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Search for *WH* production with a light Higgs boson decaying to prompt electron-jets in proton–proton collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector

The ATLAS Collaboration

Abstract. A search is performed for *WH* production with a light Higgs boson decaying to hidden-sector particles resulting in clusters of collimated electrons, known as electron-jets. The search is performed with $2.04\,\text{fb}^{-1}$ of data collected in 2011 with the ATLAS detector at the Large Hadron Collider in proton–proton collisions at $\sqrt{s} = 7$ TeV. One event satisfying the signal selection criteria is observed, which is consistent with the expected background rate. Limits on the product of the *WH* production cross section and the branching ratio of a Higgs boson decaying to prompt electron-jets are calculated as a function of a Higgs boson mass in the range from 100 to 140 GeV.

IOP Institute of Physics   **Φ** DEUTSCHE PHYSIKALISCHE GESELLSCHAFT

Contents

1. Introduction

Recently, the production of a boson with a mass of about 125 GeV has been observed by the ATLAS [1] and CMS [2] collaborations. The observation is compatible with the production and decay of the Standard Model (SM) Higgs boson [3–5] at this mass. Strengthening or rejecting the SM Higgs boson hypothesis is currently of utmost importance and thus a search for non-SM Higgs boson decays is of high interest. In this paper, a search for a Higgs boson decaying to a new hidden sector of particles is presented. The masses and couplings of the hidden-sector particles are chosen such that the Higgs boson decay cascade results in jets consisting exclusively of electrons ('electron-jets') and weakly interacting neutral particles [6, 7]. This is the first search performed for this particular channel. Moreover, in addition to a recently discovered state consistent with the SM Higgs boson, there may be other scalar fields that couple to the W boson and decay to electron-jets. These scalars arise in the Higgs boson sector in many extensions of the SM, and electron-jets could be the primary discovery channel for these new states. The search is performed in the Higgs boson mass range between 100 and 140 GeV. The analysis examines the associated Higgs boson production mechanism, $pp \to WH$, assuming SM couplings between the Higgs boson and the W boson.

Many models of physics beyond the SM contain a light hidden sector, which is composed of as yet unobserved fields that are singlets under the SM group $SU(3) \times SU(2) \times U(1)$ and that can be probed at the Large Hadron Collider (LHC) [6–17]. Models of this hidden sector vary from simple modifications of the SM [12, 13] to models motivated by string theory [14] to so-called unparticle models [15].

In the present analysis two models, discussed in [7], are considered. These differ in the way the Higgs boson decays, either via a three-step cascade (figure 1 left) or a two-step cascade (figure 1 right) to hidden-sector particles. In both models the masses of particles in a hidden-sector cascade are taken to be substantially lower than the Higgs boson mass, thus the Higgs boson decay has a two-jet topology. The models feature a dark photon γ_d that kinetically mixes with the SM photon [16, 17], a neutral weakly interacting stable scalar n_d and two hidden
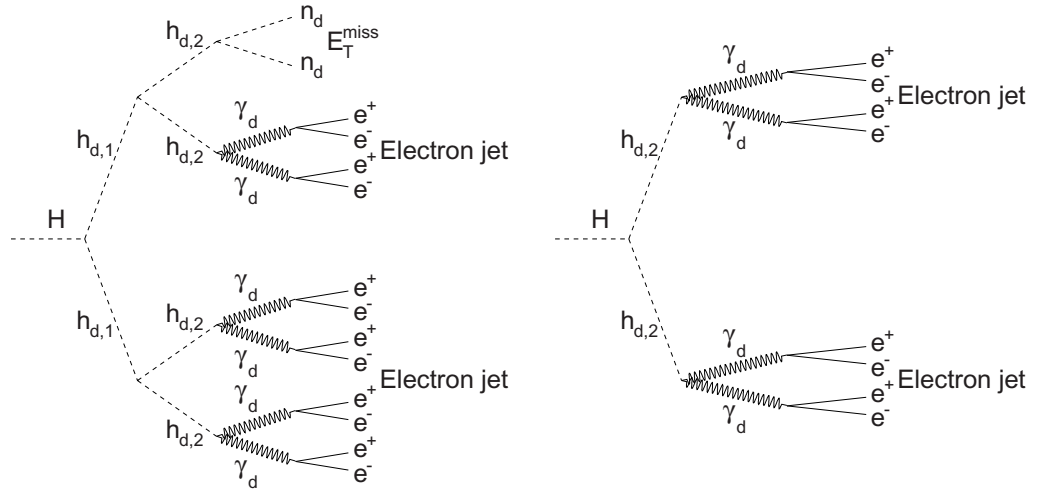
Figure 1. Diagrams illustrating the Higgs boson decay to hidden-sector particles in the (left) three-step and (right) two-step models. Each $h_{d,2}$ particle can decay to a pair of dark photons γ_d or stable scalars n_d, with the corresponding branching ratios given in table 1.

scalars $h_{d,1}$ and $h_{d,2}$. A value of the kinetic mixing parameter ϵ larger than 10^{-5} implies dark photons with very short lifetimes; thus the chosen value of $\epsilon = 10^{-4}$, recommended in [7], ensures that the decay products are prompt. The dark photon mass must be less than 2 GeV for these models to provide a viable explanation of the results of cosmic-ray and dark matter direct-detection experiments [18–21], which observe an unexpected excess of cosmic electrons and/or positrons, while there is no observed proton excess. For a dark photon mass below 210 MeV, the dark photons decay exclusively to e^+e^- pairs; dark photon masses of 100 and 200 MeV are considered in this analysis.

The signal has a distinct two-jet topology with each electron-jet having a multiplicity of $\geqslant 4$ electrons per jet, where the electrons are highly collimated. The specific hidden-sector parameters are given in table 1, and the chosen masses of the Higgs boson are 100, 125 and 140 GeV. The results of the analysis are expected to be robust with respect to the specific choice of the $h_{d,1}$, $h_{d,2}$ and n_d masses as long as these masses are significantly smaller than the Higgs boson mass, i.e. $m_{h_{d,1|2}} \leqslant 10$ GeV. In particular, as long as the $h_{d,1}$ and $h_{d,2}$ scalars are much lighter than the Higgs boson, the $h_{d,1}$ and $h_{d,2}$ are boosted, and their decay products are collimated, resulting in two distinct electron-jets. Also in the three-step model, the results are expected to be robust against the explicit choice of the branching ratio of the $h_{d,2}$ particle into weakly interacting neutral particles, n_d, as long as this branching ratio is relatively small, i.e. $\mathrm{BR}(h_{d,2} \to n_d n_d) \leqslant 0.2$. For this range of branching ratios, both the $h_{d,1}$ particles decay to visible decay products with greater than 90% probability; for larger branching ratios, there will be a considerable fraction of events where only one (or neither) $h_{d,1}$ particle decays to visible decay products.

In this analysis, the W boson produced in association with the Higgs boson is reconstructed in the $W \to e\nu$ and $W \to \mu\nu$ decay modes in order to achieve a high efficiency for online event selection and a high signal-to-background ratio. The signal topology is consequently an isolated

Table 1. Parameters of the benchmark hidden-sector models: hidden-sector particle masses, the $\gamma - \gamma_d$ kinetic mixing, and decay branching ratios of $h_{d,1}$ and $h_{d,2}$ in the three-step and two-step models.

Parameter	
$m_{h_{d,1}}$	10 GeV
$m_{h_{d,2}}$	4 GeV
m_{n_d}	90 MeV
m_{γ_d}	100, 200 MeV
ϵ	10^{-4}
Three-step model	
BR($h_{d,1} \to h_{d,2}h_{d,2}$)	1
BR($h_{d,2} \to \gamma_d\gamma_d$)	0.8
BR($h_{d,2} \to n_dn_d$)	0.2
Two-step model	
BR($h_{d,2} \to \gamma_d\gamma_d$)	1
BR($h_{d,2} \to n_dn_d$)	0

large transverse momentum lepton accompanied by missing transverse momentum and two or more electron-jets.

The sensitivity of this analysis is approximately two orders of magnitude greater than that of a previous search for similar signatures which was performed by the CDF collaboration [22]. The direct searches for prompt decays of dark photons into electron or muon pairs, as well as a search for a Higgs boson decaying into displaced muon-jets, were reported in [23–26].

2. The ATLAS detector

The ATLAS detector [27] is a multi-purpose particle physics detector with forward–backward symmetric cylindrical geometry[1]. The inner detector (ID) provides precise reconstruction of tracks with $|\eta| < 2.5$. It consists of three layers of pixel detectors close to the beam pipe, four layers of silicon microstrip detector modules in the barrel region with pairs of single-sided sensors (SCT) providing 8 hits per track at intermediate radii, and a straw-tube transition radiation tracker (TRT) at the outer radii, providing about 35 hits per track (in the range $|\eta| < 2.0$). The TRT offers substantial discriminating power between electrons and charged hadrons over a wide momentum range (between 0.5 and 100 GeV) via the detection of x-rays produced by transition radiation.

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[1] ATLAS uses a right-handed coordinate system with its origin at the nominal pp interaction point at the center of the detector. The positive *x*-axis is defined by the direction from the interaction point to the center of the LHC ring, with the positive *y*-axis pointing upwards, while the beam direction defines the *z*-axis. The azimuthal angle ϕ is measured around the beam axis with the polar angle θ is the angle from the *z*-axis. The pseudorapidity is defined as $\eta = -\ln\tan(\theta/2)$. The cone separation is defined as $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$. The transverse momentum p_T is defined as the momentum perpendicular to the beam axis: $p_T = \sqrt{p_x^2 + p_y^2}$.

The ID is surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field. A high-granularity lead/liquid-argon (LAr) sampling calorimeter measures the energy and the position of electromagnetic showers with $|\eta| < 3.2$. The total thickness of this calorimeter is more than $24X_0$ in the barrel and above $26X_0$ in the endcaps. LAr sampling calorimeters, with copper or tungsten as absorber, are used to measure hadronic showers in the endcap ($1.5 < |\eta| < 4.9$), while an iron/scintillator tile hadronic calorimeter measures hadronic showers in the central region ($|\eta| < 1.7$). The muon spectrometer (MS) surrounds the calorimeters and consists of three large superconducting air-core toroids, each with eight coils, a system of drift tubes and cathode strip chambers for precision tracking ($|\eta| < 2.7$), and fast tracking chambers for event selection in real time ($|\eta| < 2.4$).

A three-level trigger system [28] selects events to be recorded for offline analysis. The level-1 trigger is implemented in hardware, operating synchronously with the collisions, and uses a subset of detector information to reduce the event rate from 20 MHz to a maximum level-1 output rate of 75 kHz. This is followed by two software-based trigger levels, level-2 and the event filter, which together reduce the recorded event rate to approximately 300 Hz.

3. Signal and background simulation

Simulated data samples are used to estimate the signal acceptance and efficiency, to optimize the signal selection criteria and to cross-check our understanding of the backgrounds. The final background estimate is determined from the data as described in section 6.

The signal Monte Carlo (MC) samples are generated with MADGRAPH [29] to simulate the Higgs boson production and decay to the hidden sector and BRIDGE [30] to simulate the hidden-sector cascades resulting in electron-jets. The output of these two programs is then interfaced to PYTHIA [31] for subsequent hadronization and modeling of the underlying event (UE). All leptonic decays modes of the W boson ($e\nu_e, \mu\nu_\mu, \tau\nu_\tau$) are included in the signal samples.

The most important sources of background are SM W/Z + jets and $t\bar{t}$ processes. A less important source of background comes from pair production of bosons, $WW/ZZ/WZ$, hereafter referred to as diboson production. These processes result in a lepton + jets event topology. In addition, multi-jet events in some instances can be misidentified as W-bosons.

Samples of simulated $W(\to \ell\nu)$+jets and $Z(\to \ell\ell)$+jets events ($\ell = e/\mu/\tau$) are generated using ALPGEN [32] interfaced to HERWIG [34] for parton shower and fragmentation processes and to JIMMY [35] for UE simulation. In ALPGEN the fixed-order tree-level matrix-element calculations are combined with parton showers using the MLM matching scheme [33]. Simulated samples for $t\bar{t}$ processes are generated with MC@NLO [36] interfaced to HERWIG for parton showering. To study the possible dependence on the specific choice of MC generator, alternate W/Z+jets samples are also generated using SHERPA [37] with an UE modeling according to [38], and alternate top-quark production samples are generated with POWHEG [39] interfaced to PYTHIA for hadronization. The diboson processes are generated with HERWIG. Taus are decayed with TAUOLA [40] in both signal and background samples.

The event yields for $W \to \ell\nu$, $Z \to \ell\ell$ ($ell = e/\mu$) and $t\bar{t}$ processes, which give the largest contribution to background, are scaled using the measured production cross sections [41, 42]. The contributions from $W(\to \tau\nu)$ and $Z(\to \tau\tau)$, which are minor sources of background, are obtained using next-to-next-to-leading-order cross-section calculations [43]. The multi-jet background is obtained using normalized data templates [41], since the rate with which

multi-jet events mimic the combined signature of a prompt charged lepton accompanied by missing transverse momentum is difficult to simulate accurately.

The GEANT4 toolkit [44] is used for a detailed simulation of the detector response [45]. The effect of multiple pp interactions per bunch crossing (pile-up) is modeled by overlaying simulated inelastic proton–proton collisions over the original hard-scattering event. The simulated events are then passed through the same reconstruction and analysis chain as the data.

To calibrate the electron energy and to match the resolution of the electron energy and muon momentum observed in data, corrections are applied to electrons in data and electrons and muons in simulated MC samples according to the prescriptions of [46, 47].

4. Data samples and trigger selection

The data sample for this analysis was collected by the ATLAS detector in proton–proton collisions at a center-of-mass energy of 7 TeV in early 2011. The data sample used was required to be recorded during LHC stable-beam conditions when the ATLAS detector components relevant to this analysis were operating within nominal parameters. The total integrated luminosity of the selected data sample is 2.04 fb^{-1} with a 3.7% uncertainty [48, 49].

For the $W \to e\nu$ channel, at least one reconstructed electron trigger object with transverse energy above 22 GeV in the region of $|\eta| \leqslant 2.5$ is required. For the $W \to \mu\nu$ channel, a muon candidate trigger object in the region of $|\eta| \leqslant 2.4$ having transverse momentum above 18 GeV, reconstructed in both the ID and MS, is required. The muon trigger object must be consistent with having originated from the interaction region.

5. Event selection and electron-jet reconstruction

Signal events are required to have exactly one reconstructed W boson candidate in the $e\nu$ or $\mu\nu$ decay channel and at least two jets identified as electron-jets.

5.1. W boson selection

A W-decay electron candidate is required to pass the tight electron selection criteria [41, 46] with $p_T > 25$ GeV and $|\eta| \leqslant 2.47$. Electrons in the transition region between the barrel and endcap calorimeters ($1.37 < |\eta| < 1.52$) are rejected. A W-decay muon candidate is required to be identified in both the ID and the MS subsystems and to have $p_T > 20$ GeV and $|\eta| < 2.4$. To increase the robustness against track mis-reconstruction, the difference between the ID and MS p_T measurements is required to be less than 15 GeV [41].

To reduce background from multi-jet events, electron and muon candidates are required to satisfy an isolation criterion: the sum of the p_T of all tracks in a cone of $\Delta R = 0.4$ around the electron (muon) divided by the electron (muon) p_T is required to be less than 0.3 (0.2).

W boson candidates are required to have missing transverse momentum $E_T^{\text{miss}} \geqslant 25$ GeV and exactly one isolated electron or muon. Events with two or more isolated same-flavor leptons are rejected, substantially reducing the background from Drell–Yan production.

The lepton candidate from the W boson decay is required to match the object that satisfies the trigger selection criteria: the distance between the trigger object and the reconstructed $W \to \ell\nu$ ($\ell = e/\mu$) lepton is required to be $\Delta R < 0.1$.

To reduce the background from cosmic rays, heavy-flavor production and photon conversions, the W candidate is required to originate from the primary vertex. In events with multiple vertices along the beam axis, the vertex with the largest $\sum p_T^2$, where the sum is over all tracks associated with the vertex, is taken to be the primary vertex of the event. The longitudinal and transverse impact parameters of the charged-lepton track with respect to the primary vertex must be less than 10 and 0.1 mm, respectively.

5.2. Electron-jet pair selection

In this search, the signature of the Higgs boson decay is two or more electron-jets. Electron-jet candidates are formed from jets reconstructed in the calorimeters using an anti-k_t jet clustering algorithm [50] with a radius parameter $R = 0.4$.

The electrons in an electron-jet are too closely collimated to be identified efficiently with the algorithm used to identify electrons from W boson decays. Instead, electron-jets are identified with three discriminating observables, which are described in detail below: the jet electromagnetic fraction (f_{EM}), the jet charged particle fraction (f_{CH}) and the fraction of high-threshold hits originating from transition radiation in the TRT (f_{HT}).

In electron-jets, the electrons typically deposit all of their energy in the electromagnetic calorimeter, so that the fraction of the jet energy deposited in the electromagnetic calorimeter divided by the total jet energy deposited in both the electromagnetic and hadronic calorimeters, f_{EM}, is typically close to unity. The slight degradation of f_{EM} toward lower values is due to the occasional leakage of electromagnetic showers into the hadronic calorimeter, calorimeter noise and electron-jets overlapping with ordinary jets. Hadronic jets reaching the calorimeters mainly consist of $\pi^\pm$ and photons from π^0 decays. Most $\pi^\pm$ deposit a sizable fraction of their energy in the hadronic calorimeter, while photons deposit almost all their energy in the electromagnetic calorimeter. The distribution of f_{EM} is further broadened by fluctuations of the electromagnetic and hadronic showers in the detector. The pedestal corrections for noise in the hadronic calorimeter can sometimes lead to reconstructed energies in the hadronic calorimeter that are less than zero, resulting in a value of f_{EM} slightly higher than unity. The simulation models this situation accurately. The distribution of f_{EM} for hadronic jets peaks around 0.85, with a few per cent of these jets having $f_{EM} \geqslant 0.99$.

Since f_{EM} only provides limited background rejection additional variables are exploited. The quantity f_{CH} is defined as the fraction of the jet energy deposited in calorimeter cells that are associated with tracks within the jet:

$$f_{CH} = \frac{\sum_{\text{'track-cells'}} E^{\text{cell}}}{E^{\text{jet}}}. \tag{1}$$

A track is associated with a jet if it is within a distance of $\Delta R = 0.4$ from the jet axis and has $p_T \geqslant 400\,\text{MeV}$. The 'track-cells', i.e. calorimeter cells associated with tracks within the jet, consist of the cells within a cone of $\Delta R = 0.2$ around each of the tracks associated with the jet, giving the sum of energy deposits of charged particles within the jet in both the electromagnetic and hadronic calorimeters.

Signal electron-jets consist exclusively of electrons and should have large f_{EM} and f_{CH}. Hadronic jets with large f_{EM} are expected to contain mostly neutral pions decaying to photons and, therefore, fewer charged tracks and low f_{CH}. Photons that convert to electron–positron pairs in the material they traverse before entering the calorimeter increase the value of f_{CH}.

Additional rejection of hadronic jets is achieved by exploiting the identification of electrons using transition radiation. The discriminating quantity is the fraction of TRT hits on a track, f_{HT}, that exceed the high discriminator threshold in the read-out electronics of the TRT straws. Detailed studies of this quantity are reported in [46, 51]. This high-threshold setting corresponds to the size of the large energy deposit from transition radiation in the straw-tube gas. The distribution of f_{HT} for tracks from electrons has a maximum at $f_{HT} \sim 0.2$, while it peaks at zero and then decreases monotonically for charged hadron tracks. A requirement that $f_{HT} \geqslant 0.08$ has an efficiency of over 95% for electrons in the momentum range relevant to this analysis and at the same time effectively rejects charged hadrons. Exploiting the selection criteria described above, a jet is classified as an electron-jet if it satisfies the following requirements:

- jet pseudorapidity $|\eta| \leqslant 2.0$,
- jet transverse momentum $p_T \geqslant 30\,\text{GeV}$,
- jet electromagnetic fraction $f_{EM} \geqslant 0.99$,
- jet charged particle fraction $f_{CH} \geqslant 0.66$ and
- number of tracks associated with the jet $N_{track} \geqslant 2$, where the tracks must satisfy the following criteria:

  – track pseudorapidity $|\eta| \leqslant 2.0$,
  – track transverse momentum $p_T \geqslant 5\,\text{GeV}$,
  – number of hits in the pixel detector $N_{PIX} \geqslant 2$,
  – total number of pixel and SCT hits $N_{PIX} + N_{SCT} \geqslant 7$,
  – fraction of high-threshold TRT hits $f_{HT} \geqslant 0.08$.

Good agreement is observed between data and MC simulation in the f_{EM}, f_{CH} and track-related distributions at the different stages of selection, as can be seen in figure 2. The number of events observed in the data and the yields expected for the background and the signal as the selection criteria are applied are shown in table 2. The background yield given here is determined by MC.

6. Background estimation

The dominant background in this search is due to the associated production of a W boson with hadronic jets which mimic the electron-jet signature. Detailed MC studies of the background contamination from hadronic jets faking electron-jets have shown that the high electron content in those jets originates either from final-state photon radiation or from π^0 decays with subsequent photon conversions in the material of the detector. A background prediction from MC simulation would depend on the modeling of final-state photon radiation and parton showering and hadronization, which would introduce large uncertainties in the background rate. Instead, the background contamination in the signal region is estimated from the data using a simplified matrix method [52] which is completely data-driven. Two alternative background estimates were tried and found to be consistent with the matrix method result. One of these estimates—referred to as the ABCD method below—is based on data; the second estimate is based on MC simulation.
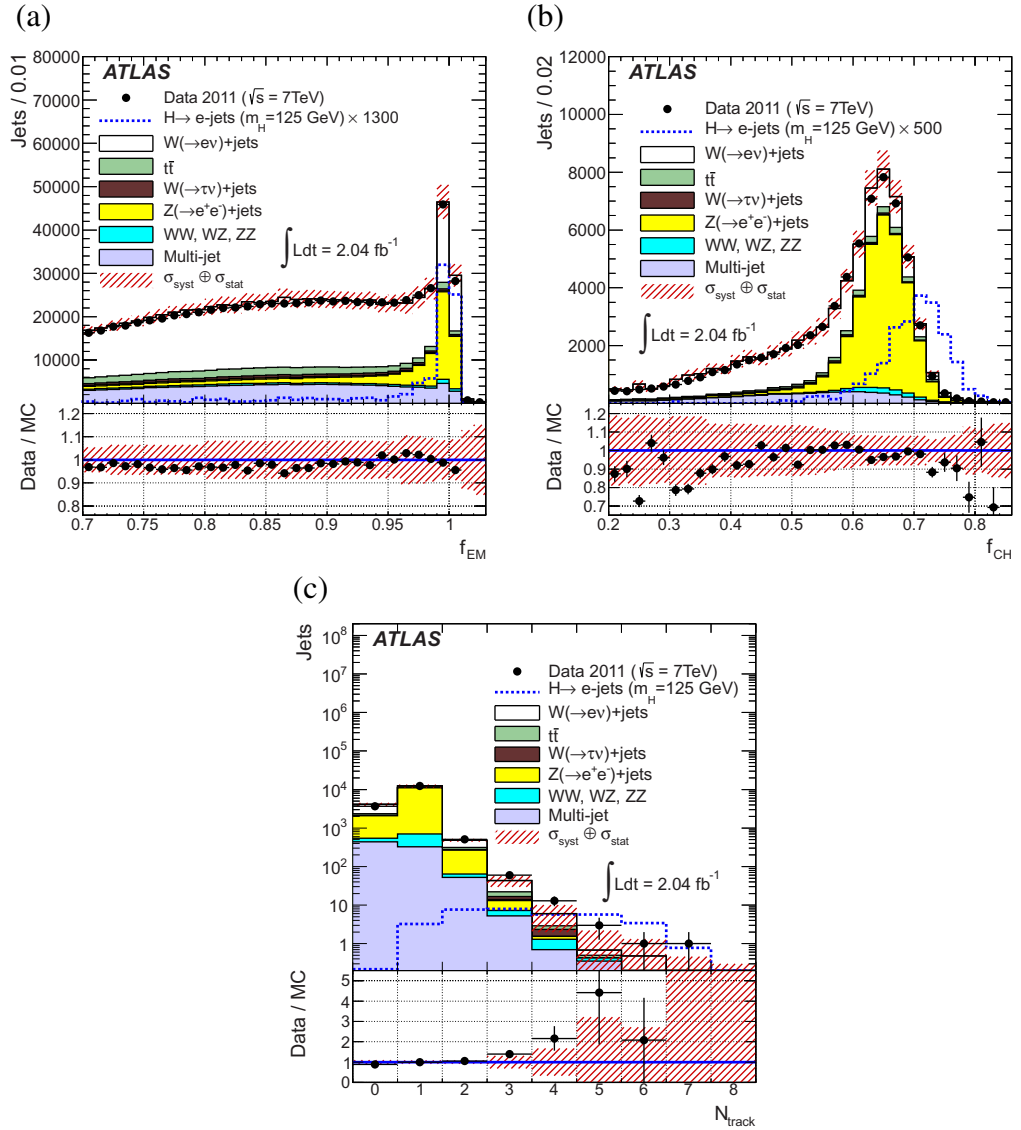
Figure 2. Distribution of the jet electromagnetic fraction, f_{EM}, after the $W \rightarrow e\nu$ selection (a), the jet charged particle fraction, f_{CH}, after the f_{EM} selection (b) and the number of associated tracks, N_{track}, fulfilling the criteria of section 5.2 after the f_{EM} and f_{CH} selection (c). Data are shown by dots with error bars and are compared to the expectation from SM processes, given by stacked histograms of different colors. The signal distributions in the three-step model of a hidden sector with dark photon mass $m_{\gamma_d} = 100$ MeV are presented as dashed histograms with arbitrary scale (a and b) and with the nominal scale (c), where nominal scale implies the SM value for WH production cross section and 100% branching ratio of a Higgs boson decaying to electron-jets. The hatched bands represent the quadratic sum of statistical and systematic uncertainties of the SM background prediction described in section 7.

Table 2. The expected number of background and signal events in $2.04\,\text{fb}^{-1}$ of data, as well as the number of events observed in the data, after applying the various signal selection criteria for the $W \to e\nu$ and $W \to \mu\nu$ channels. The '$\geqslant 2$ jets' in the first column denotes the requirement of two or more jets per event, satisfying the corresponding selection criteria. The signal predictions correspond to the three-step model with $m_\text{H} = 125\,\text{GeV}$ and $m_{\gamma_\text{d}} = 100\,\text{MeV}$. The signal efficiencies are the fraction of signal events satisfying all the selection criteria up to and including that particular criterion. They are given with respect to the signal sample including all three decay modes of the W boson ($e\nu_\text{e}$, $\mu\nu_\mu$, $\tau\nu_\tau$). The background expectations include statistical and systematic uncertainties, and are determined using the MC method (see section 6). The statistical uncertainty shown for the signal is due to MC statistics; the systematic uncertainty is only given for the final event selection and its detailed composition is given in table 4.

		Data	Expected background	Expected signal, $m_\text{H} = 125\,\text{GeV}$	Eff.
				$W \to e\nu$ channel	
$W \to e\nu$ selection		4 351 732	$4\,330\,000 \pm 250\,000$	$46.7 \pm 1.8^{(\text{stat})}$	13%
	$p_\text{T} \geqslant 30\,\text{GeV}$,				
	$|\eta| \leqslant 2.0$	173 551	$183\,000 \pm 16\,000$	$25.6 \pm 1.4^{(\text{stat})}$	7.1%
$\geqslant 2$ jets	$f_\text{EM} \geqslant 0.99$	837	1070 ± 200	$10.8 \pm 0.9^{(\text{stat})}$	3.0%
	$f_\text{CH} \geqslant 0.66$	39	35 ± 8	$6.3 \pm 0.7^{(\text{stat})}$	1.7%
	$N_\text{track} \geqslant 2$	0	$0.10^{+0.11}_{-0.10}$	$5.3 \pm 0.6^{(\text{stat})} \pm 0.4^{(\text{syst})}$	1.5%
				$W \to \mu\nu$ channel	
$W \to \mu\nu$ selection		8 870 713	$8\,620\,000 \pm 350\,000$	$60.3 \pm 2.3^{(\text{stat})}$	17%
	$p_\text{T} \geqslant 30\,\text{GeV}$,				
	$|\eta| \leqslant 2.0$	326 956	$353\,000 \pm 33\,000$	$31.5 \pm 1.7^{(\text{stat})}$	8.8%
$\geqslant 2$ jets	$f_\text{EM} \geqslant 0.99$	1008	1240 ± 180	$13.9 \pm 1.2^{(\text{stat})}$	3.9%
	$f_\text{CH} \geqslant 0.66$	45	41 ± 16	$7.5 \pm 0.9^{(\text{stat})}$	2.1%
	$N_\text{track} \geqslant 2$	1	$0.11^{+0.13}_{-0.11}$	$6.0 \pm 0.8^{(\text{stat})} \pm 0.4^{(\text{syst})}$	1.7%

In the matrix method, one defines a 'loose' electron-jet selection criterion by relaxing the minimum track p_T requirement from 5 to 2 GeV. The fraction f is the ratio of the number of jets passing the nominal signal selection N_T to that passing the loose selection N_L:

$$f = \frac{N_\text{T}}{N_\text{L}}. \tag{2}$$

The number of fake electron-jet background events passing the nominal selection criteria for two electron-jet candidates and entering the signal region is therefore

$$n_\text{bkgd} = f^2 n_\text{fake}, \tag{3}$$

where n_fake is the number of background events passing the loose criterion for both electron-jet candidates. On the other hand, the number of fake electron-jet events in which neither

electron-jet candidate passes the nominal selection criterion is

$$n_{\text{loose}} = (1 - f)^2 n_{\text{fake}}.\tag{4}$$

Combining equations (3) and (4) yields

$$n_{\text{bkgd}} = \frac{f^2}{(1 - f)^2} n_{\text{loose}} = \bar{f}^2 n_{\text{loose}},\tag{5}$$

where $\bar{f}$ is referred to below as the fake factor. In this way the number of background events is derived directly from the data events failing to pass the nominal criteria for both electron-jet candidates (n_{loose}), where the signal contamination has been checked to be small.

The fake factor $\bar{f}$ is measured from background-enriched data samples where the signal contamination is checked to be completely negligible. The first sample is obtained by reversing the W-candidate electron or muon selection criteria to select a sample of multi-jet background with kinematic characteristics similar to those of the signal sample. A fake factor is obtained from the jets in this sample. In the second sample, the fake factor is determined from a sample of jets that originate from electrons in $Z \to e^+e^-$ decays. The tight selection criteria and the lepton isolation criteria are applied to one leg of the Z boson candidate, and the invariant mass of this electron and the candidate jet, $m_{\text{e,jet}}$, is required to fall in the range $80\,\text{GeV} < m_{\text{e,jet}} < 100\,\text{GeV}$. The two fake factors are found to be consistent within statistical uncertainties: 0.44 ± 0.02 (stat) and 0.47 ± 0.03 (stat), respectively. The first value is used in the analysis and the difference between these two estimates is taken as a systematic uncertainty in the fake factor. The resulting value is $\bar{f} = 0.44 \pm 0.04$, where the uncertainty is the sum of the statistical and systematic uncertainties added in quadrature.

In the ABCD method used to cross-check the results, events are assigned to one of four regions according to whether or not the jets meet the f_{EM} and the track-quality conditions of the electron-jet classification. These two conditions are chosen because they are less correlated than other selection variables that could have been used. The background yield in the signal region is thus given by

$$n_{\text{bkgd}} = N_{\text{A}}^{\text{predicted}} = \frac{N_{\text{B}} N_{\text{C}}}{N_{\text{D}}} c_{\text{MC}} ,\tag{6}$$

where $c_{\text{MC}} = 0.36$ is the correction factor determined from MC simulation that corrects for the effect of the correlations between the two selection criteria. N_i is the number of events observed in region i.

The regions are defined as:

(A) *Signal region*. Two jets with $f_{\text{EM}} \geqslant 0.99$ are required; for both jets $N_{\text{track}} \geqslant 2$, i.e. the number of tracks associated with the candidate jets and fulfilling the requirements of the electron-jet selection must be greater than two (see section 5.2).

(B) *Anti-track quality region*. At least one jet must fail the associated track requirements of the electron-jet selection. Each of the two candidate jets must have two associated tracks separated by $\Delta R < 0.1$, both tracks satisfying looser requirements $p_{\text{T}} \geqslant 2\,\text{GeV}$ and $f_{\text{HT}} > 0$. At least one of these tracks must fail the requirement $f_{\text{HT}} > 0.08$.

(C) *Anti-f_{EM} region*. At least one jet must fail the condition $f_{\text{EM}} \geqslant 0.99$.

(D) *Anti-track quality and anti-f_{EM} region*. Both conditions (B) and (C) are fulfilled.

Table 3. Estimated number of background events after the final selection, including statistical and systematic uncertainties, from three different methods. The matrix method is used for the background estimate while the ABCD and MC methods provide a cross-check of the matrix method.

Method of background estimation		Estimated background yield
Matrix	(baseline)	0.41 ± 0.29 (stat) ± 0.12 (syst)
ABCD	(cross-check)	0.46 ± 0.32 (stat) ± 0.10 (syst)
MC	(cross-check)	0.21 ± 0.05 (stat) $^{+\,0.23}_{-\,0.21}$ (syst)

Table 4. Systematic uncertainties for the signal. The numbers in parentheses refer to the descriptions in the numbered list in the text. All uncertainties are applied to the combination of $W \to e\nu$ and $W \to \mu\nu$ channels; the only exceptions are the specific electron and muon uncertainties in items (iv) and (vii), and are applied separately. The total uncertainty is conservatively rounded and is given for the combination of channels.

	Systematic source	Systematic uncertainty (%)
(i)	MC statistics	13
(ii)	Luminosity	3.7
(iii)	$\sigma \times \mathrm{BR}$	$^{+3.7}_{-4.3}$
(iv)	Electron efficiency	5
(iv)	Muon efficiency	3
(v)	f_{EM} modeling	3
(v)	f_{CH} modeling	0.1
(vi)	f_{HT} modeling	1
(vii)	Electron energy scale	0.5
(vii)	Electron energy resolution	0.2
(vii)	Muon momentum resolution	0.5
(viii)	Pile-up	< 0.1
	Total	15

In the second cross-check of the matrix method, the background prediction is obtained by using data templates and simulated samples with the appropriate cross sections scaled by the measured integrated luminosity, as described in section 3.

The resulting background yields, together with the evaluated statistical and systematic uncertainties, are given in table 3. The estimates from the different background evaluation methods agree well within the uncertainties.

7. Systematic uncertainties

The systematic uncertainties considered for the signal are given in table 4 and described in detail below:

  (i) *MC statistics.* The uncertainty due to the limited number of MC signal events is 13%.

  (ii) *Luminosity*. The uncertainty in the integrated luminosity is determined to be 3.7% [48, 49].

(iii) *Signal cross sections.* The uncertainty of the SM *WH* production cross section at Higgs mass $m_H = 125$ GeV is $^{+3.7\%}_{-4.3\%}$ [53]. For 100 and 140 GeV Higgs mass the corresponding uncertainties are $\pm 4\%$ [53].

(iv) *Electron and muon efficiency.* The combined uncertainty on the efficiency of the lepton trigger, identification and isolation as well as transverse impact parameter requirements is found to be 5% for electrons and 3% for muons. The uncertainties were derived using data-driven methods [46, 47].

(v) *Jet electromagnetic and charged particle fractions (f_{EM} and f_{CH}).* The uncertainty due to possible mismodeling of these parameters, which impacts the signal acceptance, are studied by comparing the measured f_{EM} and f_{CH} line shape for jets, which are matched to electron from *W*-decay, to the one predicted by the simulation. They are found to be 3 and 0.1% for f_{EM} and f_{CH}, respectively.

(vi) *Fraction of high-threshold hits in the TRT (f_{HT}).* Mismodeling of the f_{HT} distribution in the simulation has been previously studied [46, 51]. The impact of this mismodeling on the signal efficiency was checked using the data samples, enriched with highly collimated pairs of electron tracks, and is found to be less than 1%.

(vii) *Electron and muon energy/momentum scale and resolution.* These uncertainties are evaluated by varying the corresponding correction factors, described in section 5.1, within their systematic uncertainties. This results in the corresponding uncertainties of 0.2, 0.5 and 0.5% for electron/muon energy resolution and electron energy scale respectively.

(viii) *Pile-up impact.* The effect of additional inelastic collisions overlapping with the primary hard scatter (pile-up) on the signal efficiency has been evaluated using simulated signal samples and found to be negligible.

The systematic uncertainties on the background determinations are estimated in the following ways:

- *Matrix method.* The uncertainty is assessed by varying the fake factor within its uncertainty and is summed in quadrature with the statistical uncertainty on the number of events observed in the loose region. An uncertainty due to possible signal contamination is also taken into account. These result in an 80% uncertainty in the background yield.

- *ABCD method.* The uncertainty is assessed by employing different region selections in the ABCD method and the difference between yields is treated as a systematic uncertainty. The uncertainty due to limited statistics in region B is also considered. The resulting uncertainty in the background yield is 70% with this method.

- *MC method.* The largest contributions to the uncertainty on the background yield are the systematic uncertainty on the MC-based prediction on the probability of two or more jets to be incorrectly identified as electron-jets (100%), modeling of f_{HT} (50%), f_{CH} (10%), f_{EM} (10%), the choice of MC generator (10%) and uncertainties on the cross section for multi-jet processes (10%). The assigned theoretical uncertainties on the cross sections are 4% ($W \to \ell\nu$, $Z \to \ell\ell$), 5% ($W \to \tau\nu$, $Z \to \tau\tau$, WZ/ZZ) and 7% ($t\bar{t}$, WW), respectively [41, 42]. Limited MC sample sizes contributes a 5% uncertainty. The total uncertainty of background estimation with MC method is 110%.

Table 5. Numbers of expected and observed events after final selection. Expected signal yields are provided for both the three-step and two-step models with dark photon masses of 100 and 200 MeV. Statistical (first) and systematic (second) uncertainties are presented separately. The results are given for the combination of the $W \to e\nu$ and $W \to \mu\nu$ channels. One candidate event is observed in the data in the $W \to \mu\nu$ channel.

Signal	Three-step model		Two-step model	
m_H (GeV)	$m_{\gamma_d} = 100$ MeV	$m_{\gamma_d} = 200$ MeV	$m_{\gamma_d} = 100$ MeV	$m_{\gamma_d} = 200$ MeV
100	$14.3 \pm 1.7 \pm 0.8$	$12.4 \pm 1.6 \pm 0.7$	$22.6 \pm 2.1 \pm 1.2$	$23.5 \pm 2.1 \pm 1.2$
125	$11.3 \pm 1.0 \pm 0.6$	$10.7 \pm 1.1 \pm 0.6$	$16.2 \pm 1.2 \pm 0.9$	$18.1 \pm 1.4 \pm 1.0$
140	$9.6 \pm 0.8 \pm 0.5$	$9.0 \pm 0.8 \pm 0.4$	$13.7 \pm 0.9 \pm 0.8$	$13.9 \pm 0.9 \pm 0.8$
Background	$0.41 \pm 0.29 \pm 0.12$			
Data	1			
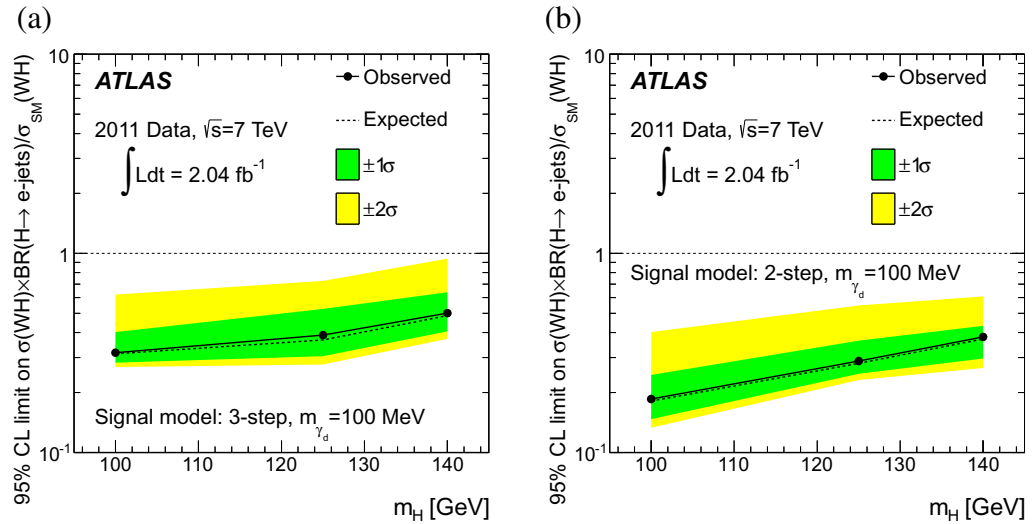
Figure 3. Observed and expected 95% CL upper limits on the signal strength, $\sigma(WH) \times \mathrm{BR}(H \to e\text{-jets})/\sigma_{\mathrm{SM}}(WH)$, as a function of the Higgs boson mass for the (left) three-step and (right) two-step models of a hidden sector with a dark photon mass $m_{\gamma_d} = 100$ MeV. The dark (light) shaded band contains 68% (95%) of the outcomes of pseudo-experiments generated under the background-only hypothesis.

8. Results and interpretation

The observed and predicted event yields after the final selection are shown in table 5. The event yield in the signal region is consistent with the background-only hypothesis, with one data event passing the final selection in the $W \to \mu\nu$ channel and no data events passing the final selection in the $W \to e\nu$ channel.

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Table 6. The 95% confidence level (CL) upper limits on the signal strength, $\sigma(WH) \times \mathrm{BR}(H \to e\text{-jets})/\sigma_{\mathrm{SM}}(WH)$, for a Higgs boson mass of 125 GeV for different choices of the hidden-sector model parameters. Here, $\sigma(WH)$ is the WH production cross section times the sum of the branching ratios for the W boson decaying to leptons ($e\nu_e$, $\mu\nu_\mu$, $\tau\nu_\tau$), $\sigma_{\mathrm{SM}}(WH)$ is the corresponding SM expectation and $\mathrm{BR}(H \to e\text{-jets})$ is the branching ratio for Higgs boson decays to electron-jets.

Model	m_{γ_d} (MeV)	Observed	Expected
Three-step	100	0.39	0.37
Three-step	200	0.45	0.44
Two-step	100	0.29	0.28
Two-step	200	0.24	0.24

Consequently one estimates a 95% confidence limit on the signal strength, $\sigma(WH) \times \mathrm{BR}(H \to e\text{-jets})/\sigma_{\mathrm{SM}}(WH)$, where $\sigma(WH)$ denotes the WH production cross section times the sum of the branching ratios for the W boson decaying to leptons ($e\nu_e$, $\mu\nu_\mu$, $\tau\nu_\tau$) and $\sigma_{\mathrm{SM}}(WH)$ is the corresponding SM expectation [53] for this quantity ($\sigma_{\mathrm{SM}}(WH) = 223^{+8}_{-10}$ fb for the Higgs boson mass of 125 GeV). $\mathrm{BR}(H \to e\text{-jets})$ denotes the branching ratio for Higgs boson decays to electron-jets. The results are presented in figure 3 and table 6 for both the three-step and two-step models. Only one limit is presented in figure 3 for each of the two-step and three-step models, because the results are compatible within the statistical uncertainty of the signal for both dark photon masses $m_{\gamma_d} = 100$ and 200 MeV. Limits are derived using the CLs technique [54]. The likelihoods are given by the Poisson distribution for the total number of events in the signal region and are calculated using the number of expected and observed events, whereby the results of the electron and muon channels are summed and enter the likelihood function together. The corresponding signal and background systematic uncertainties are incorporated into the likelihoods as nuisance parameters with Gamma probability density functions [55]. Assuming that the WH cross section has the SM value, for the specific set of hidden-sector parameters chosen here, the analysis excludes Higgs boson branching ratios to electron-jets between 24 and 45% for $m_\mathrm{H} = 125$ GeV at 95% CL.

9. Conclusions

A search is presented for a light Higgs boson decaying to a light hidden sector and subsequently into highly collimated jets of electrons, which are expected to be seen in the detector as distinct objects called 'electron-jets'. The analysis has been performed using 2.04 fb^{-1} of proton–proton collision data at $\sqrt{s} = 7$ TeV, collected with the ATLAS detector at the LHC in 2011.

The search is performed in the WH production mode with the choice of hidden-sector parameter space resulting in Higgs boson decaying into prompt electron-jets. The electron-jet identification method presented here provides good discrimination against background sources and avoids sensitivity to the detailed topology of the electrons within the electron-jet.

The observed data are consistent with the SM background hypothesis. Consequently, 95% CL limits are set on the WH production cross section times the branching ratio into electron-jets,

assuming the two benchmark models of a hidden sector and the condition of a dark photon mass below 210 MeV.

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