Search for Dark Matter Produced in Association with a Higgs Boson Decaying to $b\bar{b}$ Using 36 fb$^{-1}$ of $pp$ Collisions at $\sqrt{s} = 13$ TeV with the ATLAS Detector

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Several extensions of the standard model predict associated production of dark-matter particles with a Higgs boson. Such processes are searched for in final states with missing transverse momentum and a Higgs boson decaying to a $b\bar{b}$ pair with the ATLAS detector using 36.1 fb$^{-1}$ of $pp$ collisions at a center-of-mass energy of 13 TeV at the LHC. The observed data are in agreement with the standard model predictions and limits are placed on the associated production of dark-matter particles and a Higgs boson.

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One of the central open questions in physics today is the nature of dark matter (DM) that comprises most of the matter in the Universe [1]. A compelling candidate for DM is a stable electrically neutral particle $\chi$ whose nongravitational interactions with standard model (SM) particles are weak. This extension of the SM could be detectable at the scale of electroweak symmetry breaking [2] and accommodate the observed DM relic density [3,4]. Many models predict detectable production rates of such DM particles at the Large Hadron Collider (LHC) [5].

Most collider-based searches for DM rely on the signature of missing transverse momentum [6] $E_T^{\text{miss}}$ from DM particles recoiling against one SM particle $X$ radiated off the initial state, denoted by the “$X+E_T^{\text{miss}}$” signature. LHC experiments have searched for this $X+E_T^{\text{miss}}$ signature, where $X$ is a light quark or gluon [7–9], a $b$ or $t$ quark [10–12], a photon [13–17], or a $W$ or $Z$ boson [18–21]. The discovery of the Higgs boson $h$ [22,23] opens a new opportunity through the $h+E_T^{\text{miss}}$ signature [24–26]. Because $h$ radiation off the initial state is Yukawa suppressed, the $h+E_T^{\text{miss}}$ process represents a direct probe of the hard interaction involving DM particles.

This Letter presents a search for DM in association with a Higgs boson decaying to a pair of $b$ quarks, $h \rightarrow b\bar{b}$, with a branching ratio $B = 57\%$ [27], using 36.1 fb$^{-1}$ of $pp$ collisions at $\sqrt{s} = 13$ TeV recorded with the ATLAS detector [28,29] in run 2 of the LHC in 2015 and 2016. This search substantially extends the sensitivity relative to previous results at 8 [30,31] and 13 TeV [32–34] in the $h \rightarrow b\bar{b}$ and $h \rightarrow gg$ channels.

A type-II two-Higgs-doublet model (2HDM) with an additional $U(1)_X$ gauge symmetry yielding an additional massive $Z'$ boson provides an $h+E_T^{\text{miss}}$ signature [26] used for the optimization of the search and its interpretation. This model results in five physical Higgs bosons: a light scalar $h$ identified with the SM Higgs boson in the alignment limit [35], a heavy scalar $H$, a pseudoscalar $A$, and two charged scalars $H^\pm$. The $h+DM$ signal in this $Z'$-2HDM model is produced through $pp \rightarrow Z' \rightarrow Ah$, where $A$ decays to $\chi \chi$ with a large $B$. Relevant model parameters are the ratio of the vacuum expectation values of the two Higgs fields coupling to the up-type and down-type quarks $\tan\beta$, the $Z'$ gauge coupling $g_{Z'}$, and the masses $m_{Z'}$, $m_A$, and $m_\chi$. The results are also generically interpreted in terms of the production cross section of non-SM events with large $E_T^{\text{miss}}$ and a Higgs boson without extra model assumptions.

Monte Carlo (MC) event generators were used to simulate the $h+DM$ signal and all SM background processes, except the multijet background, which was evaluated using data. All MC event samples were processed through a detailed simulation of the ATLAS detector [36] based on GEANT4 [37], and contributions from additional $pp$ interactions (pileup) were simulated using PYTHIA 8.186 [38] and the MSTW2008LO parton distribution function (PDF) set [39].

Signal samples for the $pp \rightarrow Z' \rightarrow Ah \rightarrow \chi \chi b\bar{b}$ process were generated at leading order using MADGRAPH_AMC@NLO 2.2.3 [5,40] interfaced to PYTHIA 8.186, using the NNPDF3.0 PDF set [41]. Samples were generated in the $(m_{Z'},m_A)$ plane for 0.2 TeV < $m_{Z'}$ < 3 TeV and 0.2 TeV < $m_A$ < 0.8 TeV with $m_\chi = 100$ GeV, $\tan\beta = 1$, $g_{Z'} = 0.8$, $m_H = m_{H'} = 300$ GeV [5].

Backgrounds from top quark pair production and single top quark production were generated at next-to-leading order (NLO) in quantum chromodynamics (QCD) with POWHEG-BOX [42–46] using CT10 PDFs [47], where the parton shower was simulated with PYTHIA 6.428 [48]. The $t\bar{t}$ samples are normalized using calculations at next-to-next-to-leading order (NNLO) in QCD including
next-to-next-to-leading logarithmic corrections for soft-gluon radiation [49]. The single-top-quark processes are normalized with cross sections at NLO in QCD [50–54]. Background processes involving a vector boson $V = W, Z$ decaying leptonically in association with jets, $V + j$, were simulated with SHERPA 2.2.1 [55] including mass effects for $b$ and $c$ quarks and using NNPDF3.0 PDFs. The perturbative calculations for $V + j$ were performed at NLO for up to two partons and at leading order for up to four partons [56,57], and matched to the parton shower [58] using the ME+PS@NLO prescription from Ref. [59]. The normalizations are determined at NNLO in QCD [60]. Diboson processes ($VV$) were simulated at NLO in QCD with SHERPA 2.1.1 and CT10 PDFs. Backgrounds from associated $Vh$ production were generated with PYTHIA 8.186 using NNPDF3.0 PDFs for $gg → Vh$, and POWHEG interfaced to PYTHIA 8.186 using CT10 PDFs for $gg → Vh$.

Events are selected by an $E_T^{\text{miss}}$ trigger based on calorimeter information [61]. Its threshold was 110 GeV for most of the data taking period, and lower in the first third. Events are required to have at least one $pp$ collision vertex reconstructed from at least two inner detector (ID) tracks with $p_T^{\text{track}} > 0.4$ GeV. The primary vertex (PV) for each event is the vertex with the highest $\sum (p_T^{\text{track}})^2$.

Reconstruction of muons ($\mu$) incorporates tracks or track segments found in the muon spectrometer and matched ID tracks. Identified muons must satisfy the “loose” quality criteria [62] and have $|\eta| < 2.7$. Electrons ($e$) are reconstructed by matching an ID track to a cluster of energy in the calorimeter. Electron candidates are identified through a likelihood-based method [63] and must satisfy the loose operating point and be within $|\eta| < 2.47$. Muon and electron candidates must have $p_T > 7$ GeV and are required to be isolated by limiting the sum of $p_T$ for tracks within a cone in $\Delta R$ around the lepton direction, as in Ref. [32].

Jets reconstructed from three-dimensional clusters of calorimeter cells [64] with the anti-$k_t$ algorithm [65] are used to identify the $h → bb$ decay. For small to moderate $h$ momenta, the decay products can be resolved using jets with a radius parameter $R = 0.4$ (small-$R$ jets or $j$). The decay products of high-momenta $h$ become collimated and are reconstructed using a single jet with $R = 1.0$ (large-$R$ jet or $j$). Small-$R$ jets with $|\eta| < 2.5$ must satisfy $p_T > 20$ GeV and are called “central,” while those with $2.5 < |\eta| < 4.5$ must have $p_T > 30$ GeV and are called “forward.” Small-$R$ jets are corrected for pileup [66], and central small-$R$ jets with $20$ GeV $< p_T < 60$ GeV and $|\eta| < 2.4$ are additionally required to be identified as originating from the PV using associated tracks [67]. Small-$R$ jets closer than $\Delta R = 0.2$ to an electron candidate are rejected. Large-$R$ jets are reconstructed independently of small-$R$ jets and trimmed [68,69] to reduce the effects of pileup and the underlying event. Furthermore, large-$R$ jets must fulfill $p_T > 200$ GeV and $|\eta| < 2.0$. To improve the resolution and minimize uncertainties, the mass of large-$R$ jets is determined by the resolution-weighted mean of the mass measured using calorimeter information alone and the track-assisted jet mass [70]. The latter is obtained by scaling the mass determined using ID tracks alone by the ratio of jet $p_T$ measured in the calorimeter and in the ID.

Multivariate algorithms are used to identify jets containing $b$ hadrons ($b$ tagging), which are expected in $h → bb$ decays [69,71]. These algorithms are applied directly to small-$R$ jets, while for large-$R$ jets they are applied to track jets matched to large-$R$ jets. Track jets are reconstructed from ID tracks matched to the PV using the anti-$k_t$ algorithm with $R = 0.2$, and must fulfill $p_T > 10$ GeV and $|\eta| < 2.5$.

The $E_T^{\text{miss}}$ observable is calculated as the negative of the vector sum of the transverse momenta of $e$, $\mu$, and jet candidates in the event. The transverse momenta not associated with any $e$, $\mu$, or jet candidates are accounted for using ID tracks [72,73]. Similarly, $p_T^{\text{miss,track}}$ is defined as the negative of the vector sum of the transverse momenta of tracks with $p_T > 0.5$ GeV associated with the PV and within $|\eta| < 2.5$.

The signal is characterized by high $E_T^{\text{miss}}$, no isolated leptons, and an invariant mass of the $h$ candidate $m_h$ compatible with the observed Higgs boson mass of 125 GeV [74]. In the signal region (SR) described below, the dominant backgrounds from $Z(\nu\bar{\nu}) + j$, $W + j$, and $t\bar{t}$ production contribute, respectively, 30%–60%, 10%–25%, and 15%–50% of the total background, depending on $E_T^{\text{miss}}$ and the $b$-tag multiplicity. The models for $V + j$ and $t\bar{t}$ are constrained using two control regions (CR): the single-muon control region (1$\mu$-CR) is designed to constrain the $t\bar{t}$ and $W + j$ backgrounds, while the two-lepton control region (2$\ell$-CR) constrains the $Z + j$ background contribution.

The SR requires $E_T^{\text{miss}} > 150$ GeV, and no isolated $e$ or $\mu$. The multijet background contributes due to mismeasured jet momenta. To suppress it, additional selections are required: $\min(\Delta\phi(E_T^{\text{miss}}, p_T^{\text{miss}})) > \pi/9$ for the three highest-$p_T$ (leading) small-$R$ jets, $\Delta\phi(E_T^{\text{miss}}, p_T^{\text{miss,track}}) < \pi/2$, and $p_T^{\text{miss,track}} > 30$ GeV for events with fewer than two central $b$-tagged small-$R$ jets. The requirements using $p_T^{\text{miss,track}}$ also reduce noncollision backgrounds.

In the “resolved” regime, defined by $E_T^{\text{miss}} < 500$ GeV, the $h$ candidate is reconstructed from two leading $b$-tagged central small-$R$ jets, or, if only one $b$ tag is present in the event, from the $b$-tagged central small-$R$ jet and the leading non-$b$-tagged central small-$R$ jet. At least one of the jets comprising the $h$ candidate must satisfy $p_T > 45$ GeV. A separation in $\Delta\phi$ between the $h$ candidate and $E_T^{\text{miss}}$ of more than $2\pi/3$ is required following the back-to-back configuration of the Higgs boson recoiling against DM. To improve the trigger efficiency modeling, events are retained only if the scalar sum $H_T$ of the $p_T$ of the two (three) leading jets fulfills $H_{T,2j} > 120$ GeV ($H_{T,3j} > 150$ GeV) if two (more
than two) central jets are present. Further optimization of the event selection described below provides an additional background reduction of up to 60% relative to Ref. [32], for a small signal loss. Events with a hadronic τ-lepton candidate, identified either by an algorithm based on a boosted decision tree [75] or as small-R jets containing one to four tracks within the jet core and $\Delta \phi(E_T^{\text{miss}}, \vec{p}_T^j) < \pi/8$, are rejected to reduce the $t\bar{t}$ background, which can enter the SR if at least one top quark decays as $t \rightarrow Wb \rightarrow \tau\bar{b}$. This background is further reduced by removing events with more than two $b$-tagged central jets, which typically happens for $t\bar{t}$ events with $t \rightarrow Wb \rightarrow csb$ decays. Since most of the hadronic activity in a signal event is expected from the $h \rightarrow b\bar{b}$ decay, the scalar sum of the $p_T$ of the two jets forming the $h$ candidate and, if present, the highest-$p_T$ additional jet must be larger than 0.63 $\times$ $H_T$ all jets. Finally, $\Delta R(\vec{p}_T^1, \vec{p}_T^2) < 1.8$ is required for the two jets forming the $h$ candidate.

In the “merged” regime, defined by $E_T^{\text{miss}} > 500$ GeV, the leading large-$R$ jet represents the $h$ candidate. Further selection optimization reduces backgrounds, primarily $t\bar{t}$ production, by up to 30% relative to Ref. [32], for a small signal loss: events containing $r$-tagged candidates with $\Delta R(\vec{p}_T, \vec{p}_T^r) > 1.0$ are vetoed; no $b$-tagged central small-$R$ jets with $\Delta R(\vec{p}_T^{b\text{-tag}}, \vec{p}_T) > 1.0$ are allowed in the event; and the scalar sum of $p_T$ of the small-$R$ jets with $\Delta R(\vec{p}_T, \vec{p}_T^r) > 1.0$ is required to be smaller than 0.57 times that sum added to $p_T^r$.

The resolution in $m_h$ is improved using muons associated with small-$R$ jets in the resolved regime or with track jets matched to large-$R$ jets in the merged regime [69,76]. The event selection in the $1\mu$-CR is identical to the SR, except that exactly one isolated $\mu$ candidate with $p_T^\mu > 27$ GeV is required, and that $p_T^\mu$ is added to $E_T^{\text{miss}}$ to mimic the behavior of events contaminating the SR when the charged lepton is not detected.

Events in the $2\ell$-CR are collected using a single-$e$ or single-$\mu$ trigger, and selected by requiring one pair of isolated $e$ or $\mu$, one of which must have $p_T^\ell > 27$ GeV. Events with a Z boson candidate are retained, identified as having $83$ GeV < $m_{ee}$ < $99$ GeV or $71$ GeV < $m_{\mu\mu}$ < $106$ GeV with an opposite-charge requirement in the $\mu\mu$ case. In addition, a measure of the $E_T^{\text{miss}}$ significance given by the ratio of the $E_T^{\text{miss}}$ to the square root of the scalar sum of $p_T$ of all leptons and small-$R$ jets in the event must be less than 3.5 GeV$^{1/2}$. This requirement separates $Z(\ell\ell)$ + jets processes from $t\bar{t}$ production, as $E_T^{\text{miss}}$ originates from finite detector resolution for the former and mainly from neutrinos for the latter. To mimic $Z \rightarrow \nu\nu$ decays in the SR, the $E_T^{\text{miss}}$ is set to the $\vec{p}_T$ of the dilepton system, which is then ignored in the subsequent analysis. All other selection requirements are identical between the $2\ell$-CR and the SR.

Subdominant backgrounds, including diboson, $Vh$, single top quark, and multijet production, contribute less than 10% of the total background in the SR. Multijet production is negligible for $E_T^{\text{miss}} > 350$ GeV. Its $m_h$ distribution is determined from data in a dedicated multijet-enriched sideband, defined by inverting the min $[\Delta \phi(E_T^{\text{miss}}, \vec{p}_T^j)]$ requirement.

Dominant sources of experimental systematic uncertainty arise from the number of background MC events, the calibration of the $b$-tagging efficiency and integrated luminosity, as well as the scale and resolution of the energy and the mass of jets. Uncertainties associated with the $\tau$ vetoes are found to be negligible. Dominant sources of theoretical systematic uncertainty originate from the modeling of the signal and background processes such as $t\bar{t}$, $V +$ jets, $Vh$, diboson, and multijet production. The few relevant changes in the estimation of systematic uncertainties relative to Ref. [32] encompass the improved calibrations of the $b$-tagging efficiency using $t\bar{t}$ events [69,71] as well as of the jet energy and mass scales using various in situ methods [70,77]; the reduced uncertainty from the new jet-mass observable [69,70]; and the uncertainty of 3.4% on the integrated luminosity of data collected in 2016.

Table I quantifies dominant sources of uncertainty after the fit to data assuming three representative $Z'$-2HDM scenarios. This search is statistically limited for $E_T^{\text{miss}} \geq 300$ GeV.

A fit to the $m_h$ observable based on a binned likelihood approach [78,79] is used to search for a signal. Systematic uncertainties are included in the likelihood function as nuisance parameters with Gaussian or log-normal constraints and profiled [76]. To account for changes in the background composition and to benefit from a higher signal sensitivity with increasing $E_T^{\text{miss}}$ and $b$-tag multiplicity, the data are split into categories that are fit

<table>
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<th>Impact [%]</th>
<th>(a)</th>
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<td>Jets with $R = 0.4$</td>
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<td>12</td>
<td>43</td>
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simultaneously. Eight categories are defined for the SR and each of the two CRs: four ranges in $E_{\text{miss}}$ in GeV as [150, 200), [200, 350), [350, 500), and [500, $\infty$), which are each split into two subregions with one and two $b$ tags. In the $1\mu$-CR, the electric charge of the $\mu$ is used to separate $t\bar{t}$ from $V +$ jets since the former provides an equal number of $\mu^+$ and $\mu^-$, while a prevalence of $\mu^-$ is expected from the latter process due to PDFs [80]. Only the total event yield is considered in the $2\ell$-CR due to limited data statistics. The normalizations of $t\bar{t}$, $W +$ HF, and $Z +$ HF processes are free parameters in the fit, where HF represents jets containing $b$ or $c$ quarks. In the SR, the contribution from $Z +$ jets is increased by about 50% by the fit relative to theory predictions, staying within uncertainties, while $t\bar{t}$ is reduced by up to 30% at high $E_{\text{miss}}$. The normalizations of other backgrounds modeled using MC simulations are constrained to theory predictions within uncertainties, as detailed in Ref. [32].

The distributions of $m_{h}$ for SR events with two $b$ tags provide the highest signal sensitivity and are shown in the four $E_{\text{miss}}$ regions in Fig. 1. No significant deviation from SM predictions is observed.

The results are interpreted as exclusion limits at 95% confidence level (C.L.) on the production cross section of $h +$ DM events $\sigma_{h+\text{DM}}$ times $B(h \to b\bar{b})$ with the CLs formalism [81] using a profile likelihood ratio [82] as test statistic. Exclusion contours in the $(m_{Z'}, m_A)$ space in the $Z'$-2HDM scenario are presented in Fig. 2, excluding $m_{Z'}$ up to 2.6 TeV and $m_A$ up to 0.6 TeV, substantially extending previous limits [30–34]. Furthermore, upper limits on $\sigma_{h+\text{DM}} \times B(h \to b\bar{b})$ are provided under the minimal $h +$ DM model assumption that a Higgs boson is produced in a generic back-to-back configuration relative to $E_{\text{miss}}$.

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from DM particles. For this, limits are set on \( \sigma_{\text{vis},h(b\bar{b})+\text{DM}} \equiv \sigma_{h+\text{DM}} \times B(h \to b\bar{b}) \times A \times \epsilon \) of \( h(b\bar{b}) + \text{DM} \) events per \( E_T^{\text{miss}} \) bin at detector level, after all SR selections except the requirements on \( b\)-tag multiplicity and \( m_h \) range as used in the fit. The \( A \times \epsilon \) term quantifies the probability for an event to be reconstructed in the same \( E_T^{\text{miss}} \) bin as generated and to pass all \( \sigma_{\text{vis},h(b\bar{b})+\text{DM}} \) selections, where \( A \) represents the kinematic acceptance and \( \epsilon \) accounts for the experimental efficiency. The results are shown in Table II. To minimize the dependence on the \( E_T^{\text{miss}} \) distribution of a potential \( h + \text{DM} \) signal, the standard fit approach is modified to analyze one \( E_T^{\text{miss}} \) range at a time in the SR. The \( Z'\)-2HDM model is used to evaluate the dependence of the \( \sigma_{\text{vis},h(b\bar{b})+\text{DM}} \) limits and of \( A \times \epsilon \) on the event kinematics within a given \( E_T^{\text{miss}} \) bin. A range of \((m_Z',m_A)\) parameters that yield a sizable contribution of \( \gtrsim 10\% \times \sigma_{h+\text{DM}} \times B(h \to b\bar{b}) \) in a given \( E_T^{\text{miss}} \) bin is considered. Corresponding variations of 25\% (70\%) in the expected limits and of 50\% (25\%) in \( A \times \epsilon \) are found in the resolved (merged) regime. Table II quotes the least stringent limit and the lowest \( A \times \epsilon \) value in a given \( E_T^{\text{miss}} \) bin after rounding. The limits are valid for \( p_T,h \lesssim 1.5 \text{ TeV} \).

In summary, a search for DM produced in association with a Higgs boson in final states with \( E_T^{\text{miss}} \) and a \( b\bar{b} \) pair from the \( h \to b\bar{b} \) decay was conducted using 36.1 fb\(^{-1}\) of \( pp \) collisions at \( \sqrt{s} = 13 \text{ TeV} \) recorded by the ATLAS detector at the LHC. The results are in agreement with SM predictions, and a substantial region of the parameter space of a representative \( Z'\)-2HDM model is excluded, significantly improving upon previous results. Stringent limits are also placed on the production cross section of non-SM events with large \( E_T^{\text{miss}} \) and a Higgs boson without extra model assumptions.

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For a full list of all authors and of all collaborating institutions, see Ref. [83].
points to the center of the LHC ring, and the y axis points upward. Cylindrical coordinates $(r, \phi)$ are used in the transverse plane, $\phi$ being the azimuthal angle around the $z$ axis. The pseudorapidity is defined in terms of the polar angle $\theta$ as $\eta = -\ln \tan(\theta/2)$. The distance between two objects in $\eta$-$\phi$ space is $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}$. Transverse momentum is defined by $p_T = p \sin \theta$.


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