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 χ 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^{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, $h \to b\bar{b}$, with a branching ratio $\mathcal{B} = 57\%$ [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 $h \to b\bar{b}$ and $h \to \gamma\gamma$ channels.

A type-II two-Higgs-doublet model (2HDM) with an additional $\text{U}(1)_{Z'}$ 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 $h + \text{DM}$ signal in this Z'-2HDM model is produced through $pp \to Z' \to Ah$, where A decays to $\chi\bar{\chi}$ with a large $\mathcal{B}$. 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_χ. The results are also generically interpreted in terms of the production cross section of non-SM events with large E_T^{miss} and a Higgs boson without extra model assumptions.

Monte Carlo (MC) event generators were used to simulate the $h + \text{DM}$ 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 $pp \to Z' \to Ah \to \chi\bar{\chi}b\bar{b}$ 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 $0.2\ \text{TeV} < m_{Z'} < 3\ \text{TeV}$ and $0.2\ \text{TeV} < m_A < 0.8\ \text{TeV}$ with $m_\chi = 100$ GeV, $\tan\beta = 1$, $g_{Z'} = 0.8$, $m_H = m_{H^\pm} = 300$ 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

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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, $V+$jets, 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 $V+$jets 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 $qq \to Vh$, and POWHEG interfaced to PYTHIA 8.186 using CT10 PDFs for $gg \to Vh$.

Events are selected by an $E_T^{\rm miss}$ 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 $p_T^{\rm track} > 0.4$ GeV. The primary vertex (PV) for each event is the vertex with the highest $\sum (p_T^{\rm track})^2$.

Reconstruction of muons (μ) 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 ΔR 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 $h \to b\bar{b}$ 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 $h \to b\bar{b}$ 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 $\vec{E}_T^{\rm miss}$ observable is calculated as the negative of the vector sum of the transverse momenta of e, μ, and jet candidates in the event. The transverse momenta not associated with any e, μ, or jet candidates are accounted for using ID tracks [72,73]. Similarly, $\vec{p}_T^{\rm miss,trk}$ 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 $E_T^{\rm miss}$, 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 $Z(\nu\nu)+$jets, $W+$jets, and $t\bar{t}$ production contribute, respectively, 30%–60%, 10%–25%, and 15%–50% of the total background, depending on $E_T^{\rm miss}$ and the b-tag multiplicity. The models for $V+$jets and $t\bar{t}$ are constrained using two control regions (CR): the single-muon control region (1μ-CR) is designed to constrain the $t\bar{t}$ and $W+$jets backgrounds, while the two-lepton control region (2ℓ-CR) constrains the $Z+$jets background contribution.

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

In the "resolved" regime, defined by $E_T^{\rm miss} < 500$ 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 $\vec{E}_T^{\rm miss}$ 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 $\Delta\phi(\vec{E}_T^{\rm miss}, \vec{p}_T^{\,j}) < \pi/8$, are rejected to reduce the $t\bar{t}$ background, which can enter the SR if at least one top quark decays as $t \to Wb \to \tau\nu b$. 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 $t \to Wb \to csb$ decays. Since most of the hadronic activity in a signal event is expected from the $h \to b\bar{b}$ 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 $0.63 \times H_{T,\rm all\,jets}$. Finally, $\Delta R(\vec{p}_h^{\,j_1}, \vec{p}_h^{\,j_2}) < 1.8$ is required for the two jets forming the h candidate.

In the "merged" regime, defined by $E_T^{\rm miss} > 500$ 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 τ-lepton candidates with $\Delta R(\vec{p}^{\,\tau}, \vec{p}^{\,J}) > 1.0$ are vetoed; no b-tagged central small-R jets with $\Delta R(\vec{p}^{\,j,b\text{-tag}}, \vec{p}^{\,J}) > 1.0$ are allowed in the event; and the scalar sum of p_T of the small-R jets with $\Delta R(\vec{p}^{\,j}, \vec{p}^{\,J}) > 1.0$ is required to be smaller than 0.57 times that sum added to p_T^J.

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 1μ-CR is identical to the SR, except that exactly one isolated μ candidate with $p_T^\mu > 27$ GeV is required, and that $\vec{p}_T^{\,\mu}$ is added to $\vec{E}_T^{\rm miss}$ to mimic the behavior of events contaminating the SR when the charged lepton is not detected.

Events in the 2ℓ-CR are collected using a single-e or single-μ trigger, and selected by requiring one pair of isolated e or μ, 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 $E_T^{\rm miss}$ significance given by the ratio of the $E_T^{\rm miss}$ 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 $E_T^{\rm miss}$ originates from finite detector resolution for the former and mainly from neutrinos for the latter. To mimic $Z \to \nu\nu$ decays in the SR, the $\vec{E}_T^{\rm miss}$ 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 2ℓ-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 $E_T^{\rm miss} > 350$ GeV. Its m_h distribution is determined from data in a dedicated multijet-enriched sideband, defined by inverting the min $[\Delta\phi(\vec{E}_T^{\rm miss}, \vec{p}_T^{\,j})]$ 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 τ 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 $E_T^{\rm miss} \gtrsim 300$ 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 $E_T^{\rm miss}$ and b-tag multiplicity, the data are split into categories that are fit

TABLE I. Dominant sources of uncertainty for three representative Z'-2HDM scenarios after the fit to data (a) with $(m_{Z'}, m_A) = (0.6, 0.3\,\text{TeV})$, (b) with $(m_{Z'}, m_A) = (1.4, 0.6\,\text{TeV})$, and (c) with $(m_{Z'}, m_A) = (2.6, 0.3$ TeV). The effect is expressed as the fractional uncertainty on the signal yield. The total is the quadrature sum of statistical and total systematic uncertainties. The impact of the luminosity uncertainty, which does not affect backgrounds with free normalizations, varies due to the changing background composition with increasing $E_T^{\rm miss}$.

Source of uncertainty	Impact [%]		
	(a)	(b)	(c)
$V+$jets modeling	5.0	5.7	8.2
$t\bar{t}$, single-t modeling	3.2	3.0	3.9
SM $Vh(b\bar{b})$ normalization	2.2	6.9	6.9
Signal modeling	3.9	2.9	2.1
MC statistics	4.9	11	22
Luminosity	3.2	4.5	5.4
b tagging, track jets	1.4	11	17
b tagging, calo jets	5.0	3.4	4.7
Jets with $R = 0.4$	1.7	3.8	2.1
Jets with $R = 1.0$	<0.1	1.2	4.7
Total systematic uncertainty	10	21	36
Statistical uncertainty	6	38	62
Total uncertainty	12	43	71

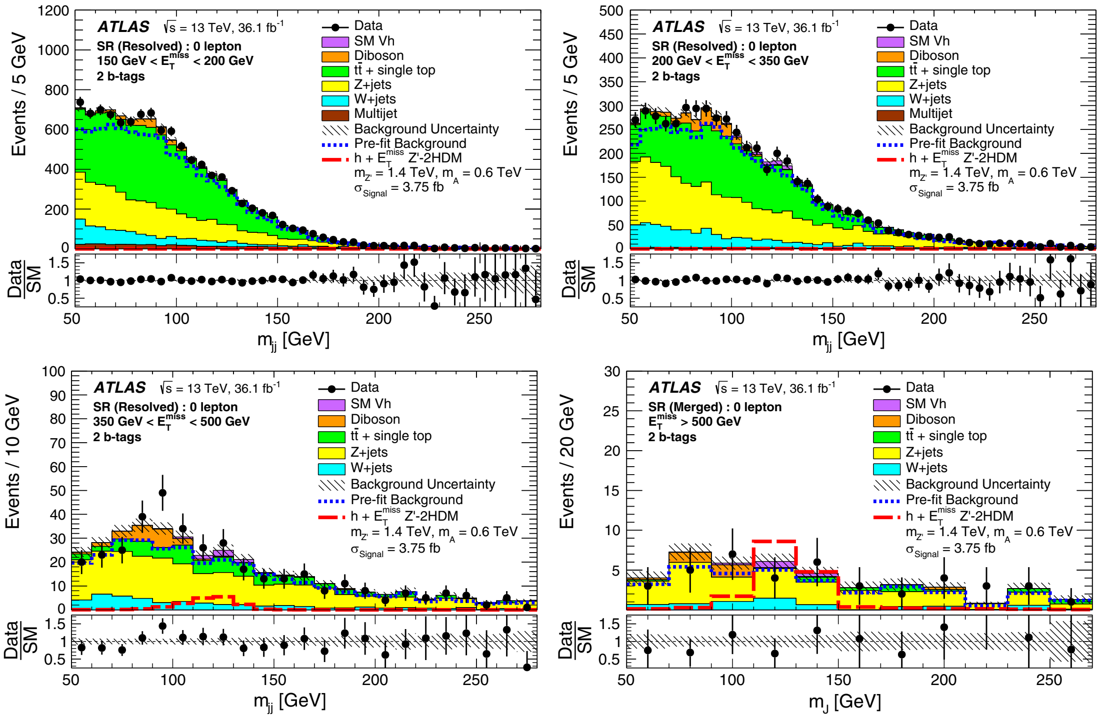

FIG. 1. Distributions of the invariant mass of the Higgs boson candidates $m_h = m_{jj}, m_J$ with two b tags in the SR for the four E_T^{miss} categories that are used as inputs to the fit. The upper panels show a comparison of data to the SM expectation before (dashed lines) and after the fit (solid histograms) with no signal included. The lower panels display the ratio of data to SM expectations after the fit, with its systematic uncertainty considering correlations between individual contributions indicated by the hatched band. The expected signal from a representative Z'-2HDM model is also shown (long-dashed line).

simultaneously. Eight categories are defined for the SR and each of the two CRs: four ranges in E_T^{miss}/GeV as [150, 200), [200, 350), [350, 500), and [500, ∞), which are each split into two subregions with one and two b tags. In the 1μ-CR, the electric charge of the μ is used to separate $t\bar{t}$ from $V+$jets since the former provides an equal number of μ^+ and μ^-, while a prevalence of μ^+ is expected from the latter process due to PDFs [80]. Only the total event yield is considered in the 2ℓ-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_T^{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_T^{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 $\mathcal{B}(h\to b\bar{b})$ with the CL_s 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 $\sigma_{h+\text{DM}} \times \mathcal{B}(h\to b\bar{b})$ are provided under the minimal $h+$DM model assumption that a Higgs boson is produced in a generic back-to-back configuration relative to $\vec{E}_T^{\text{miss}}$

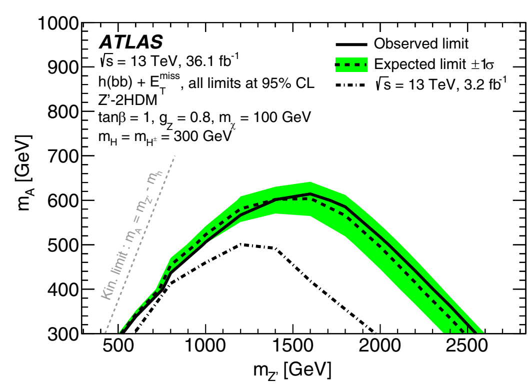

FIG. 2. Exclusion contours for the Z'-2HDM scenario in the $(m_{Z'}, m_A)$ plane for $\tan\beta = 1$, $g_{Z'} = 0.8$, and $m_\chi = 100$ GeV. The observed limits (solid line) are consistent with the expectation under the SM-only hypothesis (dashed line) within uncertainties (solid band). Observed limits from previous ATLAS results at $\sqrt{s} = 13$ TeV (dash-dotted line) [32] are also shown.

TABLE II. Observed (obs) and expected (exp) upper limits at 95% C.L. on $\sigma_{\mathrm{vis},h(b\bar{b})+\mathrm{DM}} \equiv \sigma_{h+\mathrm{DM}} \times \mathcal{B}(h \to b\bar{b}) \times \mathcal{A} \times \varepsilon$ of $h(b\bar{b}) + \mathrm{DM}$ events. Also shown are the acceptance × efficiency ($\mathcal{A} \times \varepsilon$) probabilities to reconstruct and select an event in the same E_T^{miss} bin as generated.

Range in E_T^{miss} [GeV]	$\sigma^{\mathrm{obs}}_{\mathrm{vis},h(b\bar{b})+\mathrm{DM}}$ [fb]	$\sigma^{\mathrm{exp}}_{\mathrm{vis},h(b\bar{b})+\mathrm{DM}}$ [fb]	$\mathcal{A} \times \varepsilon$ [%]
[150, 200)	19.1	$18.3^{+7.2}_{-5.1}$	15
[200, 350)	13.1	$10.5^{+4.1}_{-2.9}$	35
[350, 500)	2.4	$1.7^{+0.7}_{-0.5}$	40
[500, ∞)	1.7	$1.8^{+0.7}_{-0.5}$	55

from DM particles. For this, limits are set on $\sigma_{\mathrm{vis},h(b\bar{b})+\mathrm{DM}} \equiv \sigma_{h+\mathrm{DM}} \times \mathcal{B}(h \to b\bar{b}) \times \mathcal{A} \times \varepsilon$ of $h(b\bar{b}) + \mathrm{DM}$ events per E_T^{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 $\mathcal{A} \times \varepsilon$ term quantifies the probability for an event to be reconstructed in the same E_T^{miss} bin as generated and to pass all $\sigma_{\mathrm{vis},h(b\bar{b})+\mathrm{DM}}$ selections, where $\mathcal{A}$ represents the kinematic acceptance and ε accounts for the experimental efficiency. The results are shown in Table II. To minimize the dependence on the E_T^{miss} distribution of a potential $h + \mathrm{DM}$ signal, the standard fit approach is modified to analyze one E_T^{miss} range at a time in the SR. The Z'-2HDM model is used to evaluate the dependence of the $\sigma_{\mathrm{vis},h(b\bar{b})+\mathrm{DM}}$ limits and of $\mathcal{A} \times \varepsilon$ on the event kinematics within a given E_T^{miss} bin. A range of $(m_{Z'}, m_A)$ parameters that yield a sizable contribution of $\gtrsim 10\% \times \sigma_{h+\mathrm{DM}} \times \mathcal{B}(h \to b\bar{b})$ in a given E_T^{miss} bin is considered. Corresponding variations of 25% (70%) in the expected limits and of 50% (25%) in $\mathcal{A} \times \varepsilon$ are found in the resolved (merged) regime. Table II quotes the least stringent limit and the lowest $\mathcal{A} \times \varepsilon$ value in a given E_T^{miss} bin after rounding. The limits are valid for $p_{T,h} \lesssim 1.5$ TeV.

In summary, a search for DM produced in association with a Higgs boson in final states with E_T^{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 $\sqrt{s} = 13$ 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^{miss} and a Higgs boson without extra model assumptions.

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points to the center of the LHC ring, and the y axis points upward. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the z axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$. The distance between two objects in η–ϕ 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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