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Search for light neutral particles decaying promptly into collimated pairs of electrons or muons in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector

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Abstract A search for a dark photon, a new light neutral particle, which decays promptly into collimated pairs of electrons or muons is presented. The search targets dark photons resulting from the exotic decay of the Standard Model Higgs boson, assuming its production via the dominant gluon-gluon fusion mode. The analysis is based on 140 fb^{-1} of data collected with the ATLAS detector at the Large Hadron Collider from proton-proton collisions at a center-of-mass energy of 13 TeV. Events with collimated pairs of electrons or muons are analysed and background contributions are estimated using data-driven techniques. No significant excess in the data above the Standard Model background is observed. Upper limits are set at 95% confidence level on the branching ratio of the Higgs boson decay into dark photons between 0.001% and 5%, depending on the assumed dark photon mass and signal model.

1 Introduction

Hidden sectors near the weak scale that are motivated by naturalness, thermal dark matter, and electroweak baryogenesis are particularly compelling proposals for new phenomena beyond the Standard Model (SM) [1–4]. Several minimal extensions of the SM introduce new symmetries and hidden sectors of particles that can be investigated at the Large Hadron Collider (LHC), assuming their interaction with SM particles through specific portals. Unstable dark states may be produced at colliders and decay into SM particles with sizeable branching ratios, depending on the dark sector's structure.

This paper focuses on a blueprint extension of the SM that considers an additional broken $\mathrm{U}'(1)$ gauge symmetry mediated by a massive vector boson, referred to as 'dark photon' (γ_d). The only interaction between the dark photon and SM particles is via kinetic mixing [5] with the SM photon and the Z boson, with a coupling denoted by ϵ. Additionally, if a dark Higgs mechanism drives the spontaneous breaking of the new $\mathrm{U}'(1)$ gauge symmetry, the dark Higgs boson will generally have a coupling to the SM Higgs boson (H), leading to mixing between the two physical scalar states. The production of dark photons at the LHC can be enhanced by exotic decay modes of the Higgs boson, while its observation may be possible thanks to the kinetic mixing of the γ_d with the SM photon.

The most stringent 95% CL upper limit on the branching ratio for the SM Higgs boson decay into undetected final states is 12% [6,7], leaving ample room for the Higgs boson decay mode investigated in this paper. In the absence of lighter hidden-sector states, a dark photon with a mass (m_{γ_d}) up to a few GeV kinetically mixes with the SM photon and decays into leptons or light quarks. Under this assumption, the dark photon decay branching ratios coincide with those of virtual SM photons, which are directly measured in e^+e^- experiments [8]. The kinetic mixing parameter ϵ is related to the γ_d mean proper lifetime. This paper targets values $\epsilon \gtrsim 10^{-5}$–10^{-3}, which correspond to prompt γ_d decays [4].

The dark photon mass range targeted by this search goes from $\mathcal{O}(10\,\text{MeV})$ to $\mathcal{O}(10\,\text{GeV})$. Therefore, the small mass of the γ_d relative to the Higgs boson mass implies that the dark photon decay products are highly collimated and can be identified as bundles of electrons or muons, referred to as *Lepton-Jets* (LJ) in the following. At masses greater than $\mathcal{O}(10\,\text{GeV})$, the decay products of the dark photon become less collimated and can no longer be identified as LJs.

This paper presents a search for $\gamma_\mathrm{d} \rightarrow e^+e^-$ and $\gamma_\mathrm{d} \rightarrow \mu^+\mu^-$ reconstructed as LJs. The search is performed on proton–proton (pp) collision data at $\sqrt{s} = 13\,\text{TeV}$, collected with the ATLAS detector at the LHC between 2015 and 2018 and corresponding to an integrated luminosity of $140\,\text{fb}^{-1}$. While sufficiently massive γ_d can decay into quark-antiquark ($q\bar{q}$) or τ-lepton pairs, these channels are not considered in this study, given the presence of neutrinos from τ

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decays and the overwhelming multi-jet background. SM processes that can lead to a LJ signature include the production of light vector mesons and off-shell photons. Due to the high cross-section of these background processes, the analysis is restricted to events where two LJs are reconstructed.

Two minimal signal models where dark photons can be pair-produced are the Hidden Abelian Higgs Model (HAHM) [4] and the Falkowski–Ruderman–Volansky–Zupan (FRVZ) model [9,10]. The former allows the Higgs boson decay into a pair of γ_d, mainly via the diagram shown in Fig. 1a, while the latter includes additional dark-sector fermions coupled to the γ_d. The two dark-sector fermions (f_d) are produced by the Higgs boson decay, and they subsequently decay into a γ_d and a hidden lightest stable particle (HLSP), as shown by the diagram in Fig. 1b. More complex scenarios where multiple pairs of γ_d are produced are not considered in this paper, but the definition of the LJ and the selection implemented in the analysis are designed to allow the interpretation of models with richer phenomenology.

Related searches targeting multiple production of γ_d via the identification of LJs were conducted by the ATLAS Collaboration on the Run 1 pp collisions data at $\sqrt{s} = 8$ TeV [11–13]. Two recent results by ATLAS [14,15] have investigated the production of long-lived dark photons using $\sqrt{s} = 13$ TeV data, with masses in the $\mathcal{O}(10\,\mathrm{MeV})$–$\mathcal{O}(10\,\mathrm{GeV})$ range, probing the HAHM and FRVZ models and relying on the identification of LJs from displaced γ_d decays (referred to as 'Dark-Photon-Jets' in the papers). Other ATLAS searches targeted the scenario of dark photons with masses above $\mathcal{O}(1\,\mathrm{GeV})$ produced by Higgs boson decays, identifying resolved prompt [16] or displaced [17] decays of the γ_d. Similar searches were performed by the CMS Collaboration for prompt [18–21] and long-lived [22,23] dark photon production. Other searches conducted by the LHCb [24,25], CMS [26] and FASER [27] Collaborations do not require the H-mediated production of dark photons, but assume kinetic mixing for both dark photon production and decay. These results target dark photon decays into muons and hence probe the mass regime $m_{\gamma_\mathrm{d}} > 2m_\mu$. Several constraints on sub-GeV dark photons are set, without assuming the production from Higgs boson decays, by beam-dump and fixed-target experiments [28–38], by measurements of the anomalous magnetic moment of electrons and muons [39–41] and by astrophysical observations [42,43]. Experiments at e^+e^- colliders [44–56] also constrain the production of dark photons with masses smaller than $\mathcal{O}(10\,\mathrm{GeV})$.

This paper significantly improves the previous Run 1 result [13] thanks to a novel event selection, optimised considering multiple γ_d mass scenarios, to a new background estimate based on a bump-hunt strategy, and to the larger integrated luminosity and increased Higgs boson production cross section at $\sqrt{s} = 13$ TeV. The HAHM model, not considered by the previous search, is also constrained for the first time using prompt LJs, probing a complementary m_{γ_d} range with respect to that probed by Ref. [16].

2 ATLAS detector

The ATLAS detector [57] at the LHC covers nearly the entire solid angle around the collision point.[1] It consists of an inner tracking detector surrounded by a thin superconducting solenoid, electromagnetic and hadronic calorimeters, and a muon spectrometer incorporating three large superconducting air-core toroidal magnets with eight coils each.

The inner-detector system (ID) is immersed in a 2 T axial magnetic field and provides charged-particle tracking in the range $|\eta| < 2.5$. The high-granularity silicon pixel detector covers the vertex region and typically provides four measurements per track, the first hit generally being in the insertable B-layer (IBL) installed before Run 2 [58,59]. It is followed by the SemiConductor Tracker (SCT), which usually provides eight measurements per track. These silicon detectors are complemented by the transition radiation tracker (TRT), which enables radially extended track reconstruction up to $|\eta| = 2.0$. The TRT also provides electron identification information based on the fraction of hits (typically 30 in total) above a higher energy-deposit threshold corresponding to transition radiation.

The calorimeter system covers the pseudorapidity range $|\eta| < 4.9$. Within the region $|\eta| < 3.2$, electromagnetic calorimetry is provided by barrel and endcap high-granularity lead/liquid-argon (LAr) calorimeters, with an additional thin LAr presampler covering $|\eta| < 1.8$ to correct for energy loss in material upstream of the calorimeters. Hadronic calorimetry is provided by the steel/scintillator-tile calorimeter, segmented into three barrel structures within $|\eta| < 1.7$, and two copper/LAr hadronic endcap calorimeters. The solid angle coverage is completed with forward copper/LAr and tungsten/LAr calorimeter modules optimised for electromagnetic (EM) and hadronic energy measurements respectively.

The muon spectrometer (MS) comprises separate trigger and high-precision tracking chambers measuring the deflection of muons in a magnetic field generated by the superconducting air-core toroidal magnets. The field integral of the toroids ranges between 2.0 and 6.0 T m across most of

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

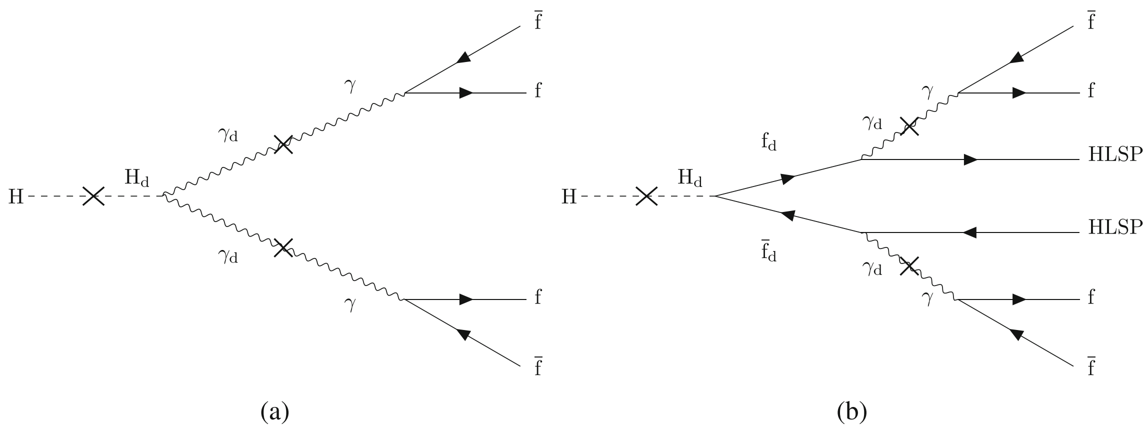


Fig. 1 Representative diagrams for the Higgs boson decay in the (**a**) HAHM and (**b**) FRVZ models. In the HAHM model, dark photons (γ_d) are produced from the decay of the Higgs boson, while in the FRVZ model, the Higgs boson decays in a pair of hidden fermions (f_d), both decaying into a dark photon and a stable hidden fermion (HLSP)

the detector. Three layers of precision chambers, each consisting of layers of monitored drift tubes, cover the region $|\eta| < 2.7$, complemented by cathode-strip chambers in the forward region, where the background is highest. The muon trigger system covers the range $|\eta| < 2.4$ with resistive-plate chambers in the barrel, and thin-gap chambers in the endcap regions.

The luminosity is measured mainly by the LUCID-2 [60] detector that records Cherenkov light produced in the quartz windows of photomultipliers located close to the beampipe.

Events are selected by the first-level trigger system implemented in custom hardware, followed by selections made by algorithms implemented in software in the high-level trigger [61]. The first-level trigger accepts events from the 40 MHz bunch crossings at a rate below 100 kHz, which the high-level trigger further reduces in order to record complete events to disk at about 1 kHz.

A software suite [62] 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 simulated event samples

Data are collected by the ATLAS detector during Run 2 of the LHC (2015–2018) at $\sqrt{s} = 13$ TeV and correspond to an integrated luminosity of 140 fb^{-1}. The highest peak instantaneous luminosity reached 2.1×10^{34} $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, with an average number of inelastic interactions per bunch crossing ranging from 13.4 to 37.8, depending on the data-taking year. These are collected using a set of triggers that require the presence of electrons [63] or muons [64] with thresholds in the transverse energy for electrons and the transverse momentum (p_T) for muons that are in the range of 6–26 GeV, depending on the lepton flavour, the number of leptons and the data-taking period [65]. Stringent data quality requirements [66] are applied, ensuring the optimal operation of all sub-detectors and stable-collision mode of the LHC beams.

Simulated Monte Carlo (MC) event samples are used to optimise the analysis selections and characterise the signal and backgrounds. The signal samples consist of events where dark photons are produced, according to the HAHM and FRVZ models, via the decay of the SM Higgs boson with mass set to 125 GeV and considering only the dominant gluon–gluon fusion production mechanism. Several samples with different γ_d masses were generated, varying from 17 MeV to 20 GeV. For the HAHM model, dark photon masses were set to 17, 100, 400, 2000, 10,000 and 20,000 MeV, while for the FRVZ model the generated samples include dark photon masses of 17, 30, 60, 100, 240, 400, 900, 2000, 6000, 10,000 MeV. The decays of the Higgs boson into dark photons through dark fermions or directly into two dark photons were simulated at the matrix-element level during the generation. The branching ratios of the dark photon decay into leptons were enhanced during event generation and the events are weighted in order to match the expected decay branching ratios of a virtual SM photon. In the FRVZ model, the mass of f_d was chosen to be small relative to the Higgs boson mass, and far from the kinematic threshold at $m_{f_\mathrm{d}} = m_\mathrm{HLSP} + m_{\gamma_\mathrm{d}}$. The values of the dark fermions masses have a negligible impact on the analysis results. In the HAHM, the Higgs boson can decay directly into a pair of dark photons leading to more boosted final states. Simulated signal events were generated with MadGraph5_aMC@NLO 2.2.3 [67] interfaced to Pythia 8.186 [68] for the parton showering and hadronisation. The matrix-element calculation was performed at tree level and the parton distribution function (PDF) set used for the generation was NNPDF2.3LO [69]. Signal samples were normalised to a total cross-section of 48.61 pb [70,71], using dedicated cross-sections calculations at NNLO in QCD and including electroweak corrections at NLO.

Simulated SM background samples were generated in order to optimise the event selection and include Z boson production in association with jets (Z+jets) and top-quark pair production ($t\bar{t}$). The production of Z+jets was simulated with the SHERPA 2.2.1 [72] generator using NLO matrix elements for up to two partons, and leading-order (LO) matrix elements for up to four partons calculated with the COMIX [73] and OPENLOOPS [74–76] libraries. They were matched with the SHERPA parton shower [77] using the MEPS@NLO prescription [78–81] using the set of tuned parameters developed by the SHERPA authors. The NNPDF3.0NNLO set of PDFs [82] was used and the samples were normalised to a NNLO prediction [83]. The production of $t\bar{t}$ events was modelled using the POWHEG BOX v2 [84–87] generator at NLO with the NNPDF3.0NLO PDF set [82] and the h_{damp} parameter set to 1.5 times the mass of the top quark [88]. The events were interfaced to PYTHIA 8.230 [89] to model the parton shower, hadronisation, and underlying event, with parameters set according to the A14 tune [90] and using the NNPDF2.3LO PDF set. The decays of bottom and charm hadrons were performed by EVTGEN 1.6.0 [91].

All MC simulated events were processed through a full simulation of the ATLAS detector geometry and detector response [92] using the GEANT4 [93] toolkit. This simulation accounts for multiple pp interactions per bunch crossing (pile-up), as well as the detector response to interactions in bunch crossings before and after the one producing the hard interaction. The multiple pp interactions were included using simulated events generated with PYTHIA 8.186 [68] using the NNPDF2.3LO PDF set and the A3 minimum-bias tune [94]. Simulated events are weighted to reproduce the distribution of the average number of interactions per bunch crossing observed in data.

4 Event reconstruction

The presence of at least one collision vertex, reconstructed from at least two ID tracks with $p_{\mathrm{T}} > 500$ MeV, is required for each event [95]. When multiple vertices satisfy this requirement, the one with the largest $\sum p_{\mathrm{T}}^2$ is selected as the primary vertex of the event.

Electrons are identified by associating a cluster of energy deposits in the electromagnetic calorimeter to at least one track in the ID. Their p_{T} must be greater than 4.5 GeV and they must be found within $|\eta| < 2.47$, with the exclusion of the transition region between the barrel and endcap electromagnetic calorimeter, defined by $1.37 < |\eta| < 1.52$. Electrons must also satisfy the *Medium* identification working point defined in Ref. [96]. In addition, for tracks associated to electrons the significance on the transverse impact parameter is required to be $|d_0| / \sigma_{d_0} < 5$ and the longitudinal impact parameter must be $|\Delta z_0 \sin\theta| < 0.5$ mm, where both impact parameters are computed with respect to the primary vertex. Track-based and calorimeter-based isolation are required according to the *Loose* criterion defined in Ref. [96]. Electromagnetic showers from light γ_{d} decaying in two electrons are often merged into a single cluster, which is then reconstructed as a single electron with two associated tracks. The impact of the isolation requirement, when two close-by electrons are identified as a single EM shower, is found to be negligible for electrons identified from simulated γ_{d} decays into electrons.

Muon tracks in the ID and the MS are used in a *Combined* muon fit [97]. For each muon, a minimum p_{T} of 3 GeV is required as well as $|\eta| < 2.5$ and the *Loose* identification working point [97] must be satisfied. Muon ID tracks are required to satisfy $|d_0| / \sigma_{d_0} < 3$ and $|\Delta z_0 \sin\theta| < 0.5$ mm. Muon isolation requirements are based on the presence of track-based or calorimeter-based energy contributions around a muon. Muons used for the definition of the regions where the background modelling is performed are required to satisfy the *PFlowLoose* isolation requirement with variable cone radius [97]. Such requirements are found to be inefficient when applied on muons originating from boosted $\gamma_{\mathrm{d}} \to \mu\mu$ decays, due to the contribution of one muon to the isolation cone of the other. A custom isolation variable, defined without considering the contribution due to nearby muons found in a 0.4 cone, is applied to muons used in the LJ reconstruction, leading to an increase of up to 80% in the selection efficiency with respect to standard requirements.

Hadronic jets are reconstructed from clusters of energy deposits in the calorimeter [98] using the anti-k_t algorithm [99,100], with a radius parameter $R = 0.4$. The energy calibration procedure described in Ref. [101] is also applied and the jets are required to have $p_{\mathrm{T}} > 20$ GeV, $|\eta| < 2.5$ and they must satisfy the *Loose* selection defined in [102]. To suppress jets from pile-up interactions, jets with $p_{\mathrm{T}} < 60$ GeV, $|\eta| < 2.5$ are required to satisfy a selection on a multivariate jet vertex tagger [103] based on tracking information.

In order to avoid double-counting of objects, electrons sharing an ID track with muons are removed. Reconstructed jets are discarded if they are found within a $\Delta R = 0.2$ cone around a lepton (and only if they have less than three ID tracks in case of muons). Remaining jets are retained against leptons if they satisfy $\Delta R < \min(0.4, 0.04 + 10\,\mathrm{GeV}/p_{\mathrm{T}}^{\ell})$, where p_{T}^{ℓ} is the p_{T} of the lepton.

LJs are identified from collimated muons or electrons originating from the decay of light γ_{d}. Two exclusive types of LJs are identified: *muon LJs* (μLJs) or *electron LJs*

(eLJs). Cambridge–Aachen clustering [104] is adopted, starting from the first lepton in the collection ordered by p_T and adding the same-flavour ones found within a $\Delta R = 0.4$ cone around the initial one. For each lepton added to the LJ, the momentum axis is recomputed as the vector sum of the four-momentum of each constituent. The procedure is repeated until no other particle can be added and until no other LJ can be reconstructed. If a different-flavour lepton is found within the cone of a given LJ, such LJ is discarded, in order to ensure orthogonality between the two types. The LJ definition is inclusive in the number of leptons to allow the interpretation of the analysis in the context of more complex models, as mentioned in Sect. 1. LJs are expected to be reconstructed with all the electrons or muons originating from the decay of a neutral particle, hence the sum of the charges of the LJ components (muons in case of μLJs and the associated ID tracks in case of eLJs) is required to be zero.

Muon LJs contain at least two muons and target the signature where one or more γ_d decay into muons. Electron LJs are required to contain at least one electron and at least two ID tracks associated to electrons, to accommodate for the scenarios in which the electrons from the γ_d decay are identified as two resolved objects, as well as the one in which the EM showers from the two electrons are merged and identified as a single electron with two associated tracks. In addition, only eLJs with $|\eta| < 1.37$, for which the leading track has a p_T >5 GeV, are retained for the selection.

The mass of a LJ is defined as the invariant mass of its components: for μLJs this corresponds to the invariant mass of the muon constituents while, for eLJs, the definition depends on the number of electron objects that are clustered. For an eLJ reconstructed from two or more electrons, its mass is taken as the invariant mass of the system of electrons. On the other hand, for an eLJ containing two ID tracks associated to one electron, the invariant mass is computed by using the associated ID tracks. This definition was found to be optimal in order to correctly reconstruct the mass of the γ_d in simulated signal events. Since this search targets the pair-production of two particles decaying into electron/muon pairs, it is also expected that the masses of the two LJs that are reconstructed are similar, hence the absolute value of the ratio between the difference and the sum of the masses of the LJs (hereafter referred to as 'mass imbalance'), is used when defining the analysis regions.

Two additional variables are defined exclusively for eLJs. The imbalance in p_T (p_T^{imb}) is defined as the absolute value of the ratio between the difference and the sum of the p_T of the ID tracks associated to an eLJ. If more than two tracks are associated to an eLJ, the p_T^{imb} is computed by considering the two leading tracks in p_T with opposite charge. The p_T^{imb} is expected to be smaller for eLJ originating from resonance decays, with respect to eLJs formed from prompt electrons matched to additional ID tracks. On the other hand, the shape of a merged EM shower originating from two close-by electrons is expected to be wider in ϕ for an eLJ originating from a γ_d decay, compared to that of a prompt electron matched to an additional track. Hence, the ratio between the energy of the EM shower, in the cells around the most energetic energy cluster measured in a $(\eta \times \phi) = 3 \times 3$ region and the one measured 3×7 region (hereafter referred to as R_ϕ) is used when defining the signal region (SR).

The presence of at least two LJs is required in each event and the event selection is performed on the leading LJ in p_T and the LJ with largest $\Delta\phi$ from the leading LJ (denoted farthest LJ). The event selection continues with two analysis channels, which are defined depending on the type of the leading and farthest LJs. The *muon channel* includes events where at least one μLJ is found and is described in Sect. 5, while the *electron channel* includes events where both LJs are of the electron type and is described in Sect. 6. Events with a single reconstructed LJ are not considered as the constraints they provide are not competitive due to the large background yields.

5 Event selection and background estimation in the muon channel

Events with at least one reconstructed μLJ are required to satisfy single-lepton or multi-lepton (dilepton and trilepton) triggers, including triggers based on mixed lepton flavour. Offline leptons used in the LJ reconstruction are required to be found within a $\Delta R = 0.2$ cone around the trigger seed and, in the case of multi-lepton triggers, the leptons matching the online objects must belong to two different LJs. Moreover, a selection on the p_T, identification and isolation of the leptons matching the trigger is applied, tighter than the requirements applied online, to be on the trigger efficiency plateau [63,64]. In order to avoid overlaps between events selected with the di-muon and the tri-muon triggers, the latter ones are utilised only for events outside the fiducial region of the di-muon triggers.

Two orthogonal regions are defined, based on the LJ multiplicity: events with at least two reconstructed μLJs and no eLJs, the μLJ–μLJ region, and events where a μLJ and an eLJ are reconstructed, the μLJ–eLJ region. While no further requirement is applied in the μLJ–μLJ region, the μLJ–eLJ region requires $p_T^{imb} < 0.8$ for eLJ and that the two LJs are back-to-back, with a minimum separation in the azimuthal angle of at least two radians, in order to improve the purity of the selection. The requirements are summarised in Table 1.

The final result of the search in the μLJs regions is obtained by fitting the invariant mass of the μLJ. In the μLJ–μLJ region, there are two entries per event, corresponding to the invariant masses of both μLJs. In the μLJ–eLJ region, only the μLJ invariant mass is utilised, as the overlapping

Table 1 Definition of the muon signal regions. In signal regions requiring events with at least two LJs, only the leading LJ and the farthest LJ are considered for the event classification

Requirement/region	μLJ–μLJ	μLJ–eLJ
Number of μLJs	≥ 2	≥ 1
Number of eLJs	0	≥ 1
Muon triggers	Yes	Yes
Electron-muon triggers	–	Yes
Electron triggers	–	Yes
eLJ $p_{\mathrm{T}}^{\mathrm{imb}}$	–	< 0.8
$\Delta\phi(\mu\mathrm{LJ}, e\mathrm{LJ})$	–	> 2

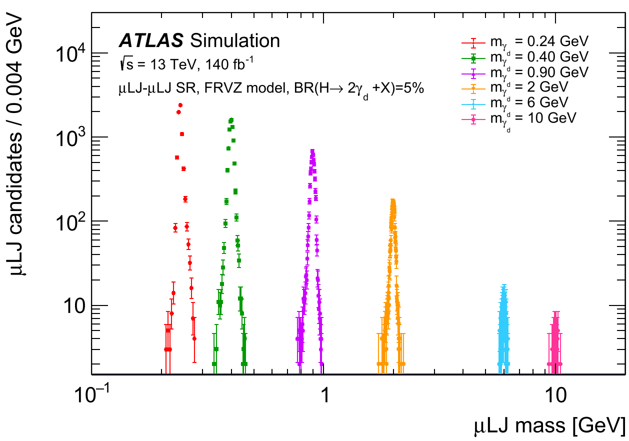


Fig. 2 Simulated distributions of the number of μLJ candidates for a selection of γ_{d} mass values. The shape and normalisation of the distributions are extracted from the parameterisation obtained for μLJ-μLJ SR, using the FRVZ model and assuming a branching ratio of the Higgs boson decay to dark photons of 5%

electron showers in the calorimeter prevented a well-defined eLJ mass reconstruction. The SM background affecting these search regions is characterised by a non-resonant component due to the production of muon pairs from virtual photons decays, plus a resonant component due to the pair-production of low-mass resonances, such as the J/ψ meson, decaying into muons. For the signal, the μLJ mass distribution is modelled using a parametric function, with parameters interpolated to include signal masses for which MC simulation is not available. A double-sided Crystal Ball function [105] is found to be an excellent choice for modelling the shape of the signal invariant mass distribution.

Examples of simulated distributions of the number of μLJ candidates within the mass range used for this region are shown in Fig. 2. The μLJ invariant mass resolution ranges from 10 to 300 MeV in the investigated mass range.

The background distribution corresponds to a smooth falling spectrum and vector meson resonances. This enables the background estimate to be performed using a data-driven method, in which the continuum shape is parameterised by an analytical function derived from two control regions (CRs). The CRs are obtained by selecting events with one reconstructed μLJ, no reconstructed eLJs, and two additional pairs of muons or electrons separated by $\Delta R \geq 1.8$, which are not used for the reconstruction of LJs. The μLJ distribution is then used to characterise the modelling of the μLJ distribution in the SR. The CR built from one μLJ and two muons is used to characterise the modelling of the μLJ–μLJ search region, while for the μLJ–eLJ region the CR built from one μLJ and two additional electrons is used. These additional leptons must fulfil the same requirements as the μLJ or eLJ constituents, ensuring that the CR closely resembles the SR. In order to minimise any signal contamination in the CRs, a requirement on the mass imbalance of the μLJ and the di-muon system, or the μLJ and di-electron system is applied, requiring it to be greater than 0.2, or 0.6, respectively.

The parametric form of the μLJ distribution for the background has two components: a double exponential function to describe the bulk non-resonant distributions, and Gaussian probability functions to capture the $\phi(1020)$, J/ψ, and $\psi(2S)$ resonances. It is parameterised as follows:

$$B(m_{\mu\mathrm{LJ}}) = N_{\mathrm{exp1}} e^{-m_{\mu\mathrm{LJ}}/\tau_2} + N_{\mathrm{exp2}} e^{-m_{\mu\mathrm{LJ}}/\tau_1} + N_{J/\psi} e^{-\left(\frac{m_{\mu\mathrm{LJ}}-\mu_{J/\psi}}{\sigma_{J/\psi}}\right)^2} + N_{\psi(2S)} e^{-\left(\frac{m_{\mu\mathrm{LJ}}-\mu_{\psi(2S)}}{\sigma_{\psi(2S)}}\right)^2} + N_{\phi} e^{-\left(\frac{m_{\mu\mathrm{LJ}}-\mu_{\phi}}{\sigma_{\phi}}\right)^2}, \quad (1)$$

where N_i, with $i = \mathrm{exp1}, \mathrm{exp2}, \phi, J/\psi, \psi(2S)$, are the normalisation factors associated to the i-th SM background process relative to the total amount of events; τ_1 and τ_2 are the parameters of the two exponential distributions. The parameters μ_{res} with res $= \phi, J/\psi, \psi(2S)$ are fixed and set to 1.02, 3.097 and 3.69 GeV, respectively [8]. The parameters σ_{res}, with res $= \phi, J/\psi, \psi(2S)$ are fixed to the fitted values in the CR. This functional form is chosen for its ability to accurately model the background shape in several control regions.

The bias from the functional form choice is evaluated by fitting signal and background contributions to data templates in signal-free regions. This *spurious signal* estimate helps gauge biases inherent in the method [106]. Various templates are created using data or simulation in the control region, and used as probability distribution functions to generate expected distributions in the SR. The extracted values of the signal yields for each γ_{d} mass assumption define an envelope approximating the method's bias, which is included as a systematic uncertainty in the final fit.

Post-fit μLJ mass distributions in the μLJ–μLJ and μLJ–eLJ signal regions are shown in Fig. 3. In this figure, a representative γ_{d} signal with a mass of 1 GeV is shown, assuming a branching ratio of $H \rightarrow 2\gamma_{\mathrm{d}}$ of 0.5%.

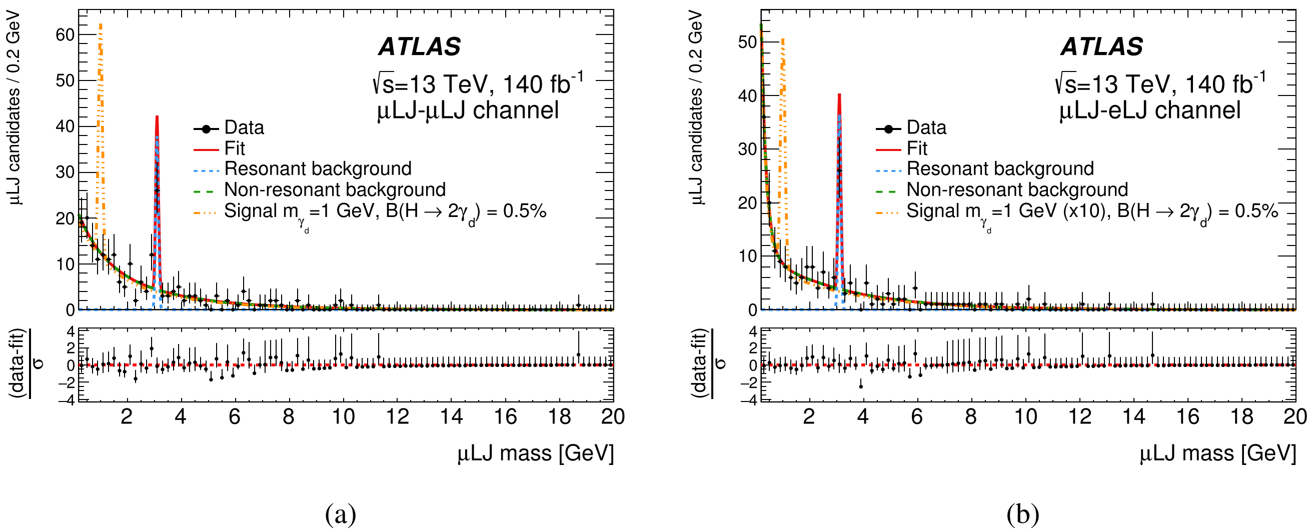


Fig. 3 The background-only fit (solid red line) with its background (dashed blue and green lines) and signal (dot-dashed orange line) components of the μLJ mass distributions for the (**a**) μLJ–μLJ and (**b**) eLJ–μLJ regions. For the μLJ–μLJ region, both the μLJs are included. A signal distribution for a dark photon mass of 1 GeV is overlaid, assuming the HAHM model and a branching ratio of the Higgs boson to dark photons of 0.5%

6 Event selection and background estimation in the electron channel

Events with two eLJs are selected by the logical or of single and di-electron triggers. As mentioned in Sect. 5, the electrons used for the eLJ reconstruction are required to be within a $\Delta R = 0.2$ cone around the trigger seed. Additional requirements on their p_{T}, identification and isolation are also applied, with tighter requirements than those applied online. In events selected by di-electron trigger, the two online electrons are required to match the two different eLJs.

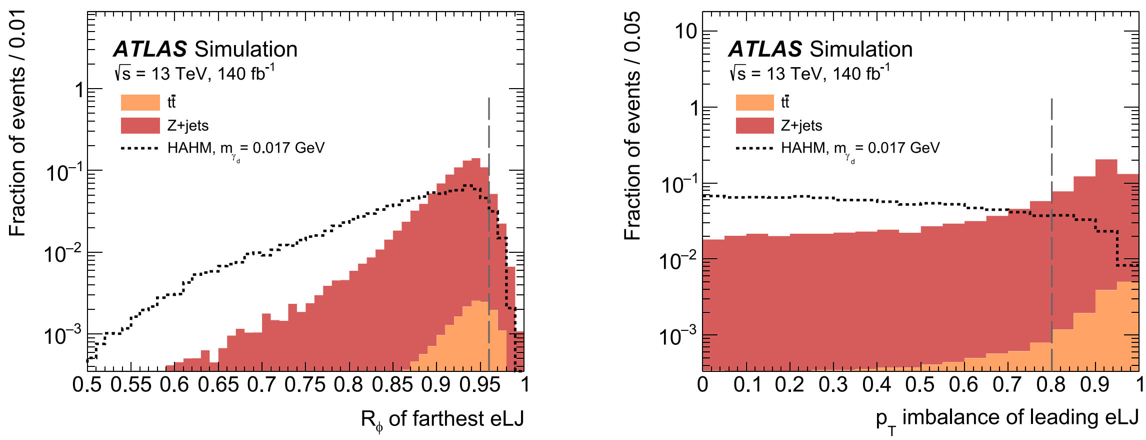
This analysis channel is optimised for the scenarios where the mass of the dark photon is smaller than the mass of a muon pair. To improve the sensitivity in this mass range, all the eLJ candidates are required to be formed by two electrons with merged EM clusters. In addition, the LJs are required to be back-to-back, with a minimum separation in the azimuthal angle of at least 2.5 radians. Events are retained only if the mass imbalance of the two eLJs is below 0.8.

The main background is composed by the random overlap of prompt electrons, produced in Z boson decays or $t\bar{t}$ events, with additional ID tracks. In order to reduce the contribution of $t\bar{t}$ processes, selected events are rejected if at least one hadronic jet with $p_{\mathrm{T}} > 40$ GeV is present. Moreover, to remove events where one Z boson decays into two electrons, the invariant mass of the system of the two eLJs ($m(\mathrm{e}LJ,\mathrm{e}LJ)$) must be outside of the interval between 80 and 100 GeV. The SR is finally defined by requiring $p_{\mathrm{T}}^{\mathrm{imb}}$ to be smaller than 0.8 for the leading eLJ, while R_{ϕ} has to be smaller than 0.96 for the farthest eLJ. The distributions of these two variables are shown in Fig. 4.

After these selections, the residual background is estimated directly from data using the so-called *ABCD* method. The overlapping electron showers in the calorimeter for the low-mass range considered in this region prevent a well-defined eLJ mass reconstruction and the use of the bump-hunting method, as in the muon channel. In the plane defined by the $p_{\mathrm{T}}^{\mathrm{imb}}$ and R_{ϕ} variables, the four regions A, B, C and D, are identified: region A corresponds to the SR, while regions B, C, D correspond to three CRs defined by reversing the selection on R_{ϕ}, $p_{\mathrm{T}}^{\mathrm{imb}}$, and both the variables, respectively. The requirements on the $p_{\mathrm{T}}^{\mathrm{imb}}$ and R_{ϕ} adopted in the definition of the SR are determined as the one that maximise the signal-to-background sensitivity, while minimising the signal contamination in regions B, C and D. These variables are considered uncorrelated when $p_{\mathrm{T}}^{\mathrm{imb}}$ is considered for the leading eLJ and R_{ϕ} for the sub-leading eLJ, with R_{ϕ} being a calorimeter-based variable and $p_{\mathrm{T}}^{\mathrm{imb}}$ being track-based.

The number of background events in the SR (N_A) can be estimated by $N_A = (N_B \times N_C)/N_D$, where N_i with $i = B, C, D$ is the number of observed data events in the three CRs. This relation is extended using a likelihood-based method analogous to the one used in Ref. [15], which fits the number of background and signal events simultaneously, taking into account any potential signal contamination in the CRs.

This method for the background estimate is validated in regions where the signal contribution is expected to be small. A first set of validation regions (VRs) is defined by combin-



(a) (b)

Fig. 4 Distribution of the (**a**) eLJ R_ϕ and (**b**) eLJ p_T imbalance, obtained for signal events generated with the HAHM model with a γ_d mass set to 17 MeV and for simulated background events. Events are selected from the electron channel, with only the trigger requirement applied. Signal and background distributions are normalised to unit area. The dashed grey line corresponds to the selection applied in the definition of the SR

ing CRs C and D, and CRs B and D, while another region (VR_Z) is defined by reversing the selection on the invariant mass of the two eLJs in the event, hence targeting pairs of LJs originating in $Z \rightarrow e^+e^-$ events. The Pearson linear correlation coefficient between the two variables defining the ABCD plane in all control and validation regions was observed to be below 2%. The signal leakage in these regions was found to be less than 10% of the total signal in the ABCD plane for all signal scenarios considered in the analysis.

The definitions of the SR A, CRs B, C and D, as well as the VR_Z are summarised in Table 2.

For each VR, alternative A, B, C, D regions are defined by dividing the plane in increasing steps of $p_\mathrm{T}^\mathrm{imb}$ and R_ϕ, in order to assert the reliability of the method in each of these regions. In all the tested regions, the observed number of events is found to be in agreement with the expected value within one standard deviation.

Figure 5 shows the distribution of events in the ABCD planes, for observed data and events simulated with the HAHM model assuming a mass of the γ_d of 17 MeV and a decay branching ratio of the Higgs boson to dark sector particles of 0.5%. The number of observed data events in the eLJ ABCD plane is reported in Table 3, where the yields in SR A are extracted by a background-only fit performed on data in all ABCD regions.

7 Systematic uncertainties

The overall uncertainty in the SRs yields is dominated by the background statistical uncertainty. For the electron channel, the uncertainty in the observed yields in the ABCD control regions are propagated to the SR expectation obtained from the ABCD method, amounting to 5%. Other potential sources of experimental uncertainties are considered for the background estimates and the simulated signal yields.

The following experimental uncertainties are taken into account in the signal distributions for the μLJ, eLJ, and μLJ–eLJ channels, as well as in the background estimations. All systematic uncertainties are incorporated into the fits using nuisance parameters, which are constrained by Gaussian terms in the likelihood function.

The background parameterisation in the muon channels is data-driven and extracted from the fit in the control region, thus only systematic uncertainties related to the background modelling and the fit are considered. The bias from the choice of the background model is evaluated with the spurious signal method, as discussed in Sect. 5. At most three spurious signal events are extracted across the full spectrum and this number is taken as an uncertainty on the signal yields independent of the assumed dark photon mass.

To account for potential biases in the signal model description, an injection test is performed to determine if the correct number of events can be extracted using a signal-plus-background fit. Pseudo-data generated from the background model with a known number of injected signal events is used and a fit is performed. The obtained value for signal yields is then compared with the injected value. The largest difference per mass point between the injected and fitted signal for each of the configurations is assigned as a systematic uncertainty, which ranges from 1% and up to 5% increasing with the mass of the dark photon.

The uncertainty in the integrated luminosity of the combined data samples from 2015 to 2018 is 0.83%, calculated

Table 2 Definition of the analysis regions of the electron channel

Requirement/region	SR	CR B	CR C	CR D	VR$_Z$
Applied to both leading and farthest *e*LJ					
Number of EM clusters in *e*LJ			1		
*e*LJ mass imbalance			< 0.8		
Selection on event-level variables					
$\Delta\phi(e\mathrm{LJ}, e\mathrm{LJ})$			> 2.5		
Number of jets ($p_\mathrm{T} > 40$ GeV)			0		
$m(e\mathrm{LJ}, e\mathrm{LJ}) \notin [80, 100]$ GeV	Yes	Yes	Yes	Yes	Veto
Leading *e*LJ $p_\mathrm{T}^\mathrm{imb}$	< 0.8	< 0.8	> 0.8	> 0.8	–
Farthest *e*LJ R_ϕ	< 0.96	> 0.96	< 0.96	> 0.96	–

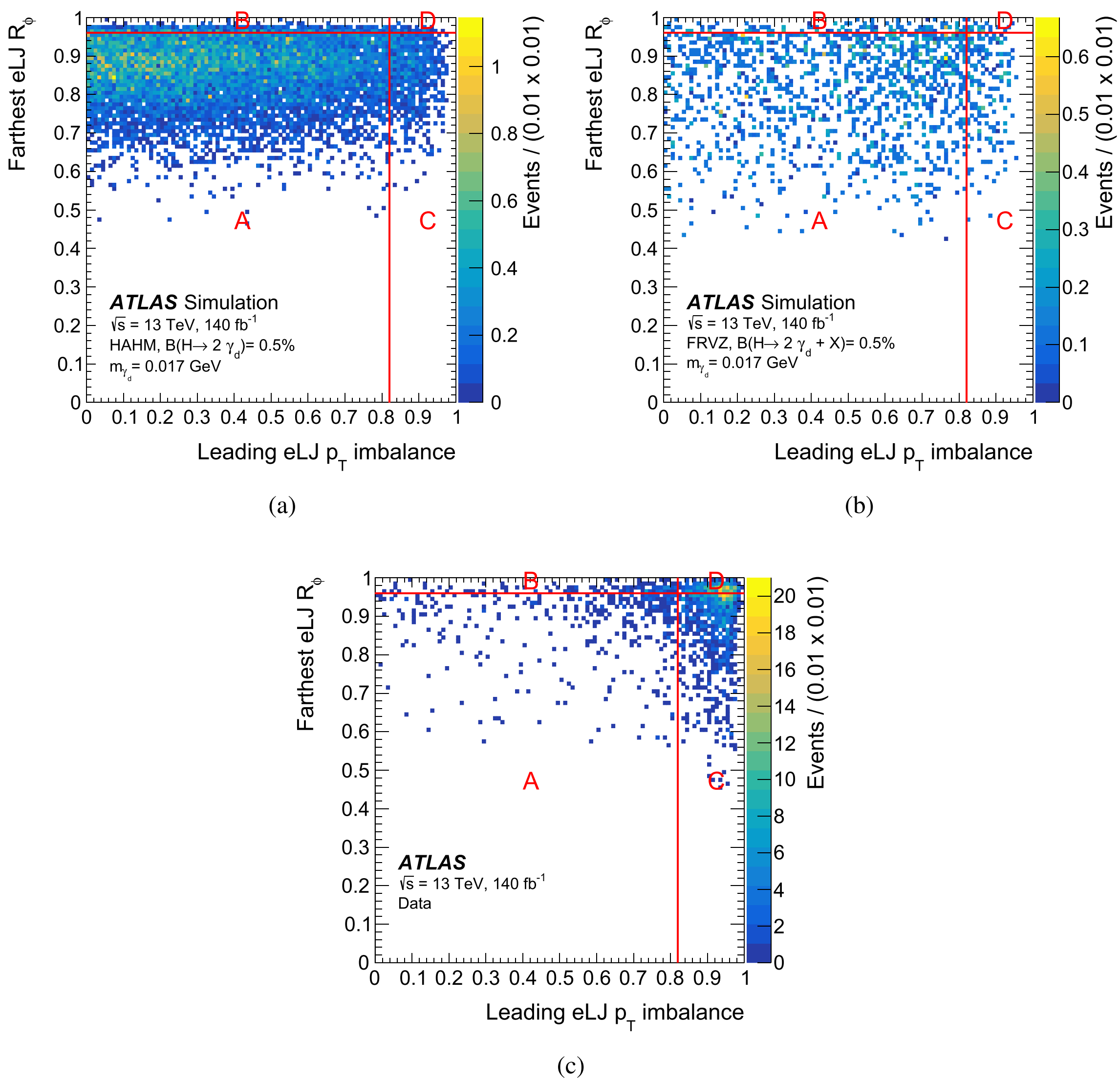


Fig. 5 Distribution of (**a**, **b**) expected signal and (**c**) observed data events in the ABCD regions defined by the leading *e*LJ $p_\mathrm{T}^\mathrm{imb}$ and farthest *e*LJ R_ϕ variables in the electron channel. Signal events are simulated according to the (**a**) HAHM and (**b**) FRVZ models, for a γ_d mass of 17 MeV and assuming a branching ratio of the Higgs boson decay to dark photons of 0.5%

Table 3 Observed data events in the four ABCD regions and the expected yields in the SR A were extracted with a background-only fit of the electron channel, assuming no signal. The a priori scenario does not consider data yields in SR A, whereas the a posteriori scenario includes data in all ABCD regions in the fit. The expected number of events is reported together with its statistical uncertainty

Region	CR B	CR C	CR D	SR expected a priori	SR expected a posteriori	SR observed
*e*LJ–*e*LJ	125	862	356	303 ± 33	334 ± 17	351

using the methodology described in Ref. [107]. The uncertainty is determined using the LUCID-2 detector [60] for primary luminosity measurements, supplemented by measurements using the inner detector and calorimeters.

The pile-up modelling uncertainty that accounts for the difference between the simulated and measured inelastic pp cross-section [108] is evaluated with a data-to-MC reweighting method of the distribution of the average number of interactions per bunch crossing. This uncertainty is propagated through the event selection, and results in a less than 4% effect on the event yield of all the signal samples.

The experimental uncertainties are related to the lepton reconstruction, identification and isolation, and are evaluated using $Z \rightarrow \ell\ell$, $J/\Psi \rightarrow \ell\ell$ events in data and MC [96,97]. The dominant uncertainties arise from muon isolation and electron identification found to be less than 1% and 2% for μLJ and eLJ channels respectively. The impact of electron isolation, lepton momentum resolution and energy scale, and muon identification are found to be sub-dominant. No additional systematic uncertainty is considered due to the additional correction added on top of the standard isolation variables. The experimental uncertainties related to the jet energy resolution and jet energy scale, evaluated from the standard calibration scheme [101], amount to up to 3% of the expected signal yields. This uncertainty is relevant only for the eLJ–eLJ channel where jets are used in the selection.

Uncertainty in the efficiency of trigger influence the expected yields and are estimated to be less than 2.2% across all signal samples. The estimates are based on studies of the detector performance using Run 2 data and changes to the MC simulation [63,64].

A summary of the experimental systematic uncertainties considered for the signal samples in this search is presented in Fig. 6. The average uncertainties represent the bulk of the signal samples, with minor variations, typically of a few percent, observed as a function of the γ_d mass.

8 Results and interpretations

The statistical analysis of the muon channel uses an unbinned maximum-likelihood fit of the μLJ mass distribution. The search is conducted in the γ_d mass range between twice the muon mass and 20 GeV for the HAHM model, while this range is limited up to 10 GeV for the FRVZ model. The fit is performed with a step size of 10 MeV, smaller than the invariant mass resolution of the reconstructed LJ. Instead, the electron channel uses a binned maximum-likelihood fit to the signal region (A) and the three control regions (B, C and D), describing the ABCD constraint and taking into account any possible signal contamination in the control regions. For the electron channel, limits are computed for the γ_d masses available from signal simulated samples (ranging from 0.017 GeV to 0.4 GeV), as no parameterisation of the signal model is performed.

No significant excesses are observed, thus expected and observed 95% confidence level (CL) exclusion limits on the cross-section times branching ratio of the process $H \rightarrow 2\gamma_d + X$ are computed as a function of the dark photon mass using the CL_s [109] modified frequentist approach. The exclusion limits are computed using the asymptotic approximation [110]. The validity of the asymptotic approximation is evaluated by comparing it with a full calculation using pseudo-experiments. The CL_s values from both methods agree within 2%, with the largest discrepancy being 10% in the high mass region. The 95% CL upper limits for the HAHM and FRVZ models are depicted in Fig. 7 for the muon and electron search channels. The muon channel sets limit for γ_d masses larger than twice the muon mass, while the electron channel covers the complementary region, down to the mass of the lightest signal sample available (0.017 GeV). The electron channel is not combined with the muon channel for γ_d masses above twice the muon mass, given the dominant sensitivity of the muon channel in this range. The upper limit is not extracted in regions where background resonances are present.

The search excludes a range of $H \rightarrow 2\gamma_d + X$ branching ratios from 0.001% to 5%, depending on the assumed dark photon mass, improving the previous search by ATLAS during Run 1 [13] by a factor of 50 when considering a dark photon with a mass of 400 MeV. This improvement is mainly due to the renewed background estimate based on the invariant mass shape fit. The muon channels are valid only for dark photon masses greater than twice the muon mass and complement the electron channel, which is covered only by ATLAS. In the FRVZ scenarios, limits are derived down to 17 MeV for the first time, significantly extending previous CMS and ATLAS searches for prompt LJs. In the HAHM scenarios, where the Higgs boson decays directly into a pair of dark photons, the sensitivity improves compared to the FRVZ

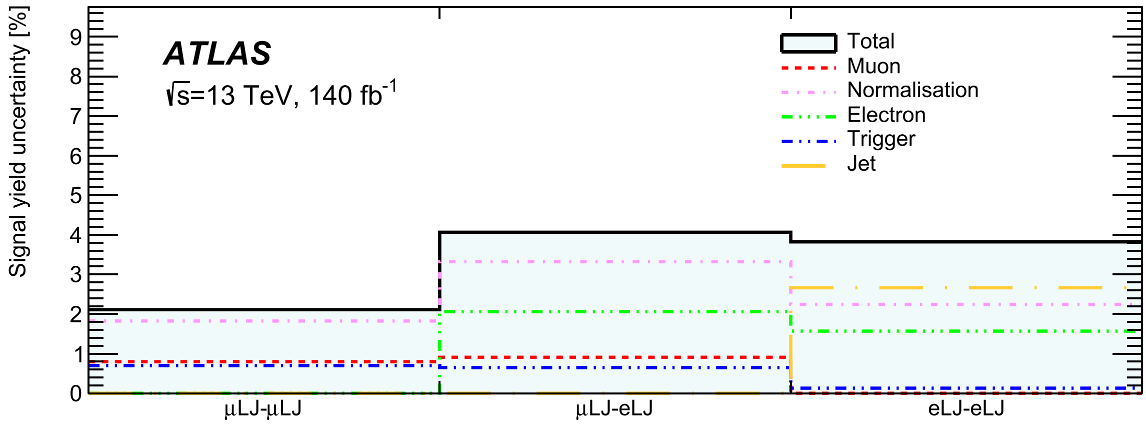
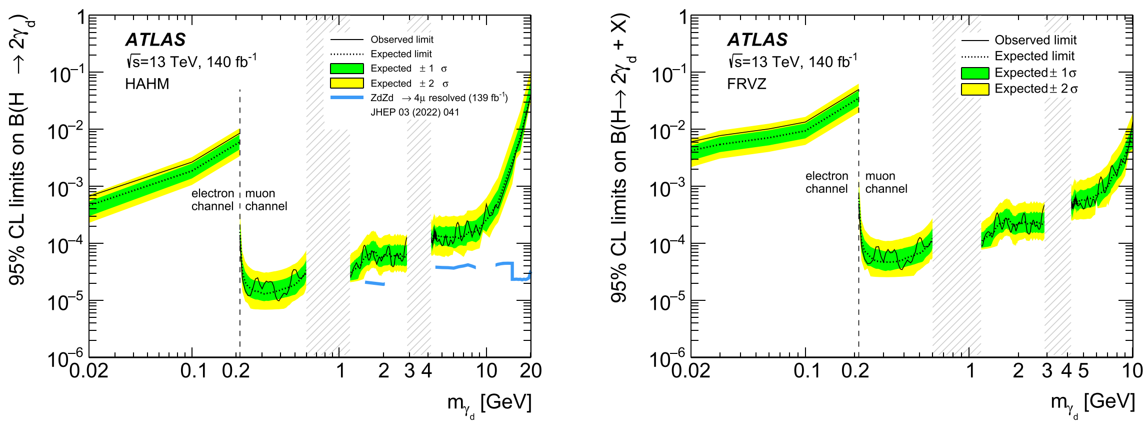


Fig. 6 Contributions from the different sources of uncertainty to the signal yields in the search channels over all simulated signal samples. The reported uncertainties are averaged over all signal MC. The 'Muon' and 'Electron' sources contain all lepton-related systematic uncertainties and are dominated by the uncertainty in the muon isolation and electron identification. The 'Triggers' source contains all trigger systematic uncertainties. The 'Jet' source, relevant only for the electron channel, contains the jet energy scale and resolution uncertainties. The 'Normalisation' source contains all systematic uncertainties affecting the overall normalisation of the yields



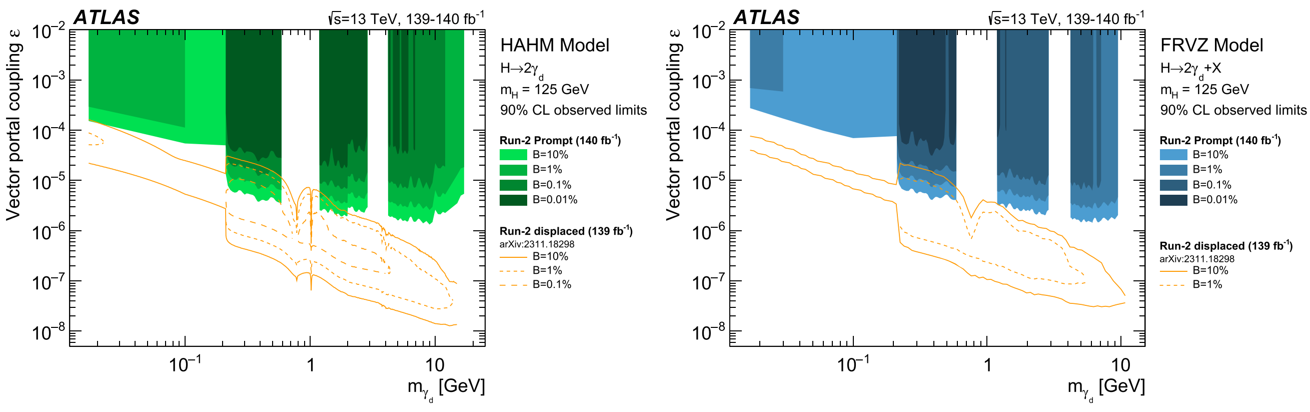
(a)

(b)

Fig. 7 95% CL exclusion limits on the branching ratio of the Higgs boson to dark photons as a function of the γ_d mass for the (**a**) HAHM and (**b**) FRVZ models. The solid (dashed) black curve shows the observed (expected) exclusion limit and the green and yellow bands represent $\pm1\sigma$ and $\pm2\sigma$ uncertainty intervals around the expected limit. The grey hatched regions indicate where the upper limit is not extracted. The figure also shows the exclusion limit from the ATLAS search for resolved prompt γ_d decays [16] (blue line)

model due to the harder dark photon energy spectrum. In the high-mass range, when the muons from the dark-photon decay have large angular separation, making lepton-jet reconstruction inefficient, the analysis steeply loses sensitivity. The result is complementary to the ATLAS search for four resolved prompt muons [16], which sets stronger limits at larger masses and remains competitive around $m_{\gamma_d} = 2$ GeV. These are the first results for this model in ATLAS with the prompt LJ signature.

Figure 8 presents the 90% CL upper limits as a function of the kinetic mixing parameter ϵ, which determines the lifetime of the dark photon, and γ_d mass in both the HAHM vector-portal and FRVZ models, showing exclusion contours on the Higgs branching ratio to dark photons for branching fractions ranging from 0.01 to 10%. The limits are interpolated between different masses by branching fraction variations [111] as a function of the γ_d mass, corrected by a linear interpolation of the signal efficiency between adjacent available MC signal samples. Simple reweighting techniques [14] were applied to determine the analysis efficiency as a function of the lifetime for each mass point, using additional generated samples with varied lifetimes. Exclusion regions from the complementary ATLAS search for displaced dark-photon [14] are also shown (orange line).



(a) (b)

Fig. 8 90% CL exclusion limit contours on the branching ratio of the Higgs boson to dark photons as functions of the γ_d mass and kinetic mixing parameter ϵ for the (**a**) HAHM model and (**b**) FRVZ model. These exclusions assume Higgs boson branching fractions to dark photons within a 0.01% and 10% range. Excluded regions from the complementary ATLAS displaced dark-photon search [14] are displayed (orange lines) for comparison

9 Conclusion

This paper details the first Run 2 search for light neutral particles decaying into collimated pairs of muons or electrons with the ATLAS detector at the LHC. By analysing data corresponding to an integrated luminosity of 140 fb^{-1} of pp collisions at a centre-of-mass energy of 13 TeV, the study investigates dark photons from Higgs boson decays, with a mass between 17 MeV and 20 GeV, extending the range of the previous search. The data is consistent with background predictions and 95% confidence level upper limits are set on the branching ratio of the Higgs boson to dark photons, ranging from 0.004 and 5% for the FRVZ model and from 0.001 to 1% for the HAHM model, depending on the dark photon mass. Compared with the previous search conducted by ATLAS during Run 1, for the FRVZ model with a dark photon with a mass of 0.4 GeV, the upper limit on the branching ratio of the Higgs boson to dark photons is improved by approximately a factor of 50. When accounting for the contributions from the increased integrated luminosity and cross-section at a higher centre-of-mass energy, this results in an improvement by a factor of about 13. The sensitivity of the muon channel has improved due to resonance search approach adopted, compared to simple use of the total event counts in the Run 1 analysis. This is the first search for prompt Lepton-Jets in the electron channel using Run 2 data of the LHC and sets the most stringent limits to date. The limits are extended down to 17 MeV in dark photon mass, significantly improving previous CMS and ATLAS results for prompt Lepton-Jets.

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Code Availability Statement This manuscript has no associated code/software. [Author's comment: ATLAS collaboration software is open source, and all code necessary to recreate an analysis is publicly available. The Athena (http://gitlab.cern.ch/atlas/athena) software repository provides all code needed for calibration and uncertainty application, with configuration files that are also publicly available via Docker containers and cvmfs. The specific code and configurations written in support of this analysis are not public; however, these are internally preserved.]

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