Search for dark matter produced in association with a Higgs boson decaying to two bottom quarks in $pp$ collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector

The ATLAS Collaboration

Abstract

This article reports on a search for dark matter pair production in association with a Higgs boson decaying to a pair of bottom quarks, using data from 20.3 fb$^{-1}$ of $pp$ collisions at a center-of-mass energy of 8 TeV collected by the ATLAS detector at the LHC. The decay of the Higgs boson is reconstructed as a high-momentum $b\bar{b}$ system with either a pair of small-radius jets, or a single large-radius jet with substructure. The observed data are found to be consistent with the expected Standard Model backgrounds. Model-independent upper limits are placed on the visible cross-sections for events with a Higgs boson decaying into $b\bar{b}$ and large missing transverse momentum with thresholds ranging from 150 GeV to 400 GeV. Results are interpreted using a simplified model with a $Z'$ gauge boson decaying into different Higgs bosons predicted in a two-Higgs-doublet model, of which the heavy pseudoscalar Higgs decays into a pair of dark matter particles. Exclusion limits are also presented for the mass scales of various effective field theory operators that describe the interaction between dark matter particles and the Higgs boson.

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1 Introduction

Although dark matter (DM) contributes a large component of the mass-energy of the universe, its properties and interactions with known particles remain unknown [1]. In light of this unsolved puzzle, searches for DM pair-produced at collider experiments provide important information complementary to direct and indirect detection experiments in order to determine whether a signal observed experimentally indeed stems from DM [2].

The leading hypothesis suggests that most of the DM is in the form of stable, electrically neutral, massive particles, i.e., Weakly Interacting Massive Particles [3]. This scenario gives rise to a potential signature at a proton-proton collider where one or more Standard Model (SM) particles, “X”, is produced and detected, recoiling against missing transverse momentum (with magnitude $E_{\text{miss}}^\gamma$) associated with the noninteracting DM. Recent searches at the Large Hadron Collider (LHC) consider “X” to be a hadronic jet [4, 5], heavy-flavor jet [6, 7], photon [8, 9], or W/Z boson [10, 11]. The discovery of the Higgs boson $h$ [12, 13] provides a new opportunity to search for DM production via the $h + E_{\text{miss}}^\gamma$ signature [14–16]. In contrast to most of the aforementioned probes, the visible Higgs boson is unlikely to have been radiated from an initial-state quark or gluon, and the signal would give insight into the structure of DM coupling to SM particles.

Two approaches are commonly used to model generic processes yielding a final state with a particle $X$ recoiling against a system of noninteracting particles. One option is to use nonrenormalizable operators in an effective field theory (EFT) framework [17], where particles that mediate the interactions between DM and SM particles are too heavy to be produced directly in the experiment and are described by contact operators. Alternatively, simplified models that are characterized by a minimal number of renormalizable interactions and hence explicitly include the particles at higher masses can be used [18]. The EFT approach is more model-independent, but is not valid when a typical momentum transfer of the process approaches the energy scale of the contact operators that describe the interaction. Simplified models do not suffer from these concerns, but include more assumptions by design and are therefore less generic. The two approaches are thus complementary and both are included in this analysis.

2 Signal models and analysis strategy

Using the EFT approach, a set of models described by effective operators at different dimensions is considered, as shown in Figure 1(a). Following the notation in Ref. [14], the effective operators in ascending order of their dimensions are:

1. $\lambda |\chi|^2 |H|^2$ (Scalar DM, dimension-4) (1)
2. $\frac{1}{\Lambda} i\gamma_5 \gamma_\mu \chi^\dagger D^\mu H$ (Fermionic DM, dimension-5) (2)
3. $\frac{1}{\Lambda^2} \partial^\mu \chi^\dagger H^\dagger D_\mu H$ (Scalar DM, dimension-6) (3)
4. $\frac{1}{\Lambda^4} \tilde{\chi} \gamma^\mu \chi B_{\mu\nu} H^\dagger D^\nu H$ (Fermionic DM, dimension-8) (4)
Here $\chi$ is the DM particle, which is a gauge singlet under $SU(3)_C \times SU(2)_L \times U(1)_Y$ and may be a scalar or a fermion as specified. $D_\mu(\gamma')$ is the covariant derivative for the full gauge group, and $B_{\mu\nu}$ is the $U(1)_Y$ field strength tensor. The parameters of these models are the DM particle mass $m_\chi$, and the coupling parameter $\lambda$ or the suppression scale $\Lambda$ of the heavy mediator that is not directly produced but described by a contact operator in the EFT framework.

A simplified model is also considered which contains a $Z'$ gauge boson and two Higgs fields resulting in five Higgs bosons (often called the two-Higgs-doublet model, 2HDM) [15], where the DM particle is coupled to the heavy pseudoscalar Higgs boson $A$, as shown in Figure 1(b). In this model ($Z'$-2HDM), the $Z'$ boson is produced resonantly and decays into $h$ and $A$ in a Type 2 two-Higgs-doublet model [19], where $h$ is the scalar corresponding to the observed Higgs boson, and $A$ has a large branching ratio to DM. The $Z'$ boson can also decay to a Higgs boson and a $Z$ boson, which in turn decays to a pair of neutrinos, thus mimicking the expected signature. While the $Ah$ decay mode is dominant for most of the parameter space probed in this analysis, the latter decay mode is an important source of signal events at large $\tan\beta$ (the ratio of the vacuum expectation values for the two-Higgs-doublets). Both sources of a Higgs boson plus missing transverse momentum are included for the analysis of this model. The results presented are for the alignment limit, in which the scalar Higgs mixing angle $\alpha$ is related to $\beta$ by $\alpha = \beta - \pi/2$. Only regions of parameter space consistent with precision electroweak constraints on the $\rho_0$ parameter [20] and with constraints from direct searches for dijet resonances [21–23] are considered. The $Z'$ boson does not couple to leptons in this model, avoiding potentially stringent constraints from dilepton searches. As the $A$ boson is produced on-shell and decays into DM, the mass of the DM particle does not affect the kinematic properties or cross-section of the signal process when it is below half of the $A$ boson mass. Hence, the $Z'$-2HDM model is interpreted in the parameter spaces of $Z'$ mass ($m_{Z'}$), $A$ mass ($m_A$), and $\tan\beta$, with the $Z'$ gauge coupling fixed to its 95% confidence level (CL) upper limit per $Z'$ mass and $\tan\beta$ value from the aforementioned electroweak and dijet search constraints.

This article describes the search for DM pair production in association with a Higgs boson using the full 2012 ATLAS data set corresponding to 20.3 fb$^{-1}$ of $pp$ collisions with center-of-mass energy $\sqrt{s} = 8$ TeV. The final state is a Higgs boson decaying to a pair of bottom quarks and large missing transverse momentum. Two Higgs boson reconstruction techniques are presented that are complementary in their acceptance. The first ‘resolved’ technique reconstructs Higgs boson candidates from pairs of nearby anti-$k_t$ jets [24] each reconstructed with radius parameter $R = 0.4$, each identified as having a $b$-hadron within...
the jet using a multivariate $b$-tagging algorithm [25]. This resolved technique offers good efficiency over a wide kinematic range with the Higgs boson transverse momentum $p_T$ between 150 and 450 GeV. However, for a Higgs boson with $p_T \gtrsim 450$ GeV, the high momentum (“boost”) of the Higgs boson causes the two jet cones containing the $b$- and $\bar{b}$-quarks from the Higgs boson decay to significantly overlap, leading to a decrease in the reconstruction efficiency of the two $b$-tagged anti-$k_t$ jets with $R = 0.4$. This motivates the use of a second “boosted” Higgs boson reconstruction technique, which maintains acceptance for these higher-$p_T$ Higgs bosons through the use of a set of jet reconstruction and identification methods that exploit the internal structure of jets, known as “jet substructure” techniques [26]. The Higgs boson candidate is reconstructed as a single anti-$k_t$ $R = 1.0$ jet, trimmed with subjet radius parameter $R_{\text{sub}} = 0.3$ and subjet transverse momentum fraction $p_{T_i}/p_T^{\text{jet}} < 0.05$, where $p_{T_i}$ is the transverse momentum of the $i$-th subjet and $p_T^{\text{jet}}$ is the $p_T$ of the untrimmed jet [27]. This $R = 1.0$ jet must be associated with two $b$-tagged anti-$k_t$ $R = 0.3$ jets reconstructed only from charged particle tracks (track-jets) [28]. The use of track-jets with a smaller $R$ parameter allows the decay products of Higgs bosons with higher $p_T$ to be reconstructed.

The interplay between the two sets of models and analysis methods has been studied. In the $Z'$-2HDM simplified model, the resonant production and decay of the $Z'$ boson leads to clear peaks in the $E_T^{\text{miss}}$ spectra, the positions of which depend on the $Z'$ and $A$ mass values. In most of the parameter space probed with $Z'$ mass between 600 and 1400 GeV, and $A$ mass between 300 and 800 GeV (where kinematically allowed), a higher signal sensitivity is achieved in the resolved channel. On the other hand, the EFT models display very different kinematics with wide tails in high $E_T^{\text{miss}}$ extending beyond 450 GeV, warranting a “boosted” reconstruction of the Higgs boson. Given the clear advantage of one analysis channel over the other for either set of models, and for simplicity, the results for the $Z'$-2HDM model are given using the resolved analysis, and the EFT models are interpreted using the boosted analysis.

The final signal regions are defined with four increasing thresholds for the missing transverse momentum in the resolved channel, and two thresholds in the boosted channel. To search for the possible presence of non-SM signals, the total numbers of observed events after applying all selection criteria are compared with the total number of expected SM events taking into account their respective uncertainties in both channels. Unlike previous ATLAS searches for resonant production with a similar final state [29, 30], this analysis explores different theoretical models, focuses on the fully hadronic channel with data-driven methods to estimate the main backgrounds, and most importantly, applies selections extending to large $E_T^{\text{miss}}$ utilizing “resolved” as well as “boosted” techniques. The approach for extracting limits in this analysis is also more suited for the models considered here, and reduces the theoretical uncertainty from modeling and fitting of the signal shape.

3 ATLAS detector

ATLAS is a multi-purpose particle physics experiment [31] at the LHC. The detector$^1$ consists of inner tracking devices surrounded by a superconducting solenoid, electromagnetic and hadronic calorimeters, and a muon spectrometer. The inner tracking system provides charged-particle tracking and vertex reconstruction in the pseudorapidity region of $|\eta| < 2.5$. It consists of a silicon pixel detector, a silicon

$^1$ 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, $\phi$ is the azimuthal angle around the beam pipe. The pseudorapidity $\eta$ is defined in terms of the polar angle $\theta$ as $\eta = \ln[\tan(\theta/2)]$. 4
microstrip tracker, and a transition radiation tracker. The system is surrounded by a solenoid that produces a 2 T axial magnetic field. The central calorimeter system consists of a liquid-argon electromagnetic sampling calorimeter with high granularity and a steel/scintillator-tile calorimeter providing hadronic energy measurements in the central pseudorapidity range ($|\eta| < 1.7$). The endcap and forward regions are instrumented with liquid-argon calorimeters for electromagnetic and hadronic energy measurements up to $|\eta| = 4.9$. The muon spectrometer is operated in a magnetic field provided by air-core superconducting toroids and includes tracking chambers for precise muon momentum measurements up to $|\eta| = 2.7$ and trigger chambers covering the range of $|\eta| < 2.4$. A three-level trigger system is used to select interesting events [32]. The Level-1 (L1) trigger reduces the event rate to below 75 kHz using hardware-based trigger algorithms acting on a subset of detector information. Two levels of software-based triggers, referred to collectively as the High-Level Trigger (HLT), further reduce the event rate to approximately 400 Hz using information from the entire detector.

4 Data and simulation samples

The data sample used in this analysis, after data quality requirements are applied, corresponds to an integrated luminosity of 20.3 fb$^{-1}$. The primary data sample is selected using an $E_T^{\text{miss}}$ trigger. The L1 $E_T^{\text{miss}}$ trigger threshold is 60 GeV, and the HLT $E_T^{\text{miss}}$ trigger threshold is 80 GeV. The trigger efficiency is above 98% for events passing the full offline selection across the full $E_T^{\text{miss}}$ range considered in this analysis. Muon triggers with transverse momentum thresholds at the HLT of 24 GeV for muons with surrounding inner detector tracking activity below a predefined level, i.e., isolated muons [33], and 36 GeV for muons with no isolation requirement, are used to select muon data used for the estimation and validation of backgrounds in control regions. A photon trigger with a transverse momentum threshold of 120 GeV at the HLT is used to select events with a high $p_T$ prompt photon for data-driven $Z(\to \nu\bar{\nu})+$jets background estimation (Section 7.1).

Monte Carlo (MC) simulated event samples are used to model both the signal and backgrounds. Effects of multiple proton–proton interactions (pileup) as a function of the instantaneous luminosity are taken into account by overlaying simulated minimum-bias events generated with Pythia8 [34] onto the hard-scattering process, such that the distribution of the average number of interactions per bunch crossing in the Monte Carlo simulated samples matches that in the data. The simulated samples are processed either with a full ATLAS detector simulation [35] based on the Geant4 program [36], or a fast simulation of the response of the electromagnetic and hadronic calorimeters [37]. The results based on fast simulations are validated against fully simulated samples and the difference is found to be negligible. The simulated samples are further processed with a simulation of the trigger system. Both the simulated events and the data are reconstructed and analyzed with the same analysis chain, using the same event selection criteria.

Table 1 summarizes the various event generators and parton distribution function (PDF) sets, as well as parton shower and hadronization software used for the analyses presented in this article.

Signal samples are generated with MadGraph [38], interfaced to Pythia8 using the AU2 parameter settings (tune) [39] for parton showering, hadronization, and underlying event simulation. The Higgs boson mass is fixed to 125 GeV. The MSTW2008LO leading-order (LO) PDF set [40] is used for the $Z'$-2HDM model, while the CTEQ6L1 PDF set [41] is used for the EFT models. For the $Z'$-2HDM model, samples are produced with $Z'$ mass values between 600 and 1400 GeV, $A$ mass values between 300 and 800 GeV (where kinematically allowed), and DM mass values between 10 and 200 GeV but always less than half
Table 1: Summary of MC event generators, PDF sets, and parton shower and hadronization models utilized in the analyses for both the signal and background processes.

<table>
<thead>
<tr>
<th>Model / Process</th>
<th>Generator</th>
<th>PDF</th>
<th>Parton Shower / Hadronization</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z' \rightarrow 2HDM$</td>
<td>MadGraph v1.5.1</td>
<td>MSTW2008LO</td>
<td>PYTHIA v8.175 with AU2 tune</td>
</tr>
<tr>
<td>EFT models</td>
<td>MadGraph v1.5.1</td>
<td>CTEQ6L1</td>
<td>PYTHIA v8.175 with AU2 tune</td>
</tr>
<tr>
<td>$W/Z/\gamma +$jets</td>
<td>SHERPA v1.4.3</td>
<td>CT10</td>
<td>SHERPA v1.4.3</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>POWHEG-BOX v1.0 r2129</td>
<td>CT10</td>
<td>PYTHIA v6.427 with P2011C tune</td>
</tr>
<tr>
<td>Single top ($s$-ch., $Wt$)</td>
<td>MC@NLO v3.3.1</td>
<td>CT10</td>
<td>JIMMY v4.31 with AUET2 tune</td>
</tr>
<tr>
<td>Single top ($t$-ch.)</td>
<td>AckerMC v3.8</td>
<td>CTEQ6L1</td>
<td>PYTHIA v6.426 with AUET2B tune</td>
</tr>
<tr>
<td>$WW/WZ/ZZ$ (resolved)</td>
<td>HERWIG v6.520</td>
<td>CTEQ6L1</td>
<td>JIMMY v4.31 with AUET2 tune</td>
</tr>
<tr>
<td>$WW/WZ/ZZ$ (boosted)</td>
<td>POWHEG r2330.3</td>
<td>CTEQ6L1</td>
<td>PYTHIA v8.175 with AU2 tune</td>
</tr>
<tr>
<td>$q\bar{q} \rightarrow Vh$</td>
<td>PYTHIA v8.175</td>
<td>CTEQ6L1</td>
<td>PYTHIA v8.175 with AU2 tune</td>
</tr>
<tr>
<td>$gg \rightarrow Zh$</td>
<td>POWHEG r2330.3</td>
<td>CT10</td>
<td>PYTHIA v8.160 with AU2 tune</td>
</tr>
<tr>
<td>multijet</td>
<td>PYTHIA v8.160</td>
<td>CT10</td>
<td>PYTHIA v8.160 with AU2 tune</td>
</tr>
</tbody>
</table>

the $A$ mass. In addition, $Z' \rightarrow Zh$ samples are produced for $Z'$ mass values between 600 and 1400 GeV. For the EFT models, samples are produced for scalar and fermionic DM particle masses ranging from 1 to 1000 GeV for both $hh$ and $hZ$ coupling to DM.

A variety of samples are used in the background determination. The dominant $Z(\rightarrow \nu\bar{\nu})+jets$ background is determined from data (Section 7.1), and samples simulated with SHERPA [42] for $Z(\rightarrow \nu\bar{\nu})+jets$, $Z(\rightarrow \ell\ell)+jets$, and $\gamma+jets$ are also used in the calculation process. The $W(\rightarrow \ell\nu)+jets$ processes are generated with SHERPA and are normalized using data as described in Section 7.3. All the SHERPA samples are generated using the CT10 PDF set [43]. The $t\bar{t}$ background is generated with POWHEG-BOX [44] interfaced with Pythia6 and the PERUGIA 2011C tune [45]. Single top quark production in the $s$- and $Wt$-channels are produced with MC@NLO [46–48] interfaced with JIMMY [49], while the $t$-channel process is produced with AckerMC [50] interfaced with Pythia6. The Diagram Removal scheme [51] is used in the single top quark production in the $Wt$-channel to remove potential overlap with $t\bar{t}$ production due to interference of the two processes. A top quark mass of 172.5 GeV is used consistently. The cross-sections of the $t\bar{t}$ and single-top-quark processes are determined at next-to-next-to-leading order (NNLO) in QCD including resummation of next-to-next-to-leading logarithmic (NNLL) soft gluon terms with Top++2.0 [52–58]. The normalization and uncertainties are calculated using the PDF4LHC prescription [59] with the MSTW2008 68% CL NNLO [40, 60], CT10 NNLO [43, 61], and NNPDF2.3 [62] PDF sets. Additional kinematic-dependent corrections to the $t\bar{t}$ sample and normalizations determined from data are described in Section 7.3. Diboson ($ZZ$, $WW$, and $WZ$) production is simulated with two different generators, both HERWIG [63] interfaced to JIMMY and POWHEG interfaced to Pythia8. The differences in event yield and kinematic distributions between the two simulated samples are found to be minimal in the analyses. The diboson samples are normalized to calculations at next-to-leading order (NLO) in QCD performed using MCFM [64]. The multijet background is estimated from data (Section 7.2), with samples simulated with Pythia8 used for validation in the control regions. For SM production of $Zh$ and $Wh$, Pythia8 is used with CTEQ6L1 PDFs, and the samples were normalized to total cross-sections calculated at NLO [65], and NNLO [66] in QCD, respectively, with NLO electroweak corrections [67] in both cases.
5 Object reconstruction

This analysis requires the reconstruction of muons, electrons, photons, jets, and missing transverse momentum. Object reconstruction efficiencies in simulated events are corrected to reproduce the performance measured in data, and their systematic uncertainties are detailed in Section 8.

Muon candidates are identified from tracks that are well reconstructed inside both the inner detector and the muon spectrometer [33], and are required to satisfy the “tight” muon identification quality criteria [33]. To reject cosmic-ray muons, muon candidates are required to be consistent with production at the primary vertex, defined as the vertex with the highest $\Sigma(p_T^{\text{track}})^2$, where $p_T^{\text{track}}$ refers to the transverse momentum of each track. In the muon control region, muon candidates are required to be isolated to reduce the multijet background. This algorithm reconstructs subjets within the large-$R$ jets as well as large-radius (large-$R$; $R = 1.0$) jets are used. The jet trimming algorithm [27] is applied to the reconstruction of large-$R$ jets to minimize the impact of energy depositions due to pileup and the underlying event. This algorithm reconstructs subjets within the large-$R$ jet using the $k_t$ algorithm [73] with radius parameter $R_{\text{sub}} = 0.3$, then removes any subjet with $p_T$ less than 5% of the large-$R$ jet $p_T$. The energies of all jets and the masses of the large-$R$ jets are then calibrated to their values at particle level using $p_T$- and $\eta$-dependent factors determined from simulation; small-$R$ jets are further calibrated using in situ measurements [74]. Small-$R$ jets with $p_T < 50$ GeV and $|\eta| < 2.4$ are required to have at least 50% of the $p_T$ sum of tracks matched to the jet belonging to tracks originating from the primary vertex (jet vertex fraction) to suppress the effects of pileup interactions [75]. Small-$R$ jets are required to satisfy either $p_T > 25$ GeV and $|\eta| < 2.4$ or $p_T > 30$ GeV and $2.4 < |\eta| < 4.5$, while large-$R$ jets are required to satisfy $p_T > 300$ GeV and $|\eta| < 2.0$.

Track-jets [76] are built from tracks using the anti-$k_t$ algorithm with $R = 0.3$. Tracks are required to satisfy $p_T > 0.5$ GeV and $|\eta| < 2.5$, and a set of hit and impact parameter criteria to ensure that those tracks are consistent with originating from the primary vertex, thereby reducing the effects of pileup.

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3 Proton–proton collision vertices are reconstructed requiring that at least five tracks with $p_T > 0.4$ GeV are associated with a given vertex.
Track-jets are matched to large-\(R\) jets using a process called “ghost association” [72, 77, 78]. Track-jets with \(p_T > 20\) GeV and \(|\eta| < 2.5\) are kept for further analysis.

Small-\(R\) jets and track-jets containing \(b\)-hadrons are identified (“\(b\)-tagged”) using the properties of the tracks associated with them, the most important being the impact parameter of each track (defined as the track’s distance of closest approach to the primary vertex in the transverse plane), as well as the presence and properties of displaced vertices. The “MV1” \(b\)-tagging algorithm [25] used in this analysis combines the above information using a neural network and is configured to achieve an average efficiency of 60% for tagging small-\(R\) jets with \(b\)-quarks, \(^3\) and has misidentification probabilities of \(~\)15% for charm-\(b\)-quark jets and less than 1% for light-flavor jets, as determined in an MC sample of \(t\bar{t}\) events. For track-jets, the corresponding numbers are 74% for \(b\)-quark jets, 15% for charm-quark jets, and \(<\)1.5% for light-flavor jets. The \(b\)-tagging algorithm is trained on MC simulations and its efficiency is scaled to match data based on studies of candidate \(t\bar{t}\) and multijet events [79]. For charm- and light-flavor track-jets, the efficiency calibrations for the small-\(R\) jets are used, with additional uncertainties to account for possible differences in \(b\)-tagging performance between small-\(R\) jets and track-jets. The flavor-tagging efficiency is only calibrated up to \(p_T\) of 300 GeV for \(b\)- and \(c\)-tagged small-\(R\) jets, 750 GeV for light-flavor-tagged small-\(R\) jets, and 250 GeV for \(b\)-tagged track-jets. Beyond the maximum \(p_T\), additional uncertainties on the \(b\)-tagging efficiency are extracted from the last calibrated \(p_T\) bin with additional uncertainties based on studies of MC-simulated events with high-\(p_T\) jets.

Energy deposits and tracks in the detector may be associated with multiple physics objects, and a procedure is implemented to remove duplication. If an electron (photon) candidate and a small-\(R\) jet that is not \(b\)-tagged overlap within \(\Delta R < 0.2\), then the object is considered to be an electron (photon) and the small-\(R\) jet is discarded. If an electron (photon) candidate and any small-\(R\) jet overlap within \(0.2 < \Delta R < 0.4\), or if an electron (photon) candidate and a \(b\)-tagged small-\(R\) jet overlap within \(\Delta R < 0.2\) of each other, then the electron (photon) is discarded and the small-\(R\) jet is retained. If a muon candidate and a small-\(R\) jet overlap within \(\Delta R < 0.4\), then the muon is discarded and the small-\(R\) jet is retained. In the boosted channel, large-\(R\) jets are removed if a photon candidate is found within \(\Delta R = 1.0\) of the large-\(R\) jet. Track-jets are removed if a muon candidate is found within \(\Delta R = 0.3\) of the track-jet.

The missing transverse momentum \(E_T^{miss}\) is defined as the negative vector sum of the transverse momenta of jets, electrons, photons, and topological calorimeter clusters not assigned to any reconstructed objects [80]. The transverse momenta of reconstructed muons are included, with the energy deposited by these muons in the calorimeters properly removed to avoid double-counting. In addition, a track-based missing transverse momentum vector \(p_T^{miss}\) is calculated as the negative vector sum of the transverse momenta of tracks with \(|\eta| < 2.4\) and the transverse and longitudinal impact parameters with respect to the primary vertex below 1.5 mm.

6 Event selection

A set of common preselection criteria is used for events to be considered for the resolved and boosted channels. An initial \(E_T^{miss}\) + jets sample is obtained by requiring an event to have passed the 80 GeV HLT \(E_T^{miss}\) trigger, to have an offline \(E_T^{miss} > 100\) GeV for the resolved channel (\(E_T^{miss} > 200\) GeV for the

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\(^3\) In simulation, a jet is labeled as a \(b\)-quark jet if a \(b\)-quark (after final-state radiation) with transverse momentum above 5 GeV is identified within a cone of \(\Delta R = 0.3\) around the jet axis. If no \(b\)-quark is identified, the jet is labeled as a charm-\(b\)-quark jet if a charm-quark is identified with the same criteria. If no charm quark is identified, the jet is labeled as a \(\tau\)-jet if a \(\tau\)-lepton is identified with the same criteria. Otherwise the jet is labeled as a light-flavor jet.
Table 2: The event selection criteria for signal regions in the resolved and boosted channels. The symbol $j$ represents an anti-$k_t$ jet ($R = 0.4$, $j^{ak}$ a track-jet ($R = 0.3$), $J$ a trimmed anti-$k_t$ jet ($R = 1.0$), $b$ a $b$-tagged anti-$k_t$ jet ($R = 0.4$), and $b^{ak}$ a $b$-tagged anti-$k_t$ track-jet ($R = 0.3$). Each $b$-tagged track-jet is matched by ghost association to the leading-$p_T$ large-$R$ jet. The subscript index $i$ of each jet collection means the $i$-th jet in descending order of the transverse momentum, of which $j$ are inclusive and may or may not be $b$-tagged.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Resolved</th>
<th>Boosted</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta\phi_{\text{min}}(E_T^{\text{miss}}, j_i)$</td>
<td>$&gt; 1.0$</td>
<td>$&gt; 1.0$</td>
</tr>
<tr>
<td>Jet multiplicity</td>
<td>$2 \leq n_j \leq 3$</td>
<td>$n_j \geq 1$</td>
</tr>
<tr>
<td>$n_k \geq 2$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$b$-jet (60% eff.) $p_T$</td>
<td>$p_T^{b} &gt; 100$ GeV</td>
<td>-</td>
</tr>
<tr>
<td>$b$-jet multiplicity</td>
<td>$n_b \geq 2$ (60% eff.)</td>
<td>$n_{b,k} \geq 2$ (70% eff.)</td>
</tr>
<tr>
<td>Jet $p_T$</td>
<td>$p_T^{b} &gt; 60$ GeV when $n_j = 3$</td>
<td>$p_T^{d} &gt; 350$ GeV</td>
</tr>
<tr>
<td></td>
<td>$p_T^{c} &gt; 100$ GeV when $n_j = 3$</td>
<td></td>
</tr>
<tr>
<td>$\Delta\phi(E_T^{\text{miss}}, p_T^{\text{miss}})$</td>
<td>-</td>
<td>$&lt; \pi/2$</td>
</tr>
<tr>
<td>Dijet separation</td>
<td>$\Delta R(j_1, j_2) &lt; 1.5$</td>
<td>-</td>
</tr>
<tr>
<td>Invariant mass</td>
<td>$90$ GeV $\leq m_{b_1b_2} \leq 150$ GeV</td>
<td>$90$ GeV $\leq m_{j_1} \leq 150$ GeV</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}$</td>
<td>$&gt; 150, 200, 300,$ or $400$ GeV</td>
<td>$&gt; 300$ or $400$ GeV</td>
</tr>
</tbody>
</table>

boosted channel), at least one small-$R$ jet, no electron with $|\eta| < 2.47$ and $p_T > 7$ GeV, and no muon with $p_T > 6$ GeV and $|\eta| < 2.5$. Events must have at least one identified $pp$ collision vertex and be produced in stable beam conditions with all relevant subdetectors functioning properly. To suppress contamination from multijet events, the smallest azimuthal angle between $E_T^{\text{miss}}$ and small-$R$ jets is required to be greater than 1.0.

For the resolved channel, a further set of selection criteria is chosen by optimizing the sensitivity to a simulated $Z'$-2HDM signal in the presence of the expected background. The selection criteria are summarized in Table 2. The requirements on the $p_T$ of the subleading $b$-tagged jet, $p_T^{b_2}$, and that of the subleading jet, $p_T^{b_1}$, for events containing three jets were found to be effective in removing top quark background. The minimum $E_T^{\text{miss}}$ value required increases with $m_{Z'}$ to take advantage of the harder $E_T^{\text{miss}}$ spectrum for higher $Z'$ mass values. The best signal sensitivity at $\tan\beta = 1$ for the signal samples used in this analysis is achieved by requiring a minimum $E_T^{\text{miss}}$ of 200 GeV for $m_{Z'} = 600$ GeV, 300 GeV for $m_{Z'} = 800$ GeV, and 400 GeV for $m_{Z'} = 1000$–1400 GeV. The product of the detector acceptance and reconstruction efficiency (selection efficiency) of the $Z' \rightarrow h(b\bar{b}) + E_T^{\text{miss}}$ signal after the full set of selection requirements varies from 5% to 10% depending on $m_{Z'}$ and $m_A$.

The boosted channel differs from the resolved channel primarily by the requirement of at least one large-$R$ jet designed to contain the decay products of a single $h \rightarrow b\bar{b}$ decay. Table 2 also lists the selection criteria for the boosted channel, designed to achieve high efficiency for the EFT models and good background rejection. The leading large-$R$ jet is required to have $p_T > 350$ GeV. At these high $p_T$ values, the decay products from top quarks are often contained inside a large-$R$ jet, so the requirement on the mass of the leading large-$R$ jet to between 90 GeV and 150 GeV provides good rejection against top quark background. The multijet background is further suppressed by requiring the azimuthal angle between $E_T^{\text{miss}}$ and $p_T^{\text{miss}}$, $\Delta\phi(E_T^{\text{miss}}, p_T^{\text{miss}})$, to be less than $\pi/2$. Similar to the resolved channel, the final $E_T^{\text{miss}}$ requirement in the boosted channel varies as the $E_T^{\text{miss}}$ distribution shifts for different EFT models and DM mass. For the models $|\chi|^2|H|^2$, $\bar{\chi}i\gamma_5\chi|H|^2$, and $\chi^T \partial^\mu \chi H^\dagger D_{\mu}H$, the minimum $E_T^{\text{miss}}$ is 300 GeV for $m_{\chi}$.
= 1, 65, and 100 GeV, and 400 GeV for \( m_\chi = 500 \) and 1000 GeV; the selection efficiency for these three EFT models varies from 1% to 8%, with a higher efficiency at larger \( m_\chi \). For the \( \bar{\chi}^0 \nu_j B_{\mu j} H D' H \) model, \( E_T^{\text{miss}} > 400 \) GeV is required for all \( m_\chi \) values, and the selection efficiency ranges from 10% to 13%, increasing slightly with \( m_\chi \).

## 7 Background estimation

The main source of irreducible background for this search is \( Z+jets \) when the \( Z \) boson decays into a pair of neutrinos. To reduce the impact of theoretical and experimental uncertainties associated with this process, which are particularly evident in regions with large \( E_T^{\text{miss}} \), \( Z(\rightarrow \nu \bar{\nu})+jets \) background is determined from data with input from simulation, as described in Section 7.1. Multijet production in which there is large \( E_T^{\text{miss}} \) is not simulated reliably, so it is also estimated using data, as described in Section 7.2. The \( W(\rightarrow \ell \nu)+jets \) and top quark production processes are estimated using the shape from MC simulation and are normalized to data in 1-lepton control regions, as described in Section 7.3. The other backgrounds are estimated from Monte Carlo simulation, namely \( Z(\rightarrow \ell \ell)+jets \), diboson production, and vector boson associated production with the Standard Model Higgs boson. Section 7.4 shows validations of the background modeling in the zero-lepton validation regions using selections close to those of the signal regions.

### 7.1 \( Z(\rightarrow \nu \bar{\nu})+jets \) background

The estimation of the \( Z(\rightarrow \nu \bar{\nu})+jets \) background is derived from two data samples. For \( E_T^{\text{miss}} < 200 \) GeV, the \( Z(\rightarrow \mu^+ \mu^-)+jets \) sample is used. The \( p_T \) spectrum of produced \( Z \) bosons and the kinematic distributions of jets are the same whether the \( Z \) boson decays into charged leptons or neutrinos. Thus the \( Z(\rightarrow \mu^+ \mu^-)+jets \) data sample provides very good modeling of the \( Z(\rightarrow \nu \bar{\nu})+jets \) background. The \( Z(\rightarrow \mu^+ \mu^-)+jets \) events are selected by requesting two isolated muons that pass the 24 GeV muon trigger in the HLT and satisfy the tight selection criteria, with opposite charge and \( p_T \) above 25 GeV, and the invariant mass of the muon pair be between 70 GeV and 110 GeV. The same selection is applied to both simulated samples and to the data. A transfer function is derived to account for the differences in branching ratio, trigger efficiency, and reconstruction efficiencies between \( Z(\rightarrow \nu \bar{\nu})+jets \) and \( Z(\rightarrow \mu^+ \mu^-)+jets \). For higher purity and larger sample size, as well as reduction of systematic uncertainties, SHERPA samples of \( Z(\rightarrow \nu \bar{\nu})+jets \) and \( Z(\rightarrow \mu^+ \mu^-)+jets \), which have the same production kinematics, are used to derive the transfer function. The samples are fully reconstructed and the trigger and event selection criteria are applied. The \( E_T^{\text{miss}} \) in each \( Z(\rightarrow \mu^+ \mu^-)+jets \) event is recalculated by adding the two muon transverse momentum vectors to the original \( E_T^{\text{miss}} \) to create a new variable called \( E_T^{\text{miss}+\ell \ell} \). This mimics the \( E_T^{\text{miss}} \) in \( Z(\rightarrow \nu \bar{\nu})+jets \) events. A transfer function is derived by fitting the ratio of the \( Z(\rightarrow \nu \bar{\nu})+jets \) \( E_T^{\text{miss}} \) distribution divided by the \( Z(\rightarrow \mu^+ \mu^-)+jets \) \( E_T^{\text{miss}+\ell \ell} \) distribution. Simulated events from other background processes that passed the aforementioned \( Z(\rightarrow \mu^+ \mu^-) \) selection are subtracted from the data to obtain a \( Z(\rightarrow \mu^+ \mu^-)+jets \) data sample with high purity. The MC-based transfer function is applied to the \( Z(\rightarrow \mu^+ \mu^-)+jets \) \( E_T^{\text{miss}+\ell \ell} \) distribution in this data sample to estimate the \( Z(\rightarrow \nu \bar{\nu})+jets \) background. As the \( Z'\)-2HDM model contains the decay mode \( Z' \rightarrow Zh \), the presence of such a signal would have a contribution to the \( Z(\rightarrow \mu^+ \mu^-)+jets \) process as well; however, in the \( E_T^{\text{miss}} < 200 \) GeV region, the expected yield from the \( Z' \rightarrow Z(\rightarrow \mu^+ \mu^-)h \) process is several orders of magnitude smaller than the standard model \( Z(\rightarrow \mu^+ \mu^-)+jets \) production, and thus has a negligible impact on the background estimation.
For $E_T^{\text{miss}} > 200 \text{ GeV}$, the limited size of the Z($\rightarrow \mu^+\mu^-)$+jets data sample reduces its usefulness. In this region the $\gamma$+jets data sample is used. For $\gamma$ transverse momenta much greater than the mass of the Z boson, the kinematic properties of $\gamma$+jets and Z+jets events are very similar [81]. A high-purity (above 99% in both the resolved and boosted channels after $b$-tagging requirements) $\gamma$+jets data sample is selected by requiring one high-$p_T$ ($\geq 125$ GeV), prompt photon that passed the 120 GeV HLT photon trigger. The transfer function is calculated from reconstructed SHERPA samples of $\gamma$+jets events that passed the same photon selection, and $Z(\rightarrow \nu\bar{\nu})$+jets events. The $E_T^{\text{miss}}$ in a $\gamma$+jets event is recalculated by using all clustered objects described in Section 5 except the leading photon, and denoted as $E_T^{\text{miss}+\gamma}$. The $Z(\rightarrow \nu\bar{\nu})$+jets background for $E_T^{\text{miss}} > 200 \text{ GeV}$ is obtained by multiplying the $\gamma$+jets $E_T^{\text{miss}+\gamma}$ distribution in data by the MC-produced transfer function. Since the photon couples to a quark through its electric charge, while the Z boson coupling depends on the weak neutral vector and axial-vector couplings, the transfer function varies slightly by $\sim 3\%$ to $10\%$ depending on the number of $b$-tagged jets in the final state. An MC-based correction factor for each value of $b$-tagged jet multiplicity is derived and applied to account for the small difference.

To test this procedure over the entire $E_T^{\text{miss}}$ distribution above 100 GeV, two control regions are defined in the resolved channel using event selection very similar to that of the signal region except requiring either zero or one $b$-tagged small-$R$ jet. A similar test is performed in the boosted channel but with $E_T^{\text{miss}}$ above 200 GeV where control regions are defined with zero, one or two $b$-tagged track-jets that are matched by ghost association to the leading large-$R$ jet. Despite the two $b$-tagged track-jets requirement in the last case, the expected discovery significance of the signal models considered is well below $2\sigma$ considering the background estimate. By keeping the yields of the other background processes constant and normalizing the total expected background to data, a scale factor of 0.9 for the $Z(\rightarrow \nu\bar{\nu})$+jets estimation is derived from the control regions with no $b$-tagged jets for both the resolved and boosted channels. The 10% difference from unity is assigned as an additional source of systematic uncertainty on the $Z(\rightarrow \nu\bar{\nu})$+jets normalization in both channels. After the corrections described above are applied, the data and background estimates agree well in all five control regions to within 3% to 10% depending on the number of $b$-tagged jets in the resolved channel, and within 1% to 20% in the boosted channel; the differences are larger in regions with higher $b$-tagged jet multiplicity and hence smaller event sample size.

### 7.2 Multijet background

The multijet background in the resolved channel is estimated from data using a “jet smearing” method [82]. A pure multijet sample, used as the “seed” events, is obtained by selecting from the data events containing multiple jets, no isolated leptons, and $E_T^{\text{miss}}$ below 120 GeV, using a set of jet triggers with different requirements on jet $p_T$ threshold and $|\eta|$ coverage. A “smeared” event is generated by multiplying each jet four-momentum in a seed event by a random number drawn from a jet response function. The response function quantifies the probability of fluctuations in the detector response to jets measured in the data. It is determined using data and simulation, and has both Gaussian and non-Gaussian components to account for both the core of the distribution and the tails. After “smearing”, the obtained multijet estimation is compared to the data in a dedicated multijet control region in which $100 < E_T^{\text{miss}} < 120 \text{ GeV}$, the leading jet has $p_T > 100 \text{ GeV}$, and $\Delta R_{\text{min}}(E_T^{\text{miss}},j_1) < 0.7$. The agreement is good with slight mismodelling likely due to the difference in $E_T^{\text{miss}}$ distributions between $b$-quark jets and light jets. Hence the “smeared” multijet sample is reweighted two-dimensionally with respect to its jet multiplicity and $b$-tagged jet multiplicity to match the numbers in the data in the multijet control region. The aforementioned small discrepancies in data and background comparison are removed after reweighting. The multijet background
is small in the other control regions in the resolved channel and negligible in the signal region.

The multijet background is estimated in the boosted channel using an “ABCD method” [83], in which the data are divided into four regions based on the \( \Delta \phi_{\text{min}}(E_T^{\text{miss}}, j_i) \) and \( \Delta \phi(E_T^{\text{miss}}, \vec{p}_T^{\text{miss}}) \) variables, such that three of the regions are dominated by background. These two variables are found to be weakly correlated in a data sample after the lepton veto, and requiring at least one large-\( R \) jet with \( p_T > 350 \) GeV, at least two track-jets matched to the large-\( R \) jet, and \( E_T^{\text{miss}} \) between 100 and 200 GeV. This observation is confirmed in a multijet event sample simulated with Pythia8. The signal region (A) is selected with \( \Delta \phi_{\text{min}}(E_T^{\text{miss}}, j_i) > 1.0 \) and \( \Delta \phi(E_T^{\text{miss}}, \vec{p}_T^{\text{miss}}) < \pi/2 \). In region C, the requirement on \( \Delta \phi(E_T^{\text{miss}}, \vec{p}_T^{\text{miss}}) \) is reversed. In regions B and D, \( \Delta \phi_{\text{min}}(E_T^{\text{miss}}, j_i) < 0.4 \) is required, with the same requirement on \( \Delta \phi(E_T^{\text{miss}}, \vec{p}_T^{\text{miss}}) \) as in regions A and C, respectively. The multijet yield in each of the regions B, C, and D is obtained by subtracting from the data the contribution of other backgrounds taken from simulation. The number of multijet events in region A is estimated as a product of the yields in regions D and C divided by the yield in region B. Due to the small number of events, the track-jet 3-tagging and the large-\( R \) jet mass requirements for the signal region are not applied in regions B, C, and D, and an additional scale factor to estimate the selection efficiencies of these two requirements is applied to the resulting yields. The number of events from multijet background in the signal region is estimated to be consistent with zero within uncertainties, and a 68\% CL upper limit of 0.1 events is used as the predicted yield.

### 7.3 W+jets and top quark backgrounds

In the resolved channel, the W+jets control region is very similar to the signal region, except that the lepton veto is replaced by the requirement of one isolated muon with \( p_T > 25 \) GeV, and the number of small-\( R \) jets must be two. The purity of the W+jets background in this control region is approximately 90\% before b-tagging requirements. By keeping the yields of the other background processes constant and normalizing the total expected background to data, a scale factor of 0.92 is derived for the W+jets background. The 8\% difference from unity is small compared to the systematic uncertainty on the W+jets normalization as discussed in Section 8. This scale factor is applied to the W+jets background when deriving the normalization for \( Z(\rightarrow \nu\bar{\nu})+\text{jets} \) background in Section 7.1. The top quark control region has the same requirements except that three small-\( R \) jets are required. The purity of the top quark background, which includes mostly \( t\bar{t} \) but also single-top-quark events, is approximately 78\% in the top quark control region after requiring at least one b-tagged small-\( R \) jet. Good agreement is observed between data and simulation and no additional scale factor is applied to the top quark background. In both control regions, as well as the combined one-lepton validation region where the jet multiplicity requirement is removed, there is good agreement between data and estimated background in both number of events and modeling of the kinematic variables.

As Monte Carlo simulation predicts a harder top quark \( p_T \) spectrum for \( t\bar{t} \) events in comparison to data, a correction is applied in the boosted channel at the level of generated top quarks in the \( t\bar{t} \) MC sample [84, 85]. For the resolved channel, the correction is not applied since the impact is small, but the effect of it is accounted for as a source of systematic uncertainty, as discussed in Section 8.

The W+jets and top quark (\( t\bar{t} + \text{single top quark} \)) backgrounds are further studied in the boosted channel in a one-lepton control region selected by requiring one isolated muon with \( p_T > 25 \) GeV, preselection criteria as described in Section 2 except the lepton veto, and the first two selections in Table 2. Events passing the one-lepton control region selections are categorized as being in the W+jets control region unless at least one b-tagged track-jet is found within \( \Delta R = 1.5 \) of the muon direction, in which case
they are used for a top quark control region. The purity of $W$+jets background in the $W$+jets control region is approximately 72%, whereas the purity of the top quark background in the top quark control region is $\sim$ 90%. A pair of linear equations to calculate the normalization factor from background to data is constructed using the predicted and observed yields of the $W$+jets and top quark backgrounds. The solution of the equations, $0.82 \pm 0.05$ and $0.89 \pm 0.06$, are applied as scale factors to the $W$+jets background and top quark background, respectively.

### 7.4 Zero-lepton validation region

![Figure 2: The distribution of the missing transverse momentum with magnitude $E_{\text{miss}}^T$ of the resolved channel (left) and the boosted channel (right) in the zero-lepton validation region (VR) for the estimated backgrounds (solid histograms) and the observed data (points). The hatched areas represent the combined statistical and systematic uncertainties in the total background estimation. At least one (exactly one) $b$-tagged jet is required in the resolved (boosted) channel. In the resolved channel, the invariant mass of the $b\bar{b}$ system in events with at least two $b$-tagged jets is required to be either less than 60 GeV or greater than 150 GeV. In the boosted channel, the invariant mass of the large-$R$ jet with exactly one $b$-tagged track-jet is required to be either less than 90 GeV or greater than 150 GeV. The minimum $E_{\text{miss}}^T$ requirement in the resolved (boosted) channel is 100 GeV (200 GeV). In the resolved channel, the small contribution from $Zh$ ($Wh$) process is included in the $Z(\rightarrow \nu\bar{\nu})$+jets ($W(\rightarrow \ell\nu)$/$Z(\rightarrow \ell\ell)$+jets) distribution. The individual background processes are studied and normalized to data in the dedicated control regions, as described in the previous sections. To examine the overall modeling of all non-Higgs background processes combined, zero-lepton validation regions are defined for both channels, with selections similar to the signal region, but reversing the requirement on the invariant mass of the $b\bar{b}$ system to be below 60 GeV (90 GeV) in the resolved (boosted) channel or above 150 GeV in both channels. Figure 2 shows the $E_{\text{miss}}^T$ distributions in both channels, with the aforementioned scale factors for the corresponding background processes applied. Good agreement between the data and the estimated background is achieved for different kinematic variables, including jet $p_T$, angular distributions, multiplicity, and number of $b$-tagged jets, at each selection stage in both channels.}
The systematic uncertainty on background estimation and signal processes using Monte Carlo samples comes from several sources, and is evaluated for each of the signal and background processes in both channels. The uncertainty associated with the $b$-tagging efficiency, which is determined from comparisons between simulation and heavy-flavor-enriched data samples [79], ranges from $\sim$ 10% to 15%. The uncertainty on the overall background estimate due to light-flavor and charm-quark jets being misidentified as $b$-quark jets [25] is calculated to be $\sim$ 1% for small-$R$ jets, and $\sim$ 2% to 3% for track-jets. The jet energy scale and resolution [71], which directly impact the $E_T^{\text{miss}}$, depend on the kinematic properties of the jet, the distance to its nearest jet neighbor, and the flavor of the initiating parton. The systematic uncertainty associated with the jet energy scale and resolution ranges from $\sim$ 5% to 15%.

In the boosted channel, the invariant mass of the $b\bar{b}$ system from the Higgs boson decay is selected by requiring the mass of the large-$R$ jet to be between 90 GeV and 150 GeV, leading to additional systematic uncertainties from the jet mass scale and resolution [77]. The uncertainties associated with jet mass are $\sim$ 1% for the EFT signals and $\sim$ 3% to 8% for most simulated background processes. While the large-$R$ jet calibration and uncertainty are derived primarily using an inclusive multijet sample, the large-$R$ jet selection in this analysis focuses specifically on identifying jets containing two $b$-hadrons. As such, there are possible additional sources of uncertainty on the modeling of the jet mass and energy due to the difference in heavy-flavor content between the calibration and analysis selections. However, studies of multijet samples enriched with jets containing two $b$-hadrons suggest that this uncertainty is small in comparison to the existing uncertainty on jet mass and energy, and thus no additional uncertainty is applied.

The uncertainty on $E_T^{\text{miss}}$ originating from the energy scale and resolution of energy clusters not included in jets [80] is small at $\sim$ 1% or less, as are the uncertainties due to possible mismodeling of the effect of multiple $pp$ collisions (pileup) and the method of removing jets coming from pileup. The uncertainty on the integrated luminosity for the data sample is 2.8%. It is derived using the same methodology as that detailed in Ref. [86].

The cross-section uncertainties for the background processes are as follows. For $t\bar{t}$ production, an uncertainty of 7% is cited from theoretical calculations [87], which is consistent with the ATLAS measurement of top quark pair production [88]. The same uncertainty is used for the small single-top-quark background [89]. For $W$+jets, a cross-section uncertainty of 20% is taken from the recent ATLAS measurement of $W$+jets production with $b$-jets [90]. The uncertainty on the simulated diboson background cross-section increases with the $E_T^{\text{miss}}$ threshold from 20% for $E_T^{\text{miss}} > 150$ GeV to 30% for $E_T^{\text{miss}} > 400$ GeV [4]. For vector boson plus Higgs boson production, an uncertainty of 3.1% on the cross-section is estimated from theoretical calculations [91] and is applied here. The signals samples from MC simulation are produced at LO. An estimated value of 10% is used as the uncertainty on the signal cross-section from NLO corrections [92]. The systematic uncertainty on the signal acceptance due to the choice of parton distribution functions (PDFs) is determined by using the uncertainty eigenvectors provided for multiple PDF sets per the PDF4LHC prescription [59]. The uncertainty from this source is given by the maximum difference in detector acceptance of the signal process when using different variations in the MSTW2008 LO [40] and NNPDF2.1 [62] PDF sets, leading to an uncertainty of $\sim$ 4% to 8% for the $Z'$-2HDM model, and $\sim$ 2% to 21% for the different EFT models. For the simulated background processes, the uncertainty due to variations in MSTW2008 NNLO [40, 60], CT10 NNLO [43, 61], and NNPDF2.3 [62] PDF sets and parton shower models is $\sim$ 5% to 7%. 

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The systematic uncertainty on the data-driven \(Z(\rightarrow \nu \bar{\nu})+\text{jets}\) background comes from the transfer function and from the simulated backgrounds that are subtracted from the \(Z(\rightarrow \mu^+\mu^-)+\text{jets}\) data sample (the high-\(p_T\) \(\gamma+\text{jets}\) sample has a purity of over 99% after \(b\)-tagging requirements). For the latter, all of the systematic uncertainties noted above are calculated for simulated samples. Since these backgrounds are subtracted here, the uncertainties are anticorrelated with the variations of the corresponding backgrounds in the signal region. For the transfer function, there are contributions from the functional form used, the fit range in \(E_T\) in the signal region. For the transfer function, there are contributions from the functional form used, the subtracted here, the uncertainties are anticorrelated with the variations of the corresponding backgrounds.

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A 10% uncertainty on the cross-section is also taken into account from the normalization factor of 0.9 applied to the \(Z(\rightarrow \nu \bar{\nu})+\text{jets}\) background, as described in Section 7.1. The theoretical uncertainty on the \(Z/\gamma\) ratio at high \(p_T\) is \(\sim 4\%\) [81], which is small in comparison and hence not applied. The total systematic uncertainty on the \(Z(\rightarrow \nu \bar{\nu})+\text{jets}\) background in the resolved channel is 20% in the lower \(E_{T,\text{miss}}\) region where \(Z(\rightarrow \mu^+\mu^-)+\text{jets}\) is used and 12% in the higher \(E_{T,\text{miss}}\) region where \(\gamma+\text{jets}\) is used. In the boosted channel, only \(\gamma+\text{jets}\) is used to estimate \(Z(\rightarrow \nu \bar{\nu})+\text{jets}\) background and the total systematic uncertainty is approximately 16%.

As explained in Section 7.3, the top quark \(p_T\) distribution is reweighted at the Monte Carlo generator level to bring it into agreement with measurements of data. The size of the correction is found to be 5.5% in shape and normalization combined in the resolved channel, where it is considered as an additional source of systematic uncertainty. The correction has a greater effect in the boosted channel as the original mismodeling in simulation is primarily in high-\(p_T\) regions. The systematic uncertainty associated with the top quark \(p_T\) reweighting is evaluated to be \(\sim 15\%\) and applied to the top quark process in the boosted channel.

Overall, the systematic uncertainty on the estimated background is calculated to be between 10% and 16% in the resolved channel, and between 12% and 14% in the boosted channel, depending on the final \(E_{T,\text{miss}}\) requirement in the signal region. Table 3 lists the main sources of systematic uncertainty for both the resolved and boosted channels, and their values for both signals and backgrounds. The values given for the backgrounds are the uncertainties on the total background with the relative weights and correlations of individual background processes taken into account.

9 Results

Table 4 shows the predicted number of background events in the signal region for each value of the ascending \(E_{T,\text{miss}}\) thresholds, along with the number of events observed in the data. The numbers of predicted background events and observed events are consistent within 1\(\sigma\) in five out of the six signal regions. For the boosted channel and \(E_{T,\text{miss}} > 300\) GeV, 20 events are observed in the data compared to a background expectation of 11.2 ± 2.3 events. The probability that the number of events in the background fluctuates to the value in the data or above corresponds to 2.2\(\sigma\). Figure 3 shows the \(E_{T,\text{miss}}\) distribution for the data and the background estimates in the signal regions of the resolved and boosted channels. Also shown in the resolved channel are the \(E_{T,\text{miss}}\) distributions for two examples of the \(Z^\prime\)-2HDM model at different \(m_{Z^\prime}\) with \(m_A = 300\) GeV and \(\tan \beta = 1\). Similarly the \(E_{T,\text{miss}}\) distributions for two examples of the EFT models with different \(m_A\) are shown in the boosted channel. The 2.2\(\sigma\) upward fluctuation mentioned above is primarily
Table 3: Summary of systematic uncertainty in percent for all backgrounds combined and signal samples in the resolved and boosted channels. The first column lists the main sources of systematic uncertainty, where the acronym JES refers to the jet energy scale, JER the jet energy resolution, JMS the jet mass scale, JMR the jet mass resolution, and JVF the jet vertex fraction. The uncertainty figures listed for “b-tagging” combine the uncertainty from both b-tagging efficiency and mistag rates. The uncertainty ranges in “Total Background” reflect the shift in value with increasing $E^\text{miss}_T$ threshold in the final signal region. The uncertainties for “$Z(\nu\bar{\nu})$ transfer function” take into account the fractional weight of the $Z(\nu\bar{\nu})$ process in total background, which differs per analysis channel and $E^\text{miss}_T$ threshold. Most of the systematic uncertainties on the signal models vary little across the parameter space in this analysis, with the exception of signal PDF and $\alpha_s$, JMS, and pileup uncertainty; hence the ranges of values are shown.

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<th>Resolved (%)</th>
<th>Boosted (%)</th>
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<tr>
<td>Total syst.</td>
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<td>10–16</td>
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due to events with $E^\text{miss}_T$ values between 300 GeV and 400 GeV, and mass of the leading large-$R$ jet below the Higgs boson mass, while signal events are most likely to have higher $E^\text{miss}_T$ values and leading large-$R$ jet mass close to Higgs boson mass.

A Frequentist approach is used for the statistical interpretation of the results [93]. The probability of the background-only hypothesis, the $p(s = 0)$-value, is calculated for each of the four signal regions with ascending $E^\text{miss}_T$ threshold in the resolved channel and the two signal regions in the boosted channel. The 95% CL upper limits on the number of non-Standard Model events in each of the signal regions are also obtained using a profile-likelihood-ratio test following the $CL_s$ prescription [94], which can be translated into model-independent 95% CL upper limits on the visible cross-section, defined as the product of production cross-section, acceptance, and reconstruction efficiency of any signal model. The limits are calculated taking into account the uncertainty on the background estimate, the integrated luminosity of the data sample, and its uncertainty. Table 5 gives the model-independent 95% CL upper limits on the visible cross-section, the observed and expected limits on the number of non-Standard Model events in the signal region, and the $p(s = 0)$-values.

As a $p(s = 0)$-value of 0.03 is calculated for $E^\text{miss}_T > 300$ GeV in the boosted channel, a calculation of the look-elsewhere effect [95] is performed. Using pseudo-experiments and taking into account correlations between all signal regions in both channels, the probability that there is a deviation in the data from the background expectation at least as significant as the one observed due to a statistical fluctuation in the background is calculated to be approximately 10%.
The large uncertainty on the $Z\rightarrow \nu\bar{\nu}$+jets process in the $E_T^{miss}$ > 150 GeV SR of the resolved channel is due to limited statistics in the $Z(\rightarrow \mu^+\mu^-)$+jets data sample used for the estimation of $Z(\rightarrow \nu\bar{\nu})$+jets with $E_T^{miss}$ < 200 GeV.

<table>
<thead>
<tr>
<th>$E_T^{miss}$</th>
<th>Resolved</th>
<th></th>
<th></th>
<th></th>
<th>Boosted</th>
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<tbody>
<tr>
<td>&gt; 150 GeV</td>
<td>&gt; 200 GeV</td>
<td>&gt; 300 GeV</td>
<td>&gt; 400 GeV</td>
<td>&gt; 300 GeV</td>
<td>&gt; 400 GeV</td>
<td>&gt; 300 GeV</td>
<td>&gt; 400 GeV</td>
<td></td>
</tr>
<tr>
<td>$Z(\rightarrow \nu\bar{\nu})$+jets</td>
<td>48 ± 32</td>
<td>21 ± 5</td>
<td>2.9 ± 1.1</td>
<td>0.3 ± 0.3</td>
<td>7.0 ± 2.0</td>
<td>5.2 ± 1.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Multijet</td>
<td>3.7 ± 3.1</td>
<td>0.02 ± 0.02</td>
<td>–</td>
<td>–</td>
<td>&lt; 0.0 ± 0.1</td>
<td>&lt; 0.0 ± 0.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$t\bar{t}$ &amp; single-top</td>
<td>48 ± 10</td>
<td>17 ± 3.8</td>
<td>1.6 ± 0.5</td>
<td>0.3 ± 0.1</td>
<td>0.8 ± 0.5</td>
<td>0.6 ± 0.4</td>
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<tr>
<td>W+jets &amp; Z+jets</td>
<td>15 ± 3.4</td>
<td>6.2 ± 1.5</td>
<td>1.1 ± 0.3</td>
<td>0.3 ± 0.1</td>
<td>1.4 ± 0.7</td>
<td>0.8 ± 0.4</td>
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<td></td>
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<tr>
<td>Diboson</td>
<td>29.4 ± 7.5</td>
<td>13.2 ± 3.8</td>
<td>2.8 ± 1.0</td>
<td>0.6 ± 0.3</td>
<td>0.9 ± 0.5</td>
<td>0.6 ± 0.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Vb(bb)$</td>
<td>5.0 ± 0.7</td>
<td>4.2 ± 0.6</td>
<td>1.0 ± 0.2</td>
<td>0.3 ± 0.1</td>
<td>1.0 ± 0.2</td>
<td>0.6 ± 0.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total background</td>
<td>148 ± 30</td>
<td>62 ± 7.5</td>
<td>9.4 ± 1.8</td>
<td>1.7 ± 0.5</td>
<td>11.2 ± 2.3</td>
<td>7.7 ± 1.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>164</td>
<td>68</td>
<td>11</td>
<td>2</td>
<td>20</td>
<td>9</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The numbers of observed events and expected background events, along with each of the signal and background statistical and systematic uncertainties, are used to determine limits for the $Z'$-2HDM model and EFT models, which are interpreted separately. Limits on the signal yield are set using a similar profile-likelihood-ratio test with the $CL_s$ method as the aforementioned model-independent upper limit calculation. Each of the systematic uncertainties is treated as a nuisance parameter, with the correlations among the sources of systematic uncertainty taken into account.
For the resolved channel, the 95% CL upper limit on the cross-section is derived and used to exclude portions of parameter space of the $Z'$-2HDM model in both the $m_Z' - m_A$ and $m_Z' - \tan\beta$ planes. In both cases, the $Z'$ gauge coupling is set to its 95% CL upper limit from precision electroweak constraints and searches for dijet resonances for the corresponding $Z'$ mass and $\tan\beta$ value. Taking the alignment limit of $\alpha = \beta - \pi/2$ evades the constraints in $\tan\beta$ for a Type 2 two-Higgs-doublet model using fits to the observed Higgs boson couplings from the LHC [96]. The exclusion region in the $m_{Z'} - m_A$ plane is shown in Figure 4(a), where $m_A \geq 300$ GeV in accordance with $b \to s\gamma$ constraints [19]. For $\tan\beta = 1$, $m_{Z'} = 700$–1300 GeV is excluded for $m_A$ up to 350 GeV, with further exclusion of larger $m_A$ for $m_{Z'}$ around 1200 GeV. Limits in the $m_{Z'} - \tan\beta$ plane are shown in Figure 4(b), where $\tan\beta \geq 0.3$ based on the perturbativity requirement of the Higgs–top Yukawa coupling [97], and is below 10 based on direct searches for the $A$ [98]. For $m_A = 300$ GeV, where $A$ decays almost exclusively to a DM pair, $m_{Z'} = 700$–1300 GeV is excluded for $\tan\beta < 2$, with further exclusion of larger $\tan\beta$ for $m_{Z'}$ between 800 GeV and 1000 GeV due to the inclusion of the $Z' \to Zh$ contribution in the final state. The limits are stronger in regions with larger $m_{Z'}$ and smaller $m_A$ (or a larger contribution from $Z' \to Zh$ where the Z boson is much lighter than A), as the harder $E_T^{\text{miss}}$ spectrum in these cases allows a higher $E_T^{\text{miss}}$ requirement with better sensitivity, as demonstrated in Table 5. The sensitivity eventually drops at very large $m_{Z'}$ due to the decrease in signal production cross-section.

For the boosted channel, limits on DM production are derived from the cross-section limits at a given DM mass $m_{\chi}$, and expressed as 95% CL limits on the suppression scale $\Lambda$ or coupling parameter $\lambda$ for the effective field theory operators described by Equations 1 to 4. As mentioned earlier, the effective field theory model becomes a poor approximation of an ultraviolet-complete model containing a heavy mediator $V$ when the momentum transferred in the interaction, $Q_{tr}$, is comparable to the mass of the intermediate state $m_V = \Lambda \sqrt{g_q g_x}$ [99, 100], where $g_q$ and $g_x$ represent the coupling of $V$ to SM and DM particles, respectively. To give an indication of the impact of the unknown ultraviolet details of the theory, a truncation method is adopted [101], and limits are computed in which only simulated events with $Q_{tr} = m_{\chi} < m_V$ are retained. These limits are calculated for both values of $g = \sqrt{g_q g_x} = 1$ and 4, the latter being the maximum possible value for the interaction to remain perturbative. The limits are derived assuming that the kinematic properties of the events in the signal processes are independent of $\Lambda(\lambda)$. The assumption is not valid in certain regions of parameter space already excluded by invisible Higgs boson [96, 102] or Z boson [103] decays or near the perturbativity boundary. The limits for operators $|\lambda|^2 |H|^2$ and $\tilde{\chi} \gamma_5 \chi |H|^2$ are calculated to be in such regions where the aforementioned kinematic

Table 5: Model-independent upper limits for the resolved and boosted channels. Left to right: signal region (SR) $E_T^{\text{miss}}$ requirement, number of observed events, number of expected background events, 95% CL upper limits on the visible cross-section ($\langle \sigma_{\text{vis}} \rangle_{\text{obs}}$) and the number of non-SM events ($N_{\text{BSM}}$). The sixth column ($N_{\text{BSM}}^{95}$) shows the expected 95% CL upper limit on the number of non-SM events, given the estimated number and the ±1σ uncertainty of background events. The last column shows the $p$-value for the background-only hypothesis ($p(s = 0)$).

<table>
<thead>
<tr>
<th>$E_T^{\text{miss}}$</th>
<th>$N_{\text{obs}}$</th>
<th>$N_{\text{bkgd}}$</th>
<th>$\langle \sigma_{\text{vis}} \rangle_{\text{obs}}^{95}$ [fb]</th>
<th>$N_{\text{BSM}}^{95}$</th>
<th>$N_{\text{BSM}}^{95}$</th>
<th>$p(s = 0)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 150 GeV</td>
<td>164</td>
<td>148</td>
<td>3.6</td>
<td>74</td>
<td>$63_{-14}^{+22}$</td>
<td>0.31</td>
</tr>
<tr>
<td>&gt; 200 GeV</td>
<td>68</td>
<td>62</td>
<td>1.3</td>
<td>27</td>
<td>$21_{-8.4}^{+4}$</td>
<td>0.28</td>
</tr>
<tr>
<td>&gt; 300 GeV</td>
<td>11</td>
<td>9.4</td>
<td>0.49</td>
<td>9.9</td>
<td>$8.2_{-1.9}^{+3.4}$</td>
<td>0.31</td>
</tr>
<tr>
<td>&gt; 400 GeV</td>
<td>2</td>
<td>1.7</td>
<td>0.24</td>
<td>4.8</td>
<td>$4.7_{-1.0}^{+1.6}$</td>
<td>0.39</td>
</tr>
<tr>
<td>Boosted</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&gt; 300 GeV</td>
<td>20</td>
<td>11.2</td>
<td>0.90</td>
<td>18</td>
<td>9.9</td>
<td>0.03</td>
</tr>
<tr>
<td>&gt; 400 GeV</td>
<td>9</td>
<td>7.7</td>
<td>0.43</td>
<td>8.8</td>
<td>7.7</td>
<td>0.37</td>
</tr>
</tbody>
</table>
Figure 4: The Z'–2HDM exclusion contour in the (a) $m_{Z'} - m_A$ plane for $\tan \beta = 1$ and (b) $m_{Z'} - \tan \beta$ plane for $m_A = 300$ GeV. The expected limit is given by the dashed blue line, and the yellow bands indicate its ±1σ uncertainty. The observed limit is given by the solid red line, and the red dotted lines show the variations of the observed limit due to a ±1σ change in the signal theoretical cross-section. The parameter spaces below the limit contours are excluded at 95% CL.

assumption is not valid, hence only limits for the $\chi^+ \partial^\mu \chi H^\dagger D^\mu H$ and $\bar{\chi} \gamma^\mu \chi B_{\mu \nu} H^\dagger D^\nu H$ operators are shown in Figure 5 for regions of parameter space where the kinematic assumption holds.

For both operators shown in Figure 5 corresponding to either fermionic or scalar DM candidates, the limits achieved by this analysis are a few times stronger than the prior ATLAS search for DM production in association with a Higgs boson where the Higgs boson decays to a pair of photons [16]. For the $\chi^+ \partial^\mu \chi H^\dagger D^\mu H$ operator, the $Z$ coupling between DM and nucleon leads to a sizable cross-section for direct detection, and results from the LUX Collaboration [104] exclude larger regions of parameter space than this search. However, the LUX limits are not applicable if the DM is inelastic leading to insufficient energy transition for direct detection. The upper limit on the branching ratio of the $Z$ boson decaying invisibly places stronger constraints for this model for DM with mass values below half of the $Z$ boson mass. For the lowest $m_\chi$ region not excluded by results from searches for invisible Higgs boson decays or invisible $Z$ boson decays near $m_\chi = m_H/2$, with the kinematic assumption, values of $\Lambda$ up to 24, 91, and 270 GeV are excluded for the $\chi i y s_\chi |H|^2$, $\chi^4 \partial^\mu \chi H^\dagger D^\mu H$, and $\bar{\chi} \gamma^\mu \chi B_{\mu \nu} H^\dagger D^\nu H$ operators respectively; values of $\lambda$ above 6.7 are excluded for the $|\chi|^2 |H|^2$ operator.
Figure 5: Limits at 95% CL on the suppression scale $\Lambda$ as a function of the DM mass ($m_\chi$) for EFT operators $\bar{\chi}\gamma\gamma\chi B_{\mu\nu}H^\dagger D_{\mu\nu}H$ (left) and $\chi^\dagger D_{\mu\nu}H^\dagger D_{\nu\lambda}H$ (right). Solid black lines are due to $h\rightarrow bb+E_{T}^{\text{miss}}$ (this article); regions below the lines are excluded. Results where EFT truncation is applied are also shown, assuming coupling values $g = \sqrt{g_q g_\chi} = 1$ (line with circles), $4\pi$ (line with squares). The $g = 4\pi$ case overlaps with the no-truncation result. The solid green line with hash marks indicates regions excluded by collider searches for $h\rightarrow \gamma\gamma+E_{T}^{\text{miss}}$ [16]. In the right figure, the region below the dashed blue line fails the perturbativity requirement, the red line indicates regions excluded by upper limits on the invisible branching ratio (BR) of the $Z$ boson [103], and the magenta line indicates regions excluded by the LUX Collaboration [104].

10 Conclusion

A search has been carried out for dark matter pair production in association with a Higgs boson that decays into two $b$-quarks, using 20.3 fb$^{-1}$ of $pp$ collisions collected at $\sqrt{s} = 8$ TeV by the ATLAS detector at the LHC. Two techniques are employed, one in which the two $b$-quark jets from the Higgs boson decay are reconstructed separately (resolved), and the other in which they are found inside a single large-radius jet using boosted jet techniques (boosted). A set of increasing $E_{T}^{\text{miss}}$ thresholds defines the final signal regions for each channel, optimized for individual signals in the parameter space probed.

The numbers of observed events are found to be consistent with Standard Model predictions. Results from the resolved channel are used to set constraints in regions of parameter space for a $Z'$-two-Higgs-doublet simplified model. For $m_A = 300$ GeV, $m_{Z'} = 700$–1300 GeV is excluded for $\tan\beta < 2$, with further exclusion of larger $m_A$ when $\tan\beta = 1$. The boosted channel results are interpreted in the framework of different effective field theory operators that describe the interaction between dark matter particles and the Higgs boson. In addition, model-independent upper limits are placed in both channels on the visible cross-section of events with large missing transverse momentum and a Higgs boson decaying to two $b$-quarks for each of the ascending $E_{T}^{\text{miss}}$ thresholds up to $E_{T}^{\text{miss}} > 400$ GeV.
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