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Search for the Decay of the Higgs Boson to Charm Quarks with the ATLAS Experiment

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A direct search for the standard model Higgs boson decaying to a pair of charm quarks is presented. Associated production of the Higgs and Z bosons, in the decay mode \(ZH \to \ell^+\ell^-c\bar{c}\) is studied. A data set with an integrated luminosity of 36.1 fb\(^{-1}\) of \(pp\) collisions at \(\sqrt{s} = 13\) TeV recorded by the ATLAS experiment at the LHC is used. The \(H \to c\bar{c}\) signature is identified using charm-tagging algorithms. The observed (expected) upper limit on \(\sigma(pp \to ZH) \times \mathcal{B}(H \to c\bar{c})\) is 2.7 (3.9\(\pm1\)) pb at the 95% confidence level for a Higgs boson mass of 125 GeV, while the standard model value is 26 fb.

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In July 2012, the ATLAS and CMS collaborations announced the discovery of a new particle with a mass of approximately 125 GeV [1,2] in searches for the standard model (SM) Higgs boson at the Large Hadron Collider (LHC) [3]. Subsequent measurements indicate that this particle is consistent with the SM Higgs boson [4–10]. Direct evidence for the Yukawa coupling of the Higgs boson to the top [11] and bottom [12,13] quarks was recently obtained. Measurements of the Yukawa coupling of the Higgs boson to quarks in generations other than the third are difficult at hadron colliders, due to small branching fractions, large backgrounds, and challenges in jet flavor identification [14,15]. This Letter presents a direct search by the ATLAS experiment for the decay of the Higgs boson to a pair of charm (c) quarks. This search targets the production of the Higgs boson in association with a Z boson decaying to charged leptons: \(Z(\ell^+\ell^-)H(c\bar{c})\), where \(\ell = e, \mu\).

The SM branching fraction for a Higgs boson with a mass of 125 GeV to decay to a pair of charm quarks is predicted to be 2.9% [16]. The inclusive cross section for \(\sigma(pp \to ZH) \times \mathcal{B}(H \to c\bar{c})\) is 26 fb at \(\sqrt{s} = 13\) TeV [17]. Rare exclusive decays of the Higgs boson to a light vector meson or quarkonium state and a photon can also probe the couplings of the second-generation quarks to the Higgs boson [18–21]. Previously, the ATLAS Collaboration presented the second search for the decay of the Higgs boson to charge leptons with a branching fraction limit of \(1.5 \times 10^{-3}\) at the 95% confidence level (C.L.), which approximately corresponds to a limit of 540 times the SM branching fraction prediction [14,20]. Bounds on the Higgs boson branching fractions to unobserved final states and fits to global rates constrain \(\mathcal{B}(H \to c\bar{c}) < 20\%\) at the 95% C.L., assuming SM production cross sections [22]. These limits can still accommodate large modifications to the Higgs boson coupling to charm quarks from new physics [22]. In this Letter, a new approach is introduced to investigate the coupling of the Higgs boson to charm quarks.

The search is performed using \(pp\) collision data recorded in 2015 and 2016 with the ATLAS detector [23] at \(\sqrt{s} = 13\) TeV. The ATLAS detector at the LHC covers nearly the entire solid angle around the collision point [24]. It consists of an inner tracking detector surrounded by a thin superconducting solenoid, electromagnetic and hadronic calorimeters, and a muon spectrometer incorporating three large superconducting toroidal magnets. An additional pixel layer was installed for the \(\sqrt{s} = 13\) TeV running period [25]. After the application of beam, detector, and data-quality requirements, the integrated luminosity corresponds to 36.1 \(\pm 0.8\) fb\(^{-1}\), measured following Ref. [26]. Events are required to contain exactly two same-flavor leptons with an invariant mass consistent with that of the Z boson, and at least two jets of which one or two are identified as charm jets (c jets). In this Letter, lepton refers to only electrons or muons. The analysis procedure is validated by measuring the yield of \(ZW\) and \(ZZ\) production, where the sample is enriched in \(W \to cs, cd\) and \(Z \to c\bar{c}\) decays. Further details can be found in Ref. [12].

Monte Carlo (MC) simulated samples were produced for signal and background processes using the full ATLAS detector simulation [27] using GEANT4 [28]. Table I provides details of the event generators used for each signal and background sample. Signal events were produced at next-to-leading order (NLO) for the \(q\bar{q} \to ZH\) process and at leading order (LO) for the \(gg \to ZH\) process with POWHEG-BOX v2 [32]. The dominant \(Z +\) jets background and the resonant diboson \(ZW\) and \(ZZ\) processes were generated using SHERPA 2.2.1 [54]. The \(\tilde{t}\tilde{t}\) background was...
TABLE I. The configurations used for event generation of the signal and background processes. If two parton distribution functions (PDFs) are shown, the first is for the matrix element calculation and the second for the parton shower, otherwise the same is used for both. Alternative event generators and configurations, used to estimate systematic uncertainties, are in parentheses. Tune refers to the underlying-event tuned parameters of the parton shower event generator. MG5_AMC refers to MadGraph5_AMC@NLO 2.2.2 [29]; PYTHIA 8 refers to version 8.212 [30]. Heavy-flavor hadron decays modeled by EvtGen 1.2.0 [31] are used for all samples except those generated using SHERPA. The order of the calculation of the cross sections used to normalize the predictions is indicated. The $q\bar{q} \rightarrow ZH$ cross section is estimated by subtracting the $gg \rightarrow ZH$ cross section from the $pp \rightarrow ZH$ cross section. The asterisk (*) in the last column denotes that the indicated order is for the $pp \rightarrow ZH$ cross section. NNLO denotes next-to-next-to-leading order; NLL denotes next-to-leading log and NNLL denotes next-to-next-to-leading log.

<table>
<thead>
<tr>
<th>Process</th>
<th>Event Generator (alternative)</th>
<th>Parton Shower (alternative)</th>
<th>PDF (alternative)</th>
<th>Tune</th>
<th>Cross section</th>
</tr>
</thead>
<tbody>
<tr>
<td>$q\bar{q} \rightarrow ZH$</td>
<td>POWHEG-BOX v2 [32] +GoSAm [35] +MiNLO [45,46]</td>
<td>PYTHIA 8 (HERWIG 7 [47])</td>
<td>PDF4LHC15NLO [33] /CTEQ6L1 [36,37]</td>
<td>AZNLO [34]</td>
<td>NNLO (QCD)*</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>NLO (EW) [38-44]</td>
</tr>
<tr>
<td>$gg \rightarrow ZH$</td>
<td>POWHEG-BOX v2</td>
<td>PYTHIA 8 (HERWIG 7)</td>
<td>PDF4LHC15NLO /CTEQ6L1</td>
<td>AZNLO</td>
<td>NLO + NNLL (QCD) [17,49-51]</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>POWHEG-BOX v2</td>
<td>PYTHIA 8 (HERWIG 7)</td>
<td>NNPDF3.0NLO /NNPDF2.3LO</td>
<td>A14</td>
<td>NLO</td>
</tr>
<tr>
<td>$ZW, ZZ$</td>
<td>SHERPA 2.2.1 [54] (POWHEG-BOX)</td>
<td>SHERPA (PYTHIA 8)</td>
<td>NNPDF3.0NNLO</td>
<td>SHERPA</td>
<td>SHERPA</td>
</tr>
<tr>
<td>$Z + \text{jets}$</td>
<td>SHERPA 2.2.1 (MG5_AMC)</td>
<td>SHERPA (PYTHIA 8)</td>
<td>NNPDF3.0NNLO /NNPDF2.3LO</td>
<td>(A14)</td>
<td>NNLO [55]</td>
</tr>
</tbody>
</table>

Events are required to contain at least two reconstructed jets. If a muon is found within a jet, its momentum is added to the selected jet. An overlap removal procedure resolves cases in which the same physical object is reconstructed multiple times, e.g. an electron also reconstructed as a jet.

<table>
<thead>
<tr>
<th>$p_T$ threshold</th>
<th>$\eta$ threshold</th>
<th>Efficiency WP</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 GeV</td>
<td>&lt; 2.5</td>
<td>41%</td>
</tr>
<tr>
<td>26 GeV</td>
<td>&lt; 2.5</td>
<td>30%</td>
</tr>
<tr>
<td>27 GeV</td>
<td>&lt; 2.5</td>
<td>20%</td>
</tr>
<tr>
<td>24 GeV</td>
<td>&lt; 2.5</td>
<td>10%</td>
</tr>
</tbody>
</table>

Events are required to contain at least two jets. If a muon is found within a jet, its momentum is added to the selected jet. An overlap removal procedure resolves cases in which the same physical object is reconstructed multiple times, e.g. an electron also reconstructed as a jet.

![ATLAS Simulation](image-url) FIG. 1. The $c$-jet-tagging efficiency (colored scale) as a function of the $b$ jet and $l$ jet rejection as obtained from simulated $t\bar{t}$ events. The cross, labeled as working point, WP, denotes the selection criterion used in this analysis. The solid and dotted black lines indicate the contours in rejection space for the fixed $c$-tagging efficiency used in the analysis and two alternatives.
Jets in simulated events are labeled according to the presence of a heavy-flavor hadron with $p_T > 5$ GeV within $\Delta R = 0.3$ from the jet axis. If a $b$ hadron is found the jet is labeled as a $b$ jet. If no $b$ hadron is found, but a $c$ hadron is present, then the jet is labeled as a $c$ jet. Otherwise the jet is labeled as a light-flavor jet ($l$ jet).

Flavor-tagging algorithms exploit the different lifetimes of $b$, $c$, and light-flavor hadrons. A $c$-tagging algorithm is used to identify $c$ jets. Charm jets are particularly challenging to tag because $c$ hadrons have shorter lifetimes and decay to fewer charged particles than $b$ hadrons. Boosted decision trees are trained to obtain two multivariate discriminants: to separate $c$ jets from $l$ jets and $c$ jets from $b$ jets. The same variables used for $b$ tagging [67,68] are used. Figure 1 shows the selection criteria applied in the two-dimensional multivariate discriminant space, to obtain an efficiency of 41% for $c$ jets and rejection factors of 4.0 and 20 for $b$ jets and $l$ jets. The efficiencies are calibrated to data using $b$ quarks from $t \rightarrow Wb$ and $c$ quarks from $W \rightarrow cs$, $cd$ with methods identical to the $b$-tagging algorithms [67]. Statistical uncertainties in the simulation are reduced, by weighting events according to the tagging efficiencies of their jets, parametrized as a function of jet flavor, $p_T$, $\eta$ and the angular separation between jets, rather than imposing a direct requirement on the $c$-tagging discriminants.

Data are analyzed in four categories with different expected signal purities. The dijet invariant mass, $m_{cc}$, constructed using the two highest-$p_T$ jets, is the discriminating variable in each category. Categories are defined using the transverse momentum of the reconstructed $Z$ boson, $p_T^Z$ ($75$ GeV $\leq p_T^Z < 150$ GeV and $p_T^Z \geq 150$ GeV) and the number of $c$ tags amongst the leading jets (either one or two). The $p_T^Z$ requirements exploit the harder $p_T^Z$ distribution in $ZH$ compared to $Z +$ jets production. Background events are rejected by requiring the angular separation between the two jets constituting the dijet system, $\Delta R_{cc}$, to be less than 2.2, 1.5, or 1.3 for events satisfying $75 \leq p_T^Z < 150$ GeV, $150 \leq p_T^Z < 200$ GeV, or $p_T^Z \geq 200$ GeV. The signal acceptance ranges from 0.5% to 3.4% depending on the category. A joint binned maximum-profile-likelihood fit to $m_{cc}$ in the categories is used to extract the signal yield and the $Z +$ jets background normalization. The fit uses 15 bins in each category within the range of 50 GeV $< m_{cc} < 200$ GeV, with a bin width of 10 GeV. The parameter of interest, $\mu$, common to all categories, is the signal strength, defined as the ratio of the measured signal yield to the SM prediction.

Systematic uncertainties affecting the signal and background predictions include theoretical uncertainties in the signal and background modeling and experimental uncertainties. Table II shows their relative impact on the fitted value of $\mu$. Uncertainties in the $m_{cc}$ shape of the backgrounds are assessed by comparisons between nominal and alternative event generators as indicated in Table I.

Systematic uncertainties are incorporated within the statistical model through nuisance parameters that modify the shape and/or normalization of the distributions. Statistical uncertainties in the simulation samples are accounted for. The $Z +$ jets background is normalized from the data through the inclusion of an unconstrained normalization parameter for each category. The fitted

<table>
<thead>
<tr>
<th>Sample</th>
<th>Yield, 50 GeV $&lt; m_{cc} &lt; 200$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 $c$ tag</td>
</tr>
<tr>
<td>$75 \leq p_T^Z &lt; 150$ GeV</td>
<td>$p_T^Z \geq 150$ GeV</td>
</tr>
<tr>
<td>$Z +$ jets</td>
<td>69400 ± 500</td>
</tr>
<tr>
<td>$ZW$</td>
<td>750 ± 130</td>
</tr>
<tr>
<td>$ZZ$</td>
<td>490 ± 70</td>
</tr>
<tr>
<td>$\bar{t}t$</td>
<td>2020 ± 280</td>
</tr>
<tr>
<td>$ZH(b\bar{b})$</td>
<td>32 ± 2</td>
</tr>
<tr>
<td>$ZH(c\bar{c})$ (SM)</td>
<td>−143 ± 170 (2.4)</td>
</tr>
<tr>
<td>Total</td>
<td>72500 ± 320</td>
</tr>
<tr>
<td>Data</td>
<td>72504</td>
</tr>
</tbody>
</table>
The analysis procedure is validated by measuring the yield of ZV production, where V denotes a W or Z boson, with the same event selection. The fraction of the ZZ yield from $Z \rightarrow c\bar{c}$ decays is $\sim 55\%$ (20\%) in the 2 c tag (1 c tag) category, while the fraction of the ZW yield from $W \rightarrow c\bar{s}$, $c\bar{d}$ is $\sim 65\%$ for both the 2 and 1 c tag categories. Contributions of Higgs boson decays to $c\bar{c}$ and $b\bar{b}$ are treated as background and constrained to the SM predictions within its theoretical uncertainties. The diboson signal strength is measured to be $\mu_{ZV} = 0.9 \pm 0.1$, with an observed (expected) significance of 1.4 (2.2) standard deviations.

The best-fit value for the $ZH(c\bar{c})$ signal strength is $\mu_{ZH} = -69 \pm 101$. By assuming a signal with the kinematics of the SM Higgs boson, model-dependent corrections are made to extrapolate to the inclusive phase space. Hence, an upper limit on $\sigma(pp \rightarrow ZH) \times B(H \rightarrow c\bar{c})$ is computed using a modified frequentist CL$_s$ method [69,70] with the profile likelihood ratio as the test statistic. The observed (expected) upper limit is found to be 2.7 (3.9$^{+2.1}_{-1.1}$) pb at the 95\% C.L. This corresponds to an observed (expected) upper limit on $\mu$ at the 95\% C.L. of 110 (150$^{+80}_{-40}$). The uncertainties in the expected limits correspond to the $\pm 1\sigma$ interval of background-only pseudoexperiments. With the current sensitivity, the result depends weakly on the assumption of the SM rate for $H \rightarrow b\bar{b}$. The observed limit remains within 5\% of the nominal value when the assumed value for normalization of the $ZH(b\bar{b})$ background is varied from zero to twice the SM prediction.

A search for the decay of the Higgs boson to charm quarks has been performed using 36.1 fb$^{-1}$ of data collected with the ATLAS detector in $pp$ collisions at $\sqrt{s} = 13$ TeV at the LHC. No significant excess of $ZH(c\bar{c})$ production is observed over the SM background expectation. The observed upper limit on $\sigma(pp \rightarrow ZH) \times B(H \rightarrow c\bar{c})$ is 2.7 pb at the 95\% C.L. The corresponding expected upper limit is 3.9$^{+2.1}_{-1.1}$ pb. This is the most stringent limit to date in direct searches for the inclusive decay of the Higgs boson to charm quarks.

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the polar angle $\theta$ as $\eta = -\ln \tan(\theta/2)$. Angular distance is measured in units of $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}$.


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