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


Published in:
Physics Letters B

DOI:
10.1016/j.physletb.2013.02.058

Link to publication

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).
Search for displaced muonic lepton jets from light Higgs boson decay in proton–proton collisions at \(\sqrt{s} = 7 \text{ TeV} \) 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 \(\sqrt{s} = 7 \text{ TeV} \) 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.

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

© CERN for the benefit of the ATLAS Collaboration.

* E-mail address: atlas.publications@cern.ch.
Fermions (see Fig. 1). The Higgs boson decays to two hidden fermions ($f_3$). Each hidden fermion decays to a $\gamma_d$ and to a stable hidden fermion ($f_1, f_2$), resulting in two muon jets from the $\gamma_d$ decays in the final state.

The signal 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 the Higgs boson decays to a pair of neutral hidden fermions ($f_3$) each of which decays to one long-lived $\gamma_d$ and one stable neutral hidden fermion ($f_1$) 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. 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 micro-strip detectors and a straw-tube tracker, provides precision tracking of charged particles for $|\eta| \leq 2.5$. 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 $\eta$-axis, where the trigger chambers of the middle stations are located. The detection efficiency can then be estimated for a range of $m_{\gamma_d}$ mean lifetimes through a study of rare, non-SM, Higgs boson decays in the (possibly extended) Higgs sector. 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 envelop 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 $f_3$ and $f_4$ are chosen to be light relative to the Higgs boson mass, and far from the kinematic threshold at $m_{f_3} + m_{\gamma_d} = m_{f_4}$. 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 boson decays into $\gamma_d + X$ 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 $m_{\gamma_d}$ is chosen such that a large fraction of the decays occurs 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 $m_{\gamma_d}$ 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 $W +$ 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 $m$C@NLO [27] ($t\bar{t}$, WW, WZ, and ZZ).

![Fig. 1. Schematic picture of the Higgs boson decay chain. $H \rightarrow 2(f_2 \rightarrow f_1 \gamma_d)$.](image-url)

### Table 1

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.

<table>
<thead>
<tr>
<th>Higgs mass [GeV]</th>
<th>$m_{f_3}$ [GeV]</th>
<th>$m_{f_4}$ [GeV]</th>
<th>$\gamma_d$ mass [GeV]</th>
<th>$\tau c$ [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>5.0</td>
<td>2.0</td>
<td>0.4</td>
<td>47</td>
</tr>
<tr>
<td>140</td>
<td>5.0</td>
<td>2.0</td>
<td>0.4</td>
<td>36</td>
</tr>
</tbody>
</table>
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 ($E_T^{miss}$), 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 $1.94 \pm 0.07$ 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 ($\Delta R < 0.1$) 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, $\epsilon_{2ROI}^{\gamma d}$, 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 $\epsilon_{2ROI}$ 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 $\Delta R < 0.1$ 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 $\epsilon_{2ROI}^{TP}/\epsilon_{1ROI}^{TP}$ ratio. Values of $\epsilon_{2ROI}^{TP}/\epsilon_{1ROI}^{TP} = 0.42 \pm 0.05_{stat}$ for the $J/\psi \rightarrow \mu^+\mu^-$ data and $\epsilon_{2ROI}^{TP}/\epsilon_{1ROI}^{TP} = 0.39 \pm 0.05_{stat}$ 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 subdetectors. 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

\[ \text{RAW TEXT END} \]
are formed. The MJ direction and momentum are obtained from the vector sum over all muons in the MJ. Only MJs with two reconstructed 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 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 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 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 calorimetric isolation variable $E_{\text{isol}}^\gamma$ 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 $E_{\text{isol}}^\gamma \leq 5$ 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: $\Delta \phi$ between the two MJs and $\sum p_T^\text{ID}$ 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 $\sum p_T^\text{ID}$. As a consequence a cut on $\sum p_T^\text{ID}$ 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 $E_{\text{isol}}^\gamma \leq 5$ 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 parameters of the muons with respect to the primary vertex: $|d_0| < 200$ mm and $|d_z| < 270$ mm.
- Require $\sum p_T^\text{ID} < 3$ GeV for both MJs.

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 $H \rightarrow \gamma\gamma\gamma + X$ 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 $p_T \geq 6$ GeV. The low reconstruction efficiency at very short $L_{xy}$ is a consequence of the $\sum p_T^\text{ID}$ cut.

The systematic uncertainty on the reconstruction efficiency is evaluated using a tag-and-probe method by comparing the reconstruction efficiency $E_{\text{rec}}$ 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 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 $J/\psi \rightarrow \mu^+\mu^-$ 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 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 $E_{\text{isol}}^\gamma - |\Delta \phi|$ plane. The region A is defined by $E_{\text{isol}}^\gamma \leq 5$ GeV and $|\Delta \phi| < 2$; the region B, defined by $E_{\text{isol}}^\gamma \leq 5$ GeV and $|\Delta \phi| > 2$, is the signal region. The regions C and D are the anti-isolated regions ($\sum p_T^\text{ID} > 5$ GeV) and they are defined by $|\Delta \phi| < 2$ and $|\Delta \phi| > 2$, respectively. Neglecting the signal contamination in regions A, C and
 Fig. 4. Plots of the variables used in the selection before the corresponding cut on Monte Carlo ($m_H = 140$ GeV) and on data. The arrows indicate in each plot the position of the cut. (a) Distribution of the calorimetric isolation around the MJ direction $E_T^{\text{iso}}$ after the requirement of two MJs in the event. (b) Distribution of $\Delta\phi$ between the two MJs after the requirement of the isolation cut. (c) Distribution of $\sum p_T^D$ of the MJ after the requirement of the impact parameters cut. The points show the data and the histogram is the signal Monte Carlo normalized to 1.9 fb$^{-1}$. 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 fb$^{-1}$. The signal yields assume the Higgs boson SM production cross sections at the two mass values and 100% branching ratio of $H \rightarrow \gamma\gamma + X$. 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>$N_{36}\gamma = 2$</td>
<td>3.0 ± 2.1</td>
<td>N/A</td>
<td>N/A</td>
<td>135 ± 11</td>
<td>90 ± 9</td>
<td>871</td>
</tr>
<tr>
<td>$E_T^{\text{iso}} &lt; 5$ GeV</td>
<td>3.0 ± 2.1</td>
<td>N/A</td>
<td>N/A</td>
<td>132 ± 11</td>
<td>88 ± 9</td>
<td>219</td>
</tr>
<tr>
<td>$</td>
<td>\Delta\phi</td>
<td>\geq 2$</td>
<td>1.5 ± 1.5</td>
<td>153 ± 18</td>
<td>9</td>
<td>155 ± 18</td>
</tr>
<tr>
<td>$Q_{MJ} = 0$</td>
<td>1.5 ± 1.5</td>
<td>57 ± 15</td>
<td>22</td>
<td>59 ± 15</td>
<td>22</td>
<td>79 ± 8</td>
</tr>
<tr>
<td>$</td>
<td>d_0</td>
<td>$, $</td>
<td>z_0</td>
<td>$</td>
<td>0.1 ± 0.0</td>
<td>111 ± 39</td>
</tr>
<tr>
<td>$\sum p_T^D &lt; 3$ GeV</td>
<td>0.1 ± 0.0</td>
<td>0.06 ± 0.02</td>
<td>0.06</td>
<td>0.06 ± 0.02</td>
<td>0.06</td>
<td>48 ± 7</td>
</tr>
</tbody>
</table>

The overall normalization uncertainty of the integrated luminosity is 3.7% [30,31].

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 $\gamma_d$ 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 $\gamma_d$ 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.
Fig. 5. $\gamma d$ reconstruction efficiency $\varepsilon_{\gamma d}$ as a function (a) of $\eta$, (b) of $\Delta R$ and (c) of the transverse decay length of the $\gamma d$ 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 ($|\eta| \leq 2.4$) with both muons having $p_T \geq 6$ GeV. The uncertainties are statistical only.

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 $\tau$ 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 $1.9 \text{fb}^{-1}$, 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 ($\sigma \times BR$) 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 $\varepsilon$ 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 $\gamma d$ is excluded at the 95% CL for $H \rightarrow \gamma d\gamma d + X$ branching ratios of 100% and 10%.

Table 3

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

- **Effect of $\sum P_T^{ID}$ cut**
  Since the $\sum P_T^{ID}$ cut could affect the minimum $\tau$ 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 data-driven method used. The systematic uncertainty amounts to $0.66\%$ on the signal, which can be 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 ($f_{d\bar{d}}$), each of which decays to a $\gamma d$ and to a stable hidden fermion ($f_{a\bar{a}}$), resulting in two muon jets from the $\gamma d$ decay in the final state. In a $1.9 \text{fb}^{-1}$ sample of $\sqrt{s} = 7 \text{ TeV}$ 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 $\varepsilon$ in the range $7 \text{ mm} \leq \varepsilon \leq 82 \text{ mm}$.
The 95% upper limits on the $\sigma \times BR$ for the process $H \rightarrow \gamma_1 \gamma_1 + X$ as a function of the dark photon $c'$ for the benchmark sample with (a) $m_{H} = 100$ GeV and with (b) $m_{H} = 140$ 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.

Fig. 7. The 95% upper limits on the $\sigma \times BR$ for the process $H \rightarrow \gamma_1 \gamma_1 + X$ as a function of the dark photon $c'$ for the benchmark sample with (a) $m_{H} = 100$ GeV and with (b) $m_{H} = 140$ 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.

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.

Figure 7: The 95% upper limits on the $\sigma \times BR$ for the benchmark sample with (a) $m_{H} = 100$ GeV and with (b) $m_{H} = 140$ 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.

References

Department of Physics, Bogazici University, Istanbul, Turkey
Division of Physics, Duzce University, Istanbul, Turkey
Department of Physics, Istanbul Technical University, Istanbul, Turkey
INSENEG Sezione di Bologna; Dipartimento di Fisica, Università di Bologna, Bologna, Italy
Physikalisches Institut, Universität Bonn, Bonn, Germany
Department of Physics, Boston University, Boston, MA, United States
Department of Physics, Brandeis University, Waltham, MA, United States
Universidade Federal do Rio de Janeiro COPPE/EEFT, Rio de Janeiro, Brazil
Federal University of Juiz de Fora (UFJF), Juiz de Fora, Brazil
Federal University of Sao Joao del Rei (UFJS), Sao Joao del Rei, Brazil
Instituto de Física, Universidade de Sao Paulo, Sao Paulo, Brazil
Physics Department, Brookhaven National Laboratory, Upton, NY, United States
National Institute of Physics and Nuclear Engineering, Bucharest; University Politehnica Bucharest, Bucharest; West University in Timisoara, Timisoara, Romania
Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
Department of Physics, Carleton University, Ottawa, ON, Canada
CERN, Geneva, Switzerland
Enrico Fermi Institute, University of Chicago, Chicago, IL, United States
Departamento de Física, Pontificia Universidad Catolica de Chile, Santiago, Chile
Departamento de Física, Universidad Tecnica Federico Santa Maria, Valparaiso, Chile
Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; Department of Modern Physics, University of Science and Technology of China, Anhui; Department of Physics, Nanjing University, Jiangsu; School of Physics, Shandong University, Shandong, China
Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France
Nevis Laboratory, Columbia University, Irvington, NY, United States
Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark
INFN Gruppo Collegato di Cosenza; Dipartimento di Fisica, Università della Calabria, Rende, Italy
AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland
The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland
Physics Department, Southern Methodist University, Dallas, TX, United States
Physics Department, University of Texas at Dallas, Richardson, TX, United States
DESY, Hamburg and Zeuthen, Germany
Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
Institut für Kern- und Teilchenphysik, Technical University Dresden, Dresden, Germany
Department of Physics, Duke University, Durham, NC, United States
SUPA – School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
INFN Laboratori Nazionali di Frascati, Frascati, Italy
Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
Section de Physique, Université de Genève, Geneva, Switzerland
(IN) Sezione di Genova; Dipartimento di Fisica, Università di Genova, Genova, Italy
E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi, Georgia
II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
SUPA – School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
Laboratoire de Physique Subatomique et de Cosmologie, Université Joseph Fourier and CNRS/IN2P3 and Institut National Polytechnique de Grenoble, Grenoble, France
Department of Physics, Hampton University, Hampton, VA, United States
Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, MA, United States
Kiichhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
Department of Physics, Indiana University, Bloomington, IN, United States
Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
University of Iowa, Iowa City, IA, United States
Department of Physics and Astronomy, Iowa State University, Ames, IA, United States
Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
Graduate School of Science, Kobe University, Kobe, Japan
Faculty of Science, Kyoto University, Kyoto, Japan
Kyoto University of Education, Kyoto, Japan
Department of Physics, Kyushu University, Fukuoka, Japan
Instituto de Fisica La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
Physics Department, Lancaster University, Lancaster, United Kingdom
(IN) Sezione di Lecce; Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
Department of Physics, Jozef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
Department of Physics and Astronomy, University College London, London, United Kingdom
Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
Fysiska institutionen, Lund universitet, Lund, Sweden
Departamento de Física Teórica C-15, Universidad Autonoma de Madrid, Madrid, Spain
Institut für Physik, Universität Mainz, Mainz, Germany
School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
Department of Physics, University of Massachusetts, Amherst, MA, United States
Department of Physics, McGill University, Montreal, QC, Canada
School of Physics, University of Melbourne, Victoria, Australia
Department of Physics, The University of Michigan, Ann Arbor, MI, United States
Department of Physics and Astronomy, Michigan State University, East Lansing, MI, United States
INFN Sezione di Milano; Dipartimento di Fisica, Università di Milano, Milano, Italy
G.N. Flerov Laboratory of Nuclear Reactions, Institute for Nuclear Research, Russian Academy of Sciences, Dubna, Russia
National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Belarus
Department of Physics, Massachusetts Institute of Technology, Cambridge, MA, United States
Group of Particle Physics, University of Montreal, Montreal, QC, Canada
<table>
<thead>
<tr>
<th>Institution</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>IMB-CNM, University of Valencia and CSIC, Valencia, Spain</td>
<td>Spain</td>
</tr>
<tr>
<td>Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany</td>
<td>Germany</td>
</tr>
<tr>
<td>Nagasaki Institute of Applied Science, Nagasaki, Japan</td>
<td>Japan</td>
</tr>
<tr>
<td>Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan</td>
<td>Japan</td>
</tr>
<tr>
<td>INFN Sezione di Napoli, Dipartimento di Scienze Fisiche, Università di Napoli, Napoli, Italy</td>
<td>Italy</td>
</tr>
<tr>
<td>Department of Physics and Astronomy, University of New Mexico, Albuquerque, NM, United States</td>
<td>United States</td>
</tr>
<tr>
<td>Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands</td>
<td>Netherlands</td>
</tr>
<tr>
<td>NIKHEF Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands</td>
<td>Netherlands</td>
</tr>
<tr>
<td>Department of Physics, Northern Illinois University, DeKalb, IL, United States</td>
<td>United States</td>
</tr>
<tr>
<td>Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia</td>
<td>Russia</td>
</tr>
<tr>
<td>Department of Physics, New York University, New York, NY, United States</td>
<td>United States</td>
</tr>
<tr>
<td>Ohio State University, Columbus, OH, United States</td>
<td>United States</td>
</tr>
<tr>
<td>Faculty of Science, Okayama University, Okayama, Japan</td>
<td>Japan</td>
</tr>
<tr>
<td>Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, OK, United States</td>
<td>United States</td>
</tr>
<tr>
<td>Palacký University, RCPTM, Olomouc, Czech Republic</td>
<td>Czech Republic</td>
</tr>
<tr>
<td>Center for High Energy Physics, University of Oregon, Eugene, OR, United States</td>
<td>United States</td>
</tr>
<tr>
<td>LAL, Université Paris-Sud et CNRS/IN2P3, Orsay, France</td>
<td>France</td>
</tr>
<tr>
<td>Graduate School of Science, Osaka University, Osaka, Japan</td>
<td>Japan</td>
</tr>
<tr>
<td>Department of Physics, University of Oslo, Oslo, Norway</td>
<td>Norway</td>
</tr>
<tr>
<td>Department of Physics, Oxford University, Oxford, United Kingdom</td>
<td>United Kingdom</td>
</tr>
<tr>
<td>INFN Sezione di Pavia, Dipartimento di Fisica, Università di Pavia, Pavia, Italy</td>
<td>Italy</td>
</tr>
<tr>
<td>Department of Physics, University of Pennsylvania, Philadelphia, PA, United States</td>
<td>United States</td>
</tr>
<tr>
<td>Petersburg Nuclear Physics Institute, Gatchina, Russia</td>
<td>Russia</td>
</tr>
<tr>
<td>INFN Sezione di Pisa, Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy</td>
<td>Italy</td>
</tr>
<tr>
<td>Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA, United States</td>
<td>United States</td>
</tr>
<tr>
<td>Laboratorio di Instrumentazione e Fisica Experimental de Particelle – LIP, Lisboa, Portugal,</td>
<td>Portugal</td>
</tr>
<tr>
<td>Department de Fisica Teorica y del Cosmos and CAPE, Universidad de Granada, Granada, Spain</td>
<td>Spain</td>
</tr>
<tr>
<td>Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic</td>
<td>Czech Republic</td>
</tr>
<tr>
<td>Faculty of Mathematics and Physics, Charles University in Prague, Prague, Czech Republic</td>
<td>Czech Republic</td>
</tr>
<tr>
<td>Czech Technical University in Prague, Prague, Czech Republic</td>
<td>Czech Republic</td>
</tr>
<tr>
<td>State Research Center Institute for High Energy Physics, Pratovino, Russia</td>
<td>Russia</td>
</tr>
<tr>
<td>Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom</td>
<td>United Kingdom</td>
</tr>
<tr>
<td>Physics Department, University of Regina, Regina, SK, Canada</td>
<td>Canada</td>
</tr>
<tr>
<td>Ritsumeikan University, Kusatsu, Shiga, Japan</td>
<td>Japan</td>
</tr>
<tr>
<td>INFN Sezione di Roma I, Dipartimento di Fisica, Università La Sapienza, Roma, Italy</td>
<td>Italy</td>
</tr>
<tr>
<td>INFN Sezione di Roma Tor Vergata, Dipartimento di Fisica, Università di Roma Tor Vergata, Roma</td>
<td>Italy</td>
</tr>
<tr>
<td>INFN Sezione di Roma Tre, Dipartimento di Fisica, Università Roma Tre, Roma, Italy</td>
<td>Italy</td>
</tr>
<tr>
<td>Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies – Université Hassan II, Caxambra,</td>
<td>France</td>
</tr>
<tr>
<td>Centre National de l’Energie des Sciences Techniques Nucleaires, Rabat,</td>
<td>Faculty des Sciences Semlalia, Université Cadi Ayyad, LPHA, Marrakech; Faculty des sciences, Université Mohamed Premier et LPTPM, Oujda; Faculty des sciences, Université Mohammed V – Agdal, Rabat, Morocco</td>
</tr>
<tr>
<td>Dipartimento di Fisica, Università Roma Tre, Roma, Italy</td>
<td>Italy</td>
</tr>
<tr>
<td>Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy</td>
<td>Italy</td>
</tr>
<tr>
<td>Dipartimento di Fisica, Università di Napoli, Napoli, Italy</td>
<td>Italy</td>
</tr>
<tr>
<td>Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy</td>
<td>Italy</td>
</tr>
<tr>
<td>Department of Physics, University of Illinois, Urbana, IL, United States</td>
<td>United States</td>
</tr>
<tr>
<td>Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden</td>
<td>Sweden</td>
</tr>
<tr>
<td>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</td>
<td>Spain</td>
</tr>
</tbody>
</table>