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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

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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 $W^\pm \rightarrow q\bar{q}'$ 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.

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After the discovery of a Higgs boson at the LHC in 2012 [1,2], an important question now is whether the newly discovered particle is part of an extended scalar sector. The discovery of additional scalar or pseudoscalar bosons would provide spectacular evidence that this is the case.

A charged Higgs boson H^\pm appears in many models with an extended scalar sector such as the two Higgs doublet model, where a second Higgs doublet is introduced [3], and the Higgs Triplet Models [4,5], where a triplet is added to the Higgs doublet of the standard model (SM). While $H^\pm \rightarrow \tau^\pm \nu, cs, tb$ decays dominate in the two Higgs doublet model at tree level, $H^\pm \rightarrow W^\pm Z$ decays are allowed at loop level [6] and are predicted at tree level in Higgs triplet models. In the search presented in this Letter, the H^\pm boson is assumed to couple to W^\pm and Z bosons. In this case, it is produced via vector-boson fusion (VBF), $W^\pm Z \rightarrow H^\pm$, at the LHC and decays to $W^\pm Z$. The search is performed in the channel with subsequent decays of $W^\pm \rightarrow q\bar{q}'$ and $Z \rightarrow \ell^+\ell^-$, over the H^\pm mass range $200 < m_{H^\pm} < 1000$ GeV. The data are compared with the Georgi-Machacek Higgs triplet model (GMHTM) [4].

Searches at LEP have looked for pair-produced charged Higgs bosons [7]. Previous searches at the Tevatron and LHC have looked for a charged Higgs boson produced in top quark decays or in associated production with a top quark [8–11]. Searches for a $W^\pm Z$ resonance have also been performed in non-Higgs-specific models [12–18], but this search is the first to look specifically for the VBF production mechanism.

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The data used in this search were recorded with the ATLAS detector in proton-proton collisions at a center-of-mass energy of $\sqrt{s} = 8$ TeV. In the ATLAS coordinate system, the polar angle θ is measured with respect to the LHC beam line and the azimuthal angle ϕ is measured in the plane transverse to the beam line. Pseudorapidity is defined as $\eta = -\ln \tan(\theta/2)$.

The ATLAS detector is described in detail elsewhere [19]. It consists of an inner tracking detector covering the range $|\eta| < 2.5$, surrounded by a superconducting solenoid providing a 2 T magnetic field, electromagnetic and hadronic calorimeters ($|\eta| < 4.9$), and an external muon spectrometer ($|\eta| < 2.7$), consisting of three air-core toroidal magnets, interspersed with high-precision tracking chambers. The integrated luminosity of the data sample, considering only data-taking periods where all relevant detector subsystems were operational, is $20.3 \pm 0.6 \text{ fb}^{-1}$ [20]. The data were collected using a combination of single-electron, single-muon, electron-electron, and muon-muon triggers. The higher level p_T thresholds for both electrons and muon triggers are 24 GeV for the single-lepton triggers and 13 GeV for the dilepton triggers.

Monte Carlo simulated events are used to estimate distributions of expected signal and background events. Signal events are generated for a narrow-width H^\pm boson produced via VBF with MADGRAPH5 [21] using CTEQ6L1 [22] parton distribution functions (PDFs). The parton showering is performed with PYTHIA8 [23,24]. The dominant background is the production of Z bosons in association with jets, which is simulated with SHERPA [25] using CT10 PDFs [26]. Top quark pair, single top quark and diboson production are simulated with POWHEG [27–29] using CTEQ6L1 PDFs.

All simulated samples are passed through the ATLAS GEANT4-based detector simulation [30,31]. The simulated events are overlaid with additional minimum-bias events to

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_r 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^{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 $Z + \text{jets}$ 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^{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 [39], $m_W = 80.4$ 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 $Z + \text{jets}$ background, cuts are imposed on the transverse momentum and azimuthal angular separation of the lepton pair: $p_T^{\ell\ell} > \min[0.46m_{\ell\ell jj} - 54 \text{ GeV}, 275 \text{ GeV}]$ and $\Delta\phi_{\ell\ell} < 1 + (270 \text{ GeV}/m_{\ell\ell jj})^{3.5}$, 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 $m_{H^\pm} = 600$ 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 $Z + \text{jets}$. 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^{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

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.

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

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.

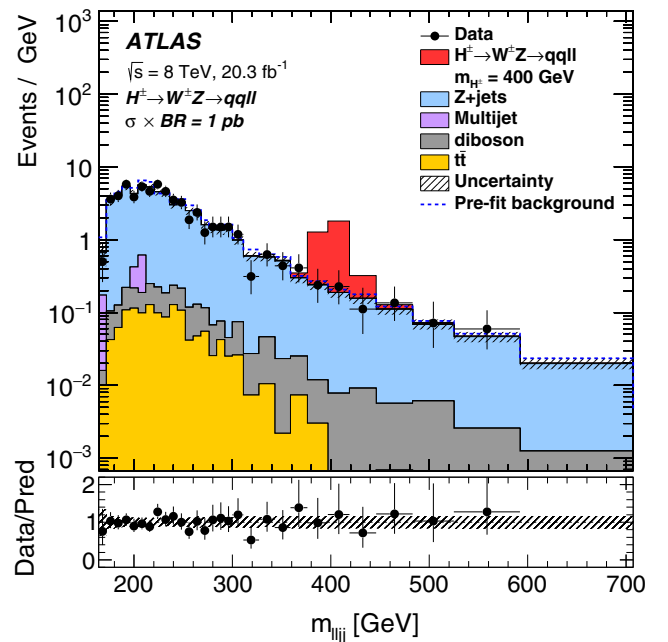


FIG. 1 (color online). The $m_{\ell\ell jj}$ distribution for data and the expected SM background. The hashed band indicates the postfit systematic uncertainty. Included in the plot is an example signal sample with $m_{H^\pm} = 400$ GeV, which has been plotted with a cross section times branching fraction, $\sigma \times \text{BR}(H^\pm \rightarrow W^\pm Z) = 1$ pb for illustration. No data events are observed for values of $m_{\ell\ell jj} > 600$ GeV.

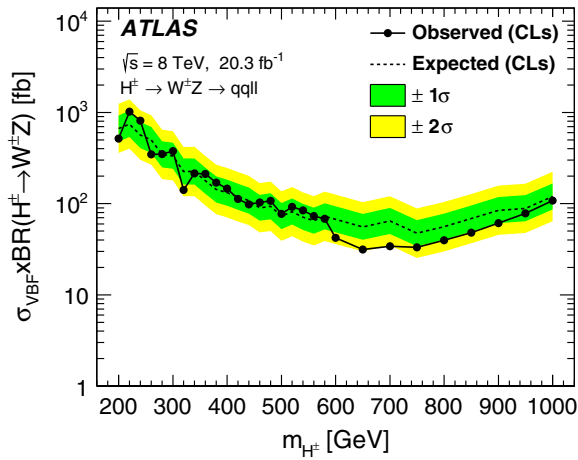


FIG. 2 (color online). Exclusion limits in fb at the 95% C.L. for the vector-boson fusion production cross section of a H^\pm boson times its branching fraction to $W^\pm Z$, assuming the signal has a narrow intrinsic width. Also included on the plot are the median, $\pm 1\sigma$, and $\pm 2\sigma$ values within which the limit is expected to lie in the absence of a signal.

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 CL_s [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 $BR(H^\pm \rightarrow W^\pm Z)$ 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 WZ 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 $H^\pm \rightarrow W^\pm Z$ 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

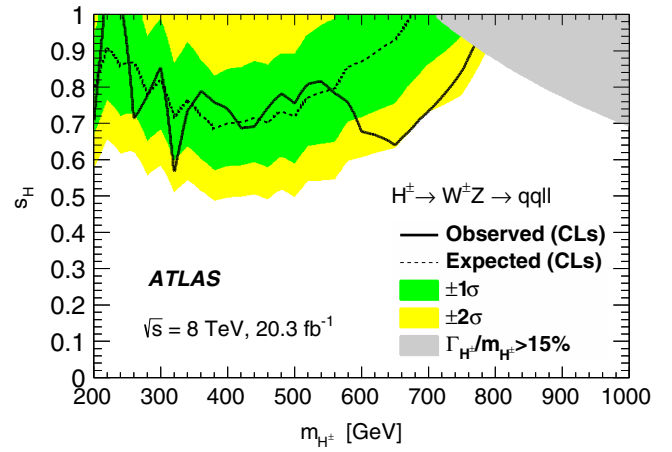


FIG. 3 (color online). Exclusion limits at the 95% C.L. for s_H versus m_{H^\pm} in the Georgi-Machacek Higgs triplet model. Also included on the plot are the median, $\pm 1\sigma$, and $\pm 2\sigma$ values within which the limit is expected to lie in the absence of a signal.

with a width as calculated in Ref. [45]. The fractional width Γ_{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 $W^\pm Z \rightarrow W^\pm Z$ 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 $H^\pm \rightarrow W^\pm Z$.

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