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Search for displaced muonic lepton jets from light Higgs boson decay in proton–proton collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector

ATLAS Collaboration

1. Introduction

A search is performed for collimated muon pairs displaced from the primary vertex produced in the decay of long-lived neutral particles in proton–proton collisions at $\sqrt{s} = 7$ TeV centre-of-mass energy, with the ATLAS detector at the LHC. In a 1.9 fb$^{-1}$ event sample collected during 2011, the observed data are consistent with the Standard Model background expectations. Limits on the product of the production cross section and the branching ratio of a Higgs boson decaying to hidden-sector neutral long-lived particles are derived as a function of the particles' mean lifetime.

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The search presented in this Letter focuses on neutral particles decaying to the simplest type of muon jets (MJs), containing only two muons; prompt MJ searches have been performed both at the Tevatron \([17,18]\) and at the LHC \([19]\). Other searches for displaced decays of a light Higgs boson to heavy fermion pairs have also been performed at the LHC \([20]\).

The benchmark model used for this analysis is a simplified scenario where Higgs boson decays to a pair of neutral hidden fermions \((f_{\Delta} g)\), each of which decays to one long-lived \(\gamma d\) and one stable neutral hidden fermion \((f_1\bar{\gamma})\) that escapes the detector unnoticed, resulting in two lepton jets from the \(\gamma d\) decays in the final state (see Fig. 1). The mass of the \(\gamma d\) (0.4 GeV) is chosen to provide a sizeable branching ratio to muons \([14]\).

### 2. The ATLAS Detector

ATLAS is a multi-purpose detector \([16]\) at the LHC, consisting of an inner tracking system (ID) embedded in a superconducting solenoid, which provides a 2 T magnetic field parallel to the beam direction, electromagnetic and hadronic calorimeters and a muon spectrometer using three air-core toroidal magnet systems.\(^1\) The trigger system has three levels \([21]\) called Level-1 (L1), Level-2 (L2) and Event Filter (EF). L1 is a hardware-based system using information from the calorimeter and muon spectrometer, and defines one or more Regions of Interest (ROIs), geometrical regions of the detector, identified by \((\eta, \phi)\) coordinates, containing interesting physics objects. L2 and the EF (globally called the High Level Trigger, HLT) are software-based systems and can access information from all sub-detectors. The ID, consisting of silicon pixel and microstrip detectors and a straw-tube tracker, provides precision tracking of charged particles for \(|\eta| \lt 2.5\). The electromagnetic and hadronic calorimeter system covers \(|\eta| \leq 4.9\) and, at \(\eta = 0\), has a total depth of 9.7 interaction lengths (22 radiation lengths in the electromagnetic part). The MS provides trigger information \((|\eta| \leq 2.4)\) and momentum measurements \((|\eta| \leq 2.7)\) for charged particles entering the spectrometer. It consists of one barrel and two endcap parts, each with 16 sectors in \(\phi\), equipped with precision tracking chambers and fast detectors for triggering. Monitored drift tubes are used for precision tracking in the region \(|\eta| \leq 2.0\) and cathode strip chambers are used for \(2.0 \leq |\eta| \leq 2.7\). The MS detectors are arranged in three stations of increasing distance from the IP: inner, middle and outer. The air core toroidal magnetic field allows an accurate charged particle reconstruction independent of the ID information. The three planes of trigger chambers (resistive plate chambers in the barrel and thin gap chambers in the endcaps) are located in middle and outer (only in the barrel) stations. The L1 muon trigger requires hits in the middle stations to create a low transverse momentum \((p_T)\) muon ROI or hits in both the middle and outer stations for a high \(p_T\) ROI. The muon ROIs have a spatial extent of \(0.2 \times 0.2 \, (\Delta \eta \times \Delta \phi)\) in the barrel and of \(0.1 \times 0.1\) in the endcap. L1 ROI information seeds, at HLT level, the reconstruction of muon momenta using the precision chamber information. In this way sharp trigger thresholds up to 40 GeV can be obtained.

### 3. Signal and background simulation

The set of parameters used to generate the signal Monte Carlo samples is listed in Table 1. The Higgs boson is generated through the gluon–gluon fusion production mechanism which is the dominant process for a low mass Higgs boson. The gluon–gluon fusion Higgs boson production cross section in the \(pp\) collisions at \(\sqrt{s} = 7\) TeV, estimated at the next-to-next-to-leading order (NNLO) \([22]\), is \(\sigma_{\text{SM}} = 24.0\) pb for \(m_H = 100\) GeV and \(\sigma_{\text{SM}} = 12.1\) pb for \(m_H = 140\) GeV. The \(\text{PYTHIA}\) generator \([23]\) is used, linked together with \text{MadGraph4.4.2} \([24]\) and \text{BRIDGE} \([25]\), for gluon–gluon fusion production of the Higgs boson and the subsequent decay to hidden-sector particles.

As discussed in the introduction, the signal is chosen to enable a study of rare, non-SM, Higgs boson decays in the (possibly extended) Higgs sector. To do so we choose two points which envelope a mass range covering the 126 GeV resonance. The lower mass point, \(m_H = 100\) GeV, is chosen to be compatible with the decay-mode-independent search by OPAL at LEP \([26]\). The higher mass point, \(m_H = 140\) GeV, is chosen well below the WW threshold, where a sizeable branching ratio into a hidden sector may be naturally achieved. The masses of \(f_2 d\) and \(f_8 d\) are chosen to be light relative to the Higgs boson mass, and far from the kinematic threshold at \(m_{f_2 d} + m_{f_8 d} = m_{f_2 d}\). For the chosen dark photon mass (0.4 GeV), the \(\gamma d\) decay branching ratios are expected to be \([14]\): 45\% \(e^+ e^-\), 45\% \(\mu^+ \mu^-\), 10\% \(\pi^+ \pi^-\). Thus 20\% of the Higgs \(H \rightarrow \gamma \gamma d\) decay rates are expected to have the required four-muon final state.

The mean lifetime \(\tau\) of the \(\gamma d\) (expressed throughout this Letter as \(\tau\) times the speed of light \(c\)) is a fixed parameter of the model. In the generated samples \(\tau\) is chosen so that a large fraction of the decays occur inside the sensitive ATLAS detector volume, i.e. up to 7 m in radius and 13 m along the \(z\)-axis, where the trigger chambers of the middle stations are located. The detection efficiency can then be estimated for a range of \(\gamma d\) mean lifetimes through re-weighting of the generated samples.

Potential backgrounds include all the processes which lead to prompt muons in the final state such as the SM processes \(W + \text{jets}, Z + \text{jets}, t\bar{t}, WW, WZ, \text{and } ZZ\). However, the main contribution to the background is expected from processes giving a high production rate of secondary muons which do not point to the primary vertex, such as decays in flight of \(K/\pi\) and heavy flavour decays in multi-jet processes, or muons due to cosmic rays. The prompt lepton background samples are generated using \text{PYTHIA} \((W + \text{jets}, Z + \text{jets})\) and \text{MC@NLO} \([27]\) \((t\bar{t}, WW, WZ, \text{and } ZZ)\).

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\(^1\) 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 coinciding with the beam pipe axis. The \(x\)-axis points from the IP to the centre of the LHC ring, and the \(y\)-axis points upward. Cylindrical coordinates \((r, \phi)\) are used in the transverse plane, \(\phi\) being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle \(\theta\) as \(\eta = -\ln \tan \theta / 2\).
The ATLAS simulation chain based on GRANT4 [28,29]. Additional pp interactions in the same and nearby bunch crossings (pile-up) are included in the simulation. All Monte Carlo samples are re-weighted to reproduce the observed distribution of the number of interactions per bunch crossing in the data. For the multi-jet background evaluation a data-driven method is used. The cosmic-ray background is also evaluated from data.

4. The kinematics of the signal

The main kinematic characteristics of the signal sample are:

- The $\gamma_d$ pair are emitted approximately back-to-back in $\phi$, with an angular spread of the decay due to the emission of the $f_{d1}$.
- The average $p_T$ of the $\gamma_d$ in the laboratory frame is about 20 GeV for $m_H = 100$ GeV and 30 GeV for $m_H = 140$ GeV; due to the small mass of the $\gamma_d$, large boost factors in the decay length should be expected.
- Fig. 2 shows the distribution of $\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2}$ between the two muons from the $\gamma_d$ decay. The $\Delta R$ is computed at the decay vertex of the $\gamma_d$ from the vector momenta of the two muons. Due to the small mass of the $\gamma_d$ the $\Delta R$ is almost always below 0.1. Since the two $f_{d1}$ are, like the two $\gamma_d$, emitted back-to-back in $\phi$, the observed missing transverse momentum $E_{miss}^T$, computed at the event-generator level, is small and cannot be used as a discriminating variable against the background.

5. Data samples and trigger selection

The dataset used for this analysis was collected at a centre-of-mass energy of 7 TeV during the first part of 2011, where a low level of pile-up events in the same bunch-crossing was present (an average of $\approx 6$ interactions per crossing). Only periods in which all ATLAS subdetectors were operational are used. The total integrated luminosity used is $1.94 \pm 0.07$ fb$^{-1}$ [30,31]. All events are required to have at least one reconstructed vertex along the beam line with at least three associated tracks, each with $p_T \geq 0.4$ GeV. The primary interaction vertex is defined to be the vertex whose constituent tracks have the largest $\sum p_T^2$. This analysis deals with displaced $\gamma_d$ decays with final states containing only muons. Signal events are therefore characterized by a four-muon final state with the four muons coming from two displaced decay vertices. Due to the relatively low $p_T$ of the muons and due to the displaced decay vertex, a low-$p_T$ multi-muon trigger with muons reconstructed only in the MS is needed. In order to have an acceptably low trigger rate at a low $p_T$ threshold, a multiplicity of at least three muons is required. Candidate events are collected using an unprescaled HLT trigger with three reconstructed muons of $p_T \geq 6$ GeV, seeded by a L1-accept with three different muon ROIs. These muons are reconstructed only in the MS, since muons originating from a neutral particle decaying outside the pixel detector will not have a matching track in the ID tracking system. The trigger efficiency for the Monte Carlo signal samples, defined as the fraction of events passing the trigger requirement with respect to the events satisfying the analysis selection criteria (described in Section 6) is $0.32 \pm 0.01$ stat for $m_H = 100$ GeV and $0.31 \pm 0.01$ stat for $m_H = 140$ GeV.

The main reason for the relatively low trigger efficiency is the small opening $\Delta R$ between the two muons of the $\gamma_d$ decay ($\Delta R \leq 0.1$) shown in Fig. 2. These values of $\Delta R$ are often smaller than the L1 trigger granularity; in this case the L1 produces only one ROI. The trigger only fires if at least one of the $\gamma_d$ produces two distinct L1 ROIs. The single $\gamma_d$ ROI efficiency, $\varepsilon_{2ROI}$ ($\varepsilon_{1ROI}$), defined as the fraction of $\gamma_d$ passing the offline selection that gave two (one) trigger ROIs is $0.296 \pm 0.004$ stat ($0.626 \pm 0.0044$ stat) for $m_H = 100$ GeV and $0.269 \pm 0.003$ stat ($0.653 \pm 0.0033$ stat) for $m_H = 140$ GeV. Fig. 3 shows the $\varepsilon_{2ROI}$ as a function of the dark photon mass $\eta$ and of the $\Delta R$ of the two muons from the $\gamma_d$ decay. The increased trigger granularity in the endcap and the efficiency decrease at small values of $\Delta R$ are clearly visible.

The systematic uncertainty on the trigger efficiency is estimated with a sample of $J/\psi \rightarrow \mu^+\mu^-$ from collision data and a corresponding sample of Monte Carlo events, using the tag-and-probe (TP) method. A cut on $\Delta R \leq 0.1$ between the two muons is used to reproduce the small track-to-track spatial separation in the MS of the signal. The tag is a $(M5 + ID)$ combined muon, defined as a MS-reconstructed muon that is associated with a trigger object and combined with a matching “good ID track”. Good ID tracks must have at least one hit in the pixel detector, at least six hits in the silicon micro-strip detectors and at least six hits in the straw-tube tracker. The probe is a good ID track which, when combined with the tag track, gives an invariant mass inside a 100 MeV window around the $J/\psi$ mass. A muon ROI that matches the probe in $\eta$ and $\phi$, and is different from the ROI associated with the tag, is searched for. The number of probes with a matched ROI divided by the number of probes without a matched ROI gives the $\varepsilon_{2ROI}/\varepsilon_{1ROI}$ ratio. Values of $\varepsilon_{2ROI}/\varepsilon_{1ROI} = 0.42 \pm 0.05$ stat for the $J/\psi \rightarrow \mu^+\mu^-$ data and $\varepsilon_{2ROI}/\varepsilon_{1ROI} = 0.39 \pm 0.05$ stat for the corresponding Monte Carlo sample are obtained. The relative statistical uncertainty on the difference between these two estimates is 17% and this is taken conservatively to be the systematic uncertainty on the trigger efficiency.

6. Muon Jet reconstruction and event selection

MJs from displaced $\gamma_d$ decays are characterized by a pair of muons in a narrow cone, produced away from the primary vertex of the event. Consequently tracks reconstructed in the MS with a good quality track fit [32] are used. MJs are identified using a simple clustering algorithm that associates all the muons in cones of $\Delta R = 0.2$, starting with the muon with highest $p_T$. The size of the cone takes into account the multiple scattering of the muons in the calorimeters. All the muons found in the cone are associated with a MJ. After this procedure, if any muons are unassociated with a MJ the search is repeated for this remainder, starting again with the highest $p_T$ muon. This continues until all possible MJs...
are formed. The MJ direction and momentum are obtained from the vector sum over all muons in the MJ. Only MJ with two reconstructed muons are accepted and only events with two MJ are kept for the subsequent analysis. In order to keep the search as model independent as possible no requirement on the muon momenta has been introduced.

The possible contribution to the background of SM processes which lead to real prompt muon pairs in the final state is evaluated using simulated samples. After the trigger and the requirement of having two MJ in the event, their contributions have been found to be negligible. The only significant background sources are expected to be from processes giving a high production rate of secondary muons which do not point to the primary vertex, such as decays in flight of $K/\pi$ and heavy flavour decays in multi-jet production, or cosmic-ray muons not pointing to the primary vertex.

In order to separate the signal from the background, a number of discriminating variables have been studied. The multi-jet background can be significantly reduced by using calorimeter isolation requirements around the MJ direction. The calorimeter isolation variable $E_{\text{isol}}^{\text{ID}}\mu$ is defined as the difference between the transverse calorimetric energy $E_T$ in a cone of $\Delta R = 0.4$ around the highest $p_T$ muon of the MJ and the $E_T$ in a cone of $\Delta R = 0.2$; a cut $E_{\text{isol}}^{\text{ID}}\mu \leq 5 \text{ GeV}$ keeps almost all the signal. The isolation modelling is validated for real isolated muons with a sample of muons coming from $Z \to \mu\mu$ decays. To further improve the signal-to-background ratio, two additional discriminating variables are used: $\Delta \phi$ between the two MJs and $\sum p_T^{ID}$ for the MJ, defined as the scalar sum of the transvers momentum of the tracks, measured in the ID, inside a cone $\Delta R = 0.4$ around the direction of the MJ. The muon tracks of the MJ in the ID, if any, are not removed from the isolation sum, so that prompt muons, which give a reconstructed track in both the ID and MS, will contribute to $\sum p_T^{ID}$. As a consequence a cut on $\sum p_T^{ID}$ of a few GeV will remove prompt MJ or MJ with very short decay length.

For the background coming from cosmic-ray muons (mainly pairs of almost parallel cosmic-ray muons crossing the detector) a cut on the impact parameters of the muon tracks with respect to the primary interaction vertex is used.

The final set of selection criteria used is the following:

- Topology cut: events are required to have exactly two MJ, $N_{\text{MJ}} = 2$.
- MJ isolation: require MJ isolation with $E_{\text{isol}}^{\text{ID}} \leq 5 \text{ GeV}$ for both MJ in the event.
- Require $|\Delta \phi| \geq 2$ between the two MJ.
- Require opposite charges for the two muons in a MJ ($Q_{\text{MJ}} = 0$).
- Require a cut on the transverse and longitudinal impact parameters of the muons with respect to the primary vertex: $|d_0| < 200 \text{ mm}$ and $|z_0| < 270 \text{ mm}$.
- Require $\sum p_{T}^{ID} \leq 3 \text{ GeV}$ for both MJ.

The distributions of the relevant variables used in the selection before each step of the cut flow are shown in Fig. 4. The results are summarized in Table 2. No events survive the selection in the data sample whereas the expected signals from Monte Carlo simulation, assuming the Higgs boson SM production cross section, 100% branching ratio for $H \to \gamma\gamma$, $H \to ZZ$ and the parameters given in Table 1, are 75 or 48 events for Higgs boson masses of 100 GeV and 140 GeV respectively. The method used to estimate the cosmic-ray and multi-jet background yields, quoted in Table 2, is discussed in Section 7.

The resulting single $\gamma\gamma$ reconstruction efficiency for the mean lifetimes given in Table 1 is shown in Fig. 5 as a function of $\eta$, the $\Delta R$ separation of the two muons from the $\gamma\gamma$ decay and the decay length in the transverse plane, $L_{xy}$, of the $\gamma\gamma$. The efficiency is defined as the number of $\gamma\gamma$ passing the offline selection divided by the number of $\gamma\gamma$ in the spectrometer acceptance ($|\eta| \leq 2.4$) with both muons having $p_T \geq 6 \text{ GeV}$. The low reconstruction efficiency at very short $L_{xy}$ is a consequence of the $\sum p_T^{ID}$ cut.

The systematic uncertainty on the reconstruction efficiency is evaluated using a tag-and-probe method by comparing the reconstruction efficiency $E_{\text{MC}}^{\text{ID}}$ for $J/\psi \to \mu^+ \mu^-$ samples from collision data and $J/\psi \to \mu^+ \mu^-$ Monte Carlo simulation. The tag-and-probe definitions and the cut on $\Delta R \leq 0.1$ between the two muons are the same as in Section 5. To measure the reconstruction efficiency the ID probe track is associated with a MS-only muon track, different from the one associated with the tag. The result is shown in Fig. 6.

The relative difference between the result obtained from the $J/\psi \to \mu^+ \mu^-$ data and the $J/\psi \to \mu^+ \mu^-$ Monte Carlo sample in the same range of $\Delta R \leq 0.1$, as for the signal, is taken as the systematic uncertainty on the reconstruction efficiency and amounts to 13%.

7. Multi-jet and cosmic-ray background evaluation

To estimate the multi-jet background contamination in the signal region we use a data-driven ABCD method slightly modified to cope with the problem of the very low number of events in the control regions. The ABCD method assumes that two variables can be identified, which are relatively uncorrelated, and which can each be used to separate signal and background. It is assumed that the multi-jet background distribution can be factorized in the MJ $E_{\text{isol}}^{\text{ID}}\cdot|\Delta \phi|$ plane. The region A is defined by $E_{\text{isol}}^{\text{ID}} \leq 5 \text{ GeV}$ and $|\Delta \phi| < 2$; the region B, defined by $E_{\text{isol}}^{\text{ID}} \leq 5 \text{ GeV}$ and $|\Delta \phi| > 2$, is the signal region. The regions C and D are the anti-isolated regions ($E_{\text{isol}}^{\text{ID}} > 5 \text{ GeV}$) and they are defined by $|\Delta \phi| < 2$ and $|\Delta \phi| > 2$, respectively. Neglecting the signal contamination in regions A, C and
as the systematic uncertainty, that amounts to triggered events is rescaled by the collision to empty bunch cross-evaluated using events collected by the trigger being active when ered and is found to be negligible.

possible signal leakage in the background regions is also consid-
vale 0 < \sum p_T^D < 3 \text{ GeV}.

\Delta \phi > 2 \quad 1.5 \pm 1.5 \quad 153 \pm 18 \pm 9 \quad 155 \pm 18 \pm 9 \quad 123 \pm 11 \pm 19 \quad 121 \pm 11 \pm 19 \quad 104

\Delta \phi \geq 2 \quad 1.5 \pm 1.5 \quad 57 \pm 15 \pm 22 \quad 59 \pm 15 \pm 22 \quad 79 \pm 8 \pm 17 \quad 80

\gamma \text{d}

\sum p_T^D > 5 \text{ GeV or } |\Delta \phi| < 2 \) the number of multi-jet background events in the signal region can be evaluated as \( N_B = N_D \times N_A / N_C. \) Due to the very low number of events in the control regions the values of \( N_A, N_C \) and \( N_B \) as a function of the cut on the final discriminant variable \( \sum p_T^D \) are extracted by modelling the \( \sum p_T^D \) distributions with bifurcated Gaussian templates, with parameters fitted from the data in the corresponding regions, and by integrating the fitted function in the range \( 0 < \sum p_T^D < 3 \text{ GeV}. \) The low statistics in the four regions at each step of the cut flow results in large fluctuations in the multi-jet background estimate; however, the expected contribution to the final number of background events is negligible and the statistical uncertainty on the data driven background is included in the systematic. The extracted yields are \( N_A = (7.1 \pm 1.5_{\text{stat}}) \times 10^{-3}, N_C = (1.81 \pm 1.0_{\text{stat}}) \cdot 10^{-3}, \) and \( N_D = (1.51 \pm 0.07_{\text{stat}}) \cdot 10^{-1}. \) The estimated number of multi-jet background events in the signal region is \( N_B = 0.06 \pm 0.02_{\text{stat}}. \)

Possible sources of systematic uncertainty related to the background estimation method are also evaluated. Various functional models are used to fit the \( \sum p_T^D \) distributions, trying extreme functional forms from linear distribution to bifurcate Gaussian in order to get an estimate of the uncertainty on the number of multi-jet background events in each control region. The procedure to estimate the number of multi-jet background events in the sig-

8. Systematic uncertainties

The following effects are considered as possible sources of sys-

- **Luminosity**
  The overall normalization uncertainty of the integrated luminosity is 3.7% \([30,31]\).
- **Muon momentum resolution**
  The systematic uncertainty on the muon momentum resolution for MS-only muons has been evaluated by smearing and shifting the momenta of the muons by scale factors derived from \( Z \rightarrow \mu \mu \) data-Monte Carlo comparison, and by observing the effect of this shift on the signal efficiency. The overall effect of the muon momentum resolution uncertainty is negligible.
- **Trigger**
  The systematic uncertainty on the single \( \gamma \) trigger efficiency, evaluated using a tag-and-probe method is 17% (see Section 5).
- **Reconstruction efficiency**
  The systematic uncertainty on the reconstruction efficiency, evaluated using a tag-and-probe method for the single \( \gamma \) reconstruction efficiency, is 13% (see Section 6).
- **Effect of pile-up**
  The systematic uncertainty on the signal efficiency related to the effect of pile-up is evaluated by comparing the number of signal events after imposing all the selection criteria on the signal Monte Carlo sample increasing the average number of interactions per crossing from \( \approx 6 \) to \( \approx 16. \) This systematic uncertainty is negligible.
uncertainties are statistical only. The uncertainties are evaluated with a similar tag-and-probe method, as shown in Fig. 6.

Tag-and-probe reconstruction efficiency for the mean lifetimes given in Table 1. The reconstruction efficiency is defined as the number of passing the offline selection divided by the number of $d_\tau$ in the spectrometer acceptance ($|\eta| < 2.4$) with both muons having $p_T > 6$ GeV. The uncertainties are statistical only.

Fig. 5. $\gamma d$ reconstruction efficiency $\epsilon_{rec}$ as a function (a) of $\eta$, (b) of $\Delta R$ and (c) of the transverse decay length of the $d_\tau$ for $m_H = 100$ GeV and $m_H = 140$ GeV and for the mean lifetimes given in Table 1. The reconstruction efficiency is defined as the number of $\gamma d$ passing the offline selection divided by the number of $\gamma d$ in the spectrometer acceptance ($|\eta| < 2.4$) with both muons having $p_T > 6$ GeV. The uncertainties are statistical only.

Fig. 6. Tag-and-probe reconstruction efficiency $\epsilon_{rec}^{TP}$ as a function of the $\Delta R$ between the two muons, evaluated on a sample of $J/\psi \rightarrow \mu^+ \mu^-$ from collision data and a corresponding sample of Monte Carlo events. The $\epsilon_{rec}^{TP}$ for the signal Monte Carlo, evaluated with a similar tag-and-probe method, is also shown. The uncertainties are statistical only.

### Table 3

Ranges in which $\gamma d$ cr is excluded at 95% CL for $m_H = 100$ GeV and $m_H = 140$ GeV, assuming 100% and 10% branching ratio of $H \rightarrow \gamma d \gamma d + X$ and the SM Higgs boson production cross section.

<table>
<thead>
<tr>
<th>Higgs boson mass [GeV]</th>
<th>Excluded cr [mm] BR(100%)</th>
<th>Excluded cr [mm] BR(10%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>1 $\leq$ cr $\leq$ 670</td>
<td>5 $\leq$ cr $\leq$ 159</td>
</tr>
<tr>
<td>140</td>
<td>1 $\leq$ cr $\leq$ 430</td>
<td>7 $\leq$ cr $\leq$ 82</td>
</tr>
</tbody>
</table>

- **Effect of $\sum p_T^{ID}$ cut**
  
  Since the $\sum p_T^{ID}$ cut could affect the minimum cr value that can be excluded, the effect of this cut on the signal Monte Carlo has been studied. A variation of 10% on the $\sum p_T^{ID}$ cut results in a relative variation of $<1\%$ on the signal, which can therefore be neglected.

- **Background evaluation**
  
  The systematic uncertainties that can affect the background estimation are related to the data-driven method used. The functional model used to fit the $\sum p_T^{ID}$ distribution is varied to evaluate the systematic uncertainty in the modelling of its shape, which also includes the effect of the $\sum p_T^{ID}$ cut on the background estimation. This systematic uncertainty amounts to $\pm 0.06$ events. The effect of signal leakage is also negligible.

### 9. Results and interpretation

The efficiency of the selection criteria described above is evaluated for the simulated signal samples (see Table 1) as a function of the mean lifetime of the $\gamma d$. The signal Monte Carlo events are weighted by the detection probability of the two $\gamma d$ in the various parts of the detector, generating their decay points according to a chosen value of the $\gamma d$ lifetime, with cr ranging from 0 to 700 mm. In this way the number of expected signal events is predicted as function of the $\gamma d$ mean lifetime. These numbers, together with the expected number of background events (multi-jet and cosmic rays) and taking into account the zero data events surviving the selection criteria in 1.9 fb$^{-1}$, are used as input to obtain limits at the 95% confidence level (CL). The CLs method [33] is used to set 95% CL upper limits on the cross section times branching ratio (σ × BR) for the process $H \rightarrow \gamma d \gamma d + X$, according to the model of Fig. 1. Here the branching ratio of $\gamma d \rightarrow \mu \mu$ is set to 45% with the $\gamma d$ mass set to 0.4 GeV, as previously discussed. The $\sigma \times BR$ is given as a function of the $\gamma d$ mean lifetime, expressed as cr for $m_H = 100$ GeV and $m_H = 140$ GeV. These limits are shown on Fig. 7. Table 3 shows the ranges in which the $\gamma d$ cr is excluded at the 95% CL for $H \rightarrow \gamma d \gamma d + X$ branching ratios of 100% and 10%.

### 10. Conclusions

The ATLAS detector at the LHC was used to search for a light Higgs boson decaying into a pair of hidden fermions ($f_{d2}$), each of which decays to a $\gamma d$ and to a stable hidden fermion ($f_{d1}$), resulting in two muon jets from the $\gamma d$ decay in the final state. In a 1.9 fb$^{-1}$ sample of $\sqrt{s} = 7$ TeV proton–proton collisions no events consistent with this Higgs boson decay mode are observed. The observed data are consistent with the Standard Model background expectations.

Limits are set on the $\sigma \times BR$ to $H \rightarrow \gamma d \gamma d + X$, according to the model of Fig. 1, as a function of the long-lived particle mean lifetime for $m_H = 100$ GeV and 140 GeV with the chosen $\gamma d$ mass that gives a decay branching ratio of 45% for $\gamma d \rightarrow \mu \mu$. Assuming the SM production rate for a 140 GeV Higgs boson, its branching ratio to two hidden-sector photons is found to be below 10%, at 95% CL for hidden photon cr in the range 7 mm $\leq$ cr $\leq$ 82 mm. Bounds
Fig. 7. The 95% upper limits on the $\sigma \times BR$ for the process $H \rightarrow \gamma \gamma X + X$ as a function of the dark photon $\gamma'$ for the benchmark sample with (a) $m_{\gamma'} = 100$ GeV and with (b) $m_{\gamma'} =$ 140 GeV, assuming the Higgs boson SM production cross section. The expected limit is shown as the dashed curve and the solid curve shows the observed limit. The horizontal lines correspond to the Higgs boson SM production cross sections at the two mass values.

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