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

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A search for the Higgs boson has been performed in the $H \to WW^{(*)} \to \ell^+ \nu \ell^- \bar{\nu}$ 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 GeV $< m_H <$ 300 GeV. The observations exclude the presence of a standard model Higgs boson with a mass $145 < m_H < 206$ GeV at 95% confidence level.

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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 ($gg \to H$) [2] due to the large gluon density, although vector boson fusion ($qq \to qqH$) [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 GeV [4]. For $m_H >$ 135 GeV, $H \to WW^{(*)}$ 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 GeV or 156 GeV $< m_H <$ 177 GeV [5] at 95% confidence level (C.L.). The search for $H \to ZZ \to \ell\ell\nu\nu$ at ATLAS excludes a standard model Higgs boson with a mass $340 < m_H < 450$ GeV, while the search for $H \to ZZ \to 4\ell$ excludes $191 < m_H < 197$ GeV, $199 < m_H < 200$ GeV, and $214 < m_H < 224$ GeV [6].

This Letter reports the results of a search for the Higgs boson in the channel $H \to WW^{(*)} \to \ell^+ \nu \ell^- \bar{\nu}$ [7] ($\ell = e/\mu$, but including contributions from $\tau \to e/\mu$ 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 $E_T > 20$ 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 $p_T > 20$ GeV and $|\eta| < 2.4$. Events are required to have a primary vertex with ≥ 3 tracks with $p_T > 0.4$ 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 depositions inside a cone $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} < 0.2$ around the lepton

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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 η 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^{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^{miss} distribution in the presence of pileup has been studied, and both E_T^{miss} as a function of the number of reconstructed primary vertices and E_T^{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 μ) 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 ($tW/tb/tqb$), WW, other diboson processes ($WZ/ZZ/W\gamma$), and W + 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 $qq/qg \rightarrow WW/WZ/ZZ$ 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 + jets and Z/γ^* + 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 Υ and Z production, respectively.

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

After these requirements, the data are separated into $H + 0 -$ jet and $H + 1 -$ jet [23] samples based on whether they have zero or exactly one jet. In the $H + 0 -$ jet channel, the dilepton system is required to have a large transverse boost, $p_T^{\ell\ell} > 30$ GeV, to suppress backgrounds from Z + jets and continuum WW production.

To suppress background from top-quark production, events in the $H + 1 -$ jet channel are rejected if the jet is identified as the decay of a b quark. These candidates are further required to have $|\mathbf{p}_T^{tot}| < 30$ GeV, where $\mathbf{p}_T^{tot}$ is the vector sum of the transverse momenta of the jet, the two leptons, and the E_T^{miss} vector. This latter selection suppresses events with significant hadronic activity that recoils against the $\mathbf{p}_T^{tot}$ system but does not leave high p_T jets in the detector. In the $H + 1 -$ 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 $(m_T)^2 = m_v^2 + 2(e_v|\mathbf{p}_{T,i}| - \mathbf{p}_{T,v} \cdot \mathbf{p}_{T,i})$, where the subscripts v and i denote the visible and invisible decay products and $e_v = \sqrt{\mathbf{p}_{T,v} \cdot \mathbf{p}_{T,v} + m_v^2}$ 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 + 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 ($m_{\mathrm{H}} = 150$ 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.

$H + 0 -$ jet Channel	Signal	WW	$W +$ jets	$Z/\gamma^* +$ jets	$t\bar{t}$	$tW/tb/tqb$	$WZ/ZZ/W\gamma$	Total Bkg.	Observed
Jet Veto	99 ± 21	524 ± 52	84 ± 41	174 ± 169	42 ± 14	32 ± 8	15 ± 4	872 ± 182	920
$p_{\mathrm{T}}^{\ell\ell} > 30$ GeV	95 ± 20	467 ± 45	69 ± 34	30 ± 12	39 ± 14	29 ± 8	13 ± 4	648 ± 60	700
$m_{\ell\ell} < 50$ GeV	68 ± 15	118 ± 15	21 ± 8	13 ± 8	7 ± 4	5.8 ± 1.8	1.9 ± 0.6	166 ± 19	199
$\Delta\phi_{\ell\ell} < 1.3$	58 ± 13	91 ± 12	12 ± 5	9 ± 6	6 ± 3	5.8 ± 1.8	1.7 ± 0.6	125 ± 15	149
$0.75m_H < m_{\mathrm{T}} < m_H$	40 ± 9	52 ± 7	5 ± 2	2 ± 4	2.4 ± 1.6	1.5 ± 1.0	1.1 ± 0.5	63 ± 9	81
$H + 1 -$ jet Channel	Signal	WW	$W +$ jets	$Z/\gamma^* +$ jets	$t\bar{t}$	$tW/tb/tqb$	$WZ/ZZ/W\gamma$	Total Bkg.	Observed
1 jet	50 ± 9	193 ± 20	38 ± 21	74 ± 65	473 ± 124	174 ± 26	14 ± 2	967 ± 145	952
$b -$ jet veto	48 ± 9	188 ± 19	35 ± 19	73 ± 61	174 ± 49	66 ± 11	14 ± 2	549 ± 83	564
$\lvert\mathbf{p}_{\mathrm{T}}^{\mathrm{tot}}\rvert < 30$ GeV	39 ± 7	154 ± 16	18 ± 9	38 ± 32	106 ± 30	50 ± 9	9.7 ± 1.5	376 ± 48	405
$Z \to \tau\tau$ veto	39 ± 7	150 ± 17	18 ± 8	34 ± 23	102 ± 23	48 ± 8	9 ± 2	361 ± 38	388
$m_{\ell\ell} < 50$ GeV	26 ± 6	33 ± 5	3.3 ± 1.4	8 ± 7	20 ± 7	11 ± 3	1.8 ± 0.5	77 ± 12	90
$\Delta\phi_{\ell\ell} < 1.3$	23 ± 5	25 ± 4	2.1 ± 1.0	4 ± 6	17 ± 6	9 ± 3	1.5 ± 0.4	60 ± 10	72
$0.75m_H < m_{\mathrm{T}} < m_H$	14 ± 3	12 ± 3	0.9 ± 0.4	1.3 ± 1.9	8 ± 2	4.0 ± 1.6	0.7 ± 0.3	28 ± 4	29
Control Regions	Signal	WW	$W +$ jets	$Z/\gamma^* +$ jets	$t\bar{t}$	$tW/tb/tqb$	$WZ/ZZ/W\gamma$	Total Bkg.	Observed
$WW0 -$ jet ($m_H < 220$ GeV)	1.7 ± 0.4	223 ± 30	20 ± 15	6 ± 8	25 ± 10	15 ± 4	8 ± 3	296 ± 36	296
$WW0 -$ jet ($m_H \geq 220$ GeV)	10 ± 2	173 ± 23	24 ± 12	13 ± 19	15 ± 6	8 ± 3	3.3 ± 0.6	236 ± 33	258
$WW1 -$ jet ($m_H < 220$ GeV)	1.0 ± 0.3	76 ± 13	5 ± 3	5 ± 5	56 ± 14	23 ± 5	5.3 ± 1.4	171 ± 21	184
$WW1 -$ jet ($m_H \geq 220$ GeV)	5.8 ± 1.5	51 ± 9	3.9 ± 1.8	10 ± 10	35 ± 9	18 ± 4	2.8 ± 0.6	120 ± 17	129
$t\bar{t}1 -$ jet	0.9 ± 0.3	3.9 ± 1.0	$\cdots$	1 ± 17	184 ± 64	80 ± 19	0.2 ± 0.9	270 ± 69	249

with $Z/\gamma^* +$ jets, $t\bar{t}$, and $tW/tb/tqb$ 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 control sample where one of the two leptons satisfies 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 $E_{\mathrm{T}}^{\mathrm{miss}}$ at high values based on the observed difference between the fraction of events passing the $E_{\mathrm{T,rel}}^{\mathrm{miss}} > 40$ 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.

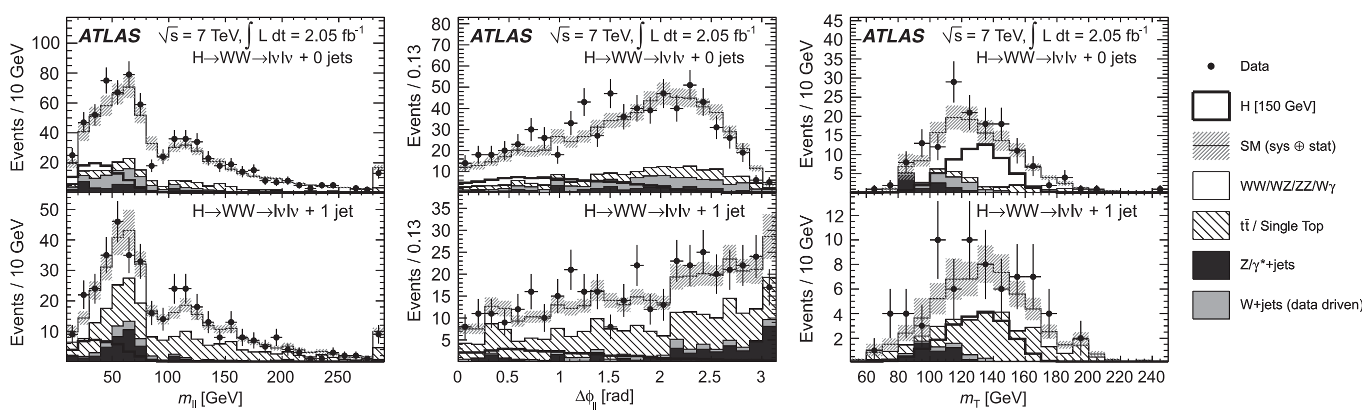

FIG. 1. Distributions of $m_{\ell\ell}$ (left), $\Delta\phi_{\ell\ell}$ (center), and m_{T} (right). The top row shows the selection for the $H + 0 -$ jet channel and the bottom row for the $H + 1 -$ jet channel. The left and central plots are shown after the $p_{\mathrm{T}}^{\ell\ell}$ selection for the $H + 0 -$ jet channel and after the $\lvert\mathbf{p}_{\mathrm{T}}^{\mathrm{tot}}\rvert$ 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 $m_H < 220$ GeV, the cut is changed to $m_{\ell\ell} > 80$ GeV, while for $m_H > 220$ GeV, the control region is the union of the regions with $15 < m_{\ell\ell} < 50$ GeV and $m_{\ell\ell} > 180$ 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 $E_{T,rel}^{miss}$. 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 $gg \to H$ and $qq \to qqH$ 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^{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.

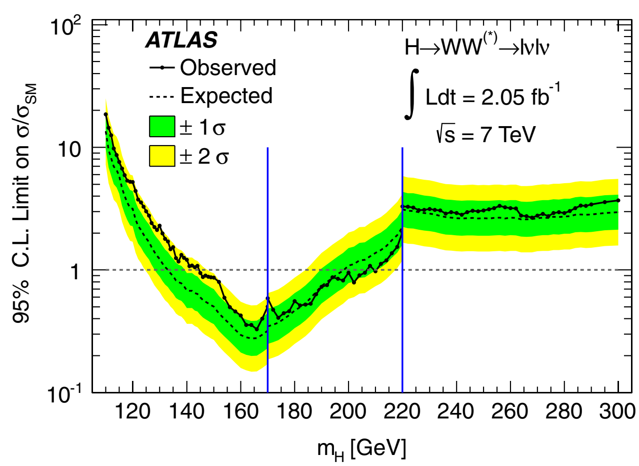

FIG. 2 (color online). The expected (dashed) and observed (solid) 95% C.L. upper limits on the cross section, normalized to the standard model cross section, as a function of the Higgs boson mass. Expected limits are given for the scenario where there is no signal. The vertical lines in the curves indicate the points where the selection cuts change, and the bands around the dashed line indicate the expected statistical fluctuations of the limit.

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 the signal regions there are less statistically correlated between adjacent masses. 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].

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