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Search for the Higgs Boson in the $H \to WW \to \ell\nu jj$ Decay Channel in $pp$ Collisions at $\sqrt{s} = 7$ TeV with the ATLAS Detector

G. Aad et al. *

(ATLAS Collaboration)

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A search for a Higgs boson has been performed in the $H \to WW \to \ell\nu jj$ channel in 1.04 fb$^{-1}$ of $pp$ collision data at $\sqrt{s} = 7$ TeV recorded with the ATLAS detector at the Large Hadron Collider. No significant excess of events is observed over the expected background and limits on the Higgs boson production cross section are derived for a Higgs boson mass in the range 240 GeV $< m_H <$ 600 GeV. The best sensitivity is reached for $m_H = 400$ GeV, where the 95% confidence level upper bound on the cross section for $H \to WW$ production is 3.1 pb, or 2.7 times the standard model prediction.

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In the standard model (SM [1–3]), a scalar field vacuum expectation value breaks the electroweak symmetry, gives masses to the $W$ and $Z$ bosons [4–6], and manifests itself directly as the so-called Higgs boson. A primary goal of the Large Hadron Collider (LHC) is to test the SM mechanism of electroweak symmetry breaking by searching for Higgs boson production in high energy proton-proton collisions. Thanks in part to the large gluon luminosity at LHC energies [7,8], the Higgs boson is predominantly produced via gluon fusion ($gg \to H$) [9–12] and to a lesser extent via vector boson fusion ($qq \to qgH$) [13–15]. Current limits from direct searches at LEP and the Tevatron exclude Higgs boson masses $m_H < 141.4$ GeV [16] and 156 GeV $< m_H < 177$ GeV [17] at 95% C.L.

For $m_H \gtrsim 135$ GeV, the dominant decay mode of the Higgs boson is $H \to WW^{(*)}$ [18,19]. The most sensitive Higgs boson search channel in the mass region around $m_H = 160$ GeV is the purely leptonic mode $H \to WW^{(*)} \to \ell\nu\ell\nu$. For $m_H \gtrsim 200$ GeV, the $H \to WW \to \ell\nu jj$ channel, where one $W$ decays to a pair of jets ($W \to jj$), also becomes important. The advantage of $H \to WW \to \ell\nu jj$ over $H \to WW \to \ell\nu\ell\nu$ is the ability to fully reconstruct the Higgs boson mass.

This Letter describes a search for a Higgs boson in the $H \to WW \to \ell\nu jj$ channel using the ATLAS detector at the LHC, based on 1.04 fb$^{-1}$ of $pp$ collision data at a center-of-mass energy $\sqrt{s} = 7$ TeV collected during 2011. In this analysis, the distribution of the $\ell\nu jj$ invariant mass $m(\ell\nu jj)$, reconstructed using the charged-lepton neutrino invariant mass constraint $m(\ell\nu) = m(W)$ and the requirement that two of the jets in the event are consistent with a $W \to jj$ decay, is used to search for a Higgs boson signal.

The results of a similar search for $H \to WW \to \ell\nu jj$ based on 35 pb$^{-1}$ of data recorded during the 2010 LHC run were presented in Ref. [20].

The present search, based on the measured shape of the $m(\ell\nu jj)$ distribution, is restricted to $m_H > 240$ GeV, in order to ensure a smoothly varying nonresonant background, well clear of the effective kinematic cutoff $m(\ell\nu jj) \sim 160$ GeV. For $m_H \gtrsim 600$ GeV, the jets from $W \to jj$ decay begin to overlap due to the large $W$ boost, and the natural width of the Higgs boson becomes large. A detailed treatment of these issues is beyond the scope of the present analysis. The best sensitivity in this analysis is expected for $m_H \sim 400$ GeV.

The ATLAS detector [21] is a multipurpose particle physics apparatus with forward-backward symmetric cylindrical geometry covering the pseudorapidity range $|\eta| < 2.5$ for track and $|\eta| < 4.9$ for jet measurements [22]. The inner tracking detector (ID) consists of a silicon pixel detector, a silicon microstrip detector, and a transition radiation tracker. The ID is surrounded by a thin superconducting solenoid providing a 2 T magnetic field, and by a high-granularity liquid-argon (LAr) sampling electromagnetic (EM) calorimeter. An iron-scintillator tile calorimeter provides hadronic coverage in the central rapidity range. The end-cap and forward regions are instrumented with LAr calorimetry for both electromagnetic and hadronic measurements. The muon spectrometer surrounds the calorimeters and consists of three large superconducting toroids, each with eight coils, a system of precision tracking chambers, and detectors for triggering.

Detailed Monte Carlo (MC) studies of signal and backgrounds have been carried out [23]. The interaction with the ATLAS detector is modeled with GEANT4 [24] and the events are processed using the same reconstruction that is used to perform the reconstruction on data. The effect of multiple $pp$ interactions in the same bunch crossing (pile-up) at the high luminosities achieved by the LHC in 2011 is modeled by superimposing, at the generation stage, several simulated minimum-bias events on the simulated signal.

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*Full author list given at the end of the article.

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reconstructed jets are calibrated using a reconstructed displaced secondary vertex consistent with and of jets in the final fit used to obtain limits, a combination of MC calculations and data-driven methods is used to better understand the background yields at this intermediate stage. Backgrounds due to W/Z + jets, t, and diboson (WW, WZ, and ZZ) production are modeled using the ALPGEN [31], MC@NLO [32], and HERWIG [33] generators, respectively. A small contribution from W/Z + γ events is generated using MADEVENT [34]. The shape of the MJ background is modeled using histograms derived from data samples selected in an identical way to the H → WW → ℓνjj selection except that the electron identification requirements are loosened and the isolation requirement on muons is inverted. In the loosened selection, electrons satisfying the complete set of identification criteria are not included. Expected contributions from non-QCD processes to the MJ shape histogram are subtracted using MC predictions.

To normalize the MJ shape histogram, the loose lepton control sample selection is further relaxed by removing the Et cut to construct a shape template for the Et distribution for the MJ background. The normalizations of this MJ template and the corresponding template for W/Z + jets taken from MC are fit to the observed Et distribution, and the resulting scale factors are then used to normalize the MJ and W/Z + jets processes in comparisons between data and expectations. Both the gluon fusion and the vector boson fusion signal production processes are simulated using the POWHEG [35,36] event generator interfaced to PYTHIA [37], normalizing to the NNLO cross sections [19] shown in Table I.
In order to reconstruct the invariant mass \(m(\ell \nu jj)\) of the WW system, the mass constraint \(m(\ell \nu) = m(W)\) is used, where the neutrino transverse momentum \(p_T^\nu\) is taken from the event \(E_T\). This equation can have real or complex solutions. In the case of complex solutions, the event is rejected. This requirement rejects 45\% of background events in both data and MC, but only 36\% of MC signal events with \(m_H = 400\) GeV. In the case of two real solutions, the solution with smaller neutrino longitudinal momentum \(|p_T^\nu|\) is taken, based on simulation studies. Table II shows the observed and expected numbers of events for signal and background after this full selection.

Figure 1 (top) shows the \(m(\ell \nu jj)\) distribution for this final sample. The expected signal for \(m_H = 400\) GeV is also shown, scaled up by a factor of 2.7. The \(m(\ell \nu jj)\) resolution is \((7.5 \pm 0.6)\%\) at \(m_H = 400\) GeV, depending mostly on the jet energy resolution as checked in data versus MC by various jet-balance techniques [38], and shows a \(1/\sqrt{m_H}\) dependence over the range of this analysis. Limits are set using a maximum likelihood fit to the shape of the observed \(m(\ell \nu jj)\) distribution in the range \(200 < m(\ell \nu jj) < 2000\) GeV. The nonresonant background in this fit is modeled by the sum of two exponential functions. The normalization and slope of each exponential are unconstrained parameters in the fit. The double-exponential form for the total background is well justified by fits to the \(m(\ell \nu jj)\) distributions obtained by selecting events with \(m_{jj}\) just below (\(50 < m_{jj} < 60\) GeV) or just above (\(100 < m_{jj} < 110\) GeV) the W peak, respectively.

As a consistency check, the background parametrization was altered to use three exponentials and the shift in signal yield as compared to the nominal background shape was found to be small as compared to other uncertainties. The \(m(\ell \nu jj)\) distribution for the expected signal at each hypothesized \(m_H\) is modeled using the signal MC samples.

The fit includes nuisance parameters which account for the uncertainty in the efficiency of the electron, muon, and jet reconstruction. The electron and muon efficiencies are varied within their uncertainties, leading to an uncertainty in the signal efficiency of \(\pm 1.6\%\) and \(\pm 0.6\%\), for electrons and muons, respectively. Varying the jet energy scale within its uncertainties yields a corresponding uncertainty of \(\pm 17\%\) in the expected signal, and smearing the jet energies within the uncertainty on their resolutions results in a signal uncertainty of \(\pm 8.6\%\). The limits also take into account a \(\pm 3.7\%\) uncertainty on the luminosity determination [39] and a \(\pm 19.4\%\) uncertainty on the predicted cross section [19], taken to be independent of mass. The off-shell effects and interference between the signal and backgrounds, which are discussed in Refs. [19,40,41], have been neglected. A conservative estimate of this uncertainty would be \(150 \times m_H^3\) (\(m_H\) in TeV), where the \(m_H^3\) form is motivated by the scaling of the Higgs width with \(m_H\) and the normalization factor is chosen to give \(~30\%\) at \(m_H = 600\) GeV, based on Fig. 6 of Ref. [41]. If this were included, it would increase the total systematic error by less than \(6\%\) for \(m_H \leq 500\) GeV, and as much as \(15\%\) for \(m_H = 600\) GeV where the limit would be increased by \(~18\%).
FIG. 1 (color online). Top: the reconstructed invariant mass \( m(l\nu jj) \) in the data summed over lepton flavor and jet multiplicity. The expected backgrounds are also shown. Bottom: the difference between data and the fitted nonresonant background. The expected contribution from Higgs boson decays for \( m_H = 400 \) GeV in the SM is also shown, multiplied by a factor of 2.7.

Figure 1 (bottom) shows the difference between the \( m(l\nu jj) \) distribution in data and the fitted background. There is no indication of any significant excess. Limits are extracted using the Profile Likelihood [42] as a test statistic and following the \( CL_s \) procedure described in Ref. [43].

Figure 2 shows the 95% CL upper bound on the cross-section times branching ratio for Higgs production in units of the Standard Model prediction, \( \sigma \times BR_{H \to WW}/(\sigma \times BR_{H \to WW})_{SM} \), as a function of \( m_H \). The observed cross section limit for \( m_H = 400 \) GeV is 3.1 pb, or 2.7 times the SM prediction, while the corresponding expected limits are 5.2 pb or 4.5 times the SM expectation. In the SM with an additional heavy fourth generation [44,45], the gluon fusion mechanism for production of a Higgs boson is expected to be substantially enhanced. Within the four generation context, a Higgs boson is excluded at 95% CL by the present data over the range \( m_H = 310–430 \) GeV.

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(ATLAS Collaboration)

1 University at Albany, Albany New York, USA
2 Department of Physics, University of Alberta, Edmonton AB, Canada
3a Department of Physics, Ankara University, Ankara, Turkey
3b Department of Physics, Dumlupinar University, Kutahya, Turkey
3c Department of Physics, Gazi University, Ankara, Turkey
3d Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey
3e Turkish Atomic Energy Authority, Ankara, Turkey
4 LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, France
5 High Energy Physics Division, Argonne National Laboratory, Argonne Illinois, USA
6 Department of Physics, University of Arizona, Tucson Arizona, USA
7 Department of Physics, The University of Texas at Arlington, Arlington Texas, USA
8 Physics Department, University of Athens, Athens, Greece
9 Physics Department, National Technical University of Athens, Zografou, Greece
10 Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
11 Institut de Física d’Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona and ICREA, Barcelona, Spain
12a Institute of Physics, University of Belgrade, Belgrade, Serbia
12b Vinca Institute of Nuclear Sciences, Belgrade, Serbia
13 Department for Physics and Technology, University of Bergen, Bergen, Norway
14 Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley California, USA
15 Department of Physics, Humboldt University, Berlin, Germany
16 Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
17 School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
18a Department of Physics, Bogazici University, Istanbul, Turkey
18b Division of Physics, Dogus University, Istanbul, Turkey
18c Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey
18d Department of Physics, Istanbul Technical University, Istanbul, Turkey
18e INFN Sezione di Bologna, Italy
19b Dipartimento di Fisica, Università di Bologna, Bologna, Italy
19c Physikalisches Institut, University of Bonn, Bonn, Germany
20 Department of Physics, Boston University, Boston Massachusetts, USA
22 Department of Physics, Brandeis University, Waltham Massachusetts, USA
23a Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil
23b Federal University of Juiz de Fora (UFJF), Juiz de Fora, Brazil
23c Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei, Brazil
23d Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil
24 Physics Department, Brookhaven National Laboratory, Upton New York, USA
25a National Institute of Physics and Nuclear Engineering, Bucharest, Romania
25b University Politehnica Bucharest, Bucharest, Romania
25c West University in Timisoara, Timisoara, Romania
26 Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
27 Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
28 Department of Physics, Carleton University, Ottawa ON, Canada
29 CERN, Geneva, Switzerland
30 Enrico Fermi Institute, University of Chicago, Chicago Illinois, USA
31a Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile
31b Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
32a Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China
32b Department of Modern Physics, University of Science and Technology of China, Anhui, China
Also at Department of Physics, California State University, Fresno CA, USA.
Also at Faculty of Physics and Applied Computer Science, AGH-University of Science and Technology, Krakow, Poland.
Also at Fermilab, Batavia IL, USA.
Also at Department of Physics, University of Coimbra, Coimbra, Portugal.
Also at Università di Napoli Parthenope, Napoli, Italy.
Also at Institute of Particle Physics (IPP), Canada.
Also at Department of Physics, Middle East Technical University, Ankara, Turkey.
Also at Louisiana Tech University, Ruston LA, USA.
Also at Group of Particle Physics, University of Montreal, Montreal QC, Canada.
Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.
Also at Manhattan College, New York, NY, USA.
Also at School of Physics and Engineering, Sun Yat-sen University, Guanzhou, China.
Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.
Also at High Energy Physics Group, Shandong University, Shandong, China.
Also at Section de Physique, Université de Genève, Geneva, Switzerland.
Also at Departamento de Física, Universidade de Minho, Braga, Portugal.
Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, USA.
Also at KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary.
Also at California Institute of Technology, Pasadena CA, USA.
Also at Department of Physics, Oxford University, Oxford, United Kingdom.
Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.
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 Department of Physics, Nanjing University, Jiangsu, China.
Also at Institute of Physics, Jagiellonian University, Krakow, Poland.
Also at Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France.