Search for a multi-Higgs-boson cascade in W+W\textminus bb^- events with the ATLAS detector in pp collisions at \(\sqrt{s} = 8\) TeV


Published in:
Physical Review D. Particles, Fields, Gravitation, and Cosmology

DOI:
10.1103/PhysRevD.89.032002

Link to publication

Citation for published version (APA):
https://doi.org/10.1103/PhysRevD.89.032002

General rights
It is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), other than for strictly personal, individual use, unless the work is under an open content license (like Creative Commons).

Disclaimer/Complaints regulations
If you believe that digital publication of certain material infringes any of your rights or privacy interests, please let the Library know, stating your reasons. In case of a legitimate complaint, the Library will make the material inaccessible and/or remove it from the website. Please Ask the Library: https://uba.uva.nl/en/contact, or a letter to: Library of the University of Amsterdam, Secretariat, Singel 425, 1012 WP Amsterdam, The Netherlands. You will be contacted as soon as possible.
I. INTRODUCTION

Recently, a Higgs boson has been discovered by the ATLAS [1] and CMS [2] Collaborations with a mass of approximately 125 GeV. This observation has been supported by complementary evidence from the CDF and D0 Collaborations [3]. The study of such a boson, responsible for breaking electroweak symmetry in the Standard Model (SM), is one of the major objectives of experimental high-energy physics. A vital question is whether this state is in fact the Higgs boson of the SM, or part of an extended Higgs sector (such as that of the minimal supersymmetric Standard Model [4,5]), a composite Higgs boson [6], or a completely different particle with Higgs-like couplings (such as a radion in warped extra dimensions [7,8] or a dilaton [9]).

This article reports a search for particles in an extension to the SM that includes heavier Higgs bosons in addition to a light neutral Higgs boson, $h^0$, with mass $m_{h^0} = 125$ GeV. Rather than assuming a particular theoretical model, this analysis follows a simplified model approach by searching for a specific multi-Higgs-boson cascade topology [10]. Many beyond-the-SM Higgs models introduce a second Higgs doublet. In addition to the $h^0$, such models contain a heavy charged Higgs-boson pair $H^\pm$ and a heavier neutral state $H^0$. An additional pseudoscalar particle, $A$, may also exist within the two-Higgs-doublet model (2HDM) [11] framework, but this analysis assumes it to be too heavy to participate in the cascade decay considered here.

This article reports the first search at the LHC for new particles in the final state $W^\pm W^\mp b\bar{b}$, via the process $gg \rightarrow H^0$ followed by the cascade, $H^0 \rightarrow W^\mp H^\pm \rightarrow W^\mp W^\pm h^0 \rightarrow W^\mp W^\pm b\bar{b}$, as illustrated in Fig. 1. Other production modes, such as associated production or vector-boson fusion lead to different final states and are not considered here. The $W^\pm W^\mp b\bar{b}$ final state also appears in top-quark pair production. In this search, one of the $W$ bosons is assumed to decay to hadrons leading to jets and the other one decays to an electron plus a neutrino ($e +$ jets) or a muon plus a neutrino ($\mu +$ jets). The same final state has been used by CDF in a similar search for Higgs-boson cascades [12]. Other related searches have been performed for charged Higgs bosons in top-quark pair decays $t \rightarrow H^\pm b$ [13–18]. Boosted decision trees (BDTs) are used to distinguish the Higgs-boson cascade events from the predominantly $t\bar{t}$ background.

![Diagram showing the Higgs-boson cascade $gg \rightarrow H^0 \rightarrow W^\mp H^\pm \rightarrow W^\mp W^\pm h^0 \rightarrow W^\mp W^\pm b\bar{b}$](image-url)

FIG. 1. Diagram showing the Higgs-boson cascade $gg \rightarrow H^0 \rightarrow W^\mp H^\pm \rightarrow W^\mp W^\pm h^0 \rightarrow W^\mp W^\pm b\bar{b}$.  

---

Published by the American Physical Society under the terms of the Creative Commons Attribution 3.0 License. Further distribution of this work must maintain attribution to the author(s) and the published articles title, journal citation, and DOI.
II. ATLAS DETECTOR AND DATA SAMPLE

The ATLAS experiment [19] at the LHC is a multipurpose particle physics detector with approximately forward-backward symmetric cylindrical geometry [20]. 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 toroid magnet assemblies.

The data used in this analysis were collected during 2012 from pp collisions at a center-of-mass energy of 8 TeV using triggers designed to select high transverse momentum ($p_T$ [20]) electrons or muons. The data sample corresponds to an integrated luminosity of 20.3 fb$^{-1}$.

III. SIGNAL AND BACKGROUND SIMULATION

The production of $H^0$ bosons via gluon fusion with $m_{H^0} = 325–1025$ GeV and subsequent decays $H^0 \rightarrow W^+W^-$ with $m_{H^0} = 225–925$ GeV and $H^0 \rightarrow W^+h^0$ with $m_{H^0} = 125$ GeV, is modeled using the MADGRAPH [21] Monte Carlo (MC) event generator with an effective vertex to model the fermion loop and a narrow natural width of 50 MeV. Additional radiation, hadronization, and showering are described by PYTHIA v6.4 [22]. Thirty-six different mass pairs are tested for the Higgs-boson cascade signal within the above $m_{H^0}$ and $m_{H^0}$ mass ranges.

The dominant SM background to this signature is top-quark pair production. This background is modeled using simulated events from the MC@NLO v4.01 [23] event generator with the CT10 [24] parton distribution functions (PDFs). The parton shower and the underlying event simulation are performed with HERWIG v6.520 [25] and JIMMY v4.31 [26], respectively, using the AUET2 tune [27]. The $t\bar{t}$ cross section for $pp$ collisions at a center-of-mass energy of $\sqrt{s} = 8$ TeV is assumed to be $\sigma_{t\bar{t}} = 253^{+15}_{-11}$ fb for a top-quark mass of 172.5 GeV. It has been calculated at next-to-next-to-leading order (NNLO) in QCD including resummation of next-to-next-to-leading-logarithmic soft-gluon terms with Top + 2.0 [28–33]. The PDF and $\alpha_s$ uncertainties are calculated using the PDF4LHC prescription [34] with the 68% C.L. of the MSTW2008 NNLO [35,36], CT10 NNLO [24,37] and NNPDF2.3 5f FFN [38] PDF sets, added in quadrature to obtain the normalization and factorization scale uncertainties. Additional $t\bar{t}$ samples used to estimate various systematic effects are generated with POWHEG [39–41] interfaced to HERWIG/JIMMY, POWHEG interfaced to PYTHIA, and AcerMC v3.8 [42] interfaced to PYTHIA. The $t\bar{t}$ modeling is also checked with samples generated by ALPGEN [43] interfaced with HERWIG.

Other backgrounds are expected to originate from vector-boson production with associated jets (W-boson + jets and Z-boson/$\gamma^*$ + jets), as well as single top-quark, diboson ($WW$, $WZ$, $ZZ$), and multijet production. All background predictions, except that for multijet production, are obtained from simulated events.

The $W/Z$-boson + jets contribution is simulated using ALPGEN interfaced to HERWIG/JIMMY, and is normalized to NNLO theoretical cross sections [44,45]. The contribution from single top-quark production is simulated using MC@NLO interfaced to HERWIG/JIMMY for the $s$-channel top-quark production and $t\bar{t}$ production, and with AcerMC interfaced to HERWIG and normalized to next-to-leading order (NLO) theoretical cross sections [46]. Finally, diboson production is simulated with HERWIG and normalized to next-to-leading order (NLO) theoretical cross sections [49].

All generated events are passed through the detailed ATLAS detector simulation [50] based on GEANT4 [51], with the exception of the additional samples used to account for systematic effects in $t\bar{t}$ production, for which a parametrized simulation [50] of the calorimeter response is used. The events are then processed with the same reconstruction software as the data. MC events are overlaid with additional minimum bias events generated with PYTHIA to simulate the effect of pileup (additional $pp$ interactions in either the same or close by bunch crossings as the primary interaction); the number of overlaid proton-proton interactions is chosen to match the distribution of the number of additional interactions observed in the data.

Multijet production may mimic the presence of a lepton, but the contribution from these processes is found to be small. It is estimated from the data by the matrix method [52] in the $u +$ jets and $e +$ jets channels. The matrix method is a technique to estimate the number of events with a fake, isolated lepton in the signal selection, and uses loose and tight isolation definitions for leptons. The tight isolation definitions are those used in this analysis, and tight leptons are a subset of the loose leptons. In a selection dominated by real leptons, the efficiency ($\epsilon_{\text{real}}$) of a loose lepton to also pass the tight isolation requirements is measured. The rate ($\epsilon_{\text{fake}}$) of loose leptons passing the tight requirements is measured in a multijet-dominated selection. These rates, $\epsilon_{\text{real}}$ and $\epsilon_{\text{fake}}$, are used to estimate the multijet contribution to the analysis selection.

IV. EVENT SELECTION

This analysis relies on the measurement of jets, electrons, muons and the missing transverse momentum ($E_T^{\text{miss}}$) [53]. Since this analysis investigates a final state dominated by top-quark pair production, a selection similar to the top-quark cross-section measurement by the ATLAS Collaboration [54] is used.

Jets are reconstructed using the anti-$k_t$ algorithm [55] with a radius parameter $R = 0.4$, and are calibrated at the energy cluster level [56] to compensate for differing calorimeter response to hadronic and electromagnetic showers. A correction for pileup is applied to the jet energy [57]. Jets are required to have $p_T > 25$ GeV and $|\eta| < 2.5$.
Jets from additional pp interactions are suppressed by requiring the jet vertex fraction (JVF) to be larger than 0.5 for jets with \( p_T < 50 \text{ GeV} \) and \( |\eta| < 2.4 \). The JVF variable is defined as the transverse momentum weighted fraction of tracks associated with the jet that are compatible with originating from the primary vertex. The primary vertex is defined as the vertex with the largest \( \sum p_T^2 \) of associated tracks. Jets are \( b \) tagged (identified as the product of a \( b \) quark) using the MV1 tagger [58], which combines several tagging algorithms [59] using an artificial neural network. A 70\% tagging efficiency is achieved in identifying \( b \) jets with \( p_T > 20 \text{ GeV} \) and \( |\eta| < 2.5 \) in simulated \( t\bar{t} \) events, while the light-jet rejection factor is 130. Additional corrections to the tagging efficiency and mistagging rate are derived from data and applied to all simulated samples [58,60–62].

Electrons are identified [63] as energy clusters in the electromagnetic calorimeter matched to reconstructed tracks in the inner detector. Selected electrons are required to pass stringent selection requirements that provide good discrimination between isolated electrons and jets. Isolation requirements are imposed in cones of calorimeter energy deposits \( \Delta R(e, \text{deposit}) < 0.2 \) and inner-detector tracks \( \Delta R(e, \text{track}) < 0.3 \) around the electrons direction where \( \Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} \). The calorimeter isolation is corrected for leakage of the energy of the electron into the isolation cone and for energy deposits from pileup events. Both the calorimeter and the inner-detector isolation requirements are chosen to give 90\% efficiency. Selected electrons are required to have transverse momentum \( p_T > 25 \text{ GeV} \) and pseudorapidity in the range \( |\eta| < 2.47 \), excluding the calorimeter barrel/end-cap transition region \( 1.37 < |\eta| < 1.52 \).

Muons are reconstructed [64] using information from the muon spectrometer and the inner detector and are required to fulfill isolation requirements. Muons are required to have transverse momentum \( p_T > 25 \text{ GeV} \) and \( |\eta| < 2.5 \). The isolation variable [65,66] for muons is defined as \( I_\mu = \sum p_{T\text{track}}^\mu / p_{T\text{track}}^\mu \), where the sum runs over all tracks (except the one matched to the muon) that pass quality requirements and have \( p_{T\text{track}}^\mu > 1 \text{ GeV} \) and \( \Delta R(\mu, \text{track}) < 10 \text{ GeV} / p_{T\text{track}}^\mu \). Muons with \( I_\mu < 0.05 \) are selected.

The transverse momentum of neutrinos is inferred from the magnitude of the missing transverse momentum in the event. The missing transverse momentum is constructed from the negative vector sum of the reconstructed jets, the topological calorimeter energy deposits outside of jets, and the muon momenta, all projected onto the transverse plane.

Overlapping objects are subject to a removal procedure. The jet closest to a selected electron is removed, if it is within \( \Delta R(e, \text{jet}) < 0.2 \). Electrons with \( \Delta R(e, \text{jet}) < 0.4 \) to any remaining jets and muons with \( \Delta R(\mu, \text{jet}) < 0.4 \) between the muon and nearest jet are removed since their likely origin is hadron decays.

Events are selected using single-lepton triggers with \( p_T \) thresholds of 24 or 36 GeV for muons and 24 or 60 GeV for electrons (the lower momentum triggers also apply isolation requirements). Events are required to have exactly one reconstructed isolated electron or muon matching the corresponding trigger object and a primary vertex reconstructed from at least five tracks, each with \( p_T > 400 \text{ MeV} \). At least four jets with \( p_T > 25 \text{ GeV} \) and \( |\eta| < 2.5 \) are required, of which at least two must be identified as \( b \) jets. Additional requirements to reduce the multijet background are applied:

(i) in the \( e + \) jets channel: \( E_T^{\text{miss}} > 30 \text{ GeV} \) and \( m_T^W > 30 \text{ GeV} \),

(ii) in the \( \mu + \) jets channel: \( E_T^{\text{miss}} > 20 \text{ GeV} \) and \( m_T^W + E_T^{\text{miss}} > 60 \text{ GeV} \).

The transverse \( W \)-boson mass is defined as \( m_W^T = \sqrt{2 p_T^e p_T^\ell(1 - \cos(\varphi - \varphi'))} \), where \( p_T \) is the transverse momentum, \( \varphi \) is the azimuthal angle, and \( \ell \) and \( \nu \) refer to the charged lepton and the neutrino, respectively. Different requirements are used for the muon and electron channels due to different levels of multijet background contamination. The signal preregion (SPR) is defined to contain events that pass these requirements. Table I illustrates the expected yields of the background and the observed number of events in this region.

### V. EVENT RECONSTRUCTION AND MULTIVARIATE ANALYSIS

#### A. Event reconstruction

The Higgs-boson cascade event reconstruction begins with identification of the leptonically decaying W boson. It is assumed that the missing transverse momentum is due to the resulting neutrino. The neutrino pseudorapidity is set to the value which results in an invariant mass of the lepton

<table>
<thead>
<tr>
<th>Source</th>
<th>( e/\mu )</th>
<th>( \geq 4 ) jets</th>
<th>SPR yields</th>
</tr>
</thead>
<tbody>
<tr>
<td>( t\bar{t} )</td>
<td>( 36.0^{+3.7}_{-3.8} \times 10^4 )</td>
<td>( 14.0^{+2.1}_{-2.0} \times 10^4 )</td>
<td></td>
</tr>
<tr>
<td>W-boson + jets LF</td>
<td>( 16.0^{+8.2}_{-8.3} \times 10^4 )</td>
<td>( 6.0^{+4.4}_{-4.1} \times 10^2 )</td>
<td></td>
</tr>
<tr>
<td>W-boson + jets HF</td>
<td>( 8.6^{+4.4}_{-4.4} \times 10^4 )</td>
<td>( 4.6^{+2.5}_{-2.4} \times 10^3 )</td>
<td></td>
</tr>
<tr>
<td>Z-boson + jets LF</td>
<td>( 26.0^{+6.7}_{-6.4} \times 10^3 )</td>
<td>( 11.0^{+8.3}_{-7.7} \times 10^3 )</td>
<td></td>
</tr>
<tr>
<td>Z-boson + jets HF</td>
<td>( 4.9^{+1.1}_{-1.0} \times 10^3 )</td>
<td>( 6.7^{+1.6}_{-1.6} \times 10^2 )</td>
<td></td>
</tr>
<tr>
<td>Single top-quark</td>
<td>( 16.0^{+2.0}_{-2.0} \times 10^3 )</td>
<td>( 46.0^{+7.0}_{-7.0} \times 10^2 )</td>
<td></td>
</tr>
<tr>
<td>WW, WZ, ZZ</td>
<td>( 26.0^{+5.4}_{-5.5} \times 10^2 )</td>
<td>( 6.9^{+1.9}_{-2.0} \times 10^1 )</td>
<td></td>
</tr>
<tr>
<td>Fake leptons</td>
<td>( 1.8^{+1.8}_{-1.8} \times 10^4 )</td>
<td>( 8.6^{+8.6}_{-8.6} \times 10^2 )</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>( 68.0^{+14.0}_{-18.0} \times 10^4 )</td>
<td>( 15.1^{+2.2}_{-2.4} \times 10^4 )</td>
<td></td>
</tr>
<tr>
<td>Observed</td>
<td>664876</td>
<td>151123</td>
<td></td>
</tr>
</tbody>
</table>
and neutrino closest to the nominal W-boson mass [67]; in the case of degenerate solutions, the smallest magnitude of pseudorapidity is chosen. Next, the two $b$-tagged jets are used to reconstruct the lightest Higgs-boson candidate, $h^0$; if there are more than two $b$-tagged jets, the two jets with the highest $b$-tagging scores [58] are used. The hadronically decaying W boson is identified from the remaining jets as the pair with reconstructed dijet mass closest to the nominal W-boson mass. The charged Higgs-boson candidate $H^\pm$ is constructed from the light $h^0$ and the W-boson candidate which gives the larger value of $m_{jj}$. The heavy neutral Higgs-boson candidate $H^0$ is then formed as $bbWW$. Figure 2 illustrates the reconstructed mass distributions for the $h^0$, $H^\pm$, and $H^0$ in simulation for selected mass values. Note that incorrect choice of neutrino rapidity or incorrect assignment of jets to the W-boson or Higgs-boson candidates will lead to a broadening of the reconstructed mass distributions, rather than a systematic bias.

Since the dominant background is top-quark pair production, the two $b$ quarks and two $W$ bosons are combined in $Wb$ pairs to give top-quark candidates. The combination which minimizes the sum of the absolute value of their differences from the nominal top-quark mass [67] for both pairs is chosen. The invariant masses of the top-quark candidates are useful to discriminate $t\bar{t}$ events from the Higgs-boson signal. The masses ($m_t$, $m_{t\bar{t}}$) of the two top-quark candidates and the absolute values of their differences ($|m_t - m_{t\bar{t}}|$) are calculated.

### B. Multivariate analysis

A multivariate analysis is performed to distinguish the Higgs-boson cascade from $t\bar{t}$ events. Several reconstructed kinematic quantities, including the invariant masses of the Higgs-boson candidates as described above, are used as inputs to a BDT classifier, provided in the TMVA [68] package. TMVA provides a ranking for the input variables, which is derived by counting how often an input variable is used to split decision tree nodes, and by weighing each split occurrence by the square of the gain in signal-to-background separation it has achieved and by the number of events in that node. Several combinations of input variables are tested in training the BDTs. The inputs for the BDTs are optimized for the best expected cross-section limits while avoiding overtraining, and the variable rankings of TMVA are used as heuristics in choosing the BDT inputs. Seven kinematic variables are chosen to achieve the best expected result across the entire signal mass grid:

- (i) $m_{bb}$, $m_{bWW}$ and $m_{b\bar{b}WW}$, as described above;
- (ii) $\Delta R(b, \bar{b})$, the angular distance between the pair of $b$-tagged jets used to reconstruct the light Higgs-boson candidate;
- (iii) leptonic $m_t$, the top-quark mass reconstructed using the leptonically decaying W boson;
- (iv) hadronic $m_{t\bar{t}}$, the top-quark mass reconstructed using the hadronically decaying W boson;
- (v) $|m_t - m_{t\bar{t}}|$.

For cascades originating from a high-mass Higgs boson, the reconstructed top-quark masses along with $m_{WWbb}$ are the highest-ranked input variables. For the low-mass Higgs-boson cascades, $m_{bb}$ and $\Delta R(b, \bar{b})$ have the highest rank. Since the kinematics of the Higgs-boson cascade vary greatly with the masses of the heavy and intermediate Higgs bosons, a different BDT is trained for each signal mass hypothesis.

Only MC events that pass the SPR requirements are used in the training of the BDTs. Each BDT is constructed as a forest with 750 decision trees, and is trained against simulated background event samples. The stochastic gradient boosting method [68] is used to improve classification accuracy and its robustness against statistical fluctuations. Each BDT is checked for overtraining with a statistically independent test sample.

For each of the 36 signal mass points, a final threshold is chosen for its respective BDT output which gives the best expected sensitivity, measured using the same confidence-level calculations as applied to the data and described below. A counting experiment is then performed using events that pass those BDT output thresholds. In this way, the BDT thresholds divide the SPR into 36 nonorthogonal signal regions, one for each signal mass point.
VI. BACKGROUND VALIDATION IN CONTROL REGIONS

The modeling of the SM backgrounds is validated in three background-dominated control regions. The control regions retain the requirements of one lepton and at least four jets, and each region has additional requirements. In control regions with fewer than two $b$-tagged jets, the two jets with the highest $b$-tagging scores are used to reconstruct the lightest Higgs boson, $h^0$. The following control regions are used:

(i) Control Region 1 (CR1): at least four jets, exactly one lepton and at least two $b$-tagged jets. This region validates primarily the $W$-boson + jets modeling. This region is background enriched relative to the hypothetical signal due to the $b$-tag veto.

(ii) Control Region 2 (CR2): at least four jets, exactly one lepton and exactly one $b$-tagged jet. This region validates primarily the modeling of the $t\bar{t}$ background.

(iii) Control Region 3 (CR3): at least four jets, exactly one lepton, at least two $b$-tagged jets, and $m_{bb} > 150$ GeV. This region focuses primarily on validation of the modeling of the $t\bar{t}$ background with kinematics similar to the hypothetical signal, but is background enriched due to the $m_{bb} > 150$ GeV requirement.

Figures 3 and 4 illustrate the modeling of the Higgs-boson mass reconstruction in CR1, CR2 and CR3. The data and simulation agree within total uncertainties over the entire phase space. This is important, as the BDT may utilize any part of this phase space to build a powerful discriminant. In

This background is fractionally larger, compared to a hypothetical signal, here than in the signal region due to the $b$-tagging cut, which preferentially selects the higher $p_T$ $b$ quarks from top-quark decay. Although a potential signal would not be absent in this control region, the different levels of signal and $t\bar{t}$ contributions allow a test of $t\bar{t}$ modeling by comparing levels of agreement between data and prediction in the signal and CR2 regions.
addition, the BDT output in each of the three control regions is compared to the predicted output and found to agree within statistical and systematic uncertainties.

VII. SYSTEMATIC UNCERTAINTIES

Several sources of systematic uncertainties are relevant to this analysis.

Instrumental systematic uncertainties are related to the reconstruction of physics objects. For jets, systematic uncertainties on the jet energy scale, energy resolution, and reconstruction efficiency are included. For leptons, the systematic uncertainties from the momentum or energy scale and resolution, trigger efficiency, reconstruction, and identification efficiency are incorporated. Systematic uncertainties related to the performances of the reconstruction of physics objects. For jets, systematic uncertainties from the momentum or energy scale and resolution are included. For leptons, the uncertainties in the energy scale and resolution are included. For both leptons, uncertainties on the trigger, identification, and reconstruction efficiencies are incorporated.

Due to the presence of multiple (≥4) jets and the dominant t¯t background (roughly 90% in the signal region), significant systematic uncertainties are associated with jets and the modeling of the t¯t background. Table II lists the impact of these uncertainties on the background estimates and signal efficiency for an example signal region given by the BDT threshold for a signal with m_{tW}, m_{tZ} = 425, 225 GeV.

Several sources of uncertainty on the jet energy scale calibration are considered, such as uncertainties due to pileup and the light-quark and gluon composition. These uncertainties are evaluated in data and MC [58]. The BDT output in each of the three control regions is compared to the predicted output and found to agree within statistical and systematic uncertainties. Table II lists the impact of these uncertainties on the background estimates and signal efficiency for an example signal region given by the BDT threshold for a signal with m_{tW}, m_{tZ} = 425, 225 GeV. The signal region for this mass point is defined as the events that pass the BDT threshold for this mass sample. The positive and negative relative shifts have been averaged for compactness.

An overall uncertainty of 4% is applied to the background in the signal region, systematic uncertainties associated with them are found to have a small impact on the overall background uncertainty. The systematic uncertainty related to the modeling of W-boson + jets is determined by varying the parametrization of the renormalization and factorization scales in ALPGEN. As default, both scales are set to \( m_{tW} + (p_T^W)^2 \) and this is varied by factors of 2 and by changing the form to \( m_{tW} + \sum_{jets} p_T^2 \). This systematic uncertainty is found to be small (<1%).

An overall uncertainty of 4% is applied to the W-boson + jets estimate due to uncertainties in the cross section, with an additional 24% per jet added in quadrature due to the uncertainty in Berends scaling [72]. This results in a
48% uncertainty for events with four jets, contributing to the overall 5.5% uncertainty on the background normalization.

The systematic uncertainty due to single top-quark, diboson, and Z-boson + jets production is evaluated by varying their cross sections within their uncertainties as described in Ref. [52]. Since these contributions are small, the systematics associated with them are found to be negligible (< 1%).

Finally, the luminosity uncertainty, measured using techniques similar to those described in Ref. [73], is 2.8%.

**VIII. RESULTS**

The yields in the signal regions are given in Table III. The observed yields are found to be consistent with SM background expectations, within uncertainties. The BDT outputs for three example signal mass points are illustrated in Fig. 5.
FIG. 5 (color online). Distributions of the BDT output in the signal regions for three example signal mass points, \( m_{H^\pm}, m_{H^\mp} = 1025, 225 \) GeV (top), \( m_{H^\pm}, m_{H^\mp} = 625, 325 \) GeV (middle), \( m_{H^\pm}, m_{H^\mp} = 1025, 625 \) GeV (bottom). Signal histograms have been scaled to a production cross section of 1 pb. BDT thresholds are shown as dashed lines for each mass point. The background model is shown as the colored stacked histogram. The final bin contains any overflow events.

The background model is shown as the colored stacked histogram. BDT thresholds are shown as dashed lines for each mass point. The final bin contains any overflow events.

The 95% confidence-level production cross-section upper limits for the various signal hypotheses are obtained using the CLs frequentist method [74], with the profile likelihood ratio of the number of events that pass the BDT threshold as the test statistic [75] as implemented in Ref. [76]. Systematic uncertainties are treated as nuisance parameters and the calculation uses the asymptotic approximation [75]. Table III presents the signal efficiencies, the
total expected background and observed event counts for each signal case, as well as the expected and observed limits with the local \( p \) values. The \( p \) values are defined as the probabilities under the background-only hypothesis to observe these data or data which are more signal-like. The \( p \) values have a maximum possible value of 0.5, which is the case when \( n < b \), where \( b \) is the number of events expected from the background model and \( n \) is the number of events observed in the data.

Since the signal regions are correlated, background-only pseudoexperiments are used to estimate the expected distribution of the \( p \) values in all the signal regions, accounting for the correlations. The observed distribution of \( p \) values is found to be consistent with the expectation from pseudoexperiments. The expected and observed limits as a function of the \( H^0 \) and \( H^\pm \) masses are illustrated in Fig. 6. The limits are the weakest in low Higgs-boson mass regions due to the poorer separation between \( t\bar{t} \) and signal events.

In order to facilitate the comparison of these results with those obtained by other experiments, the observed cross-section limits are compared to the predictions for a heavy Higgs boson with SM-like \( gg \)-fusion production (Fig. 6). The theoretical production cross section of a heavy SM-like Higgs boson (only gluon fusion is considered) is calculated in the complex-pole scheme using the dFG [77] program, to NNLO in QCD. NLO electroweak corrections are also applied, as well as QCD soft-gluon resumptions up to next-to-next-to-leading log. Using this benchmark, the cross-section upper limits observed are greater than the theoretical cross sections of the heavy Higgs boson, \( H^0 \), for all mass points tested. Therefore, the current limits are not stringent enough to exclude models with SM-like production rates even with 100% branching ratios for both \( H^0 \to H^\pm W^\mp \) and \( H^\pm \to h^0 W^\mp \) and SM values for BR \( (h^0 \to b\bar{b}) \). The limits are most stringent in the high \( H^0 \) and \( H^\pm \) mass regions, where the ratio of the limits to the theoretical cross section is nearly unity. This search produces tighter bounds than those obtained by the CDF Collaboration [12].

Additionally, the results of this search are interpreted in the context of a heavy \( CP \)-even Higgs boson of a type-II two-Higgs-doublet model [78] produced via gluon fusion. This model has seven free parameters: the mass of the \( CP \)-even Higgs bosons \( (m_{h^0} \text{ and } m_{h^\pm}) \), the mass of the \( CP \)-odd Higgs boson \( (m_A) \), the mass of the charged scalar \( (m_{H^\pm}) \), the mixing angle between the \( CP \)-even Higgs bosons \( (\alpha) \), the ratio of the vacuum expectation values of the two Higgs doublets \( (\tan \beta) \), and the \( Z_2 \)-symmetry soft-breaking-term coefficient of the Higgs potential \( (M^2) \). The parameter space of the type-II 2HDM is sampled for given values of \( m_{h^0} \) and \( m_{H^\pm} \) and assuming \( m_{h^\pm} = 125 \) GeV and \( \sin(\beta - \alpha) \geq 0.99 \). The latter assumptions are made in order to maintain a SM-like Higgs boson with properties similar to those observed at the LHC. The gluon-fusion production cross section is calculated with SusHi [79] at NNLO precision in QCD corrections, and the branching ratio of the cascade \( H^0 \to W^\mp H^\pm \to W^+ W^- h \to W^+ W^- b\bar{b} \) with 2HDMC [80]. Only parameter space points that satisfy theory constraints are considered. The theory constraints include Higgs-potential stability, tree-level unitarity for Higgs-boson scattering [81], and the perturbative nature of the quartic Higgs-boson couplings, as these are implemented in 2HDMC. The type-II 2HDM phase space is scanned with a million random points per \( (m_{h^0}, m_{H^\pm}) \) pair. The majority of the spanned phase space violates the theoretical constraints mentioned above. The points with
the lowest cross section times branching fraction $\sigma \times BF$ (excluded) $/ \sigma \times BF$ (theory) which satisfy the above constraints are shown in Table IV, where $\sigma$ is the cross section and BF is the branching fraction. None are excluded by the limits presented here.

In conclusion, the first LHC search for a topology in which a heavy Higgs boson decays via a cascade of lighter charged and neutral Higgs bosons has been performed by the ATLAS experiment using data corresponding to an integrated luminosity of 20.3 fb$^{-1}$ in $pp$ collisions at $\sqrt{s} = 8$ TeV. No significant excess of events above the expectation from the SM background was found and limits on the production cross section have been set.

**ACKNOWLEDGMENTS**

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; BMWF 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; GSRT and NSRF, Greece; ISF, MINERVA, GIF, DIP 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; MNEIFA, Romania; MES of Russia and ROSATOM, Russian Federation; JINR; MSTD, Serbia; MSSR, Slovakia; ARRS and MIZS, 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, United States of America. 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 (U.K.) and BNL (U.S.) and in the Tier-2 facilities worldwide.

[20] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the center of the detector and the z axis along the beam pipe. The x axis points from the IP to the center of the LHC ring, and the y axis points upwards. Cylindrical coordinates $(r, \phi)$ are used in the transverse plane, $\phi$ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle $\theta$ as $\eta = -\ln \tan(\theta/2)$.
SEARCH FOR A MULTI-HIGGS-BOSON CASCADE IN ...

PHYSICAL REVIEW D 89, 032002 (2014)
SEARCH FOR A MULTI-HIGGS-BOSON CASCADE IN ...

PHYSICAL REVIEW D 89, 032002 (2014)
AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland

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

The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland

Physics Department, Southern Methodist University, Dallas, Texas, USA

DESY, Hamburg and Zeuthen, Germany

Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany

Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany

Department of Physics, Duke University, Durham, North Carolina, USA

SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom

INFN Laboratori Nazionali di Frascati, Frascati, Italy

Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany

Section de Physique, Université de Genève, Geneva, Switzerland

INFN Sezione di Genova, Italy

Dipartimento di Fisica, Università di Genova, Genova, Italy

E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi, Georgia

High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia

II Physikalisches Institut, Justus-Liebig-Universität Gießen, Gießen, Germany

SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom

II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany

Laboratoire de Physique Subatomique et de Cosmologie, Université Joseph Fourier and CNRS/IN2P3 and Institut National Polytechnique de Grenoble, Grenoble, France

Department of Physics, Hampton University, Hampton, Virginia, USA

Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, Massachusetts, USA

Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany

Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany

ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany

Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan

Department of Physics, Indiana University, Bloomington, Indiana, USA

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

University of Iowa, Iowa City, Iowa, USA

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

Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia

KEK, High Energy Accelerator Research Organization, Tsukuba, Japan

Graduate School of Science, Kobe University, Kobe, Japan

Faculty of Science, Kyoto University, Kyoto, Japan

Kyoto University of Education, Kyoto, Japan

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

INFN Sezione di Lecce, Italy

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

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

Department of Physics, Jožef Stefan Institute and 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, Surrey, United Kingdom

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

Louisiana Tech University, Ruston, Louisiana, USA

Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France

Fysiska institutionen, Lunds universitet, Lund, Sweden

Departamento de Física Teórica C-15, Universidad Autonoma 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 and CNRS/IN2P3, Marseille, France

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

Department of Physics, McGill University, Montreal, Quebec, Canada

School of Physics, University of Melbourne, Victoria, Australia

Department of Physics, The University of Michigan, Ann Arbor, Michigan, USA
SEARCH FOR A MULTI-HIGGS-BOSON CASCADE IN …

PHYSICAL REVIEW D 89, 032002 (2014)

89 Department of Physics and Astronomy, Michigan State University, East Lansing, Mississippi, USA
90 INFN Sezione di Milano, Italy
91 B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus
92 National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus
93 Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA
94 Group of Particle Physics, University of Montreal, Montreal, Quebec, Canada
95 P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
96 Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
97 Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia
98 D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
99 Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
100 Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
101 Nagasaki Institute of Applied Science, Nagasaki, Japan
102 Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
103 INFN Sezione di Napoli, Italy
104 Department of Physics and Astronomy, University of Texas at Austin, Austin, Texas, USA
105 Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
106 Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
107 Department of Physics, Northern Illinois University, DeKalb, Illinois, USA
108 Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
109 Department of Physics, New York University, New York, New York, USA
110 Ohio State University, Columbus, Ohio, USA
111 Faculty of Science, Okayama University, Okayama, Japan
112 Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma, USA
113 Department of Physics, Oklahoma State University, Stillwater, Oklahoma, USA
114 Palacký University, RCPTM, Olomouc, Czech Republic
115 Center for High Energy Physics, University of Oregon, Eugene, Oregon, USA
116 LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France
117 Graduate School of Science, Osaka University, Osaka, Japan
118 Department of Physics, University of Oslo, Oslo, Norway
119 Department of Physics, Oxford University, Oxford, United Kingdom
120 INFN Sezione di Pavia, Italy
121 Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania, USA
122 Petersburg Nuclear Physics Institute, Gatchina, Russia
123 INFN Sezione di Pisa, Italy
124 Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania, USA
125 Laboratorio de Instrumentacao e Fisica Experimental de Particulas - LIP, Lisboa, Portugal
126 Instituto de Fisica Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada, Spain
127 Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
128 Czech Technical University in Prague, Praha, Czech Republic
129 Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
130 State Research Center Institute for High Energy Physics, Protvino, Russia
131 Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
132 Physics Department, University of Regina, Regina, Saskatchewan, Canada
133 INFN Sezione di Roma I, Italy
134 INFN Sezione di Roma Tor Vergata, Italy
135 INFN Sezione di Roma Tre, Italy
136 Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca, Morocco
SEARCH FOR A MULTI-HIGGS-BOSON CASCADE IN ...

PHYSICAL REVIEW D 89, 032002 (2014)

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

\(^{179}\)Deceased.
\(^{1}\)Also at Department of Physics, King’s College London, London, United Kingdom.
\(^{2}\)Also at Laboratorio de Instrumentacao e Fisica Experimental de Partículas - LIP, Lisboa, Portugal.
\(^{3}\)Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
\(^{4}\)Also at Faculdade de Ciencias and CFNUL, Universidade de Lisboa, Lisboa, Portugal.
\(^{5}\)Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom.
\(^{6}\)Also at TRIUMF, Vancouver BC, Canada.
\(^{7}\)Also at Department of Physics, California State University, Fresno CA, United States of America.
\(^{8}\)Also at Novosibirsk State University, Novosibirsk, Russia.
\(^{9}\)Also at Department of Physics, University of Coimbra, Coimbra, Portugal.
\(^{10}\)Also at Università di Napoli Parthenope, Napoli, Italy.
\(^{11}\)Also at Institute of Particle Physics (IPP), Canada.
\(^{12}\)Also at Department of Physics, Middle East Technical University, Ankara, Turkey.
\(^{13}\)Also at Louisiana Tech University, Ruston LA, United States of America.
\(^{14}\)Also at Dep Fisica and CEFITEC of Faculdade de Ciencias e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal.
\(^{15}\)Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.
\(^{16}\)Also at Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America.
\(^{17}\)Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece.
\(^{18}\)Also at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.
\(^{19}\)Also at Department of Physics, University of Cape Town, Cape Town, South Africa.
\(^{20}\)Also at CERN, Geneva, Switzerland.
\(^{21}\)Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan.
\(^{22}\)Also at Manhattan College, New York NY, United States of America.
\(^{23}\)Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.
\(^{24}\)Also at School of Physics and Engineering, Sun Yat-sen University, Guanzhou, China.
\(^{25}\)Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.
\(^{26}\)Also at Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France.
\(^{27}\)Also at School of Physical Sciences, National Institute of Science Education and Research, Bhubaneswar, India.
\(^{28}\)Also at Dipartimento di Fisica, Università La Sapienza, Roma, Italy.
\(^{29}\)Also at DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat à l’Energie Atomique et aux Energies Alternatives), Gif-sur-Yvette, France.
\(^{30}\)Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.
\(^{31}\)Also at Section de Physique, Université de Genève, Geneva, Switzerland.
\(^{32}\)Also at Departamento de Fisica, Universidade de Minho, Braga, Portugal.
\(^{33}\)Also at Department of Physics, The University of Texas at Austin, Austin TX, United States of America.
\(^{34}\)Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.
\(^{35}\)Also at DESY, Hamburg and Zeuthen, Germany.
\(^{36}\)Also at International School for Advanced Studies (SISSA), Trieste, Italy.
\(^{37}\)Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, United States of America.
\(^{38}\)Also at Faculty of Physics, M.V. Lomonosov Moscow State University, Moscow, Russia.
\(^{39}\)Also at Hebrew University, Jerusalem, Israel.
\(^{40}\)Also at Physics Department, Brookhaven National Laboratory, Upton NY, United States of America.
\(^{41}\)Also at Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia.
\(^{42}\)Also at Department of Physics, Oxford University, Oxford, United Kingdom.
\(^{43}\)Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.
\(^{44}\)Also at Department of Physics, The University of Michigan, Ann Arbor MI, United States of America.
\(^{45}\)Also at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa.