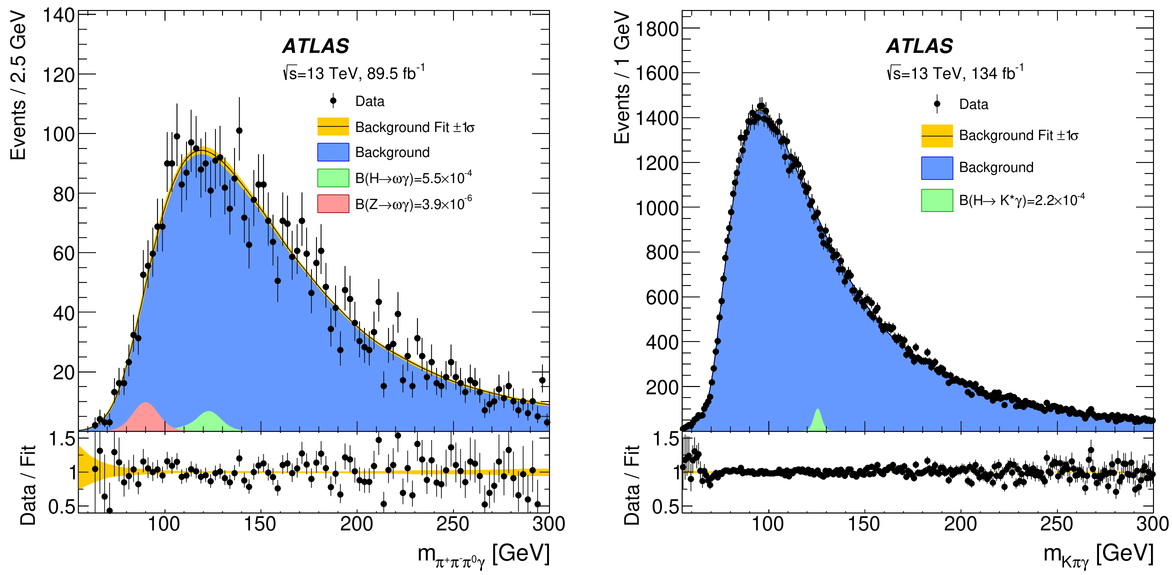


Fig. 3. Distributions of ((a), (c), (e)) $m_{\pi\pi\pi\gamma}$ and ((b), (d), (f)) $m_{K\pi\gamma}$ in data compared with the prediction of the background model for the VR1, VR2a and VR2b validation regions. The background model is normalised to the observed number of events within the region shown. The uncertainty band corresponds to the uncertainty envelope derived from variations in the background modelling procedure, described in Section 5. The ratio of the data to the background model is shown below the distributions.



(a) (b)

Fig. 4. Background-only fits performed in the signal region for the (a) $\omega\gamma$ and (b) $K^*\gamma$ final states. The branching fraction of each of the signals is set to the observed 95% CL upper limit. The yellow band represents the uncertainty in the fit arising from the constrained background shape systematic uncertainties.

LAS detector at the LHC corresponding to integrated luminosities of 89.5 fb^{-1} and 134 fb^{-1} respectively. The ω and K^* mesons are reconstructed via their dominant decays into $\pi^+\pi^-\pi^0$ and $K^\pm\pi^\pm$ final states, respectively. The background model is derived using a fully data-driven approach and validated in a number of different regions. No significant excess of events above the SM background expectations is observed. The obtained 95% CL upper limits are $\mathcal{B}(H \to \omega\gamma) < 5.5 \times 10^{-4}$ (370×SM), $\mathcal{B}(Z \to \omega\gamma) < 3.9 \times 10^{-6}$ (140×SM), and $\mathcal{B}(H \to K^*\gamma) < 2.2 \times 10^{-4}$. The result for $Z \to \omega\gamma$ corresponds to a two-orders-of-magnitude improvement over the previously set limit at DELPHI.

Declaration of competing interest

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

Data availability

The data for this manuscript are not available. The values in the plots and tables associated to this article are stored in HEPDATA (https://hepdata.cedar.ac.uk).

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