Search for the Higgs Boson in the $H \rightarrow WW^{(*)} \rightarrow l^+\nu l^-\bar{\nu}$ Decay Channel in $pp$ Collisions at $\sqrt{s} = 7$ TeV with the ATLAS Detector

G. Aad et al.*
(ATLAS Collaboration)
(Received 12 December 2011; published 13 March 2012)

A search for the Higgs boson has been performed in the $H \rightarrow WW^{(*)} \rightarrow \ell^+\nu l^-\bar{\nu}$ channel ($\ell = e/\mu$) with an integrated luminosity of 2.05 fb$^{-1}$ of $pp$ collisions at $\sqrt{s} = 7$ TeV collected with the ATLAS detector at the Large Hadron Collider. No significant excess of events over the expected background is observed and limits on the Higgs boson production cross section are derived for a Higgs boson mass in the range $110 \text{ GeV} < m_H < 300 \text{ GeV}$. The observations exclude the presence of a standard model Higgs boson with a mass $145 < m_H < 206 \text{ GeV}$ at 95% confidence level.

DOI: 10.1103/PhysRevLett.108.111802
PACS numbers: 14.80.Bn, 12.15.Ji, 13.85.Rm, 14.70.Fm

The standard model of particle physics postulates the existence of a complex scalar doublet with a vacuum expectation value, which spontaneously breaks the electroweak symmetry, gives masses to all the massive elementary particles in the theory, and gives rise to a physical scalar known as the Higgs boson [1]. At the LHC, the Higgs boson is expected to be produced mainly through gluon fusion ($gg \rightarrow H$) [2] due to the large gluon density, although vector boson fusion ($q\bar{q} \rightarrow q\bar{q}H$) [3] is also important. Associated production of Higgs bosons ($WH, ZH$) also contributes more than 4% to the total rate for $m_H \leq 135 \text{ GeV}$ [4]. For $m_H > 135 \text{ GeV}$, $H \rightarrow WW^{(*)}$ is the dominant decay mode of the Higgs boson. Direct searches at LEP and the Tevatron exclude a standard model Higgs boson with a mass $m_H < 114.4 \text{ GeV}$ or $156 \text{ GeV} < m_H < 177 \text{ GeV}$ [5] at 95% confidence level (C.L.). The search for $H \rightarrow ZZ \rightarrow \ell^+\ell^-\nu\nu$ at ATLAS excludes a standard model Higgs boson with a mass $340 < m_H < 450 \text{ GeV}$, while the search for $H \rightarrow ZZ \rightarrow 4\ell$ excludes $191 < m_H < 197 \text{ GeV}$, $199 < m_H < 200 \text{ GeV}$, and $214 < m_H < 224 \text{ GeV}$ [6].

This Letter reports the results of a search for the Higgs boson in the channel $H \rightarrow WW^{(*)} \rightarrow \ell^+\nu l^-\bar{\nu}$ [7] ($\ell = e/\mu$, but including contributions from $\tau \rightarrow e/\mu$ decays) in 2.05 fb$^{-1}$ of $pp$ collisions at $\sqrt{s} = 7$ TeV recorded by the ATLAS detector during the LHC run of spring and summer 2011. As described in detail below, the search examines events containing two leptons and up to one jet. The main backgrounds are suppressed by cuts on angular distributions, invariant masses, and $b$ - jet tagging information. The background normalization and composition is estimated in situ using several control samples defined by relaxing or reversing selection cuts. Similar searches were performed by CMS and ATLAS in 36 pb$^{-1}$ [8] and 35 pb$^{-1}$ [9], respectively. The ATLAS experiment [10] is a multipurpose particle physics detector with forward-backward symmetric cylindrical geometry allowing tracks within the pseudorapidity range $|\eta| < 2.5$ and energy deposits in calorimeters covering $|\eta| < 4.9$ to be reconstructed. It is modeled using GEANT4 [11] and simulated events are reconstructed using the same software that is used to perform the reconstruction on data. The effects of multiple $pp$ interactions (“in-time” pileup) and residual energy deposits from neighboring bunch crossings (“out-of-time” pileup) are modeled in the Monte Carlo (MC) samples by superimposing a number of simulated minimum-bias events on the simulated signal and background events. MC samples with different numbers of pileup interactions are reweighted to match the conditions observed in the present data: about 6 interactions per bunch crossing, with a 50 ns bunch spacing. The data used in this analysis were recorded during periods when all ATLAS subdetectors were operating under nominal conditions. The events were triggered [12] by requiring the presence of a high-$p_T$ electron or muon in the event.

Electron candidates are selected from clustered energy deposits in the electromagnetic (EM) calorimeter with an associated track reconstructed in the inner detector and are required to satisfy a stringent set of identification cuts [13] with an efficiency of 71% for electrons with transverse momentum $E_T > 20 \text{ GeV}$ and $|\eta| < 2.47$. Muons are reconstructed by combining tracks in the inner detector and muon spectrometer. The efficiency of this reconstruction is 92% for muons with $p_T > 20 \text{ GeV}$ and $|\eta| < 2.4$. Events are required to have a primary vertex with $\geq 3$ tracks with $p_T > 0.4 \text{ GeV}$. For both electrons and muons, the track associated with the lepton candidate is required to be consistent with having been produced at the event’s primary vertex. Leptons are required to be isolated, satisfying stringent cuts on tracks and calorimeter deposits inside a cone $\Delta R = \sqrt{\Delta \phi^2 + \Delta \eta^2} < 0.2$ around the lepton

*Full author list given at the end of the article.
candidate, where $\Delta \phi$ and $\Delta \eta$ are the transverse opening angle and pseudorapidity difference between the lepton and the track or energy deposit. The lepton reconstruction efficiencies are evaluated with tag-and-probe methods using $Z \rightarrow \ell \ell$, $J/\psi \rightarrow \ell \ell$, and $W \rightarrow \ell \nu$ events in data [14].

Jets are reconstructed from calibrated clusters using the anti-$k_t$ algorithm [15] with radius parameter $R = 0.4$. Jet energies are calibrated using $E_T$ and $\eta$ dependent correction factors based on MC simulation and validated by test beam and collision data studies [16]. They are required to have $E_T > 25$ GeV and $|\eta| < 4.5$. Jets are identified as having been produced by $b$ quarks using an algorithm that combines information about the impact parameter significance of tracks in the jet and the topology of semileptonic $b$- and $c$-hadron decays [17]. The missing transverse momentum $E_T^{\text{miss}}$ [18] is reconstructed from calibrated energy clusters in the calorimeters and the reconstructed momenta of the muons, which generally deposit only a small fraction of their energy in the calorimeters. The $E_T^{\text{miss}}$ distribution in the presence of pileup has been studied, and both $E_T^{\text{miss}}$ as a function of the number of reconstructed primary vertices and $E_T^{\text{miss}}$ as a function of the event’s position in the bunch train are well-modeled by MC calculations.

Exactly two opposite-sign lepton candidates ($e$ or $\mu$) with $p_T > 15$ GeV for muons or $E_T > 20$ GeV for electrons are required. The leading lepton must have transverse momentum $>25$ GeV so the selected events have a high efficiency for the trigger selection.

After the selection of events with two leptons, the significant backgrounds are the Drell-Yan process, $t\bar{t}$ and single top ($tW/tb/tq\bar{b}$), $WW$, other diboson processes ($WZ/ZZ/W\gamma$), and $W + \text{jets}$ where a jet is misidentified as a lepton. In addition to data-driven validations of the background estimates discussed later, MC simulations of the signal and backgrounds are studied in detail. The $gg \rightarrow H$ and $qq \rightarrow qqH$ processes are modeled using POWHEG, with PYTHIA to handle the parton shower [19], and the $gg \rightarrow H$ Higgs boson $p_T$ spectrum is reweighted to agree with the prediction of Ref. [20]. PYTHIA is used to model $WH/ZH$ production. Signal MC calculations are performed in steps of 5 GeV for $m_H$ below 200 GeV and in steps of 20 GeV for larger masses. Signal expectations for intermediate mass values are obtained by linear interpolation of the signal efficiency. The $t\bar{t}$, $s$-channel single top ($tb$), and $qq/qq \rightarrow WW/WZ/ZZ$ processes are generated with MC@NLO, $t$-channel and $Wt$ single top with ACERMC (interfaced to the parton shower algorithm in PYTHIA), $gg \rightarrow WW$ with GG2WW interfaced to the parton shower algorithm in HERWIG [21], $W\gamma$ with MADGRAPH interfaced to PYTHIA, and $W + \text{jets}$ and $Z/\gamma^* + \text{jets}$ with ALPGEN interfaced to PYTHIA [22].

If the two leptons have different flavors, their invariant mass ($m_{\ell\ell}$) is required to be above 10 GeV. Otherwise, they must satisfy $m_{\ell\ell} > 15$ GeV and they must lie outside the region with $|m_{\ell\ell} - m_Z| < 15$ GeV to suppress backgrounds from $Y$ and $Z$ production, respectively.

The quantity $E_{T_{\text{rel}}}^{\text{miss}}$ is defined as $E_T^{\text{miss}}$ if the angle $\Delta \phi$ between the missing transverse momentum and the transverse momentum of the nearest lepton or jet is greater than $\pi/2$, or $E_T^{\text{miss}} \sin(\Delta \phi)$ otherwise. $E_{T_{\text{rel}}}^{\text{miss}}$ is less sensitive to the mismeasurement of a single lepton or jet than $E_T^{\text{miss}}$. To suppress backgrounds from multijet events and Drell-Yan production, it is required that $E_{T_{\text{rel}}}^{\text{miss}} > 40$ GeV if the two leptons have the same flavor, or $E_{T_{\text{rel}}}^{\text{miss}} > 25$ GeV if they have different flavor.

After these requirements, the data are separated into $H + 0 - \text{jet}$ and $H + 1 - \text{jet}$ samples based on whether they have zero or exactly one jet. In the $H + 1 - \text{jet}$ channel, the dilepton system is required to have a large transverse boost, $p_T^{\ell\ell} > 30$ GeV, to suppress backgrounds from $Z + \text{jets}$ and continuum $WW$ production.

To suppress background from top-quark production, events in the $H + 1 - \text{jet}$ channel are rejected if the jet is identified as the decay of a $b$ quark. These candidates are further required to have $|p_T^{\text{jet}}| < 30$ GeV, where $p_T^{\text{jet}}$ is the vector sum of the transverse momenta of the jet, the two leptons, and the $E_T^{\text{miss}}$ vector. This latter selection suppresses events with significant hadronic activity that recoils against the $p_T^{\text{jet}}$ system but does not leave high $p_T$ jets in the detector. In the $H + 1 - \text{jet}$ channel, the event is required to pass the $Z \rightarrow \tau\tau$ rejection cut used in the $H \rightarrow WW$ analysis of Ref. [24].

Top and $WW$ backgrounds are suppressed by an upper bound on $m_{\ell\ell}$. Because the $m_{\ell\ell}$ distribution for the signal depends strongly on $m_H$, the chosen upper bound depends on the Higgs boson mass hypothesis. For $m_H < 170$ GeV, $m_{\ell\ell} < 50$ GeV is required, while for $170 \leq m_H < 220$ GeV, the cut is $m_{\ell\ell} < 65$ GeV. For $m_H \geq 220$ GeV, the requirement is $50 < m_{\ell\ell} < 180$ GeV.

For $m_H < 220$ GeV, an upper bound is imposed on the azimuthal angle between the two leptons to exploit differences in spin correlations between signal and background: $\Delta \phi_{\ell\ell} < 1.3$ for $m_H < 170$ GeV, or $\Delta \phi_{\ell\ell} < 1.8$ for $m_H < 220$ GeV. The final requirement uses the transverse mass $m_T$ [25] which is defined as $(m_T)^2 = m_{\ell\ell}^2 + 2(e_{\ell\ell}|p_T^{\ell\ell}| - p_T^{\ell\ell} \cdot p_T^{\ell\ell})$, where the subscripts $\ell$ and $i$ denote the visible and invisible decay products and $e_{\ell\ell} = \sqrt{p_T^{\ell\ell} \cdot p_T^{\ell\ell} + m_{\ell\ell}^2}$ denotes the transverse energy. The transverse mass $m_T$ is required to lie within $0.75m_H < m_T < m_H$ if $m_H < 220$ GeV or $0.6m_H < m_T < m_H$ otherwise. The upper bound on this window reduces the $WW$ and top backgrounds and excludes regions of phase space where interference effects between the signal and the $gg \rightarrow WW$ background are large [26].

Table I shows the expected and observed event yields after these cuts. As described below, the $W + \text{jets}$ background is entirely determined from data, whereas for the other processes the expectations are based on simulation,
TABLE I. The expected numbers of signal ($m_H = 150$ GeV) and background events after the requirements listed in the first column, as well as the observed numbers of events in data. All numbers are summed over lepton flavor.

<table>
<thead>
<tr>
<th>$H + 0 -$ jet Channel</th>
<th>Signal</th>
<th>WW</th>
<th>$W +$ jets</th>
<th>$Z/\gamma^* +$ jets</th>
<th>$t\bar{t}$</th>
<th>$tW/tb/tq$</th>
<th>$WZ/ZZ/W\gamma$</th>
<th>Total Bkg.</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet Veto</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$p_T^{\ell} &gt; 30$ GeV</td>
<td>99 ± 21</td>
<td>524 ± 52</td>
<td>84 ± 41</td>
<td>174 ± 169</td>
<td>42 ± 14</td>
<td>32 ± 8</td>
<td>15 ± 4</td>
<td>872 ± 182</td>
<td>920</td>
</tr>
<tr>
<td>$m_{\ell\ell} &lt; 50$ GeV</td>
<td>95 ± 20</td>
<td>467 ± 45</td>
<td>69 ± 34</td>
<td>30 ± 12</td>
<td>39 ± 14</td>
<td>29 ± 8</td>
<td>13 ± 4</td>
<td>648 ± 60</td>
<td>700</td>
</tr>
<tr>
<td>$\Delta\phi_{\ell\ell} &lt; 1.3$</td>
<td>68 ± 15</td>
<td>118 ± 15</td>
<td>21 ± 8</td>
<td>13 ± 8</td>
<td>7 ± 4</td>
<td>5.8 ± 1.8</td>
<td>1.9 ± 0.6</td>
<td>166 ± 19</td>
<td>199</td>
</tr>
<tr>
<td>$0.75m_H &lt; m_{\ell &lt; m_H}$</td>
<td>58 ± 13</td>
<td>91 ± 12</td>
<td>12 ± 5</td>
<td>9 ± 6</td>
<td>6 ± 3</td>
<td>5.8 ± 1.8</td>
<td>1.7 ± 0.6</td>
<td>125 ± 15</td>
<td>149</td>
</tr>
<tr>
<td>$H + 1 -$ jet Channel</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 jet</td>
<td>40 ± 9</td>
<td>52 ± 7</td>
<td>5 ± 2</td>
<td>2 ± 4</td>
<td>2.4 ± 16</td>
<td>1.5 ± 1.0</td>
<td>1.1 ± 0.5</td>
<td>63 ± 9</td>
<td>81</td>
</tr>
<tr>
<td>$b -$ jet veto</td>
<td>50 ± 9</td>
<td>193 ± 20</td>
<td>38 ± 21</td>
<td>74 ± 65</td>
<td>473 ± 124</td>
<td>174 ± 26</td>
<td>14 ± 2</td>
<td>967 ± 145</td>
<td>952</td>
</tr>
<tr>
<td>$p_T^{\ell} &lt; 30$ GeV</td>
<td>39 ± 7</td>
<td>154 ± 16</td>
<td>18 ± 9</td>
<td>38 ± 32</td>
<td>106 ± 30</td>
<td>50 ± 9</td>
<td>9.7 ± 1.5</td>
<td>376 ± 48</td>
<td>405</td>
</tr>
<tr>
<td>$Z = \tau\tau$ veto</td>
<td>39 ± 7</td>
<td>150 ± 17</td>
<td>18 ± 8</td>
<td>34 ± 23</td>
<td>102 ± 23</td>
<td>48 ± 8</td>
<td>9 ± 2</td>
<td>361 ± 38</td>
<td>388</td>
</tr>
<tr>
<td>$m_{\ell\ell} &lt; 50$ GeV</td>
<td>26 ± 6</td>
<td>33 ± 5</td>
<td>3.3 ± 1.4</td>
<td>8 ± 7</td>
<td>20 ± 7</td>
<td>11 ± 3</td>
<td>1.8 ± 0.5</td>
<td>77 ± 12</td>
<td>90</td>
</tr>
<tr>
<td>$\Delta\phi_{\ell\ell} &lt; 1.3$</td>
<td>23 ± 5</td>
<td>25 ± 4</td>
<td>2.1 ± 1.0</td>
<td>4 ± 6</td>
<td>17 ± 6</td>
<td>9 ± 3</td>
<td>1.5 ± 0.4</td>
<td>60 ± 10</td>
<td>72</td>
</tr>
<tr>
<td>$0.75m_H &lt; m_{\ell &lt; m_H}$</td>
<td>14 ± 3</td>
<td>12 ± 3</td>
<td>0.9 ± 0.4</td>
<td>1.3 ± 1.9</td>
<td>8 ± 2</td>
<td>4.0 ± 1.6</td>
<td>0.7 ± 0.3</td>
<td>28 ± 4</td>
<td>29</td>
</tr>
</tbody>
</table>

Control Regions | Signal | WW | $W +$ jets | $Z/\gamma^* +$ jets | $t\bar{t}$ | $tW/tb/tq$ | $WZ/ZZ/W\gamma$ | Total Bkg. | Observed |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>WW0 - jet ($m_H &lt; 220$ GeV)</td>
<td>1.7 ± 0.4</td>
<td>225 ± 30</td>
<td>20 ± 15</td>
<td>6 ± 8</td>
<td>25 ± 10</td>
<td>15 ± 4</td>
<td>8 ± 3</td>
<td>296 ± 36</td>
<td>296</td>
</tr>
<tr>
<td>WW0 - jet ($m_H \geq 220$ GeV)</td>
<td>10 ± 2</td>
<td>173 ± 23</td>
<td>24 ± 12</td>
<td>13 ± 19</td>
<td>15 ± 6</td>
<td>8 ± 3</td>
<td>3.3 ± 0.6</td>
<td>236 ± 33</td>
<td>258</td>
</tr>
<tr>
<td>WW1 - jet ($m_H &lt; 220$ GeV)</td>
<td>1.0 ± 0.3</td>
<td>76 ± 13</td>
<td>5 ± 3</td>
<td>5 ± 5</td>
<td>56 ± 14</td>
<td>23 ± 5</td>
<td>5.3 ± 1.4</td>
<td>171 ± 21</td>
<td>184</td>
</tr>
<tr>
<td>WW1 - jet ($m_H \geq 220$ GeV)</td>
<td>5.8 ± 1.5</td>
<td>51 ± 9</td>
<td>3.9 ± 1.8</td>
<td>10 ± 10</td>
<td>35 ± 9</td>
<td>18 ± 4</td>
<td>2.8 ± 0.6</td>
<td>120 ± 17</td>
<td>129</td>
</tr>
<tr>
<td>$t\bar{t}$ - jet</td>
<td>0.9 ± 0.3</td>
<td>3.9 ± 1.0</td>
<td>...</td>
<td>1 ± 17</td>
<td>184 ± 64</td>
<td>80 ± 19</td>
<td>0.2 ± 0.9</td>
<td>270 ± 69</td>
<td>249</td>
</tr>
</tbody>
</table>

with $Z/\gamma^* +$ jets, $t\bar{t}$, and $tW/tb/tq$ corrected by scale factors derived from control samples. The uncertainties shown are the sum in quadrature of systematic uncertainties and statistical errors due to the finite number of MC events. Figure 1 shows the distributions of $m_{\ell\ell}$ and $\Delta\phi_{\ell\ell}$ before the final cut on $m_{\ell\ell}$, and the distribution of $m_T$ after the cut on $\Delta\phi_{\ell\ell}$.

The background from $W +$ jets events where one jet is misidentified as a lepton is estimated from data using a loosened set of identification and isolation criteria but not the full set of criteria normally used. The extrapolation from this control sample to the signal region is extracted from dijet events [27].

The Drell-Yan background is corrected for mismodeling of the distribution of $E_T^{\text{miss}}$ at high values based on the observed difference between the fraction of events passing the $E_T^{\text{miss}} > 40$ GeV selection in data and MC simulation for events with $m_{\ell\ell}$ within 10 GeV of the Z boson mass. The correction factors are all found to be between 0.8 and 0.9, which indicates that the background in the signal region is about 15% less than the MC estimates.

FIG. 1. Distributions of $m_{\ell\ell}$ (left), $\Delta\phi_{\ell\ell}$ (center), and $m_T$ (right). The top row shows the selection for the $H + 0 -$ jet channel and the bottom row for the $H + 1 -$ jet channel. The left and central plots are shown after the $p_T^{\ell\ell}$ selection for the $H + 0 -$ jet channel and after the $p_T^{b}$ cut for the $H + 1 -$ jet channel. For the rightmost plots, the distributions are shown after all the cuts for $m_H = 150$ GeV except the cut on $m_T$ itself. The background distributions are stacked, so that the top of the diboson background coincides with the standard model line which includes the statistical and systematic uncertainties on the expectation in the absence of a signal. The expected signal for $m_H = 150$ GeV is shown as a separate thicker line, and the final bin includes the overflow.
The \(WW\) and top backgrounds are normalized by a simultaneous fit to the numbers of observed events in the signal region and several control samples. A sample enriched in \(WW\) background is defined by removing the selections on \(m_T\) and \(\Delta \phi_{\ell\ell}\) and changing the selection on \(m_{\ell\ell}\). For \(m_H < 220\ \text{GeV}\), the cut is changed to \(m_{\ell\ell} > 80\ \text{GeV}\), while for \(m_H > 220\ \text{GeV}\), the control region is the union of the regions with \(15 < m_{\ell\ell} < 50\ \text{GeV}\) and \(m_{\ell\ell} > 180\ \text{GeV}\). This control sample is studied separately for the \(H + 0\) – jet channel and the \(H + 1\) – jet channel, and the observed yields are consistent with expectations in both cases. The yields in these control regions, shown in Table I, are propagated to the signal region using scale factors computed with MC.

In the \(H + 0\) – jet channel, the top-enriched control sample consists of the same preselected sample used in the rest of this analysis: events with two leptons and \(E_T^{\text{miss}}\). The scale factor used to propagate the \(t\bar{t}\) yield from this sample to the signal region is estimated as the square of the efficiency for one top decay to survive the jet veto (estimated using another control sample, defined by the presence of an additional \(b\) – jet), with a correction computed using MC to account for the presence of single top [28]. A sample enriched in top background is defined for the \(H + 1\) – jet channel by reversing the \(b\) – jet veto and removing the cuts on \(\Delta \phi_{\ell\ell}, m_{\ell\ell}, \) and \(m_T\). The extrapolation to the signal region is done using a scale factor computed using MC. The control samples for top in the \(H + 0\) – jet and \(H + 1\) – jet channels also normalize the top contamination in the corresponding \(WW\) control regions. In both cases, the estimated top backgrounds are consistent with the expected yields in Table I.

The signal significance and limits on Higgs boson production are derived from a likelihood function that is the product of the Poisson probabilities of each of the lepton flavor and jet multiplicity yields for the signal selections, the \(WW\) \(0\) – jet and \(WW\) \(1\) – jet control regions, and top control region for the \(H + 1\) – jet channel. The normalization of the signal, the \(WW\) cross sections for the \(H + 0\) – jet and \(H + 1\) – jet channels, and the top cross section for the \(H + 1\) – jet channel are allowed to vary independently; the control regions included in the fit constrain all of these except the signal yield. All other components are normalized to their expectations scaled by nuisance parameters constrained by Gaussian terms that include the systematic uncertainties described below. The results from the control sample measurements for the top background in the \(H + 0\) – jet channel and for the \(W +\) jets and Drell-Yan backgrounds everywhere are used as the expected values for the corresponding backgrounds in the fit. Since these contributions are small, the control samples themselves are not explicitly modeled in the fit as they are for top in the \(H + 1\) – jet channel and for \(WW\) everywhere.

The systematic uncertainties include contributions from the 3.7% uncertainty in the luminosity [29], and from theoretical uncertainties, which are \(-8/ +12\%\) and \(\pm 8\%\) from the QCD scale and 1% and 4% from the parton density functions, for \(gg \rightarrow H\) and \(qq \rightarrow qqH\) respectively. Additional theoretical uncertainties on the acceptance are assessed as described in Ref. [30]. In particular, the uncertainty in the assignment of events to jet multiplicity bins is included separately as an uncertainty on the cross section of each bin, calculated from the approximate 10% and 20% uncertainties of the inclusive 0 – jet and 1 – jet cross sections, respectively.

Several sources of measurement uncertainty are taken into account. The uncertainty on the jet energy scale is less than 10% on the global scale including flavor composition effects, with an additional uncertainty of up to 7% due to pileup [16]. The electron and muon efficiencies are determined from samples of \(W\) and \(Z\) boson data with uncertainties of 2%–5% and 0.3%–1%, respectively, depending on \(|\eta|\) and \(p_T\). Uncertainties are \(<1\%\) and \(<0.1\%\), respectively, on the lepton energy scale and \(<0.6\%\) and \(<5\%\) on the resolution [14]. The uncertainties on the \(b\)-tagging efficiency and mistag rate are 6%–15% and up to 21%, respectively [17]. A 13% uncertainty is applied to the energy scale for low-\(p_T\) depositions in the \(E_T^{\text{miss}}\) measurement. All these sources of detector uncertainty are propagated to the result by varying reconstructed quantities and observing the effect on the expected yields. For the \(WW\) background, the total (theoretical and experimental) uncertainty on the ratio of cross sections in the signal and control regions is 7.6% in the \(H + 0\) – jet channel and 21% in the \(H + 1\) – jet channel; for the top background in \(H + 1\) – jet the total for the extrapolation to the signal region is 38%, and 29% to the \(WW\) control region.
No significant excess of events is observed. The largest observed deviation from the expected background is 1.9σ. A 95% C.L. upper bound is set on the Higgs boson cross section as a function of $m_H$ using the $CL_s$ formalism [31]. Figure 2 shows the expected and observed limits. Discontinuities occur where the selection changes, since in the absence of a signal, one would expect to exclude a standard model Higgs boson in the range $134 < m_H < 200$ GeV at the 95% C.L. The Higgs boson mass interval excluded by the measurements presented in this Letter, $145 < m_H < 206$ GeV, is consistent with that expectation. This measurement excludes, at 95% C.L., a larger part of the mass range favored by the electroweak fits than previous limits [32].

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently.

We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWF, Austria; AHAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNRF, DNSRC and Lundbeck Foundation, Denmark; ARTEMIS, European Union; IN2P3-CNRS, CEA-DSM/IRFU, France; GNAS, Georgia; BMFB, DFG, HGF, MPG and AvH Foundation, Germany; GSRT, Greece; ISF, MINERVA, GIF, DIP and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; RCN, Norway; MNiSW, Poland; GRICES and FCT, Portugal; MERSYS (MECTS), Romania; MES of Russia and ROSATOM, Russian Federation; JINR; MSTD, Serbia; MSSR, Slovakia; ARRS and MVZT, Slovenia; DST/NRF, South Africa; MICINN, Spain; SRC and Wallenberg Foundation, Sweden; SER, SNSF and Cantons of Bern and Geneva, Switzerland; NSC, Taiwan; TAEK, Turkey; STFC, the Royal Society and Leverhulme Trust, United Kingdom; DOE and NSF, United States of America.

The crucial computing support from all WLCG partners is acknowledged gratefully, in particular, from CERN and the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA) and in the Tier-2 facilities worldwide.


158b Department of Physics and Astronomy, York University, Toronto, Ontario, Canada
159 Institute of Pure and Applied Sciences, University of Tsukuba, Ibaraki 305-8571, Japan
160 Science and Technology Center, Tufts University, Medford, Massachusetts, USA
161 Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
162 Department of Physics and Astronomy, University of California Irvine, Irvine, California, USA
163 INFN Gruppo Collegato di Udine, Italy
163 ICTP, Trieste, Italy
163 Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
164 Department of Physics, University of Illinois, Urbana, Illinois, USA
165 Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
166 Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNMT), University of Valencia and CSIC, Valencia, Spain
167 Department of Physics, University of British Columbia, Vancouver, British Colombia, Canada
168 Department of Physics and Astronomy, University of Victoria, Victoria, British Colombia, Canada
169 Waseda University, Tokyo, Japan
170 Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
171 Department of Physics, University of Wisconsin, Madison, Wisconsin, USA
172 Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
173 Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany
174 Department of Physics, Yale University, New Haven, Connecticut, USA
175 Yerevan Physics Institute, Yerevan, Armenia
176 Domaine scientifique de la Doua, Centre de Calcul CNRS/IN2P3, Villeurbanne Cedex, France

a Deceased.
b Also at Laboratorio de Instrumentacao e Fisica Experimental de Particulas—LIP, Lisboa, Portugal.
c Also at Faculdade de Ciencias and CFNUL, Universidade de Lisboa, Lisboa, Portugal.
d Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom.
e Also at Novosibirsk State University, Novosibirsk, Russia.
f Also at TRIUMF, Vancouver, BC, Canada.
g Also at Department of Physics, California State University, Fresno, CA, United States of America.
h Also at Fermilab, Batavia, IL, USA.
i Also at Department of Physics, University of Coimbra, Coimbra, Portugal.
j Also at Università di Napoli Parthenope, Napoli, Italy.
k Also at Institute of Particle Physics (IPP), Canada.
l Also at Department of Physics, Middle East Technical University, Ankara, Turkey.
m Also at Louisiana Tech University, Ruston, LA, USA.
n Also at Department of Physics and Astronomy, University College London, London, United Kingdom.
o Also at Group of Particle Physics, University of Montreal, Montreal, QC, Canada.
p Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
q Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.
r Also at Manhattan College, New York, NY, USA.
s Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.
t Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China.
u Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.
v Also at High Energy Physics Group, Shandong University, Shandong, China.
w Also at Section de Physique, Université de Genève, Geneva, Switzerland.
x Also at Departamento de Fisica, Universidade de Minho, Braga, Portugal.
y Also at Department of Physics and Astronomy, University of South Carolina, Columbia, SC, USA.
z Also at KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary.
aa Also at California Institute of Technology, Pasadena, CA, USA.
bb Also at Institute of Physics, Jagiellonian University, Krakow, Poland.
cc Also at Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China.
dd Also at Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom.
ee Also at Department of Physics, Oxford University, Oxford, United Kingdom.
ff Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.
gg Also at Department of Physics, The University of Michigan, Ann Arbor, MI, USA.
Also at DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat a l’Energie Atomique), Gif-sur-Yvette, France.

Also at Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France.