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Search for Higgs and Z Boson Decays to $\phi\gamma$ with the ATLAS Detector

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A search for the decays of the Higgs and Z bosons to a ϕ meson and a photon is performed with a pp collision data sample corresponding to an integrated luminosity of 2.7 fb^{-1} collected at $\sqrt{s} = 13$ TeV with the ATLAS detector at the LHC. No significant excess of events is observed above the background, and 95% confidence level upper limits on the branching fractions of the Higgs and Z boson decays to $\phi\gamma$ of 1.4×10^{-3} and 8.3×10^{-6}, respectively, are obtained.

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Rare decays of the 125 GeV Higgs boson [1,2] H to a light meson and a photon γ have been suggested to present one viable probe of the Yukawa coupling of the Higgs boson to light (u, d, s) quarks [3–5]. While the Standard Model (SM) predicts these couplings to be small, substantial modifications are predicted in several scenarios beyond the SM, which include the minimal flavor 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]. The light-quark Yukawa couplings are almost entirely unconstrained by existing data and the large multijet background at the Large Hadron Collider (LHC) severely inhibits the study of such couplings with inclusive $H \to q\bar{q}$ decays. The decay of the Higgs boson to a ϕ meson and a photon would give access to the strange-quark Yukawa coupling and to potential deviations from the SM prediction. The expected SM branching fraction is $\mathcal{B}(H \to \phi\gamma) = (2.3 \pm 0.1) \times 10^{-6}$ [4], and no direct experimental information about this decay mode currently exists. The analogous rare decays of the Higgs boson to a heavy quarkonium state and a photon offer sensitivity to the charm- and bottom-quark Yukawa couplings [11–13]. The Higgs boson decays to $J/\psi\gamma$ and $\Upsilon\gamma$ have already been searched for by the ATLAS Collaboration [14]. The former decay mode has also been searched for by the CMS Collaboration [15].

The corresponding decay of the Z boson has also been considered from a theoretical perspective [16,17], as it offers a precision test of the SM and the predictions of the factorization approach in quantum chromodynamics [17]. Owing to the large Z boson production cross section at the LHC, rare Z boson decays can be probed at branching fractions much smaller than for Higgs boson decays to the same final state. The most precise prediction for the SM branching fraction is $\mathcal{B}(Z \to \phi\gamma) = (1.17 \pm 0.08) \times 10^{-8}$ [16]. The decay $Z \to \phi\gamma$ has not yet been observed and is not well constrained by existing measurements of Z boson decays.

This Letter describes a search for Higgs and Z boson decays to the exclusive final state $\phi\gamma$. The decay $\phi \to K^+K^-$ is used to reconstruct the ϕ meson. The search is performed with a sample of pp collision data corresponding to an integrated luminosity of 2.7 fb^{-1} recorded at a center-of-mass energy $\sqrt{s} = 13$ TeV with the ATLAS detector, described in detail in Ref. [18].

Higgs boson production is modeled using the POWHEG-BOX v2 Monte Carlo (MC) event generator [19–23] for the gluon fusion (ggH) and vector-boson fusion (VBF) processes calculated up to next-to-leading order in α_S with CT10 parton distribution functions [24]. Additional contributions from the associated production of a Higgs boson and a W or Z boson (denoted WH and ZH, respectively) are modeled by the PYTHIA 8.186 MC event generator [25,26] with NNPDF 2.3 parton distribution functions [27]. The production rates and dynamics for a SM Higgs boson with $m_H = 125$ GeV, obtained from Ref. [28], are assumed throughout this analysis. The ggH signal model is appropriately scaled to account for the production of a Higgs boson in association with a $t\bar{t}$ or $b\bar{b}$ pair. The POWHEG-BOX v2 MC event generator, with the CTEQ6L1 parton distribution functions [29], is used to model Z boson production. The total cross section is obtained from the measurement in Ref. [30], with an uncertainty of 5.5%.

The Higgs and Z boson decays are simulated as a cascade of two-body decays. Effects of the helicity of the ϕ mesons on the $K^\pm$ kinematics are found to modify the acceptance by at most $\pm 1\%$ and this is corrected for in the Higgs boson case and treated as a systematic uncertainty in the Z boson case, due to the unknown Z boson polarization.

PYTHIA 8.186 [25,26] with the AZNLO set of hadronization and underlying-event parameters [31] is used to simulate showering and hadronization. The simulated

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events are passed through the detailed GEANT4 simulation of the ATLAS detector [32,33] and processed with the same software used to reconstruct data.

The data sample used in this analysis was collected with a dedicated trigger, commissioned in September 2015, requiring an isolated photon with a transverse momentum p_T greater than 35 GeV and an isolated pair of tracks with an invariant mass loosely consistent with the ϕ meson mass of 1019.5 MeV [34], one of which must have a transverse momentum greater than 15 GeV. The trigger efficiency for both the Higgs and Z boson signals is around 80% with respect to the offline selection. Events are retained for analysis if collected under stable LHC beam conditions and the detector was operating normally.

For this analysis, in the absence of particle identification capabilities in the relevant momentum range, every reconstructed charged particle satisfying the following requirements is assumed to be a $K^{\pm}$ meson. Events are selected if there are at least two tracks with $p_T > 400$ MeV originating from the primary vertex, which is defined as the vertex with the largest $\sum p_T^2$ in the event. The charged kaons are reconstructed from inner-detector tracks that satisfy quality requirements, including a requirement on the number of hits in the silicon detectors [35]. The $K^{\pm}$ candidates are required to have pseudorapidity [36] $|\eta| < 2.5$ and $p_T > 15$ GeV. The $\phi \to K^+K^-$ decays are reconstructed from pairs of oppositely charged inner detector tracks. The higher-p_T track in a pair, denoted the leading track, is required to have $p_T > 20$ GeV. The experimental resolution in $m_{K^+K^-}$ is around 4 MeV, comparable to the natural width of the ϕ meson, $\Gamma_\phi = 4.266 \pm 0.031$ MeV [34]. Track pairs with a mass $m_{K^+K^-}$ within ± 20 MeV of the ϕ meson mass [34] are selected as $\phi \to K^+K^-$ candidates. Selected $\phi \to K^+K^-$ candidates are required to satisfy an isolation requirement: the sum of the p_T of the reconstructed inner detector tracks from the main vertex within $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.2$ of the leading track (excluding both tracks constituting the $\phi \to K^+K^-$ candidate) is required to be less than 10% of the p_T of the ϕ candidate, $p_T^{K^+K^-}$.

Photons are reconstructed from clusters of energy in the electromagnetic calorimeter. Clusters without matching tracks are classified as unconverted photon candidates while clusters matched to tracks consistent with the hypothesis of a photon conversion into an e^+e^- pair are classified as converted photon candidates [37]. Reconstructed photon candidates are required to have transverse momentum $p_T^\gamma > 35$ GeV, pseudorapidity $|\eta^\gamma| < 2.37$, excluding the barrel or endcap calorimeter transition region $1.37 < |\eta^\gamma| < 1.52$, and to satisfy the "tight" photon identification criteria [38]. An isolation requirement is imposed to further suppress the contamination from jets. The sum of the transverse momenta of all tracks within $\Delta R = 0.2$ of the photon direction, excluding those associated with the reconstructed photon, is required to be less than 5% of p_T^γ. The effects of multiple pp interactions per bunch crossing (pile-up) in this calculation are reduced by removing tracks that do not originate from the primary vertex. Additionally, the sum of the transverse momenta of all energy deposits in the calorimeters within $\Delta R = 0.4$ of the photon direction, excluding those associated with the reconstructed photon, is required to be less than $(2.45\ \text{GeV} + 0.022 \times p_T^\gamma)$. The calorimeter isolation measurements are also corrected for the effects of pile-up.

Combinations of a $\phi \to K^+K^-$ candidate and a photon, satisfying $\Delta\phi(K^+K^-, \gamma) > 0.5$, are retained for further analysis. When multiple combinations are possible, the combination of the highest-p_T photon and the $\phi \to K^+K^-$ candidate with a mass closest to the ϕ meson mass is retained. The transverse momentum of $\phi \to K^+K^-$ candidates is required to be greater than a threshold that varies as a function of the invariant mass of the three-body system, $m_{K^+K^-\gamma}$. Thresholds of 40 GeV and 45 GeV are imposed for the regions $m_{K^+K^-\gamma} < 91$ GeV and $m_{K^+K^-\gamma} \geq 125$ GeV, respectively. The threshold is varied from 40 GeV to 45 GeV as a linear function of $m_{K^+K^-\gamma}$ in the region $91 \leq m_{K^+K^-\gamma} < 125$ GeV. This approach ensures optimal sensitivity for both the Higgs and Z boson searches. The total signal efficiency (kinematic acceptance, and trigger and reconstruction efficiencies) is 18% and 8% for the Higgs and Z boson decays, respectively. The difference in efficiencies primarily arises due to the softer p_T^γ and $p_T^{K^+K^-}$ distributions in the case of $Z \to \phi\gamma$ production. The $m_{K^+K^-\gamma}$ resolution is around 1.8% for both the Higgs and Z boson decays. The $m_{K^+K^-}$ distribution for selected $\phi\gamma$ candidates, with no $m_{K^+K^-}$ requirement applied, is shown in Fig. 1 and exhibits a clear peak at the ϕ meson mass.

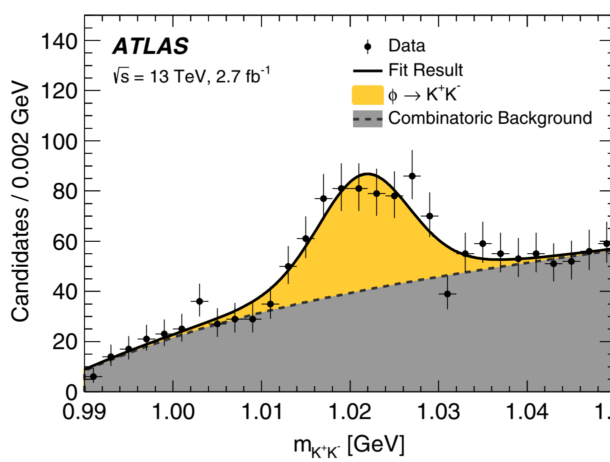

FIG. 1. The $m_{K^+K^-}$ distribution of selected $\phi\gamma$ combinations with the complete event selection applied (see text), apart from the requirement on $m_{K^+K^-}$. The data are fitted with the convolution of a Breit-Wigner distribution, using the ϕ width [34], and a Gaussian distribution to represent the experimental resolution, while the background is modeled with an analytical function, commonly used to describe a kinematic threshold [39].

The main source of background to the search comes from events involving inclusive multijet or photon + jet processes where a $\phi \to K^+K^-$ candidate is reconstructed from tracks associated with a jet. The normalization of this inclusive background is extracted directly from a fit to data. The selection criteria discussed earlier shape the $m_{K^+K^-\gamma}$ distribution for background such that it exhibits a threshold structure near 100 GeV, and falls then smoothly towards higher mass values. Given the nontrivial shape of this background, these processes are modeled with a nonparametric data-driven approach using templates to describe the kinematic distributions. A similar procedure was used in the search for Higgs and Z boson decays to $J/\psi\gamma$ and $\Upsilon(nS)\gamma$ described in Ref. [14]. The approach exploits a sample of around 4000 $K^+K^-\gamma$ candidate events passing all of the kinematic selection requirements described previously, except that the photon and $\phi \to K^+K^-$ candidates are not required to satisfy the nominal isolation requirements. The events satisfying this selection are collected in a generation region (GR). The contamination of this sample from signal events is expected to be negligible and is verified not to affect the shape of the background model. Probability density functions (pdfs) that model the $p_T^{K^+K^-}$, p_T^γ, $\Delta\eta(K^+K^-, \gamma)$, and $\Delta\phi(K^+K^-, \gamma)$ distributions of this sample are constructed using a Gaussian kernel density estimation [40]. Correlations between these variables and p_T^γ in the event were studied and accounted for in the background model by deriving separate pdfs in 13 exclusive regions of p_T^γ. In the case of the $\phi \to K^+K^-$ and photon isolation variables, correlations are accounted for by using two-dimensional histograms derived in the same 13 exclusive regions of p_T^γ. Values of $m_{K^+K^-}$ are sampled from the corresponding distribution in the GR. The pdfs of these kinematic and isolation variables are sampled to generate an ensemble of pseudocandidates, each with a complete $K^+K^-\gamma$ four-vector and an associated pair of $\phi \to K^+K^-$ and photon isolation values. The nominal selection requirements are imposed on the ensemble and the surviving pseudocandidates are used to construct templates for the $m_{K^+K^-\gamma}$ distribution.

To validate this background model with data, the $m_{K^+K^-\gamma}$ distributions in several 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. The $m_{K^+K^-\gamma}$ distribution in one of these validation regions, defined by the GR selection with the addition of the nominal photon isolation requirement, is shown in Fig. 2. The background model is found to describe the data well, and within the observed statistical uncertainties. A consistency test of the background modeling procedure has been performed with a sample of simulated photon + jet events in place of the data; similarly good agreement is observed. The robustness of the background model is further validated by splitting the data into high- and low-$p_T^{K^+K^-\gamma}$ subsets, that exhibit different threshold structures, and confirming that the background model describes the shapes of both $m_{K^+K^-\gamma}$ distributions. Further exclusive background contributions from $Z \to \ell\ell\gamma$ decays have been studied but are found to represent a negligible contribution for the selection requirements and data set used in this analysis.

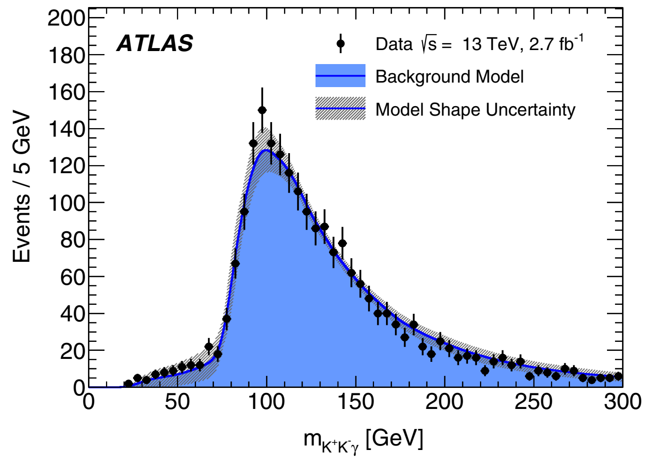

FIG. 2. The distribution of $m_{K^+K^-\gamma}$ in data compared to the prediction of the background model for a validation control sample defined by the GR selection with the addition of the nominal photon isolation requirement. The background model is normalized to the observed number of events within the region shown. The uncertainty band corresponds to the uncertainty envelope derived from variations in the background modeling procedure.

Trigger and identification efficiencies for photons are determined from samples enriched with $Z \to e^+e^-$ events in data [37,41]. The systematic uncertainty on the expected signal yield associated with the trigger efficiency is estimated to be 2%. The photon identification efficiency uncertainties, for both the converted and unconverted photons, are estimated to be 2.4% and 2.6% for the Higgs and Z boson signals, respectively. An uncertainty of 6% is assigned to the track reconstruction efficiency and includes effects associated with the material budget of the inner detector and the behavior of the track reconstruction algorithm if a nearby track is present. The integrated luminosity of the data sample has an uncertainty of 5% derived using the method described in Ref. [42]. The

TABLE I. The number of observed events and the expected background yield for the two $m_{K^+K^-\gamma}$ ranges of interest. The Higgs and Z boson contributions expected for branching fraction values of 10^{-3} and 10^{-6}, respectively, and estimated using Monte Carlo simulations are also shown.

Observed (expected) background					Expected signal	
Mass range [GeV]					Z	H
All	81–101		120–130		$\mathcal{B}[10^{-6}]$	$\mathcal{B}[10^{-3}]$
1065	288	(266 ± 9)	89	(87 ± 3)	6.7 ± 0.7	13.5 ± 1.5

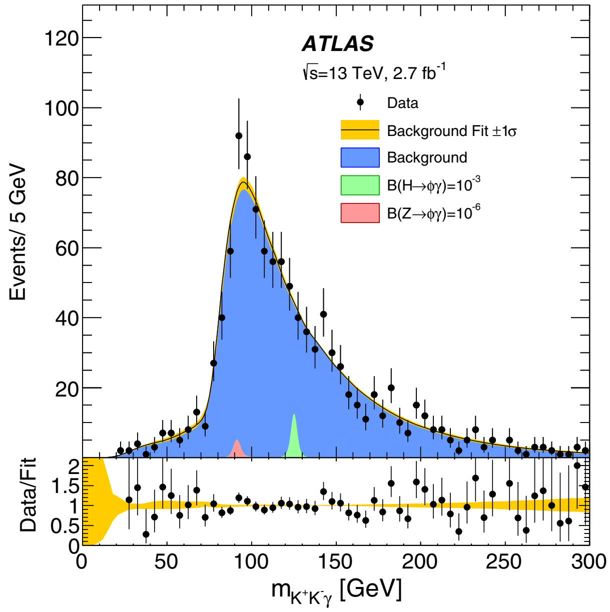

FIG. 3. The $m_{K^+K^-\gamma}$ distributions of the selected $\phi\gamma$ candidates, along with the results of the maximum-likelihood fit with background-only model. The 1σ uncertainty band corresponds to the total uncertainty of the background model. The Higgs and Z boson contributions, expected for branching fraction values of 10^{-3} and 10^{-6}, respectively, are also shown.

photon energy scale uncertainty, determined from $Z \to e^+e^-$ events and validated using $Z \to \ell\ell\gamma$ events [43], is propagated through the simulated signal samples as a function of η^γ and p_T^γ. The uncertainty associated with the description of the photon energy scale in the simulation is found to be less than 0.3% of the three-body invariant mass while the uncertainty associated with the photon energy resolution is found to be negligible relative to the overall three-body invariant mass resolution. Similarly, the systematic uncertainty associated with the track momentum measurement is found to be negligible.

The uncertainty on the shape of the inclusive multijet and photon + jet background is estimated through the study of variations in the background modeling procedure. The shape of the background model is allowed to vary around the nominal shape within an envelope associated with shifts in the $p_T^{K^+K^-}$ distribution, tilts of the $\Delta\phi(K^+K^-, \gamma)$ distribution, and by neglecting the weakest correlation accounted for in the nominal background model.

Results are compared to background and signal predictions using an unbinned maximum-likelihood fit to the $m_{K^+K^-\gamma}$ distribution. The fit uses the selected events with $m_{K^+K^-\gamma} < 300$ GeV. The systematic uncertainties described above result in a 3% deterioration of the sensitivity to the $H \to \phi\gamma$ decay. For the Z boson decay the reduction is larger, 13%, mainly due to the systematic uncertainty in the background shape. The expected and observed numbers of background events within the $m_{K^+K^-\gamma}$ ranges relevant to the Higgs and Z boson signals are shown in Table I.

TABLE II. Expected and observed branching fraction limits at 95% C.L. for 2.7 fb^{-1} of pp collision data at $\sqrt{s} = 13$ TeV. The $\pm 1\sigma$ intervals of the expected limits are also given.

Branching fraction limit (95% C.L.)	Expected	Observed
$\mathcal{B}(H \to \phi\gamma)[10^{-3}]$	$1.5^{+0.7}_{-0.4}$	1.4
$\mathcal{B}(Z \to \phi\gamma)[10^{-6}]$	$4.4^{+2.0}_{-1.2}$	8.3

On the basis of the observed data, upper limits are set on the branching fractions for the Higgs and Z boson decays to $\phi\gamma$ using the CL_s modified frequentist formalism [44] with the profile-likelihood ratio test statistic [45]. The result of the background-only fit is shown in Fig. 3; a small excess of two standard deviations is observed in the Z boson mass region, estimated using the asymptotic approximation for the distribution of the test statistic. The expected 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 [30]. The results are summarized in Table II. The observed 95% confidence level (C.L.) upper limits on the branching fractions for $H \to \phi\gamma$ and $Z \to \phi\gamma$ decays are around 600 and 700 times the expected SM branching fractions, respectively.

In conclusion, a search for the decay of Higgs or Z bosons to $\phi\gamma$ has been performed with a pp collision data sample at $\sqrt{s} = 13$ TeV corresponding to an integrated luminosity of 2.7 fb^{-1} collected with the ATLAS detector at the LHC. No significant excess of events is observed above the background. Upper limits at the 95% C.L. are set on the branching fractions for the decay of the 125 GeV SM Higgs boson and the Z boson to $\phi\gamma$. The obtained limits are $\mathcal{B}(H \to \phi\gamma) < 1.4 \times 10^{-3}$ and $\mathcal{B}(Z \to \phi\gamma) < 8.3 \times 10^{-6}$.

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