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

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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 ☆

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ABSTRACT

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.

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, γ_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 γ_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 $m_H < 2m_W$. 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 be 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.

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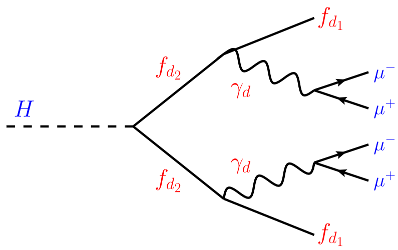

Fig. 1. Schematic picture of the Higgs boson decay chain, $H \to 2(f_{d2} \to f_{d1}\gamma_d)$. The Higgs boson decays to two hidden fermions (f_{d2}). Each hidden fermion decays to a γ_d and to a stable hidden fermion (f_{d1}), resulting in two muon jets from the γ_d decays in the final state.

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 the Higgs boson decays to a pair of neutral hidden fermions (f_{d2}) each of which decays to one long-lived γ_d and one stable neutral hidden fermion (f_{d1}) that escapes the detector unnoticed, resulting in two lepton jets from the γ_d decays in the final state (see Fig. 1). The mass of the γ_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 (η, ϕ) 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 $|\eta| \leqslant 2.5$. The electromagnetic and hadronic calorimeter system covers $|\eta| \leqslant 4.9$ 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 ($|\eta| \leqslant 2.4$) and momentum measurements ($|\eta| \leqslant 2.7$) for charged particles entering the spectrometer. It consists of one barrel and two endcap parts, each with 16 sectors in ϕ, equipped with precision tracking chambers and fast detectors for triggering. Monitored drift tubes are used for precision tracking in the region $|\eta| \leqslant 2.0$ and cathode strip chambers are used for $2.0 \leqslant |\eta| \leqslant 2.7$. 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 0.2×0.2 ($\Delta\eta \times \Delta\phi$) in the barrel and of 0.1×0.1 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.

[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, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$.

Table 1
Parameters used for the Monte Carlo simulation. The last column is the γ_d mean lifetime τ multiplied by the speed of light c, expressed in mm.

Higgs mass [GeV]	$m_{f_{d2}}$ [GeV]	$m_{f_{d1}}$ [GeV]	γ_d mass [GeV]	$c\tau$ [mm]
100	5.0	2.0	0.4	47
140	5.0	2.0	0.4	36

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_{d2} and f_{d1} are chosen to be light relative to the Higgs boson mass, and far from the kinematic threshold at $m_{f_{d1}} + m_{\gamma_d} = m_{f_{d2}}$. For the chosen dark photon mass (0.4 GeV), the γ_d decay branching ratios are expected to be [14]: 45% e^+e^-, 45% $\mu^+\mu^-$, 10% $\pi^+\pi^-$. Thus 20% of the Higgs $H \to \gamma_d\gamma_d + X$ decays are expected to have the required four-muon final state.

The mean lifetime τ of the γ_d (expressed throughout this Letter as τ times the speed of light c) is a free parameter of the model. In the generated samples $c\tau$ 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 γ_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/π 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).

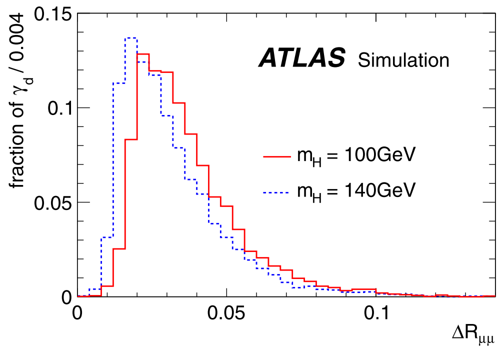

Fig. 2. ΔR distribution between the two muons from the γ_d decay for the signal Monte Carlo samples with $m_H = 100$ GeV and $m_H = 140$ GeV.

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 γ_d pair are emitted approximately back-to-back in ϕ, with an angular spread of the distribution due to the emission of the f_{d1}.
- The average p_T of the γ_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 γ_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 γ_d decay. The ΔR is computed at the decay vertex of the γ_d from the vector momenta of the two muons. Due to the small mass of the γ_d the ΔR is almost always below 0.1.

Since the two f_{d1} are, like the two γ_d, emitted back-to-back in ϕ, 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).[2] 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 $p_T \geqslant 0.4$ 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 γ_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 $p_T \geqslant 6$ 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 ΔR between the two muons of the γ_d decay ($\Delta R \leqslant 0.1$) shown in Fig. 2. These values of ΔR 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 γ_d produces two distinct L1 ROIs. The single γ_d ROI efficiency, ε_{2ROI} (ε_{1ROI}), defined as the fraction of γ_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 ε_{2ROI} as a function of the dark photon η and of the ΔR of the two muons from the γ_d decay. The increased trigger granularity in the endcap and the efficiency decrease at small values of ΔR are clearly visible.

The systematic uncertainty on the trigger efficiency is estimated with a sample of $J/\psi \to \mu^+\mu^-$ from collision data and a corresponding sample of Monte Carlo events, using the tag-and-probe (TP) method. A cut on $\Delta R \leqslant 0.1$ 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/ψ mass. A muon ROI that matches the probe in η and ϕ, 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 $\varepsilon^{TP}_{2ROI}/\varepsilon^{TP}_{1ROI}$ ratio. Values of $\varepsilon^{TP}_{2ROI}/\varepsilon^{TP}_{1ROI} = 0.42 \pm 0.05_{stat}$ for the $J/\psi \to \mu^+\mu^-$ data and $\varepsilon^{TP}_{2ROI}/\varepsilon^{TP}_{1ROI} = 0.39 \pm 0.05_{stat}$ 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 γ_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

[2] High pile-up levels will introduce a pile-up dependence for the isolation variables used in the analysis and needs to be further investigated.

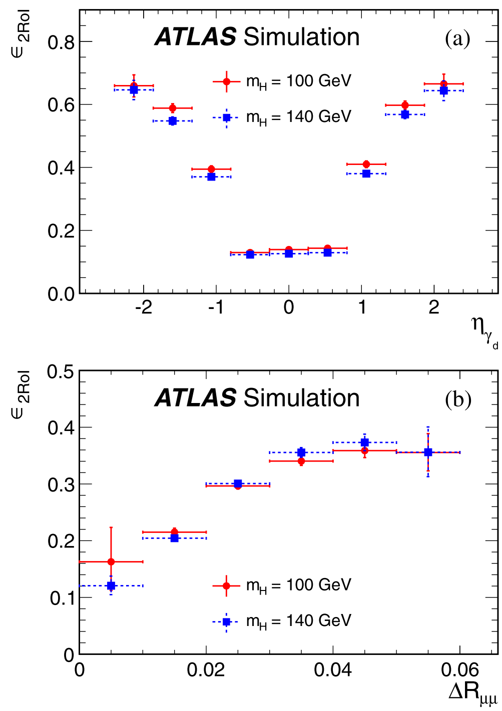

Fig. 3. $\varepsilon_{2\mathrm{ROI}}$ as a function (a) of the η of the γ_d and (b) of the ΔR of the muon pair for the Monte Carlo samples with Higgs boson masses of 100 GeV and 140 GeV. The errors are statistical only.

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/π 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 $E_{\mathrm{T}}^{\mathrm{isol}}$ 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 $E_{\mathrm{T}}^{\mathrm{isol}} \leqslant 5$ 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 $\sum p_{\mathrm{T}}^{\mathrm{ID}}$ 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 $\sum p_{\mathrm{T}}^{\mathrm{ID}}$. As a consequence a cut on $\sum p_{\mathrm{T}}^{\mathrm{ID}}$ 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, $N_{\mathrm{MJ}} = 2$.
- MJ isolation: require MJ isolation with $E_{\mathrm{T}}^{\mathrm{isol}} \leqslant 5$ GeV for both MJs in the event.
- Require $|\Delta\phi| \geqslant 2$ between the two MJs.
- Require opposite charges for the two muons in a MJ ($Q_{\mathrm{MJ}} = 0$).
- Require a cut on the transverse and longitudinal impact parameters of the muons with respect to the primary vertex: $|d_0| < 200$ mm and $|z_0| < 270$ mm.
- Require $\sum p_{\mathrm{T}}^{\mathrm{ID}} < 3$ 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 $H \to \gamma_d\gamma_d + X$ 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 γ_d reconstruction efficiency for the mean lifetimes given in Table 1 is shown in Fig. 5 as a function of η, the ΔR separation of the two muons from the γ_d decay and the decay length in the transverse plane, L_{xy}, of the γ_d. The efficiency is defined as the number of γ_d passing the offline selection divided by the number of γ_d in the spectrometer acceptance ($|\eta| \leqslant 2.4$) with both muons having $p_{\mathrm{T}} \geqslant 6$ GeV. The low reconstruction efficiency at very short L_{xy} is a consequence of the $\sum p_{\mathrm{T}}^{\mathrm{ID}}$ cut.

The systematic uncertainty on the reconstruction efficiency is evaluated using a tag-and-probe method by comparing the reconstruction efficiency $\varepsilon_{\mathrm{rec}}^{\mathrm{TP}}$ 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 $\Delta R \leqslant 0.1$ 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 $\Delta R \leqslant 0.1$, 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 $E_{\mathrm{T}}^{\mathrm{isol}}$–$|\Delta\phi|$ plane. The region A is defined by $E_{\mathrm{T}}^{\mathrm{isol}} \leqslant 5$ GeV and $|\Delta\phi| < 2$; the region B, defined by $E_{\mathrm{T}}^{\mathrm{isol}} \leqslant 5$ GeV and $|\Delta\phi| \geqslant 2$, is the signal region. The regions C and D are the anti-isolated regions ($E_{\mathrm{T}}^{\mathrm{isol}} > 5$ GeV) and they are defined by $|\Delta\phi| < 2$ and $|\Delta\phi| \geqslant 2$, respectively. Neglecting the signal contamination in regions A, C and

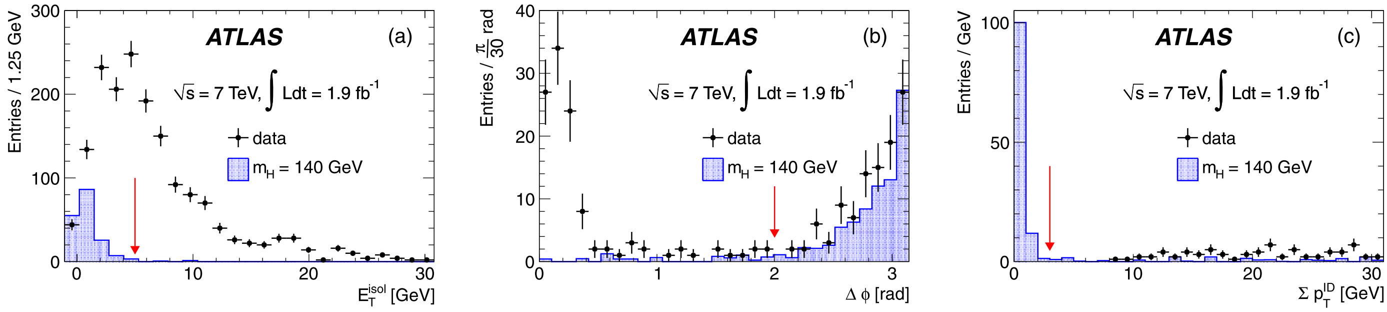

Fig. 4. Plots of the variables used in the selection before the corresponding cut on Monte Carlo ($m_H = 140$ GeV) and on data. The arrows indicate in each plot the position of the cut. (a) Distribution of the calorimetric isolation around the MJ direction E_T^{isol} after the requirement of two MJs in the event. (b) Distribution of $\Delta\phi$ between the two MJs after the requirement of the isolation cut. (c) Distribution of $\sum p_T^{ID}$ 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 1.9 fb^{-1}. The signal yields assume the Higgs boson SM production cross sections at the two mass values and 100% branching ratio of $H \to \gamma_d\gamma_d + X$. The first uncertainties are statistical and the second systematic.

Cut	Cosmic-rays	Multi-jet	Total background	$m_H = 100$ GeV	$m_H = 140$ GeV	Data
$N_{MJ} = 2$	3.0 ± 2.1	N/A	N/A	$135 \pm 11^{+29}_{-21}$	$90 \pm 9^{+17}_{-13}$	871
$E_T^{isol} \leqslant 5$ GeV	3.0 ± 2.1	N/A	N/A	$132 \pm 11^{+28}_{-21}$	$88 \pm 9^{+17}_{-13}$	219
$\lvert\Delta\phi\rvert \geqslant 2$	1.5 ± 1.5	$153 \pm 18 \pm 9$	$155 \pm 18 \pm 9$	$123 \pm 11^{+26}_{-19}$	$81 \pm 9^{+15}_{-12}$	104
$Q_{MJ} = 0$	1.5 ± 1.5	$57 \pm 15 \pm 22$	$59 \pm 15 \pm 22$	$121 \pm 11^{+26}_{-19}$	$79 \pm 8^{+15}_{-12}$	80
$\lvert d_0\rvert$, $\lvert z_0\rvert$	$0^{+1.64}_{-0}$	$111 \pm 39 \pm 63$	$111 \pm 39 \pm 63$	$105 \pm 10^{+22}_{-16}$	$66 \pm 8^{+12}_{-10}$	70
$\sum p_T^{ID} < 3$ GeV	$0^{+1.64}_{-0}$	$0.06 \pm 0.02^{+0.66}_{-0.06}$	$0.06^{+1.64+0.66}_{-0.02-0.06}$	$75 \pm 9^{+16}_{-12}$	$48 \pm 7^{+9}_{-7}$	0

D ($E_T^{isol} > 5$ 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_D as a function of the cut on the final discriminant variable $\sum p_T^{ID}$ are extracted by modelling the $\sum p_T^{ID}$ distributions with bifurcated Gaussian templates, with parameters fitted from the data in the corresponding regions, and by integrating the fitted function in the range $0 < \sum p_T^{ID} < 3$ 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 $N_A = (7.1 \pm 1.5_{stat}) \cdot 10^{-3}$, $N_C = (1.81 \pm 1.0_{stat}) \cdot 10^{-2}$ and $N_D = (1.51 \pm 0.07_{stat}) \cdot 10^{-1}$ and the estimated number of multi-jet background events in the signal region is $N_B = 0.06 \pm 0.02_{stat}$.

Possible sources of systematic uncertainty related to the background estimation method are also evaluated. Various functional models are used to fit the $\sum p_T^{ID}$ 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 signal region is then repeated. The maximum variation in N_B is taken as the systematic uncertainty, that amounts to $^{+0.66}_{-0.06}$. The effect of possible signal leakage in the background regions is also considered and is found to be negligible.

The background induced by muons from cosmic-ray showers is evaluated using events collected by the trigger being active when there are no collisions (empty bunch crossings). The number of triggered events is rescaled by the collision to empty bunch crossing ratio and for the active time (since the trigger in the empty bunch crossing was not active in all the runs). No events survived the requirements on the impact parameters with respect to the primary vertex ($|d_0| < 200$ mm and $|z_0| < 270$ mm), resulting in a cosmic-ray contamination estimate of $0^{+1.64}_{-0}$. The final yields for the different background sources are summarized in Table 2.

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 $Z \to \mu\mu$ 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 γ_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 γ_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 ≈ 6 to ≈ 16. This systematic uncertainty is negligible.

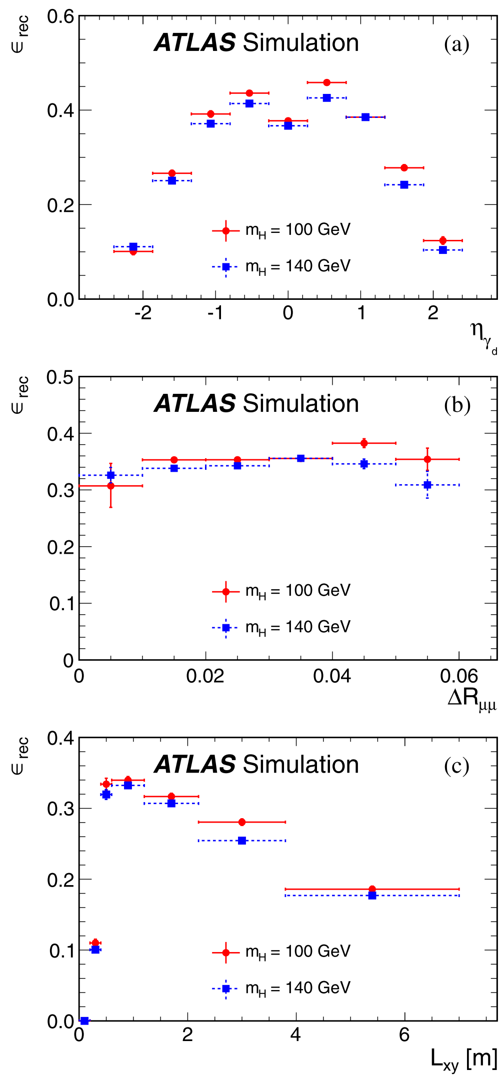

Fig. 5. γ_d reconstruction efficiency $\varepsilon_{\mathrm{rec}}$ as a function (a) of η, (b) of ΔR and (c) of the transverse decay length of the γ_d for $m_H = 100$ GeV and $m_H = 140$ GeV and for the mean lifetimes given in Table 1. The reconstruction efficiency is defined as the number of γ_d passing the offline selection divided by the number of γ_d in the spectrometer acceptance ($|\eta| \leqslant 2.4$) with both muons having $p_{\mathrm{T}} \geqslant 6$ GeV. The uncertainties are statistical only.

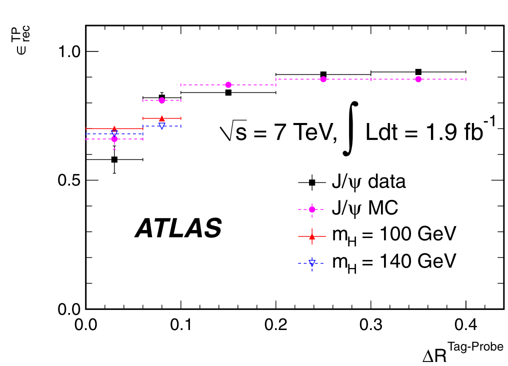

Fig. 6. Tag-and-probe reconstruction efficiency $\varepsilon^{\mathrm{TP}}_{\mathrm{rec}}$ as a function of the ΔR between the two muons, evaluated on a sample of $J/\psi \to \mu^+\mu^-$ from collision data and a corresponding sample of Monte Carlo events. The $\varepsilon^{\mathrm{TP}}_{\mathrm{rec}}$ 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 γ_d $c\tau$ is excluded at 95% *CL* for $m_H = 100$ GeV and $m_H = 140$ GeV, assuming 100% and 10% branching ratio of $H \to \gamma_d\gamma_d + X$ and the SM Higgs boson production cross section.

Higgs boson mass [GeV]	Excluded $c\tau$ [mm] BR(100%)	Excluded $c\tau$ [mm] BR(10%)
100	$1 \leqslant c\tau \leqslant 670$	$5 \leqslant c\tau \leqslant 159$
140	$1 \leqslant c\tau \leqslant 430$	$7 \leqslant c\tau \leqslant 82$

- **Effect of $\sum p_{\mathrm{T}}^{\mathrm{ID}}$ cut**
  Since the $\sum p_{\mathrm{T}}^{\mathrm{ID}}$ cut could affect the minimum $c\tau$ value that can be excluded, the effect of this cut on the signal Monte Carlo has been studied. A variation of 10% on the $\sum p_{\mathrm{T}}^{\mathrm{ID}}$ 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 $\sum p_{\mathrm{T}}^{\mathrm{ID}}$ distribution is varied to evaluate the systematic uncertainty in the modelling of its shape, which also includes the effect of the $\sum p_{\mathrm{T}}^{\mathrm{ID}}$ cut on the background estimation. This systematic uncertainty amounts to $^{+0.66}_{-0.06}$ 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 γ_d. The signal Monte Carlo events are weighted by the detection probability of the two γ_d in the various parts of the detector, generating their decay points according to a chosen value of the γ_d lifetime, with $c\tau$ ranging from 0 to 700 mm. In this way the number of expected signal events is predicted as function of the γ_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 ($\sigma \times \mathrm{BR}$) for the process $H \to \gamma_d\gamma_d + X$, according to the model of Fig. 1. Here the branching ratio of $\gamma_d \to \mu\mu$ is set to 45% with the γ_d mass set to 0.4 GeV, as previously discussed. The $\sigma \times \mathrm{BR}$ is given as a function of the γ_d mean lifetime, expressed as $c\tau$ 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 γ_d $c\tau$ is excluded at the 95% *CL* for $H \to \gamma_d\gamma_d + X$ 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 γ_d and to a stable hidden fermion (f_{d1}), resulting in two muon jets from the γ_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 $\sigma \times \mathrm{BR}$ to $H \to \gamma_d\gamma_d + X$, 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 γ_d mass that gives a decay branching ratio of 45% for $\gamma_d \to \mu\mu$. 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 $c\tau$ in the range 7 mm $\leqslant c\tau \leqslant$ 82 mm. Bounds

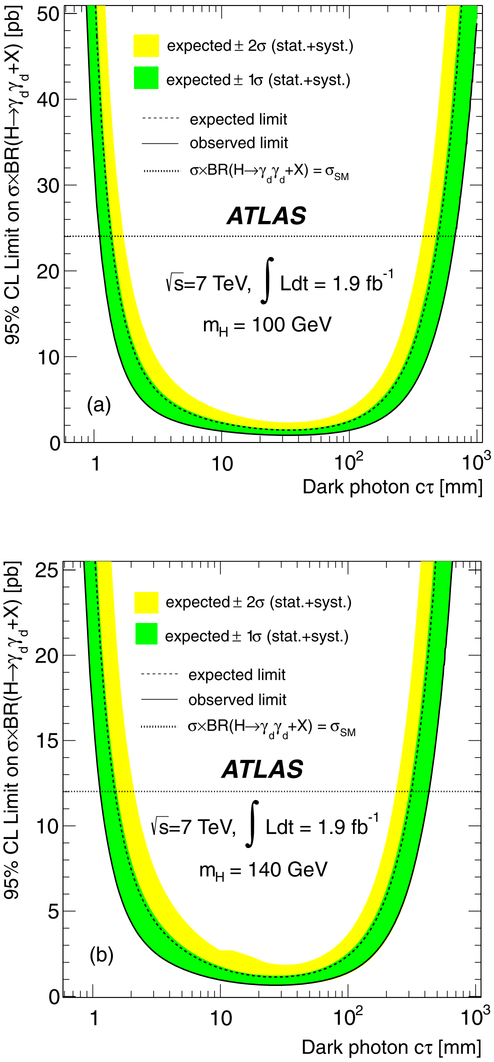

Fig. 7. The 95% upper limits on the $\sigma \times$ BR for the process $H \to \gamma_d \gamma_d + X$ as a function of the dark photon $c\tau$ for the benchmark sample with (a) $m_H = 100$ GeV and with (b) $m_H = 140$ GeV, assuming the Higgs boson SM production cross section. The expected limit is shown 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.

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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