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A search for prompt lepton-jets in pp collisions at √s = 7 TeV with the ATLAS detector

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A search for prompt lepton-jets in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector ☆

ATLAS Collaboration *

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ABSTRACT

We present a search for a light (mass < 2 GeV) boson predicted by Hidden Valley supersymmetric models that decays into a final state consisting of collimated muons or electrons, denoted "lepton-jets". The analysis uses 5 fb^{-1} of $\sqrt{s} = 7$ TeV proton–proton collision data recorded by the ATLAS detector at the Large Hadron Collider to search for the following signatures: single lepton-jets with at least four muons; pairs of lepton-jets, each with two or more muons; and pairs of lepton-jets with two or more electrons. This study finds no statistically significant deviation from the Standard Model prediction and places 95% confidence-level exclusion limits on the production cross section times branching ratio of light bosons for several parameter sets of a Hidden Valley model.

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1. Introduction

A light boson at the GeV scale, in a model where a Hidden Valley sector is weakly coupled to the Standard Model (SM) sector [1–3], has been proposed to explain several recently observed anomalies in cosmic-ray and dark matter direct-detection experiments. These observations include an unexpected excess of cosmic electrons and/or positrons [4–7] and signals from certain dark matter direct-detection experiments [8–10]. The proposed boson could be created at particle accelerators and produce distinctive final states of tightly collimated "lepton-jets" consisting of close by electrons or muons [11–15]. Such lepton-jet decays are also a generically interesting signature that may be produced by rare decays of, for instance, Z or Higgs bosons [16]. Upper limits on lepton-jet production have already been set by previous analyses of collider data [17,18].

In Hidden Valley models, the universe consists of SM and supersymmetric (SUSY) particles, together with an additional spectrum of dark matter particles charged under a hidden gauge group (called the dark sector). Certain particles called messengers are charged under both the dark sector and the SM and SUSY gauge symmetries, permitting decay chains through the normal and dark sectors. For example, the lightest supersymmetric particle, which cannot decay to SM particles due to R-parity conservation, can decay into less-massive dark sector states ending with the lightest particle in the dark sector, a dark photon denoted γ_D. This dark photon can decay into light SM fermions by kinetic mixing [19] of the dark gauge sector and SM gauge symmetries. These models aim to explain the excess of cosmic-ray positrons, in the absence of any observed proton excess, with a dark boson γ_D that has a mass below the proton–antiproton kinematic threshold of ~2 GeV. Such low-mass dark photons can decay to electrons, muons, and pions, whereas decays to protons are kinematically forbidden. Due to the boost of the γ_D, the light SM decay products are highly collimated, providing a striking signature for new physics.

The data is interpreted in a model where a pair of squarks is produced and each of the squarks cascade decays into dark sector particles, including one or more dark photons. The dark photons decay into pairs of leptons, forming lepton-jets. Additionally, dark sector particles may radiate multiple dark photons, increasing the lepton multiplicities and number of the lepton-jets [16]. The amount of radiation is determined by the dark sector gauge coupling parameter α_d. Setting $\alpha_d = 0.0$ results in a simple lepton-jet with two hard leptons. Larger values of α_d may produce lepton-jets with four, six, eight, or more prompt leptons from the decay of overlapping dark photons, albeit with reduced boost. The transverse momentum (p_{T}) of the leptons increases with dark photon mass, but decreases with α_d. This Letter considers values of α_d of 0.0, 0.1, and 0.3, and dark photon masses (m_{γ_D}) of 150, 300, and 500 MeV. For $m_{\gamma_D} = 150$ MeV, the dark photon is below the muon–antimuon threshold and can only decay to electrons. With $m_{\gamma_D} \geqslant 300$ MeV, the dark photon decays to electron and muon pairs. Additionally, for $m_{\gamma_D} = 500$ MeV, 20% of the decays produce pion pairs. These nine signal operating points cover a wide range of phase space from low-multiplicity lepton-jets containing leptons of only one flavour, to high-multiplicity lepton-jets containing a mix of electrons and muons.

The data samples used in this analysis were collected with the ATLAS detector during the 2011 run of the Large Hadron Collider at centre-of-mass energy $\sqrt{s} = 7$ TeV and correspond to 4.5 fb^{-1}

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of integrated luminosity for the muon analyses and 4.8 fb^{-1} for the electron analysis [20,21], after their respective data quality requirements have been applied. This Letter considers lepton-jets in three signatures: single muon-jets with four or more muons, pairs of muon-jets each with two or more muons, and pairs of electron-jets each with two or more electrons. The selection is designed to enhance the signal relative to the SM backgrounds, the largest of which is multi-jet production. In multi-jet production the background arises from either real leptons from the decay of SM particles, from hadrons that are misidentified as leptons, or in the case of electrons, from photon conversions. All other SM background sources are expected to be negligible after the final selection cuts are applied. The multi-jet background is reduced through a variety of selection cuts, and the remaining background is estimated with two different data-driven techniques.

No requirements are made on the remaining activity in the event beyond the one or two lepton-jets in order to avoid introducing a strong model dependence in the analysis. For example, no cuts are made on the presence of other particles or jets, the event track multiplicity, or the presence of missing transverse energy.

2. The ATLAS detector

ATLAS is a general purpose detector [22] consisting of an inner tracking detector (ID) embedded in a 2 T solenoid, electromagnetic and hadronic calorimeters and a muon spectrometer (MS) employing toroidal magnets. The ID provides precision tracking of charged particles for $|\eta| < 2.5$ using silicon pixel and microstrip detectors and a straw-tube transition radiation tracker (TRT) that relies on transition radiation to distinguish electrons from pions in the range $|\eta| < 2.0$. Liquid argon (LAr) electromagnetic sampling calorimeters, with excellent energy and position resolution, cover the range $|\eta| < 3.2$ with a typical granularity of $\Delta\eta \times \Delta\phi$ of 0.025×0.025. A scintillator-tile calorimeter, which is divided into a large barrel and two smaller extended-barrel cylinders, one on each side of the central barrel, provides hadronic calorimetry in the range $|\eta| < 1.7$. In the end-caps ($|\eta| > 1.5$), LAr is also used for the hadronic calorimeters, matching the outer $|\eta|$ limit of end-cap electromagnetic calorimeters. The LAr forward calorimeters provide both electromagnetic and hadronic energy measurements, and extend the coverage to $|\eta| = 4.9$. The calorimeter system has a minimum depth of 9.7 interaction lengths at $\eta = 0$. The MS covers $|\eta| < 2.7$ and provides triggering and precision tracking for muons.[1]

A three-level trigger system is used to select events. The Level 1 (L1) trigger is implemented in hardware and uses information from the calorimeters and muon sub-detectors to reduce the event rate to a design value of at most 75 kHz. This is followed by two software-based trigger levels, Level 2 (L2) and Event Filter (EF), which together reduce the event rate to 300 Hz on average. The L1 trigger generates a list of Regions of Interest (RoI) η–ϕ coordinates with associated thresholds. The muon RoI have a spatial extent of 0.2 in $\Delta\eta$ and $\Delta\phi$ in the MS barrel, and 0.1 in the MS endcap. The electromagnetic calorimeter RoI have a spatial extent of 0.2 in $\Delta\eta$ and $\Delta\phi$. At L2, most reconstruction uses simplified algorithms running on data localized to an RoI which was reported by L1. At the EF level, the trigger system has access to the full event for processing.

3. Event reconstruction and selection

The analysis used only data from stable running periods, and required events to have a primary collision vertex containing at least three tracks with $p_{\mathrm{T}} > 400$ MeV in order to remove cosmic rays.

3.1. Electron-jet channel

Events containing electron-jets were selected using single electron triggers with an online p_{T} threshold of 20 or 22 GeV, the latter being used after there was a substantial increase in the instantaneous luminosity during 2011. To ensure proper modelling of the trigger acceptance, events were required to contain at least one reconstructed electron with $p_{\mathrm{T}} > 35$ GeV, above which the trigger efficiency is constant. The reconstructed electron was required to match an electron reconstructed above the p_{T} threshold in the trigger system with a separation in R ($\Delta R \equiv \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$) less than 0.2.

The electron-jet candidates were built from electromagnetic clusters with minimum transverse energy $E_{\mathrm{T}} > 10$ GeV inside the calorimeter fiducial region ($|\eta| < 2.47$, excluding the barrel/end-cap transition region $1.37 < |\eta| < 1.52$ where there is substantial dead material that is difficult to model accurately). At least two tracks from the primary vertex (transverse impact parameter $|d_0| < 1$ mm) having $p_{\mathrm{T}} > 10$ GeV were required to have $\Delta R < 0.1$ of the cluster position in the second sampling layer of the calorimeter. Additional requirements were made on the number of hits along the track in the silicon pixel and silicon microstrip detectors to suppress backgrounds from photon conversions. The analysis required two lepton-jet candidates in each event, with one cluster matching the electron reconstructed in the trigger system. The invariant mass of the two highest-p_{T} tracks associated with each electron-jet had to be less than 2 GeV.

The background for the electron-jets analysis comes primarily from multi-jet events, and to a lesser extent from photon + jet events. Five variables were used to reduce the remaining background for electron-jet candidates. The electron cluster energy concentration shown in Fig. 1(a), $R_{\eta 2}$, must exceed 0.92. $R_{\eta 2}$ is defined as the ratio of total energy in 3×7 cells to the total energy in 7×7 cells in η–ϕ in the second sampling layer of the electromagnetic calorimeter. The electron cluster lateral shower width in the calorimeter, $w_{\eta 2}$, shown in Fig. 1(b), must be less than 0.0115, where

$$w_{\eta 2} = \sqrt{\frac{\sum_i E_i \times \eta_i{}^2}{\sum_i E_i} - \left(\frac{\sum_i E_i \times \eta_i}{\sum_i E_i}\right)^2}. \quad (1)$$

Here E_i and η_i represent the energy and pseudorapidity of the ith cell in a 3×5 η–ϕ window in the second sampling layer of the electromagnetic calorimeter. The ratio of the number of high-threshold hits [22], indicative of transition radiation, to the total number of hits from the TRT associated with each track, f_{HT}, was required to be greater than 0.05 to remove pions. The f_{HT} distribution per track is shown in Fig. 1(c). The sharp peak at zero arises from tracks matched to an electron candidate outside of the TRT acceptance. A scaled isolation variable is defined as the transverse energy within $0.1 < \Delta R < 0.4$ around the cluster divided by cluster E_{T}; events were required to have scaled isolation below 30% as shown in Fig. 1(d). Finally, a requirement that the fraction of the lepton-jet energy found in the electromagnetic calorimeter, f_{EM} must be larger than 0.98, was used to reject activity from hadrons, as shown in Fig. 1(e).

[1] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the centre of the LHC ring, and the y-axis points upward. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$.

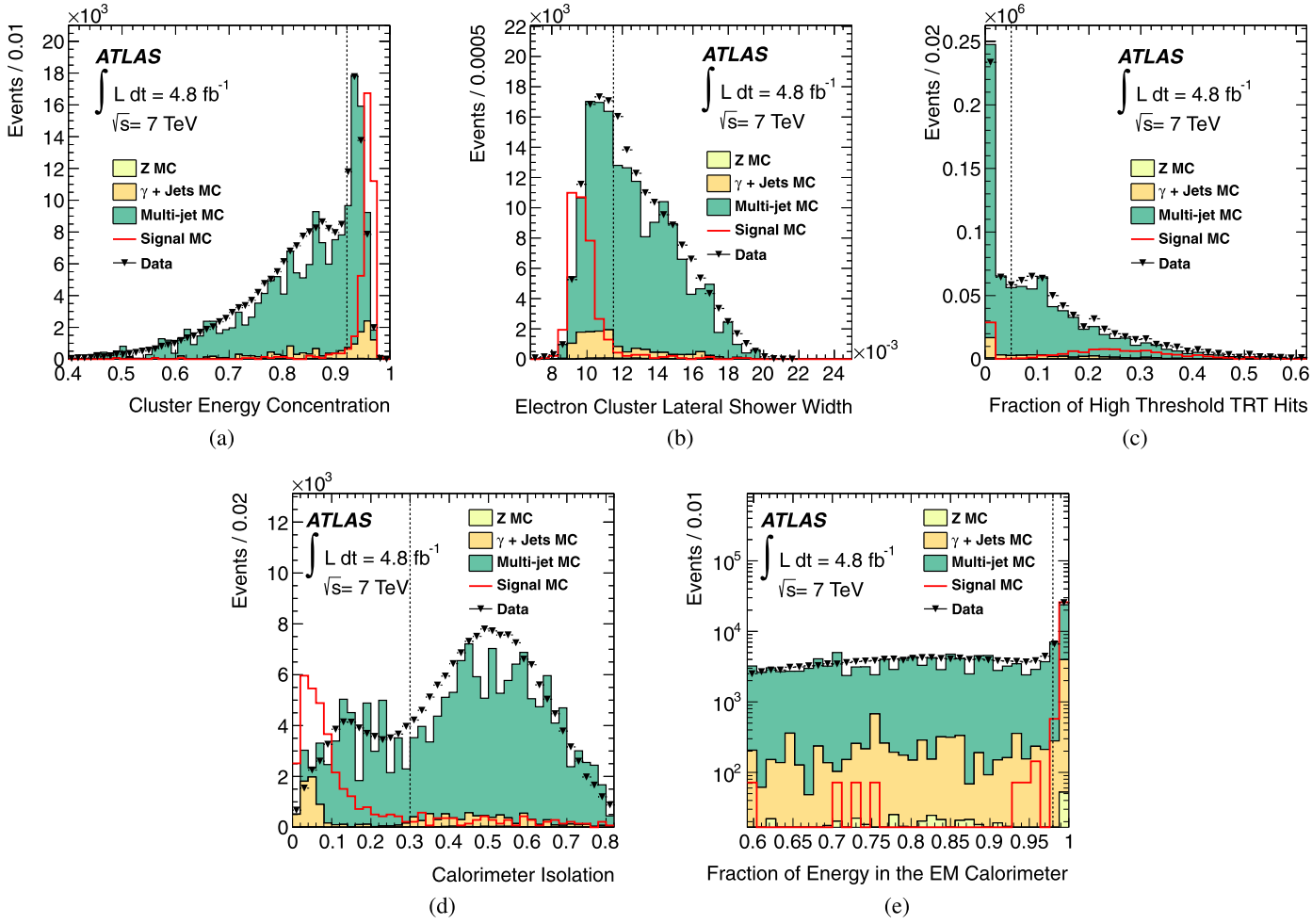

Fig. 1. Distributions of the five discriminating variables used after selection of events which have passed the trigger and contain two or more electron-jet candidates, shown separately for the multi-jet, $Z \to ee$ and γ + jets backgrounds as well as for the signal sample with $\alpha_d = 0.0$ and $m_{\gamma_D} = 150$ MeV. The signal MC normalization is arbitrary. The dashed black vertical line shows the cut values at (a) cluster energy concentration $R_{\eta 2} \geqslant 0.92$, (b) electron cluster lateral shower width $w_{\eta 2} \leqslant 0.0115$, (c) fraction of high threshold TRT hits $f_{\rm HT} \geqslant 0.05$, (d) calorimeter isolation $\leqslant 0.3$, and (e) fraction of energy in the EM calorimeter $f_{\rm EM} \geqslant 0.98$. The hadronic jet and γ + jets distributions are shown here from PYTHIA MC for illustrative purposes.

3.2. Muon-jet channels

Single muon-jet events were selected from events satisfying a trigger with a single muon having more than 18 GeV in $p_{\rm T}$. Candidates for double muon-jets were taken with either a single muon trigger with a $p_{\rm T}$ threshold of 18 GeV or a three-muon trigger with a $p_{\rm T}$ threshold of 6 GeV. The muon triggers were complementary, as the three-muon trigger has reduced efficiency for high-$p_{\rm T}$ muons from a single lepton-jet which may be too close together to produce more than one RoI.

Muon candidates must have been reconstructed in both the ID and the MS and have $|\eta| < 2.5$. Additional requirements were made on the number of associated hits in the silicon pixel and microstrip detectors, as well as on the number of track segments in the MS. The muons were required to come from the primary vertex by imposing a $|d_0| < 1$ mm cut on the tracks. The muon-jets were reconstructed in an iterative procedure using all candidate muons, by seeding the jet candidate with the highest-$p_{\rm T}$ muon, and adding all muons within $\Delta R = 0.1$. Additional jets were formed using the remaining muons, again seeding the muon-jet with the remaining highest-$p_{\rm T}$ muon. For the double muon-jet analysis, two muons with $p_{\rm T} > 11$ GeV were required per jet with the additional requirement that the leading muon $p_{\rm T}$ be greater than 23 GeV for the single muon trigger events. For the single muon-jet analysis, four muons were required per jet with $p_{\rm T} > 19, 16, 14$ GeV, respectively, for the three highest-$p_{\rm T}$ muons, and $p_{\rm T} > 4$ GeV for all additional muons.

Within a muon-jet, the two muons closest in $p_{\rm T}$ were required to have an invariant mass less than 2 GeV. A scaled isolation variable was formed by summing the $E_{\rm T}$ of all calorimeter cells within $\Delta R = 0.3$ of any of the muon-jet's component muons while excluding cells found within $\Delta R = 0.05$ of the muons, and dividing by the muon-jet $p_{\rm T}$. The scaled isolation was required to be less than 0.3 (0.15) per muon-jet for the double (single) muon-jet analyses, to suppress muons from hadronic jets.

As noted earlier, a signature of the dark matter signal is a muon-jet composed of two or more muon tracks confined to a narrow cone. One source of collimated muons arises from the decay of low-mass states, since the opening angle is in inverse proportion to the Lorentz boost. The background from boosted low-mass states with an invariant mass less than 3.5 GeV is displayed in Fig. 2 showing the opening angle ΔR vs invariant mass for all dimuon pairs. This plot was produced using the same muon selection used for the muon-jet analysis, excluding the ΔR requirement. The invariant mass of muon pairs falls off smoothly, interrupted by easily observable narrow peaks produced by low-mass resonances such as ϕ (~1 GeV), and ω and ρ (~0.7 GeV). For smaller opening angles, $\Delta R \lesssim 0.03$, the low-mass resonances barely stand out from

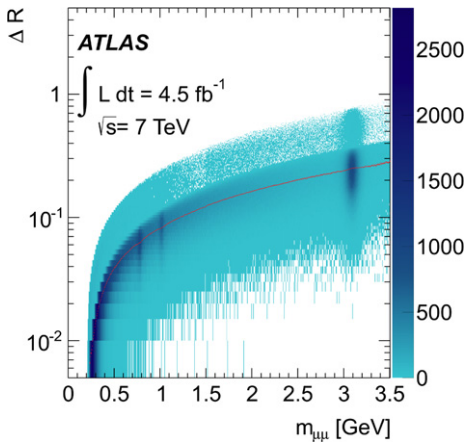

Fig. 2. The opening angle ΔR vs invariant mass for all muon pairs in the 4.5 fb^{-1} data sample. The overlaid red points show the profile of the ΔR distribution for each dimuon mass bin. The position of each point is the mean value of the vertical slice and its width is the RMS. The secondary distribution running along the top of the distribution arises from events with more than two muons, where a third muon triggers at a higher p_{T}, allowing for combinations of dimuon pairs with a larger opening angle. (For interpretation of the references to color in this figure, the reader is referred to the web version of this Letter.)

the rest of the background. It was not practical to exclude the ω/ρ and ϕ peak regions from the analysis. However, the J/ψ was removed for the electron-jet and muon-jet search by a 2 GeV mass cut. A second smoothly falling distribution is also visible in this figure from events with an additional three or more muons, one of which has a high enough p_{T} to fire the trigger, producing an additional combinatorial background.

4. Signal and background estimation

Both MC and data-driven methods were used for background and efficiency estimations. Various SM processes can mimic the signal due to misreconstructed objects, such as jets misidentified as electrons, or chance overlap of leptons. We have considered MC hadronic multi-jet events, $\gamma+$ jets events, $W\to\ell\nu+$ jets, $Z\to\ell^+\ell^-+$ jets, $t\bar{t}$ and diboson (WW, WZ, ZZ) events at $\sqrt{s}=7$ TeV. Pythia6 [23] was used for all samples except $t\bar{t}$, WW, WZ, ZZ for which MC@NLO [24] was used. The contribution from WZ and ZZ backgrounds, when one of the bosons is off-shell, was modeled with Sherpa [25]. Of all the backgrounds considered, only the hadronic multi-jet and $\gamma+$ jets events contribute significantly to the final background expectation. In addition, signal MC simulation was generated using MadGraph [26] with the CTEQ6L1 set of parton distribution functions [27], and a custom-made Mathematica [28] package to model the dark sector cascade decay described in Refs. [11,16], followed by Pythia6 for hadronization. All MC samples include the effect of multiple pp interactions per bunch crossing and are assigned an event weight such that the distribution of the number of pp interactions matches that in data. The mean momentum of the dark photons depends strongly on α_d and therefore the acceptance of the lepton-jets also depends on this parameter. At $\alpha_d=0.0$ the mean momentum of the dark photon is 73, 76, and 82 GeV for $m_{\gamma_D}=150, 300,$ and 500 MeV, respectively, with no cuts applied. For $\alpha_d=0.1$, the mean dark photon momentum decreases to 30.4, 35.9, and 41.6 GeV. At $\alpha_d=0.3$ the mean values are 21.1, 25.7, and 30.9 GeV. All MC events were processed with the Geant4 based ATLAS detector simulation [29,30] and then analyzed with the standard ATLAS reconstruction software.

Due to the very small acceptance for hadronic jets passing our signal criteria, $\mathcal{O}(10^{-3})$ to $\mathcal{O}(10^{-4})$ for jets with $50<p_{\mathrm{T}}<400$ GeV, there were too few MC events to accurately estimate background yields. The background MC samples were used to help establish the event selection criteria, based on characteristics of the background. All the samples were required to satisfy the trigger conditions, with efficiencies ranging from 40% to 75% for the lepton-jet models considered.

4.1. Background estimation with the ABCD-likelihood method

In the lepton p_{T} and dilepton invariant mass ranges relevant to this study, the level of the background is best estimated using a data-driven method, rather than by MC simulation where the number of events is low and the backgrounds may be poorly modeled. This Letter uses an ABCD-likelihood method to determine the lepton-jet backgrounds which was cross-checked with a tag-and-probe fake-rate estimate. The traditional implementation of the ABCD method consists of using two uncorrelated or loosely correlated variables from the event selection to define four regions labeled A, B, C and D, as illustrated in Fig. 3. The background in the signal region is estimated by taking the ratio of events in the adjacent regions. This method breaks down in the presence of significant signal contamination in the side-band regions, or when there are too few events. The ABCD-likelihood method addresses both of these issues. A likelihood function, formed from the product of Poisson probability functions describing the signal and background expectations, is fit to all four of the regions simultaneously.

The likelihood takes the form:

$$L(n_{\mathrm{A}},n_{\mathrm{B}},n_{\mathrm{C}},n_{\mathrm{D}}|\mu,\theta_\mu)=\prod_{i=\mathrm{A,B,C,D}}\frac{e^{-\mu_i}\mu_i^{n_i}}{n_i!} \tag{2}$$

where n_{A}, n_{B}, n_{C}, and n_{D} are the numbers of events observed in each of the four regions, and μ_{A}, μ_{B}, μ_{C}, and μ_{D} are linear combinations of signal (μ) and multi-jet background (μ^U) expectations. In region A, the expected number of events $\mu_{\mathrm{A}}=\mu^U+\mu$. In region B, $\mu_{\mathrm{B}}=\mu^U\tau_{\mathrm{B}}+\mu b$, where τ_{B} is the ratio of background events expected in region B to that in region A and b gives the signal contamination in region B. Similarly, the expected number of events in region C is expressed as $\mu_{\mathrm{C}}=\mu^U\tau_{\mathrm{C}}+\mu c$. In region D, $\mu_{\mathrm{D}}=\mu^U\tau_{\mathrm{B}}\tau_{\mathrm{C}}+\mu d$, such that the multi-jet background contribution is determined using the product of the ratios. The signal contamination coefficients are taken from MC simulation for each signal sample, while μ^U and the τ_i values are allowed to float in a simultaneous fit to the four data regions.

For the electron-jet analysis, the ABCD-likelihood method used boundaries at $R_{\eta 2}=0.92$ and $f_{\mathrm{EM}}=0.98$ on the second highest-E_{T} lepton-jet to define these four regions. In photon + jet events, the photon will typically deposit more energy in the EM calorimeter than the hadronic jet. Using the subleading cluster to estimate the background thus accounts for both the photon + jet and multi-jet backgrounds. The double (single) muon-jet analysis used the scaled isolation variable and the p_{T} cut on the fourth (third) muon in the event, associated with a muon-jet. The two-dimensional distributions with the A, B, C and D regions are shown in Fig. 3. In the absence of signal, the numbers of events predicted in region A for the single muon-jet channel, the double muon-jet channel, and the double electron-jet channel are 3.0 ± 1.0, 0.5 ± 0.3, and 15.2 ± 2.7, respectively. The quoted errors are statistical only.

4.2. Background estimation using jet probabilities

Both the electron-jet and muon-jet analyses used a tag-and-probe method to cross-check the amount of background in the signal region using back-to-back hadronic jet pairs with $p_{\mathrm{T}}>30$ GeV and $|\Delta\phi|>2$ but with different selection criteria.

For the electron-jet analysis, the tag was chosen by matching a jet with $f_{\mathrm{EM}}<0.9$ to a trigger jet. Using the highest-E_{T}

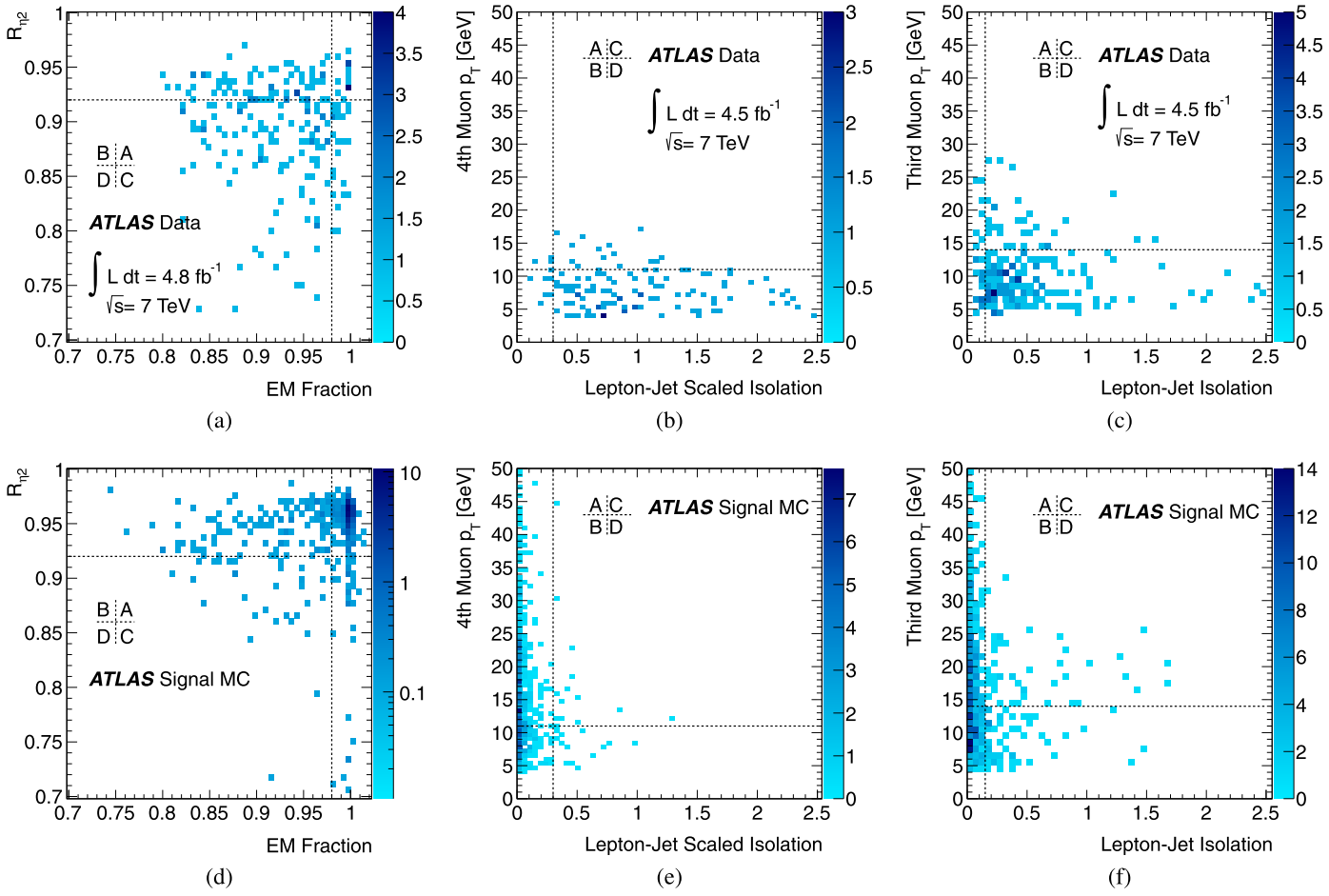

Fig. 3. Variables used for ABCD-likelihood method from data (top) and MC signal (bottom) using $\alpha_d = 0.1$ and $m_{\gamma_D} = 300$ MeV for the electron channel and $\alpha_d = 0.0$ and $m_{\gamma_D} = 300$ MeV for the two muon channels. The dashed black lines show the cuts used to define the four regions. Shown are (left) electron-jet: $R_{\eta 2}$ vs EM fraction; (centre) double muon-jet: scaled isolation vs p_{T} of the fourth muon; (right) single muon-jet: scaled isolation vs p_{T} of the third muon.

electromagnetic cluster within $\Delta R = 0.4$ of the probe jet as a seed for the electron-jet, the fake rate was extracted from the probe jets that satisfied the electron-jet criteria, as well as the probability for such electron-jets to pass the electron trigger. Jet triggers with different p_{T} thresholds were used to determine the rates over the full range of probe-jet p_{T} values. These probabilities were then used to calculate event weights for the inclusive multi-jet MC sample to estimate the number of events which would pass the electron trigger and electron-jet selection requirements. This method predicted $14.55^{+0.23}_{-0.04}$ background events after all analysis cuts were applied to the data. The quoted error is statistical only.

The double muon-jet analysis used two criteria to select either light-quark or b-quark jets by requiring that either the tag jets contain no muons and no b-tag, or the tag jets have a b-tag. The probe jets were then used to determine the probability that a hadronic jet could satisfy the muon selection criteria and the probability that it could satisfy the muon-jet selection criteria, as a function of the probe-jet p_{T}. The ratio of these two probabilities was used in events containing three muons (of which at least two formed a muon-jet and the third was embedded in a hadronic jet) to estimate the background from multi-jet production, accounting for the flavour of the hadronic jet. This method predicted 2.2 ± 0.9 events from multi-jet production. The quoted error is statistical only.

The fake rates for muon-jets and electron-jets were found to be consistent with those obtained from the ABCD-likelihood method, which were discussed in Section 4.1 and are summarized in Table 1. This cross-check thus validates the background estimates.

Table 1
The number of events in the signal region (A) observed in data and expected from background sources estimated with the ABCD-likelihood method. The quoted error is statistical only.

	Electron LJ	1 muon LJ	2 muon LJ
Data	15	7	3
All background	15.2 ± 2.7	3.0 ± 1.0	0.5 ± 0.3

Table 2
The acceptance times trigger, reconstruction, and selection efficiency ($\mathrm{A} \times \epsilon$) expected in the signal region (A) from various signal hypotheses for the three different lepton-jet (LJ) channels. Note that the $m_{\gamma_D} = 150$ MeV dark photon cannot decay to muons.

Signal parameters		Electron LJ	1 muon LJ	2 muon LJ
α_d	m_{γ_D} [MeV]	$\mathrm{A} \times \epsilon$ [%]	$\mathrm{A} \times \epsilon$ [%]	$\mathrm{A} \times \epsilon$ [%]
0.0	150	3.01 ± 0.30		
0.0	300	2.7 ± 0.5	4.3 ± 0.9	9.2 ± 0.9
0.0	500	1.8 ± 0.5	1.7 ± 1.3	8.5 ± 1.1
0.10	150	2.69 ± 0.23		
0.10	300	1.04 ± 0.19	3.7 ± 0.5	7.10 ± 0.39
0.10	500	1.17 ± 0.23	5.0 ± 0.8	8.1 ± 0.6
0.30	150	2.49 ± 0.22		
0.30	300	0.80 ± 0.13	2.16 ± 0.29	7.47 ± 0.42
0.30	500	0.37 ± 0.10	3.16 ± 0.46	6.23 ± 0.43

Table 3
Contributions to the systematic uncertainty on the signal yields for the three different lepton-jet (LJ) channels given as percentages. A "NA" means this source does not apply.

	Electron LJ [%]	1 muon LJ [%]	2 muon LJ [%]
Luminosity	3.9	3.9	3.9
Trigger efficiency	1.5	2.0	3.6
Offline ΔR efficiency	13.0	10.7	10.7
Lepton momentum scale	0.6	1.0	1.0
Isolation	5.2	< 0.1	< 0.1
$R_{\eta 2}$ and $w_{\eta 2}$ efficiency	8.0	NA	NA
f_{HT} efficiency	1.0	NA	NA
f_{EM} efficiency	3.0	NA	NA
Muon momentum resolution	NA	< 1.0	< 1.0

5. Results and interpretation

Table 1 shows the number of events passing all analysis cuts compared to the background expectation from the ABCD-likelihood method. A slight excess is observed in both the single and the double muon-jet signal regions corresponding to p-values (the probability the background process would produce at least this many events) of 0.06 and 0.04, respectively. The acceptance times trigger, reconstruction, and selection efficiency for the various signal points are listed in Table 2. It ranges from about 0.4% to 10% depending on the model parameter α_d, the mass of the dark photon, and the analysis channel. The estimate of the background from the ABCD-likelihood method has a large statistical error, which reduces the expected sensitivity of the analysis. The systematic uncertainty on the ABCD-likelihood method due to correlation between the variables, 3% (4%) for the single (double) muon-jets channel, is small by comparison.

Table 3 lists the systematic uncertainties on the signal yields. The possible mismodelling of track reconstruction at very small opening angles ("Offline ΔR Efficiency" in Table 3) introduces a $\sim$10% systematic error on the signal acceptance. The size of the systematic uncertainty on the acceptance was estimated by measuring the tracking efficiency using a tag-and-probe method with J/ψ data and MC. For $\Delta R > 0.05$ the data and MC agree to within $\sim$4%. However, a systematic variation of $\sim$10% is observed in the efficiency for the smaller ΔR region, which is probably due to a slightly softer p_{T} distribution in the MC than in the data. Systematic errors are also assigned to the determination of the luminosity, the modelling of the trigger acceptance, the modelling of the lepton reconstruction efficiency, and the modelling of each of the analysis cuts.

The 95% confidence-level upper limits on the number of expected events from new phenomena producing collimated pairs of prompt leptons were calculated using the CLs method [31] with a log-likelihood ratio (LLR) test statistic. Ensembles of pseudo-experiments were generated for the signal-only hypothesis and the signal + background hypothesis, varying the LLR according to the statistical and systematic uncertainties. The upper limits were determined by performing a scan of p-values corresponding to LLR values larger than the one observed in data. For broad applicability, the limits are expressed in terms of the signal cross section times branching ratio to the final state under consideration, using the expected signal acceptance for each of the pairings of dark photon masses and dark sector gauge coupling parameter values in Table 4.

The observed limits in the electron-jets channel are in good agreement with the expected limits, and are the first inclusive study of prompt electron-jets at the LHC. The limits in the muon-jet channels are slightly higher than expected as a result of the slight excesses, but are within 2σ of the SM expectation for both channels. The limits on the production of prompt lepton-jets in the muon-jet channel improve upon previous results by an order of magnitude.

Table 4
Observed (expected) upper limits for cross section times branching ratio ($\sigma \times$ BR) to the final state under consideration, in units of pb for the three different lepton-jet (LJ) channels.

Signal parameters		Electron LJ	1 muon LJ	2 muon LJ
α_d	m_{γ_D} [MeV]	Obs. (Exp.) pb	Obs. (Exp.) pb	Obs. (Exp.) pb
0.0	150	0.082 (0.082)	–	–
0.0	300	0.11 (0.11)	0.060 (0.035)	0.017 (0.011)
0.0	500	0.20 (0.21)	0.15 (0.090)	0.019 (0.012)
0.10	150	0.096 (0.10)	–	–
0.10	300	0.37 (0.37)	0.064 (0.036)	0.018 (0.011)
0.10	500	0.39 (0.39)	0.053 (0.035)	0.018 (0.011)
0.30	150	0.11 (0.11)	–	–
0.30	300	0.40 (0.40)	0.099 (0.055)	0.020 (0.012)
0.30	500	1.2 (1.2)	0.066 (0.043)	0.022 (0.015)

6. Conclusions

A search for collimated pairs of muons or electrons, lepton-jets, has been performed using nearly 5 fb^{-1} of pp collisions at $\sqrt{s} = 7$ TeV recorded with the ATLAS detector at the LHC. Such final states have been proposed as a possible explanation of recently observed anomalies in cosmic-ray and dark matter direct-detection experiments. No significant excess of data compared to the SM expectation was observed in any of the three channels, and 95% confidence-level upper limits have been computed on the cross section times branching ratio for several parameter values of a Hidden Valley model. The limits range from 0.017 to 1.2 pb.

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