Search for a Charged Higgs Boson Produced in the Vector-Boson Fusion Mode with Decay $H^\pm \rightarrow W^\pm Z$ using pp Collisions at $\sqrt{s} = 8$ TeV with the ATLAS Experiment


DOI
10.1103/PhysRevLett.114.231801

Publication date
2015

Document Version
Final published version

Published in
Physical Review Letters

Citation for published version (APA):
Search for a Charged Higgs Boson Produced in the Vector-Boson Fusion Mode with Decay $H^\pm \rightarrow W^\pm Z$ using pp Collisions at $\sqrt{s} = 8$ TeV with the ATLAS Experiment

G. Aad et al.*
(ATLAS Collaboration)

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

A search for a charged Higgs boson, $H^\pm$, decaying to a $W^\pm$ boson and a $Z$ boson is presented. The search is based on 20.3 fb$^{-1}$ of proton-proton collision data at a center-of-mass energy of 8 TeV recorded with the ATLAS detector at the LHC. The $H^\pm$ boson is assumed to be produced via vector-boson fusion and the decays $W^\pm \rightarrow q\tilde{q}^*$ and $Z \rightarrow e^+e^-/\mu^+\mu^-$ are considered. The search is performed in a range of charged Higgs boson masses from 200 to 1000 GeV. No evidence for the production of an $H^\pm$ boson is observed.

Upper limits of 31–1020 fb at 95% C.L. are placed on the cross section for vector-boson fusion production of an $H^\pm$ boson times its branching fraction to $W^\pm Z$. The limits are compared with predictions from the Georgi-Machacek Higgs triplet model.

DOI: 10.1103/PhysRevLett.114.231801 PACS numbers: 14.80.Fd, 12.60.Fr
account for the effect of multiple $pp$ interactions (pileup) occurring in the same and neighboring bunch crossings [32].

Electrons are identified for $|\eta| < 2.47$ and $p_T > 7$ GeV from energy clusters in the electromagnetic calorimeter that are matched to tracks in the inner detector [33]. Quality requirements on the calorimeter clusters and tracks are applied to reduce contamination from jets. The jet background is further reduced by applying isolation requirements that are based on tracking information within a cone around the electron candidate [34].

Muons are reconstructed in the muon spectrometer in the range $|\eta| < 2.7$ and $p_T > 7$ GeV [35]. For $|\eta| < 2.5$, the muon spectrometer track must be matched with a track in the inner detector and information from both is used to reconstruct the momentum. The muon candidates are required to pass isolation requirements similar to those for electrons.

Jets are reconstructed using the anti-$k_T$ algorithm [36] with size parameter $R = 0.4$ and are restricted to $|\eta| < 4.5$ in order to fully contain each of the jets in the calorimeters. Those jets with $|\eta| < 2.5$, where there is good tracking coverage, are called central jets and are required to have $p_T > 20$ GeV. Those jets with $2.5 < |\eta| < 4.5$ are required to have $p_T > 30$ GeV. Low-$p_T$ central jets from pileup are suppressed with the following requirement: for jets with $|\eta| < 2.4$ and $p_T < 50$ GeV, tracks associated with the primary vertex must contribute over 50% to the scalar sum of the $p_T$ of all the tracks associated with the jet. Jets originating from $b$-quark fragmentation are selected using a multivariate tagging algorithm ($b$-tagging) [37]. The $b$-tagging algorithm is only applied to central jets and its operating point is chosen such that the efficiency to select $b$-quark jets is approximately 70%.

The magnitude of the missing transverse momentum ($E_T^{\text{miss}}$) is computed using fully calibrated electrons, muons, jets, and calorimeter clusters not associated with other physics objects [38].

The $Z \rightarrow \ell^+\ell^-$ decay is reconstructed from two electrons or two muons. In events with muons, where there is a very low charge misidentification probability, the leptons must be oppositely charged. In order to match the single-lepton trigger threshold and reduce the multijet background, tighter requirements are placed on one of the leptons. These requirements are that the lepton has $p_T > 25$ GeV and, if it is a muon, is restricted to $|\eta| < 2.5$. The mass of the $Z$ boson candidate is reconstructed from the two leptons and must satisfy $83 < m_{\ell\ell} < 99$ GeV.

The VBF process generally contains two reconstructed jets, referred to as tag jets, with high $|\eta|$ in opposite directions. The tag-jet selection begins by requiring two non-$b$-tagged jets in opposite hemispheres. If more than one such pair is found, the one with the highest invariant mass is selected. The tag-jet pair must have an invariant mass greater than 500 GeV and $|\Delta\eta| > 4$.

Once a tag-jet pair has been identified, the $W^\pm \rightarrow q\bar{q}'$ decay is reconstructed from the two highest-$p_T$ remaining central jets. These jets are referred to as signal jets. In order to reduce the $Z +$ jets background, at least one signal jet is required to have $p_T > 45$ GeV. A cut on the dijet invariant mass of $60 < m_{jj} < 95$ GeV, consistent with the $W^\pm$ mass, is made.

Background from top quark production is reduced by rejecting events with two or more $b$-tagged jets and requiring the $E_T^{\text{miss}}$ significance $E_T^{\text{miss}}/\sqrt{H_T} < 6$ GeV$^{0.5}$, where $H_T$ is the scalar sum of the transverse momenta of all jets and leptons in the event.

The invariant mass of the two leptons and two signal jets $m_{\ell\ell jj}$ is used to reconstruct the charged Higgs boson mass, $m_{H^\pm}$. The resolution is improved by using the $W^\pm$ mass $m_W = 80.4$ GeV, as a constraint by scaling the energy of each jet by $m_W/m_{jj}$. The resulting experimental resolution on $m_{\ell\ell jj}$, determined from simulation, is on average 2.4% and is approximately independent of $m_{\ell\ell jj}$ over the range of the analysis.

In order to reduce the $Z +$ jets background, cuts are imposed on the transverse momentum and azimuthal angular separation of the lepton pair: $p_T^\ell > \min[0.46m_{\ell\ell jj} - 54$ GeV, $275$ GeV] and $\Delta\phi_{\ell\ell} < 1 + (270$ GeV$/m_{\ell\ell jj})^{1.35}$, and also on the transverse momentum of the signal jets $p_T^j > 0.1m_{\ell\ell jj}$. These cuts depend on the reconstructed charged Higgs boson mass since the decay products of the $W^\pm$ and $Z$ bosons in signal events tend to be at higher transverse momentum and more collimated as $m_{\ell\ell jj}$ increases. The cut values were chosen which maximized the sensitivity of the analysis.

After all cuts, a total of 506 data events are selected. The efficiency of the signal selection is 5% for a narrow width $H^\pm$ at $m_{H^\pm} = 200$ GeV, rising to a maximum of 9% at $m_{H^+} = 600$ GeV. The efficiency rises with increasing $m_{H^\pm}$ because the $W$ and $Z$ bosons receive a higher transverse boost, so fewer events fail the minimum transverse momentum requirements on the leptons and jets. The efficiency falls to 2% at 1 TeV since the products from the $W$ decay begin to overlap to form a single jet.

The dominant background after all cuts is $Z +$ jets. Other smaller backgrounds that are taken into account are top pair production, single top production, diboson production, and multijet background. The shapes of all backgrounds are determined from simulation, apart from the multijet background, which is estimated from data.

In the electron channel, the multijet background is determined by selecting a sample of events with a reversed isolation requirement on the electron. This is normalized by performing a fit to the $m_{\ell\ell}$ distribution of the data, with the normalizations of the multijet background and of a template made from the sum of the remaining backgrounds left as free parameters. The systematic error on the multijet normalization is evaluated to be 50%. It is determined by looking at the difference in scale factors obtained for a sample of events with either two or three
central jets. The multijet background in the muon channel is found to be negligible.

The normalization of the $Z + \text{jets}$ background is determined from the signal region by leaving it as a free parameter of the profile likelihood fit as discussed below. The contribution to the expected number of events in the signal region due to top quark production is constrained by comparing the observed and expected yields in a control region enriched in top quark pairs. This control region is defined by selecting events with the same cuts as those for the signal region but with an electron and a muon, rather than two same-flavor leptons, and two $b$-tagged jets with $50 < m_{jj} < 180$ GeV replacing the central-jet requirements. A total of 261 data events are selected. The other backgrounds, diboson and single top quark production, are normalized according to the theory cross section calculated at next-to-leading order as listed in Ref. [34].

The largest systematic uncertainties arise from the signal acceptance modeling, the normalization, and modeling of the $Z + \text{jets}$ and top backgrounds and from the jet energy scale.

The jet energy scale systematic uncertainty arises from several sources including uncertainties from the in situ calibration, pileup-dependent corrections, and the jet flavor composition [32]. A systematic error on the jet energy resolution is also included. These uncertainties are propagated to the $E_T^{\text{miss}}$, which also has a contribution from hadronic energy that is not included in jets [38]. The uncertainty in the pileup is accounted for by varying the cut against pileup jets and varying the assumed number of pileup interactions in the simulated events. The $b$-tagging efficiency uncertainty is dependent on jet $p_T$ and comes mainly from the uncertainty on the measurement of the efficiency in top quark pair events [37]. Other experimental systematic uncertainties that are included arise from the lepton energy scale, lepton identification efficiency, and the uncertainty on the multijet background prediction.

In addition to the experimental systematic uncertainties, modeling systematic uncertainties are included to account for possible differences between the data and the simulation model that is used for each background process, following closely the procedure described in Ref. [34]. The $Z + \text{jets}$ background includes uncertainties on the relative fractions of the different flavor components, the shape of distributions of $m_{jj}$, the azimuthal separation of the central jet pair, and the transverse momentum of the lepton pair. For top quark pair production, uncertainties on the top quark transverse momentum and $m_{jj}$ distributions are included. Uncertainties on the ratio of the numbers of events containing two and three reconstructed signal jets are also included for each background.

Modeling uncertainties on the signal acceptance are taken into account by varying the factorization and normalization scale up and down by a factor of 2, varying the amount of initial- and final-state radiation and comparing the default CTEQ6L1 PDFs to MSTW2008lo68cl [40] and NNPDF21_lo_as_0119_100 [41] PDFs. The combined signal acceptance uncertainty is $\sim 10\%$ and approximately constant with $m_{H^\pm}$.

The contribution of the various sources of uncertainty for an example production scenario is given in Table I.

### Table I. The percentage impact of the various sources of uncertainty on the expected $H^\pm$ production cross section for $m_{H^\pm} = 400$ GeV and $\sigma \times \text{BR}(H^\pm \rightarrow W^\pm Z) = 1$ pb.

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Impact (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>20</td>
</tr>
<tr>
<td>Statistical</td>
<td>14</td>
</tr>
<tr>
<td>Systematic</td>
<td>14</td>
</tr>
<tr>
<td>Experimental uncertainties</td>
<td></td>
</tr>
<tr>
<td>$\text{Jets} + E_T^{\text{miss}}$</td>
<td>8.8</td>
</tr>
<tr>
<td>Luminosity</td>
<td>2.8</td>
</tr>
<tr>
<td>Leptons</td>
<td>0.9</td>
</tr>
<tr>
<td>$b$-tagging</td>
<td>0.2</td>
</tr>
<tr>
<td>Theoretical and modeling uncertainties</td>
<td></td>
</tr>
<tr>
<td>Signal</td>
<td>10</td>
</tr>
<tr>
<td>Top</td>
<td>3.8</td>
</tr>
<tr>
<td>$Z + \text{jets}$</td>
<td>3.7</td>
</tr>
<tr>
<td>Multijet</td>
<td>0.1</td>
</tr>
</tbody>
</table>

FIG. 1 (color online). The $m_{\ell\ell jj}$ distribution for data and the expected SM background. The hashed band indicates the postfit systematic uncertainty. Included in the plot is an example signal sample with $m_{H^\pm} = 400$ GeV, which has been plotted with a cross section times branching fraction, $\sigma \times \text{BR}(H^\pm \rightarrow W^\pm Z) = 1$ pb for illustration. No data events are observed for values of $m_{\ell\ell jj} > 600$ GeV.
The data are compared with the SM expectation in Fig. 1. The expectation is determined with a profile likelihood fit [42] using the modified frequentist method, also known as CLs [43]. The fit is performed on the $m_{\ell\ell jj}$ mass distribution in the signal region and the number of events in the top quark control region. No significant excess of events is observed in the data compared with the SM expectation.

Figure 2 shows the exclusion limits at the 95% confidence level (C.L.) on the VBF production cross section times the branching fraction $\text{BR}(H^\pm \to W^\pm Z)$ as a function of $m_{H^\pm}$, assuming the signal has a small intrinsic width, i.e. much smaller than the experimental resolution. The observed limits range from 31 fb at $m_{H^\pm} = 650$ GeV to 1020 fb at $m_{H^\pm} = 220$ GeV; the corresponding expected limits are 55 fb and 719 fb, respectively. The observed limits are better for masses less than around 800 GeV than those obtained from the inclusive ATLAS WW resonance search, presented in Ref. [17], by up to a factor of 6.

The exclusion limits are compared with predicted charged Higgs boson production cross sections in the GMHTM [44], calculated at $\sqrt{s} = 8$ TeV [45]. In this model, the quantity $s_H^2$ is a free parameter that represents the fraction of the square of the gauge boson masses $m_W^2$ and $m_Z^2$ that is generated by the vacuum expectation value of the triplet, while $1 - s_H^2$ represents the fraction generated by the SM Higgs doublet. The production cross section and $H^\pm$ width are proportional to $s_H^2$. The branching fraction of $H^\pm \to W^\pm Z$ is expected to be very high above the $W^\pm Z$ threshold, so for simplicity it is set to 1. For this comparison, a nonzero intrinsic $H^\pm$ width must be taken into account. This is done by smearing the signal $m_{\ell\ell jj}$ distributions with a relativistic Breit-Wigner distribution with a width as calculated in Ref. [45]. The fractional width $\Gamma_{H^\pm}/m_{H^\pm}$ for $s_H = 1$ increases from 0.2% at $m_{H^\pm} = 200$ GeV to 31% at $m_{H^\pm} = 1000$ GeV. Comparisons with the GMHTM are only shown for $\Gamma_{H^\pm}/m_{H^\pm} < 0.15$, since higher values may violate perturbative unitarity of the $W^\pm Z \to W^\pm Z$ scattering amplitudes. As shown in Fig. 3, the data exclude a charged Higgs boson over the range $240 < m_{H^\pm} < 700$ GeV for $s_H = 1$, with weaker limits for smaller values of $s_H$.

In conclusion, data recorded by the ATLAS experiment at the LHC, corresponding to an integrated luminosity of 20.3 fb$^{-1}$ at a center-of-mass energy of 8 TeV, have been used to search for a charged Higgs boson, produced via vector-boson fusion and decaying to $W^\pm Z$, over the charged Higgs boson mass range 200–1000 GeV. This is the first search for this process. No deviation from the SM background prediction is observed. Upper limits at the 95% confidence level on the cross section of a VBF-produced $H^\pm$ boson times its branching fraction to $W^\pm Z$ are set between 31 and 1020 fb for a narrow $W^\pm Z$ resonance. The data exclude a charged Higgs boson in the range $240 < m_{H^\pm} < 700$ GeV within the Georgi-Machacek Higgs triplet model with parameter $s_H = 1$ and 100% branching fraction of $H^\pm \to W^\pm Z$.

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; BMWFW and FWF, Austria; ANAS, Azerbaijan; STFC, 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; EPLANET, ERC and NSRF, European Union; IN2P3-CNRS, CEA-DSM/IRFU, France; GNSF, Georgia; BMBF, DFG, HGF, MPG and AvH Foundation, Germany; SRRT and NSRF, Greece; RGC, Hong Kong SAR, China; ISF, MINERVA, GIF, I-CORE and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; BRF and RCN, Norway; MNISw and NCN, Poland; GRICES and FCT, Portugal; MNE/IFA, Romania; MES of Russia and ROSATOM, Russian Federation; JINR; MSTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DST/NRF, South Africa; MINECO, 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, USA. 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.

Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
School of Physics, University of Sydney, Sydney, Australia
Institute of Physics, Academia Sinica, Taipei, Taiwan
Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
Department of Physics, University of Toronto, Toronto, Ontario, Canada
TRIUMF, Vancouver, British Columbia, Canada
Department of Physics and Astronomy, York University, Toronto, Ontario, Canada
Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan
Department of Physics and Astronomy, Tufts University, Medford, Massachusetts, USA
Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
Department of Physics and Astronomy, University of California Irvine, Irvine, California, USA
INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine, Italy
ICTP, Trieste, Italy
Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
Department of Physics, University of Illinois, Urbana Illinois, USA
Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectronica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain
Department of Physics, University of British Columbia, Vancouver, British Columbia, Canada
Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia, Canada
Department of Physics, University of Warwick, Coventry, United Kingdom
Waseda University, Tokyo, Japan
Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
Department of Physics, University of Wisconsin, Madison, Wisconsin, USA
Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany
Department of Physics, Yale University, New Haven, Connecticut, USA
Yerevan Physics Institute, Yerevan, Armenia
Centre de Calcul de l’Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France

\(^{a}\)Deceased.
\(^{b}\)Also at Department of Physics, King’s College London, London, United Kingdom.
\(^{c}\)Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
\(^{d}\)Also at Novosibirsk State University, Novosibirsk, Russia.
\(^{e}\)Also at TRIUMF, Vancouver BC, Canada.
\(^{f}\)Also at Department of Physics, California State University, Fresno CA, USA.
\(^{g}\)Also at Department of Physics, University of Fribourg, Fribourg, Switzerland.
\(^{h}\)Also at Departamento de Fisica e Astronomia, Faculdade de Ciencias, Universidade do Porto, Portugal.
\(^{i}\)Also at Tomsk State University, Tomsk, Russia.
\(^{j}\)Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.
\(^{k}\)Also at Università di Napoli Parthenope, Napoli, Italy.
\(^{l}\)Also at Department of Particle Physics (IPP), Canada.
\(^{m}\)Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom.
\(^{n}\)Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia.
\(^{o}\)Also at Louisiana Tech University, Ruston LA, USA.
\(^{p}\)Also at Instituto Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.
\(^{q}\)Also at Department of Physics, National Tsing Hua University, Taiwan.
\(^{r}\)Also at Department of Physics, The University of Texas at Austin, Austin TX, USA.
\(^{s}\)Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.
\(^{t}\)Also at CERN, Geneva, Switzerland.
\(^{u}\)Also at Georgian Technical University (GTU), Tbilisi, Georgia.
\(^{v}\)Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan.
\(^{w}\)Also at Manhattan College, New York NY, USA.
\(^{x}\)Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.
\(^{y}\)Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.
\(^{z}\)Also at LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France.
Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.

Also at School of Physics, Shandong University, Shandong, China.

Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.

Also at Section de Physique, Université de Genève, Geneva, Switzerland.

Also at International School for Advanced Studies (SISSA), Trieste, Italy.

Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, USA.

Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China.

Also at Faculty of Physics, M.V.Lomonosov Moscow State University, Moscow, Russia.

Also at National Research Nuclear University MEPhI, Moscow, Russia.

Also at Department of Physics, Stanford University, Stanford CA, USA.

Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.

Also at Department of Physics, The University of Michigan, Ann Arbor MI, USA.

Also at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa.

Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia.