



## Letter

# Searches for exclusive Higgs boson decays into $D^*\gamma$ and $Z$ boson decays into $D^0\gamma$ and $K_s^0\gamma$ in $pp$ collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

The ATLAS Collaboration <sup>\*</sup>



## ARTICLE INFO

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## ABSTRACT

Searches for exclusive decays of the Higgs boson into  $D^*\gamma$  and of the  $Z$  boson into  $D^0\gamma$  and  $K_s^0\gamma$  can probe flavour-violating Higgs boson and  $Z$  boson couplings to light quarks. Searches for these decays are performed with a  $pp$  collision data sample corresponding to an integrated luminosity of  $136.3 \text{ fb}^{-1}$  collected at  $\sqrt{s} = 13$  TeV between 2016–2018 with the ATLAS detector at the CERN Large Hadron Collider. In the  $D^*\gamma$  and  $D^0\gamma$  channels, the observed (expected) 95% confidence-level upper limits on the respective branching fractions are  $B(H \rightarrow D^*\gamma) < 1.0(1.2) \times 10^{-3}$ ,  $B(Z \rightarrow D^0\gamma) < 4.0(3.4) \times 10^{-6}$ , while the corresponding results in the  $K_s^0\gamma$  channel are  $B(Z \rightarrow K_s^0\gamma) < 3.1(3.0) \times 10^{-6}$ .

## 1. Introduction

After the observation of the Higgs boson ( $H$ ) with a mass of 125 GeV by the ATLAS [1] and CMS [2] Collaborations [3,4], many studies were performed to measure its properties which, so far, are consistent with Standard Model (SM) expectations [5,6]. These have confirmed its role in the spontaneous breaking of electroweak symmetry and the mass generation of the massive vector bosons [7,8]. A complete observation of the Higgs boson Yukawa couplings to third-generation charged fermions was achieved by the ATLAS and CMS collaborations through the observation of the decays  $H \rightarrow \tau^+\tau^-$  [9,10] and  $H \rightarrow b\bar{b}$  [11,12], and the production of Higgs bosons with top-quark pairs [13,14]. Evidence was also reported for the decay  $H \rightarrow \mu^+\mu^-$  [15,16], and direct searches for  $H \rightarrow c\bar{c}$  [17,18] and  $H \rightarrow e^+e^-$  decays [19,20] were performed, but there is no further experimental evidence for the Higgs boson couplings to the first and second generations of fermions. Instead, the light ( $u$ ,  $d$ ,  $s$ ) quark couplings to the Higgs boson are loosely constrained by existing data on the total Higgs boson's width and combined measurements of Higgs boson production and decays [5,6].

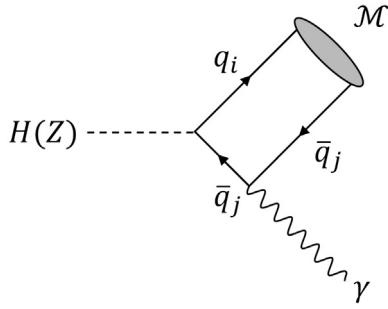
The ATLAS and CMS Collaborations have also investigated potential beyond-the-SM (BSM) couplings of the Higgs boson, including searches for the lepton-flavour-violating decays  $H \rightarrow e\mu$ ,  $H \rightarrow e\tau$  and  $H \rightarrow \mu\tau$  [19,21–23] and for flavour-changing neutral currents via the  $t$ -quark decays  $t \rightarrow cH$  and  $t \rightarrow uH$  [24–27]. An overview of BSM theories which allow flavour-violating couplings of the Higgs boson to quarks is presented in Ref. [28]. These include BSM scenarios such as the minimal flavour violation framework [29] and the Giudice–Lebedev Higgs boson dependent Yukawa couplings model [30].

Rare exclusive decays of the Higgs boson into a meson and a photon probe both the potential flavour-violating Higgs boson couplings and the Yukawa couplings of the SM [31–39]. Analogous decays of the  $Z$  boson into a meson and a photon offer unique tests of the factorisation approach in quantum chromodynamics, QCD [40–42], and in particular, probes of potential flavour-changing neutral current interactions of the  $Z$  boson via such decays are discussed in Ref. [41]. Searches for these exclusive decays were performed by the ATLAS and CMS Collaborations [43–50], and the ATLAS constraints on them, with corresponding SM predictions, are summarised in Ref. [51]. Fig. 1 shows an illustrative Feynman diagram of the  $H(Z) \rightarrow \mathcal{M}\gamma$  process (where  $\mathcal{M}$  denotes a meson) which proceeds via a flavour-violating coupling that can be probed with searches for exclusive Higgs bosons and  $Z$  boson decays into a meson and a photon, as done previously in the ATLAS search for  $H \rightarrow K^*\gamma$  [48].

Motivated by the potential for flavour-violating interactions in the couplings of the Higgs and  $Z$  bosons to quarks, searches are described for the decays  $H \rightarrow D^*\gamma$ ,  $Z \rightarrow D^0\gamma$  (and the corresponding charge-conjugate decays  $H \rightarrow \bar{D}^*\gamma$  and  $Z \rightarrow \bar{D}^0\gamma$ ) and  $Z \rightarrow K_s^0\gamma$ , which use  $136.3 \text{ fb}^{-1}$  of ATLAS  $pp$  collision data collected at  $\sqrt{s} = 13$  TeV. For the  $D^*\gamma$ ,  $D^0\gamma$  and  $K_s^0\gamma$  final states, only the three previously mentioned specific decay channels are allowed by angular momentum conservation. Hereafter,  $D^*$  includes the  $D^*$  and its anti-particle  $\bar{D}^*$ , and  $D^0$  includes the  $D^0$  and its anti-particle  $\bar{D}^0$ .

In the SM, the  $D^*\gamma$  decay arises only from loop contributions. The SM branching fraction for Higgs boson decays into  $\bar{c}u$  or  $\bar{u}c$  has been calculated to be  $B(H \rightarrow \bar{c}u/\bar{u}c) = 5 \times 10^{-20}$  [52], while the branching fraction for  $H \rightarrow D^*\gamma$  is expected to be much smaller, estimated at

<sup>\*</sup> E-mail address: [atlas.publications@cern.ch](mailto:atlas.publications@cern.ch).



**Fig. 1.** An illustrative Feynman diagram depicting the flavour-violating  $H \rightarrow M\gamma$  and  $Z \rightarrow M\gamma$  processes considered in this search, where  $M$  is a flavoured meson. For Higgs boson decays,  $M = D^*$ ; for  $Z$  boson decays,  $M = D^0, K_s^0$ . The indices  $i$  and  $j$  refer to the flavour of the quark, and  $i \neq j$ .

$7 \times 10^{-27}$  [53]. The corresponding SM branching fractions for the  $Z$  boson decays are similarly small [41,53], estimated at  $1.4 \times 10^{-25}$  and  $3.3 \times 10^{-20}$  for the  $Z \rightarrow D^0\gamma$  and  $Z \rightarrow K_s^0\gamma$  decays, respectively [53]. The decays  $H \rightarrow D^*\gamma$  and  $Z \rightarrow D^0\gamma$  probe for flavour-violating couplings of the Higgs and  $Z$  bosons to  $u$ - and  $c$ -quarks, and the decay  $Z \rightarrow K_s^0\gamma$  probes for flavour-violating couplings of the  $Z$  boson to  $d$ - and  $s$ -quarks. The LHCb experiment has searched for the decay  $Z \rightarrow D^0\gamma$  using  $2.0 \text{ fb}^{-1}$  of data collected at  $\sqrt{s} = 13 \text{ TeV}$ , yielding a 95% CL upper limit of  $2.1 \times 10^{-3}$  [54], but there are no further experimental constraints on these decays. Given that the expected SM branching fractions for these decays are vanishingly small, an observation could imply physics beyond the SM, such as the existence of these flavour-violating couplings.

The signatures of the exclusive decays into a meson and a photon include a high-energy photon and a meson appearing approximately back-to-back in the detector following the decay of the  $H$  or  $Z$  boson, where there is a resonance in di-track mass to reconstruct the meson and in three-body mass to reconstruct the initial boson [43–50]. The decays considered in this paper have an additional feature of a displaced decay vertex, either through the decay of the  $D^0$  in  $H \rightarrow D^*\gamma$  and  $Z \rightarrow D^0\gamma$ , or the decay of the  $K_s^0$  in  $Z \rightarrow K_s^0\gamma$ . This provides a particularly distinct signature as requirements on the vertex displacement are used to reject multijet events, the dominant contribution to the background. The backgrounds in these searches are considered inclusively, and originate primarily from multijet and  $\gamma$ +jet events involving the production of the meson or a non-resonant di-track system near its mass. The two primary decay channels of the  $D^*$  are considered, into  $D^0\pi^0$  and  $D^0\gamma$ , where the  $\pi^0$  and photon are soft and are not explicitly reconstructed. The searches for  $H \rightarrow D^*\gamma$  and  $Z \rightarrow D^0\gamma$  are grouped into a single event selection which targets the decay  $D^0 \rightarrow K^-\pi^+$ , while the search for  $Z \rightarrow K_s^0\gamma$  has a separate selection which targets the decay  $K_s^0 \rightarrow \pi^+\pi^-$ .

## 2. ATLAS detector

The ATLAS detector [1] is a multipurpose particle physics detector with an approximately forward–backward symmetric cylindrical geometry and near  $4\pi$  coverage in solid angle.<sup>1</sup> 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 of  $|\eta| < 2.5$ , 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 [55,56]. 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 of  $|\eta| < 4.9$ . 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  $\eta$  and  $\phi$ . A steel/scintillator-tile calorimeter provides hadronic calorimetry in the range of  $|\eta| < 1.7$ , 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 online selection and record events for offline analysis [57]. 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 [58] 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 simulation

The searches are performed with a sample of  $pp$  collision data collected at a centre-of-mass energy  $\sqrt{s} = 13 \text{ TeV}$  from 2016–2018. The total integrated luminosity available is  $136.3 \text{ fb}^{-1}$  for each final state, following the requirement that events must be collected under stable LHC beam conditions with all relevant detector components in good operating condition [59].

The data samples were recorded by a combination of dedicated triggers that were available from May 2016 and remained operational until the end of data taking in 2018. The search for  $H \rightarrow D^*\gamma$  and  $Z \rightarrow D^0\gamma$  uses triggers which target  $D^0 \rightarrow K^-\pi^+$  decays whilst the search for  $Z \rightarrow K_s^0\gamma$  uses triggers which target  $K_s^0 \rightarrow \pi^+\pi^-$  decays. These decay channels were selected as they each involve exactly two charged hadrons, such that the meson candidates can be fully reconstructed, thus providing favourable information for triggering. Each trigger requires a photon at the level-1 trigger with  $p_T > 24 \text{ GeV}$ . At the high-level trigger, an isolated photon with a transverse momentum  $p_T^\gamma > 35 \text{ GeV}$  [60] is required for the 2016 data taking period, and with a reduced threshold of  $p_T^\gamma > 25 \text{ GeV}$  throughout 2017–2018. For the ID tracks required at the high-level trigger, modified versions of the  $\tau$ -lepton trigger algorithms [61] are used. Each trigger requires a pair of tracks that is matched to a topological cluster of calorimeter cells [62] with a transverse energy greater than 25 GeV. Within the pair, one track is required to have  $p_T$  greater than 15 GeV. Different requirements on the invariant mass of the pair of tracks are applied, depending on the targeted meson decay. For  $D^0 \rightarrow K^-\pi^+$  an invariant mass of the pair of tracks in the range 1800–1930 MeV is required under the  $K^\pm\pi^\mp$  hypothesis,

<sup>1</sup> 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  $(r, \phi)$  are used in the transverse plane,  $\phi$  being the azimuthal angle around the  $z$ -axis. The pseudorapidity is defined in terms of the polar angle  $\theta$  as  $\eta = -\ln \tan(\theta/2)$ .

whilst for  $K_s^0 \rightarrow \pi^+\pi^-$  an invariant mass in the range 460–538 MeV is required under the charged-pion hypothesis.

The generation and normalisation of simulated signal samples follow the methods used in the search for  $H \rightarrow K^*\gamma$  and  $H(Z) \rightarrow \omega\gamma$  [48] and are summarised here. Higgs boson production through gluon ( $ggH$ ) and vector-boson fusion (VBF) processes was modelled up to next-to-leading-order (NLO) in  $\alpha_s$  using the POWHEG BOX v4 Monte Carlo (MC) event generator [63–67]. POWHEG BOX v4 was interfaced with the PYTHIA 8.244 MC event generator [68] to model the parton shower, hadronisation and underlying event, with parameter values set according to the AZNLO set of tuned parameters (“tune”) [69] and using CTEQ6L1 parton distribution functions (PDFs) [70]. Additional contributions from the production of a Higgs boson with a  $W^\pm$  or  $Z$  boson (denoted by  $WH$  and  $ZH$ , respectively) were also modelled with POWHEG BOX v4, but interfaced to PYTHIA 8.244 with NNPDF2.3LO PDFs [71] and the A14 tune [72] for hadronisation and the underlying event. Higgs boson production with top quarks ( $t\bar{t}H$ ) was modelled at NLO using the event generator AMC@NLO [73] interfaced to PYTHIA 8.244, again with the NNPDF2.3LO PDFs and A14 tune. Events were generated assuming a Higgs boson mass of  $m_H = 125$  GeV, but were normalised to cross-sections associated with  $m_H = 125.09$  GeV. These were obtained from Ref. [74] and are summarised below. The  $ggH$  production rate was 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 [75,76]. The VBF production rate was normalised to an approximate next-to-next-to-leading-order (NNLO) QCD cross-section with NLO electroweak corrections applied [77–79]. The  $WH$  and  $ZH$  production rates were normalised to cross-sections calculated at NNLO in QCD with NLO electroweak corrections [80] including the NLO QCD corrections for  $gg \rightarrow ZH$ . POWHEG BOX v4 was also used to model inclusive  $Z$  boson production with CT10 PDFs [81]. PYTHIA 8.244 with CTEQ6L1 PDFs [70] 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. [82].

The Higgs and  $Z$  boson decays were simulated as a cascade of two-body decays. The branching fractions for  $D^* \rightarrow D^0\pi^0$  and  $D^* \rightarrow D^0\gamma$  are  $(64.7 \pm 0.9)\%$  and  $(35.3 \pm 0.9)\%$  respectively [83]. The branching fraction for the decay  $D^0 \rightarrow K^-\pi^+$  is  $(3.947 \pm 0.030)\%$  and the branching fraction for the decay  $K_s^0 \rightarrow \pi^+\pi^-$  is  $(69.20 \pm 0.05)\%$ . The natural lifetime of the  $D^0$  meson is  $(4.103 \pm 0.010) \times 10^{-13}$  s and for the  $K_s^0$  meson is  $(8.954 \pm 0.004) \times 10^{-11}$  s. The simulated events were passed through a detailed GEANT4 simulation of the ATLAS detector [84,85] and processed with the same software used to reconstruct the data. The generation of the simulated event samples includes the effect of multiple  $pp$  interactions per bunch crossing, and the effect on the detector response due to interactions from bunch crossings before or after the one containing the hard interaction.

#### 4. Physics objects and event selection

In addition to the trigger and data-quality requirements, several selection criteria are defined to retain events for further analysis. The searches are split into two distinct event selections that share several common requirements. The first selection, henceforth called the  $D^0\gamma$  selection, covers the search for both the  $H \rightarrow D^*\gamma$  and  $Z \rightarrow D^0\gamma$  decays and targets the reconstruction of the  $D^0$  meson. The additional soft daughter pion or photon from the decay of the  $D^*$  is not explicitly reconstructed; this does not deteriorate the sensitivity to the  $H \rightarrow D^*\gamma$  signal. The second selection, the  $K_s^0\gamma$  selection, covers the search for the  $Z \rightarrow K_s^0\gamma$  signal and targets the reconstruction of the  $K_s^0$  meson.

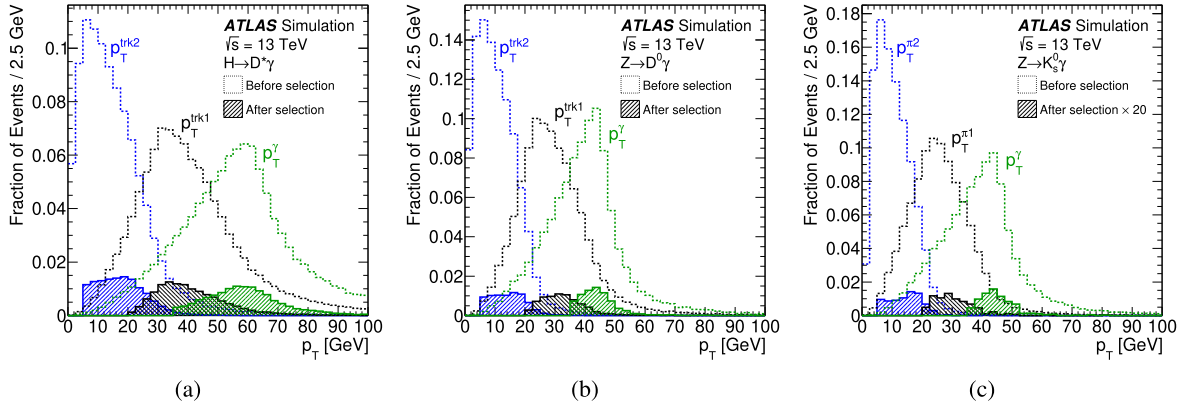
Events with a  $pp$  interaction vertex reconstructed from at least two ID tracks with  $p_T > 500$  MeV are considered in the analysis. Within an event, the primary vertex is defined as the reconstructed vertex with the largest  $\sum p_T^2$  of associated ID tracks. Common to each event selection are the photon and charged-hadron requirements. Photons are recon-

structed from clusters of energy in the electromagnetic calorimeter, and clusters which match ID tracks consistent with the hypothesis of a photon conversion into  $e^+e^-$  are classified as converted photon candidates, whilst clusters which have no matching ID tracks are classified as unconverted photon candidates [86]. Photon candidates are required to satisfy ‘tight’ photon identification criteria [86], and have the kinematic and geometric requirements of  $p_T^\gamma > 35$  GeV and  $|\eta^\gamma| < 2.37$ , excluding the barrel-to-endcap calorimeter transition region  $1.37 < |\eta^\gamma| < 1.52$ . Track- and calorimeter-isolation requirements are imposed to further suppress contamination from jets. For the track isolation, 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 matched to the reconstructed photon itself, is required to be less than 5% of  $p_T^\gamma$ . To mitigate the effects of multiple  $pp$  interactions in the same or neighbouring bunch crossings (pile-up events), only ID tracks consistent with originating from the primary vertex are considered [87]. For the calorimeter isolation, the sum of the transverse momenta of all calorimeter energy deposits within  $\Delta R = 0.4$  of the photon direction, excluding those matched to the reconstructed photon, is required to be less than  $2.45 \text{ GeV} + 0.022 \times p_T^\gamma$  [GeV]. The effects of the underlying event and pile-up events are also accounted for on an event-by-event basis using an average underlying-event energy density determined from data [86].

Charged-hadron candidates are reconstructed from ID tracks and are required to satisfy ‘loose’ track identification criteria [88], and require  $p_T > 5$  GeV and  $|\eta| < 2.5$ . Pairs of charged-hadron candidates are combined to form the meson candidate  $\mathcal{M}$  for each selection, and must have opposite charges. For the  $D^0\gamma$  final state,  $\mathcal{M}$  is a  $D^0$  meson candidate, and for the  $K_s^0\gamma$  final state,  $\mathcal{M}$  is a  $K_s^0$  meson candidate. The charged-hadron candidate in a pair with the higher  $p_T$ , the leading track, must satisfy  $p_T > 20$  GeV. Meson candidates must satisfy the isolation requirement that the sum of the  $p_T$  of the reconstructed ID tracks originating from the primary vertex within  $\Delta R = 0.2$  of the leading charged-hadron candidate, excluding the pair of tracks which define the meson candidate itself, must be less than 10% of the  $p_T$  of the meson candidate.

Combinations of meson and photon candidates must also satisfy  $\Delta\phi > \pi/2$ , where  $\Delta\phi$  is the difference between the azimuthal angle of the two candidates. If an event has multiple photon candidates, the candidate with highest  $p_T$  is chosen; if the event has multiple meson candidates, the candidate with mass closest to the target meson is selected. However, these situations arise in a small fraction of data events: fewer than 5% of events which satisfy the trigger have more than one meson candidate, and fewer than 0.5% of events have more than one photon candidate.

The differences between the two event selections arise from requirements on  $\mathcal{M}$  mass and  $p_T$ , and requirements on the meson candidate vertex. In the  $K_s^0\gamma$  channel, both the tracks are assigned the charged pion mass to calculate the  $\mathcal{M}$  candidate mass. In the  $D^0\gamma$  final state, given the absence of particle identification information in the relevant momentum range, the assignment of the charged kaon or pion masses which gives a value of the  $\mathcal{M}$  mass closest to the  $D^0$  mass is chosen. The  $D^0\gamma$  final state requires that the meson candidate satisfies  $1800 \text{ MeV} < m_{\mathcal{M}} < 1930 \text{ MeV}$  and  $p_T^{\mathcal{M}} > 39$  GeV; the  $K_s^0\gamma$  final state requires  $460 \text{ MeV} < m_{\mathcal{M}} < 538 \text{ MeV}$  and  $p_T^{\mathcal{M}} > 38$  GeV. To reject contributions from events with prompt vertices, requirements on  $L_{xy}/\sigma_{L_{xy}}$ , the  $L_{xy}$  significance of the meson candidate vertex, are imposed. Here  $L_{xy}$  is the signed projection of the vector leading from the primary vertex to the meson candidate vertex onto the direction of the  $\mathcal{M}$  candidate’s  $p_T$ , and its corresponding uncertainty is  $\sigma_{L_{xy}}$ . The  $D^0\gamma$  final state requires  $L_{xy}/\sigma_{L_{xy}} > 3$ , whilst the  $K_s^0\gamma$  final state requires  $L_{xy}/\sigma_{L_{xy}} > 5$ . To remove events from particle interactions in the detector material, the radius of the meson candidate vertex must satisfy  $r < 15$  mm for the  $D^0\gamma$  selection, inside the beampipe, and  $r < 65$  mm for the  $K_s^0\gamma$  selection, between the second and third layers of the pixel detector. While many  $K_s^0$  decays are expected to occur beyond this region, the trigger algorithm described in Section 3 is very inefficient for such events and



**Fig. 2.** Generator-level transverse momentum ( $p_T$ ) distributions of the photon and of the tracks, ordered in  $p_T$ , for (a)  $H \rightarrow D^*\gamma$ , (b)  $Z \rightarrow D^0\gamma$ , and (c)  $Z \rightarrow K_s^0\gamma$  simulated signal events. The hatched histograms denote the full event selection while the dashed histograms show the events at generator level that fall in the geometric acceptance (both the tracks are required to have  $|\eta| < 2.5$  while the photon is required to have  $|\eta'| < 2.37$ , excluding the region  $1.37 < |\eta'| < 1.52$ ). The dashed histograms are normalised to unity, and the relative difference between the two sets of distributions corresponds to the effects of reconstruction, trigger, and event selection efficiencies. The leading track is denoted by  $p_T^{\text{trk}1}$  and the subleading candidate by  $p_T^{\text{trk}2}$  for  $H \rightarrow D^*\gamma$  and  $Z \rightarrow D^0\gamma$ . For  $Z \rightarrow K_s^0\gamma$  these are labelled  $p_T^{\pi 1}$  and  $p_T^{\pi 2}$ .

offline reconstructed vertices with  $r > 65$  mm are dominated by material interactions not matched to the trigger signature. These selection criteria define the nominal ‘Signal Region’ (SR) for each final state, and events which satisfy these criteria are retained for further analysis.

## 5. Signal modelling

Fig. 2 shows the generator-level  $p_T$  distributions of the two tracks and the photon reconstructed in each of the signal decays before and after implementing the nominal SR event selection for each final state. The trigger efficiency after the offline selection is 66% for  $H \rightarrow D^*\gamma$ , 69% for  $Z \rightarrow D^0\gamma$ , and 39% for  $Z \rightarrow K_s^0\gamma$  and is primarily due to differences between online and offline tracking performance. For the  $H \rightarrow D^*\gamma$  signals, the total signal efficiency, including kinematic acceptance, trigger and reconstruction efficiencies, is approximately 9%. The corresponding total efficiency for  $Z \rightarrow D^0\gamma$  is 3% and for  $Z \rightarrow K_s^0\gamma$  is 0.2%. Overall, the lower efficiency to reconstruct the  $Z$  boson decays is due to the softer  $p_T$  distributions of the decay products. The particularly small total efficiency for the  $Z \rightarrow K_s^0\gamma$  signal is related to the large lifetime of the  $K_s^0$  meson, as most decays occur beyond the inner layers of the ID, where the track reconstruction efficiency is significantly reduced.

The Higgs boson mass distribution for  $H \rightarrow D^*\gamma$  is modelled with a sum of two Gaussian probability density functions (pdf) with a common mean value. The mass resolution achieved is 2.2%, and the mean is shifted to approximately 121 GeV without the reconstruction of the additional daughter  $\pi^0$  or photon from the decay of the  $D^*$ . For the  $Z$  boson signals the  $Z$  boson mass distribution is modelled with a Voigtian pdf, a convolution of relativistic Breit–Wigner and Gaussian pdfs, corrected with a mass-dependent efficiency factor which accounts for the turn on in signal efficiency versus  $Z$  boson mass due to the kinematic requirements of the event selection. The mass resolutions achieved are 1.9% for  $Z \rightarrow D^0\gamma$  and 2.3% for  $Z \rightarrow K_s^0\gamma$ , and for each signal the mean of the Voigtian is approximately 91 GeV.

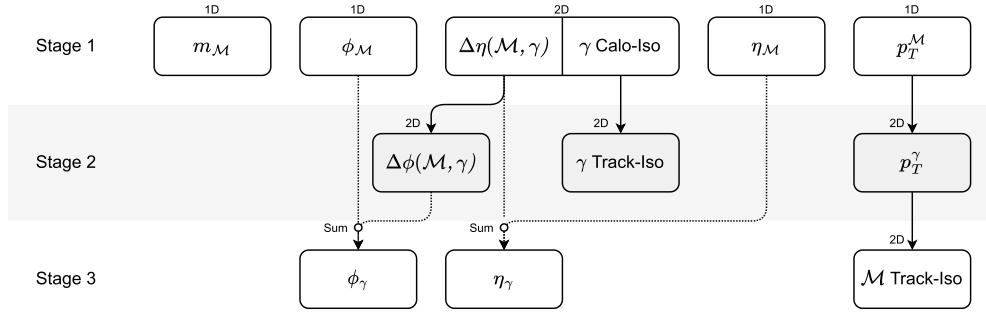
## 6. Background modelling and validation

For each final state, the main sources of background are events involving inclusive multijet or  $\gamma + \text{jet}$  processes, where a meson candidate is reconstructed from ID tracks originating from a jet, and these show a non-resonant kinematic structure in the three-body mass distribution. The background processes are modelled with a non-parametric data-driven approach using very finely binned templates to describe the Higgs and  $Z$  boson mass distributions [89]. The procedure captures

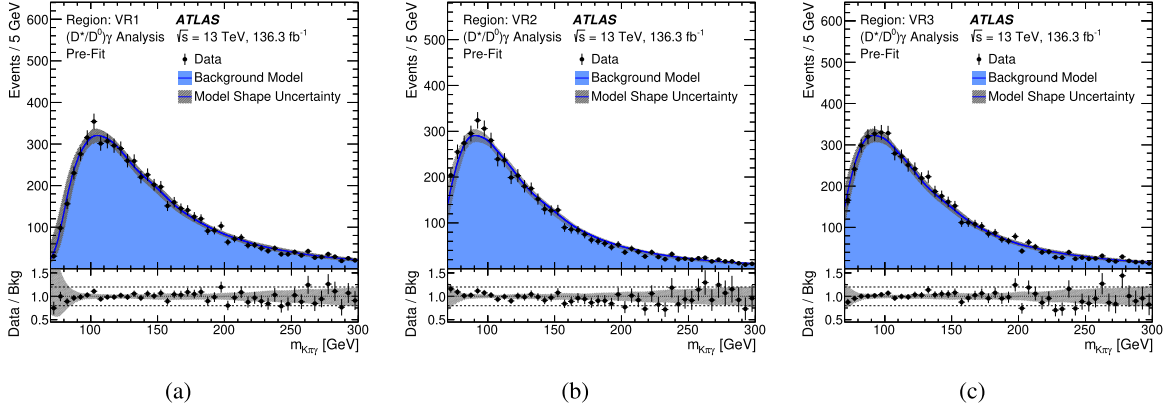
the correlations between the kinematic and isolation variables, thus both the multijet and  $\gamma + \text{jet}$  processes can be modelled inclusively. This technique was also employed in previous ATLAS searches for exclusive decays of the Higgs and  $Z$  bosons into a meson and a photon [43–48], and the specific implementation in this search is summarised below.

A loose, background-dominated selection is defined, denoted the ‘generation region’ (GR), where the nominal isolation requirements from the SR are removed and the meson candidate  $p_T$  requirement is relaxed to  $p_T > 25$  GeV. The GR contains approximately 9700 events for the  $D^0\gamma$  final states, and 1600 events for the  $K_s^0\gamma$  final state. From the events in the GR, pdfs are constructed to describe the distributions of the relevant kinematic and isolation variables and their most important correlations. Pseudo-events, composed of a four momentum vector and isolation variable for both the meson and photon, are generated from these pdfs using the ancestral sampling procedure described in Fig. 3. In this diagram, the labels ‘1D’ and ‘2D’ refer to the dimensionality of the pdfs used to draw the associated variables. Where two boxes in the diagram share a border, the values of the corresponding variables are sampled simultaneously from a combined pdf, and arrows leading into boxes show that the variable is drawn from a pdf described in bins of the input variable generated in a previous stage in the sampling. Vertices in the diagram labelled ‘Sum’ show that the output variable, denoted by the arrow leading out of the vertex, is calculated as a sum of the input variables, denoted by the dashed lines leading in to the vertex. The nominal SR requirements are imposed on the ensemble of pseudo-events generated by this scheme, and the surviving pseudo-events are used to construct finely binned templates for the  $m_{M\gamma}$  distributions in each search, the discriminating variable used in the likelihood fit to the data. These templates are smoothed using Gaussian kernel density estimation [90].

The possibility of residual mismodelling of the background is addressed in the context of the maximum-likelihood fit described in Section 8. The normalisation of the background model is determined directly from a fit to the observed data in the SR. To allow the model to adjust its shape in the context of the fit to the  $m_{M\gamma}$  distributions of the data, three variations to the nominal model are derived which show notably distinct shapes in the  $m_{M\gamma}$  distribution. The first two alternative models are associated with distortions of the model’s internal histograms for two kinematic variables, namely the photon candidate  $p_T$  and the angle  $\Delta\phi$  between the pseudocandidate photon and meson. The form of the chosen distortions is motivated to introduce a large enough shape variation to the resulting  $m_{M\gamma}$  template, ensuring the flexibility of the model to accommodate even large residual shape differences with the data. The third alternative model is obtained by a direct trans-



**Fig. 3.** The ancestral sampling scheme used in the non-parametric data-driven model for each final state, see text for details. Solid arrows indicate that the output variable is sampled in bins of the input variable, whilst dashed arrows indicate that the output variable is calculated as a sum of the input variables.



**Fig. 4.** The  $m_{K^0\pi^0\gamma}$  distribution of the data and pre-fit background model prediction of validation regions for the  $D^0\gamma$  final state. VR1 is shown in (a), where the meson candidate is required to satisfy  $p_T > 39$  GeV in addition to the GR requirements. VR2 is shown in (b), where the meson-candidate isolation requirement used in the SR is applied, in addition to the GR requirements. VR3 is shown in (c), where the photon-candidate isolation requirements used in the SR are applied, in addition to the GR requirements. In all cases, the ratio of the data to the prediction of the background model is shown in the lower panel.

formation of the  $m_{M\gamma}$  template, based on a reweighting function with a linear dependence on  $m_{M\gamma}$ . This form is motivated by the general shape of the small residual pre-fit mismodelling observed in some earlier applications of the method [43–48]. The technique of moment morphing is applied to parameterise the adjustment of the background prediction's shape between that of the nominal model and each variation [91]. Each of the three shape variations has a dedicated nuisance parameter. To help stabilize the fit described in Section 8, the two nuisance parameters associated with the  $\Delta\phi$  and photon  $p_T$  distortions are each constrained by a separate Gaussian term in the likelihood. However, the data in the SR has enough statistical power that all three nuisance parameters are well constrained in the fit to values associated with shape variations much milder than those of the three alternative models.

The just described model was validated through the definition of three intermediate event selection requirements, denoted validation regions (VR). Each validation region is defined by the loose GR selection with one key additional requirement taken from the tight SR selection, as outlined in Table 1. The background modelling process was used to derive predictions for each of the three VRs, which were found to provide a good description of corresponding data samples, as shown in Fig. 4 for the  $D^0\gamma$  final state and Fig. 5 for the  $K_s^0\gamma$  final state. To further validate the model, the background modelling process was repeated with three additional independent validation regions, built using the same sampling scheme and including the shape variations. These validation regions were identical to the nominal SR up to a single change in one of the requirements, resulting in event samples orthogonal to the SR. One pair of validation regions, defined for both the  $D^0\gamma$  and  $K_s^0\gamma$  final states, involved a prompt-vertex selection region, in which the  $L_{xy}$  significance requirement is inverted. Another pair of validation regions considered events in which the two ID tracks that form the me-

**Table 1**

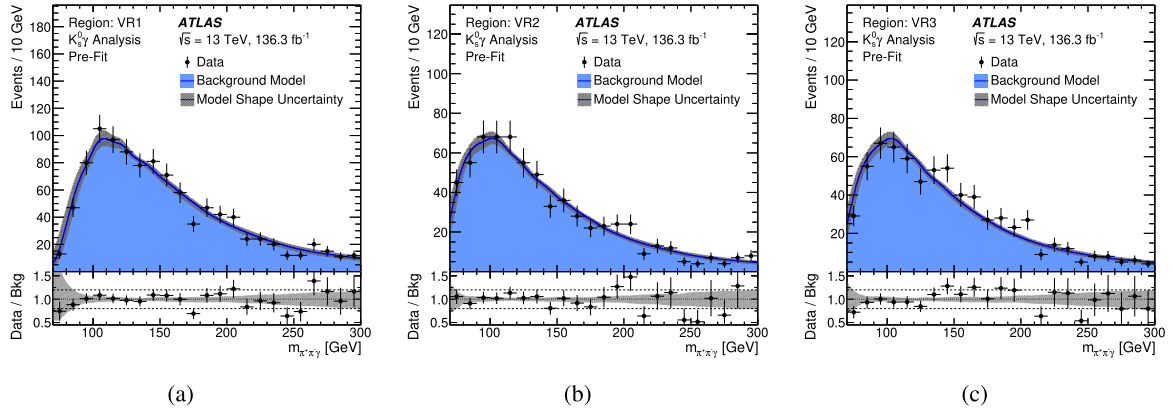
Definition of validation regions, each of which is based on the GR selection with a single additional requirement associated with the SR selection. In the case of the meson  $p_T$  requirement, the value for the  $K_s^0\gamma$  final state is shown in parentheses, while the value for the  $D^0\gamma$  final state is not. The isolation requirements of all regions are common to both the  $D^0\gamma$  and  $K_s^0\gamma$  final states.

Selection	Meson $p_T$	Meson Isolation	Photon Isolation
GR	> 25 GeV	None	None
VR1	> 39(38) GeV	None	None
VR2	> 25 GeV	Tight	None
VR3	> 25 GeV	None	Tight
SR	> 39(38) GeV	Tight	Tight

son candidate are required to have the same sign charge, rather than be oppositely charged. One further validation region was defined for the  $K_s^0\gamma$  final state which selected  $K_s^0$  candidates in a sideband of the mass peak, by requiring  $538 \text{ MeV} < m_{K_s^0} < 1075 \text{ MeV}$ . In all cases, the background modelling procedure, when applied to these validation regions, exhibited good agreement with the data and served as a further validation of the procedure. Studies indicate that potential signal contamination in the GR would not be expected to result in a significant bias in the background prediction in the SR [89].

## 7. Systematic uncertainties

Systematic uncertainties in the signal yield and inferred branching fraction of the Higgs and  $Z$  boson decays are considered. Uncertain-



**Fig. 5.** The  $m_{\pi^+\pi^-\gamma}$  distribution of the data and pre-fit background model prediction of validation regions for the  $K_S^0\gamma$  final state. VR1 is shown in (a), where the meson candidate is required to satisfy  $p_T > 38$  GeV, in addition to the GR requirements. VR2 is shown in (b), where the meson-candidate isolation requirement used in the SR is applied, in addition to the GR requirements. VR3 is shown in (c), where the photon-candidate isolation requirements used in the SR are applied, in addition to the GR requirements. In all cases, the ratio of the data to the prediction of the background model is shown in the lower panel.

ties in the Higgs boson production cross sections from the QCD scale total 5.0% and from the PDFs and strong coupling constant,  $\alpha_s$ , total 3.2% [28,92].

The corresponding uncertainty in the  $Z$  boson production cross-section is 2.9% [82]. The estimated integrated luminosity has an uncertainty of 0.84%, which is calculated using the method described in Ref. [93], and uses the LUCID-2 detector [94] for the primary luminosity measurements, complemented by measurements using the inner detector and calorimeters.

The uncertainty in the acceptance of the Higgs boson signal is estimated by varying the QCD normalisation and factorisation scales,  $\alpha_s$ , PDFs, set of tuned parameters for the underlying event, and parton showering at generator level. The total uncertainty in the  $H \rightarrow D^*\gamma$  signal acceptance is estimated to be 2.0%. For the  $Z$  boson, the respective signal acceptance uncertainty is determined to be 0.40%–0.52% by comparing the  $Z$  boson kinematic distributions in simulated events with measurements in data [95].

Trigger efficiencies for photons are determined from samples enriched with  $Z \rightarrow e^+e^-$  events in data [60]. The photon trigger efficiency is estimated to contribute a systematic uncertainty of 0.66%–0.72% to each of the expected signal yields [60,96]. The uncertainty in the track component of the trigger is derived by varying the leading track  $E_T/p_T$  distribution based on comparisons between data measurements and simulated events in Ref. [97], and is 2.9% for  $H \rightarrow D^*\gamma$ , 3.9% for  $Z \rightarrow D^0\gamma$ , and 6.0% for  $Z \rightarrow K_S^0\gamma$ . Photon identification efficiencies are determined using the enriched  $Z \rightarrow e^+e^-$  event samples, and inclusive photon events and  $Z \rightarrow \ell^+\ell^-\gamma$  events [86]. The photon identification efficiency uncertainties are 1.6%–1.9% for the Higgs and  $Z$  boson signals. The photon energy scale uncertainty, determined from  $Z \rightarrow e^+e^-$  events and validated using  $Z \rightarrow \ell^+\ell^-\gamma$  events [86], is propagated through the simulated samples as a function of  $\eta^\gamma$  and  $p_T^\gamma$ .

The track reconstruction efficiency uncertainties total 1.0%. The uncertainty in the photon energy scale and in the resolution in the simulation has a 0.12%–0.44% effect on the Higgs and  $Z$  boson signal yields. To assess any effect on the expected signal yield from imperfect modelling of pile-up, the average number of pile-up interactions is varied in the simulation; the corresponding uncertainty is 2.9%–3.1%. The uncertainty in the efficiency to reconstruct decays with displaced vertices is estimated by using the studies in Ref. [98], and is 1.5% for the  $D^0$  mesons in  $H \rightarrow D^*\gamma$  and  $Z \rightarrow D^0\gamma$ , and 3.5% for the  $K_S^0$  mesons in  $Z \rightarrow K_S^0\gamma$ .

Combining the individual sources of uncertainty gives a total uncertainty in the signal yields equal to 7.9% for the  $H \rightarrow D^*\gamma$  signal, 6.4% for  $Z \rightarrow D^0\gamma$ , and 8.5% for  $Z \rightarrow K_S^0\gamma$ . The uncertainty in the shape from each of the considered signal systematic uncertainties and from the sta-

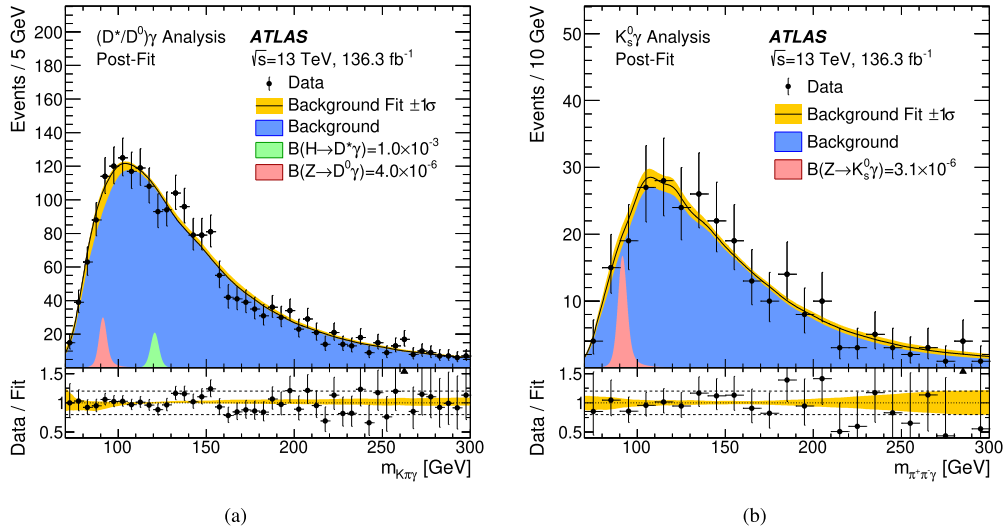
tistical uncertainty in the simulated samples was found to be negligible. Systematic uncertainties in the shape of the background model are also considered, as described in Section 6.

## 8. Results

In total, 2243 events are observed in the signal region for the  $D^0\gamma$  and  $D^*\gamma$  final states and 283 events are observed in the signal region for the  $K_S^0\gamma$  final state. The selected data are compared with background and signal predictions using an unbinned maximum-likelihood fit to the  $m_{M\gamma}$  distribution in the range of  $70 \text{ GeV} < m_{M\gamma} < 300 \text{ GeV}$ . The parameters of interest are the Higgs and  $Z$  boson signal normalisations, and systematic uncertainties are modelled using additional nuisance parameters in the fit. The background normalisation is a free parameter in the model. Upper limits are set on the branching fractions for each of the Higgs and  $Z$  boson signal decays using the  $\text{CL}_s$  modified frequentist formalism [99] with the profile-likelihood-ratio test statistic and the asymptotic approximations derived in Ref. [100]. For  $D^0\gamma$  and  $D^*\gamma$  final states, limits on the  $H \rightarrow D^*\gamma$  signal are obtained while profiling the signal normalisation parameter of the  $Z \rightarrow D^0\gamma$  process (and vice versa). 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 signals, as discussed in Section 5.

The results of the background-only fits for each search are shown in Fig. 6, where the signal distributions shown correspond to the extracted 95% confidence-level (CL) branching fraction upper limits. The expected and observed numbers of background events in the three-body mass ranges relevant to the Higgs and  $Z$  boson signals are given in Table 2, where the expected backgrounds are obtained from fits to these backgrounds. Table 2 also shows the expected number of signal events for reference branching fractions near the sensitivity of the analysis:  $10^{-3}$  for  $H \rightarrow D^*\gamma$  and  $10^{-6}$  for  $Z \rightarrow D^0\gamma$  and  $Z \rightarrow K_S^0\gamma$ . No significant signal is observed in any of the search channels and the  $p$ -values for the background only hypothesis are 0.24, 0.23 and 0.43 in the  $H \rightarrow D^*\gamma$ ,  $Z \rightarrow D^0\gamma$  and  $Z \rightarrow K_S^0\gamma$  channels, respectively.

The expected and observed 95% CL upper limits on the branching fractions for Higgs and  $Z$  boson decays into each final state are presented in Table 3, along with the observed upper limits in terms of Higgs and  $Z$  boson production cross-section times branching fraction for each decay. The systematic uncertainties in the signal normalisation and background shape described respectively in Sections 5 and 6 result in a 2% increase of the expected 95% CL upper limit on the branching fraction of the  $H \rightarrow D^*\gamma$  decay, a 9% increase for the  $Z \rightarrow D^0\gamma$  decay, and a 10% increase for the  $Z \rightarrow K_S^0\gamma$  decay, mostly due to the systematic uncertainty in the background shape.



**Fig. 6.** Comparison between data and background prediction for the  $m_{M\gamma}$  distribution after the background-only fit (“Post-Fit”) in the signal region for the (a)  $D^*\gamma$  and  $D^0\gamma$  final states and for the (b)  $K_s^0\gamma$  final state. The unbinned background pdf is shown with a yellow band that represents the uncertainty in the fit arising from the constrained background shape systematic uncertainties. This uncertainty is largest in the region  $m_{M\gamma} < 100$  GeV, where the gradient of the distributions varies most. The choice of bin width is motivated only to best visualise the data and is independent of the likelihood definition. The lower panels show the ratio between the data and the background prediction. The expected signal distributions are shown normalised to a branching fraction corresponding to the observed 95% CL upper limit.

**Table 2**

Numbers of observed and expected background events for the  $m_{M\gamma}$  ranges of interest. Each expected background and the corresponding uncertainty is obtained by integrating the total pdf after a background-only fit to the data, where the uncertainty does not take into account statistical fluctuations in each mass range. Expected Higgs and Z boson signal contributions, with their corresponding total systematic uncertainty, are shown for reference branching fractions of  $10^{-3}$  and  $10^{-6}$ , 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 $B = 10^{-3}$	Z signal $B = 10^{-6}$
$H \rightarrow D^*\gamma$	116–126	203 (214.8 $\pm$ 5.5)	25.4 $\pm$ 2.0	–
$Z \rightarrow D^0\gamma$	86–96	215 (206 $\pm$ 14)	–	10.3 $\pm$ 0.7
$Z \rightarrow K_s^0\gamma$	86–96	21 (19.5 $\pm$ 2.0)	–	4.2 $\pm$ 0.4

**Table 3**

Observed and expected (with the corresponding  $\pm 1\sigma$  intervals) 95% CL upper limits on the branching fractions for  $H \rightarrow D^*\gamma$ ,  $Z \rightarrow D^0\gamma$  and  $Z \rightarrow K_s^0\gamma$ . Standard Model production of the Higgs boson is assumed. The corresponding upper limits on the production cross-section times branching fraction  $\sigma \times B$  are also shown.

Channel	95% CL upper limits			
	Branching Fraction		$\sigma \times B$ [fb]	
	Observed	Expected	Observed	Expected
$H \rightarrow D^*\gamma$	$1.0 \times 10^{-3}$	$1.2^{+0.5}_{-0.3} \times 10^{-3}$	58	$68^{+28}_{-19}$
$Z \rightarrow D^0\gamma$	$4.0 \times 10^{-6}$	$3.4^{+1.4}_{-1.0} \times 10^{-6}$	235	$200^{+82}_{-56}$
$Z \rightarrow K_s^0\gamma$	$3.1 \times 10^{-6}$	$3.0^{+1.3}_{-0.8} \times 10^{-6}$	185	$176^{+77}_{-49}$

## 9. Conclusions

Searches for the flavour-violating exclusive decays of the Higgs boson  $H \rightarrow D^*\gamma$ ,  $Z \rightarrow D^0\gamma$  and  $Z \rightarrow K_s^0\gamma$  were made using  $136.3 \text{ fb}^{-1}$  of  $pp$  collision data at  $\sqrt{s} = 13$  TeV collected with the ATLAS detector at the LHC. Each of these decay channels involve a displaced vertex, either from the decay of a  $D^0$  meson or from a  $K_s^0$  meson. The observed data are compatible with the expected backgrounds. The observed 95% CL upper limits are  $B(H \rightarrow D^*\gamma) < 1.0 \times 10^{-3}$ ,  $B(Z \rightarrow D^0\gamma) < 4.0 \times 10^{-6}$ ,

and  $B(Z \rightarrow K_s^0\gamma) < 3.1 \times 10^{-6}$ . The corresponding expected 95% CL upper limits on the branching fractions of each decay are  $B(H \rightarrow D^*\gamma) < 1.2 \times 10^{-3}$ ,  $B(Z \rightarrow D^0\gamma) < 3.4 \times 10^{-6}$ , and  $B(Z \rightarrow K_s^0\gamma) < 3.0 \times 10^{-6}$ , where Standard Model Higgs boson production is assumed. These results represent the first limits set on the decays  $H \rightarrow D^*\gamma$  and  $Z \rightarrow K_s^0\gamma$ , and a factor of approximately 500 improvement on the  $Z \rightarrow D^0\gamma$  limit set by LHCb.

## 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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## The ATLAS Collaboration

G. Aad<sup>103, [id](#)</sup>, E. Aakvaag<sup>16, [id](#)</sup>, B. Abbott<sup>121, [id](#)</sup>, K. Abeling<sup>55, [id](#)</sup>, N.J. Abicht<sup>49, [id](#)</sup>, S.H. Abidi<sup>29, [id](#)</sup>, M. Aboelela<sup>44, [id](#)</sup>, A. Aboulhorma<sup>35e, [id](#)</sup>, H. Abramowicz<sup>152, [id](#)</sup>, H. Abreu<sup>151, [id](#)</sup>, Y. Abulaiti<sup>118, [id](#)</sup>, B.S. Acharya<sup>69a,69b, [id](#)</sup>, A. Ackermann<sup>63a, [id](#)</sup>, C. Adam Bourdarios<sup>4, [id](#)</sup>, L. Adamczyk<sup>86a, [id](#)</sup>, S.V. Addepalli<sup>26, [id](#)</sup>, M.J. Addison<sup>102, [id](#)</sup>, J. Adelman<sup>116, [id](#)</sup>, A. Adiguzel<sup>21c, [id](#)</sup>, T. Adye<sup>135, [id](#)</sup>, A.A. Affolder<sup>137, [id](#)</sup>, Y. Afik<sup>39, [id](#)</sup>, M.N. Agarar<sup>13, [id](#)</sup>, J. Agarwala<sup>73a,73b, [id](#)</sup>, A. Aggarwal<sup>101, [id](#)</sup>, C. Agheorghiesei<sup>27c, [id](#)</sup>, A. Ahmad<sup>36, [id](#)</sup>, F. 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Amirie<sup>156, [id](#)</sup>, S.P. Amor Dos Santos<sup>131a, [id](#)</sup>, K.R. Amos<sup>164, [id](#)</sup>, S. An<sup>84, [id](#)</sup>, V. Ananiev<sup>126, [id](#)</sup>, C. Anastopoulos<sup>140, [id](#)</sup>, T. Andeen<sup>11, [id](#)</sup>, J.K. Anders<sup>36, [id](#)</sup>, S.Y. Andreatan<sup>47a,47b, [id](#)</sup>, A. Andreatza<sup>71a,71b, [id](#)</sup>, S. Angelidakis<sup>9, [id](#)</sup>, A. Angerami<sup>41, [id](#)</sup>, A.V. Anisenkov<sup>37, [id](#)</sup>, A. Annovi<sup>74a, [id](#)</sup>, C. Antel<sup>56, [id](#)</sup>, M.T. Anthony<sup>140, [id](#)</sup>, E. Antipov<sup>146, [id](#)</sup>, M. Antonelli<sup>53, [id](#)</sup>, F. Anulli<sup>75a, [id](#)</sup>, M. Aoki<sup>84, [id](#)</sup>, T. Aoki<sup>154, [id](#)</sup>, J.A. Aparisi Pozo<sup>164, [id](#)</sup>, M.A. Aparo<sup>147, [id](#)</sup>, L. Aperio Bella<sup>48, [id](#)</sup>, C. Appelt<sup>18, [id](#)</sup>, A. Apyan<sup>26, [id](#)</sup>, S.J. Arbiol Val<sup>87, [id](#)</sup>, C. Arcangeletti<sup>53, [id](#)</sup>, A.T.H. Arce<sup>51, [id](#)</sup>, E. Arena<sup>93, [id](#)</sup>, J-F. Arguin<sup>109, [id](#)</sup>, S. Argyropoulos<sup>54, [id](#)</sup>, J.-H. Arling<sup>48, [id](#)</sup>, O. Arnaez<sup>4, [id](#)</sup>, H. Arnold<sup>115, [id](#)</sup>, G. Artoni<sup>75a,75b, [id](#)</sup>, H. Asada<sup>112, [id](#)</sup>, K. Asai<sup>119, [id](#)</sup>, S. Asai<sup>154, [id](#)</sup>, N.A. Asbah<sup>36, [id](#)</sup>, K. Assamagan<sup>29, [id](#)</sup>, R. Astalos<sup>28a, [id](#)</sup>, K.S.V. Astrand<sup>99, [id](#)</sup>, S. Atashi<sup>160, [id](#)</sup>, R.J. Atkin<sup>33a, [id](#)</sup>, M. Atkinson<sup>163, [id](#)</sup>, H. Atmani<sup>35f, [id](#)</sup>, P.A. Atmasiddha<sup>129, [id](#)</sup>, K. Augsten<sup>133, [id](#)</sup>, S. Auricchio<sup>72a,72b, [id](#)</sup>, A.D. Auriol<sup>20, [id](#)</sup>, V.A. Austrup<sup>102, [id](#)</sup>, G. Avolio<sup>36, [id](#)</sup>, K. Axiotis<sup>56, [id](#)</sup>, G. Azuelos<sup>109, [id](#)</sup>, D. Babal<sup>28b, [id](#)</sup>, H. Bachacou<sup>136, [id](#)</sup>, K. Bachas<sup>153, [id](#)</sup>, A. Bachiu<sup>34, [id](#)</sup>, F. Backman<sup>47a,47b, [id](#)</sup>, A. Badea<sup>39, [id](#)</sup>, T.M. Baer<sup>107, [id](#)</sup>, P. Bagnaia<sup>75a,75b, [id](#)</sup>, M. Bahmani<sup>18, [id](#)</sup>, D. Bahner<sup>54, [id](#)</sup>, K. Bai<sup>124, [id](#)</sup>, J.T. Baines<sup>135, [id](#)</sup>, L. Baines<sup>95, [id](#)</sup>, O.K. Baker<sup>173, [id](#)</sup>, E. Bakos<sup>15, [id](#)</sup>, D. Bakshi Gupta<sup>8, [id](#)</sup>, V. Balakrishnan<sup>121, [id](#)</sup>, R. Balasubramanian<sup>115, [id](#)</sup>, E.M. Baldin<sup>37, [id](#)</sup>, P. Balek<sup>86a, [id](#)</sup>, E. Ballabene<sup>23b,23a, [id](#)</sup>, F. Balli<sup>136, [id](#)</sup>, L.M. Baltes<sup>63a, [id](#)</sup>, W.K. Balunas<sup>32, [id](#)</sup>, J. Balz<sup>101, [id](#)</sup>, E. Banas<sup>87, [id](#)</sup>, M. Bandieramonte<sup>130, [id](#)</sup>, A. Bandyopadhyay<sup>24, [id](#)</sup>, S. 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 M. Belfkir <sup>117b, [id](#)</sup>, G. Bella <sup>152, [id](#)</sup>, L. Bellagamba <sup>23b, [id](#)</sup>, A. Bellerive <sup>34, [id](#)</sup>, P. Bellos <sup>20, [id](#)</sup>, K. Beloborodov <sup>37, [id](#)</sup>,  
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 M. Campanelli <sup>97, [id](#)</sup>, A. Camplani <sup>42, [id](#)</sup>, V. Canale <sup>72a,72b, [id](#)</sup>, A.C. Canbay <sup>3a, [id](#)</sup>, E. Canonero <sup>96, [id](#)</sup>, J. Cantero <sup>164, [id](#)</sup>,  
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M. Chatterjee <sup>19, [id](#)</sup>, C. Chauhan <sup>134, [id](#)</sup>, Y. Che <sup>14c, [id](#)</sup>, S. Chekanov <sup>6, [id](#)</sup>, S.V. Chekulaev <sup>157a, [id](#)</sup>, G.A. Chelkov <sup>38, [id](#), [a](#)</sup>,  
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M. Corradi <sup>75a, 75b, [id](#)</sup>, F. Corriveau <sup>105, [id](#), [w](#)</sup>, A. Cortes-Gonzalez <sup>18, [id](#)</sup>, M.J. Costa <sup>164, [id](#)</sup>, F. Costanza <sup>4, [id](#)</sup>,  
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F. Curcio <sup>164, [id](#)</sup>, J.R. Curran <sup>52, [id](#)</sup>, P. Czodrowski <sup>36, [id](#)</sup>, M.M. Czurylo <sup>36, [id](#)</sup>,  
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S.J. Das <sup>29, [id](#), [ag](#)</sup>, F. Dattola <sup>48, [id](#)</sup>, S. D'Auria <sup>71a, 71b, [id](#)</sup>, A. D'Avanzo <sup>72a, 72b, [id](#)</sup>, C. David <sup>33a, [id](#)</sup>, T. Davidek <sup>134, [id](#)</sup>,  
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 X. Lou<sup>14a,14e, [ib](#)</sup>, A. Lounis<sup>66, [ib](#)</sup>, P.A. Love<sup>92, [ib](#)</sup>, G. Lu<sup>14a,14e, [ib](#)</sup>, M. Lu<sup>66, [ib](#)</sup>, S. Lu<sup>129, [ib](#)</sup>, Y.J. Lu<sup>65, [ib](#)</sup>,  
 H.J. Lubatti<sup>139, [ib](#)</sup>, C. Luci<sup>75a,75b, [ib](#)</sup>, F.L. Lucio Alves<sup>14c, [ib](#)</sup>, F. Luehring<sup>68, [ib](#)</sup>, I. Luise<sup>146, [ib](#)</sup>, O. Lukianchuk<sup>66, [ib](#)</sup>,  
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 A. Maio<sup>131a,131b,131d, [ib](#)</sup>, K. Maj<sup>86a, [ib](#)</sup>, O. Majersky<sup>48, [ib](#)</sup>, S. Majewski<sup>124, [ib](#)</sup>, N. Makovec<sup>66, [ib](#)</sup>, V. Maksimovic<sup>15, [ib](#)</sup>,  
 B. Malaescu<sup>128, [ib](#)</sup>, Pa. Malecki<sup>87, [ib](#)</sup>, V.P. Maleev<sup>37, [ib](#)</sup>, F. Malek<sup>60, [ib](#),<sup>n</sup></sup>, M. Mali<sup>94, [ib](#)</sup>, D. Malito<sup>96, [ib](#)</sup>,  
 U. Mallik<sup>80, [ib](#)</sup>, S. Maltezos<sup>10</sup>, S. Malyukov<sup>38</sup>, J. Mamuzic<sup>13, [ib](#)</sup>, G. Mancini<sup>53, [ib](#)</sup>, M.N. Mancini<sup>26, [ib](#)</sup>,  
 G. Manco<sup>73a,73b, [ib](#)</sup>, J.P. Mandalia<sup>95, [ib](#)</sup>, I. Mandić<sup>94, [ib](#)</sup>, L. Manhaes de Andrade Filho<sup>83a, [ib](#)</sup>, I.M. Maniatis<sup>170, [ib](#)</sup>,  
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 C. Meroni <sup>71a,71b, [ID](#)</sup>, J. Metcalfe <sup>6, [ID](#)</sup>, A.S. Mete <sup>6, [ID](#)</sup>, C. Meyer <sup>68, [ID](#)</sup>, J-P. Meyer <sup>136, [ID](#)</sup>, R.P. Middleton <sup>135, [ID](#)</sup>,  
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 M. Mlinarevic <sup>97, [ID](#)</sup>, T. Mlinarevic <sup>97, [ID](#)</sup>, M. Mlynarikova <sup>36, [ID](#)</sup>, S. Mobius <sup>19, [ID](#)</sup>, P. Mogg <sup>110, [ID](#)</sup>,  
 M.H. Mohamed Farook <sup>113, [ID](#)</sup>, A.F. Mohammed <sup>14a,14c, [ID](#)</sup>, S. Mohapatra <sup>41, [ID](#)</sup>, G. Mokgatitwane <sup>33g, [ID](#)</sup>,  
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 B.P. Nachman <sup>17a, [ID](#)</sup>, O. Nackenhorst <sup>49, [ID](#)</sup>, K. Nagai <sup>127, [ID](#)</sup>, K. Nagano <sup>84, [ID](#)</sup>, J.L. Nagle <sup>29, [ID](#)</sup>, E. Nagy <sup>103, [ID](#)</sup>,  
 A.M. Nairz <sup>36, [ID](#)</sup>, Y. Nakahama <sup>84, [ID](#)</sup>, K. Nakamura <sup>84, [ID](#)</sup>, K. Nakkalil <sup>5, [ID](#)</sup>, H. Nanjo <sup>125, [ID](#)</sup>, R. Narayan <sup>44, [ID](#)</sup>,  
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 F. Nechansky <sup>48, [ID](#)</sup>, L. Nedic <sup>127, [ID](#)</sup>, T.J. Neep <sup>20, [ID](#)</sup>, A. Negri <sup>73a,73b, [ID](#)</sup>, M. Negrini <sup>23b, [ID](#)</sup>, C. Nellist <sup>115, [ID](#)</sup>,  
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 J. Ocariz <sup>128, [ID](#)</sup>, A. Ochi <sup>85, [ID](#)</sup>, I. Ochoa <sup>131a, [ID](#)</sup>, S. Oerdek <sup>48, [ID](#)</sup>, J.T. Offermann <sup>39, [ID](#)</sup>, A. Ogrodnik <sup>134, [ID](#)</sup>,  
 A. Oh <sup>102, [ID](#)</sup>, C.C. Ohm <sup>145, [ID](#)</sup>, H. Oide <sup>84, [ID](#)</sup>, R. Oishi <sup>154, [ID](#)</sup>, M.L. Ojeda <sup>48, [ID](#)</sup>, Y. Okumura <sup>154, [ID](#)</sup>,  
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 V. O'Shea <sup>59, [ID](#)</sup>, L.M. Osojnak <sup>129, [ID](#)</sup>, R. Ospanov <sup>62a, [ID](#)</sup>, G. Otero y Garzon <sup>30, [ID](#)</sup>, H. Otono <sup>89, [ID](#)</sup>, P.S. Ott <sup>63a, [ID](#)</sup>,  
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Y. Zhao<sup>137, [ID](#)</sup>, Z. Zhao<sup>62a, [ID](#)</sup>, Z. Zhao<sup>62a, [ID](#)</sup>, A. Zhemchugov<sup>38, [ID](#)</sup>, J. Zheng<sup>14c, [ID](#)</sup>, K. Zheng<sup>163, [ID](#)</sup>, X. Zheng<sup>62a, [ID](#)</sup>,  
Z. Zheng<sup>144, [ID](#)</sup>, D. Zhong<sup>163, [ID](#)</sup>, B. Zhou<sup>107, [ID](#)</sup>, H. Zhou<sup>7, [ID](#)</sup>, N. Zhou<sup>62c, [ID](#)</sup>, Y. Zhou<sup>14c, [ID](#)</sup>, Y. Zhou<sup>7, [ID](#)</sup>,  
C.G. Zhu<sup>62b, [ID](#)</sup>, J. Zhu<sup>107, [ID](#)</sup>, X. Zhu<sup>62d, [ID](#)</sup>, Y. Zhu<sup>62c, [ID](#)</sup>, Y. Zhu<sup>62a, [ID](#)</sup>, X. Zhuang<sup>14a, [ID](#)</sup>, K. Zhukov<sup>37, [ID](#)</sup>,  
N.I. Zimine<sup>38, [ID](#)</sup>, J. Zinsser<sup>63b, [ID](#)</sup>, M. Ziolkowski<sup>142, [ID](#)</sup>, L. Živković<sup>15, [ID](#)</sup>, A. Zoccoli<sup>23b,23a, [ID](#)</sup>, K. Zoch<sup>61, [ID](#)</sup>,  
T.G. Zorbas<sup>140, [ID](#)</sup>, O. Zormpa<sup>46, [ID](#)</sup>, W. Zou<sup>41, [ID](#)</sup>, L. Zwalinski<sup>36, [ID](#)</sup>

<sup>1</sup> Department of Physics, University of Adelaide, Adelaide; Australia<sup>2</sup> Department of Physics, University of Alberta, Edmonton AB; Canada<sup>3</sup> (a) Department of Physics, Ankara University, Ankara; (b) Division of Physics, TOBB University of Economics and Technology, Ankara; Türkiye<sup>4</sup> LAPP, Université Savoie Mont Blanc, CNRS/IN2P3, Annecy; France<sup>5</sup> APC, Université Paris Cité, CNRS/IN2P3, Paris; France<sup>6</sup> High Energy Physics Division, Argonne National Laboratory, Argonne IL; United States of America<sup>7</sup> Department of Physics, University of Arizona, Tucson AZ; United States of America<sup>8</sup> Department of Physics, University of Texas at Arlington, Arlington TX; United States of America<sup>9</sup> Physics Department, National and Kapodistrian University of Athens, Athens; Greece<sup>10</sup> Physics Department, National Technical University of Athens, Zografou; Greece<sup>11</sup> Department of Physics, University of Texas at Austin, Austin TX; United States of America<sup>12</sup> Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan<sup>13</sup> Institut de Física d'Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona; Spain<sup>14</sup> (a) Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; (b) Physics Department, Tsinghua University, Beijing; (c) Department of Physics, Nanjing University, Nanjing; (d) School of Science, Shenzhen Campus of Sun Yat-sen University; (e) University of Chinese Academy of Science (UCAS), Beijing; China<sup>15</sup> Institute of Physics, University of Belgrade, Belgrade; Serbia<sup>16</sup> Department for Physics and Technology, University of Bergen, Bergen; Norway<sup>17</sup> (a) Physics Division, Lawrence Berkeley National Laboratory, Berkeley CA; (b) University of California, Berkeley CA; United States of America<sup>18</sup> Institut für Physik, Humboldt Universität zu Berlin, Berlin; Germany<sup>19</sup> Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern; Switzerland<sup>20</sup> School of Physics and Astronomy, University of Birmingham, Birmingham; United Kingdom<sup>21</sup> (a) Department of Physics, Bogaziçi University, Istanbul; (b) Department of Physics Engineering, Gaziantep University, Gaziantep; (c) Department of Physics, Istanbul University, Istanbul; Türkiye<sup>22</sup> (a) Facultad de Ciencias y Centro de Investigaciones, Universidad Antonio Nariño, Bogotá; (b) Departamento de Física, Universidad Nacional de Colombia, Bogotá; Colombia<sup>23</sup> (a) Dipartimento di Fisica e Astronomia A. Righi, Università di Bologna, Bologna; (b) INFN Sezione di Bologna; Italy<sup>24</sup> Physikalisches Institut, Universität Bonn, Bonn; Germany<sup>25</sup> Department of Physics, Boston University, Boston MA; United States of America<sup>26</sup> Department of Physics, Brandeis University, Waltham MA; United States of America<sup>27</sup> (a) Transilvania University of Brasov, Brasov; (b) Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest; (c) Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi; (d) National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca; (e) National University of Science and Technology<sup>28</sup> Politehnica, Bucharest; (f) West University in Timisoara, Timisoara; (g) Faculty of Physics, University of Bucharest, Bucharest; Romania<sup>29</sup> (a) Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava; (b) Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice; Slovak Republic<sup>30</sup> Physics Department, Brookhaven National Laboratory, Upton NY; United States of America<sup>31</sup> Universidad de Buenos Aires, Facultad de Ciencias Exactas y Naturales, Departamento de Física, y CONICET, Instituto de Física de Buenos Aires (IFIBA), Buenos Aires; Argentina<sup>32</sup> California State University, CA; United States of America<sup>33</sup> Cavendish Laboratory, University of Cambridge, Cambridge; United Kingdom<sup>34</sup> (a) Department of Physics, University of Cape Town, Cape Town; (b) iThemba Labs, Western Cape; (c) Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg;<sup>35</sup> (d) National Institute of Physics, University of the Philippines Diliman (Philippines); (e) University of South Africa, Department of Physics, Pretoria; (f) University of Zululand, KwaDlangezwa;<sup>36</sup> School of Physics, University of the Witwatersrand, Johannesburg; South Africa<sup>37</sup> Department of Physics, Carleton University, Ottawa ON; Canada<sup>38</sup> (a) Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies – Université Hassan II, Casablanca; (b) Faculté des Sciences, Université Ibn-Tofail, Kénitra; (c) Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA, Marrakech; (d) LPMR, Faculté des Sciences, Université Mohamed Premier, Oujda; (e) Faculté des sciences, Université Mohammed V, Rabat;<sup>39</sup> (f) Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir; Morocco<sup>40</sup> CERN, Geneva; Switzerland<sup>41</sup> Affiliated with an institute covered by a cooperation agreement with CERN<sup>42</sup> Affiliated with an international laboratory covered by a cooperation agreement with CERN<sup>43</sup> Enrico Fermi Institute, University of Chicago, Chicago IL; United States of America<sup>44</sup> LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand; France<sup>45</sup> Nevis Laboratory, Columbia University, Irvington NY; United States of America<sup>46</sup> Niels Bohr Institute, University of Copenhagen, Copenhagen; Denmark<sup>47</sup> (a) Dipartimento di Fisica, Università della Calabria, Rende; (b) INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; Italy<sup>48</sup> Physics Department, Southern Methodist University, Dallas TX; United States of America<sup>49</sup> Physics Department, University of Texas at Dallas, Richardson TX; United States of America<sup>50</sup> National Centre for Scientific Research “Demokritos”, Agia Paraskevi; Greece<sup>51</sup> (a) Department of Physics, Stockholm University; (b) Oskar Klein Centre, Stockholm; Sweden<sup>52</sup> Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen; Germany<sup>53</sup> Fakultät Physik, Technische Universität Dortmund, Dortmund; Germany<sup>54</sup> Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden; Germany<sup>55</sup> Department of Physics, Duke University, Durham NC; United States of America<sup>56</sup> SUPA – School of Physics and Astronomy, University of Edinburgh, Edinburgh; United Kingdom<sup>57</sup> INFN e Laboratori Nazionali di Frascati, Frascati; Italy<sup>58</sup> Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg; Germany

- 55 II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen; Germany
- 56 Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland
- 57 <sup>(a)</sup> Dipartimento di Fisica, Università di Genova, Genova; <sup>(b)</sup> INFN Sezione di Genova; Italy
- 58 II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen; Germany
- 59 SUPA – School of Physics and Astronomy, University of Glasgow, Glasgow; United Kingdom
- 60 LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble; France
- 61 Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA; United States of America
- 62 <sup>(a)</sup> Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei; <sup>(b)</sup> Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao; <sup>(c)</sup> School of Physics and Astronomy, Shanghai Jiao Tong University, Key Laboratory for Particle Astrophysics and Cosmology (MOE), SKLPPC, Shanghai; <sup>(d)</sup> Tsung-Dao Lee Institute, Shanghai; <sup>(e)</sup> School of Physics and Microelectronics, Zhengzhou University; China
- 63 <sup>(a)</sup> Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; <sup>(b)</sup> Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; Germany
- 64 <sup>(a)</sup> Department of Physics, Chinese University of Hong Kong, Shatin, N. T., Hong Kong; <sup>(b)</sup> Department of Physics, University of Hong Kong, Hong Kong; <sup>(c)</sup> Department of Physics and Institute for Advanced Study, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong; China
- 65 Department of Physics, National Tsing Hua University, Hsinchu; Taiwan
- 66 IJCLab, Université Paris-Saclay, CNRS/IN2P3, 91405, Orsay; France
- 67 Centro Nacional de Microelectrónica (IMB-CNM-CSIC), Barcelona; Spain
- 68 Department of Physics, Indiana University, Bloomington IN; United States of America
- 69 <sup>(a)</sup> INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine; <sup>(b)</sup> ICTP, Trieste; <sup>(c)</sup> Dipartimento Politecnico di Ingegneria e Architettura, Università di Udine, Udine; Italy
- 70 <sup>(a)</sup> INFN Sezione di Lecce; <sup>(b)</sup> Dipartimento di Matematica e Fisica, Università del Salento, Lecce; Italy
- 71 <sup>(a)</sup> INFN Sezione di Milano; <sup>(b)</sup> Dipartimento di Fisica, Università di Milano, Milano; Italy
- 72 <sup>(a)</sup> INFN Sezione di Napoli; <sup>(b)</sup> Dipartimento di Fisica, Università di Napoli, Napoli; Italy
- 73 <sup>(a)</sup> INFN Sezione di Pavia; <sup>(b)</sup> Dipartimento di Fisica, Università di Pavia, Pavia; Italy
- 74 <sup>(a)</sup> INFN Sezione di Pisa; <sup>(b)</sup> Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa; Italy
- 75 <sup>(a)</sup> INFN Sezione di Roma; <sup>(b)</sup> Dipartimento di Fisica, Sapienza Università di Roma, Roma; Italy
- 76 <sup>(a)</sup> INFN Sezione di Roma Tor Vergata; <sup>(b)</sup> Dipartimento di Fisica, Università di Roma Tor Vergata, Roma; Italy
- 77 <sup>(a)</sup> INFN Sezione di Roma Tre; <sup>(b)</sup> Dipartimento di Matematica e Fisica, Università Roma Tre, Roma; Italy
- 78 <sup>(a)</sup> INFN-TIFPA; <sup>(b)</sup> Università degli Studi di Trento, Trento; Italy
- 79 Universität Innsbruck, Department of Astro and Particle Physics, Innsbruck; Austria
- 80 University of Iowa, Iowa City IA; United States of America
- 81 Department of Physics and Astronomy, Iowa State University, Ames IA; United States of America
- 82 Istinye University, Sariyer, Istanbul; Türkiye
- 83 <sup>(a)</sup> Departamento de Engenharia Elétrica, Universidade Federal de Juiz de Fora (UFJF), Juiz de Fora; <sup>(b)</sup> Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; <sup>(c)</sup> Instituto de Física, Universidade de São Paulo, São Paulo; <sup>(d)</sup> Rio de Janeiro State University, Rio de Janeiro; <sup>(e)</sup> Federal University of Bahia, Bahia; Brazil
- 84 KEK, High Energy Accelerator Research Organization, Tsukuba; Japan
- 85 Graduate School of Science, Kobe University, Kobe; Japan
- 86 <sup>(a)</sup> AGH University of Krakow, Faculty of Physics and Applied Computer Science, Krakow; <sup>(b)</sup> Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow; Poland
- 87 Institute of Nuclear Physics Polish Academy of Sciences, Krakow; Poland
- 88 Faculty of Science, Kyoto University, Kyoto; Japan
- 89 Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka; Japan
- 90 L2IT, Université de Toulouse, CNRS/IN2P3, UPS, Toulouse; France
- 91 Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata; Argentina
- 92 Physics Department, Lancaster University, Lancaster; United Kingdom
- 93 Oliver Lodge Laboratory, University of Liverpool, Liverpool; United Kingdom
- 94 Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana; Slovenia
- 95 School of Physics and Astronomy, Queen Mary University of London, London; United Kingdom
- 96 Department of Physics, Royal Holloway University of London, Egham; United Kingdom
- 97 Department of Physics and Astronomy, University College London, London; United Kingdom
- 98 Louisiana Tech University, Ruston LA; United States of America
- 99 Fysiska institutionen, Lunds universitet, Lund; Sweden
- 100 Departamento de Física Teórica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid; Spain
- 101 Institut für Physik, Universität Mainz, Mainz; Germany
- 102 School of Physics and Astronomy, University of Manchester, Manchester; United Kingdom
- 103 CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille; France
- 104 Department of Physics, University of Massachusetts, Amherst MA; United States of America
- 105 Department of Physics, McGill University, Montreal QC; Canada
- 106 School of Physics, University of Melbourne, Victoria; Australia
- 107 Department of Physics, University of Michigan, Ann Arbor MI; United States of America
- 108 Department of Physics and Astronomy, Michigan State University, East Lansing MI; United States of America
- 109 Group of Particle Physics, University of Montreal, Montreal QC; Canada
- 110 Fakultät für Physik, Ludwig-Maximilians-Universität München, München; Germany
- 111 Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München; Germany
- 112 Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya; Japan
- 113 Department of Physics and Astronomy, University of New Mexico, Albuquerque NM; United States of America
- 114 Institute for Mathematics, Astrophysics and Particle Physics, Radboud University/Nikhef, Nijmegen; Netherlands
- 115 Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam; Netherlands
- 116 Department of Physics, Northern Illinois University, DeKalb IL; United States of America
- 117 <sup>(a)</sup> New York University Abu Dhabi, Abu Dhabi; <sup>(b)</sup> United Arab Emirates University, Al Ain; United Arab Emirates
- 118 Department of Physics, New York University, New York NY; United States of America
- 119 Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo; Japan
- 120 Ohio State University, Columbus OH; United States of America
- 121 Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK; United States of America
- 122 Department of Physics, Oklahoma State University, Stillwater OK; United States of America
- 123 Palacký University, Joint Laboratory of Optics, Olomouc; Czech Republic
- 124 Institute for Fundamental Science, University of Oregon, Eugene, OR; United States of America
- 125 Graduate School of Science, Osaka University, Osaka; Japan
- 126 Department of Physics, University of Oslo, Oslo; Norway
- 127 Department of Physics, Oxford University, Oxford; United Kingdom
- 128 LPNHE, Sorbonne Université, Université Paris Cité, CNRS/IN2P3, Paris; France
- 129 Department of Physics, University of Pennsylvania, Philadelphia PA; United States of America

- <sup>130</sup> Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA; United States of America
- <sup>131</sup> <sup>(a)</sup> Laboratório de Instrumentação e Física Experimental de Partículas – LIP, Lisboa; <sup>(b)</sup> Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa; <sup>(c)</sup> Departamento de Física, Universidade de Coimbra, Coimbra; <sup>(d)</sup> Centro de Física Nuclear da Universidade de Lisboa, Lisboa; <sup>(e)</sup> Departamento de Física, Universidade do Minho, Braga; <sup>(f)</sup> Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada (Spain); <sup>(g)</sup> Departamento de Física, Instituto Superior Técnico, Universidade de Lisboa, Lisboa; Portugal
- <sup>132</sup> Institute of Physics of the Czech Academy of Sciences, Prague; Czech Republic
- <sup>133</sup> Czech Technical University in Prague, Prague; Czech Republic
- <sup>134</sup> Charles University, Faculty of Mathematics and Physics, Prague; Czech Republic
- <sup>135</sup> Particle Physics Department, Rutherford Appleton Laboratory, Didcot; United Kingdom
- <sup>136</sup> IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette; France
- <sup>137</sup> Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA; United States of America
- <sup>138</sup> <sup>(a)</sup> Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; <sup>(b)</sup> Millennium Institute for Subatomic physics at high energy frontier (SAPHIR), Santiago; <sup>(c)</sup> Instituto de Investigación Multidisciplinario en Ciencia y Tecnología, y Departamento de Física, Universidad de La Serena; <sup>(d)</sup> Universidad Andres Bello, Department of Physics, Santiago; <sup>(e)</sup> Instituto de Alta Investigación, Universidad de Tarapacá, Arica; <sup>(f)</sup> Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso; Chile
- <sup>139</sup> Department of Physics, University of Washington, Seattle WA; United States of America
- <sup>140</sup> Department of Physics and Astronomy, University of Sheffield, Sheffield; United Kingdom
- <sup>141</sup> Department of Physics, Shinshu University, Nagano; Japan
- <sup>142</sup> Department Physik, Universität Siegen, Siegen; Germany
- <sup>143</sup> Department of Physics, Simon Fraser University, Burnaby BC; Canada
- <sup>144</sup> SLAC National Accelerator Laboratory, Stanford CA; United States of America
- <sup>145</sup> Department of Physics, Royal Institute of Technology, Stockholm; Sweden
- <sup>146</sup> Departments of Physics and Astronomy, Stony Brook University, Stony Brook NY; United States of America
- <sup>147</sup> Department of Physics and Astronomy, University of Sussex, Brighton; United Kingdom
- <sup>148</sup> School of Physics, University of Sydney, Sydney; Australia
- <sup>149</sup> Institute of Physics, Academia Sinica, Taipei; Taiwan
- <sup>150</sup> <sup>(a)</sup> E. Andronikashvili Institute of Physics, Iv. Javakishvili Tbilisi State University, Tbilisi; <sup>(b)</sup> High Energy Physics Institute, Tbilisi State University, Tbilisi; <sup>(c)</sup> University of Georgia, Tbilisi; Georgia
- <sup>151</sup> Department of Physics, Technion, Israel Institute of Technology, Haifa; Israel
- <sup>152</sup> Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv; Israel
- <sup>153</sup> Department of Physics, Aristotle University of Thessaloniki, Thessaloniki; Greece
- <sup>154</sup> International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo; Japan
- <sup>155</sup> Department of Physics, Tokyo Institute of Technology, Tokyo; Japan
- <sup>156</sup> Department of Physics, University of Toronto, Toronto ON; Canada
- <sup>157</sup> <sup>(a)</sup> TRIUMF, Vancouver BC; <sup>(b)</sup> Department of Physics and Astronomy, York University, Toronto ON; Canada
- <sup>158</sup> Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba; Japan
- <sup>159</sup> Department of Physics and Astronomy, Tufts University, Medford MA; United States of America
- <sup>160</sup> Department of Physics and Astronomy, University of California Irvine, Irvine CA; United States of America
- <sup>161</sup> University of Sharjah, Sharjah; United Arab Emirates
- <sup>162</sup> Department of Physics and Astronomy, University of Uppsala, Uppsala; Sweden
- <sup>163</sup> Department of Physics, University of Illinois, Urbana IL; United States of America
- <sup>164</sup> Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia – CSIC, Valencia; Spain
- <sup>165</sup> Department of Physics, University of British Columbia, Vancouver BC; Canada
- <sup>166</sup> Department of Physics and Astronomy, University of Victoria, Victoria BC; Canada
- <sup>167</sup> Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg; Germany
- <sup>168</sup> Department of Physics, University of Warwick, Coventry; United Kingdom
- <sup>169</sup> Waseda University, Tokyo; Japan
- <sup>170</sup> Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot; Israel
- <sup>171</sup> Department of Physics, University of Wisconsin, Madison WI; United States of America
- <sup>172</sup> Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal; Germany
- <sup>173</sup> Department of Physics, Yale University, New Haven CT; United States of America

<sup>a</sup> Also Affiliated with an institute covered by a cooperation agreement with CERN.

<sup>b</sup> Also at An-Najah National University, Nablus; Palestine.

<sup>c</sup> Also at Borough of Manhattan Community College, City University of New York, New York NY; United States of America.

<sup>d</sup> Also at Center for High Energy Physics, Peking University; China.

<sup>e</sup> Also at Center for Interdisciplinary Research and Innovation (CIRI-AUTH), Thessaloniki; Greece.

<sup>f</sup> Also at Centro Studi e Ricerche Enrico Fermi; Italy.

<sup>g</sup> Also at CERN, Geneva; Switzerland.

<sup>h</sup> Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland.

<sup>i</sup> Also at Departament de Física de la Universitat Autònoma de Barcelona, Barcelona; Spain.

<sup>j</sup> Also at Department of Financial and Management Engineering, University of the Aegean, Chios; Greece.

<sup>k</sup> Also at Department of Physics, California State University, Sacramento; United States of America.

<sup>l</sup> Also at Department of Physics, King's College London, London; United Kingdom.

<sup>m</sup> Also at Department of Physics, Stanford University, Stanford CA; United States of America.

<sup>n</sup> Also at Department of Physics, Stellenbosch University; South Africa.

<sup>o</sup> Also at Department of Physics, University of Fribourg, Fribourg; Switzerland.

<sup>p</sup> Also at Department of Physics, University of Thessaly; Greece.

<sup>q</sup> Also at Department of Physics, Westmont College, Santa Barbara; United States of America.

<sup>r</sup> Also at Hellenic Open University, Patras; Greece.

<sup>s</sup> Also at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona; Spain.

<sup>t</sup> Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg; Germany.

<sup>u</sup> Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia; Bulgaria.

<sup>v</sup> Also at Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir; Morocco.

<sup>w</sup> Also at Institute of Particle Physics (IPP); Canada.

<sup>x</sup> Also at Institute of Physics and Technology, Mongolian Academy of Sciences, Ulaanbaatar; Mongolia.

<sup>y</sup> Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan.

<sup>z</sup> Also at Institute of Theoretical Physics, Ilia State University, Tbilisi; Georgia.

<sup>aa</sup> Also at Lawrence Livermore National Laboratory, Livermore; United States of America.

<sup>ab</sup> Also at National Institute of Physics, University of the Philippines Diliman (Philippines); Philippines.

<sup>ac</sup> Also at Technical University of Munich, Munich; Germany.

<sup>ad</sup> Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing; China.



<sup>ae</sup> Also at TRIUMF, Vancouver BC; Canada.

<sup>af</sup> Also at Università di Napoli Parthenope, Napoli; Italy.

<sup>ag</sup> Also at University of Colorado Boulder, Department of Physics, Colorado; United States of America.

<sup>ah</sup> Also at Washington College, Chestertown, MD; United States of America.

<sup>ai</sup> Also at Yeditepe University, Physics Department, Istanbul; Türkiye.

\* Deceased.