Search for Higgs boson decays into a Z boson and a light hadronically decaying resonance using 13 TeV pp collision data from the ATLAS detector

Aad, G.; ATLAS Collaboration

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Search for Higgs Boson Decays into a Z Boson and a Light Hadronically Decaying Resonance Using 13 TeV pp Collision Data from the ATLAS Detector

G. Aad et al.*
(ATLAS Collaboration)

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A search for Higgs boson decays into a Z boson and a light resonance in two-lepton plus jet events is performed, using a pp collision dataset with an integrated luminosity of 139 fb$^{-1}$ collected at $\sqrt{s} = 13$ TeV by the ATLAS experiment at the CERN LHC. The resonance considered is a light boson with a mass below 4 GeV from a possible extended scalar sector or a charmonium state. Multivariate discriminants are used for the event selection and for evaluating the mass of the light resonance. No excess of events above the expected background is found. Observed (expected) 95% confidence-level upper limits are set on the Higgs boson production cross section times branching fraction to a Z boson and the signal resonance, with values in the range 17–340 pb (16.5–320$^{+130}_{-60}$ pb) for the different light spin-0 boson mass and branching fraction hypotheses, and with values of 110 and 100 pb (100$^{+40}_{-30}$ and 100$^{+40}_{-30}$ pb) for the $\eta_c$ and $J/\psi$ hypotheses, respectively.

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The structure of the standard model (SM) scalar sector is the subject of intense scrutiny by the ATLAS [1] and CMS [2] Collaborations at the CERN Large Hadron Collider (LHC) [3]. At the current level of precision, all of the measured properties of the Higgs boson ($H$) [4,5] are found to be consistent with their SM predictions [6–10], and no additional Higgs boson has been observed to date. However, given the small natural decay width of the Higgs boson, even small additional contributions from physics beyond the SM can lead to final states with substantial, and thus possibly detectable, branching fractions ($B$) [11]. This Letter presents a search for Higgs boson decays into a Z boson and a hadronically decaying light resonance in events with a same-flavor lepton pair (electrons or muons) and a jet in the ATLAS detector. Hadronic decays of an $\eta_c$ or of a $J/\psi$ charmonium resonance ($Q$), or of a light spin-0 boson from an extended Higgs sector with a mass up to 4 GeV, are considered and are reconstructed as a single jet.

The Yukawa sector of the SM [12] does not provide an explanation for the observed fermion mass hierarchy. As a result, a wide range of new physics scenarios have been proposed, including the Froggatt-Nielsen mechanism [13] and the Higgs-dependent Yukawa couplings model [14]; for a recent overview, see Ref. [15]. The couplings of the Higgs boson to the third-generation fermions [16–21] have been observed, and a program to probe its couplings to the first- and second-generation charged leptons has been established [22–25]. For its couplings to first- and second-generation quarks, several approaches are being explored. Focusing on the Higgs boson’s coupling to the charm quark, direct searches have been performed for Higgs boson decays into charm quarks [26,27] and for exclusive decays into a $J/\psi$ and a photon [28,29], with no excess observed. Constraints from differential cross section measurements of Higgs boson production versus transverse momentum ($p_T$) have also been derived [30,31]. Higgs boson decays into a gauge boson and a charmonium state, including an $\eta_c$ or a $J/\psi$, have been proposed as another way to access the coupling of the Higgs boson to the charm quark [32–34] and to probe the nature of the Higgs boson [35]. This search follows the last approach and maximizes the signal acceptance by focusing on inclusive hadronic final states of the mesons in $H \to Z\eta_c$ and $H \to ZJ/\psi$ decays, which have SM branching fractions of $1.4 \times 10^{-5}$ and $2.2 \times 10^{-6}$ [35], respectively.

While the SM postis a single complex Higgs doublet field [36,37], extended Higgs sectors are motivated [38] and provide a rich phenomenology of additional scalars. Two such models discussed here are the two-Higgs-doublet model (2HDM) [11,39] and the 2HDM with an additional scalar singlet (2HDM + S) [11,40]. These represent two of the simplest extensions of the scalar sector, and with their type-II fermion couplings they are necessary to generate the masses in the minimal supersymmetric SM and the next-to-minimal supersymmetric SM, respectively [41]. Both of these models can include additional light pseudoscalars ($a$) with significant $B(H \to Za)$ or $B(H \to aa)$ [11]. In the
2HDM(±S), these two $B$ values can be adjusted independently, therefore searches for $H \to aa$ do not constrain $B(H \to Za)$, so that searches for the latter decay are required [11,34]. Despite the Yukawa nature of the $a$ to fermion couplings, there are large regions of parameter space depending on the mass of $a$ and the ratio of the vacuum expectation values of the two Higgs-doublet fields ($\tan \beta$) [11], where these pseudoscalars decay mainly to gluons and light up-type quarks, as the decays into down-type fermions are suppressed. These experimental signatures are also relevant in axion models [42–44], models of electroweak baryogenesis [45], neutrino mass models [46], dark-matter models [46,47], and models of grand unification [48]. Previous searches for Higgs boson decays into light scalars have been performed at the Tevatron [49] and the LHC [50–59]. However, these were mostly focused on searches for $H \to aa$, in final states including leptons, photons, or bottom quarks. By targeting the classification performance over the full mass range, the classifier is provided with previously unexplored regions of the parameter space.

Searches for hadronic decays of light resonances are challenging at the LHC due to the large multijet background. However, substantial progress has been made in the use of jet substructure techniques in boosted final states [60], typically in searches or measurements involving heavy resonances [61,62]. In this Letter, jet substructure variables enable the reconstruction of a light, boosted, hadronic final state. Information from the individual substructure variables is combined using machine learning techniques. Specifically, for event selection, a multilayer perceptron (MLP) [63] classifier is employed. Given the range of masses considered, the classifier is provided with resonance-mass-related information from a separate MLP-based mass estimator, which results in improved classification performance over the full mass range.

This search is performed using the complete run 2 $pp$ collision dataset, produced between 2015 and 2018 at a center-of-mass energy $\sqrt{s} = 13$ TeV by the LHC. The data were collected by the ATLAS detector [1] and correspond to an integrated luminosity of 139 fb$^{-1}$.

Monte Carlo (MC) samples of simulated events are used to model the signal selection efficiency. The signal samples were generated via the gluon-gluon fusion process using POWHEG-BOX v2 [64–66], with the CT10 next-to-leading order (NLO) parton distribution function (PDF) set [67]. Particle decays, hadronization, parton showers, and the underlying event were modeled using PYTHIA v8.230 and EvtGen v1.6.0. The NNPDF 2.3 (LO) PDF set [75] and the A14 set of tuned parameters [76] were used.

The simulation of the ATLAS detector [77] in GEANT4 [78] was used to model the interaction of particles with the detector in all the MC samples. Data-driven corrections are applied to the event-level trigger efficiencies, the jet vertex tagging efficiency [79], the electron [80] reconstruction, isolation, and track-to-vertex association efficiencies.

Events are selected by a combination of single electron or muon triggers for each data-taking period [82–85], and the online lepton reconstructed by the trigger is required to be within $\Delta R = 0.1$ [86] of an off-line reconstructed lepton. Events are required to have at least one reconstructed primary interaction vertex [87]. Electron candidates are reconstructed by matching tracks in the inner detector to topological energy clusters in the electromagnetic calorimeter [80] and must pass a likelihood-based selection, which requires the shower profile to be compatible with that of an electromagnetic shower. Muons are reconstructed using tracks in the muon spectrometer, matched to tracks in the inner detector where available [88]. Electrons and muons are each required to have $p_T > 18$ GeV, and at least one must have $p_T > 27$ GeV. Electrons (muons) are required to be reconstructed within $|\eta| < 2.47$ ($|\eta| < 2.7$), but electrons within $1.37 < |\eta| < 1.52$ are excluded. The transverse energy sum in a cone of size $\Delta R = 0.2$ around the electron [muon] in the calorimeter must be less than 20% (30%) of the lepton’s $p_T$, and the summed $p_T$ of tracks within a cone of variable size $\Delta R = \min(0.2, 10 \text{ GeV}/p_T)$ [$\Delta R = \min(0.15, 10 \text{ GeV}/p_T)$] around the electron [muon] must be less than 15% of its $p_T$. Contributions from nearby electrons and muons are removed from these cones. If an inner detector track is present, muons must also have a longitudinal impact parameter $|d_0| \sin \theta < 0.5$ mm and a transverse impact parameter $|d_0| < 1$ mm relative to the primary interaction vertex. At least two same-flavor
opposite-sign electrons or muons are required to pass this selection and have an invariant mass compatible with the mass of the Z boson: $81 < m_{\ell\ell} < 101$ GeV. If multiple same-flavor opposite-sign lepton pairs fulfill this requirement, the pairing with an invariant mass closest to that of the Z boson is chosen. $Z \rightarrow \tau\tau$ decays are reconstructed through the leptonic decays of the $\tau$ leptons.

The hadronically decaying resonance is reconstructed as a single jet using the anti-$k_t$ jet algorithm [89,90] with a radius parameter of 0.4, formed from topological calorimeter energy clusters [91,92] and calibrated to the electromagnetic energy scale. Jet energies are corrected for contributions from simultaneous inelastic $pp$ interactions (pileup) using a jet-area-based technique [93,94] and calibrated [95,96] using $p_T$- and $\eta$-dependent correction factors determined from simulation, with residual corrections from in situ measurements applied to data and internal jet properties. Jets are required to have $p_T > 20$ GeV and $|\eta| < 2.5$ and satisfy a jet cleaning requirement [97]. To reject jets from pileup interactions, jets with $p_T < 60$ GeV and $|\eta| < 2.4$ are required to pass a “jet vertex tagger” [79] requirement. An overlap removal procedure resolves cases in which multiple electrons, muons, or jets are reconstructed from the same detector signature. Higgs boson candidates are reconstructed from the lepton pair and jet system, which is required to have an invariant mass passing a loose preselection requirement: $m_{\ell\ell} < 250$ GeV. If multiple jets satisfy these requirements, the jet with the highest $p_T$ is selected. The acceptance for this preselection, evaluated using generator-level MC samples, varies between 28% and 29% for the different $Q/a$ signal hypotheses.

MLPs [63] are used to select signal events passing this preselection. The MLP input variables are built using tracks matched to the calorimeter jet by ghost association [93], in which the tracks are included in the jet clustering process as with negligible energy and their angles from the jet axis. This allows the MLP to benefit from the high resolution of the tracking detector. These tracks must have $p_T > 500$ MeV and $|\eta| < 2.5$ and pass loose quality and track-to-vertex association requirements [98] to reject fake tracks from the reconstruction and tracks from pileup, respectively. Six dimensionless variables are constructed using these tracks: the ratio of the $p_T$ of the highest $p_T$ track to the $p_T$ of the ghost-associated track system; the angular separation $\Delta R$ between the highest-$p_T$ track and the calorimeter jet axis; NSubJettiness 2 [99], using exclusive-$k_t$ subject axes with radius parameters of 0.2, and a jet axis radius parameter of 0.4; angularity(2) [100]; and $U_1(0.7)$ and $M_2(0.3)$, which are modified energy correlation functions [101] designed for quark-gluon discrimination and to target two-pronged substructure, respectively. These variables primarily capitalize on the presence of a narrow resonance or two-pronged substructure in the track system. Initially, a regression MLP [63], using four hidden layers of 12 nodes, is trained using the above input variables and the $a$ signal samples to estimate the mass of $a$, as shown in Fig. 1(a). This estimated mass is then

![FIG. 1. Output of (a) the regression and (b) the classification MLPs, for data, background, and three signal hypotheses. Events are required to pass the complete event selection, including the $120 < m_{\ell\ell} < 135$ GeV requirement, but not the requirement on the classification MLP output variable. The background normalization is set equal to that of the data, and the signal normalizations assume the SM Higgs boson inclusive production cross section and $B(H \rightarrow Za) = 100\%$, and in (a) the signal normalization is scaled up by a factor of 100. The error bars (hatched regions) represent the data (MC) sample statistical uncertainty, in both the histograms and the ratio plots. In (b) the region to the right of the dashed line is the signal region.](221802-3)
The efficiencies for the complete selection are estimated of the SR and the 4260 and 4370 for between \( \sigma(pp \rightarrow H)B[H \rightarrow Z(Q/a)] \) is extracted for a given signal hypothesis using a maximum-likelihood fit [103] to the number of events observed in the SR. The systematic uncertainties are included in the likelihood fit as nuisance parameters, which modify the signal efficiencies or the simulation-based correction used to calculate the expected background yield. These systematic uncertainties include uncertainties in the signal and background modeling and experimental uncertainties. The sources of modeling uncertainty include the limited MC sample statistics, renormalization scale and choice of MC generator for the signal and background, and a signal uncertainty to account for the extrapolation from gluon-gluon fusion signal samples to the inclusive Higgs boson production cross section. The effects of factorization scale and PDF uncertainties are found to be negligible. The experimental uncertainties considered are due to the luminosity [104], pileup [105], triggers, lepton [81,106,107], and jet [96] reconstruction. The total uncertainty on the extracted signal yield is dominated by the background modeling uncertainties, the largest being due to limited MC sample statistics. The total uncertainty on the background in the SR is 3700 events, and the uncertainty due to the limited data and MC sample statistics is 2900 and the modeling uncertainty is 2300. The data statistical uncertainty corresponds to approximately 8% of the total uncertainty on the extracted signal yield.

The SR contains 82 908 data events. This result is compatible with the SM background-only expectation, and the three-body mass distribution is shown in Fig. 2. Upper limits at 95% confidence level (CL) are set on \( \sigma(pp \rightarrow H)B[H \rightarrow Z(Q/a)] \) for the various signal hypotheses, using the profile-likelihood test statistic [103] and the CLs technique [108]. The observed (expected) upper limits for the \( H \rightarrow Z\eta_c \) and \( H \rightarrow ZJ/\psi \) hypotheses are 110 and 100 pb (100±40 and 100±40 pb), respectively, while the upper limits for the \( H \rightarrow Za \) signal hypotheses are given in Table I. In the absence of systematic uncertainties, these limits would range between 1.9 and 55 pb for the different signal hypotheses. To simplify the interpretation, the upper limits are quoted for \( B(a \rightarrow gg) = 100\% \) and \( B(a \rightarrow s\bar{s}) = 100\% \). Because of the Yukawa ordering of the decays of Higgs bosons, only decays into gluon and strange quark pairs are considered. The tighter limits for the \( a \rightarrow s\bar{s} \) decays are due to a higher MLP selection efficiency. The systematic uncertainties for \( a \rightarrow gg \) and \( a \rightarrow s\bar{s} \) decay hypotheses are estimated using the inclusive decays as modeled in PYTHIA 8, which is a good approximation due to the dominance of the background modeling.
In conclusion, a search has been performed for Higgs boson decays into a $Z$ boson and either a $\eta_c$ or $J/\psi$ charmonium state, or a light spin-0 boson. No excess is found, and 95\% CL upper limits are set on $\sigma(pp \to H)B(H \to Z(\eta_c))$, with values of 110 and 100 pb for the $H \to Z\eta_c$ and $H \to ZJ/\psi$ hypotheses, respectively, and with values in the range 17–340 pb for the $H \to Z\eta_c$ signal hypotheses. Assuming the SM prediction for inclusive Higgs boson production, the limits on charmonium decay modes correspond to branching fraction limits in excess of 100\%. This is the first direct limit on decays of the observed Higgs boson to light scalars, decaying to light quarks or gluons. Because of the large value of $B(a \to \text{hadrons})$ over the entire 2HDM($+S$) parameter space, these limits represent tight, direct constraints for low (high) tan$\beta$ in the type-II and type-III (type-VI) 2HDM + $S$ [109].

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\[ B(\eta_c \to J/\psi \eta_c) = 9\% \]
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(ATLAS Collaboration)
Dipartimento Politecnico di Ingegneria e Architettura, Università di Udine, Udine, Italy
INFN Sezione di Lecce, Italy

Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
INFN Sezione di Lecce, Italy

Dipartimento di Fisica, Università di Milano, Milano, Italy
INFN Sezione di Milano, Italy

Dipartimento di Fisica, Università di Napoli, Napoli, Italy
INFN Sezione di Napoli, Italy

Dipartimento di Fisica, Università di Pavia, Pavia, Italy
INFN Sezione di Pavia, Italy

Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
INFN Sezione di Roma, Italy

Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
INFN Sezione di Roma Tor Vergata, Italy

Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
INFN Sezione di Roma Tre, Italy

Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
INFN-TIFPA, Italy

Universitätsforschungszentrum für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria

Department of Physics and Astronomy, Iowa State University, Ames, Iowa, USA

Joint Institute for Nuclear Research, Dubna, Russia

Departamento de Engenharia Elétrica, Universidade Federal de Juiz de Fora (UFJF), Juiz de Fora, Brazil

Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil

Universidade Federal de São João del Rei (UFSJ), São João del Rei, Brazil

Instituto de Física, Universidade de São Paulo, São Paulo, Brazil

KEK, High Energy Accelerator Research Organization, Tsukuba, Japan

Graduate School of Science, Kobe University, Kobe, Japan

AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland

Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland

Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland

Faculty of Science, Kyoto University, Kyoto, Japan

Kyoto University of Education, Kyoto, Japan

Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka, Japan

Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina

Physics Department, Lancaster University, Lancaster, United Kingdom

Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom

Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana, Slovenia

School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom

Department of Physics, Royal Holloway University of London, Egham, United Kingdom

Department of Physics and Astronomy, University College London, London, United Kingdom

Louisiana Tech University, Ruston, Louisiana, USA

Fysiska institutionen, Lunds universitet, Lund, Sweden

Centre de Calcul de l’Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France

Departamento de Física Teorica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid, Spain

Institut für Physik, Universität Mainz, Mainz, Germany

School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom

CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France

Department of Physics, University of Massachusetts, Amherst, Massachusetts, USA

Department of Physics, McGill University, Montreal QC, Canada

School of Physics, University of Melbourne, Victoria, Australia

Department of Physics, University of Michigan, Ann Arbor, Michigan, USA

Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA

B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Belarus

Research Institute for Nuclear Problems of Byelorussian State University, Minsk, Belarus

Group of Particle Physics, University of Montreal, Montreal QC, Canada

P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia
Deceased.
\(^{a}\) Also at Department of Physics, King’s College London, London, United Kingdom.
\(^{b}\) Also at Instituto de Física Teórica, IFT-UAM/CSIC, Madrid, Spain.
\(^{c}\) Also at TRIUMF, Vancouver BC, Canada.
\(^{d}\) Also at Department of Physics and Astronomy, University of Louisville, Louisville, Kentucky, USA.
\(^{e}\) Also at Physics Department, An-Najah National University, Nablus, Palestine.
\(^{f}\) Also at Department of Physics, University of Fribourg, Fribourg, Switzerland.
\(^{g}\) Also at Departament de Fisica de la Universitat Autonoma de Barcelona, Barcelona, Spain.
\(^{h}\) Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.
\(^{i}\) Also at Department of Physics, Ben Gurion University of the Negev, Beer Sheva, Israel.
\(^{j}\) Also at Universita di Napoli Parthenope, Napoli, Italy.
\(^{k}\) Also at Institute of Particle Physics (IPP), Canada.
\(^{l}\) Also at Dipartimento di Matematica, Informatica e Fisica, Università di Udine, Udine, Italy.
\(^{m}\) Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia.
\(^{n}\) Also at Borough of Manhattan Community College, City University of New York, New York, New York, USA.
\(^{o}\) Also at Department of Physics, California State University, Fresno, USA.
\(^{p}\) Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece.
\(^{q}\) Also at Centro Studi e Ricerche Enrico Fermi, Italy.
\(^{r}\) Also at Department of Physics, California State University, East Bay, USA.
\(^{s}\) Also at Insttitucio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.
\(^{t}\) Also at IJCLab, Université Paris-Saclay, CNRS/IN2P3, 91405, Orsay, France.
\(^{u}\) Also at Graduate School of Science, Osaka University, Osaka, Japan.
\(^{v}\) Also at Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany.
\(^{w}\) Also at University of Chinese Academy of Sciences (UCAS), Beijing, China.
\(^{x}\) Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
\(^{y}\) Also at Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands.
\(^{aa}\) Also at CERN, Geneva, Switzerland.
\(^{bb}\) Also at Joint Institute for Nuclear Research, Dubna, Russia.
\(^{cc}\) Also at Hellenic Open University, Patras, Greece.
\(^{dd}\) Also at The City College of New York, New York, New York, USA.
\(^{ee}\) Also at Department of Physics, California State University, Sacramento, USA.
\(^{ff}\) Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland.
Also at Louisiana Tech University, Ruston, Louisiana, USA.

Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia, Bulgaria.

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

Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.

Also at CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France.

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

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

Also at Giresun University, Faculty of Engineering, Giresun, Turkey.

Also at Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA.