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


DOI
10.1016/j.physletb.2013.01.034

Publication date
2013

Document Version
Final published version

Published in
Physics Letters B

Citation for published version (APA):

General rights
It is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), other than for strictly personal, individual use, unless the work is under an open content license (like Creative Commons).

UvA-DARE is a service provided by the library of the University of Amsterdam (https://dare.uva.nl)
A search for prompt lepton-jets in \( pp \) collisions at \( \sqrt{s} = 7 \) TeV with the ATLAS detector

ATLAS Collaboration

A R T I C L E   I N F O
Article history:
Received 21 December 2012
Received in revised form 15 January 2013
Accepted 17 January 2013
Available online 26 January 2013
Editor: W.-D. Schlatter

A B S T R A C T
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.

© 2013 CERN. Published by Elsevier B.V. All rights reserved.

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 \( \gamma_D \). 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 \( \gamma_D \) that has a mass below the proton–antiproton kinematic threshold of \( \sim 2 \) 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 \( \gamma_D \), 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 \( \alpha_d \). Setting \( \alpha_d = 0.0 \) results in a simple lepton-jet with two hard leptons. Larger values of \( \alpha_d \) 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 \( \alpha_d \). This Letter considers values of \( \alpha_d \) of 0.0, 0.1, and 0.3, and dark photon masses \( (m_{\gamma_D}) \) 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 \( m_{\gamma_D} \geq 300 \) 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\(^{-1}\)
of integrated luminosity for the muon analyses and 4.8 fb\(^{-1}\) for
the electron analysis \cite{20,21}, after their respective data quality re-
quirements 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 back-
ground arises from either real leptons from the decay of SM parti-
cles, 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 intro-
ducing 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 en-
ergy.

2. The ATLAS detector

ATLAS is a general-purpose detector \cite{22} consisting of an inner
tracking detector (ID) embedded in a 2 T solenoid, electromag-
etic and hadronic calorimeters and a muon spectrometer (MS)
employing toroidal magnets. The ID provides precision tracking of
charged particles for |η| < 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 |η| < 2.0. Liquid argon (LAr) electromagnetic sam-
ping calorimeters, with excellent energy and position resolution,
cover the range |η| < 3.2 with a typical granularity of Δη × Δϕ
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 |η| < 1.7. In the end-caps (|η| > 1.5), LAr is also used for
the hadronic calorimeters, matching the outer |η| limit of end-cap
electromagnetic calorimeters. The LAr forward calorimeters pro-
vide both electromagnetic and hadronic energy measurements, and
extend the coverage to |η| = 4.9. The calorimeter system has a
minimum depth of 9.7 interaction lengths at η = 0. The MS cov-
ers |η| < 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 Δη and Δϕ in the MS barrel, and 0.1 in the MS endcap.
The electromagnetic calorimeter RoI have a spatial extent of 0.2 in
Δη and Δϕ. 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 pro-
cessing.

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 \( p_T > 400 \) MeV in order to remove cosmic
rays.

3.1. Electron-jet channel

Events containing electron-jets were selected using single elec-
tron triggers with an online \( p_T \) threshold of 20 or 22 GeV, the
latter being used after there was a substantial increase in the in-
stantaneous luminosity during 2011. To ensure proper modelling
of the trigger acceptance, events were required to contain at least one
reconstructed electron with \( p_T > 35 \) GeV, above which the trig-
ger 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 \( R (ΔR ≡ √((Δϕ)^2 + (Δη)^2) \) lest
than 0.2.

The electron-jet candidates were built from electromagnetic
clusters with minimum transverse energy \( E_T > 10 \) GeV inside the
calorimeter fiducial region (|η| < 2.47, excluding the barrel/end-
cap transition region 1.37 < |η| < 1.52 where there is substi-
tual dead material that is difficult to model accurately). At least
two tracks from the primary vertex (transverse impact parameter
|d_{0}| < 1 mm) having \( p_T > 10 \) GeV were required to have
ΔR < 0.1 of the cluster position in the second sampling layer of
the calorimeter. Additional requirements were made on the num-
ber 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 back-
ground for electron-jet candidates. The electron cluster energy
concentration shown in Fig. 1(a), \( R_{\eta2} \), must exceed 0.92. \( R_{\eta2} \) 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 electro-
magnetic calorimeter. The electron cluster lateral shower width in
the calorimeter, \( w_{\eta2} \), shown in Fig. 1(b), must be less than 0.0115,
where

\[
w_{\eta2} = \sqrt{\frac{\sum_i E_i \times \eta_i^2}{\sum_i E_i} - \left(\frac{\sum_i E_i \times \eta_i}{\sum_i E_i}\right)^2}.\]

(1)

Here \( E_i \) and \( \eta_i \) 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 \cite{22}, indicative of transition radiation, to the total
number of hits from the TRT associated with each track, \( f_{\text{HR}} \),
was required to be greater than 0.05 to remove pions. The \( f_{\text{HR}} \) distri-
bution 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 < ΔR < 0.4 around the cluster divided by clus-
ter \( E_T \); 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, \( f_{3M} \)
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, θ) 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 \( \eta = -\ln(\tan(θ/2)) \).
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 $p_T$. Candidates for double muon-jets were taken with either a single muon trigger with a $p_T$ threshold of 18 GeV or a three-muon trigger with a $p_T$ threshold of 6 GeV. The muon triggers were complementary, as the three-muon trigger has reduced efficiency for high-$p_T$ 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-$p_T$ 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-$p_T$ muon. For the double muon-jet analysis, two muons with $p_T > 11$ GeV were required per jet with the additional requirement that the leading muon $p_T$ be greater than 23 GeV for the single muon trigger events. For the single muon-jet analysis, four muons were required per jet with $p_T > 19, 16, 14$ GeV, respectively, for the three highest-$p_T$ muons, and $p_T > 4$ GeV for all additional muons.

Within a muon-jet, the two muons closest in $p_T$ were required to have an invariant mass less than 2 GeV. A scaled isolation variable was formed by summing the $E_T$ 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 $p_T$. 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 $\Delta R$ vs invariant mass for all dimuon pairs. This plot was produced using the same muon selection used for the muon-jet analysis, excluding the $\Delta R$ requirement. The invariant mass of muon pairs falls off smoothly, interrupted by easily observable narrow peaks produced by low-mass resonances such as $\phi (~1$ GeV), and $\omega$ and $\rho (~0.7$ GeV). For smaller opening angles, $\Delta R < 0.03$, the low-mass resonances barely stand out from...
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:

$$L(n_A, n_B, n_C, n_D | \mu, \theta) = \prod_{i=A,B,C,D} \frac{e^{-\mu_i} \mu_i^{n_i}}{n_i!}$$

where $n_A$, $n_B$, $n_C$, and $n_D$ are the numbers of events observed in each of the four regions, and $\mu_A$, $\mu_B$, $\mu_C$, and $\mu_D$ are linear combinations of signal ($\mu$) and multi-jet background ($\mu^B$) expectations. In region A, the expected number of events $\mu_A = \mu^U + \mu$. In region B, $\mu_B = \mu^U \tau_B + \mu_b$, where $\tau_B$ 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 $\mu_C = \mu^U \tau_C + \mu_C$. In region D, $\mu_D = \mu^U \tau_D \tau_C + \mu_d$, 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 $\mu^U$ and the $\tau_i$ 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 $R_{ge} = 0.92$ and $f_{EM} = 0.98$ 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 $3.0 \pm 1.0$, $0.5 \pm 0.3$, and $15.2 \pm 2.7$, 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 $p_T > 30$ GeV and $|\Delta \phi| > 2$ but with different selection criteria.

For the electron-jet analysis, the tag was chosen by matching a jet with $f_{EM} < 0.9$ 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.

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 $p_T$. This method predicted $2.2^{+0.2}_{-0.2}$ 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 $2.2 \pm 0.9$ 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.
The limits on the production of prompt lepton-jets in the muon-jet channel improve upon previous results by an order of magnitude.

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.

Acknowledgements

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently.

We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWF and FWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNRF, DNSRC and Lundbeck Foundation, Denmark; EPLANET, ERC and NSRF, European Union; IN2P3-CNRS, CEA-DSM/IRFU, France; GNSF, Georgia; BMBF, DFG, MPG and AvH Foundation, Germany; CSR and NSRF, Greece; ISF, MINERVA, GIF, DIP and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; BRF and RCN, Norway; MNiSW, Poland; GRICES and FCT, Portugal; MERYS (MECTS), Romania; MES of Russia and ROSATOM, Russian Federation; JINR; MSTD, Serbia; MSSR, Slovakia; ARRS and MVZT, Slovenia; DST/NRF, South Africa; BAEF, Spain; SSHRM, Turkey; UM, United Kingdom; and the AECC,acciing to the ATLAS Collaboration / Physics Letters B 719 (2013) 299–317

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

<table>
<thead>
<tr>
<th>Source</th>
<th>Electron LJ [%]</th>
<th>1 muon LJ [%]</th>
<th>2 muon LJ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity</td>
<td>3.9</td>
<td>3.9</td>
<td>3.9</td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>1.5</td>
<td>2.0</td>
<td>3.6</td>
</tr>
<tr>
<td>Offline $\Delta R$ efficiency</td>
<td>13.0</td>
<td>10.7</td>
<td>10.7</td>
</tr>
<tr>
<td>Lepton momentum scale</td>
<td>0.6</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Isolation</td>
<td>5.2</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>$R_{\text{pt}}$ and $w_{\text{pt}}$ efficiency</td>
<td>8.0</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>$f_{\text{eff}}$ efficiency</td>
<td>1.0</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>$f_{\text{tot}}$ efficiency</td>
<td>3.0</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Muon momentum resolution</td>
<td>NA</td>
<td>&lt; 1.0</td>
<td>&lt; 1.0</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Signal parameters</th>
<th>Electron LJ</th>
<th>1 muon LJ</th>
<th>2 muon LJ</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_d$</td>
<td>$m_{\gamma}$ [MeV]</td>
<td>Obs. (Exp.) pb</td>
<td>Obs. (Exp.) pb</td>
</tr>
<tr>
<td>0.0</td>
<td>150</td>
<td>0.082 (0.082)</td>
<td>–</td>
</tr>
<tr>
<td>0.0</td>
<td>300</td>
<td>0.11 (0.11)</td>
<td>0.060 (0.035)</td>
</tr>
<tr>
<td>0.0</td>
<td>500</td>
<td>0.20 (0.21)</td>
<td>0.15 (0.090)</td>
</tr>
<tr>
<td>0.10</td>
<td>150</td>
<td>0.096 (0.10)</td>
<td>–</td>
</tr>
<tr>
<td>0.10</td>
<td>300</td>
<td>0.37 (0.37)</td>
<td>0.064 (0.036)</td>
</tr>
<tr>
<td>0.10</td>
<td>500</td>
<td>0.39 (0.39)</td>
<td>0.053 (0.035)</td>
</tr>
<tr>
<td>0.30</td>
<td>150</td>
<td>0.11 (0.11)</td>
<td>–</td>
</tr>
<tr>
<td>0.30</td>
<td>300</td>
<td>0.40 (0.40)</td>
<td>0.099 (0.055)</td>
</tr>
<tr>
<td>0.30</td>
<td>500</td>
<td>1.2 (1.2)</td>
<td>0.066 (0.043)</td>
</tr>
</tbody>
</table>

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 $\alpha_d$, 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 $\Delta R$ 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 $J/\psi$ 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 $\Delta R$ 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 $2\sigma$ 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.

The study of prompt electron-jets at the LHC. The limits in the muon-jet channel improve upon previous results by an order of magnitude.
Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain
Centre de Calcul de l’Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France
Yerevan Physics Institute, Yerevan, Armenia
Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany
Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
Department of Physics, University of Wisconsin, Madison, WI, United States
Waseda University, Tokyo, Japan
Department of Physics, University of Warwick, Coventry, United Kingdom
Department of Physics, University of British Columbia, Vancouver, BC, Canada
Department of Physics, University of Illinois, Urbana, IL, United States
Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
Department of Physics, Simon Fraser University, Burnaby, BC, Canada
SLAC National Accelerator Laboratory, Stanford, CA, United States
Department of Mathematics, Physics & Informatics, Comenius University, Bratislava; (b) Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
Department of Physics, University of Johannesburg, Johannesburg; (b) School of Physics, University of the Witwatersrand, Johannesburg, South Africa
Department of Physics, Stockholm University; (b) The Oskar Klein Centre, Stockholm, Sweden
Department of Physics, Royal Institute of Technology, Stockholm, Sweden
Department of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook, NY, United States
Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
School of Physics, University of Sydney, Sydney, Australia
Institute of Physics, Academia Sinica, Taipei, Taiwan
Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
Department of Physics, University of Toronto, Toronto, ON, Canada
TRIUMF, Vancouver, BC; (b) Department of Physics and Astronomy, York University, Toronto, ON, Canada
Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan
Department of Physics and Astronomy, Tufts University, Medford, MA, United States
Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
Department of Physics and Astronomy, University of California Irvine, Irvine, CA, United States
INFN Gruppo Collegato di Udine; (c) ICTP Trieste; (c) Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
Department of Physics, University of Illinois, Urbana, IL, United States
Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain
Department of Physics, University of British Columbia, Vancouver, BC, Canada
Department of Physics and Astronomy, University of Victoria, Victoria, BC, Canada
Department of Physics, University of Warwick, Coventry, United Kingdom
Waseda University, Tokyo, Japan
Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
Department of Physics, University of Wisconsin, Madison, WI, United States
Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany
Department of Physics, Yale University, New Haven, CT, United States
Yerevan Physics Institute, Yerevan, Armenia
Centre de Calcul de l’Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France

\[a\] Also at Department of Physics, King's College London, London, United Kingdom.
\[b\] Also at Instituto de Instrumentacao e Física Experimental de Partículas – IFF, Lisboa, Portugal.
\[c\] Also at Faculdade de Ciências e Tecnologia, Universidade do Porto, Porto, Portugal.
\[d\] Also at Institute of Physics, Ankara, Turkey.
\[e\] Also at Department of Physics, University of Bari, Bari, Italy.
\[f\] Also at INFN Sezione di Bari, Bari, Italy.
\[g\] Also at Dipartimento di Fisica, Università di Salerno, Fisciano, Italy.
\[h\] Also at INFN Sezione di Bari, Bari, Italy.
\[i\] Also at Department of Physics, University of Cambridge, Cambridge, UK.
\[j\] Also at INFN Sezione di Bari, Bari, Italy.
\[k\] Also at Department of Physics, University of Ferrara, Ferrara, Italy.
\[l\] Also at INFN Sezione di Bari, Bari, Italy.
\[m\] Also at INFN Sezione di Bari, Bari, Italy.
\[n\] Also at Università di Torino, Torino, Italy.
\[o\] Also at Dipartimento di Fisica, Università di Chieti, Chieti, Italy.
\[p\] Also at INFN Sezione di Pisa, Pisa, Italy.
\[q\] Also at INFN Sezione di Pisa, Pisa, Italy.
\[r\] Also at Politecnico di Torino, Torino, Italy.
\[s\] Also at Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy.
\[t\] Also at INFN Sezione di Roma, Roma, Italy.
\[u\] Also at INFN Sezione di Roma, Roma, Italy.
\[v\] Also at INFN Sezione di Roma, Roma, Italy.
\[w\] Also at INFN Sezione di Roma, Roma, Italy.
\[x\] Also at INFN Sezione di Roma, Roma, Italy.
\[y\] Also at INFN Sezione di Roma, Roma, Italy.