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 presented for long-lived neutral particles decaying to final states containing collimated muon pairs in proton–proton collisions at $\sqrt{s} = 7$ TeV centre-of-mass energy. The event sample, collected during 2011 at the LHC with the ATLAS detector, corresponds to an integrated luminosity of 1.9 fb$^{-1}$. The model considered in this analysis consists of a Higgs boson decaying to a new hidden sector of particles which finally produce two sets of collimated muon pairs, but the search described is equally valid for other, distinct models such as heavier Higgs boson doublets or singlet scalars, produced through gluon fusion, that decay to a hidden sector and eventually produce collimated muon pairs.

Recently, evidence for the production of a boson with a mass of about 126 GeV has been published by ATLAS [1] and CMS [2]. The observation is compatible with the expected production and decay of the Standard Model (SM) Higgs boson [3–5] at this mass. Testing the SM Higgs hypothesis is currently of utmost importance. To this end two effects may be considered: (i) additional resonances which arise in an extended Higgs sector found in many extensions of the SM, or (ii) rare Higgs boson decays which may deviate from those predicted by the SM. In this Letter we search for a scalar, produced through gluon fusion, that decays to a light hidden sector, according to the topology of Fig. 1, focusing on the 100 GeV to 140 GeV mass range.

The phenomenology of light hidden sectors has been studied extensively over the past few years [6–10]. Possible characteristic topological signatures of such extensions of the SM are “lepton jets”. A lepton jet is a cluster of highly collimated particles: electrons, muons and possibly pions [7,11–13]. These arise if light unstable particles with masses in the MeV to GeV range (for example dark photons, $\gamma_d$) reside in the hidden sector and decay predominantly to SM particles. At the LHC, hidden-sector particles may be produced with large boosts, causing the visible decay products to form jet-like structures. Hidden-sector particles such as $\gamma_d$ may be long-lived, resulting in decay lengths comparable to, or larger than, the detector dimensions. The production of lepton jets can occur through various channels. For instance, in supersymmetric models, the lightest visible superpartner may decay into the hidden sector. Alternatively, a scalar particle that couples to the visible sector may also couple to the hidden sector through Yukawa couplings or the scalar potential. This analysis is focused on the case where the Higgs boson decays to the hidden sector [14,15]. The SM Higgs boson has a narrow width into SM final states if $m_H < 2 m_W$. Consequently, any new (non-SM) coupling to additional states, which reside in a hidden sector, may contribute significantly to the Higgs boson decay branching ratios. Even with new couplings, the total Higgs boson width is typically small, well below the order of one GeV. If a SM-like Higgs boson is confirmed, it will remain important to constrain possible rare decays, e.g. into lepton jets.

Neutral particles with large decay lengths and collimated final states represent, from an experimental point of view, a challenge both for the trigger and for the reconstruction capabilities of the detector. Collimated particles in the final state can occur hard to disentangle due to the finite granularity of the detectors; moreover, in the absence of inner tracking detector information and a primary vertex constraint, it is difficult to reconstruct charged-particle tracks from decay vertices far from the interaction point (IP). The ATLAS detector [16] is equipped with a muon spectrometer (MS) with high-granularity tracking detectors that allow charged-particle tracks to be reconstructed in a standalone configuration using only the muon detector information (MS-only). This is a crucial feature for detecting muons not originating from the primary interaction vertex.
The benchmark model used for this analysis is a simplified scenario where the Higgs boson decays to a pair of neutral fermions ($f_d$), each of which decays to one long-lived $\gamma_d$ and one stable neutral hidden fermion ($f_{H1}$) 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].

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 $pp$ collisions at $\sqrt{s} = 7$ TeV, estimated at the next-to-next-to-leading order (NNLO) [22], is $\sigma_{SM} = 24.0$ pb for $m_H = 100$ GeV and $\sigma_{SM} = 12.1$ pb for $m_H = 140$ GeV. The PYTHIA generator [23] is used, linked together with MadGraph4.4.2 [24] and 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 $f_d$ and $f_{H1}$ are chosen to be light relative to the Higgs boson mass, and far from the kinematic threshold at $m_{f_d} + m_{\gamma_d} = m_{f_{H1}}$. 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 $H \rightarrow \gamma_d\gamma_d + X$ decays 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 free parameter of the model. In the generated samples $\tau r$ 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 real prompt muons in the final state such as the SM processes $W +$ jets, $Z +$ jets, $t\bar{t}$, $WW$, $WZ$, 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 PYTHIA ($W +$ jets, and $Z +$ jets) and MC@NLO [27] ($t\bar{t}$, $WW$, $WZ$, and $ZZ$).

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|}
\hline
Higgs mass & $m_{f_d}$ & $m_{\gamma_d}$ & $\gamma_d$ mass & $\tau r$[mm] \\
\hline
100 & 5.0 & 2.0 & 0.4 & 47 \\
140 & 5.0 & 2.0 & 0.4 & 36 \\
\hline
\end{tabular}
\caption{Parameters used for the Monte Carlo simulation. The last column is the $\gamma_d$ mean lifetime $\tau$ multiplied by the speed of light $c$, expressed in mm.}
\end{table}

\footnote{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 generated Monte Carlo events are processed through the full ATLAS simulation chain based on GEANT4 [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 distribution 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 ≈ 6 interactions per crossing). Only periods in which all ATLAS subdetectors were operational are used. The total integrated luminosity used is 1.94 ± 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 $p_T \geq 4$ GeV. The primary interaction vertex is defined to be the vertex whose constituents 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 ($\Delta R < 0.1$) 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, $E_{\gamma_d ROI} (\epsilon_{\gamma_d ROI})$, defined as the fraction of $\gamma_d$ passing the offline selection that give two (one) trigger ROIs is $0.296 \pm 0.004_{stat} (0.626 \pm 0.004_{stat})$ for $m_H = 100$ GeV and $0.269 \pm 0.003_{stat} (0.653 \pm 0.003_{stat})$ for $m_H = 140$ GeV. Fig. 3 shows the $E_{\gamma_d ROI}$ as a function of the dark photon $\eta$ 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 $\Delta R \lesssim 0.1$ 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 (MS + 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 $E_{\gamma_d ROI} (\epsilon_{\gamma_d ROI})$ ratio. Values of $E_{\gamma_d ROI} (\epsilon_{\gamma_d ROI}) = 0.42 \pm 0.05_{stat}$ for the $J/\psi \rightarrow \mu^+\mu^-$ data and $E_{\gamma_d ROI} (\epsilon_{\gamma_d ROI}) = 0.39 \pm 0.05_{stat}$ 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 $\Delta R \leq 0.2$, 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 MJs with two re-
constructed muons are accepted and only events with two MJs are
kept for the subsequent analysis. In order to keep the search as
model independent as possible no requirement on the muon mo-
mentum has been introduced.

The possible contribution to the background of SM processes
which lead to real prompt muon pairs in the final state is evalu-
ated using simulated samples. After the trigger and the require-
ment of having two MJs 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 sec-
tary muons which do not point to the primary vertex, such as
decays in flight of K/π and heavy flavour decays in multi-jet pro-
duction, 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 back-
ground can be significantly reduced by using calorimeter isolation
requirements around the MJ direction. The calorimetric isolation
variable $E_{\text{T}}^{\text{isol}}$ is defined as the difference between the transverse
calorimetric energy $E_{\text{T}}$ in a cone of $\Delta R = 0.4$ around the high-
est $p_{\text{T}}$ muon of the MJ and the $E_{\text{T}}$ in a cone of $\Delta R = 0.2$; a cut
$E_{\text{T}}^{\text{isol}} \leq 5$ GeV keeps almost all the signal. The isolation modelling
is validated for real isolated muons with a sample of muons coming
from $Z \rightarrow \mu \mu$ decays. To further improve the signal-to-background
ratio, two additional discriminating variables are used: $\Delta \phi$ be-
tween the two MJs and $\sum p_{\text{T}}^{\text{ID}}$ for the MJ, defined as the scalar
sum of the transverse 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 the $\sum p_{\text{T}}^{\text{ID}}$. As a
consequence a cut on $\sum p_{\text{T}}^{\text{ID}}$ of a few GeV will remove prompt MJs
or MJs 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 MJs,
  $N_{\text{MJ}} = 2$.
- MJ isolation: require MJ isolation with $E_{\text{T}}^{\text{isol}} \leq 5$ GeV for both
  MJs in the event.
- Require $|\Delta \phi| \geq 2$ between the two MJs.
- Require opposite charges for the two muons in a MJ ($Q_{\text{MJ}} = 0$).
- Require a cut on the transverse and longitudinal impact pa-
  rameters of the muons with respect to the primary vertex:
  $|d_0| < 200$ mm and $|z_0| < 270$ mm.
- Require $\sum p_{\text{T}}^{\text{ID}} < 3$ GeV for both MJs.

The distributions of the relevant variables used in the selection be-
fore 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 simula-
tion, assuming the Higgs boson SM production cross section, 100%
branching ratio for $H \rightarrow \gamma \gamma$ and $H \rightarrow Z \gamma$ and the parameters given in Ta-
ble 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 resultant $\gamma \gamma$ 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 de-
finied 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 $p_{\text{T}} \geq 6$ GeV. The low reconstruction efficiency
at very small $L_{xy}$ is a consequence of the $\sum p_{\text{T}}^{\text{ID}}$ cut.

The systematic uncertainty on the reconstruction efficiency is
evaluated using a tag-and-probe method by comparing the recon-
struction efficiency $E_{\text{TP}}$ for $J/\psi \rightarrow \mu^+ \mu^-$ samples from collision
data and $J/\psi \rightarrow \mu^+ \mu^-$ 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 effi-
ciency 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
$J/\psi \rightarrow \mu^+ \mu^-$ data and the $J/\psi \rightarrow \mu^+ \mu^-$ Monte Carlo sample in
the same range of $\Delta R \leq 0.1$, as for the signal, is taken as the sys-
tematic 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 sig-
nal 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 $E_{\text{T}}^{\text{isol}}-|\Delta \phi|$ plane. The region A is defined by $E_{\text{T}}^{\text{isol}} \leq 5$ GeV and
$|\Delta \phi| < 2$; the region B, defined by $E_{\text{T}}^{\text{isol}} < 5$ GeV and $|\Delta \phi| > 2$, is
the signal region. The regions C and D are the anti-isolated regions
($E_{\text{T}}^{\text{isol}} > 5$ GeV) and they are defined by $|\Delta \phi| < 2$ and $|\Delta \phi| > 2$, re-
spectively. Neglecting the signal contamination in regions A, C and

![ATLAS Simulation](image-url)
Due to the very low number of events in the control regions the discriminating variable $\Delta \phi$ is fitted from the data in the corresponding regions, and by integrating the fitted function in the range $0 < \Delta \phi < 2$. The uncertainties are statistical only.

### Table 2

Cut flow for the event selection on the cosmic-ray background, the multi-jet background estimation from the ABCD method (described in Section 7), the signal Monte Carlo and the data; the background event and signal yields are normalized to an integrated luminosity of 1.9 fb$^{-1}$. The signal yields assume the Higgs boson SM production cross sections at the two mass values and 100% branching ratio of $H \rightarrow \gamma \gamma$ or $H \rightarrow Z \gamma$ or $H \rightarrow W^+W^-$ or $H \rightarrow ZZ$. The first uncertainties are statistical and the second systematic.

<table>
<thead>
<tr>
<th>Cut</th>
<th>Cosmic-rays</th>
<th>Multi-jet</th>
<th>Total background</th>
<th>$m_H = 100$ GeV</th>
<th>$m_H = 140$ GeV</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{\text{trig}} = 2$</td>
<td>$3.0 \pm 2.1$</td>
<td>$N/A$</td>
<td>$N/A$</td>
<td>$135 \pm 11_{-29}^{+26}$</td>
<td>$90 \pm 9_{-17}^{+15}$</td>
<td>871</td>
</tr>
<tr>
<td>$E_T^{\text{iso}} &lt; 5$ GeV</td>
<td>$3.0 \pm 2.1$</td>
<td>$N/A$</td>
<td>$N/A$</td>
<td>$132 \pm 11_{-28}^{+26}$</td>
<td>$88 \pm 9_{-17}^{+15}$</td>
<td>219</td>
</tr>
<tr>
<td>$</td>
<td>\Delta \phi</td>
<td>\geq 2$</td>
<td>$1.5 \pm 1.5$</td>
<td>$153 \pm 18 \pm 9$</td>
<td>$155 \pm 18 \pm 9$</td>
<td>$123 \pm 11_{-19}^{+26}$</td>
</tr>
<tr>
<td>$Q_{\text{MJ}} = 0$</td>
<td>$1.5 \pm 1.5$</td>
<td>$57 \pm 15 \pm 22$</td>
<td>$59 \pm 15 \pm 22$</td>
<td>$121 \pm 11_{-19}^{+26}$</td>
<td>$79 \pm 8_{-13}^{+15}$</td>
<td>80</td>
</tr>
<tr>
<td>$</td>
<td>d_0</td>
<td>,</td>
<td>z_0</td>
<td>$</td>
<td>$0.1^{+0.06}_{-0.0}$</td>
<td>$111 \pm 39 \pm 63$</td>
</tr>
<tr>
<td>$\sum p_T^{\text{D}} &lt; 3$ GeV</td>
<td>$0.1^{+0.06}_{-0.0}$</td>
<td>$0.06 \pm 0.02^{+0.06}_{-0.06}$</td>
<td>$0.06^{+0.06}_{-0.06}$</td>
<td>$75 \pm 9_{-12}^{+15}$</td>
<td>$48 \pm 7_{-9}^{+10}$</td>
<td>0</td>
</tr>
</tbody>
</table>

8. **Systematic uncertainties**

The following effects are considered as possible sources of systematic uncertainty:

- **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 $\gamma \gamma$ 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 $\gamma \gamma$ 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.
The uncertainties are statistical only.

The reconstruction 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 $p_T \geq 6$ GeV. The uncertainties are statistical only.

**Effect of $\sum p_T^{ID}$ cut**

Since the $\sum p_T^{ID}$ cut could affect the minimum $c_T$ 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 $p_T$ 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 $0.06 \pm 0.06$ 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 $\gamma\gamma$. The signal Monte Carlo events are weighted by the detection probability of the two $\gamma\gamma$ in the various parts of the detector, generating their decay points according to a chosen value of the $\gamma\gamma$ lifetime, with $c_T$ ranging from 0 to 700 mm. In this way the number of expected signal events is predicted as function of the $\gamma\gamma$ 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, result in two muon jets from the $\gamma\gamma$ and to a stable hidden fermion ($\tau$), which also includes the effect of the $\sum p_T^{ID}$ cut on the background estimation. These systematic uncertainties amount to $0.06 \pm 0.06$ events. The effect of signal leakage is also negligible.

**10. Conclusions**

The ATLAS detector at the LHC was used to search for a light Higgs boson decaying into a pair of hidden fermions ($f\bar{f}$), each of which decays to a $\gamma\gamma$ and to a stable hidden fermion ($f\bar{f}$), resulting in two muon jets from the $\gamma\gamma$ 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 $H \rightarrow \gamma\gamma\gamma\gamma + X$, according to the model of Fig. 1, as a function of the $\gamma\gamma$ mean lifetime, expressed as $c_T$ 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 $\gamma\gamma$ cut is excluded at the 95% CL for $H \rightarrow \gamma\gamma\gamma\gamma + X$ branching ratios of 100% and 10%.

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

**Table 3**

Ranges in which $\gamma\gamma$ cut is excluded at 95% CL for $m_H = 100$ GeV and $m_H = 140$ GeV, assuming 100% and 10% branching ratio of $H \rightarrow \gamma\gamma\gamma\gamma + X$ and the SM Higgs boson production cross section.
on the $\sigma \times BR$ of a 126 GeV Higgs boson may be conservatively extracted using the corresponding 140 GeV exclusion curve.

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