Search for a light Higgs boson decaying to long-lived weakly interacting particles in proton-proton collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector


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A search for the decay of a light Higgs boson (120–140 GeV) to a pair of weakly interacting, long-lived particles in 1.94 fb$^{-1}$ of proton-proton collisions at $\sqrt{s} = 7$ TeV recorded in 2011 by the ATLAS detector is presented. The search strategy requires that both long-lived particles decay inside the muon spectrometer. No excess of events is observed above the expected background and limits on the Higgs boson production times branching ratio to weakly interacting, long-lived particles are derived as a function of the particle proper decay length.

Consequently the experimental challenge is to develop signature-driven triggers to select displaced decays throughout the ATLAS detector volume [13].

This analysis requires both $\pi_\nu$ decays to occur near the outer radius of the hadronic calorimeter ($r \sim 4$ m) or in the muon spectrometer (MS). Such decays give a ($\eta, \phi$) cluster of charged and neutral hadrons in the MS. Requiring both $\pi_\nu$’s to have this decay topology improves background rejection. The analysis uses specialized tracking and vertex reconstruction algorithms, described below, to reconstruct vertices in the MS. The analysis strategy takes advantage of the kinematics of the gluon fusion production mechanism and subsequent two-body decay, $h^0 \rightarrow \pi_\nu\pi_\nu$, which results in events with back-to-back $\pi_\nu$’s, by requiring two well-separated vertices [$\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2} > 2$] [14] in the MS.

The data used in this analysis were collected in the first half of 2011 with the LHC operating at 7 TeV. Applying beam, detector, and data quality requirements resulted in a total integrated luminosity of 1.94 fb$^{-1}$. The integrated luminosity has a relative uncertainty of 3.7% [15,16].

Signal Monte Carlo (MC) samples were generated using PYTHIA [17,18] to simulate gluon fusion production ($gg \rightarrow h^0$) and the decay of the Higgs boson ($h^0 \rightarrow \pi_\nu\pi_\nu$). Four samples were generated: $m_{h^0} = 120$ and 140 GeV and for each $m_{h^0}$, two $\pi_\nu$ masses of 20 and 40 GeV. The predicted Higgs boson production cross sections [19] are $\sigma(m_{h^0} = 120 \text{ GeV}) = 16.6^{+3.3}_{-2.5}$ pb and $\sigma(m_{h^0} = 140 \text{ GeV}) = 12.1^{+2.1}_{-1.8}$ pb, and the branching ratio (BR) for $h^0 \rightarrow \pi_\nu\pi_\nu$ is assumed to be 100%. The response of the ATLAS detector was modeled with GEANT4 [20,21].

The effect of multiple $pp$ collisions occurring during the same bunch crossing (pileup) was simulated by superimposing several minimum bias events on the signal event. The MC events were weighted so that the pileup in the simulation agrees with pileup conditions found in data.

ATLAS is a multipurpose detector [22] consisting of an inner tracking detector (ID) surrounded by a superconducting...
solenoid that provides a 2 T field, electromagnetic and hadronic calorimeters and a MS with a toroidal magnetic field. The ID, consisting of silicon pixel and strip detectors and a straw tube tracker, provides precision tracking of charged particles for $|\eta| \leq 2.5$. The calorimeter system covers $|\eta| \leq 4.9$ and has 9.7 interaction lengths at $\eta = 0$. The MS consists of a barrel and two forward spectrometers, each with 16 $\phi$ sectors instrumented with detectors for first level triggering and precision tracking detectors for muon momentum measurement. Each spectrometer has three stations along the muon flight path: inner, middle, and outer. In the barrel, the stations are located at radii of $\sim 4.5$, 7, and 10 m, while in the forward MS, they are located at $|z| \sim 7.5$, 14, and 20 m. This analysis uses muon tracking for $|\eta| \leq 2.4$, where each station is instrumented with two multilayers of precision tracking chambers, monitored drift tubes (MDTs). It also utilizes level 1 [23] (L1) muon triggering in the barrel MS ($|\eta| \leq 1$). The trigger chambers are located in the middle and outer stations. The L1 muon trigger requires hits in the middle station to create a low $p_T$ muon region of interest (RoI) or hits in both the middle and outer stations for a high $p_T$ RoI. The muon RoIs have a spacial extent of $0.2 \times 0.2$ in $\Delta \eta \times \Delta \phi$ and are limited to two RoIs per sector.

A dedicated, signature-driven trigger, the muon RoI cluster trigger [13], was developed to trigger on events with a $\pi^\nu$ decaying in the MS. It selects events with a cluster of three or more muon RoIs in a $\Delta R = 0.4$ cone in the MS barrel trigger chambers. This trigger configuration implies that one $\pi^\nu$ must decay in the barrel spectrometer, while the second $\pi^\nu$ may decay either in the barrel or the forward spectrometer. With this trigger, it is possible to trigger on $\pi^\nu$ decays at the outer radius of the hadronic calorimeter and in the MS with high efficiency. The backgrounds of punch-through jets [24] and muon bremsstrahlung are suppressed by requiring no calorimeter jets with $E_T \geq 30$ GeV in a cone of $\Delta R = 0.7$ and no ID tracks with $p_T \geq 5$ GeV within a region of $\Delta \eta \times \Delta \phi = 0.2 \times 0.2$ around the RoI cluster center. This isolation criteria result in a negligible loss in the simulated signal while significantly reducing the backgrounds.

As depicted in Fig. 1(a) [25], MC studies show the RoI cluster trigger is $\sim 30\%$–$50\%$ efficient in the region from 4 to 7 m. The $\pi^\nu$’s that decay beyond a radius of $\sim 7$ m do not leave hits in the trigger chambers located at $\sim 7$ m, while the $\pi^\nu$ decays that occur before $r \sim 4$ m are located in the calorimeter and do not produce sufficient activity in the MS to pass the muon RoI cluster trigger. The $m_\phi = 120$ GeV and $m_n = 40$ GeV sample has a relatively lower efficiency because the $\pi^\nu$’s have a lower boost and arrive later at the MS. As a result, the trigger signal may be associated with the incorrect bunch crossing, in which case the event is lost.

The systematic uncertainty of the muon RoI cluster trigger efficiency is evaluated on data using a sample of events containing a punch-through jet. This sample of events is similar to signal events as it contains both low energy photons and charged hadrons in a localized region of the MS. These punch-through jets are selected to be in the barrel calorimeter ($|\eta| \leq 1.4$), have $E_T \geq 20$ GeV, have at least four tracks in the ID, each with $p_T \geq 1$ GeV, and have at least 20 GeV of missing transverse momentum aligned with the jet. To ensure significant activity in the MS, the jet is required to contain at least 300 MDT hits in a cone of $\Delta R = 0.6$, centered around the jet axis [26]. The muon RoI cluster trigger algorithm was run in the vicinity of the punch-through jet for both data and MC events. The distribution of RoIs contained in the cluster for data and MC events, normalized to the number of data events, is shown in Fig. 2. The shapes of the distribution match well between data and MC events. A horizontal line fit to the ratio, as a function of $N_{RoI} \geq 1$, yields $1.14 \pm 0.09$, and 14% is taken as the systematic uncertainty. The effects of uncertainties in the jet energy scale (JES) [27], in the initial state radiation (ISR) spectrum [28], and in the amount of pileup were found to be
negligible when varying these quantities by their uncertainties.

A specialized tracking and vertex reconstruction algorithm was developed to identify $\pi_\nu$'s that decay inside the MS. The decay of a $\pi_\nu$ results in a high multiplicity of low $p_T$ particles ($1 \leq p_T \leq 5$ GeV) containing $\sim 10$ charged particles and $\sim 5$ $\pi^0$'s clustered in a small $\Delta R$ region of the spectrometer. The $\pi_\nu$'s that decay before the last sampling layer of the hadronic calorimeter do not produce a significant number of tracks in the MS. Thus, detectable decay vertices must be located in the region between the outer radius of the hadronic calorimeter and the middle station of the MS. Over a wide range of acceptance in the barrel MS, the total amount of material traversed is roughly 1.3 radiation lengths [22]; therefore, as a consequence of the $\sim 5$ $\pi^0$'s produced in signal events, large electromagnetic showers accompany the $\sim 10$ charged particles from $\pi_\nu$ decays. The resulting MS environment contains, on average, approximately 800 MDT hits, of which $\sim 75\%$ are from the electromagnetic showers.

The design of the muon chambers [22] is exploited in order to reconstruct tracks in this busy environment. The separation of the two multilayers inside a single muon chamber provides a powerful tool for track pattern recognition. This separation provides enough of a lever arm to allow, in the barrel, a momentum measurement with acceptable resolution for tracks up to approximately 10 GeV [29]. In the forward spectrometers, the muon chambers are outside the magnetic field region; therefore, it is not possible to measure the track momentum inside of a single chamber. In both cases, the tracklets used in the vertex reconstruction are formed using hits in single muon chambers.

The MS vertex algorithm begins by grouping the tracklets using a simple cone algorithm with $\Delta R = 0.6$. In the barrel, the tracklets are extrapolated through the magnetic field, and the vertex position is reconstructed as the point in $(r, z)$ that uses the largest number of tracklets to reconstruct a vertex with a $\chi^2$ probability greater than 5%. In the forward spectrometer, the reconstructed tracklets do not have a measurement of the momentum; therefore, the vertex is found using a least squares regression that assumes the tracklets are straight lines. Vertices are required to be reconstructed using at least three tracklets, point back to the interaction point (IP) [30] and have $|\eta| \leq 2.2$. After requiring the MS vertex to be separated from ID tracks with $p_T \geq 5$ GeV and jets with $E_T \geq 15$ GeV by $\Delta R = 0.4$ and $\Delta R = 0.7$, respectively, the algorithm has an efficiency of $\sim 40\%$ in signal MC events throughout the barrel region ($4 \leq r \leq 7.5$ m) and a resolution of 20 cm in $z$, 32 cm in $r$, and 50 mrad in $\phi$. In the forward spectrometer, the algorithm is $\sim 40\%$ efficient in the region $8 \leq |z| \leq 14$ m. Figure 1(b) [25] shows the vertex reconstruction efficiency for the barrel reconstruction algorithm in MC signal events that passed the muon RoI cluster trigger.

The MC description of hadrons and photons in the MS was validated on the same sample of events containing a punch-through jet used to evaluate the trigger performance. The fraction of these jets that produce a MS vertex was compared in data and QCD dijet MC events. Table I shows the fraction of punch-through jets that produce a vertex in data and MC events as a function of the number of MDT hits in a cone of $\Delta R = 0.6$ around the jet axis. The data-to-MC ratio is fit to a flat distribution that yields a ratio consistent with unity with a 15% statistical uncertainty, which is taken to be the systematic uncertainty in the vertex reconstruction efficiency. The systematic uncertainties arising from the JES, ISR spectrum, and the amount of pileup were estimated by varying these quantities by their uncertainties and calculating the change in the vertex reconstruction efficiency. The total systematic uncertainty of 16% for the efficiency of reconstructing a vertex is the sum in quadrature of the uncertainties in the efficiency of the isolation criteria due to varying the JES, ISR, and pileup (3%, 3%, and 2%, respectively) and the uncertainty in comparing data and MC events (15%).

The final event selection requires two good MS vertices separated by $\Delta R > 2$. The background due to events with two jets, both of which punch through the calorimeter, is a negligible contribution to the total background due to the tight isolation criteria applied to each vertex. The background is calculated using a fully data-driven method by

<table>
<thead>
<tr>
<th>Number of MDT hits</th>
<th>QCD dijet Monte Carlo</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>$300 \leq N_{\text{MDT}} &lt; 400$</td>
<td>$10.1 \pm 2.2%$</td>
<td>$9.1 \pm 0.5%$</td>
</tr>
<tr>
<td>$400 \leq N_{\text{MDT}} &lt; 500$</td>
<td>$9.2 \pm 2.8%$</td>
<td>$10.5 \pm 0.7%$</td>
</tr>
<tr>
<td>$500 \leq N_{\text{MDT}} &lt; 600$</td>
<td>$13.1 \pm 5.4%$</td>
<td>$13.0 \pm 0.9%$</td>
</tr>
<tr>
<td>$N_{\text{MDT}} \geq 600$</td>
<td>$16.5 \pm 4.5%$</td>
<td>$16.7 \pm 0.7%$</td>
</tr>
</tbody>
</table>
measuring the probability for a random event to contain an MS vertex \((P_{\text{vertex}})\) and the probability of reconstructing a vertex given that the event passed the RoI cluster trigger \((P_{\text{reco}})\). Because \(P_{\text{vertex}}\) and \(P_{\text{reco}}\) are measured in data, they incorporate backgrounds from cosmic showers, beam halo, and detector noise. The background is calculated as

\[
N_{\text{fake}}(2 \text{ MS vertex}) = N(\text{MS vertex, 1 trig}) P_{\text{vertex}} + N(\text{MS vertex, 2 trig}) P_{\text{reco}}.
\]

\(N(\text{MS vertex, 1 trig})\) is the number of events with a single muon RoI cluster trigger object and an isolated MS vertex. \(N(\text{MS vertex, 2 trig})\) is the number of events with an isolated vertex and a second RoI cluster trigger object. The first term in the equation is the expected number of background events with one vertex that randomly contain a second vertex. \(P_{\text{reco}}\) is the probability to reconstruct a vertex given there was an RoI cluster trigger; thus, the second term in the equation is the expected number of events with two RoI clusters that have two vertices in the MS. \(P_{\text{vertex}}\) was measured using zero bias data [31] to be \((9.7 \pm 6.9) \times 10^{-7}\), and \(P_{\text{reco}}\) was measured using the events that pass the muon RoI cluster trigger to be \((1.11 \pm 0.01) \times 10^{-2}\). The expected signal would cause, at most, a relative change in \(P_{\text{reco}}\) of \(-1\%\). \(P_{\text{reco}}\) was also measured using a sample of events recorded when there were no collisions. In this sample of noncollision background events, \(P_{\text{reco}}\) was measured to be \((7.0 \pm 0.6) \times 10^{-3}\). For calculating the background, the larger value of \(P_{\text{reco}}\) \((1.11 \times 10^{-2})\) is taken since it gives a conservative estimate of the background. \(N(\text{MS vertex, 1 trig})\) and \(N(\text{MS vertex, 2 trig})\) are 15 543 and 1, respectively. Therefore, the background is calculated to be \(0.03 \pm 0.02\) events.

No events in the data sample pass the selection requiring two isolated, back-to-back vertices in the muon spectrometer. Since no significant excess over the background prediction is found, exclusion limits for \(\sigma_{h^0} \times \text{BR}(h^0 \rightarrow \pi^0 \pi^0)\) are set by rejecting the signal hypothesis at the 95% confidence level (CL) using the CLs procedure [32]. Figure 3 shows the 95% CL upper limit on \(\sigma_{h^0} \times \text{BR}(h^0 \rightarrow \pi^0 \pi^0)/\sigma_{\text{SM}}\) as a function of the \(\pi^0\) proper decay length \((\tau)\) in multiples of the SM Higgs boson cross section, \(\sigma_{\text{SM}}\). As expected, the Higgs boson and \(\pi^0\) mass combinations with the largest boosts leading to larger \(\beta\gamma\tau\) have the smallest exclusion limits.

In 1.94 fb\(^{-1}\) of \(pp\) collision data at a center-of-mass energy of 7 TeV, there is no evidence of an excess of events containing two isolated, back-to-back vertices in the ATLAS muon spectrometer. Using the model of a light Higgs boson decaying to weakly interacting, long-lived pseudoscalars, limits have been placed on the pseudoscalar proper decay length. Table II shows the broad range of \(\pi^0\) proper decay lengths that have been excluded at the 95% CL, assuming 100% branching ratio for \(h^0 \rightarrow \pi^0 \pi^0\). These limits also apply to models in which the Higgs boson decays to a pair of weakly interacting scalars that, in turn, decay to heavy quark pairs.

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aDeceased.
bAlso at Laboratorio de Instrumentacao e Fisica Experimental de Particulas-LIP, Lisboa, Portugal.
cAlso at Faculdade de Ciencias and CFNUL, Universidade de Lisboa, Lisboa, Portugal.
dAlso at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom.